Lattice scattering and 1/f noise in semiconductors

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Lattice Scattering and 1/f Noise in Semiconductors

Xu-yuan Chen
LATTICE SCATTERING AND 1/f NOISE IN SEMICONDUCTORS

Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof. dr. M. Rem, voor een commissie aangewezen door het College van Dekanen in het openbaar te verdedigen op vrijdag 11 april 1997 om 16.00 uur

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# CONTENTS

## 1. General Introduction
- Electrical noise ................................................................. 1
- 1/f noise ............................................................................. 2
- Lattice scattering and 1/f noise ........................................... 4
- Scope of the thesis ............................................................ 5
- References .......................................................................... 7

## 2. 1/f noise in epilayers of semiconductors 9

### 2.1 Low frequency noise in p⁺-GaAs with non-alloyed contacts

- Introduction ........................................................................ 11
- Experiments ....................................................................... 11
- Results and discussion ....................................................... 11
- Conclusions ...................................................................... 12
- References ....................................................................... 12

### 2.2 Study of 1/f noise in InP grown by CBE

*Solid-State Electronics*, vol 39, no. 8, pp. 1149-1153, 1996
- Introduction ........................................................................ 13
- Experimental procedures .................................................... 14
- Experimental results and discussion ................................... 14
- Conclusions ...................................................................... 16
- References ....................................................................... 17

### 2.3 Low frequency noise in B-doped diamond grown by CVD

Submitted to Electronics letters.
- Introduction ........................................................................ 18
- Experiments ....................................................................... 18
- Noise measurements and results ........................................ 19
- Discussion ........................................................................ 20
- Conclusions ...................................................................... 21
- References ....................................................................... 22

## 3. Unsolved problems - temperature dependence of 1/f noise

- Introduction ........................................................................ 23
- Experimental results of $\alpha (T)$ ........................................ 24
- Discussion ........................................................................ 24
- Conclusions and questions ................................................ 27
- References ....................................................................... 30

## 4. The temperature dependence of 1/f noise in InP

*Solid-State Electronics,(1997) (in press)*
- Introduction ........................................................................ 31
- Experimental results......................................................... 31
- Discussion ........................................................................ 31
- Conclusions and questions ................................................ 31
- References ....................................................................... 31
Chapter 1

GENERAL INTRODUCTION

I ELECTRICAL NOISE

The term "noise" is used for the phenomenon of random spontaneous fluctuations in a quantity, like current, loudness of music, the level of the Nile, traffic flow, etc. In electronic systems, such spontaneous fluctuations - electrical noise - always manifest themselves as fluctuations in the voltage (or current) at terminals of electronic devices and systems. The noise originates in the random, microscopic behavior of the charge carriers, and hence it is inherent in the system itself.

Electrical noise, as an undesirable phenomenon, has been the subject of numerous investigations for a long time. Most people who study the origin of the electrical noise do this because they hope to find ways to eliminate the noise. The study of the electrical noise often leads to a better understanding of the transport mechanism of the free charge carriers, and hence to more insights in the physics of the systems [1].

This dissertation deals with the low-frequency noise in modern semiconductor materials. There are four important kinds of noise that are usually considered, thermal noise, shot noise, generation - recombination noise, and 1/f noise.

A Thermal noise

Thermal noise or Nyquist noise was first observed by Johnson [2 - 4] and therefore it is sometimes referred to as Johnson noise. This noise stems from the Brownian motion of the free charge carriers in thermal equilibrium. At frequencies low compared to the reciprocal of the collision time of the free charge carriers, the power spectral density of the short-circuit current fluctuation $S_I$ is a white noise and given by [5, 6]

$$S_I = 4 k T / R,$$

where $k$ is Boltzmann's constant, $T$ the temperature, and $R$ the resistance of the sample.

B Shot noise

Shot noise is generated when current carriers cross barriers independently and at random. The physical origin of the shot noise is a fluctuation in the emission rate of the charge carriers. At frequencies small compared to the reciprocal of the transit
time, the short-circuit power spectral density of the shot noise is white and given by [5, 6]

\[ S_T = 2qI, \] (2)

where q is the elementary charge and I the current through the sample.

C. Generation - recombination noise (g-r noise)

Traps and recombination centers are particular to semiconductors and semiconductor devices. The random trapping and detrapping of the charge carriers result in fluctuations in the number of the free charge carriers N. Hence, the conductance fluctuates. This fluctuation is called generation-recombination noise, or g-r noise for short. The power spectral density of g-r noise is given by [5, 6]

\[ S_N = \langle \Delta N^2 \rangle \cdot \frac{4\tau}{1 + (2\pi f^2 \tau)^2} \] (3)

where \( \tau \) is the relaxation time of the trapping process, \( \langle \Delta N^2 \rangle \) the variance of the fluctuations, and \( f \) the frequency.

D 1/f noise

1/f noise or flicker noise is named after its spectrum, where the power spectral density is inversely proportional to the frequency,

\[ S_X \propto \frac{1}{f}, \] (4)

with \( f \) the frequency. The index X can refer to voltage \( V \), current \( I \), resistance \( R \), conductance \( G \), etc.

The origins of the first three types of noise (A, B, C) are well understood. The origin of the 1/f noise still is a mystery, although an enormous amount of data has been accumulated on 1/f noise in electronic devices.

II 1/f NOISE

1/f noise is ubiquitous in physical systems. Therefore, it is expected that there is one physical principle behind all the mechanisms by which the 1/f noise is generated. The origin of the 1/f noise still has not been discovered, although several breakthroughs have been made concerning this problem [7 - 9]. Hooge's empirical relation provides a way to characterize the 1/f noise in homogeneous materials, see equation (5) [9],

\[ \frac{S_G}{G^2} = \frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{\alpha}{Nf}, \] (5)

where \( G \) is the conductance, \( R \) is the resistance, \( V \) is the voltage, \( I \) is the current, \( N \) is the total number of current carriers in the volume involved in the generation of
the 1/f noise, f is the frequency, and α is the Hooge parameter. This relation shows that the 1/f noise is a bulk effect and a fluctuation in the conductance. This empirical relation implies that the electrons contribute to the 1/f noise independently. From relation (5) one cannot say anything about the noise mechanisms, like for example, whether the noise is due to fluctuation of the mobility or the number of the free charge carriers. It has been clear for years now that the 1/N dependence is inherent to the 1/f noise [10 - 14]. The relative contribution per free charge carrier is given by α/f, therefore, one can approach the problem by studying which parameters control the α. At the time when the relation was proposed, α was considered as a universal constant of 2 x 10^-3. Because of the fact that α varied between 10^-7 and 10^-2 [15], much criticism arose against relation (5) [16 - 18]. It turned out that the noise in damaged materials is high [19]. If one notices the significant improvement in the quality of the samples grown by modern technology, such as MBE (molecular beam epitaxy) or CBE (chemical beam epitaxy), one can not be surprised by the wide range of α values found in materials prepared by different techniques. In our present view, α has not to be a universal constant for all materials. The spread in value of α cannot be an argument against the correctness of relation (5). On the other hand, the variety in α values for different samples, like for example, differently doped samples of the same material, gives more information on the basic properties of 1/f noise [20 - 22].

Concerning the origin of 1/f noise, all experimental findings cannot be explained by a single model. Nowadays, there are two competing models: the mobility fluctuation model [9], and the number fluctuation model [7]. In addition, the role of defects is a cause of much controversy [23].

1) The number fluctuation model was proposed by McWhorter [7], and was based on trap-induced charge carrier fluctuations. Under the preconditions of this model, it is easy to produce a 1/f law. However, this 1/f noise is attributed to a surface effect. The model is certainly challenged by bulk noise very frequently observed in semiconductors and other materials [9, 21, 22, 24 - 26].

2) The mobility fluctuation is a commonly discussed model for 1/f noise. Experimentally, the mobility fluctuation is well established [9, 15, 20 - 22, 25, 26]. However, a theory has not been developed. One can consider mobility fluctuations induced by bulk [25, 26] and surface [27], by lattice vibration modes [12, 20 - 22, 28], as well as by impurities and defects [8, 29, 30]. The mobility fluctuations in semiconductors have been adequately explained by the lattice scattering model. This thesis focuses on such a lattice scattering model.

3) Concerning the relation between defects and 1/f noise, it is widely accepted that 1/f noise in metal films is produced by mobile defects [8, 30]. By contrast, the 1/f noise in epilayers of GaAs and InP does not correlate with impurities, where the 1/f noise is assumed to be generated by phonon number fluctuations [19, 20]. Point defects created by electron irradiation in MBE GaAs do not produce 1/f noise either [31]. However, a so-called extrinsic noise is created in MBE GaAs damaged by proton-irradiation. This extrinsic noise is found to be strongly dependent on the degree of imperfection created by the proton irradiation [19]. In addition, damage due to mechanical stress also leads to very high 1/f noise.
There is a question whether the noise increase after damage results from a high degree of imperfection of the lattice as a whole, or whether the extra noise is directly generated by the defects themselves. What the precise relation is between defects and 1/f noise still is an open question.

III LATTICE SCATTERING 1/f NOISE

The fluctuation in mobility is interpreted by several models in correspondence with different generation mechanisms [9, 15], [12, 28], [29, 30], and [34, 35]. For each model, there are experiments in favor of it. Here I shall not spend time describing each model. Instead, more attention is paid to the mobility-fluctuation model developed by the Eindhoven group [9, 15]. For homogeneous semiconductors, the Eindhoven model is now moving to the lattice scattering model where the 1/f noise is generated by the lattice scattering only.

Mobility fluctuation 1/f noise has to be related to scattering mechanisms. Matthiessen's rule can be applied to different types of scattering mechanisms,

\[
\frac{1}{\mu_{\text{meas}}} = \frac{1}{\mu_{\text{Latt}}} + \frac{1}{\mu_{\text{imp}}},
\]

where \(\mu_{\text{meas}}\) is the measured mobility, \(\mu_{\text{Latt}}\) the mobility limited by lattice scattering, and \(\mu_{\text{imp}}\) the mobility limited by impurity scattering. The fluctuations in mobilities can be expressed as follows,

\[
\Delta \mu_{\text{meas}} = \left(\frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}}\right)^2 \times \Delta \mu_{\text{Latt}} + \left(\frac{\mu_{\text{meas}}}{\mu_{\text{imp}}}\right)^2 \times \Delta \mu_{\text{imp}}.
\]

If it is assumed that \(\Delta \mu_{\text{Latt}} \neq 0\) and \(\Delta \mu_{\text{imp}} = 0\), we obtain for the relative spectral noise density of the mobility fluctuations [9],

\[
\frac{S_{\mu_{\text{meas}}}}{\mu_{\text{meas}}^2} = \left(\frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}}\right)^2 \times \frac{S_{\mu_{\text{Latt}}}}{\mu_{\text{Latt}}^2}.
\]

From equation (5), it follows that

\[
\alpha_{\text{meas}} = \left(\frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}}\right)^2 \times \alpha_{\text{Latt}},
\]

where \(\alpha_{\text{meas}}\) is the normal Hooge parameter and \(\alpha_{\text{Latt}}\) is a material constant that probably depends on temperature. The physical meaning of this expression is that the 1/f noise is in the scattering cross-section of the lattice vibration modes, whereas impurity scattering does not play any role in generating the 1/f noise. Both \(\alpha_{\text{meas}}\) and \(\alpha_{\text{Latt}}\) have values that can be experimentally determined. They are not universal constants. The parameter \(\alpha_{\text{Latt}}\) may be different for different materials, but should be the same in different samples of the same material.
The cross-section fluctuates because the number of phonons fluctuates. To build up an 1/f spectrum, it is assumed that the number of the phonons fluctuates with an 1/f law in each mode. For the time being, a satisfactory theoretical explanation has not been reached for this assumption. There is ample experimental evidence for the correctness of equation (9) [9, 20 - 22]. The variation of the noise in differently doped samples of the same material is successfully explained by the lattice scattering model. Although experimental evidence for this model is continually accumulating, the model is also challenged, now and then, by some experimental findings [36, 37]. Therefore, further experiments will have to be carried out to confirm the model. What should be pointed out is that before analyzing the experimental results, one has to be sure where the noise comes from and how the noise sources distribute in a sample. Failing to understand the noise mechanisms described in the preceding sentence can bring one in a perplexing situation, and set an obstacle to discover the origin of the 1/f noise. For example, a kind of average $\alpha_{\text{meas}}$ for inhomogeneous samples cannot directly be substituted in relation (9), see chapters 5 and 6 in this thesis. In relation (9), the contributions by different phonons are not distinguished. The phonon scattering is treated as a simple phenomenon, described by a single value of $\alpha_{\text{Latt}}$. For further study, we can distinguish several scattering mechanisms (optical and acoustic phonons) in the phonon scattering, see chapter 4.

In addition, for a long time various temperature dependencies of the 1/f noise have been observed [38 - 42]. The existing models that work well at a constant temperature do not explain the temperature dependence. Therefore, an analysis of the temperature dependence of $\alpha_{\text{Latt}}$ is needed, see chapters 3 and 4.

IV Scope of the thesis

In this thesis, the noise in homogenous materials is investigated at temperatures ranging from 77 K to 500 K. The relation between the 1/f noise and scattering mechanisms is analyzed by measurements on samples with different levels of impurity scattering, and on $\delta$-doped layers where the different groups of carriers suffer different levels of impurity scattering. The correlation between 1/f noise and defects is also analyzed by studying the effects on the 1/f noise of proton damage and post-annealing restoration. In addition 1/f noise in polycrystalline material and semiconducting diamond are investigated at 300 K.

Chapter 2 contains three papers. The first paper deals with the noise investigation on the P$^+$-type MBE GaAs samples. The non-alloyed contacts on the P$^+$-type MBE GaAs are characterized by noise measurements. The second paper is about 1/f noise in CBE InP samples at 300 K and 77 K. The noise versus doping level, and versus mobility is analyzed. The last paper reports the 1/f noise in semiconductor diamond. Here, the parameter $\alpha$ for diamond is determined for the first time.

Chapter 3 contains a paper that reviews the temperature dependence of 1/f noise in semiconductors. We present here what a confusion is in the reported results
about the temperature dependence of the 1/f noise in semiconductors. We also try to determine the temperature dependence of $\alpha_{\text{Latt}}$ for InP in this paper.

Chapter 4 describes the 1/f noise in InP grown by chemical beam epitaxy (CBE) at temperatures varying from 77 K to 500 K. Here we take into account that the lattice scattering composes of the acoustic and the polar optical phonon scattering. The temperature dependence of the parameter $\alpha_{\text{Latt}}$ is analyzed according to phonon number fluctuations.

Chapter 5 presents the study of the 1/f noise in δ-doped GaAs in which the conductance is well confined to a bulk layer. This structure has the following characteristics. The electrons in different subbands have different mobilities that depend on the degree of overlap of the electron wave-function with impurities. In addition, in this structure the two-dimensional transport in real space results in a distribution of wave vector in $k$ space that is different from the distribution of wave vector in $k$ space of three-dimensional transport. The 1/f noise is analyzed in terms of mobility fluctuations.

Chapter 6 is concerned with the 1/f noise in polycrystalline SiGe where the different regions of the grains are involved, as for example, grain boundaries, depletion regions, and neutral regions. Great attention has paid to the question: from which region does the 1/f noise stem? Therefore the 1/f noise from different regions is separately analyzed.

Chapter 7 presents the correlation between 1/f noise and defects determined by measuring 1/f noise in GaAs samples damaged by proton irradiation and annealed after irradiation.
References

Chapter 1. General introduction


Chapter 2

1/f Noise in Epilayers of Semiconductors

Three papers are included in this chapter.

1. Low frequency noise in p'-GaAs with non-alloyed contacts

2. Study of 1/f noise in InP grown by CBE

3. Low frequency noise in B-doped diamond grown by CVD
   Submitted to Electron. Lett.
Low frequency noise in $p^+\text{-GaAs}$ with non-alloyed contacts

X.Y. Chen, M.R. Leys and F.W. Ragay

Indexing terms: Gallium arsenide, Semiconductor device noise

Measurements of 1/f noise were performed including and excluding the influence of the contacts formed by metallic aluminum layers (MBE) deposited on the $p^+\text{-GaAs}$ (MBE). The results show that the MBE process can produce non-alloyed ohmic contacts free of noise. The 1/f noise of bulk $p^+\text{-GaAs}$ is characterized by $S_{\text{0}} = 5 \times 10^{-7}$.

Introduction: 1/f noise is notorious for its ubiquity in electronic devices and electrode contacts. Experimental studies on 1/f noise in semiconductor GaAs have focused on n-type GaAs. There are only two publications about 1/f noise in p-type GaAs [1, 2]. The two values of $\alpha$ reported in these papers differ by two orders of magnitude. Therefore, we further investigated the 1/f noise in p-type GaAs.

We used a new procedure for making contacts. We grew an epitaxial layer of $p^+\text{-GaAs}$ and immediately deposited a 0.2$\mu$m thick aluminum layer on it in the MBE chamber at $+20$ sample (W214) and $-25^\circ\text{C}$ (sample W249 and 243), respectively [3]. Noise-free contacts of low resistance were obtained.

Experiments: The structures of the samples are a bridge-shape Hall bar (BSHB) or a transmission line model (TLM) (Fig. 1). Their preparation was described in detail elsewhere [3]. The acceptor concentration in $p^+\text{-GaAs}$ and the contact resistivity $\rho_0$ are as follows: W214, $3.3 \times 10^{10}$ cm$^{-3}$, $1.5 \times 10^{-2} \Omega \cdot \text{cm}^2$; W249, $3.4 \times 10^{10}$ cm$^{-3}$, $5.7 \times 10^{-4} \Omega \cdot \text{cm}^2$; W243, $1.1 \times 10^{10}$ cm$^{-3}$, $2.5 \times 10^{-4} \Omega \cdot \text{cm}^2$ [3]. The noise measurements were performed at room temperature, in the $1\text{Hz}$ - $20\text{kHz}$ frequency range, at different bias currents. The transverse noise (measured at the 3-6, 4-7, or 5-8 pair of terminals) and the longitudinal noise (measured at the 1-2, 3-4, or 6-8 pair of terminals, and so on) were obtained using BSHB samples with the current always flowing through contacts 1 and 2. Using a TLM sample, we could only measure the longitudinal noise. In four-point measurements, the sensors used to measure the noise power densities are not the same as the drivers that carry the current; in two-point measurements the sensors and the drivers are the same.

Results and discussion: In this Letter, we express the spectral density of the noise voltage by $S$, which is the measured result minus the thermal noise and the noise of the preamplifier.

(i) In the two-point measurements, the longitudinal noise is the sum of the bulk noise and the contact noise:

$$S = (S(1/f) + S(g-r))_{\text{bulk}} + S_{\text{contacts}}$$

(ii) In the four-point measurements, the longitudinal noise is

$$S = \left(\frac{R_1}{R_1 + R}\right)^2 S(1/f) + \left(\frac{R}{R_1 + R}\right)^2 S_{\text{contacts}}$$

with $R$, the series resistance in the measurement circuit and $R$ the resistance of the measured sample element.

Fig. 2 shows that the noise spectra have a pure 1/f shape with $\gamma = 1$ for the samples W249 and W243, with $\gamma = 1.1$ for W214. We do not observe a g-r noise bump in the noise spectra. Therefore, there are no traps that can cause g-r noise in the bulk of the sample and the contact regions. Here the sample W214 is an exception, in which we observe very strong noise.

In four-point measurement, the contact noise of drivers can be removed from the results by selecting $R_2 > > R$. The linear dependence of the $S$ on $L$ (Fig. 3b) for W243 and W249 with the TLM structure is proof of the fact that the contact noise does not contribute to the result. Hence the noise we measured is purely from the bulk. The $\alpha$ values from the empirical equation are $2 \times 10^{-5}$ and $2.2 \times 10^{-4}$, respectively, for W243 and W249. The meaning of $L$ is explained in Fig. 3a which suggests a model for the current through these samples. The contact resistivity is so small here that the contacts short-circuit the parts of the sample directly beneath them. This model is proved by the linear dependence of $S$ and the resistance on the length $L$ as it is defined here. Furthermore, the results of these samples, that include the contact noise in two-point measurements and exclude contact noise in four-point measurements, are the same for a chosen pair of terminals. Clearly, the contacts on the samples W243 and W249 are free of noise. Another proof for this conclusion is that for W249 with the BSHB structure, the ratio of the longitudinal noise $S_0$ to the transverse noise $S_{\text{tr}}$ at the same current through contacts 1 and 2 is $<0.1$ in accordance with calculations given in [5], where the contacts were considered as ideal.
contacts mode at 25°C

\[
\begin{align*}
W243 & \quad \text{contacts mode at 25°C} \\
W216 & \quad \text{contacts mode at -20°C}
\end{align*}
\]

Fig. 3 Sample W214 with TLM structure

- a Model for current through samples
- b Noise power density against length L, which is a for adjacent contacts and \( \Sigma a \) for non-adjacent contacts
- c Noise power density against length L

\[ L = a \text{, } \Sigma a \text{ as in Fig. 3b} \]

\( \Delta \) = centre-to-centre distance between contacts

Only \( \Delta \) gives a straight line, which means that the noise is generated in the bulk below the contacts.

As for sample W214 with TLM structure, the model for current through the sample is also presented in Fig. 3. It is proved by the linear dependence of resistance on L, whereas in this case we define L as the centre-to-centre distance between the two contacts. The contact resistance is so high here that the current only passes through the GaAs layer. The process of conducting at the high temperature of +25°C influences the quality of the parts of the sample located directly under the contact, which is the source of the high 1/f noise shown in Fig. 3c. We cannot be sure that this process does not create traps in the sample, even if we do not observe the g-r noise spectrum. Maybe the 1/f noise is so high that it dominates a possible g-r noise spectrum.

Both lattice scattering and impurity scattering contribute to the measured mobility \( \mu_{\text{meas}} \) and to its fluctuations characterised by \( \sigma_{\mu,\text{meas}} \). The relationship between \( \alpha_{\mu,\text{meas}} \) and \( \sigma_{\mu,\text{meas}} \) is given by \( \alpha_{\mu,\text{meas}} = (\mu_{\text{meas}}/\mu_0 \times \sigma_{\mu,\text{meas}}) \) as is explained in [4]. The results for \( \alpha_{\mu,\text{meas}} \) are presented in Fig. 4, where we use \( \mu_0 = 4000 \text{cm}^2/\text{Vs} \) and \( \mu_{\text{meas}} = 120 \text{cm}^2/\text{Vs} \) for our samples.

Conclusion: Noise-free contacts of low resistance can be prepared by an MBE process at \(-25°C\). There are no traps in the bulk or the contact area that cause g-r noise in the measuring frequency range. However, depositions at \(+25°C\) produce very noisy contacts of higher resistance.

The 1/f noise we measured in p-GaAs is bulk noise caused by mobility fluctuations, related to the scattering by the crystal lattice. The value of \( \alpha_{\mu} \) for our samples is \( 5 \times 10^{-4} \).

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References

The origin of 1/f noise ubiquitously exists in physical systems. It sets a critical limit to applications of modern devices. The elimination of noise is becoming more and more important. However, the origin of 1/f noise still is a problem. The theoretical interpretation is complicated by experimental results that vary from sample to sample, even in elemental semiconductors. The models proposed previously have only been suitable for special situations. The most commonly accepted conclusion was obtained from a huge number of experimental results. The relative noise power density is inversely proportional to the total number of carriers[1],

$$\frac{S_R}{S_V} = \frac{\alpha}{R^3} = \frac{\alpha}{V^2} = \frac{\alpha}{fN^2}.$$  \hspace{1cm} (1)

Nowadays 1/f noise is generally characterized by the parameter $\alpha$. It was found that $\alpha$ can vary by many orders of magnitude, even in the same material, which used to be prepared as a single crystal[2] and is now prepared as an epitaxial layer[3,4]. The value of $\alpha$ depends on the way in which the samples were prepared and on the doping level[5]. $\alpha$ appears to depend on the quality of the crystal. In perfect material $\alpha$ can be two or three orders lower than in imperfect material[6]. However, $\alpha$ sometimes is much higher in rather pure epilayer material[7] than in the same material with a high-doping level[8]. Its value scatters so wildly and irregularly that it is extremely difficult to discover the origin of 1/f noise.

We work on InP epilayers. InP layers are a promising material for radiation resistant devices in space and ultra-high speed optical and electronic devices. Knowledge of noise properties of material is the key to the development of low-noise devices. However, so far, only few data about noise in InP have been reported[8,10,11]. There are no experimental data of the noise in epitaxial layers on InP growth by CBE.

We studied which parameters control the value of $\alpha$ in a series of InP layers doped at different levels. We conclude that low-frequency noise is mobility noise that only originates from lattice scattering. The noise parameter $\alpha_{\text{lat}}$ can be determined and appears to be a useful material parameter for designers of low-noise devices.
EXPERIMENTAL PROCEDURES

The samples were grown in a Riber CBE 32 system. Trimethylindium (TMIn) and phosphine (PH₃) were used as source materials. The InP layers with thicknesses between 2 and 5.6 μm were grown on semi-insulating Fe-doped InP wafers. The preparation and optical and electrical properties of our InP unintentionally doped epitaxial layers have been discussed in more detail elsewhere[9]. Progressively we have succeeded in improving the quality, as is clear from the data given in Table 1. The samples selected for noise measurement are given in Table 1. The layers were grown at temperatures varying from 520 to 535°C. The ratio of source material flows PH₃ to TMIn is indicated in the table. C252 samples are the purest ones. Bridge-shaped Hall bar structures were obtained by conventional photolithography. Etching was done using a citric acid/NaClO₃ mixture in water. The samples were manufactured with tin contacts or Au/Ge/Ni contacts. Figure 1 shows the geometry of the samples.

The voltage fluctuations were measured by a four-points method. The current is always through the contacts 1 and 2. We were able to measure the longitudinal noise from a pair of terminals parallel to the current direction, and the transverse noise from a pair of terminals vertical to the current direction. We applied an electrical field well below 2 kV m⁻¹. This guarantees that noise spectra were measured in the Ohmic region. The samples were mounted in a cryostat that was contained in a Faraday cage, together with a low noise preamplifier and batteries. A wire-wound resistor of more than 800 kΩ was used in series to the sample, to eliminate the noise of the current contacts. The noise spectra were obtained in a frequency range from 1 Hz to 40 kHz at 300 and 77 K.

EXPERIMENTAL RESULTS AND DISCUSSION

Electrical properties

The Hall effect results show n-type conductivity in all samples. The temperature-dependence of the free charge carrier concentration and the mobility are shown in Figs 2 and 3. The mobility limited by lattice scattering is also plotted to guide the eye. μₑ is the mobility limited by the scattering of the optical phonons, and μₓ the mobility limited by the scattering of the acoustic phonons. For the calculation of μₓ, the value of the deformation potential ξ is needed. Two limiting values are mentioned in the literature, 6.8 eV[15] and 14.5 eV[16]. Calculated curves using both values are plotted. A value somewhat lower than 14.5 eV gives the best agreement to our experimental results.

For thin layers of high-purity, the depletion layers at the surface and the interface can not be neglected compared to the thickness of the sample. The measured layer thickness has thus been corrected for the surface and interface depletion layers to obtain the correct carrier concentration. The pinning potentials at the surface are taken to be 0.32 eV. The calculation was made by the method given in Ref. [12]. Figure 2 displays the results after the correction.

From Fig. 3, it follows that μₓB is smaller than 0.25 for all samples when using B = 0.5 T at 300 K. This obeys the weak field condition[17]. Since the mobility changes with temperature by more than an order of magnitude, the μₓB value will increase and reach

Table 1. Characteristics of samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>C116</th>
<th>C048</th>
<th>C117</th>
<th>C178</th>
<th>C252</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth T (°C)</td>
<td>520</td>
<td>530</td>
<td>535</td>
<td>535</td>
<td>535</td>
</tr>
<tr>
<td>PH₃/TMIn ratio</td>
<td>4.5</td>
<td>4.75</td>
<td>4.5</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Growth rate (μm h⁻¹)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>77 K μ (m² V⁻¹ s⁻¹)</td>
<td>3.0</td>
<td>3.8</td>
<td>3.8</td>
<td>4.8</td>
<td>12.5</td>
</tr>
<tr>
<td>n (10¹⁵ cm⁻³)</td>
<td>2.3</td>
<td>1.6</td>
<td>1.4</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>300 K μ (m² V⁻¹ s⁻¹)</td>
<td>0.40</td>
<td>0.40</td>
<td>0.42</td>
<td>0.44</td>
<td>0.56</td>
</tr>
<tr>
<td>n (10¹⁵ cm⁻³)</td>
<td>3.7</td>
<td>2.6</td>
<td>2.0</td>
<td>0.75</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Fig. 1. The geometry of the samples in μm. The numbers 1–8 refer to contacts; 1 and 2 are used as current contacts.

Fig. 2. Temperature-dependence of the carrier concentration, ○: C116; ◦: C048; △: C117; ▽: C178; ●: C252.
the value $\mu B = 7.5$ for C252 and $\mu B \approx 1.5-1.9$ for other samples at 77 K. This will cause an error if it is assumed that $\gamma_H = 1$ throughout the whole temperature range.

The Hall factor depends on the scattering mechanism and the magnetic field. In a high magnetic field ($\mu B \gg 1$) $\gamma_H = 1$, whatever the scattering mechanism. Because the samples are rather pure, the acoustic phonon scattering will govern the mobility at 77 K. In this case, the Hall factor for a weak field is $\gamma_H = \gamma_H(0) = 1.18$. At 300 K, the polar optical phonon scattering will be predominant. Thus, $\gamma_H = \gamma_H(0) \approx 1.11$ for a weak field. When the temperature is in the range in which the transition between the two scattering mechanisms occurs, the Hall factor for a weak field will be between 1.11 and 1.18. The magnetic field dependence of $\gamma_H$ is shown in Fig. 4. The curve around $\mu B = 1$ is uncertain. However, the point at $\mu B = 1$ can be determined by measuring Hall coefficient $R_H$ at $B = 0.05$ T ($\mu B = 1$) and $R_H$ at $B = 1$ T ($\mu B = 20$). $\gamma_H$ is equal to $R_H/R_{H2}$, and it is about 0.94. It is clear that the error caused by always using $\gamma_H = 1$ is about 10%. This is confirmed by measuring at $B = 0.05$, 0.5 and 1 T.

\subsection*{1/f noise}

We measured the noise using different currents through the samples at temperatures of 77 and 300 K. The noise level is quadratically dependent on the applied voltage. The longitudinal noise is proportional to the length between measuring terminals when we apply the same current through the samples. From transverse noise spectra, values are calculated using the method outlined in Ref. [13]. The same values of $x$ are obtained from longitudinal noise and transverse noise spectra. Therefore, we can be sure that the measured noise spectra are free from the noise of the current contacts, and that the spectra are from the bulk of the samples.

At 300 K, some generation–recombination bumps are superimposed on the 1/f spectra in the purest sample C252, but not so at 77 K. However, pure 1/f spectra appear in the other samples at 300 and 77 K. This can be explained by the fact that the intrinsic deep levels[9] act differently in C252 and the other samples due to the different position of Fermi level $E_F$ in the band gap. In the purest sample C252, the Fermi level is at a relatively low position. When the temperature is high enough, electrons in the deep levels will be excited to the conduction band. Then generation–recombination processes occur between the deep levels and conduction band. By contrast, in all other samples, the Fermi level is far away from the deep levels. The levels are fully occupied and the relaxation times of the trapping process to the deep levels are long. Therefore we cannot see the $g-r$ components in the measuring frequency range.

The noise parameter $x$ is calculated from eqn (1). In order to find the correct pure 1/f noise level in C252 at room temperature, we had to measure the noise spectra at temperatures a little above and well below room temperature. Consequently, the level of the generation–recombination bump could be adequately determined at room temperature.

Figures 5 and 6 show the $x$ vs measured mobility for all samples.

From Matthiessen's rule, eqn (2) is derived if it is assumed that $\Delta \mu_{\text{ext}} \neq 0$ and $\Delta \mu_{\text{imp}} = 0[14]$. These assumptions were proved to be correct in previous studies of general semiconductor materials[6].

\begin{equation}
\frac{S_x}{\mu^2} = \left( \frac{\mu}{\mu_{\text{ext}}} \right)^2 \times \frac{S_{\text{ext}}}{\mu_{\text{ext}}^2}. \tag{2}
\end{equation}
From eqn (1), it follows that

$$\alpha = \left( \frac{\mu}{\mu_{\text{lat}}} \right)^2 \times \alpha_{\text{lat}},$$

(3)

where $\mu_{\text{lat}}$ is the mobility exclusively due to lattice scattering, $\alpha$ is the experimentally determined constant from eqn (1), and $\alpha_{\text{lat}}$ is constant depending on the material.

Our results in Figs 5 and 6 show that $\alpha$ is quadratically dependent on $\mu$. This certainly is firm evidence for lattice scattering as the source of $1/f$ noise. In Figs 5 and 6 we have added all previous data. All these data stem from Tacano et al.[8,10,11] and are indicated by the letter T with the year of publication. At 77 K, there is no difficulty in fitting all data on InP to the line (Fig. 5). At 300 K, the point T91 is far away from the line (Fig. 6). Actually the data T91[10] and T92[8] were obtained from samples that were prepared by the same processes and with the same dimension. A focused Si+ beam with an energy of 140 keV was irradiated onto a Fe-doped InP substrate to a dose of $5 \times 10^{12}$ cm$^{-2}$. Then the substrate was consequently annealed at 700°C for 15 min. The configuration of the samples was a Greek-cross with a dimension of $1/4 \times 1/4$ $\mu$m. In Ref. [10] the mobility was reported to be $3.6 \times 10^{-1}$ m$^2$V$^{-1}$s$^{-1}$, but about $6.4 \times 10^{-2}$ m$^2$V$^{-1}$s$^{-1}$ in Ref. [8]. If we use the latest value for the mobility here, the point T91 disappears from our plot. The dashed line has a slope of 2, although it is lower than the solid line. The shift between the two lines could be caused by a systematic error. In general, an ion-implanted InP sample has a distribution with a doping profile as that shown in Ref. [11]. The Hall mobility should be an average over all free electrons, which is higher than the mobility of the electrons in the activated-layers due to stronger scattering by impurities. On the other hand, if we take the average mobility, then the total number of electrons will be higher than that in the activated-layers. Either lower mobility or higher total number of carriers will result in shifting the dashed line towards the solid line in Fig. 6. In conclusion, all data at 300 K fit our line without serious problems.

The samples with different doping levels and different geometry, made in different ways, have $\alpha$ values that differ greatly. It does not mean that the noise sources in InP are different. The samples with stronger scattering by impurities have a lower level of $1/f$ noise. That can be easily explained by the model in which the fluctuations are in the lattice scattering. The noise in all InP samples can be characterized by a single parameter $\alpha_{\text{lat}}$. If the lattice is damaged, $\alpha_{\text{lat}}$ may increase, and new noise sources may appear.

**CONCLUSIONS**

$1/f$ noise in InP is a bulk noise caused by mobility fluctuations of the carriers. Fluctuations in the lattice scattering are the origin. The noise in InP material is well characterized by the parameter $\alpha_{\text{lat}}$. At 300 K $\alpha_{\text{lat}}$ is about $3 \times 10^{-3}$. At 77 K $\alpha_{\text{lat}}$ is about $2.3 \times 10^{-3}$.

**Acknowledgements**—The authors would like to express their appreciation to Professor Dr F. N. Hooge for his inspiration and constructive discussions. We are grateful to H. Vonk for the growth of the samples, to P. A. M. Nouwens for the preparation of perfect Ohmic contacts, to S. Fassetta from the University of Montpellier, and to D. de Bruin for their help in the measurements.
Study of 1/f noise in InP grown by CBE

REFERENCES

Chapter 2. 1/f noise in epilayers of semiconductors

LOW-FREQUENCY NOISE IN B-DOPED DIAMOND GROWN BY CVD

X. Y. Chen and G. J. Bauhuis

Indexing terms: Semiconductor device noise, boron-doped diamond.

Boron-doped diamond films were fabricated by hot filament-assisted chemical vapor deposition (CVD) on (100) and (110) natural diamond substrates. Low-frequency noise in such homoepitaxial films was measured at 300 K. 1/f noise spectra were observed at low frequencies in all samples. A high level of 1/f noise was found in a poor quality film that was grown along the (110) orientation. The 1/f noise parameter $\alpha$ varies from $10^{-6}$ to $4 \times 10^{-3}$ for different orientations.

Introduction: Semiconductor diamond is a promising material for high power and high frequency applications and for electronic devices used at high temperatures, in corrosive and intensive irradiation environments [1, 2]. This is due to the unique material properties: a wide-band-gap of 5.45 eV, high thermal conductivity, chemical inertness, a high breakdown field of $10^6$-$10^7$ Vcm$^{-1}$, and a low dielectric constant of 5.7. Homoeptaxial diamond film can be grown by various techniques of chemical vapor deposition (CVD). The study of the electrical properties of homoeptaxial diamond is on the upswing. A study on the 1/f noise in semiconductor diamond has never been reported before. The figure of 1/f noise in a sample can be helpful in understanding the 1/f noise in perhaps totally different another sample. Here, we carried out the low-frequency noise measurements on homoeptaxial diamond films grown by hot-filament-assisted CVD. Exact 1/f spectra were observed.

Experiments: The diamond films were grown in one run in a conventional hot-filament-assisted CVD reactor using a gas mixture of 0.67% CH$_4$ in H$_2$ at 50 mbar with a flow rate of 0.3 standard liters per minute. The deposition time was 6 h. The substrates used were natural type IIa, polished diamond plates of (100) and (110) orientation and resistivity $> 10^{16}$ $\Omega$ cm. The filament temperature was 1910 °C. Boron doping was achieved by heating the hexagonal BN substrate holder, which led to outdiffusion of boron into the gas phase. The boron content of the diamond films was controlled by adjusting the temperature of the substrate holder. After
growing, ohmic metal contacts consisting of Ti/Pt/Au layers were sputtered and the samples were laser-cut into a clover-leaf shape (see fig. 1).

Fig. 1 Structure of samples. 1 - 4 are the contacts.

The detailed characterization of these samples is described elsewhere [3, 4]. Carrier concentrations and mobilities were determined by Hall effect measurements using a magnetic field of 0.7 T [4]. The electrical properties and dimensions of the samples are listed in table I.

Table I Characteristics of the samples.

<table>
<thead>
<tr>
<th>sample code</th>
<th>HF-3 (100)</th>
<th>HF-3 (110)</th>
</tr>
</thead>
<tbody>
<tr>
<td>substrate orientation</td>
<td>(100)</td>
<td>(110)</td>
</tr>
<tr>
<td>film thickness d (µm)</td>
<td>1.5</td>
<td>7.4</td>
</tr>
<tr>
<td>l (mm) (see Fig. 1)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>L (mm) (see Fig. 1)</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>neutral B concentration (cm⁻³)</td>
<td>(2.7 \pm 0.7) x 10¹⁸</td>
<td>(18 \pm 2) x 10¹⁸</td>
</tr>
<tr>
<td>hole concentration p (cm⁻³)</td>
<td>(1.32 \times 10^{14})</td>
<td>(5.7 \times 10^{15})</td>
</tr>
<tr>
<td>mobility (\mu) (cm²/Vs)</td>
<td>580</td>
<td>13</td>
</tr>
<tr>
<td>noise parameter (\alpha)</td>
<td>((1 \pm 0.5) \times 10^{-5})</td>
<td>((4 \pm 1) \times 10^{-3})</td>
</tr>
</tbody>
</table>

Noise measurements and results: First, the I-V characteristics of the samples were measured. A typical ohmic behavior was observed. We carried out the measurement of the voltage fluctuations in the ohmic range at 300 K. Two configurations were used for the noise measurements, 1) the two-point method where the noise was measured between the current contacts, and 2) the four-point method where the noise was measured between a pair of contacts (e.g. contacts 3 and 4) while the current passed through another pair of contacts (e.g. contacts 1 and 2). Typical power-spectral densities measured by the four-point method are given in figure 2. It is shown that exact 1/f noise is found at low frequencies and white noise at high
frequencies. The levels of both 1/f noise and white noise are proportional to the square of the voltage across the contacts where the noise was measured. Hooge's empirical relation for homogeneous material was used to characterize the 1/f noise [5].

\[
\frac{S_v}{V^2} = \frac{\alpha}{Nf},
\]

(1)

where \(S_v\) is the noise power spectral density, \(V\) is the applied voltage, \(f\) is the frequency, and \(N\) the total number of free charge carriers in the area involved in the noise generation.

For the two-point method, the noise parameter \(\alpha\) can be easily calculated using relation (1), but the contact noise cannot be avoided. A noisy contact can lead to a big error in \(\alpha\). In the four-point method, the so-called longitudinal noise is measured. The noise of the current carrying contacts can be eliminated by using a high resistance for the series resistor in the measurement circuit, see discussion in Ref. [6]. Because of the complicated structure of the sample, \(\alpha\) was calculated by using an effective total number of free charge carriers. The results are listed in table I. \(\alpha\) is two orders lower for samples grown on \{100\} substrate than for samples grown on \{110\} substrate. \(\alpha = (1 \pm 0.5) \times 10^{-6}\) for HF-3 (100) and \((4 \pm 1) \times 10^{-3}\) for HF-3 (110).

![Fig. 2 Typical noise power spectral densities measured by the four-point method from sample HF-3 (100) at different voltages. The solid line with slope = - 1 for guiding the eye.

Discussion: The white noise is proportional to the square of the voltage. Therefore, it is not the thermal noise. This white noise has to be the plateau of a generation-recombination noise (g-r noise) due to holes being trapped and detrapped from some level in the band-gap. Because of the high activation energy for boron (0.38 eV), the...
concentration of the free charge carriers at 300 K still is very low compared to the concentration of the neutral boron atoms (see table I). Therefore, at room temperature, the relaxation time of the g-r process of the boron level is long. The g-r noise is possibly generated from this boron level.

In table I we see that the mobility for sample HF-3 (100) is much larger than that of sample HF-3 (110). However, the value of $\alpha$ is two orders lower for sample HF-3 (100) compared to sample HF-3 (110). These experimental results for diamond are not in agreement with the experimental results in III-V semiconductors [7, 8], where $\alpha$ was proportional to the square of the mobility. This controversy can be interpreted as a difference in quality of the two samples. The growth mechanism for the (100) orientation is essentially different from that for the (110) orientation. The (100) surfaces are characterized by slow layer growth involving step and kink sites. This leads to a relatively good crystallographic quality and low impurity content. On the (110) surfaces growth species are directly integrated into the lattice. Therefore, the growth velocity and the impurity incorporation are much higher than for the (100) surface. Table I shows that the (100) sample has a thinner grown layer and an higher B concentration than the (110) sample. Many experimental results from semiconductors have shown that the poorer the quality of the sample, the higher the 1/f noise [9, 10]. Thus, we cannot analyze the noise in the two diamond samples in the same way as [7, 8].

Conclusions: 1/f noise spectra were observed at the low frequencies in two homoepitaxial films of semiconducting diamond. The g-r noise at high frequencies is possibly generated by the boron acceptors. The noise parameter $\alpha$ is about $10^{-5}$ for the samples of high quality and $4 \times 10^{-3}$ for the samples of poor quality.

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References


Chapter 3

UNSOLVED PROBLEMS - TEMPERATURE DEPENDENCE OF 1/f NOISE

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We discuss here the temperature dependence of 1/f noise in semiconductors. The experimental results from InP and GaAs epitaxial layers are presented. Previous measurements on semiconductors like InSb, Si and Ge are reviewed. No single model can explain all the findings.
I INTRODUCTION

In homogeneous samples of semiconductors the $1/f$ noise can be described by equation (1) [1]. The $1/f$ noise is characterized by a parameter $\alpha$

$$\frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{\alpha}{fN}. \tag{1}$$

Various trends in the temperature dependence of $\alpha$ have been observed. The problem is: the existing models that work well at a constant temperature do not explain the temperature dependence of $\alpha$.

In this contribution, we present recent results of the temperature dependence of $\alpha$ measured on InP and GaAs. For a review of the problem, all results from the last 15 years are also cited here. We may have some possible explanation for each specific situation. However, we do not understand the general results.

II EXPERIMENTAL RESULTS OF $\alpha(T)$

A The results for InP

We measured the noise in unintentional doped InP grown by chemical beam epitaxy (CBE). A series of samples are used. Gradually, we have succeeded in improving the quality of the samples. Figure 1 shows the temperature dependence of $\alpha$. In figure 1 we also plotted the results reported by Tacano et al.[2] who measured the noise in heavily doped so-called FIB InP samples. The noise level is more than two orders lower than in our samples.

![Fig. 1 $\alpha(T)$ in InP. ◆: Tacano's InP [2]. The others are CBE InP, ○: The purest CBE InP.](image-url)
B  The results for GaAs

When studying the annealing effect on the proton damaged GaAs, we measured the temperature dependence in MBE (molecular beam epitaxy) GaAs. The results are given in figure 2. The damage by proton irradiation introduces the excess 1/f noise that can be reduced by annealing. Annealing can repair the lattice to a certain extent [3]. In figure 2 we also plotted the results for GaAs reported by Ren et al. [4], and for InGaAs hetero-structures by Tacano et al. [5].

![Figure 2](image1)

Fig. 2  $\alpha (T)$ in GaAs and InGaAs [5]. ●: MBE GaAs, △: Ren [4], Δ: Tacano [5].

C  The results for InSb

![Figure 3](image2)

Fig. 3  $\alpha (T)$ in InSb from Alekperov [6]. +: With inhomogeneous distribution of impurities; ●: purer InSb.
Alekperov et al. [6, 7] reported the results for single crystal InSb. The results based on n-type InSb are shown in figure 3. When the distribution of impurities in the sample was inhomogeneous, the noise becomes high and weakly dependent on temperature (see the data of the I series in fig. 3). For p-type InSb, the original paper showed the relative voltage fluctuation $S_v / \sqrt{V^2}$ versus temperature instead of $a$ versus $T$. The noise parameter $a$ increases with decreasing temperature [7].

![n-Si graph]

**Fig. 4** $\alpha (T)$ in crystal n-Si. ◊: Palenskis [9], □ ○ Δ: Luo [10], ●: Bisschop [11].

![p-Si graph]

**Fig. 5** $\alpha (T)$ in crystal p-Si. ◊: Palenskis [9], □ ○ Δ: Luo [10], ●: Bisschop [11].

### D The results for Si and Ge

The temperature dependence of the 1/f noise in Si has been intensively studied. Clevers [8] reported many data from single crystal Si. It was shown that in
all cases the noise was bulk noise. Various trends in the temperature dependence of $\alpha$ have been observed. There do not seem to be any reproducible results for different samples with different doping levels and different structures in geometry. He concluded that the different ways in which the samples were prepared might create different temperature dependencies. Figures 4, 5 and 6 show the results reported by Palanskis et al. [9], Luo et al. [10], and Bisschop et al. [11].

One can conclude:

a) Various trends of $\alpha(T)$ exist, even in the same material.

b) The value of $\alpha$ scatters on a large scale in the same material with different doping levels.

III DISCUSSION

A Temperature dependence

Usually the 1/f noise increases with increasing temperature. The dependence of the 1/f noise on temperature could be anything if there is non-bulk 1/f noise. Therefore we would rather concentrate on samples where the bulk 1/f noise dominates. For these samples a promising common trend of temperature dependence of 1/f noise can be found. Generally in a good quality material like MBE and/or CBE grown semiconductors, and pure crystal semiconductors, the temperature dependence of $\alpha$ composes of two branches, (i) a branch independent of temperature at lower temperatures and (ii) another branch with strong dependence on temperature at higher temperatures. The latter can be fitted either by an
activated process or by a power law as expressed in equation (2) and (3). The activation energy $\Delta E$ or the power constant $\gamma$ is different in different cases.

$$\alpha = \alpha_0 + b \times \exp\left(\frac{-\Delta E}{kT}\right),$$  \hspace{2cm} (2)

$$\alpha = \alpha_0 + \beta T^\gamma,$$  \hspace{2cm} (3)

where $\alpha_0$, $b$ and $\beta$ are temperature independent.

In a narrow temperature range it is very hard to distinguish between the curves of equation (2) and (3), because for each value of $\Delta E$ one can always choose a proper value of $\gamma$ that makes the curve of equation (3) very close to the curve of equation (2). $\Delta E$ was found between 0.1 and 0.2 eV. However, what that activated process is, is a mystery. $\gamma$ is then found between 4 and 8 around room temperature.

Luo et al. [10] also offered an alternative explanation by assuming that the $1/f$ noise originates in a thin surface layer via carrier trapping at the interface to the oxide layer or in the layer itself. Tacano et al. [2, 5] observed the temperature dependence of $\alpha$ in III-V compounds. They interpreted it by the Handel’s quantum theory.

### B Wide range of $\alpha$ values

The wide range of $\alpha$ values was not only found in the experiments discussed above, it is quite common. To solve this problem, Hooge and Vandamme [12] proposed a model in which only lattice scattering shows $1/f$ noise when several scattering mechanisms are present. Then $\alpha$ can be expressed by

$$\alpha = \left(\frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}}\right)^2 \times \alpha_{\text{Latt}},$$  \hspace{2cm} (4)

where $\mu_{\text{Latt}}$ is the lattice scattering mobility, $\mu_{\text{meas}}$ the measured mobility and $\alpha_{\text{Latt}}$ a constant depending on the material. This model can explain the wide spread of $\alpha$ in good quality samples of the same material. Each material can be characterized by a value of $\alpha_{\text{Latt}}$, but $\alpha_{\text{Latt}}$ has different values in different materials. At room temperature, $\alpha_{\text{Latt}} = (5 \text{ to } 7) \times 10^{-4}$ for GaAs [4, 13, 14], $\alpha_{\text{Latt}} = 3 \times 10^{-3}$ for InP [15], $\alpha_{\text{Latt}} = 2 \times 10^{-3}$ for Si [11]. However, this model does not work so well at 77 K where we do not always find $\alpha$ proportional to $\mu_{\text{meas}}^2$ [8, 11]. Except for the recently published results for InP at 77 K [15], there is no evidence for the correctness of equation (4) at 77 K.

The temperature dependence of $\alpha_{\text{Latt}}$ can be determined from equation (4) for a material. Palenskis et al. [9] reported that the temperature dependence of $\alpha$ in a Si sample follows the temperature dependence of $(\mu_{\text{meas}}/\mu_{\text{Latt}})^2$, and hence that $\alpha_{\text{Latt}}$ is a constant. Later Bisschop et al. [11] measured the noise from a series of samples with different impurity scattering, the model $\alpha \propto \mu_{\text{meas}}^2$ holds at
temperatures down to 150 K, not at temperatures below 150 K. He proposed that when a sample is pure enough the measured $\alpha$ is $\alpha_{\text{Latt}}$. He concluded that the $\alpha_{\text{Latt}}$ in Si and Ge follows a thermally activated process as in equation (5) where $\Delta E = 0.1eV$. However, we are left with the problem why the model of the 1/f noise in lattice scattering can not explain the results for highly doped Si at low temperatures. More recently, Ren et al. [4] used a series of n-GaAs samples with different contributions from impurity scattering. Their results again showed that the model holds above 150 K. They ended the discussion by simply taking $\alpha_{\text{Latt}}$ equal to a constant $7 \times 10^{-5}$ (A) at lower temperatures. $\alpha_{\text{Latt}}$ is also described by equation (5) with $\Delta E = 0.13eV$.

$$\alpha_{\text{Latt}} = A + B \cdot \exp\left(\frac{-\Delta E}{kT}\right).$$ (5)

Our low temperature results for the purest InP sample are not consistent with the results given above. While cooling down the purest InP samples, the $\alpha$ value passes through a minimum and then increases again with decreasing temperature. In the other InP samples, $\alpha$ is temperature dependent and more or less follows equation (2). All results, including Tacano’s, fit equation (4) at 300 K and 77 K [15]. By using equation (4) we obtain a temperature dependence of $\alpha_{\text{Latt}}$ for all InP samples. The temperature dependence of $\alpha_{\text{Latt}}$ plotted in figure 7 is similar to that of $\alpha$ from the purest sample. We do not understand why $\alpha_{\text{Latt}}$ depends on temperature in this way. Such temperature dependence of $\alpha_{\text{Latt}}$ was also found with other pure semiconductors. Tacano et al. measured the noise in heterostructure devices where the 1/f noise comes from two-dimensional electronic gas in the undoped channel. The noise increases with decreasing temperature below 150 K (see Fig. 2). Bisschop obtained such a trend in his purest Si sample too (see Fig. 4).

![Fig. 7. $\alpha_{\text{Latt}}(T)$ for CBE InP. o: the purest sample.](image-url)
Chapter 3. Unsolved problems - temperature dependence of 1/f noise

IV CONCLUSIONS AND QUESTIONS

Bulk 1/f noise of semiconductors has various temperature dependencies. In a good quality sample the 1/f noise increases with increasing temperature. At temperatures around room temperature, the 1/f noise can either be described by a thermally activated process or by a power law. It is not understood what causes this dependence. The model with 1/f noise in the lattice scattering can successfully explain most results at higher temperatures, but not all at lower temperatures. \( \alpha_{\text{latt}} \) in pure samples increases with decreasing temperature. We do not understand that at all.

References

Chapter 4

THE TEMPERATURE DEPENDENCE OF 1/f NOISE IN InP

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Noise spectra were measured on CBE grown InP samples in the frequency range from 1 Hz to $10^4$ kHz at temperatures from 77 K to 500 K. The experimental results show that 1/f noise stems from the lattice scattering. The 1/f noise in InP is well characterized by a parameter $\alpha_{\text{Latt}}$ in this temperature range. The temperature dependence of $\alpha_{\text{Latt}}$ was experimentally determined. Assuming that the number of phonons in a mode fluctuates with a 1/f spectrum, we are able to derive a theoretical expression for $\alpha_{\text{Latt}}$ in terms of the contributions by the acoustic phonons and the polar optical phonons. At low temperatures (< 200 K), the temperature dependence of $\alpha_{\text{Latt}}$ can be analyzed by this model with two kinds of phonons. However, at temperatures above 200 K, the model does not lead to satisfactory results.
I. INTRODUCTION

In a previous paper we reported on the 1/f noise in epitaxial InP [1]. We then studied the noise at room temperature and at 77 K. Special attention was paid to the influence of the scattering mechanisms at a constant temperature. The noise was studied from samples with different levels of doping, and therefore with different levels of impurity scattering. Both at 77 K and at 300 K the 1/f noise could be well described by the model of 1/f noise in the lattice scattering [2, 3]. In that first paper we found $\chi_{\text{latt}}(77 \text{ K}) = 2.3 \times 10^{-3}$, and $\chi_{\text{latt}}(300 \text{ K}) = 3 \times 10^{-3}$. The same model was used by Bisschop and Cuijpers [4], and by Clevers [5] to explain experimental results for Si and Ge at a constant temperature near 300 K.

In this second paper on 1/f noise in InP we measure - on the same samples - the temperature influence in the range from 77 K to 500 K. We interpret the experimental results in this temperature-range by using the model of 1/f noise in the lattice scattering. That means that we convert $\chi$ into $\chi_{\text{latt}}$. The temperature dependence of $\chi_{\text{latt}}$ is experimentally obtained. The interesting question is how to interpret this empirical temperature dependence of the noise in the lattice scattering. In the calculations, we split the contribution of the lattice scattering in two contributions, one from the acoustic deformation scattering, characterized by $\chi_A$, and one from the polar optical scattering, characterized by $\chi_O$. Numerical fitting shows that at lower temperatures the temperature dependence of $\chi_{\text{latt}}$ can be well explained as function of $\chi_A$ and $\chi_O$. However, when the temperature increases above 200 K, the noise increases rapidly. This fast increase of $\chi_{\text{latt}}$ cannot be described as a function of $\chi_A$ and $\chi_O$.

Fig. 1 Schematic diagram of the balance configuration for noise measurements. $R_1$ and $R_2$ are series resistors with exactly equal values.
II. EXPERIMENTAL PROCEDURES

We used the same samples as those used in our previous paper [1]. All samples were structured as Bridge-shaped Hall bar which was shown in figure 1 of Ref. [1]. We characterize the concentrations and mobilities by Hall effect measurements with a current of 10 µA and a magnetic field of 0.5 T at temperatures between 77 K and 500 K.

The voltage noise spectra were measured in the frequency range from 1 Hz to 10^4 Hz. The samples were mounted in a cryostat when the noise was measured at temperatures below 300 K. A detailed description of the noise measurement can be found in our previous paper [6]. At temperatures above 300 K, the samples were heated in a N_2 / H_2 atmosphere or in vacuum. We measured the noise either by using the conventional configuration or a bridge configuration as shown in figure 1. By using the latter configuration, we can exclude correlated noise, such as noise resulting from temperature fluctuations [7]. The reason is the following. When the sample is heated to high temperature, the temperature of the sample fluctuates due to the control system. The voltage fluctuation ΔV is ΔV = I (ΔRR - ΔRL) → 0, where ΔRR and ΔRL are the resistance fluctuations caused by the temperature fluctuations in the sample parts at both sides of the bridge.

![Figure 2](image_url)

Fig. 2 Temperature-dependencies of mobilities. Points are experimental results. •: C116; ◊: C048; △: C117; ▽: C178; ○: C252. The lines represent the results of theoretical calculations. The dashed lines: Opt, polar optical phonons; Ac, acoustic phonons; μ_Latt, mobility of the total lattice scattering. The solid lines are for sample C252: Ion, ionized impurities (n_d + n_a = 2.2 × 10^{14} cm^{-3}); Neu, neutron impurities (n_dd = 3.3 × 10^{14} cm^{-3}); μ, the best fitting to the total mobility.
III. EXPERIMENTAL RESULTS

A. Hall effect characterization

The samples are all unintentionally-doped InP CBE epilayers. A Hall effect measurement indicates n-type conductance. There is some problem with the purer samples, because the depletion effects at surface and interface are not negligible. The Hall factor is not a constant at the temperatures from 77 K to 500 K due to the fact that \( \mu_B \) varies strongly in this temperature range. The problem with the Hall factor, and the correction for the surface and interface depletion effects, are discussed in detail in the previous paper [1]. In figures 2 and 3, we present the results of the temperature-dependence of mobility and the free charge carrier concentration after these corrections.

![Figure 3](image-url)  
Fig. 3 Temperature-dependence of the Hall concentration. The symbols are the same as in figure 2.

Figure 4 presents the mobility versus carrier concentration at 77 K. Using the analysis proposed by Walukiewicz et. al. [8], we obtain the compensation ratio \( \Theta \), which is the concentration ratio of acceptors \( n_a \) to shallow-donors \( n_d \). As shown in figure 4, the values of \( \Theta \) are between 0.25 and 0.4. Walukiewicz et. al. used a deformation potential \( \Xi \) of 6.8 eV. Different values of \( \Xi \) have been reported ranging from 14.5 to 6.8 eV [9, 10]. In a recent paper [11] the experimental results were well analyzed by using a \( \Xi = 7 \) eV. Therefore this value will also be used in our work. In figure 2, the theoretical lattice mobility is also plotted. The material constants listed in table I are used. In addition, we show the best fit to the experimental results for sample C252. The ionized impurity concentration \( (n_d + n_a) \) is estimated from \( \Theta = 0.4 \) and from the measured carrier concentration \( (n_d - n_a) \). The polar optical phonon mobility is calculated as in reference [12]. To fit the experimental results at low temperatures, we have to introduce scattering by neutral impurity
Experimental results

We use Erginsoy's formula [13] for the neutral impurity scattering. From the Hall effect we see that deep donor exhaustion is not reached until 300 K, therefore we can find the concentration of the neutron impurity from the mobility fit: It is equal to $3.3 \times 10^{14}$ cm$^{-3}$. The data in table I [14] have been used in the calculations of the mobilities.

![Graph](image)

**Fig. 4** The Hall mobility versus the Hall concentration. The lines are from Walukiewicz et al. [8]. $R_{\text{com}}$ is the rate of compensation. The symbols are the same as in figure 2.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Material parameters of InP used in our calculations [14].</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>lattice parameter a$_0$</strong></td>
<td>5.87 Å</td>
</tr>
<tr>
<td><strong>effective mass m$^*$</strong></td>
<td>0.08 m$_0$</td>
</tr>
<tr>
<td><strong>LO phonon energy E$_0$ (Debye $T_0$)</strong></td>
<td>43.5 meV ($T_0 = 504$ K)</td>
</tr>
<tr>
<td><strong>static dielectric constant $\varepsilon_0$</strong></td>
<td>12.4</td>
</tr>
<tr>
<td><strong>optical dielectric constant $\varepsilon_{\infty}$</strong></td>
<td>9.5</td>
</tr>
<tr>
<td><strong>deformation potential $\Xi$</strong></td>
<td>7.0 eV</td>
</tr>
<tr>
<td><strong>piezoelectric constant $h_{14}$</strong></td>
<td>$0.32 \times 10^9$ V / m</td>
</tr>
<tr>
<td><strong>longitudinal elastic constant $C_l$</strong></td>
<td>$1.27 \times 10^{11}$ N / m$^2$</td>
</tr>
<tr>
<td><strong>transverse elastic $C_t$</strong></td>
<td>$0.40 \times 10^{-11}$ N / m$^2$</td>
</tr>
</tbody>
</table>

At high temperatures (> 200 K), the polar optical phonon scattering dominates (see figure 2). The mobilities of all samples approximate the theoretical mobility limited by polar optic-phonon scattering. Therefore, above 300 K the concentration of the free electrons was also determined from the mobility $\mu_{\text{Latt}}$ and the measured
resistance. The results are in agreement with the Hall effect measurements. In figure 3, we show the concentration above 300 K for sample C252 only. At around 77 K, impurity (neutral and ionized) scattering leads to differences in the mobility from sample to sample. After optimizing the growth conditions, we obtained the purest sample C252 in which the mobility at 77 K was about $1.2 \times 10^5$ cm$^2$/Vs. In sample C252 there are still about $3.3 \times 10^{14}$ cm$^{-3}$ neutral impurities (deep donors) which limit the mobility at 77 K. See figure 2.

B. $1/f$ noise measurement

Noise spectra were measured with different voltages (electrical field < 2 kV/m) and at different temperatures (77 K $\leq$ T $\leq$ 500 K). The measured noise spectra are superposition of generation-recombination noise (g-r), thermal noise $4kTR$ and $1/f$ noise. The first two types of noise are well understood. We can easily determine the $1/f$ noise spectrum by subtracting the g-r noise and thermal noise from the measured spectrum.

In the frequency range of 1 Hz to $10^4$ Hz we obtained pure $1/f$ noise spectra in most of the samples, but not in sample C252 where a g-r bump was observed around room temperature. The contacts are proved to be free from noise by comparing the results measured via two-point and four-point measurements. Therefore, the bulk noise is dominant.

In homogeneous ohmic semiconductor samples, the experimental results - current or voltage fluctuations - are given as spectral power densities $S_T$ or $S_V$. The noise is characterized by the parameter $\alpha$ that is defined by the phenomenological expression

$$S_R = \frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{\alpha}{Nf}.$$  \hspace{1cm} (1)

Here we have assumed independent contributions from the N electrons. On average, $\alpha$ is the contribution to the noise of one electron [15].

The temperature-dependencies of $\alpha$ in all samples are shown in figure 5. Above 300 K, the noise is only measured on C252. For most of the samples, the trends of $\alpha(T)$ from 77 K to 300 K are quite common as in other semiconductors [16, 17]. Sample C252 is a exception, where $\alpha(T)$ increases with decreasing temperature below 200 K. The $\alpha(T)$ can often be fitted by an exponential function (2) over the whole range 77 K - 300 K (see the solid lines in figure 5), as reported elsewhere [4, 17].

$$\alpha = a \cdot \exp \left( \frac{-\Delta E}{kT} \right) + b,$$  \hspace{1cm} (2)

where a, b, and $\Delta E$ are temperature independent and vary from sample to sample. $\Delta E$ of figure 5 varies between 0.05 eV and 0.13 eV.

Alternatively, $\alpha(T)$ can also be fitted numerically by a power function as in equation (3) (see the dashed lines in figure 5),
\[ \alpha = c \cdot T^\gamma + d, \]  
\hspace{1cm} (3)

where \( c, d, \) and \( \gamma \) are temperature independent. For each value of \( \Delta E \) one can always choose a value of \( \gamma \) that brings the curve of equation (3) very close to the curve of equation (2). \( \gamma \) varies between 3 and 5. In a narrow temperature range it is impossible to distinguish between the curves of equations (2) and (3). In order to show the difference between equations (2) and (3), we have to measure the noise at high temperatures. Unfortunately, we cannot heat the samples above 500 K, because the contacts or the defects in the lattice can be unstable above 500 K. The temperature range we can use is too narrow to permit a distinction between \( \exp(-\Delta E/kT) \) and \( T^\gamma \) (see Fig. 5).

![Graph](image)

### Fig. 5
Temperature-dependence of \( \alpha \). + : FIB InP from Tacano et al. [22]. The other symbols are the same as in figure 2. The solid lines are the best fit by the exponential function with \( E = 0.13 \) eV for CBE InP, and \( E = 0.05 \) eV for FIB InP. The dashed lines are the best fit by the power function with \( \gamma = 5 \) for CBE InP, and \( \gamma = 3 \) for FIB InP.

### IV. THEORETICAL MODEL

Basically, the 1/f noise is attributed to the fluctuations of the conductance. The interpretation of such 1/f noise is currently a point of debate [18].

We discuss homogeneous ohmic semiconductor samples. As described in section III B, the noise is characterized by the parameter\( \alpha \). The value of\( \alpha \) is strongly influenced by changing the contribution of different scattering mechanisms. \( \alpha \) depends on temperature. In the following, we consider how the different scattering mechanisms take their role in the 1/f noise phenomenon. We try to formulate how the noise depends on temperature.

Musha [19] obtained a 1/f spectrum in the light scattered by the lattice modes of a quartz crystal. More recently, 1/f noise in light scattering was confirmed by van...
Kemenade et. al. [20]. These experiments strongly suggest that the number of phonons in a mode fluctuates with a 1/f spectrum. In electronic systems, there is ample experimental evidence that the 1/f noise in homogeneous semiconductors is in the scattering cross-section of the lattice vibration modes [1-3]. The cross-section fluctuates because the number of phonons fluctuates. It was experimentally proved that the 1/f noise parameter $\alpha$ can be described as following [1, 2, 21].

$$\alpha = \frac{\mu}{\mu_{\text{Latt}}} \cdot \alpha_{\text{Latt}}. \quad (4)$$

The physical meaning of this expression is that in homogenous semiconductors the 1/f noise stems from mobility fluctuations in the phonon scattering, whereas impurity scattering does not play any role in generating the 1/f noise. $\alpha_{\text{Latt}}$ is a material constant that probably depends on temperature.

Until here phonon scattering was treated as a simple phenomenon described by a single value for $\alpha_{\text{Latt}}$. But we can distinguish several scattering mechanisms in the phonon scattering, so that Matthiessen's rule can be applied to different types of phonon scattering:

$$\frac{1}{\mu_{\text{Latt}}} = \frac{1}{\mu_A} + \frac{1}{\mu_O}, \quad (5)$$

where the subscript A indicates acoustic-phonon scattering and O indicates optic-phonon scattering. We only consider these two scattering mechanisms, as the others are thought to be very weak in III-V compounds. The fluctuation of $\mu_{\text{Latt}}$ can be written as following.

$$\left( \frac{\Delta \mu_{\text{Latt}}}{\mu_{\text{Latt}}} \right)^2 \approx \left( \frac{\mu_{\text{Latt}}}{\mu_A} \right)^2 \left( \frac{\Delta \mu_A}{\mu_A} \right)^2 + \left( \frac{\mu_{\text{Latt}}}{\mu_O} \right)^2 \left( \frac{\Delta \mu_O}{\mu_O} \right)^2, \quad (6)$$

Using equation (1) for each scattering mechanism, we have:

$$\alpha_{\text{Latt}} = \left( \frac{\mu_{\text{Latt}}}{\mu_A} \right)^2 \alpha_A + \left( \frac{\mu_{\text{Latt}}}{\mu_O} \right)^2 \alpha_O. \quad (7)$$

where $\alpha_A$ and $\alpha_O$ are defined as follows,

$$\frac{S_{\mu_A}^2}{\mu_A^2} = \frac{\alpha_A}{fN} \quad \text{and} \quad \frac{S_{\mu_O}^2}{\mu_O^2} = \frac{\alpha_O}{\mu_O}. \quad (8)$$

Because we try to understand the influence of temperature on $\alpha$, we have to find the temperature-dependencies of $\alpha_A$ and $\alpha_O$.

In the case of carriers that are scattered by the long wavelength acoustic phonons, the scattering is elastic since the energy of the acoustic phonon is
negligible. Therefore the relaxation-time approximation can be applied:

\[ \mu_A = \frac{e^{(\tau_A)}}{m}, \]

hence,

\[ \mu_A = A(T) \cdot \frac{1}{\Phi_A}. \quad (9) \]

where the function \( A(T) \) varies slowly with \( T \), \( \Phi_A \) is total number of acoustic phonons.

Now, we consider that electrons are scattered by polar optical phonons. The situation is much more complicated. The relaxation-time is not a useful concept due to the inelastic scattering. The electron mobility \( \mu_O \), limited by polar optical phonon scattering, is obtained by numerically solving the Boltzmann equation [12].

\[ \mu_O = B(T) \cdot (e^{\hbar \omega_o / kT - 1}), \]

where \( \hbar \omega_o \) is the energy of the polar optic-phonon, and \( B(T) \) is a slowly varying function of \( T \). In good approximation \( \mu_O \) is inversely proportional to the population of the polar optical phonons \( \propto (e^{\hbar \omega_o / kT - 1})^{-1} \) which are involved in the process of the inelastic scattering.

Hence,

\[ \mu_O \propto C(T) \cdot \frac{1}{\Phi_O}, \quad (10) \]

where the function \( C(T) \) also varies slowly with \( T \).

If the number of phonons fluctuates with a 1/f spectrum, the scattering cross-section also has 1/f noise. When electrons are scattered at the mode, the 1/f noise is observed as a fluctuation in their mobility \( \mu \). Bose-Einstein statistics give for the number of phonons in a mode with superscript \( j \),

\[ \phi^j = \frac{1}{e^{\hbar \omega_o / kT} - 1}, \quad (11) \]

\[ (\Delta \phi^j)^2 = \phi^j + \langle \phi^j \rangle^2, \quad (12) \]

\[ \frac{(\Delta \phi^j)^2}{\langle \phi^j \rangle^2} = e^{\tau_o / T}, \quad (13) \]

Relation (13) is exact. If we assume that the phonon number fluctuations in different modes are independent, then we have:

\[ \frac{\langle \Delta \mu_i \rangle^2}{\mu_i^2} \propto \frac{\langle \Delta \phi_i \rangle^2}{\phi_i^2} \propto \frac{(\Delta \phi^j)^2}{\langle \phi^j \rangle^2} = e^{\hbar \omega_o / kT}, \]
The temperature dependence of 1/f noise in InP

\[
\frac{S_{\mu_i}}{\mu_i^2} \propto \frac{S_{\phi_i^j}}{(\Phi_i^j)^2} = e^{\hbar \omega_i^j / kT},
\]

where \( i \) indicates the acoustic or polar optical branch of phonons. In analogy to equation (8), we have,

\[
\alpha_i \propto e^{\hbar \omega_i^j / kT}.
\]

In view of above discussion, the temperature dependencies of the \( \alpha \) values for the three scattering mechanisms are as following:

i) Impurity scattering: \( \alpha_{\text{imp}} = 0 \).

ii) Lattice scattering, Acoustic phonons: \( \alpha_A \propto e^{\hbar \omega_A^j / kT} \).

For acoustic phonons: \( \exp(\hbar \omega_A^j / kT) = 1 \), which has tacitly been used in all previous publications.

\[
\alpha_A = D_A \cdot e^{\hbar \omega_A^j / kT} \equiv D_A.
\]

iii) Lattice scattering, Polar optical phonons: \( \alpha_O \propto e^{\hbar \omega_O^j / kT} \).

The dispersion curve of polar optical phonons is nearly flat

\[
\alpha_O = D_O \cdot e^{T_D / T},
\]

where \( T_D \) is the Debye temperature that can be regarded as independent of the lattice temperature (above 77 K).

Substituting equations (17) and (18) into (7), we get \( \alpha_{\text{Latt}} \) as following,

\[
\alpha_{\text{Latt}} = \left( \frac{\mu_{\text{Latt}}}{\mu_A} \right)^2 \cdot D_A + \left( \frac{\mu_{\text{Latt}}}{\mu_O} \right)^2 \cdot e^{T_D / T} \cdot D_O,
\]

where \( D_A \) and \( D_O \) may be constants or slowly varying functions of \( T \).

In this paper it is our first concern to present reliable experimental data. From curves of \( \alpha \) values versus mobility we found that the noise is in the lattice scattering and we obtained \( \alpha_{\text{Latt}} \) as function of temperature. Now we go one step further in trying to find an interpretation of the experimental results for \( \alpha_{\text{Latt}} \) by using constant values of \( D_A \) and \( D_O \). In this discussion we will show that the experimentally found trend in \( \alpha_{\text{Latt}}(T) \) is in agreement with the general idea of 1/f noise in the number of phonons as expressed by relation (19). However, precise numerical agreement cannot be obtained as long as we treat \( D_A \) and \( D_O \) as constants.
V. DISCUSSION

In section III B, we mentioned that the measured noise is normally described either by equation (2) or by equation (3). However, if we look at figure 5, we see that the $\alpha$ versus $T$ is quite different for different samples. The uprising branch at lower temperatures is found with high purity sample C252. Such a behavior has also been observed by Tacano [22]. This uprising branch cannot be described by equations (2) and (3). We will show that it makes more sense if we use $\alpha_{\text{latt}}$ instead of $\alpha$.

In the following, we apply the model proposed in section IV to analyze the experimental results. First, we demonstrate the model of the fluctuations in the lattice scattering by analyzing the noise in differently doped samples.

The impurity scattering does not generate $1/f$ noise, but reduces the $1/f$ noise in accordance with equation (4). Thus, when the doping is high enough to influence the mobility at a constant temperature, the value of $\alpha$ is reduced. In figure 5, it is clearly shown that $\alpha$ values for the very heavily doped sample FIB InP [22] are more than two orders smaller than $\alpha$ values for CBE InP samples which contain only native impurities. In CBE InP samples, the impurity scattering is so weak at high temperatures ($>200$ K) that the mobilities for all samples are very close to $\mu_{\text{latt}}$. Therefore, we expect that $\alpha$ will be close to $\alpha_{\text{latt}}$, and we indeed see that $\alpha$ values for these samples are almost equal. At low temperature, however, $\alpha$ values for these samples scatter on a large scale because the impurity scattering reduces the mobility in different degrees for different samples.

![Figure 6](image)

Fig. 6 Temperature-dependence of $\alpha_{\text{latt}}$. The symbols represent the results calculated by equation (4) - the lattice scattering model - for the same samples as those in figure 2. Solid line: The best fit if the noise only is in the acoustic phonon scattering ($D_A = 8 \times 10^{-2}$, and $D_O = 0$). Dashed line: the best fit if the noise only is in the polar optical phonon scattering ($D_A = 0$, and $D_O = 4 \times 10^{-5}$).
In our previous paper [1] we showed that at each constant temperature (300 K or 77 K), the very different \( \alpha \) values for all samples of figure 5 yielded one single value of \( \alpha_{\text{Latt}} \) via equation (4). In this paper, equation (4) is applied at all temperatures between 77 K to 300 K. What we obtained is shown in figure 6. The data points for \( \alpha_{\text{Latt}} \) at each constant temperature are now close together. Thus, at each constant temperature a single value of \( \alpha_{\text{Latt}} \) is found, although the original \( \alpha \) values of differently doped samples scatter widely. In this way we have experimentally proven the correctness of the model of 1/f noise in the lattice scattering, and proven that impurity scattering does not generate 1/f noise. At 77 K \( \alpha_{\text{Latt}} \) differs from the results in Ref. [1]. This is caused by that in [1] we used deformation potential \( \Xi = 14.5 \, \text{eV} \) to determine \( \mu_{\text{Latt}} \).

We obtained the temperature dependence of \( \alpha_{\text{Latt}} \) in InP. Two branches are shown: i) above 200 K, \( \alpha_{\text{Latt}} \) increases with increasing temperature; ii) below 200 K, \( \alpha_{\text{Latt}} \) increases with decreasing temperature. There is a minimum in the curve of \( \alpha_{\text{Latt}} \) versus \( T \) at about 200 K. The high-temperature-result i) was also observed in other semiconductors [4, 17, 23], the low-temperature-result ii) is very surprising. This trend ii) of \( \alpha_{\text{Latt}} (T) \) was never reported before, and the trend differs from previous results on GaAs from Ren and Hooge [21] as well as on Si from Palenskis and Shobitzkas [24]. Ren and Hooge measured the noise on MBE GaAs, they took an \( \alpha_{\text{Latt}} = 7 \times 10^{-5} \) which was independent of temperature at low temperatures. Palenskis and Shobitzkas measured the noise on single-crystal-Si, and they found that \( \alpha_{\text{Latt}} \) was a constant at all temperatures. A point of argument is that Palenskis and Shobitzkas did not compare differently doped samples, while that is the only way to be sure that the noise is due to fluctuations in the lattice scattering. Our result ii) for \( \alpha_{\text{Latt}} \) is supported by the measurements of \( \alpha (T) \) on the purest CBE InP C252 samples, and by the measurements of \( \alpha (T) \) on the heterostructure of InGaAs samples by Tacano [22]. In such both types of samples the lattice scattering is the dominant scattering mechanism. Therefore, the \( \alpha (T) \) is then close to \( \alpha_{\text{Latt}} (T) \). We see that for these two types of samples \( \alpha (T) \) increases with decreasing temperature at low temperatures.

Up to now, we showed how \( \alpha_{\text{Latt}} \) depends on temperature, without giving any explanation. A further analysis explains this temperature dependence of \( \alpha_{\text{Latt}} \). The theoretical analysis in section IV yields equation (19), which gives the temperature dependence of \( \alpha_{\text{Latt}} \). The factors \( D_A \) and \( D_O \) can be used as fitting parameters that determine the magnitude of \( \alpha_{\text{Latt}} \). We plot the two terms at the right side of equation (19) separately versus temperature in figure 7, where we take \( D_A = D_O = 1 \). According to figure 7, three situations are possible.

1) If the 1/f noise is due to polar optical phonon scattering only. In figure 6, we show the best fitting to the experimental points by the dashed line with \( D_O = 4 \times 10^{-5} \).

2) If the 1/f noise is only due to acoustic phonon scattering. In figure 6, the best fitting is given by the solid line with \( D_A = 8 \times 10^{-2} \).
3) If the two terms in equation (19) are close to each other, the observed noise is a summation of two 1/f noises, 1) and 2). In figure 8, we show the best fitting by the solid line, where we take equal contributions by each kind of phonons: \( D_O = 2 \times 10^{-5} \) and \( D_A = 4 \times 10^{-2} \).

![Fig. 7](image1.png)

**Fig. 7** Temperature-dependencies of the two terms at the right-hand side of equation (19) in the situation where \( D_A = D_O = 1 \). The data of fig. 2 are used.

![Fig. 8](image2.png)

**Fig. 8** The best fit if the noise is both in the acoustic phonon scattering and in the polar optical phonon scattering (\( D_A = 4 \times 10^{-2} \), and \( D_O = 2 \times 10^{-5} \)).

We have no idea what the value of \( D_O \) or \( D_A \) should be. The cases 2) and 3) give better results. Case 1) is less accurate. Nevertheless, at low temperatures all three fitting curves show agreement with the experimental trend of \( \alpha_{\text{Latt}} (T) \), which
increases with decreasing temperature. Therefore, we cannot determine the two contributions of acoustic and optical phonons in the lattice scattering.

At higher temperatures, above 200 K, we have a problem. At any constant temperature, relation (4) applies, which allows us to determine $\alpha_{\text{Latt}}$. $\alpha_{\text{Latt}}$ increases quickly. If we express this temperature dependence of $\alpha_{\text{Latt}}$ by an exponential, the best fit is obtained with $\Delta E = 0.15 \text{ eV}$. This corresponds to a $T^5$ dependence. In the narrow range 200 K - 500 K we cannot distinguish between these two curves. Our present results on InP and also previous results on GaAs [17] support the general idea behind relation (19). This relation predicts that $\alpha_{\text{Latt}}$ increases with increasing temperature, due to the strong contribution of acoustic scattering, which has the right slope at higher temperatures (see fig. 7). But whatever combination of the two contributions we take, it is impossible that $\alpha_{\text{Latt}}$ starts to increase at 200 K. The solid lines in figures 6 and 8 show that $\alpha_{\text{Latt}}$ increases with increasing temperature only above 300 K. The question arises, whether treating $D_A$ and $D_O$ as constants creates this problem, or whether there is another type of mobility noise that operates at high temperatures.

VI. CONCLUSIONS

The 1/f noise in InP is found to be proportional to $\mu^2$ in the temperature range of from 77 K to 300 K, which proves that the 1/f noise is in the lattice scattering.

The temperature dependence of $\alpha_{\text{Latt}}$ consists of two branches. The dependence at lower temperatures can be well explained by phonon number fluctuations. In theory $\alpha_{\text{Latt}}$ can be split into two parts, $\alpha_A$, the contribution of acoustic phonons, and $\alpha_O$, the contribution of polar optical phonons. The dependence of $\alpha_{\text{Latt}}$ on $\alpha_A$ and $\alpha_O$, equation (19), determines the temperature dependence of $\alpha_{\text{Latt}}$.

Precise numerical agreement cannot be obtained as long as we treat $D_A$ and $D_O$ as constants. Especially at higher temperatures above 200 K, we are not able to give a satisfactory interpretation of $\alpha_{\text{Latt}}$ as function of temperature.

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References:

Chapter 5

LOW FREQUENCY NOISE IN δ-DOPED GaAs

TWO PAPERS ARE INCLUDED IN THIS CHAPTER:

1. 1/f noise in δ-doped GaAs, analyzed in terms of mobility fluctuations

2. Spectroscopy of low-frequency noise in δ-doped GaAs grown by MBE
1/f noise in $\delta$-doped GaAs, analyzed in terms of mobility fluctuations

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This paper presents 1/f noise measurements on Si $\delta$-doped GaAs structures. The samples are characterized by Hall, magnetoresistance, and Schubnikov–de Haas measurements. The distribution of electrons over the two lowest subbands in these structures varies with temperature and illumination, and so does the noise. The 1/f noise is characterized by the usual parameter $\alpha$. We show in detail how to interpret the 1/f noise in the two-subbands system. We find that $\alpha$ increases by a factor of 30 upon population of a second subband either by illuminating the sample or by raising the temperature to 100 K. This strong increase in the 1/f noise is successfully described by the mobility fluctuation model, where only the lattice scattering contributes to the 1/f noise. The 1/f noise of the electrons in both subbands can be characterized by the same value of $\alpha=0.4$, which is strong support for the model. [S0163-1829(97)00308-1]

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I. INTRODUCTION

Many semiconductor devices suffer from 1/f noise. Before anything can be done to remedy this, we need to understand the physical nature of this type of noise. The study of the origin of 1/f noise requires simple well-defined samples: a $\delta$-doped layer is such a structure.

The ideas about 1/f noise in semiconductors are moving toward a model of mobility fluctuations in the bulk of the material. Yet, there still is experimental evidence that in some cases 1/f noise might be generated by traps at the surface which would mean that 1/f noise is a fluctuation in the number of electrons (e.g., metal-oxide-semiconductor transistor).

The Eindhoven group proposed a model in which the mobility fluctuations are due to the lattice scattering only. The strongest experimental evidence they presented for their point of view is from the noise of a series of similar devices where the impurity scattering varies because of different doping levels. "Diluting" the constant lattice scattering with noise-free impurity scattering reduces the 1/f noise systematically. Although the acceptance of the mobility model is growing, the problem is far from settled. Therefore, we undertook this noise study of $\delta$-doped layers in order to find different experimental arguments for the model.

In the first place the conducting $\delta$-doped layer is far from the surface and there are no interfaces such as those found in two-dimensional heterostructures. Second, the electrons in the $\delta$-doped layer are distributed over different subbands, each with its own mobility and contribution to the noise. The important point is that the electrons in different subbands are scattered by the same lattice vibrations in the same volume. The model then predicts the same contribution from lattice scattering to the 1/f noise.

Typically, a $\delta$-doped layer of Si in GaAs, grown at a low temperature, has a thickness of only a few atomic layers. Due to the narrow size of the potential well of a $\delta$-doping layer, a two-dimensional electron gas (2DEG) is formed at the doping plane. Because the doping concentration is above the Mott density ($=3\times10^{11}$ cm$^{-2}$ for GaAs:Si), there is no carrier freeze out at low temperatures. A typical picture of the electronic band structure of the $\delta$-doped layer is shown in Fig. 1. The electrons may populate several subbands in the potential well. The scattering cross section of electrons on the ionized donor atoms is different for electrons in different subbands, because the electron wave functions have different $z$ dependences. The electron mobility in each subband depends, in a complicated way, on the shape of the wave funct.

![FIG. 1. The electronic structure of a $\delta$-doped layer. The dashed-dotted line represents the potential well. The dashed line presents the Fermi level. The solid lines represent the subband levels and the electron wave functions. The second subband is a few meV above the Fermi level.](image-url)

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tion, the population of the level, and the screening. Experimental and theoretical analysis have shown that the mobility in a higher subband is higher than in a lower subband.

The electronic properties of δ-doped layers have been studied intensively. Compared with homogeneously doped GaAs, significant advantages in the electronic properties have been found in δ-doped structures. Some different devices have been developed by using δ-doped layers. In this contribution, the results of noise measurements on a δ-doped structure are presented.

We carried out measurements in the temperature range of 77 to 300 K. We experimentally changed the distribution of the electrons over the subbands either by illuminating the sample with a red light-emitting diode or by increasing the temperature above 100 K. We studied the influence of this redistribution on the 1/f noise. The results enable us to demonstrate that the 1/f noise is due to mobility fluctuations related to phonon scattering exclusively.

II. SAMPLE GROWTH AND CHARACTERIZATION

A. Sample growth

The sample was grown in our Varian-Gen II molecular-beam epitaxy. The structure consists of a Si δ-doped layer centered between two Al0.3Ga0.7As barriers each at 500 Å away from the δ-doped layer. We used a low growth temperature of 480 °C to limit the thickness of the doping layer to 20 Å. This part of the structure is grown on top of a 1 μm-thick GaAs buffer layer. A schematic diagram showing the layer structure is given in Fig. 2. The δ-doping layer contained about 3×10^{12} Si atoms per cm^2. In our GaAs structures grown at 480 °C we typically find a p-type background concentration of about 10^{19} cm^{-3}, this is about a factor 10 higher than in GaAs grown at the optimal growth temperature of 650 °C. The p-type background concentration in Al0.3Ga0.7As grown at this low temperature proved to be much higher than 10^{15} cm^{-3}. We find values in the range of 10^{17}–10^{18} cm^{-3}. A schematic diagram of the conduction band of the structure is shown in Fig. 3. A Hall bar structure was prepared by the conventional lithography process. Ohmic contacts were made by annealing Sn balls on the surface of the sample at 450 °C in an atmosphere of N_2/H_2. The configuration of the sample is given in Fig. 4.

B. Hall characterization

The samples were first characterized by simple Hall measurements. We prepared the samples into either Van der Pauw structures or Hall bar structures as given in Fig. 4. The samples are characterized as a function of temperature from 5 up to 300 K. We characterized the samples in the dark and

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**FIG. 2.** Cross-section of the sample.

**FIG. 3.** Schematic diagram of the structure of the conduction band of the sample. 1 and 2 indicate subbands 1 and 2. \( E_r \) is the Fermi level.

**FIG. 4.** Geometry of the sample. The numbers 1–8 refer to contacts; 1 and 2 are used as current contacts.

**FIG. 5.** Temperature dependencies of the surface Hall concentration and Hall mobility. The solid symbols represent the results in dark, and the open symbols present the results after illumination.
TABLE I. Characteristics of the sample. SdH: Schubnikov–de Haas measurement from which the quantum mobility is obtained. CMR: Classical magnetoresistance measurement from which the transport mobility is obtained. Hall: Hall measurement. PPC (5 K): Persistent photoconductivity (PPC) after illumination at 5 K. PPC (77 K): PPC after illumination at 77 K.

<table>
<thead>
<tr>
<th>Temperature</th>
<th></th>
<th>(n_H (10^{12} \text{ cm}^{-2}))</th>
<th>(\mu_H (10^3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}))</th>
<th>(n_t (10^{12} \text{ cm}^{-2}))</th>
<th>(n_s (10^{12} \text{ cm}^{-2}))</th>
<th>(\mu_t (\text{cm}^2 \text{V}^{-1} \text{s}^{-1}))</th>
<th>(\mu_s (\text{cm}^2 \text{V}^{-1} \text{s}^{-1}))</th>
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<td>5 K</td>
<td>Dark</td>
<td>(1.60 \pm 0.03)</td>
<td>(900 \pm 50)</td>
<td>(1.88 \pm 0.02)</td>
<td>(1.91 \pm 0.02)</td>
<td>(950 \pm 50)</td>
<td>(460 \pm 30)</td>
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<tr>
<td></td>
<td>Hall</td>
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<tr>
<td></td>
<td>PPC (5 K)</td>
<td>(2.11 \pm 0.02)</td>
<td>(0.50 \pm 0.02)</td>
<td>(600 \pm 80)</td>
<td>(215 \pm 150)</td>
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<td>CMR</td>
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<td>(0.4 \pm 0.1)</td>
<td>(1400 \pm 100)</td>
<td>(4100 \pm 200)</td>
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<tr>
<td></td>
<td>Hall</td>
<td>(1.58 \pm 0.03)</td>
<td>(900 \pm 50)</td>
<td>(1.70 \pm 0.02)</td>
<td>(1050 \pm 50)</td>
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<tr>
<td>77 K</td>
<td>PPC (5 K)</td>
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<td>(1400 \pm 50)</td>
<td>(5200 \pm 300)</td>
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<tr>
<td></td>
<td>CMR</td>
<td>(1.58 \pm 0.03)</td>
<td>(900 \pm 50)</td>
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<td>(1220 \pm 30)</td>
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<td>Hall</td>
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<td>(1900 \pm 100)</td>
<td></td>
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</tr>
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</table>

After short illumination pulses at either 5 or 77 K. In Fig. 5 we show the temperature dependence of \(n_{Hall}\) and \(\mu_{Hall}\) in the range from 5 to 300 K, measured in the dark and after illumination at 5 K.

We find that the Hall electron density, \(n_{Hall}\), does not strongly depend on the temperature or the illumination conditions. The Hall mobility, \(\mu_{Hall}\), shows a small increase when we increase the temperature above 80 K, but remains constant below 80 K. This temperature independence of the Hall mobility below 80 K is mainly due to the fact that we have a highly degenerate electron gas in which ionized impurity scattering is the main scattering mechanism. In \(\delta\)-doped layers the mobility is considerably lower than in modulation doped GaAs/Al\(_{x}\)Ga\(_{1-x}\)As heterostructures, where ionized donors are separated from free electrons. Due to the very strong ionized impurity scattering, phonon scattering is not important in the whole temperature range.

In the dark, \(\mu_{Hall}\) increases with temperatures above 80 K. We will later show that this is due to the population of the second subband, which has a higher mobility. After illumination at 5 K, the Hall mobility increases by about a factor of three. This mobility enhancement factor remains constant up to temperatures of about 80 K and it decreases at higher temperatures. At about 200 K the Hall mobility falls back to the dark value. Thus, persistent photoconductivity (PPC) is weakened above 80 K and above 300 K it disappears.

It is difficult to draw quantitative conclusions from these Hall measurements. This is due to the fact that in \(\delta\)-doped samples more than one subband is normally populated. The Hall density and Hall mobility, in such a case, depend on the strength of the magnetic field, the population of each subband, and the mobility in each subband.

C. Classical magnetoresistance measurements

In the case that multiple subbands are populated we can determine the carrier mobility and population in each individual subband from an analysis of the classical magnetoresistance measurements. Classical means that no quantum effects from the magnetic field should influence \(\sigma_{x}(B)\) and \(\sigma_{y}(B)\), i.e., that no Schubnikov–de Haas oscillations or quantum Hall plateaus should be observed. In this classical regime the magnetoresistance tensor elements are

\[
\sigma_{x}(B) = \sigma_{y}(B) = \sum_{r} \frac{q\mu_{r}}{1 + (\mu_{r}B)^{2}},
\]

where \(\sigma_{x}(B)\) is the longitudinal magnetoresistance, \(\sigma_{y}(B)\) the transversal magnetoresistance or Hall conductivity, \(n_{t}\) the subband population, \(\mu_{t}\) the subband mobility, and \(q\) the elementary charge. The resistivity tensor elements \(\rho_{xx}(B)\) and \(\rho_{xy}(B)\) can be obtained by inverting the conductivity tensor.

By analyzing the magnetic-field dependence of the \(\rho_{xx}(B)\) and \(\rho_{xy}(B)\) measurements, we obtain the individual subband mobilities and subband densities. We have used the mobility spectrum analysis technique proposed by Beck and Anderson to obtain these values from classical magnetoresistance measurements.

The results obtained from the magnetoresistance measurements in the magnetic-field range from 0–5 T are shown in Table I. The results obtained at 77 K show that in the dark only one subband is populated. If the temperature is raised to room temperature it is clear that two subbands are populated. These results prove that above 80 K the second subband becomes populated by thermal redistribution of the free carriers. After illumination we also find that the second subband is populated. The persistent enhancement of the total electron concentration is due to neutralization of the depletion charges in the depletion regions next to the \(\delta\) layers. We find a somewhat higher PPC effect in this structure than in our normal \(\delta\) layers. This is due to the fact that in \(\delta\)-doped structures we normally do not include Al\(_{x}\)Ga\(_{1-x}\)As barriers, which have a very high background concentration of defects when grown at 480 °C.

The second subband has a higher mobility compared to the lowest subband. This mobility enhancement is mainly
due to the smaller overlap of the electron wave function in the second subband with the ionized impurity distribution compared to the overlap of electron wave function of the lowest subband.5 The mobility enhancement after illumination at 77 K is smaller than after illumination at 5 K. We also observe a smaller persistent increase of the total electron density. During illumination at 77 K we cannot neutralize the depletion charges as effectively as during illumination at 5 K.

D. Schubnikov-de Haas measurements

In order to strengthen the arguments discussed in the previous paragraph we also performed Schubnikov-de Haas (SdH) measurements at 5 K.12 The results of the SdH analysis are also shown in Table I. We find, just as in the classical magnetoresistance measurements, that only one subband is populated in the dark. The SdH measurements also show that after illumination a second subband is populated. The electron densities obtained from the SdH measurements compare reasonably with the densities obtained from the classical magnetoresistance analysis. From the magnetic-field dependence of the amplitudes of the SdH oscillations we are able to determine the quantum mobility of the carriers in each individual subband.13 The quantum mobility is proportional to the scattering lifetime of a carrier, i.e., the scattering probability is not weighed by a factor $\cos \theta$, with $\theta$ the scattering angle, as in the case for the transport mobility.14 Similar to the transport mobilities obtained from the classical magnetoresistance measurements, we find that the mobility in the second subband is about a factor 3 higher than the mobility in the lowest subband. Finally, we would like to remark that a SdH analysis is only possible at temperatures below 40 K. Above this temperature the amplitude of the oscillations is so weak that it is impossible to analyze it properly.

E. Discussion of the subband structure

In $\delta$-doped structures with a doping concentration of about $3 \times 10^{12}$ cm$^{-2}$, we expect to find two populated subbands before illumination.1 In the present structures in the dark we only find one populated subband below 80 K. We think that this is due to the high density of $\delta$-type defects in the Al$_x$Ga$_{1-x}$As barrier layers. We have the following arguments to support this idea. (1) Although we doped the structure at about $3 \times 10^{14}$ cm$^{-2}$, we only have $1.6 \times 10^{12}$ cm$^{-2}$ free electrons. Thus many electrons are lost to deep defects. (2) In normal $\delta$-doped structures we find a persistent enhancement of the electron density after an illumination of approximately $0.3 \times 10^{12}$ cm$^{-2}$. In the present structure we find an enhancement of $0.8 \times 10^{12}$ cm$^{-2}$. Apparently there are more depletion charges that can be neutralized in the present structure. (3) If electrons from the doping layer are transferred to the Al$_x$Ga$_{1-x}$As layer, an electric field will form due to the charge separation. This electric field will lead to a steeper potential well and consequently to a further separation of the lowest and second subband. This can lift the energy position of the second subband above the Fermi level. If we perform self-consistent calculations we find that only a single subband is populated when the background concentration in the Al$_x$Ga$_{1-x}$As layer is about $5 \times 10^{12}$ cm$^{-2}$. This defect density is in agreement with defect concentration measurements we performed in homogeneous Al$_x$Ga$_{1-x}$As layers grown at 480°C.

F. Conclusions from the sample characterization

In conclusion we have shown that in the dark at temperatures below 80 K only the lowest subband is populated. The second subband becomes populated by thermal excitation above 80 K. After illumination the second subband is also persistently populated. The mobility in the second subband is about 3 times the value of the mobility in the lowest subband. The population and mobilities in each subband are almost independent of temperatures below 80 K. Above 80 K the PPC effect starts to disappear.

III. NOISE MEASUREMENTS AND DISCUSSION

The voltage fluctuations were measured in a frequency range from 1 Hz to 40 kHz by the four-point method. Details of the configuration for the noise measurement were described elsewhere.13 We carried out noise measurements in the dark and also several minutes after illumination. The noise levels are proportional to the square of the voltage and the length of the sample, which shows that the sample can be considered as a homogeneous Ohmic resistor.

Normally, a spectrum of low-frequency noise consists of thermal noise and 1/f noise; sometimes generation-recombination $(g-r)$ noise is found. The thermal noise is the fluctuation of the velocities of electrons, and its power density $S_0$ is given by Eq. (2). The $g-r$ noise stems from $g-r$ centers, and its power density $S_{g-r}$ is described by equation (3). 1/f noise is a fluctuation of the conductance. The origin of 1/f noise is unknown. The normalized 1/f noise $S_{1/f}$ for Ohmic samples can be expressed by Eq. (4).16

$$S_{g-r} = 4k_B TR.$$  

(2)

$$S_{1/f} = \frac{C}{f^{1/2}}.$$  

(3)

$$S_g - S_{g-r} S_{1/f} = \frac{\alpha}{f^{1/2}}.$$  

(4)

where $k_B$ is Boltzmann's constant, $T$ is the temperature, $R$ is the resistance, $V$ is the voltage, $C$ is a constant, $\tau$ is the characteristic time of the $g-r$ process, $f$ is the frequency, $\sigma$ is the conductance, $\alpha$ is the noise parameter, and $N$ is the total number of carriers in the volume involved in the noise generation. Some typical measured spectra are given in Figs. 6 and 7.

After illumination, at temperatures below 100 K we observed exact 1/f noise. When we illuminated the samples below 100 K, the resistance of the sample decreases. Several minutes after turning off the light, the resistance became stable. The photoexcited electrons were frozen mainly in subband 2, the remainder in subband 1. The relaxation time is so long that the sample is stable enough for noise measurements. The noise after illumination was then measured. The spectra showed 1/f noise (see Fig. 6). When the temperature rises, the time dependence of PPC shows up. At temperatures above 100 K, the relaxation time became...
1/f noise in $\delta$-doped GaAs, analyzed in terms ...  

1/f NOISE IN $\delta$-DOPED GaAs ANALYZED IN TERMS ...  

![Graph 1](image1.png)

**FIG. 6.** Typical low-frequency noise spectra. ○: in the dark at room temperature; △: in the dark at 77 K; +: several minutes after the illumination at 83 K; V: several minutes after the illumination at 77 K. The dashed line is for guiding the eye.

shorter than the time we needed for a noise measurement. Therefore, we could not measure the noise after illumination at higher temperatures.

In the dark, the noise was measured at temperatures from 77 to 300 K. Exact 1/f noise spectra were again observed at temperatures below 100 K. We frequently observed $g-r$ components in the spectra measured above 100 K due to deep levels in GaAs. A detailed analysis of $g-r$ noise is not included in this paper. However, the $g-r$ noise was considered in the fitting procedure in order to determine accurately the 1/f noise level (see Fig. 7).

![Graph 2](image2.png)

**FIG. 7.** A typical low-frequency noise spectrum with a $g-r$ component. △: measured in the dark at 191 K. The dashed lines represent the individual components of $g-r$ noise, 1/f noise, and thermal noise. The solid line represents the best fitting summation of the three noise components.

In the following discussion of 1/f noise, we shall characterize the 1/f spectra by $\alpha$ defined in Eq. (4), where $N$ is obtained from $N = l \times w \times n_{\text{Hall}}$, with $l$ and $w$ the length and the width of the sample, and $n_{\text{Hall}}$ the measured Hall concentration (Fig. 5). $\alpha$ is an empirical parameter, expressing the relative strength of the 1/f noise per electron. The temperature dependence of $\alpha$ is given in Fig. 8. $\alpha$ in the dark increases quickly above 80 K. At temperatures below 80 K, the value of $\alpha$ is much higher after illumination than in the dark. However, at 100 K, the value of $\alpha$ after illumination and in the dark become comparable. It is clear that, in the dark, there is a transition from a low noise level to a high noise level. This transition starts to occur at 80 K and ends at about 100 K. As discussed in Sec. II, above 80 K, electrons are thermally redistributed so that the second level starts to be populated, this leads to the increase of the 1/f noise. Above 100 K, the second subband contributes significantly to the 1/f noise.

According to the above discussion, the noise increases very strongly when the second subband, with high mobility, is populated by either photonexcited electrons or thermally excited electrons. In other words, we observe a higher level of 1/f noise, when the average mobility of electrons is higher. This encourages us to consider the model for 1/f noise, where mobility fluctuations are only assumed in the lattice scattering.

According to this model, $S_{\mu_l} = 0$ and $S_{\mu_{\text{mob}}} = 0$. It is straightforward to derive from Matthiessen's rule

$$\alpha = \left( \frac{\mu}{\mu_L} \right)^2 \alpha_L.$$  

where $\alpha_L$ is a material constant, $\mu$ the total mobility, $\mu_L$ the mobility limited by the lattice scattering. Thus, $\alpha$ is proportional to the square of the mobility. This model was described in detail in Refs. 2 and 19. The model works very well for the 1/f noise in III-V compound materials.
It could well be that the impurity scattering dominates the other scattering mechanisms. The average mobility $\mu$ is then close to $\mu_{\text{imp}}$, the mobility due to impurity scattering. Nevertheless, only the lattice scattering generates 1/f noise. The dominating impurity scattering then reduces the numerical value of $\alpha$ according to Eq. (5).

In this $\delta$-doped sample, where two groups of electrons with different mobilities can contribute to the noise, we cannot simply put $\alpha$ into Eq. (5) to determine $\alpha_1$ for the $\delta$-doped layers. We have to determine the individual contribution by each group of electrons.

When the second subband gradually becomes populated, we should take into account that two types of carriers are present in the sample. We describe the 1/f noise of the electrons in the two subbands as noise from two parallel conduction mechanisms, i.e., from electrons in subband 1 and in subband 2. For the noise in the conductance we then write

$$S_C = \frac{S_{C1} + S_{C2}}{\sigma^2} = \frac{(n_1 \mu_1)^2}{(\sigma_1 + \sigma_2)^2} = \frac{n_1 \mu_1 + n_2 \mu_2}{n_1 \mu_1 + n_2 \mu_2} \alpha,$$

(6)

where $n_1$ and $\mu_1$ are the concentration and mobility of electrons in the 1st subband, and $\alpha$ is the volume involved in the noise generation. Relation (4) has been used here for each type of electron.

Relation (7) directly follows from (4) and (6) without any further assumption or approximation,

$$\alpha = n_{\text{Hall}} \frac{(n_1 \mu_1 + n_2 \mu_2)^2}{(n_1 \mu_1 + n_2 \mu_2)^2},$$

(7)

where

$$n_{\text{Hall}} = \frac{(n_1 \mu_1 + n_2 \mu_2)^2}{n_1 \mu_1^2 + n_2 \mu_2^2},$$

(8)

hence,

$$\alpha = \frac{n_1 \mu_1^2}{n_1 \mu_1^2 + n_2 \mu_2^2} \alpha_1 + \frac{n_2 \mu_2^2}{n_1 \mu_1^2 + n_2 \mu_2^2} \alpha_2.$$

(9)

In the situation that two subbands are populated, we see that it is impossible to determine $\alpha_1$ and $\alpha_2$ by a single measurement. We need to prepare two situations with different distributions of the electrons over subbands 1 and 2 in order to obtain two independent equations with two unknown parameters $\alpha_1$ and $\alpha_2$. We have seen that at 77 K we can prepare a situation with either one (in the dark) or two (after illumination) subbands populated. Thus, at 77 K we can find both $\alpha_1$ and $\alpha_2$. Above 100 K there is no PPC effect and, therefore, we are not able to prepare two different situations. Hence we cannot determine $\alpha_1$ and $\alpha_2$ separately above 100 K.

Relation (9) will now be used for the analysis of the results that were obtained at 77 K, either in the dark or after illumination. Table I shows the numerical values to be used together with estimates of their errors. At 77 K, there is the advantage that the 1/f noise from subband 1 in the dark can be separately measured due to the fact that the subband 2 is not populated. The value of $\alpha_1$ immediately follows from the dark situation since $n_2 = 0$. We obtain,

$$\alpha_1 = 7 \times 10^{-6}.$$

(10)

We use $\mu_{\text{L}} = 2 \times 10^5$ cm$^2$/V s from Ref. 22. Relation (5) then yields

$$\alpha_{e1} = 0.3 \pm 0.1.$$

(11)

The analysis of the situation after illumination yields the value of $\alpha_2$. Assuming the same value in dark and after illumination for $\alpha_1$, we find that after illumination the term with $\alpha_1$ in Eq. (9) is two orders of magnitude smaller than $\alpha$. Therefore we neglect the $\alpha_1$ term in this case and find from Eq. (9)

$$\alpha_2 = 2 \times 10^{-6}.$$

(12)

The impurity scattering is different for the electrons in subband 1 and subband 2, because of the different overlap of the electron wave functions with the impurity profile, but the lattice scattering is the same. Therefore we take $\mu_{\text{L2}} = \mu_{\text{L1}}$ when applying Eq. (5)

$$\alpha_{e2} = 0.5 \pm 0.2.$$

(13)

We assume that this value, determined from the situation after illumination, is a constant, independent of the level of illumination. Comparing the results from (10)–(13) strongly supports our model with noise sources exclusively in the lattice scattering. Although $\alpha_1$ and $\alpha_2$ differ by a factor 30, they lead to $\alpha_1$ values that are very close. In view of the inaccuracy we venture to conclude that they yield the same value:

$$\alpha = 0.4 \pm 0.2 \text{ at 77 K}.$$

(14)

Comparing the value of $\alpha$, in two dimensions (2D) with that in three dimensions (3D), we find that $\alpha_1$ (2D) = $10^4$ x $\alpha_1$ (3D). This high value may result (i) from the different number of the lattice modes involved, (ii) from the strongly disordered crystal lattice in the $\delta$-doped layer, where islands of Si have been observed. Strongly enhanced 1/f noise has been found in disordered GaAs crystals.24-28

IV CONCLUSIONS

Our studies of the 1/f noise in 2DEG structures have shown the following.

(1) The electrons in a $\delta$-doped layer give a perfect 1/f noise.

(2) 1/f noise in our samples is not due to any surface or interface effect.

(3) The noise from the two lowest levels can be characterized by a single value $\alpha$, equal to 0.4.

(4) The single value of $\alpha$ supports the model in which fluctuations in the lattice scattering generate the 1/f noise.

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1/f noise in δ-doped GaAs, analyzed in terms of...

SPECTROSCOPY OF LOW-FREQUENCY NOISE IN δ-DOPED GaAs GROWN BY MBE

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The noise properties of a δ-doped semiconductor structure was investigated at temperatures from 77 K to 300 K. The temperature-dependence of the parameter α of 1/f noise was experimentally determined. The activation energies of the trapping centers in each sample were determined by analyzing the temperature dependence of the generation-recombination noise (g-r noise).
I. INTRODUCTION

δ-doped semiconductor structure has an extremely narrow, but well-defined doping profile. A 2-dimensional electron gas results. It is a promising structure for semiconductor devices with a smaller size, higher operating speed and lower power consumption [1-3]. The electronic properties have been studied intensively. The noise of the δ-doped structure, which is a problem in application of the devices, is rarely investigated. We report on the results of noise measurements in Si δ-doped GaAs.

II. EXPERIMENTAL PROCEDURES

Our samples were grown by an MBE process. We used a low growth temperature of 480°C to limit the thickness of the doping layer to 20 Å [4]. In sample W294, the δ-doped layer was at the center of a 2 μm thick GaAs layer. In sample W261, two Al0.3Ga0.7As barriers, each 500 Å away from the δ-doped layer were grown. The doping concentrations of the two samples are 3.5 × 10^{12} cm·² for W261 and 2.5 × 10^{12} cm·² for W294. The electronic structure of the δ-layer is shown in fig. 1. In the previous investigation [5], we found that for W261 only the lowest subband is populated below 80 K due to electron capture by deep defects in the barrier layers (Al0.3Ga0.7As). In sample W294, more than two subbands are always populated [4]. Noise and Hall effect were measured at temperatures from 77K to 300K.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The Hall effect was measured at temperatures from 77 K to 300 K using a current of 10 μA and a magnetic field of 0.5 T. The results are shown in fig. 2.

The longitudinal noise was measured by a four-point method in the ohmic range of the samples. Typical spectra are shown in figures 3 and 4.
Chapter 5. Low frequency noise in δ-doped GaAs

Fig. 2. Temperature dependence of the Hall concentrations and the Hall mobilities. The solid symbols: W261; The open symbols: W294.

Fig. 3. Spectra measured from W294 at Temperatures from 82 K to 177 K. Two g-r components changing with temperature are observed. The solid lines represent the best fitting summations of g-r noise, 1/f noise and thermal noise. Points are the measured spectra with an arbitrary scale.

A. g-r noise

If we consider an energy level in the forbidden gap, its g-r noise appears only if the Fermi level is less than several kT away from the level. There will be several g-r spectra at any temperature T at which different levels are active. These g-r spectra can be distinguished due to the different characteristic times $\tau_i$ of the different generation and recombination processes. The g-r spectrum with its $\tau$ can be determined from the measured noise spectrum as shown in figs. 3 and 4. The
characteristic time \( \tau_1 \) is determined by the corner frequency of the Lorentzian shape. The temperature dependencies of \( \tau_1 \) are given in figures 5 and 6. Several straight lines are drawn. Each of the lines correspond to a g-r process. This is because \( \tau_1 \) varies with temperature, as \( \tau_1 = \tau_{10} \exp (E_i / kT) \), where \( E_i \) is the activation energy of the ith trap or center. Thus the activation energies for the g-r levels are determined by the slopes of the lines. All energies we obtained have been reported as the activation energies of electron traps in GaAs or AlGaAs (see figure 2.2 in Ref. 6 and table II in Ref. 7).

![Fig. 4](image)

**Fig. 4.** Two typical spectra measured from W261 at different temperatures. The dashed lines represent the individual components of the noise: g-r noise, 1/f noise, and thermal noise. The solid lines represent the best fitting summations of the all noise components. O: at 191 K, and \( \Delta \): at 286 K.

![Fig. 5](image)

![Fig. 6](image)

**Fig. 5.** Temperature dependence of the relaxation time of sample W294.  
**Fig. 6.** Temperature dependence of the relaxation time of sample W261.

The levels that are found in W261 but not in W294 have to be the deep levels in the AlGaAs. We can not rule out the possibility that DX centers are also g-r
generators. The energy of 0.21 eV possibly is the activation energy of DX centers in the potential well or in the vicinal layers of the potential well [8-10].

B. 1/f noise

1/f noise, at temperatures from 77K to 300 K, is characterized by $\alpha$ that is defined by equation (1).

$$\frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{S_I}{I^2} = \frac{\alpha}{N}$$

with $N$ the total number of the carriers measured by Hall effect, $R$ the resistance, $V$ the voltage, $I$ the current, $f$ the frequency and $S_x$ the noise power spectral density. The temperature dependence of $\alpha$ is shown in fig. 7.

![Fig. 7: $\alpha$ versus $1/T_{meas}$ (in dark, +: W294, Δ: W261, after illumination ●: W261).](image)

In W261 the noise is much lower at low temperatures at which the electrons only populate the lowest subband. After illumination, the second subband of W261 is also populated due to photo-excitation. The noise level increases significantly. In W294 more than two subbands are populated, so the noise is even higher at 77 K.

In δ-doped layers, the scattering cross-section of electrons on the ionized donor atoms is different for electrons in different subbands, because the electron wave-functions have different $z$-dependencies. The electron mobility in each subband depends, in a complicated way, on the shape of the wave-function, the population of the level and the screening. Experimental and theoretical analysis have shown that the mobility in a higher subband is higher than in a lower subband [11]. We see that the higher the mobility is, the higher the noise level. This is consistent with the model that 1/f noise is the mobility fluctuation in lattice scattering only. However $\alpha$ does not agree with equation (2) that normally represents the model of the noise in lattice scattering.
Spectroscopy of low-frequency noise in δ-doped GaAs

\[ \alpha = \left( \frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}} \right)^2 \alpha_{\text{Latt}}. \]  

This problem is caused by the fact that \( \alpha \) is an average value over all electrons. Therefore, it does not make sense to apply (2) in this case. The detailed analysis is given elsewhere [5].

IV. CONCLUSIONS

Different samples have different trapping processes. In sample W261, there are more trapping centers due to the poor quality of the AlGaAs layers. 1/f noise in Si δ-doped GaAs layers are similar to the noise in bulk GaAs layers. The noise can be analyzed in terms of mobility fluctuations. Heavily doped layers could have a high level of the noise, because low quality of the lattice could give rise to a large value of \( \alpha_{\text{Latt}} \).

References

Chapter 6

1/f Noise in Polycrystalline Silicon-Germanium

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Polycrystalline layers of Si_{0.7}Ge_{0.3} were deposited using Low Pressure Chemical Vapor Deposition (LPCVD) to a thickness of 500 nm on an n-type silicon wafer covered by SiO₂. The Si_{0.7}Ge_{0.3} layers were doped with different concentrations of boron by ion implantation. Resistance fluctuations were measured both by a four-point method and by a two-point method. Pure 1/f noise spectra were observed. The 1/f noise parameter α for differently doped layers has values varying from 10^{-5} (doped at 10^{20} cm^{-3}) to 10^{-2} (doped at 10^{18} cm^{-3}). Decreasing boundary scattering at higher free carrier concentrations results in increased mobility. However, surprisingly enough, we found that when the complete sample was considered, the α value decreases with increasing mobility. In a further analysis we distinguished 1/f noise from grain-boundaries, depletion region and neutral region of the grains. We proved that the noise is mainly generated in the depletion region of the grains. This 1/f noise is mobility noise due to lattice scattering, because α_{g} the 1/f noise parameter of the grains is proportional to the square of μ_{Latt}, the mobility limited by the lattice scattering in the grains.
1. INTRODUCTION

The development and characterization of polycrystalline SiGe material are motivated by the potential use for making devices with high integration levels, small volume, low cost, and advanced performance [1 - 4]. The technological importance of polycrystalline SiGe has increased to the point where a knowledge of noise properties is of value to the design and process engineer. Up to now, the noise in polycrystalline SiGe has never been reported.

Few investigations of noise in a polycrystalline Si can be found in the literature. In 1982, de Graaff and Huybers [5] reported that the 1/f noise of polysilicon is due to mobility fluctuations. They observed that $\alpha_g$, the noise parameter for the bulk of grain decreases with the well-known factor $(\mu / \mu_{Latt})^2$ for samples doped at different levels. Therefore, they concluded that their 1/f noise was due to the lattice scattering. Two comments can be made on de Graaff and Huybers' paper. First of all, de Graaff and Huybers' treatment to extract the noise parameter $\alpha_g$ was not correct [6]. Secondly, $\alpha_g$ was defined for the bulk of the grain. Hence, $\mu_g$, the mobility in the grain has to be used in the factor $(\mu / \mu_{Latt})^2$ to verify the lattice scattering model, not $\mu$, the Hall mobility. In 1990 Luo and Bosman [6] made a correction to the de Graaff and Huybers' model by considering a position-dependence weight function that couples the local noise sources to the external circuit. They concluded that the mobility 1/f noise of low to moderately doped polysilicon samples is mainly produced in the depletion regions. In 1990, Jang [7] pointed out that fluctuations in the built-in potential resulting from mobility fluctuation are important, which Luo and Bosman did not agree with in their paper in 1994 [8]. All three papers [5, 6, 7] stated that the noise was due to mobility fluctuation, but nothing was said concerning a further interpretation of the mobility fluctuations. In 1988 Madenach and Werner [9] attributed their 1/f-like noise in polycrystalline Si to fluctuations in the barrier height due to trapping of carriers at the grain boundaries. The potential fluctuations yield a summation of Lorentzians resulting in a 1/f -like noise. This model is a typical number-fluctuation model that does not agree with the widely accepted mobility fluctuation model for semiconductors. We will use Luo and Bosman's treatment of polycrystalline Si to determine the 1/f noise parameter $\alpha$ for differently doped samples of polycrystalline SiGe and discuss the mechanism of mobility fluctuations in grainy layers.

For a long time the origin of the low-frequency noise has been the object of numerous investigations. The noise in semiconductors has been explained to be a bulk effect due to the mobility fluctuations. The mobility fluctuations has adequately been interpreted by the lattice scattering model. The experimental evidence supporting the lattice scattering model was obtained from measuring the 1/f noise in homogeneous semiconductor resistors. In this paper, we study the noise in a series of polycrystalline SiGe film-resistors that were systematically doped with boron at different levels. Such studies, from which the origin of the 1/f noise can be determined, have only been performed with single crystals or epitaxial layers [10 - 13]. Section III of the present paper describes the measurement configurations. It explains why the 1/f noise parameter $\alpha$ has to be determined by so-called
transversal noise measured by a four-point method. Section IV focuses on the lattice scattering model. The parameter $\alpha$ is determined using Luo and Bosman's equations. The noise characteristics are analyzed in terms of doping levels, $n_A$. Unlike in homogeneous semiconductors, in polycrystalline material we have to analyze the correlation between parameter $\alpha$ and the 1/f noise from a specific region. Our results demonstrate that the 1/f noise in polycrystalline SiGe film-resistors stems from the depletion part of the grains, and that the 1/f noise from this part is due to lattice scattering.

Fig. 1  a) Geometry of the sample. The black flaps are heavily doped areas necessary for ohmic contacts. The hatched regions are the locations where the transversal noise is generated. b) Enlarged picture of the neck, connecting the contact flap and crossbar. c) Badly shaped neck.
II. PREPARATION AND CHARACTERIZATION OF THE SAMPLES

A. Sample preparation

Polycrystalline layers of Si$_{0.7}$Ge$_{0.3}$ were deposited using Low Pressure Chemical Vapor Deposition (LPCVD) to a thickness of about 500 nm on an n-type silicon wafer covered by SiO$_2$. Silane (SiH$_4$) and germane (GeH$_4$) were used as source materials. The deposition temperature was 510 °C, and the pressure 0.5 mbar.

The Si$_{0.7}$Ge$_{0.3}$ layers were doped with boron by ion implantation at 70 keV. The dopant concentration $n_A$ varies from $10^{18}$ cm$^{-3}$ to $10^{20}$ cm$^{-3}$. To prevent contamination of the layers, a thin SiO$_2$ layer was formed on the Si$_{0.7}$Ge$_{0.3}$ layers before implantation. The samples were annealed in an N$_2$ ambient to obtain homogenous doping profiles. The annealing conditions were optimized as regards the activation of dopant and the electrical properties. Finally we annealed the samples at 800 °C for 60 min. Such an annealing process ensures a homogeneous doping profile and also makes the thermal budget compatible to current CMOS processing. The samples were prepared into Van der Pauw structures as given in figure 1. The flaps 1 to 4 were heavily doped to prepare Ohmic contacts.

Fig. 2 AFM picture of the surface of the sample.

Fig. 3 TEM pictures of the cross-section of the sample.
B. Characterizations

The surface of the poly-layer was analyzed by Atomic Force Microscopy (AFM). The results are given in figure 2. A homogeneous distribution of grains was observed. Transmission Electronic Microscope (TEM) image of the cross-section is given in figure 3. It is shown that the grains with the columnar shape are perpendicular to the sample surface. The average grain size determined by AFM and TEM is listed in table I.

<table>
<thead>
<tr>
<th>sample code</th>
<th>born dose (cm⁻³)</th>
<th>grain-column radius (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AFM</td>
</tr>
<tr>
<td>r25</td>
<td>1.1 × 10²⁰</td>
<td>130</td>
</tr>
<tr>
<td>r55</td>
<td>2.1 × 10¹⁹</td>
<td>170</td>
</tr>
<tr>
<td>r11</td>
<td>2.2 × 10¹⁸</td>
<td>170</td>
</tr>
<tr>
<td>r38</td>
<td>9.7 × 10¹⁸</td>
<td></td>
</tr>
</tbody>
</table>

Table II Characteristics of the samples. The Hall factor for monosilicon was used.

* By interpolation using n_H versus n_A and μ_H versus n_A. r25-r38, annealing: 800 °C, 60 min. in N₂. Ref. a, annealing: 900 °C, 40 min. in Ar.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>n_A (cm⁻³)</th>
<th>n_H (cm⁻³)</th>
<th>μ_H (cm²/Vs)</th>
<th>Thickness (nm)</th>
<th>Mobility reduction γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>r25</td>
<td>1.1 × 10²⁰</td>
<td>7.2 × 10¹⁹</td>
<td>32.9</td>
<td>437</td>
<td>~ 1.5</td>
</tr>
<tr>
<td>r55</td>
<td>2.1 × 10¹⁹</td>
<td>1.5 × 10¹⁹</td>
<td>24.0</td>
<td>477</td>
<td>3.3</td>
</tr>
<tr>
<td>poly-SiGe</td>
<td>r10</td>
<td>1.1 × 10¹⁹</td>
<td>6.6 × 10¹⁸</td>
<td>18.1</td>
<td>436</td>
</tr>
<tr>
<td></td>
<td>r11</td>
<td>2.2 × 10¹⁸</td>
<td>* 1.4 × 10¹⁸</td>
<td>* 13.0</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>r38</td>
<td>9.7 × 10¹⁷</td>
<td>6 × 10¹⁷</td>
<td>11.7</td>
<td>515</td>
</tr>
<tr>
<td>Ref. a</td>
<td>1.3 × 10²⁰</td>
<td>2</td>
<td>26</td>
<td>300</td>
<td>~ 2</td>
</tr>
</tbody>
</table>

for reference, lattice scattering of SiGe b

|      |           |           |                |           |                   |
| 1    | 1 × 10¹⁵ | 260       |                |           |                   |
| 2    | 1 × 10¹⁷ | 190       |                |           |                   |
| 3    | 1 × 10¹⁸ | 90        |                |           |                   |
| 4    | 1 × 10¹⁹ | 84        |                |           |                   |
| mono-SiGe c | |     | |          |       |
| 1    | 1 × 10¹⁸ | 90        |                |           |                   |
| 2    | 1 × 10¹⁹ | 60        |                |           |                   |
| 3    | 1 × 10²⁰ | 45        |                |           |                   |

|      |           |           |                |           |                   |
| 1    |           |           |                |           |                   |
| mono-Si d | |     | |          |       |
| 2    |           |           |                |           |                   |
| 3    |           |           |                |           |                   |

a Reference [4]; b Reference [14, 15]; c Reference [14]; d Reference [21]
We characterized the samples by Hall measurements using a low strength magnetic field (< 1 T). Because alloy scattering in SiGe is negligible [14], the Hall scattering factor of mono-Si can be used in good approximation. The results are given in table II which shows that \( n_H = 0.7 \, n_A \). We were not able to obtain results for sample r11 \( (n_A = 2.2 \times 10^{18} \text{ cm}^{-3}) \) because of instabilities in the measurement. Using the value \( n_A = 2.2 \times 10^{18} \text{ cm}^{-2} \) we estimated \( n_H = 1.4 \times 10^{18} \text{ cm}^{-3} \) and \( \mu_H = 13.0 \, \text{cm}^2/\text{Vs} \) for r11 by interpolation. For comparison with the unstrained SiGe alloy, in table II we list the hole mobility limited by lattice scattering and the hole mobility in doped monocrystal SiGe [14, 15]. The mobility \( \mu_H = 84 \, \text{cm}^2/\text{Vs} \) for the unstrained Si\(_{0.7}\)Ge\(_{0.3}\) doped with boron to a level of \( 10^{19} \, \text{cm}^{-3} \) [14], and \( \mu_H = 18.1 \, \text{cm}^2/\text{Vs} \) for our sample doped at this concentration (sample r10). We see that at this doping level, the effects of boundaries are quite strong and that the boundaries limit the transport of carriers as well. The mobility versus doping concentration is plotted in figure 4. Increasing dopant concentration results in increasing mobility because the potential barriers of the grain-boundaries was lowered by increasing dopant concentration.

\[
\begin{align*}
\mu_H (\text{cm}^2/\text{Vs}) & \quad n_A (\text{cm}^{-3}) \\
\text{slope} = 0.23 & \quad 50 \quad 5 \quad 10^{17} \quad 10^{18} \quad 10^{19} \quad 10^{20} \\
\text{slope} = 0.3 & \quad 50 \quad 5 \quad 10^{17} \quad 10^{18} \quad 10^{19} \quad 10^{20}
\end{align*}
\]

Fig. 4 Hall mobility \( \mu_H \) of complete layers versus dopant concentration. ●: The Hall factor for monosilicon was used, which varies from 0.8 at \( n_A = 10^{18} \, \text{cm}^{-3} \) to 0.67 at \( n_A = 10^{20} \, \text{cm}^{-3} \) [22]; ○: The Hall factor = 1 was used.

III. 1/f Noise measurements and results

A. Noise measurements

General speaking, 1/f noise is a fluctuation in the conductance. Such a fluctuation of the conductance is normally observed as the voltage fluctuation or the current fluctuation at terminals of a device. The voltage noise can be measured with two configurations. i) The two-point method: the noise is measured between the current contacts (longitudinal noise \( S_{VL} \)). ii) The four-point method: the noise is
measured between a pair of contacts while the current passed through another pair of contacts. With our sample we measured noise between contacts 1 and 2 (or 3 and 4) while the current passed through contacts 3 and 4 (or 1 and 2) respectively, see figure 1. This is the way in which so-called transversal noise $S_{VT}$ is obtained. Pure 1/f noise spectrum was observed from all samples. The 1/f noise was found to be proportional to the square of the applied voltage. This means that we have measured conductance noise in the ohmic range.

We used silver glue painted on the heavily doped area to make contacts. These painted contacts act like contacts formed by metal on heavily doped semiconductors. The noise from such contact is represent by $S_{contact}$. As shown in figure 1 b), a narrow neck connects the contact flap to the cross bar. In the case of measuring noise via current contacts, the noise from the neck $S_{neck}$ has to be taken into account. Therefore, The total longitudinal noise $S_{VL}$ measured between two flaps is,

$$S_{VL} = S_{contact} + S_{neck} + S_{bar}$$

(1)

It follows that when we perform a two-points measurement, it is the shape of the connection between the flap and the crossbar that will strongly influence the noise results. It is difficult to determine the noise from a badly shaped neck like the one shown in fig. 1 C), although we can measure its geometrical dimensions. To overcome the difficulties caused by the neck, we painted silver glue across the neck up to the bar. Thereby we short-circuited the voltage and its fluctuations across the neck. We then have

$$S_{VL} = S_{contact} + S_{bar}$$

(2)

Equations (1) and (2) contain the contact noise term that is difficult to determine. Poor quality contacts result in very high 1/f noise. Only if the contacts were noise-free, we could use the two-point method to measure the noise and determine precisely the noise parameter $\alpha$ of the sample layer. A technique for getting rid of the contact problem is measuring transversal noise. As described above, the transversal noise $S_{VT}$ was measured from a pair of terminals that were perpendicular to the current flow in the sample. This noise is generated at the hatched locations in figure 1 a) [16]. Therefore, $S_{VT}$ is free of the contact noise because the current contacts are outside of the hatched regions. As in reference [16], we approximate relation (3), either in the case that the neck is painted or in the case that the neck is not painted.

$$\frac{S_{VL}}{S_{VT}} \approx \frac{l}{w_b}$$

(3)

here $S_{VT}$ is the transversal noise that is free from the noise from the contacts or the neck, $w_b$ is the width of the bar of the sample, $l$ the length across which the voltage $V$ was measured, and $S_{VL}$ the equivalent longitudinal noise in the bulk of the sample part of length $l$.

B. Experimental results
As described in the above section, we can measure 1/f noise using several configurations. To present the experimental results, we express the 1/f noise by the empirical relation (4) [10].

\[
\frac{S_R}{R^2} = \frac{S_G}{G^2} = \frac{S_V}{V^2} = \frac{\alpha}{fN},
\]

(4)

where R is the resistance, G the conductance, V the voltage, \(S_X\) the noise power density of the quantity \(X\), \(\alpha\) the noise parameter and \(N\) the total number of carriers in the volume involved in the noise generation.

This relation was proposed to express 1/f noise in homogeneous situations. In the situation where the noise generators are not homogeneously distributed, \(N\) is an effective number of carriers. Neglecting the complications of the barriers distributed in the polycrystalline film, we calculate \(\alpha\) using Hall concentrations as measured. We have to stress that this \(\alpha\) does not have the meaning originally proposed, so it is different from the one of homogeneous semiconductors. The further analysis of the origin of the noise cannot be carried out by using the value of this \(\alpha\) only. Nevertheless, such an \(\alpha\) is a good measure of the relative strength of the noise in the layer.

In view of the discussion in section 3.2, we determine the 1/f noise parameter \(\alpha\) using the results measured by the four-point method only.

I. Four-point measurements where the necks were not painted. Because the width of the neck is larger than the length of the neck, the voltage across the neck is negligible compared with the voltage across the bar. Following eqs. (3) and (4), we derived:

\[
\frac{S_T}{V^2} = \frac{S_T}{V^2} = \frac{\alpha}{n_Hd_Wf},
\]

(5)

where V is the voltage measured from the current-contacts, \(l_b\) the length and \(W_b\) the width of the bar, \(d\) the thickness of the layer and \(n_H\) the Hall concentration.

II. Four-point measurements where the necks were painted. Equation (6) can be derived:

\[
\frac{S_T}{V^2} = \frac{S_T}{V^2} = \frac{\alpha}{n_Hd_Wf},
\]

(6)

with V measured between the painted current-contacts, and \(l_c\) the distance between the painted current-contacts.

Using equations (5) and (6), we determine values for \(\alpha\). As an example, figure 5 shows \(\alpha\) values for sample r25 (\(n_A = 1.1 \times 10^{20} \text{cm}^{-3}\)). The crosses and the diamonds represent the measurements from different pairs of the terminals. We see that exchanging the terminals does not influence the values of \(\alpha\) in the two cases. The values of \(\alpha\) in the case II where the neck was painted, are in a good agreement with the values of \(\alpha\) in the case I where the neck was not painted. This indicates that the values of \(\alpha\) are not influenced by the neck or the contact quality.
Fig. 5 $\alpha$ of sample r25 calculated from different measurement configurations, I to III. Diamonds $\Diamond$ and crosses $\times$ represent the results measured between different pairs of terminals. I: from SyT where the necks were not painted. II: from SyT where the necks were painted. III: from the two-point measurement where the necks were painted.

Actually, the four necks of the sample are not identical. When the two-point method was used, we did observe a difference in the noise if we exchanged the terminals. When the necks were painted up to the bar, the contact quality was poor because the areas under the silver contacts were damaged by scratching the oxide cover. The level of the 1/f noise measured by the two-point method was very high. For comparison, we plot the value of $\alpha$, obtained by the two-point method when the necks were painted, as III in fig. 5.

Fig. 6 $\alpha$ versus Hall mobility. The bars represent experimental values.
From these measurements, it is experimentally proved that the transversal noise is not influenced by the current contacts. Fig. 5 shows that the best estimated value for $\alpha$ of sample r25 is $1 \times 10^{-4}$. The results for all samples are presented in figures 6 and 7. Fig. 7 shows that the dependence of $\alpha$ on the doping level is similar to that in crystalline semiconductors. However, unlike in crystalline semiconductors the $\alpha$ of the grainy SiGe layers decreases with increasing mobility (see fig. 6). This surprising dependence will be further discussed in following section.

IV. DISCUSSION

A. Carrier-transport in polycrystalline material

According to a generally accepted model, the polycrystalline material is composed of small crystallites joined together by grain boundaries. The grain is viewed as a single crystal, while the grain-boundaries are composed of disordered atoms and contain large numbers of defects due to dangling bonds. The grain-boundaries serve as a source for the centers that trap carriers and accommodate dopant atoms.

Mandurah et.al. [17] proposed a model where the band gap of grain-boundary material is larger than that of the grain. The Fermi level is pinned near midgap. A heterojunction is formed at the interface between a crystallite and a grain-boundary, with the grain-boundary material behaving as an intrinsic wide-band gap semiconductor. Therefore, the effect of the grain-boundaries can be modeled by potential barriers. They pointed out that the height of the grain-boundary barriers is a property of the grain-boundary material alone, i.e., it is not a function of the dopant concentration. Many experiments of others [18, 19] have demonstrated that the grain-boundary area is full of boundary-trapping states and dopant segregation.
sites. The trapped-charge distribution over a grain-boundary region establishes a potential barrier. The barrier height varies when the dopant concentration is changed.

In view of the above description, the effect of the grain-boundaries can be modeled by the potential barriers. We assume that the height of the grain-boundary barrier depends on the doping level. The layer can be modeled by an equivalent circuit shown in figure 8 a). Perpendicular to the conduction direction, the potential barriers of grain-boundaries impede the charge transport. $R_b$ expresses this impedance. Parallel to the conduction, the grain-boundaries do not influence the conductance because the grain-boundaries are fully depleted and their widths are small compared to the grain size. The resistance of grains is expressed by $R_g$, which includes the resistance of the neutral regions and the depletion regions in the grains.

![Band diagrams and equivalent circuits. a) Grain-boundary impedance is expressed by $R_b$. $R_g$ is resistance of grains, including the contributions from the neutral regions and from the depletion regions. b) from Ref. [2].](image-url)
In this model, the free charge carriers pass through three different regions, the potential barriers, the depletion part of the grains and the neutral part of the grains. The charges pass the barriers by a tunneling process and/or by a thermionic emission. When the charges pass through the depletion part or the neutral part of the grains, the mobility in the grain is assumed to be the same as that in the single crystal. The mobility \( \mu_H \) averaged over the complete layer is smaller than \( \mu_g \) due to the impedance of the barriers. From figure 8 a), it follows that

\[
R = R_g + R_b = (1 + R_b / R_g)R_g,
\]

hence,

\[
\mu_H = \mu_g \left( 1 + \frac{R_b}{R_g} \right)^{-1} = \gamma^{-1} \mu_g. (7)
\]

Here, we introduce \( \gamma \) as a reduction factor due to the grain-boundaries. \( R \) is the resistance of the layer. By using the data in table II, we obtain the reduction factor \( \gamma \) equal to 8 for the lowest doped sample and 1.5 for the highest doped sample. Therefore, increasing dopant concentration will result in a weaker effect of the grain-boundaries on charge transport. The mobility will increase with increasing dopant. Figure 4 shows that this is indeed the case.

B. 1/f noise due to lattice scattering

In homogeneous semiconductors, the 1/f noise has been interpreted by the lattice scattering model. This lattice scattering model cannot directly be applied in polycrystalline layers because the \( \alpha \) for the layers is an average value from different regions. For discussing the origin of the 1/f noise in polycrystalline layers, we introduce a parameter \( \alpha_g \) as the 1/f noise parameter for the grains. \( \alpha_g \) has the same value in the neutral part and the depletion part of the grains. The grains are the same material as single crystals. Thus in the grains we can apply the model of the 1/f noise due to the lattice scattering [10, 13]. As a result we have

\[
\alpha_g = \left( \frac{\mu_g}{\mu_{\text{Latt}}} \right)^2 \cdot \alpha_{\text{Latt}}, (8)
\]

where \( \mu_g \) is the mobility in the grain, \( \mu_{\text{Latt}} \) is the mobility limited by lattice scattering, and \( \alpha_{\text{Latt}} \) is a material constant characterizing the 1/f noise only due to the lattice scattering.

Substituting (7) in (8), we obtain

\[
\alpha_g = \left( \frac{\mu_g}{\mu_{\text{Latt}}} \right)^2 \cdot \alpha_{\text{Latt}} = \gamma^2 \left( \frac{\mu_H}{\mu_{\text{Latt}}} \right)^2 \cdot \alpha_{\text{Latt}} = \left( 1 + \frac{R_b}{R_g} \right)^2 \left( \frac{\mu_H}{\mu_{\text{Latt}}} \right)^2 \cdot \alpha_{\text{Latt}}, (9)
\]

\( R_b / R_g \) depends on the dopant concentration and thus depends on the mobility. Therefore, in polycrystalline materials the \( \alpha_g \) will not be proportional to the square of the Hall mobility as in single crystals, even if the noise is due to lattice
scattering only. Therefore, De Graaff and Huybers' method of reasoning for that the 1/f noise is due to lattice scattering is not correct [5].

We will now determine how $\alpha$, the noise parameter of the layers, depend on the doping levels. From the analysis of this dependence we show that the 1/f noise is generated in the depletion regions. This result is in agreement with the model where 1/f noise is due to lattice scattering.

1). Noise from the neutral region.

The noise is not generated in the grain-boundaries $R_b$, because the charges pass the barriers by a tunneling process and/or by a thermionic emission, neither generate 1/f noise. The 1/f noise is generated in the grains $R_g$, either in the neutral parts or in the depletion parts. In our analysis we use Luo and Bosman's model [6] where the equivalent circuit was proposed as in figure 8 b). The noise from the grain was divided into two parts, 1) the noise from the neutral part of the grain, 2) and the noise from the depletion part of the grain.

If the measured 1/f noise came from the neutral part, this noise is given by Luo and Bosman as following,

$$S_I = \frac{\alpha_g I_0^2}{f \cdot n(d) \cdot a A} \left( \frac{r_C}{N \cdot r_C + N_{eff} \cdot r_{SCR}(I_0)} \right)^2. \quad (10)$$

Here, $S_I$ is the measured noise power density, $\alpha_g$ is the noise parameter for the grains, $a$ is the average size of the grains, $A$ is the cross-section of the sample, $I_0$ the bias current, $n(d)$ the charge concentration of the neutral region of the grain, $N$ the total number of the grains along the conductance direction, $N_{eff}$ the number of the higher potential barriers that impede the charge transport efficiently, $r_C$ the resistance of the neutral region of one grain, $f$ the frequency, $r_{SCR}$ the resistance of the space charge area, i.e. the depletion region plus the grain-boundary. Since $r_{SCR}$ depends on the bias condition, the measured 1/f noise dominated by the noise from the neutral regions will not be proportional to $I_0^2$. Luo and Bosman observed that the noise spectra were proportional to $I_0^2$, and concluded that the noise is not generated in the neutral regions. Because equation (10) only deviates a little from the $I_0^2$ dependence (see Fig. 5 in Ref. 6), it is not safe to decide in which region the noise is generated using eq. (10) only. Luo and Bosman numerically analyzed their results from one sample, and found that the measured noise is not generated in the neutral region.

Here we apply the lattice scattering model to analyze the noise from systematically doped samples. We obtain the same conclusion as Luo and Bosman. If measured noise is from the neutral regions, we take $N_{eff} = N$. Eq. (10) is rewritten as:

$$\frac{S_I}{I_0^2} = \frac{\alpha_g}{N_g f} \left( 1 + \frac{r_{SCR}}{r_C} \right)^2,$$

with $N_g$ the total number of free charges in the neutral regions.
\( \alpha \) of the layer defined in section III. B, follows from:

\[
\frac{S_L}{I_0^2} = \frac{\alpha}{N_H f} = \frac{\alpha g}{N_g f} \left( 1 + \frac{r_{SCR}}{r_C} \right)^{-2},
\]

where \( N_H \) is the total number of free charges in the sample. \( N_H = n_g \). Applying eq. (8), we obtain:

\[
\alpha = \left( 1 + \frac{r_{SCR}}{r_C} \right)^{-2} \cdot \alpha_g = \left( 1 + \frac{r_{SCR}}{r_C} \right)^{-2} \cdot \left( \frac{\mu_g}{\mu_{Latt}} \right)^2 \cdot \alpha_{Latt}, \tag{12}
\]

\[
\alpha = \left( 1 + \frac{R_b}{R_g} \right)^2 \cdot \left( 1 + \frac{r_{SCR}}{r_C} \right)^{-2} \cdot \left( \frac{\mu_H}{\mu_{Latt}} \right)^2 \cdot \alpha_{Latt}. \tag{13}
\]

By assuming that the measured noise is from the neutral regions, we obtain relation (13) where \( \alpha \) for the layer is proportional to \( \mu_H^2 \) because

\[
\left( 1 + \frac{R_b}{R_g} \right)^2 \left( 1 + \frac{r_{SCR}}{r_C} \right)^{-2} = 1,
\]

However, experimental results in figure 6 show quite a different behavior: \( \alpha \) decreases with increasing \( \mu_H \). Therefore, our noise cannot be generated in the neutral regions, it has to stem from the depletion regions.

2). Noise from the depletion region.

Luo and Bosman [6] derived for the noise from the depletion regions,

\[
\frac{S_{ISCR}}{I_0^2} = \frac{1}{N_{eff}} \frac{v_r}{v_d} q^2 d \cdot \alpha_g \cdot \exp \left( \frac{q \phi_b}{kT} \right), \tag{14}
\]

where \( S_{ISCR} \) is the measured noise power density, \( v_r \) is the recombination velocity given by \( (kT / 2\pi n^* )^{1/2} \), \( v_d \) the diffusion velocity given by \( \mu_g E_{max} \), \( E_{max} \) the maximum electric field near the interface, \( \varepsilon \) the dielectric constant, \( k \) the Boltzmann's constant, \( \Phi_b \) the height of the barrier, and \( d \) the width of one side space charge region that is given by [20]

\[
d = \left( \frac{2\varepsilon \phi_b}{q n_A} \right)^{1/2}. \tag{15}
\]

Using (14), we analyze the \( n_A \) dependence of \( \alpha \) in the following. Analogous to equation (12), we have:

\[
\alpha = \frac{N_H}{N} \left( \frac{v_r}{v_d} \right)^2 \frac{q^2 d}{3\varepsilon kTA} \cdot \exp \left( \frac{q \phi_b}{kT} \right) \alpha_g, \tag{16}
\]

where we take \( N_{eff} = N, N_H = n_H \times (1 \times A) \). The volume of the sample is \( (1 \times A) \).
By approximation, \( n_H \) equals the dopant concentration \( n_A \). Substituting \( \nu_d = \mu g E_{\text{max}} \) in (16), we rewrite (16) as

\[
\alpha = a \frac{q^2 \nu_r^2}{3ekT} \cdot n_A \left( \frac{1}{\mu g E_{\text{max}}} \right)^2 \cdot d \cdot \exp \left( \frac{q \phi_b}{kT} \right) \cdot \alpha_g .
\]  

(17)

We are only interested in the \( n_A \) dependent factors. Therefore,

\[
\alpha \propto n_A \left( \frac{1}{\mu g E_{\text{max}}} \right)^2 \cdot d \cdot \exp \left( \frac{q \phi_b}{kT} \right) \cdot \alpha_g .
\]  

(18)

where \( E_{\text{max}} \) approximately equals,

\[
E_{\text{max}} = \frac{q}{e} n_Ad .
\]  

Thus

\[
\alpha \propto \frac{1}{n_Ad} \cdot \frac{1}{\mu g} \cdot \exp \left( \frac{q \phi_b}{kT} \right) \cdot \alpha_g .
\]  

(19)

If the lattice scattering model is applied, substituting eq. (8) in eq. (19) we obtain:

\[
\alpha \propto \frac{1}{n_Ad} \cdot \exp \left( \frac{q \phi_b}{kT} \right) \cdot \frac{1}{\mu g} \cdot \exp \left( \frac{q \phi_b}{kT} \right) .
\]  

(20)

From Ref. [6], the resistance of the poly-layer is found to be

\[
R = \frac{N_{\text{eff}} kT}{q^2 A \cdot n(d) \cdot \nu_r} \cdot \exp \left( \frac{q \phi_b}{kT} \right) .
\]  

(21)

Thus,

\[
\mu_H = \frac{aq \nu_r}{kT} \cdot \exp \left( \frac{-q \phi_b}{kT} \right) .
\]  

(22)

where we use \( N_{\text{eff}} = N \), sample length = \( N \times a \), a is the size of the grain, and \( n(d) \) the concentration at the edge of the depletion region equals \( n_H \).

The experimental results of figure 4 can be expressed as

\[
\mu_H \propto n_A^\xi .
\]  

(23)

with \( \xi \) varying from 0.23 to 0.3 depending on what we take for the Hall factor.

From (22) and (23) we can deduce that

\[
\exp \left( \frac{-q \phi_b}{kT} \right) \propto n_A^\xi .
\]  

(24)

Substituting (24) and (15) into (20), it follows that

\[
\alpha \propto n_A^{- (1/2 + \xi)} .
\]  

(25)

We experimentally find from the data points in figure 7,
with $\lambda$ varying from 0.7 to 1.1. According to (25), the model gives $\lambda$ varying between 0.7 and 0.8. The experimental results can very well be analyzed by applying the lattice scattering model. The conclusions then are that the 1/f noise in polycrystalline SiGe films is generated in the depletion regions, and that the lattice scattering model can be applied in this case.

V. CONCLUSIONS

1/f noise spectra were observed in poly-SiGe. The noise parameter $\alpha$ for the layers has values varying from $10^{-5}$ to $10^{-2}$ for differently doped samples. The 1/f noise is generated in the depletion region of the grains, and the 1/f noise decreases with increasing Hall mobility and dopant concentration. The origin of the 1/f noise is a fluctuation in the mobility due to the lattice scattering. Due to the complicated structure of a polycrystalline layer, $\alpha$ of the whole layer is not proportional to $\mu_H^2$ as in homogeneous samples.

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Chapter 6. 1/f noise in polycrystalline silicon-germanium

References

Chapter 7

ANNEALING OF PROTON-DAMAGED GaAs AND 1/f NOISE

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GaAs layers were grown by MBE. The layers were then damaged by 3 MeV proton irradiation and later annealed. We performed Hall effect and low-frequency noise measurements at temperatures between 77 K and 300 K after each step. Several g-r noise components created by proton-irradiation disappeared completely after the annealing. The 1/f noise created by proton irradiation did not depend on the measurement temperature. It could be reduced systematically by annealing at temperatures in the range of 543 - 563 K. In an isochronal annealing procedure, annealing at different temperature for a constant length of time, we found annealing effects on the free charge carrier concentration, but not on the 1/f noise. 1/f noise is a fluctuation in mobility originating from clusters of defects. The annealing of damaged GaAs characterizes these noise generating defects by an activation energy of 1 eV.
I. INTRODUCTION

A common feature of 1/f noise in semiconductors is its variation in intensity from sample to sample. There seem to be different sources of 1/f noise: intrinsic and extrinsic, bulk and surface or interface. One thing is certain: 1/f noise is a fluctuation in the conductance. There are two competing models to explain the conductance fluctuations: the mobility fluctuation model [1], and the number fluctuation model [2, 3].

For homogeneous semiconductors, the model of the mobility fluctuation is moving to the lattice scattering model where the 1/f noise is generated by the lattice scattering only [1, 4]. The variation of the noise in differently doped samples of the same material is a strong argument in favor of the lattice scattering model. Experimental evidence for this model is accumulating [5 - 8]. However, the model is also challenged, now and then, by some experimental findings [9, 10]. By measuring low-frequency noise in homogeneous GaAs layers grown by Molecular Beam Epitaxy (MBE GaAs), we now add further evidence to support the lattice scattering model for high quality semiconductors.

Many studies on 1/f noise in metal films have been published [11]. In metal films there is a strong relation between 1/f noise and defects. Creation of defects enhances the noise; reduction of defects by annealing decreases the noise. One could think of models where the defects act as generation - recombination centers generating 1/f noise in the number of free electrons, analogously to the McWhorter model [2]. Or the defects may act as scattering centers influencing the mobility and the noise in the mobility. How this works in detail is an unsolved problem. Generally, a decrease in mobility of only a few percent goes hand in hand with an increase in the noise by a factor 2 or 3. The extra 1/f noise, induced by the defects, could be generated directly by the defects themselves, or the extra noise is due to the high degree of imperfection of the lattice as a whole.

There is ample experimental evidence that shows that in metals the 1/f noise is closely related to the defects. It is highly impossible, however, that the models proposed for metals can be applied to semiconductors, where the concentration of defects is extremely low compared to the defects concentration in the highly disordered metal layers. In nearly perfect semiconductor layers it is certain that the 1/f noise is mobility noise [1].

We performed noise measurements with different conditions of the samples: (i) the perfect lattice grown by MBE, (ii) the lattice damaged by proton-irradiation, and (iii) the lattice repaired to some extent by the annealing. After steps (ii) and (iii), several types of defects were created by proton irradiation and modified by annealing. The correlation between 1/f noise and defects is studied by measuring the effects of annealing on the concentration of the free electrons, the mobility, and the noise. The 1/f noise in irradiated samples, where defects are created, could very well be number fluctuation noise. We cannot decide the nature of the extra noise. We will show, however, that the extra noise is closely related to the defects.
Proton irradiation or implantation is technologically important. It has been widely used in the simulation of radiation damage in solar cells under space conditions [12, 13], and in the semiconductor industry, i.e. for producing high-resistivity regions in microelectronic devices [14, 15]. Our knowledge of the damage in the materials and the relation of the electronic properties with defects is still incomplete. Study of 1/f noise may help to understand the role of defects [16, 17].

II. EXPERIMENTAL PROCEDURES

The MBE GaAs layers were grown on the semi-insulating GaAs substrate to a thickness of 3 μm and doped to a level of $1.6 \times 10^{16}$ cm$^{-3}$ with Si. The growing temperature was 650 °C at the speed of 1 μm per hour. Ohmic contacts to the n-type GaAs were formed by putting a tin ball on the contact areas and performing subsequent annealing in a flowing N$_2$ / H$_2$ ambiance at 450 °C for 1 min. The geometry of our sample is shown in figure (1).

Fig. 1 The geometry of the samples in μm. Numbers 1 to 8 are contact codes. The dashed rectangle is the window for the incident proton beam.

We irradiated the samples in a proton beam with an energy of 3 MeV to the dose of $1.5 \times 10^{13}$ cm$^{-2}$ or less. The beams were produced by the 30 MeV AVF cyclotron of Eindhoven University of Technology. A diffuser was used to homogenize the beam with a radius of 4 mm. This beam passed through a diaphragm with a diameter of 4 mm in front of the sample. A tantalum disk with a rectangular hole (0.6 mm × 1.5 mm) was used to protect the contacts from irradiation. The center part of sample with 0.6 mm × 1.5 mm area was exposed to the incoming protons (see figure 1). The dose of the irradiation was monitored by the change in resistance. As a rule of thumb: when the dose was $1.5 \times 10^{13}$ cm$^{-2}$ the resistance changed by a factor 2. The duration of the irradiation spread over a large range from 27 s to 153 s, while the irradiation dose was always equal to $1.5 \times 10^{13}$ cm$^{-2}$. The reason was that the proton beam densities were very different.

The isochronal procedure was employed for the analysis of the annealing effects on the 1/f noise. In other words, the sample was annealed at successively higher temperatures for a definite period of time. Then the measurements of the concentration, mobility and noise after each annealing step were carried out at a
lower temperature. The annealing period was 5 min. To preserve the epitaxial layer structure as grown, we did not anneal the samples above 573 K. Therefore, the annealing temperatures varied in a narrow range from 543 K to 563 K. Several identical samples were used for each annealing. Some samples underwent a second annealing for 10 min at the same temperature as that of their first step. This means those samples underwent annealing for 15 min in total.

The noise and Hall effect measurements in the temperature range of 77 K to 300 K were carried out after each step, using the normal measurement configuration.

III. EXPERIMENTAL RESULTS

Before analyzing the 1/f noise we first have to characterize electronic properties of the samples because 1/f noise refers to transport phenomena of free charge carriers.

![Fig. 2](image)

**Fig. 2** Hall concentration versus measurement temperature. Different symbols are used for different samples. The irradiation doses are equal to $1.5 \times 10^{13} \text{ cm}^{-2}$. Before irradiation, the samples were identical. There is no significant difference in the annealing effects for samples that are annealed at different temperatures (543 K - 563 K), or for different time periods (5 min or 15 min).

Hall effect experiments were carried out applying a current of 10 µA and a magnetic field of 0.5 T. We used a Hall factor equal to 1 for all samples at each step with temperatures varying from 77 K to 300 K. This may not be very accurate, but is good enough for an approximation because $\mu B < 1$ always holds good. Figures 2 and 3 show the temperature dependencies of the concentration and the mobility measured after each step. The significant reduction in the concentration after irradiation shows that the irradiation creates compensation centers, i.e. acceptors,
and also some deep trapping centers. After annealing, the results show that most of these centers can be annealed at temperatures above 543 K. We see that the mobility decreases after irradiation and increases after annealing. This is because the irradiation creates more scattering centers that are repaired by annealing.

Fig. 3 Hall mobility versus measurement temperatures. Different symbols are used for different samples. The irradiation doses are equal to \(1.5 \times 10^{13}\) cm\(^{-2}\). Before irradiation, the samples were identical. After irradiation with the same dose, only small difference can be seen in the mobilities for different samples. After annealing at different temperatures (from 543 K to 563 K) for different time periods (5 min or 15 min), the mobilities recover to the same level.

The noise in voltage was measured by a four-point method while contacts 1 and 2 were always used as current contacts, see figure 1. Two configurations were employed: a) the transverse noise was measured between a pair of voltage contacts that were perpendicular to the current direction, like for example the pair of contacts 4 and 7, b) the longitudinal noise was measured between a pair of voltage contacts that were parallel to the current direction, like for instance the pair of contacts 3 and 5. Typical experimental spectra measured after each step are shown in figure 4. Before irradiation we observed exact 1/f noise in the frequency range of 1 Hz to \(10^4\) Hz at all temperatures. Several, sometimes unclear, g-r bumps appeared after irradiation and disappeared completely after annealing.

The 1/f noise is characterized by a parameter \(\alpha_{\text{meas}}\), which is the relative noise magnitude at 1 Hz normalized by the total number of free electrons [1]. \(\alpha_{\text{meas}}\) is defined by (1).

\[
\frac{S_R}{R^2} = \frac{S_V}{V^2} = \frac{\alpha_{\text{meas}}}{Nf}, \quad (1)
\]
where R is resistance, V is voltage, $S_R$ and $S_V$ are noise power densities of R and V, $f$ is frequency, and N is the total number of free charge carriers in the volume involved in generation of 1/f noise. $\alpha_{\text{meas}}$ versus temperature after each step is given in figure 5.

Fig. 4 Transversal noise measured on the same sample after the each step. Irradiation dose was equal to $1.5 \times 10^{13} \text{ cm}^{-2}$. The sample was annealed at 543 K for 5 min. The noise measurements were carried out at temperature $T_{\text{meas}} = 200$ K. The applied voltage $V_{\text{meas}}$ between contacts 3 and 5 (see figure 1) were: $\triangle$: 0.92 V, $\bigcirc$: 0.95 V, $\times$: 0.88 V. The dashed lines are the best fits with pure 1/f noise plus thermal noise. The solid line is the best fit with pure 1/f noise plus thermal noise and a g-r noise with a corner frequency equal to 20 Hz. The dotted line is the g-r component.

Fig. 5 Noise parameter $\alpha_{\text{meas}}$ versus measurement temperatures after each step. Different symbols are used for different samples. The slope of both lines is $0.16 \pm 0.03$ eV. $+$: after annealing at 543 K for 15 min, $\bigcirc$: after annealing at 563 K for 5 min.
Experimental results

Two branches of 1/f noise clearly appear: i) a branch not influenced by annealing seems to be a thermally active process with activation energy about 0.16 ± 0.03 eV. This agrees with the result reported by Ren [5] who called this branch intrinsic [18], ii) the temperature-independent branch in the low temperature range is sensitive to the modification of the crystal structure by irradiation and by annealing. So this branch reflects the radiation damage in the sample. Ren called this branch extrinsic [18].

\[
\text{dose} = 1.5 \times 10^{13} \text{ cm}^{-2}
\]

\[
\alpha_{\text{meas}}
\]

\[
\Delta \alpha: 0.8 \times 10^{-4}
\]

\[
\Delta \alpha: 1.2 \times 10^{-4}
\]

\[
\Delta \alpha: 2.2 \times 10^{-4}
\]

\[
T_{\text{ann}} (K): 543 \quad 563 \quad 543 \quad 563
\]

\[
3 \times 10^{-6}
\]

Fig. 6 Parameter \( \alpha_{\text{meas}} \) after different steps measured at 77 K. Annealing period: 5 min.

\[
10^{-3}
\]

\[
\Delta \alpha_{\text{meas}}
\]

\[
10^{-4}
\]

\[
T_{\text{ann}} (K)
\]

\[
540 \quad 545 \quad 550 \quad 555 \quad 560 \quad 565
\]

Fig. 7 Reduction of noise \( \Delta \alpha_{\text{meas}} \) at 77 K versus annealing temperature. \( \Delta \) for 5 min; \( \diamond \): for 15 min.
Chapter 7. Annealing of proton-damaged GaAs and 1/f noise

He also studied a series of samples with different original doping levels. All samples were irradiated with the same dose; they had, therefore, the same concentration of defects created by the irradiation. The plot of $\alpha_{\text{meas}}$ versus $\mu$ suggests that extrinsic 1/f noise is mobility noise [19].

Figure 6 shows the changes in the 1/f noise intensity of our samples after irradiation followed by annealing. Low dose irradiation results in a smaller increase of $\alpha_{\text{meas}}$ than large dose irradiation. The decrease of $\alpha_{\text{meas}}$ after annealing measured at 77 K versus annealing temperature is plotted in figure 7.

IV. DISCUSSION

A. Before proton irradiation

From the lattice scattering model, it follows that the noise parameter $\alpha_{\text{meas}}$ obeys the following relation (1) [1, 4].

$$\alpha_{\text{meas}} = \left( \frac{\mu_{\text{meas}}}{\mu_{\text{latt}}} \right)^2 \cdot \alpha_{\text{latt}},$$

(2)

where $\mu_{\text{meas}}$ and $\mu_{\text{latt}}$ represent the measured mobility and the mobility limited by lattice scattering respectively. $\alpha_{\text{latt}}$ is a material constant and represents the lattice scattering noise. The scattering by the surface and impurities make no contribution to the 1/f noise. Diluting the constant lattice scattering with other noise-free scattering mechanisms decreases the noise parameter $\alpha_{\text{meas}}$. Therefore, analyzing the 1/f noise in differently doped samples enables us to verify the correctness of relation (2). Our data measured before the irradiation are plotted in figure 8 together with the results reported earlier by Ren and Leys [20].

![Graph](image)

Fig. 8 Noise parameter $\alpha_{\text{meas}}$ versus Hall mobility at 300 K before irradiation. ◆: our measurement results; x: Ren and Leys [20]
Figure 8 demonstrates that 1/f noise in MBE GaAs, as grown, is due to lattice scattering. Applying (2) to $\alpha_{\text{meas}}$ at all measurement temperatures, we find a temperature dependence with a minimum of $\alpha_{\text{Latt}}$ as given in figure 9. Such a temperature dependence of $\alpha_{\text{Latt}}$ was also found in InP epilayers [7]. Assuming that the number of phonons in a mode fluctuates with a 1/f spectrum, we are able to derive a theoretical expression for $\alpha_{\text{Latt}}$ in terms of the contributions by the acoustic phonons and the polar optical phonons. In this way we can explain how $\alpha_{\text{Latt}}$ increases with decreasing temperature at lower temperatures, see Ref. [7].

**Fig. 9** Temperature dependence of $\alpha_{\text{Latt}}$. From noise measurements before irradiation.

**B. After proton irradiation**

With proton irradiation, the profiles of the damage density are characterized by a relatively low and homogeneous damage density along the proton track and by a higher damage density near the end of the proton track. For a 3 MeV proton, the end of the proton track is much deeper than the thickness of the MBE layer 3 $\mu$m [13]. This is confirmed by the fact that there is no enhanced mobility by hydrogen-passivation in our irradiated samples. Therefore, the heavy damage in the samples is mainly deep in the substrate, and the damage in the 3 $\mu$m MBE layer is homogeneous. The degree of such homogeneous damage depends on the dose of the protons, and not on the density of the proton beam. Experimentally we found: a) the higher the dose, the bigger the reduction in the mobility and in the concentration, the higher the level of the 1/f noise (see figure 6), b) if the doses are kept constant, differences in duration of the irradiation do not make differences in the mobility, the concentration, or the value of $\alpha_{\text{meas}}$ (see figures 2 and 3).

The damage along the track is composed of several types of defects. They are simple defects such as isolated point defects (vacancies, interstitials and antisites), close-pairs, and defect clusters or complexes due to the cascade effect. As the free
charge carriers are partly compensated after the irradiation, some of created defects act as acceptors. Some generation-recombination noise spectra were observed after the irradiation. These g-r noise components are caused by electrons being trapped and detrapped in some deep centers. Hence, the irradiation certainly creates trapping centers. In the case of high energy proton irradiation, most of the defects are defect clusters and complexes. The reason for the formation of the clusters and complexes is the following. When the primary atom is ejected with high energy protons, the energy transmitted to the displaced atom is much higher than the threshold displacement energy. Thus, the displaced atom may produce additional displaced atoms by colliding with other atoms. Such displacement cascades lead to an accumulation of defects that form defect clusters or complexes. When we refer to clusters in what follows, we also mean complexes.

Obviously, the 1/f noise in the damaged MBE GaAs increased due to the defects in the lattice. Two explanations can be forwarded: First, these defects in the lattice lead to changes in the modes of the lattice vibrations, consequently leading to a different value of $\alpha_{\text{Latt}}$. Second, these defects themselves are the direct noise sources that generate extra 1/f noise on the top of the normal 1/f noise that is found in perfect material. Both explanations are difficult to verify. A fortiori, it is very difficult to make a distinction between the two.

C. After annealing

Heat treatment is used to restore the initial structure of the damaged crystal. Before the recovery is complete, the crystal will frequently go through a number of metastable states corresponding to different types of defects. If these defects are properly separated regarding their energy, the recovery will occur in separate stages, i.e. different annealing processes will occur in different temperature ranges. Isochronal experiments are useful in exploring the temperature ranges of the various annealing stages. A plot of $n$, $\mu$ or $\alpha_{\text{meas}}$ as a function of annealing temperature could show a number of steps, each corresponding to a different annealing stage.

We now compare experimental results for samples irradiated with the same proton dose ($1.5 \times 10^{13}$ cm$^{-2}$). After annealing, the increase of carrier concentration and mobility show that the sample is restored to some extent but not completely. Figure 10 shows the concentration and the mobility versus annealing temperatures.

The restored carrier concentrations are the same at the different annealing temperatures. The mobilities are a little different, but not distinct, at different annealing temperatures. Annealing for a longer time at a fixed temperature leads to a small increase in the mobility, but not to any difference in the carrier concentration. The results from the limited temperature range of from 543 K to 563 K, suggest that the sample is partly restored but not completely. Most types of defects that cause compensation in carrier concentration were annealed at the annealing temperatures, but some types of compensating defects were not. From figure 2, we see that the slopes of concentration versus inverse temperature are the same after annealing and before irradiation. After annealing we did not find any
trapping at low temperatures, which we did find in the plot after irradiation. The g-r noise disappeared after annealing. Therefore, the defects that served as the trapping centers disappeared completely, and those that served as acceptors mainly disappeared after annealing. They could be the simple point defects described above.

We take $\alpha_{\text{meas}}$ as a measure of damage in the samples, the higher the value of $\alpha_{\text{meas}}$, the more seriously the samples are damaged. The annealing restores the lattice so it reduces the noise. Figure 7 shows that the noise reduction by annealing increases slowly with the annealing temperature. The annealing effects on the concentration or the mobility are different from the annealing effects on the 1/f noise. The defects that strongly influence the concentration and the mobility do not influence the 1/f noise in the same way. Thus, the irradiation creates some noisy defects and also some non-noisy defects. The 1/f noise is not generated by simple point defects, as we know from measurements of electron irradiated GaAs [21]. So, the 1/f noise has to be caused by defect clusters. This is in agreement with the local interference (LI) model [11]. The point symmetry of a point defect is the same as that of the lattice site. Therefore, the motion of the point defects cannot contribute to 1/f noise. However, the motion of the individual defect that is in the clusters or that decorates the dislocations, can generates 1/f noise according to this LI model.

Now we discuss how annealing influences the clusters, and consequently reduces the 1/f noise.

The cluster is formed by an aggregation center or dislocation that getters point defects as well as impurities. A cluster is surrounded by a larger region free of defects and impurities. Its structure is more compact towards the center. The temperature should be higher than 700 K to anneal the clusters. In our case the annealing temperatures are much too low to break down the clusters completely. So the result of annealing is not a change in the number of clusters. Instead, it is a
change in their size, easier mobile defects dissociate from the clusters. Therefore, 1/f noise is reduced, but not too much because the number of clusters is constant. The distribution of the defects in a cluster is determined by the annealing temperature and time. Therefore, the reduction of 1/f noise is also determined by annealing temperature and time. Figure 7 shows that the reduction of 1/f noise is bigger for long annealing time at lower temperatures than that for short annealing time at higher temperatures.

In the following we will estimate an effective activation energy $E_a$ for the dissociation of mobile defects from the clusters. We assume that $\alpha_{\text{mean}}$ is a linear function of the concentration of the mobile defects in the clusters. The fraction $\varphi$ of mobile defects that are still present after the annealing period is

$$\varphi = \frac{\alpha_{\text{an}} - \alpha_{\text{bi}}}{\alpha_{\text{ai}} - \alpha_{\text{bi}}},$$

where, $\alpha_{\text{bi}}$ and $\alpha_{\text{an}}$ are the noise parameter after irradiation, before irradiation and after annealing respectively.

$E_a$ is the activation energy of dissociation of the mobile defects. The annealing process proceeds according to the following expression:

$$-\frac{d\varphi}{dt} = A\varphi \cdot e^{-\frac{E_a}{kT}},$$

where $T$ is temperature, $k$ is Boltzmann's constant, $t$ is time, and $A$ is a constant.

![Graph](image)

**Fig. 11** $\ln \varphi$ at 77 K versus annealing temperature.

For an isochronal experiment, in which the duration $\Delta t$ of the annealing is constant, it follows that

$$\ln \varphi = -A \cdot \Delta t \cdot e^{-\frac{E_a}{kT}}.$$

(5)
In figure 11 \( \ln \varphi \) is plotted as a function of the annealing temperature. Fig. 11 shows in the first place that \( \alpha_{ai} \) and \( \alpha_{an} \) can be measured accurately, so that \( \varphi \) varies systematically with \( T \) without much scattering. From the slope of the best fitting line, we obtain \( E_a \) equal to 1 eV. This value is the order of the energy needed to repair a damaged lattice. Therefore, the effects of the annealing on the 1/f noise reflects the annealing of the mobile defects in the clusters.

Now one may wonder why the mobility recovered efficiently after annealing, where as the noise does not change much. The explanation could be that the clusters do not have an important influence on the average mobility which is determined by the point defects. The influence of the clusters on the noise is high because their shape fluctuates since the point defects at a large distance from the center of are mobile. The motion of these mobile defects changes the shape around the spots where the electrons are scattered.

V. CONCLUSIONS

Before irradiation, 1/f noise in homogenous MBE GaAs layers stems from the lattice scattering only as shown by the dependence of \( \alpha_{\text{meas}} \) on \( \mu_{\text{meas}} \) (Fig. 8).

The 1/f noise increases in MBE GaAs damaged by proton irradiation. Proton irradiation creates simple point defects and defect clusters. The defect clusters generate this 1/f noise. The 1/f noise can be modified by annealing. The annealing effect on defects that induce 1/f noise can be characterized by an activation energy \( E_a = 1 \text{ eV} \). This energy is of the order of the cohesive energy for a damaged lattice.

Several g-r noise spectra from point defects created by proton-irradiation disappear completely after the annealing process.

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References

SUMMARY AND CONCLUSIONS

In this dissertation, we have investigated the 1/f noise in diamond and III-V compounds, GaAs grown by Molecular Beam Epitaxy (MBE) and InP grown by Chemical Beam Epitaxy (CBE). It is experimentally confirmed that the 1/f noise is an intrinsic property of semiconductors. The 1/f noise is generated by lattice scattering only. The experimental evidence for phonon number fluctuations follows from the analysis of the temperature dependence of the 1/f noise parameter $\alpha$. The correlation between 1/f noise and defects is analyzed by studying the effects of proton damage and post-annealing restoration on the 1/f noise. In addition, the 1/f noise in a polycrystalline material of SiGe is investigated at 300 K.

The 1/f noise parameter $\alpha$ for diamond is determined for the first time. We find that the parameter $\alpha$ depends on the crystal orientation along which the diamond layers are grown. This indicates that the parameter $\alpha$ depends on the quality of the lattice, $\alpha = (1 \pm 0.5) \times 10^{-5}$ for the samples of high quality and $\alpha = (4 \pm 1) \times 10^{-3}$ for the samples of poor quality.

The 1/f noise in p$^+$-type MBE GaAs samples is characterized by the parameter $\alpha_{\text{Latt}} = 5 \times 10^{-4}$. By comparing $\alpha_{\text{Latt}}$ of n-type MBE GaAs with p-type MBE GaAs, it is experimentally proved that $\alpha_{\text{Latt}}$ is a material constant related to the lattice only, and does not depend on what type of conductance is in the semiconductor material. The experimental noise data in p$^+$-GaAs with non-alloyed contacts helped us to determine the quality and reliability of the metal-semiconductor contacts.

The 1/f noise in CBE InP samples at 300 K and 77 K is analyzed in terms of doping level, thus also the measured mobility. The results firmly prove that the lattice scattering only generates 1/f noise, and that impurity scattering reduces the magnitude of the 1/f noise following equation (9) in chapter 1.

The temperature dependence of the parameter $\alpha$ in semiconductors in general is still an open question. The parameter $\alpha$ in CBE InP at temperatures varying from 77 K to 500 K is analyzed in terms of phonon number fluctuations with a 1/f spectrum for each mode. The experimental temperature dependence of $\alpha_{\text{Latt}}$ is then interpreted by two contributions from acoustic and polar optical phonons. Below 200 K the parameter $\alpha_{\text{Latt}}$ increases with decreasing temperature. This trend is experimentally confirmed by measuring $\alpha_{\exp}$ of pure CBE InP samples, where there is only lattice scattering.

In $\delta$-doped GaAs the conductance is well confined to a bulk layer. The 1/f noise certainly is a bulk effect. The average $\alpha$ over the two groups of electrons does not provide any information about the physical origin of the 1/f noise. However, taking into account the individual contributions by each group of electrons proves the correctness of the model of mobility fluctuations related to lattice scattering (see chapter 5). In addition, in this structure the two-dimensional transport in real space...
Summary and conclusions

results in a distribution of the wave vector in k space that is different from the distribution of the wave vectors of the phonons in k-space of three-dimensional transport. Exact 1/f noise is observed. Therefore, the model of 1/f noise from Lorentzian phonon number fluctuations in each individual mode is refuted.

The 1/f noise in polycrystalline SiGe is mainly generated in the depletion regions of the grains. Decreasing boundary scattering at higher free carrier concentrations results in increased mobility. However, the measured noise parameter $\alpha$ decreases with increasing Hall mobility. This is not an argument against the lattice scattering model where the parameter $\alpha$ is proportional to the square of the Hall mobility. The measured parameter $\alpha$ here is an average over different regions, hence it does not make sense to apply equation (9) of chapter 1 in this case. The doping level dependence of $\alpha$ can be interpreted with the model in which the noise is generated by lattice scattering only.

The temperature dependence of $\alpha_{\text{Latt}}$ in MBE GaAs is similar to that in InP. Proton irradiation creates simple point defects, defect clusters and complexes. The 1/f noise increases in MBE GaAs damaged by proton irradiation. The defect clusters and the complexes generate this 1/f noise, but the point defects do not. The 1/f noise can be modified by the different annealing processes. The effects on defects related to 1/f noise can be characterized by an activation energy $E_a = 1$ eV. This energy is of the order of the cohesive energy for a damaged lattice.

The main conclusions of this dissertation are:

i) 1/f noise in semiconductor materials is a bulk effect and an intrinsic property of the material.

ii) The 1/f noise is generated by fluctuations in the number of phonons in the modes of the lattice vibrations. The parameter $\alpha_{\text{Latt}}$ depends on material and measuring temperature.

iii) Damaging the lattice results in increasing the 1/f noise.
Samenvatting

Dit proefschrift beschrijft het onderzoek van 1/f ruis in diamant en in III-V verbindingen: GaAs gegroeid met Molecular Beam Epitaxy (MBE) en InP gegroeid met Chemical Beam Epitaxy (CBE). We vonden experimentele bevestiging voor de opvatting dat 1/f ruis een intrinsieke eigenschap van halfgeleiders is. Alleen de roosterstrooing genereert 1/f ruis. De analyse van de temperatuurafhankelijkheid van de ruisparameter α wijst op fluctuaties in het aantal fononen.

Door bestraling met protonen kan het GaAs rooster beschadigd worden; door annealing kan deze schade gedeeltelijk hersteld worden. We hebben de ruis-intensiteit gemeten als functie van de mate van beschadiging. Zo is de relatie bestudeerd tussen 1/f ruis en roosterfouten.

Verder is de 1/f ruis van polykristallijn SiGe bestudeerd bij kamertemperatuur.

We zijn er als eerste in geslaagd de waarde van α voor diamant te bepalen. De α-waarde hangt van de kristalrichting af waarin de lagen zijn gegroeid. Dit wijst er op dat α afhankt van de kwaliteit van het kristalrooster. Voor diamant van hoge kwaliteit is α = (1 ± 0.5) x 10⁻⁵; voor diamant van lage kwaliteit is α = (4 ± 1) x 10⁻³.

De 1/f ruis in p⁺-type MBE GaAs wordt beschreven door α_Latt = 5 x 10⁻⁴. De vergelijking van α_Latt van n-type met p-type MBE GaAs wijst erop dat α_Latt een materiaalconstante is, die betrekking heeft op het rooster zelf, en niet op de ladingstragers. De metingen van ruis in p⁺-type GaAs met niet-gelegeerde contacten maakte de bestudering mogelijk van kwaliteit en betrouwbaarheid van de metaal-halfgeleider contacten.

De 1/f ruis in CBE InP bij 77 K en bij 300 K is bestudeerd als functie van de dotering, en daardoor dus ook van de beweeglijkheid. De resultaten bewijzen dat alleen roosterstrooing 1/f ruis genereert, en dat onzuiverheidsstrooing de gemiddelde intensiteit van de ruis reduceert volgens formule 9 in hoofdstuk 1. De temperatuurafhankelijkheid van α in halfgeleiders is in zijn algemeenheid nog steeds een ongelost probleem. De gemeten variatie van α in CBE InP in het temperatuurtraject van 77 K tot 500 K is geanalyseerd aan de hand van een model waarin het aantal fononen fluctueert, en wel met een 1/f spectrum van het aantal fononen in iedere individuele mode van de roostertrillingen. Het experimentele verloop van α_Latt wordt dan opgevat als te zijn opgebouwd uit twee bijdragen van akoestische fononen en van optische fononen. Beneden 200 K neemt α_Latt toe met afnemende temperatuur. Dit verloop is bevestigd door metingen van α_exp in extreem zuiver CBE InP, waarin natuurlijk alleen roosterstrooing optreedt.

In “δ-doped” GaAs is de geleiding beperkt tot een dunne laag in de bulk. In de δ-laag zijn er twee groepen van electronen. Uit de gemiddelde waarde van α kunnen we geen informatie krijgen over de oorsprong van de ruis. Maar als we de ruis-
bijdrage van iedere groep onderscheiden blijkt opnieuw het beweeglijkheidsmodel goed te werken (zie hoofdstuk 5). Bovendien, het twee-dimensionale transport in deze structuren correspondeert in de k-ruimte met een verdeling van k-vectoren van de fononen die wezenlijk verschilt van de verdeling van k-vectoren voor driedimensionaal transport. De waargenomen spectra zijn precies 1/f. Dit wijst er op dat de 1/f ruis niet opgebouwd is uit Lorentz spectra, doordat in iedere individuele mode de fonon fluctuaties een Lorentz spectrum hebben.

De 1/f ruis in polykristallijn SiGe wordt gegenereerd in de verarmingslagen van de korrels. Bij hogere concentraties van de ladingsdragers neemt de grensvlakstrooiing af, waardoor de beweeglijkheid toeneemt. Toch blijkt de ruisparameter $\alpha$ af te nemen met toenemende Hall-beweeglijkheid. Dit is echter geen argument tegen het roosterstrooiningsmodel, dat voor homogene lagen voorspelt dat $\alpha$ evenredig is met het kwadraat van de Hall-beweeglijkheid. In de SiGe lagen is de parameter $\alpha$ een gemiddelde over de verschillende gebieden. Daarom heeft het geen zin om hier vergelijking 9 uit hoofdstuk 1 toe te passen. Het gevonden verband tussen $\alpha$ en het verontreinigingsnivo kan goed geïnterpreteerd worden met het model waarin alleen de roostertrillingen 1/f ruis genereren.

De temperatuurafhankelijkheid van $\alpha_{\text{Latt}}$ in MBE GaAs lijkt op die in InP. De 1/f ruis in MBE GaAs neemt toe als het kristalrooster beschadigd wordt door bestraling met protonen. De bestraling vormt naast eenvoudige puntfouten ook clusters en complexen van fouten. De clusters en complexen genereren 1/f ruis, maar de puntfouten niet. De 1/f ruis kan verminderd worden door annealing. Het annealing proces is gekarakteriseerd door een activeringsenergie $E_a = 1$ eV. Dit is van de orde van de cohesie energie van een beschadigd kristalrooster.

De belangrijkste conclusies van dit proefschrift zijn:

i) 1/f ruis in halfgeleiders is een intrinsieke eigenschap van het materiaal. De ruis is een bulk effect.

ii) De 1/f ruis wordt gegenereerd door fluctuaties in het aantal fononen in modi van de roostertrillingen. De parameter $a_{\text{Latt}}$ is afhankelijk van het materiaal en de temperatuur.

iii) Beschadiging van het kristalrooster veroorzaakt een toename van de 1/f ruis.
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STELLINGEN

behorende bij het proefschrift getiteld

Lattice scattering and 1/f noise in semiconductors

door

Xu-yuan Chen

1. Apart from the spectrum, there is nothing in common between electrical $1/f$ noise and magnetic $1/f$ noise.

2. If we accept that the $1/f$ noise in semiconductors stems from fluctuations in the number of phonons, we have the problem that there is no theory to explain why fluctuations in the number of phonons have a $1/f$ frequency dependence.

3. According to Kogan: “In some systems, for instance, in spin glasses and in metals, the mechanism of $1/f$ noise is already, to some extent, known. However, for the absolute majority of systems exhibiting $1/f$ noise, this part of the problem has been solved to a much lesser degree......”. This is correct in principle. However, “metals” should be replaced by “highly disordered metals”.


4. $1/f$ noise in semiconductors cannot be interpreted by the models that hold for the $1/f$ noise in metals.

5. The number-fluctuation theory of $1/f$ noise is based on a model where a wide distribution of time constants is assumed. However, it is not realistic to assume such a distribution of time constants in semiconductors.

6. The experimental finding that the parameter $\alpha_{\text{Latt}}$ is the same for p- and n-type GaAs whereas the parameter $\alpha_{\text{meas}}$ is not, supports the idea that $\alpha_{\text{Latt}}$ is a material constant depending on the quality of the material.

   Chapters 2 and 5 of this thesis

7. For samples with two or more types of free charge carriers or
transportation regions involved in generating $1/f$ noise, one cannot verify the lattice scattering model by substitution of the parameter $\alpha_{\text{meas}}$ in,

$$\alpha_{\text{meas}} = \left(\frac{\mu_{\text{meas}}}{\mu_{\text{Latt}}}\right)^2 \cdot \alpha_{\text{Latt}}.$$

*Chapters 5 and 6 of this thesis.*

8. Modern integrated circuit technology is based on principles of controlled charge transfer which cannot be understood without a firm background in semiconductor physics.


9. Teaching has to be different from delivering a speech in which simple things are often complicated to motivate the listeners. In teaching complicated matters are simplified and delivered to students in careful formulations, differing every time.

10. A cloned sheep just is a copy of its origin in all senses of the word copy. Cloned human beings only have the same physical appearance. They may become Christians, Islamites, or Buddhists.

11. In a feudal society, it is not allowed for people to follow any ideology. In a dictatorship, it is allowed to follow one ideology only. Therefore, dictatorship is even worse than feudalism.

12. Freedom is not perfect as long as travel of people is not like migration of birds.