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Electric field induced parallel conduction in GaAs/AlGaAs heterostructures

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A new mechanism to understand time-dependent features in the conduction of a two-dimensional electron gas (2 DEG) in high electric fields is proposed and discussed. The mechanism is based on the idea that not only the properties of the GaAs/AlGaAs heterostructure have to be included, but also the properties of the transition from the ohmic contact to the heterostructure. We show that the ohmic contact to the heterostructure is fundamentally different from the contact to a bulk semiconductor. In low electric fields electrons cannot move from the contact into the AlGaAs since the conduction band normally lies above the Fermi level. However, when high enough electric fields are applied, the barrier between the contact and AlGaAs is pulled down, allowing conduction in both the AlGaAs and the 2 DEG. We propose a model, in which time-dependent phenomena in the conduction of the 2 DEG can be associated with trapping and detrapping of charge carriers in the AlGaAs. Time-resolved experiments are shown which confirm this hypothesis.

I. INTRODUCTION

The two-dimensional electron gas of a modulation-doped GaAs/AlGaAs heterostructure is widely applied for high speed so-called high electron mobility transistors (HEMTs).¹ Initially these HEMTs were thought to have high speed because of their high low-field mobility. Soon after its invention, however, it became clear that this mobility decreases rapidly with applied electric field down to about the mobility value of a bulk sample under the same conditions. In spite of this low high-field mobility HEMTs operate at lower power and noise levels.

Since HEMTs operate at high electric fields with fast switching times, understanding of time-dependent high-field effects is necessary. Quite a number of papers rather briefly refer to unexplained time-dependent properties of the 2 DEG. The general trend is the disappearance of a substantial amount of the electrons in fields between 0.3 and 3.0 kV/cm. An early paper by Keever *et al.*² describes how the current through the 2 DEG collapses within a few nanoseconds after the field has been switched on. In the weakly doped samples these effects, appearing at several kV/cm, are attributed to real space transfer. In the heavily doped samples, however, the effects are already present at 0.35 kV/cm, and have been attributed to the presence of surface acoustic waves (acoustoelectric effect). In 1983 Tsubaki *et al.*³ reported on a negative differential resistance at fields of 0.8 kV/cm, which they ascribe to the sudden onset of intersubband scattering. Schubert *et al.*,⁴ van Welzenis *et al.*,⁵ and Hirakawa and Sakaki,⁶ who measured the high-field mobility and electron concentration, also observed instabilities and current collapse, which thus far have not been understood.

Recently, several papers⁷⁻⁹ discuss the presence of oscillations in the current of the 2 DEG of modulation doped heterostructures and quantum wells. Balkan and Ridley^{8,9}

attributed these oscillations to the acoustoelectric effect. The oscillations in the current as presented in Ref. 7, which were not understood at the time, will be elucidated further on in this paper.

In the discussions to explain these phenomena only properties of the 2 DEG have been addressed. The transitional area between the GaAs/AlGaAs heterostructure and the ohmic (mainly AuGeNi) contacts have never been included in these discussions. The transition from an ohmic contact to a heterostructure is fundamentally different from the transition from an ohmic contact to a bulk semiconductor. We show that it is necessary to account for this region, as we will discuss in detail in the next section. In this paper we argue that the application of a high electric field (although well below the threshold of real-space transfer) introduces a second conducting channel in the AlGaAs, not present at low electric fields or in bulk samples.

II. THE CONCEPT OF ELECTRIC FIELD INDUCED PARALLEL CONDUCTION

In order to perform experiments on the electrical transport of hot electrons in the 2 DEG of an AlGaAs/GaAs heterostructure, one needs to make good (i.e., low ohmic, nonrectifying and homogeneous) ohmic contacts to the 2 DEG. Since the 2 DEG is buried about 100 nm below the free surface of the sample one has to alloy through the top layers (mostly a GaAs cap layer, a Si-doped AlGaAs layer, and an undoped AlGaAs spacer layer). Thus one also makes contact to these layers. Since the conduction band of the AlGaAs lies sufficiently far above the Fermi level in properly designed heterostructures, only conduction through the 2 DEG occurs. However, under the influence of an applied electric field this situation changes dramatically as we will argue here. In Fig. 1(a) we have

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FIG. 1. (a) Three dimensional picture of the band edge of a GaAs/AlGaAs heterostructure and its connection to an ohmic contact. Indicated are paths I and II through the GaAs and the AlGaAs, respectively, as used in (b). U_{min} is the minimum of the conduction band of the AlGaAs (b) The energy as a function of position through the 2 DEG (curves I) and the AlGaAs (curves II) for three electric fields. Indicated are the zero field case (F_0), the warm electron case (F_1), and the hot electron case (F_2).

drawn a three-dimensional (one energy dimension and two spatial dimensions) picture of a GaAs/AlGaAs heterostructure and the metallic contacts connected to it. We assume that we have an ideal contact as can be seen from the absence of barriers between the 2 DEG and the contact. The transition from the contact to the semiconductor (both GaAs and AlGaAs) is shown as a gradual and smooth curve. Although not known in any detail, we think this to be appropriate since a AuGeNi (or any other ohmic) contact heavily dopes the adjacent semiconductor, which results in a gradual and smooth bending of the conduction band to the Fermi level. To illustrate the effect of an electric field within this framework, we track the energy of an electron following two different paths: the first path starts in contact 1 (source), goes through the 2 DEG and ends in contact 2 (drain) [This is denoted in Fig. 1(b) with curves I]. The second path again starts in the source but goes through the minimum of the AlGaAs conduction band and ends in the drain [curves II of Fig. 1(b)].

In the zero field case (F_0) as shown in the upper two curves of Fig. 1(b), electrons only flow through the 2 DEG, since they cannot gain enough energy to move into the AlGaAs. If we raise the field to F_1 , the situation remains almost the same. Only few electrons have enough energy to move from the contact into the AlGaAs. In the

high field case (F_2) the situation becomes totally different. The barrier is pulled down and electrons can flow almost freely into the AlGaAs. We now have electric field induced parallel conduction. The height of the barrier will strongly depend on the material parameters.

If an electron moves through the AlGaAs the scattering rate is high due to the high impurity concentration of Si donors. It is even likely that electrons are trapped by these ionized donor atoms (either shallow donors or "DX" centers). Since the mobility of an electron in the AlGaAs is low, the main contribution to the conduction of the heterostructures is by the 2 DEG. However, the properties of 2 DEG are strongly affected by charges in the AlGaAs. Due to extra electrons in the AlGaAs the charge density in the AlGaAs decreases, immediately modifying the band structure. Since the potential distribution is governed by Poisson's equation, Schrödinger's equation, and charge neutrality, every extra electron in the AlGaAs removes one electron from the 2 DEG. Note that no transfer over the barrier (real-space transfer) is required. In this way the electron density of the 2 DEG can be modulated by electrons flowing in the AlGaAs. Thus, properties of the 2 DEG are influenced substantially by the properties of the AlGaAs.

A second effect of the charge carriers in the AlGaAs is that the minimum of the conduction band (U_{min}) reduces linearly with increasing electron density of the 2 DEG, as we calculated using a self-consistent algorithm as described in Ref. 10 and modified to take into account the surface depletion.¹¹ As the barrier becomes lower the probability of the transfer of an electron from a contact to the AlGaAs increases exponentially. Within the above-described framework we conclude that properties of the AlGaAs are as equally important as the properties of the 2 DEG. This confirms the main conclusion of a paper by Kastalsky and Kiehl,¹² who performed experiments on both bulk GaAs and AlGaAs and on GaAs/AlGaAs heterostructures with and without gates. They have clearly demonstrated that the properties of the AlGaAs cause the current collapse in HEMTs. However, they did not discuss the underlying principle.

III. EXPERIMENTAL SETUP

In our experiment we use two types of samples. Samples I are selectively doped GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures ($x=0.38$) grown by molecular beam epitaxy on a semi-insulating GaAs substrate. Subsequently are grown a 1- μm GaAs buffer layer, an undoped 6-nm AlGaAs spacer layer, a 50-nm Si-doped AlGaAs layer and a 20-nm undoped GaAs cap layer. AuGeNi ohmic contacts were made by evaporation of 175 nm of eutectic AuGe and 36 nm of Ni, and alloying the contacts in a H_2 ambient for 3 min. The contacts were arranged in a transmission line geometry of 100 μm wide and a contact spacing of 60, 30, 15, and 5 μm , enabling us to determine the contact resistances.¹³ The contact resistances, measured with these transmission lines, were about 0.3 $\Omega \cdot \text{mm}$. Samples II have a 1- μm GaAs buffer layer, 1.7-nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ spacer layer, a 40-nm $1.5 \times 10^{24} \text{ m}^{-3}$ Si-doped $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$,

and a 20-nm undoped GaAs top layer, with AuGeNi contacts, 600 μm apart. The differences in Al content of the AlGaAs layer is of influence on the incorporation of the Si donor atoms and will result in a different behavior in high electric fields.

To prevent lattice heating we performed pulsed experiments, using either a 50- Ω output HP 8112A pulse generator (0–8 V output) or a high impedance charging line-type pulse generator (>8 V) and a HP 1400—series sampling scope (resolution <50 ps). Both the applied voltage and the current are measured over the 50 Ω terminator of a sampler. Essentially two terminal experiments are performed, in which the only nonmatched impedances are the sample and (if used) the high-impedance pulse generator. When using the latter, the main pulse is followed by two reflections after 600 and 1200 ns. These reflections are used as probe pulses. When using the 50- Ω HP 8112A pulse generator no reflections are present. The pulse length was varied from 100 to 400 ns with a repetition rate of 40 Hz.

To measure the mobility we used the geometrical magnetoresistance method described in Refs. 13–15 and previously used on GaAs/AlGaAs heterostructures by Maselink *et al.*¹⁶ We determined the mobility from the resistance difference of the sample with and without magnetic field normalized to the zero-magnetic field resistance ($\Delta R/R$). While the resistance as a function of the magnetic field depends on the electron density, $\Delta R/R$ is independent of the electron concentration. We measured the contact resistances as a function of the electric field and have taken them into account in the determination of the mobility.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

First, we will briefly discuss some experiments on the type I samples in the regime that the electric field is high enough to heat the electrons sufficiently to influence the mobility but not high enough to inject carriers into the AlGaAs. [This is regime F_1 of Fig. 1 (b).] In Fig. 2(a) the I - V characteristics at 300, 77, and 4.2 K are given, while for the same temperatures the mobility as function of the electric field is depicted in Fig. 2(b). The latter was measured using the geometrical magnetoresistance effect. We used the single subband formulas in higher fields too. This is appropriate if no higher subbands are occupied or if the mobilities in the different subbands are almost the same. This is expected in the higher field region, since there the polar optical phonon scattering dominates over the remote impurity scattering. It is thus not possible to see whether a second subband becomes occupied or not.

Due to the persistent photoconductivity effect, we can raise the electron density by emptying DX centers by illumination [Figs. 2(c) and 2(d)] ($T=4.2$ K). At low fields the mobility is enhanced with increasing electron density due to the intensified screening, which reduces the remote impurity scattering. At higher electric fields the dominant scattering mechanism is the interaction of the electrons with polar optical phonons. In this region the scattering rates do not depend on the electron density and the six

FIG. 2. (a) I - V characteristics at 4.2, 77, and 300 K, and (b) the corresponding mobility as a function of the electric field. (c) I - V characteristic at 4.2 K for three different electron densities and (d) the corresponding mobility as a function of the electric field.

curves of Figs. 2(b) and 2(d) coincide. The mobility saturates at a value independent of temperature, electron density, and zero field mobility with a corresponding electron velocity of approximately 2×10^5 m/s. These results are in perfect agreement with the results of Hirakawa and Sakaki.⁶

When we apply higher electric fields (about 1 kV/cm) we observe time-dependent features in the current. In samples II we observe that the current drops sharply, shortly after the voltage is switched on [Fig. 3(a)]. The associated resistance is depicted in Fig. 3(b). The resistance of the sample does not recover immediately after the voltage is switched off. This is illustrated by the two probe pulses which follow the first pulse (these pulses are 30% and 10% of the original pulse, respectively). The resistances are equal in these situation. To determine whether it is the mobility or the electron density that varies as a function of time, we performed a geometrical magnetoresistance experiment ($\Delta R/R$ vs B) at different times within the pulse (Fig. 4). One directly notices that the curves in the top of the current pulse and near the end exactly coincide. Since the geometrical magnetoresistance effect only depends on the geometry and the product of mobility and magnetic field and not on the electron density,^{13–16} we conclude that the mobility remains unchanged during the pulse and that we consequently lose electrons. This conclusion can only be drawn since in this hot electron regime the mobility is independent of the electron concentration [compare with Fig. 2(d)].

To understand the phenomena described above we assume that the electrons move from the contact into the AlGaAs and are trapped by Si^+ impurities. This changes the electron concentration in the 2 DEG immediately. The detrapping must occur within 25 ms because we use repetitive pulses with a 40-Hz repetition rate and a sampling technique to measure the voltage and current shapes.

This detrapping time strongly depends on how the Si-doped AlGaAs has been grown, i.e., the doping level, and the incorporation of the Si in the lattice as shallow or deep

FIG. 3. (a) Current and voltage pulse. One notices that the current drops in the first 100 ns while the voltage is still increasing. In the two probe pulses the shapes of current and voltage pulses are identical. (b) The resistance as a function of time as deduced from (a). The resistance drastically increases in the first 100 ns and then remains nearly constant.

donor are important factors. In the samples I described in Sec. III we observe the presence of oscillations in the current at 77 K in the range of 800–1200 V/cm (Fig. 5). We attribute these oscillations to the successive population and depopulation of the AlGaAs with electrons from the

FIG. 4. The geometrical magnetoresistance curves taken in the first pulse at four different times (12, 50, 200, and 300 ns after the beginning of the pulse). From the coincidence of the four magnetoresistance curves we conclude that the mobility is constant. Thus the increase in resistance must be attributed to a loss of electrons.

FIG. 5. Current as a function of time at about 1 kV/cm. The current oscillates with a frequency of about 200 MHz.

source contact. In this way the electron density of the 2 DEG is varied. The population time (equivalent to the time of collapse of the current) is determined by the time the electrons need to overcome the barrier and settle in the AlGaAs, while the depopulation time (or the relaxation of the current to its original value) is attributed to the detrapping time and consecutive release of the electrons to the drain contact. The population depends on the height of the barrier which is determined by the electron density of the 2 DEG and is, like the detrapping, a highly nonlinear process. To understand the oscillatory behavior we compare our system with a bulk GaAs sample, in which avalanche of electrons from shallow donors causes current fluctuations.^{17,18} Such a system can show steady state, oscillatory, and chaotic behavior due to the nonlinear process of detrapping.¹⁷ Assuming that such a process is also possible in AlGaAs, electrons, which move from the contact to the AlGaAs will modulate the charge density in the AlGaAs. Consequently, the 2 DEG electron concentration and thus its conductivity is changed. If the avalanche process in the AlGaAs is oscillatory the conduction in the 2 DEG oscillates too. Since the resistance of the 2 DEG is much lower than the resistance of the AlGaAs we only determine the current through the 2 DEG, which will oscillate as is shown in Fig. 5. In our case we observe steady-state behavior in fields below 800 V/cm (Fig. 2), oscillatory behavior between 800 and 1200 V/cm, while the situation becomes unstable above 1200 V/cm. The fields at which the oscillations occur are more than one order of magnitude higher than in the bulk GaAs case. This can be understood by the difference in energy levels of the Si ions incorporated in the GaAs or AlGaAs, and the field necessary to overcome the barrier between the contact and AlGaAs.

When applying minor magnetic fields (< 0.1 T) we observe that the oscillations become more stable in agreement with Ref. 17. If the magnetic fields are increased above 0.5 T, the oscillations abruptly disappear.

To illustrate that the detrapping is field dependent we determined the time between two dips in the current oscil-

FIG. 6. The time between two successive current dips as a function of the electric field. This decreases as the electric field increases. The four curves denote four different electron concentrations. Increasing electron concentration diminishes the threshold field for the oscillations.

lations as a function of the electric field (see Fig. 6). If we increase the electric field the detrapping becomes faster as is noticed from the fact that the frequency of the oscillations is enhanced. It is also possible to increase the 2 DEG electron density with the persistent photoconductivity effect. The consequence of this increase is that the Fermi level rises and the minimum in the AlGaAs conduction band comes nearer to the Fermi level. In the case of the oscillatory behavior one notices that the threshold electric field decreases. We thus conclude that the threshold field of the oscillations is determined by the height of the minimum of the AlGaAs conduction band, while the oscillation period is dependent on the electric field.

V. CONCLUSIONS

We proposed a new mechanism, which simply explains the time-dependent behavior of the conduction in GaAs/AlGaAs heterostructures in high electric fields. The novel idea with respect to previously reported interpretations of high-field effects is that ohmic contacts, which are funda-

mentally different from those in bulk semiconductors, play a crucial role. We discussed that the transfer at high electric fields of electrons from the contact to the AlGaAs introduces a parallel conducting channel in the AlGaAs layer. We conclude that the properties of the AlGaAs layer and the properties of the 2 DEG are equally important in understanding the properties of the conduction in these structures at high electric fields.

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