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Current oscillations at high electrical fields in the two-dimensional electron gas in GaAs/AlGaAs heterostructures

P. Hendriks, A. A. M. Staring, R. G. van Welzenis, and J. H. Wolter
Eindhoven University of Technology, Faculty of Physics, NL-5600 MB Eindhoven, The Netherlands

W. Prost and K. Heime
Universität Duisburg, Fachgebiet Halbleitertechnik/technologie, D-4100 Duisburg 1,
Federal Republic of Germany

W. Schlapp and G. Weimann
Forschungsinstitut der Deutschen Bundespost beim FTZ, D-6100 Darmstadt, Federal Republic of Germany

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In the two-dimensional electron gas (2DEG) of GaAs/AlGaAs heterostructures, we observe a new type of oscillation in the current at electric fields above 0.8 kV/cm. These oscillations have two characteristic frequencies, around 200 MHz and 2.5 GHz. We show that these oscillations arise from properties of the 2DEG and depend on both electric field and magnetic fields. They disappear abruptly when magnetic fields above 0.5 T are applied.

During the last decade epitaxial crystal growth techniques [like molecular beam epitaxy (MBE) and metalorganic vapor phase epitaxy (MOVPE)] have developed rapidly. With these techniques thin layer semiconductor structures can be made, like, e.g., the selectively doped heterostructure¹ and the quantum well structure. These growth techniques have a tremendous impact on both fundamental and applied physics. Highlights are the discovery of the quantum Hall effect and the design of the high electron mobility transistor (HEMT).²

For the understanding of the operation of a HEMT a profound knowledge of the behavior of electrons in high electric fields is necessary, since already low source-drain voltages cause high electric fields in these small devices (typically 1 μm). Experimental results show that the mobility decreases rapidly with the applied electric field.³⁻⁵ Hirakawa and Sakaki show that independent of the low-field mobility the mobility decreases with the reciprocal electric field and approaches the same value at sufficiently high electric fields.⁵ This kind of behavior can be ascribed to the emission of polar optical phonons.³

Most experimental papers on high electric field effects in GaAs/AlGaAs heterostructures deal with the quasi-static situation near the end of the voltage pulse only, without describing the actual shapes of the voltage and current pulses. An exception is a letter by Kever *et al.*,⁶ which reports on a peak in the current, observed during the first nanosecond in electric fields above 3 kV/cm. They ascribe this peak to the modulation of the interfacial capacitance due to the transfer of electrons from the two-dimensional electron gas (2DEG) to the AlGaAs layer ("real-space transfer").

Balkan and Ridley⁷ recently reported on an oscillation in the current in single and multiple quantum wells at frequencies between 1 and 5 MHz. They ascribe the oscillations to an acousto-electric effect, although the frequencies are eight times too high.

In this letter we report on the discovery of a new time-dependent high-field effect in GaAs/AlGaAs heterostructures. We found that in samples with very low ohmic electri-

cal contacts the current oscillates when the applied voltage is above 0.8 kV/cm. Two different types of behavior and frequencies were observed. One type of oscillation at about 200 MHz has a sawtooth-like shape as a function of time. The second type at 2.5 GHz has a sinusoidal shape.

The samples we investigated are selectively doped GaAs/Al_xGa_{1-x}As heterostructures ($x = 0.38$) grown by MBE on a semi-insulating GaAs substrate. The layer composition is depicted in Fig. 1(a). The low-field mobility and electron concentration are $12 \times 10^4 \text{ cm}^2/\text{Vs}$ and $6.0 \times 10^{11} \text{ cm}^{-2}$ at 77 K and $0.8 \times 10^4 \text{ cm}^2/\text{Vs}$ and $7.1 \times 10^{11} \text{ cm}^{-2}$ at 300 K. The values of the mobility were verified using the geometrical magnetoresistance method^{8,9} at both 77 and 300 K. AuGeNi ohmic contacts were made by evaporating subsequent layers of 175 nm eutectic AuGe and 36 nm Ni and alloying the contacts in a H₂ ambient for 3 min. The geome-

FIG. 1. (a) Layered structure of the MBE material used in this study and (b) geometry in which the AuGeNi contacts were formed. Also indicated is the equivalent circuit used in the experiments. The voltage pulse is applied at V_{in} and measured at V_{out} with a 50 Ω coaxial cable leading to a sampler, which is terminated with 50 Ω . The current is measured at $V_{current}$. The dashed resistors are disk resistors located at the beginning of the coaxial cable at approximately 1 cm from the sample.

try of the contacts was photolithographically defined and is indicated in Fig. 1(b). We note that the contact resistances of the samples were extremely small. For one of the samples studied the resistances of the 60- μm and 30- μm -long devices were 64 and 38 Ω , respectively, at 77 K, and 719 and 362 Ω at 300 K. Thus the contact resistances are 0.6 Ω mm at 77 K and 0.25 Ω mm at 300 K. Furthermore, the resistances of the 2DEG are almost equal to the resistances calculated from the product of the sheet resistance and the length to width ratio. This proves that the contact resistances are indeed much smaller than the sample resistances. We observe that the latter is of great importance for the two-point measurements described in this letter.

To prevent lattice heating, high-field experiments are usually performed with pulsed electric fields. We used an experimental setup with an HP8112A pulse generator, a cryostat (300, 77, and 4.2 K), and an HP 1400-series sampling scope. The measuring system is automated by means of a personal computer. The only nonmatched impedance in our circuit is the sample. The current is proportional to the voltage measured over the 50 Ω terminator of the sampler which is indicated in Fig. 1(b). However, in some experiments we also inserted parallel to the 50 Ω coaxial cable a 10 Ω (or 1 Ω) disk resistor at approximately 1 cm from the sample in the cryostat. The width of the pulses was varied between 100 and 400 ns with a rise and fall time of 4.5 ns and a repetition rate of 40 s^{-1} .

At room temperature the voltage and current pulses have identical shapes and the current saturates at approximately 10 mA in fields above 2.5 kV/cm. At 77 K the current saturates at about the same value but already at fields above 0.5 kV/cm. However, when fields above 0.8 kV/cm are applied at 77 K the shape of the current pulse changes dramatically. When the applied voltage pulse reaches the threshold when it rises the current drops about a factor of 2 within 1 ns. Thereafter the current slowly returns to its top value in about 4 ns. If we increase the field to 1.2 kV/cm, the number of dips increases and the current starts to oscillate

FIG. 2. Current as a function of time. It is observed that the current oscillates at these high electric fields of about 1.2 kV/cm with a frequency of about 200 MHz. One notices that the current drops within 1 ns and then slowly returns to its previous value.

FIG. 3. We have enlarged the first dip in the current of Fig. 2. We observe a second oscillation at a higher frequency (2.5 GHz). Both the rapid and the slow oscillations are only present in sufficiently high electric fields and disappear when magnetic fields above 0.5 T are applied.

(Fig. 2). The oscillations are perfectly stable and do not show any jitter which we detected by a sampling technique. To measure the shape of the current pulse, 40 000 subsequent pulses are needed. The measurements reproduced after several cooldowns and even in different devices made from the same material.

Looking in more detail at the first current dip, one observes a second oscillation period with a higher frequency of about 2.5 GHz superimposed on the dip (see Fig. 3). This frequency did not noticeably change for devices of different lengths indicating that the phenomenon observed cannot simply be due to Gunn-domain propagation along the sample. We note, however, that the observed frequency is of the right order of magnitude.

Changing the electron concentration of the 2DEG by emptying DX centers with a short light pulse lowered the threshold field but left the frequencies of the oscillations unaltered. However, with increasing electric field the frequency of the 200 MHz oscillation increases. If a magnetic field is gradually increased from 0.0 to 0.5 T the frequency of the 200 MHz oscillation decreases, while the magnitude of the oscillations remains the same. If we increase the magnetic field above 0.5 T both the 200 MHz and 2.5 GHz oscillations disappear abruptly. From the dependence of the frequencies on both electric and magnetic field, we conclude that the effect observed originates from the 2DEG and not from the circuitry.

However, the circuitry has some influence. If we change the circuit by inserting a 10 Ω (or 1 Ω) disk resistor parallel to the 50 Ω coaxial cable [see Fig. 1(b)], the amplitude of the 2.5 GHz oscillations is enhanced. Because both the contact resistances and the 10 Ω (or 1 Ω) disk resistor act as a kind of attenuator in the circuit, this is consistent with our observations that the low contact resistances are of great importance to observe this phenomenon. This is confirmed by measurements on samples with a higher contact resistance. In high electric fields the shape of the current pulse changed: A decrease of the current was observed, but no oscillations appeared.

At present we have no explanation for the phenomena observed. In particular the sample parameters responsible for the values of the oscillation frequencies observed and the occurrence of the sawtooth-like shape in the current have not been identified so far. Real-space transfer can be excluded because this effect only occurs in fields of about 3 kV/cm. Also simple propagation of Gunn domains along the sample can be excluded.

In conclusion, we have found a new time-dependent high electric field effect in the 2DEG of a GaAs/AlGaAs heterostructure and we have proven that although the circuit plays a certain role the effect is originated and initiated by properties of the 2DEG. Further investigations are needed to reveal the origin of these oscillations.

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