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Magnetoconductivity of GaAs Transistors as Detectors of THz Radiation

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Magnetotransport characterisation of field effect transistors processed on GaAs/GaAlAs heterostructure was done at 4.2 K for magnetic fields (B) up to 7 T. Three field effect transistors were processed on a single dice and differed by the length (L) of the gate. Electron mobility (μ) in field effect transistors was estimated from dependence of transistor's conductivity vs. B. The results show a decrease in μ with decreasing L that suggests that scattering by edges of the gated part of a transistor limits the electron mobility. Quality factor (Q) of transistors as resonant detectors of THz radiation was calculated. A high value of Q shows that such field effect transistors with sub-micron L are promising devices that can operate at THz frequencies.

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1. Introduction

Development of semiconductor sources and detectors that can operate at THz range of the electromagnetic spectrum is important from the point of view of technical and basic research reasons. Energy of many excitations in condensed matter (like phonons or cyclotron resonance related transitions) corresponds to this frequency range. THz radiation becomes an alternative for a non-destructive tissue investigation in medicine and biology [1]. Construction of a transistor operating at THz frequency is also a goal that would enable production of fast processors overcoming today's limit.

One of lines of research concentrates on generation and detection of THz radiation by field effect transistors (FETs) with gates of a sub-micron length, L. The underlying idea is based on a theoretical prediction proposed by Dyakonov and Shur [2, 3] who showed that a formal description of an electron plasma flow in a ballistic FET is identical to hydrodynamic equations for shallow water. It follows that plasma waves can be generated in such a device and their amplitude will grow due to subsequent reflections from transistor's boundaries. Plasma oscillations in a FET mean periodic changes of sheet charge density coupled with simultaneous changes of the image charge. This forms an oscillating dipole that can be both a source and a detector of the electromagnetic radiation. An efficient performance of such a device requires a high value of the quality factor $Q = \omega_0\tau$, where ω_0 is the fundamental frequency of the oscillations and τ is the electron scattering time. Approximately, in a FET with a gate of the length L, $\omega_0 = \pi s/(2L)$, where s is a velocity of plasma waves. On the other hand, s depends on the carrier density in the transistor's channel, n, and the gate-to-channel capacitance per unit area ($C = \varepsilon\varepsilon_0/d$): $s = \sqrt{e^2 n/(mC)}$, where e and m are the electron charge and the effective mass, respectively, ε is a dielectric constant and d is the gate to channel distance. In the gradual channel approximation, the carrier density in the channel is related to the gate-to-source voltage, U_{gs}, by the relation $n = CU_0/e$, where U_0 is the gate-to-channel voltage swing, $U_0 = U_{\mathrm{gs}} - U_{\mathrm{th}}$, and U_{th} is the threshold voltage. Using typical values of m and n, one can estimate that to get emission and/or detection of THz radiation one needs a transistor with a very short gate, below 1 μm.

An important point to be stressed is that both generation of radiation and detection of external signals by excitation of the plasma waves is resonant, i.e. it should occur at frequency ω_0 and its harmonics. Also, these frequencies are tuneable by the gate voltage, since n depends on U_0. This makes such devices a promising tool convenient in applications. However, although the theory sketched above has been known for 10 years now, only resonant detection of THz radiation has been reported so far [4–6].

Combining the above relations, one concludes that Q depends, essentially, on two parameters: the electron concentration n (determining ω_0) and the mobility μ (determining τ). It follows that determination of n and μ is crucial from the point of view of characterisation of a FET as a plasma device. In the present paper we present how these parameters can be evaluated by low-temperature magnetotransport measurements.

Magnetoconductivity tensor, $\boldsymbol{\sigma}$, relates the current density, $\boldsymbol{j}$, with the electric field, $\boldsymbol{E}$, by the relation: $\boldsymbol{j} = \boldsymbol{\sigma E}$, with $\sigma_{xx} = \sigma_0/(1 + \mu^2 B^2)$ and $\sigma_{xy} = \sigma_0 \mu B/(1+\mu^2 B^2)$ given by the Drude–Boltzmann theory. These equations must be supplied with appropriate boundary conditions. In the case of a Hall bar ($L \gg D$, where D is a lateral dimension of a sample), one requires $j_y = 0$ which leads to zero magnetoresistance: $E_x = j_x/\sigma_0$. A transistor's geometry is the opposite case: $L \ll D$, and the boundary condition is $E_y = 0$ which means that no Hall voltage is created because it is short-circuited by wide current-supplying contacts. This geometry is similar to that of the Corbino disk. In such a case, the so-called geometrical magnetoresistance develops and $E_x = j_x(1 + \mu^2 B^2)/\sigma_0$.

2. Experiment and results

The measurements were carried out at 4.2 K on a dice cut from a wafer of GaAs/GaAlAs modulation-doped heterostructure. Three transistors, T1, T4, and T3 with $L = 0.8$, 1.5, and 2.5 μm, respectively, and a lateral dimension of 110 μm were processed on the dice. A drain-to-source distance was equal to 10 μm in each case. A gated Hall bar structure was also situated next to transistors. Output characteristics (drain current, I_d, vs. drain-to-source voltage, U_ds) and transfer characteristics (I_d vs. gate-to-source voltage, U_gs) were measured at several values of the magnetic field B up to 1 T. The transfer characteristics (measured in the case of each transistor at $U_\mathrm{ds} = 20$ mV) were used for determination of a dependence of the conductivity vs. the magnetic field at small B. Output and transfer characteristics were measured also on a Hall bar structure at $U_\mathrm{ds} = 20$ mV (with drain and source meaning in this case current supplying contacts) and measurements of the Hall effect were done at $U_\mathrm{ds} = 20$ mV and $B = 0.2$ T for different values of the gate-to-source voltage. This allowed to determine the concentration and the mobility in the Hall bar as a function of the gate potential.

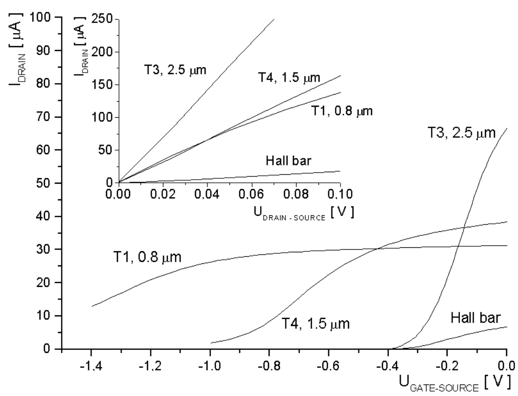

Fig. 1. Transfer characteristics of investigated transistors and the Hall bar at $T = 4.2$ K and $B = 0$ T. Each curve was measured at $U_\mathrm{ds} = 0.02$ V and is described by a transistor's name and the length L of the gate. The estimated values of threshold voltage are, respectively, –1.75 V, –0.4 V, –0.92 V, and –0.35 V. The inset shows linear behaviour of output characteristics at $T = 4.2$ K and $B = 0$ T, for small U_ds.

The inset in Fig. 1 shows output characteristics for the measured devices. For small U_{ds}, the characteristics are approximately linear, although for larger U_{ds} they show a sub-linear shape and even, in some cases, develop a negative differential conductivity. The value of $U_{\mathrm{ds}} = 0.02$ V was chosen for measurements of transfer characteristics and magnetic field dependence because at this bias a linearity of output characteristic of all gate potentials and magnetic fields was preserved with a good accuracy. Transfer characteristics presented in Fig. 1 show

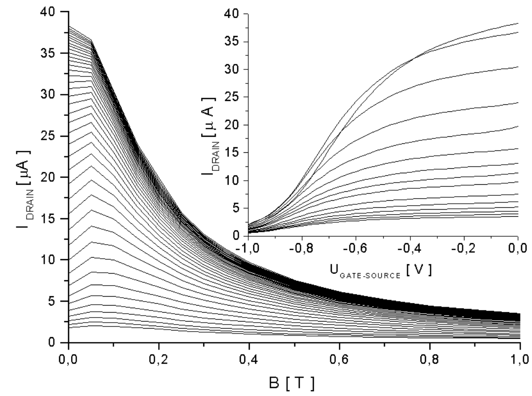

Fig. 2. Magnetic field dependence of the drain current for different gate-to-source voltages between 0 V (the highest lying curve) to –1 V (the lowest lying curve), every 0.025 V. These curves are vertical sections of a bunch of transfer characteristics shown in the inset, measured every 0.05 T for B between 0 T and 0.4 T and every 0.1 T for B between 0.4 T and 1 T.

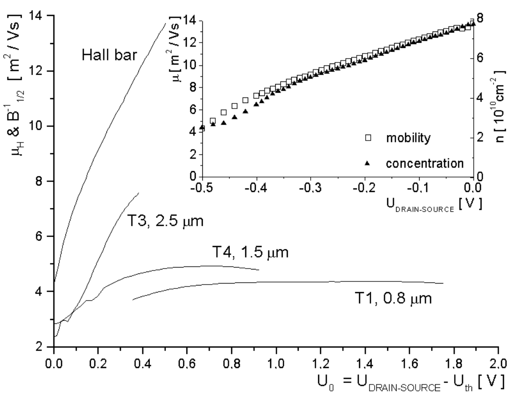

Fig. 3. The inverse of the half width of the Lorenzian — like dependence of magnetoconductivity, $B_{1/2}^{-1}$, for the transistors T1, T4, and T3 vs. the swing voltage, U_0. The inset shows dependence of the electron mobility and the concentration on the gate voltage for the Hall bar.

a systematic increase in the threshold voltage with decreasing the length of the gate. A magnetic field dependence of transfer characteristics of the transistor T4 is shown in the inset in Fig. 2; similar pictures were obtained for other devices. This set of characteristics was transformed into Lorentzian-like curves shown in Fig. 2, where each curve corresponds to a given gate-to-source voltage. Fitting of each curve with a Lorentz function gave a value of its half width, $B_{1/2}$, dependent on U_{gs}. The fitting did not involve the smallest magnetic field ($B < -0.1$ T) where magnetoconductivity is positive. An inverse of $B_{1/2}$, a quantity of dimension of mobility, is shown in Fig. 3 as a function of the swing voltage, U_0. Figure 3 includes also results of the Hall effect measurements on the Hall bar. One can see that both the electron mobility and the concentration decreases with an increase in the gate potential.

3. Discussion

The inset in Fig. 1 shows that in the linear part of output characteristics, there is a systematic increase in the transistor's resistance with decreasing the gate length (see also the ordering of transfer characteristics at $U_{\mathrm{gs}} = 0$ V in Fig. 1). Bearing in mind that apart from the length of the gate, all the transistors have the same geometry, we conclude the following. First, just putting metallic gate on a heterostructure influences conductivity of the electrons in the channel. Obviously, this can come from a decrease in the concentration of electrons and/or their mobility. However, an *increase* in the resistance with *decreasing* L contradicts simple expectations which assume a gated region to be a high resistance placed in series with ungated part: in such a case the transistor's resistance would increase with increasing L. Second, the threshold voltage increases with decreasing the gate's length. This can be related to a parallel conductivity that the harder to suppress the shorter is the area where blocking potential is applied.

Transfer characteristics presented in the inset in Fig. 2 show a systematic decrease in the conductivity with an increase in magnetic field, except for the smallest B and $U_{\mathrm{gs}} > -0.5$ V. This positive magnetoconductivity is observed for all transistors but the magnitude of the effect decreases with increasing L. It is tentatively attributed to weak localisation, but this effect was not studied in the present paper. In Fig. 3 the parameter $B_{1/2}^{-1}$ is plotted as a function of the swing voltage together with the results of mobility measurements carried out on the Hall bar. Obviously, $B_{1/2}^{-1}$ gives an estimation of an average mobility in a transitor. Generally, the observed magnetoresistance is of a geometrical type, since for investigated transitors $D/L = 11$. A more detailed discussion of an influence of transistor's geometry on magnetoconductivity curves can be found in [7]. Let us note that for small swing voltage, i.e., for U_{gs} close to the threshold voltage, the $B_{1/2}^{-1}$ curves coincide for T3 and T4 transistors and the T1 curve seem to tend to join them, too. This means that near the threshold gate voltage when transistor's resistance is determined with a good approximation by the gated part only, the electron mobility has a universal behaviour. The same result was obtained previously for other GaAs/GaAlAs transistors [7].

An important result is that the mobility decreases with an applied gate voltage. Such a behaviour is characteristic not only of transistors but also of a gated Hall bar (see the inset in Fig. 3). In the latter case, an influence of the gate potential on the electron mobility and the concentration was obtained by direct measurements. A decrease in the mobility is accompanied by a decrease in electron concentration that drops due to enlargement of a depletion layer below the gate. A decrease in the electron mobility can be understood as a result of a decrease in efficiency of screening due to reduced 2DEG density. Similar reasoning can be applied to explain a decrease in the mobility in the case of transistors.

The value of $B_{1/2}^{-1}$ for the transistors and the concentration determined from the investigation of the Hall bar allow us to estimate the quality factor for investigated transistors as resonant plasma detector. Basing on Figs. 2 and 3 one can estimate threshold voltages for the transistors (see the caption to Fig. 2) and one can assume a mobility of 4 $m^2/(V\ s)$ for all them, together with the electron concentration of 8×10^{10} cm^{-2}. These values lead to curves shown in Fig. 4. One can see that T1 transistor ($L = 0.8$ μm) fulfils very well conditions for resonant THz plasma detection showing a quality factor of the order of 1 for a frequency of a few THz. On the other hand, the transistor T4 ($L = 1.5$ μm) is on the limit of the resonant detection in the THz range while the transistor T3 ($L = 2.5$ μm) cannot be used as such a device.

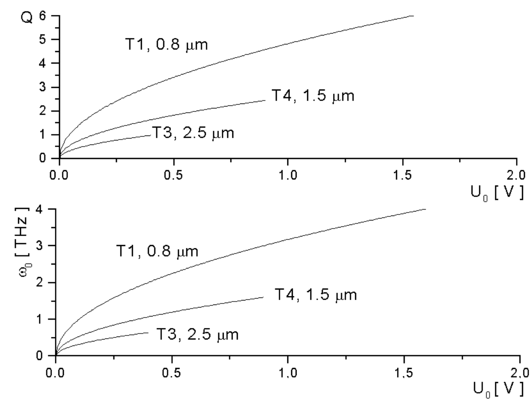

Fig. 4. The quality factor (top) and the resonant frequency (bottom) of GaAs T1, T4, and T3 transistors.

In conclusion, it was shown that high mobility field effect transistors with a gate length smaller than 1 μm fulfil conditions of resonant detectors of THz radiation. In view of well-established technological possibilities of production of high mobility GaAs devices, this result shows promising perspectives for GaAs-based THz electronics.

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