EFFECT OF PULSED FIR LASER RADIATION ON TUNNEL AND CHANNEL RESISTANCE OF δ-DOPED GaAs

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Investigations of the fast response of Schottky-barrier tunnel junctions (SBTJ) to high power pulsed FIR laser radiation have shown that under the condition of plasma reflection the change in the junction resistance is connected with a deformation of the self-consistent potential barrier [1-3]. This deformation is caused by radiation pressure on the free electron plasma in the semiconductor. The observed photoresistive effect allows to consider SBTJ as a detector of pulsed FIR laser radiation with high temporal and spatial resolution [4] .The two-dimensional electron gas (2DEG) in the potential well of the δ-doped semiconductor represents a similar system with a self-consistent potential. The properties of this system depend on the redistribution of free carriers in the direction perpendicular to the plane of the δ-layer. This work presents the first results of photoresponse experiments with δ-doped GaAs structures.

The investigated samples consist of MBE grown GaAs with one δ-layer, 5 mm long and 1 mm wide, at a distance of 20 nm from the semiconductor surface. The donor atoms are Si with a density of $6\cdot10^{12}$ cm^{-2}. The 2DEG density is $3\cdot10^{12}$ cm^{-2} due to the spatial redistribution of carriers between the surface states and the δ-layer.

Two different types of samples were used: structures with a plain GaAs surface and structures with an aluminum gate. In gated samples the current through the Schottky barrier between the gate and the channel is carried by tunneling electrons. Investigations of the samples at 4.2 K temperature have shown, that the tunneling-spectroscopy and magneto-transport data are in a good agreement with the results of self-consistent calculations of the energy structure of two-dimensional subbands in a δ-doped layer of 5 nm thickness [5].

The radiation sources used were pulsed NH_3 and CH_3F molecular lasers optically pumped by a TEA CO_2 laser providing ≤100 ns pulses. The measurements have been carried out at the wavelengths λ of 90.55 μm and 250 μm. The maximum intensity of radiation in the sample was 1 MW/cm^2. For varying the intensity calibrated teflon attenuators have been used. The intensity incident on the sample has additionally been controlled by a fast photon drag detector.

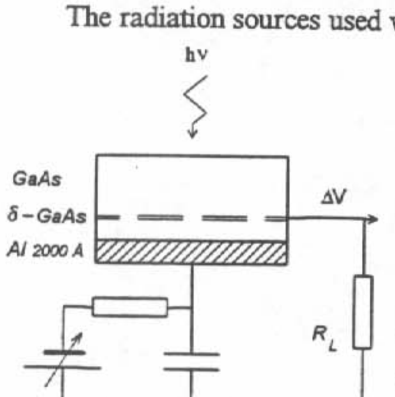

Fig. 1. Scheme of measurements

The gated samples have been irradiated from the substrate side. The photoresponse measurements of gateless samples have been performed with irradiation on the δ-layer side. It was proved that the magnitude of the signal is only slightly smaller when the substrate side is irradiated. Fig. 1 shows a sketch of a sample and the measurement scheme.

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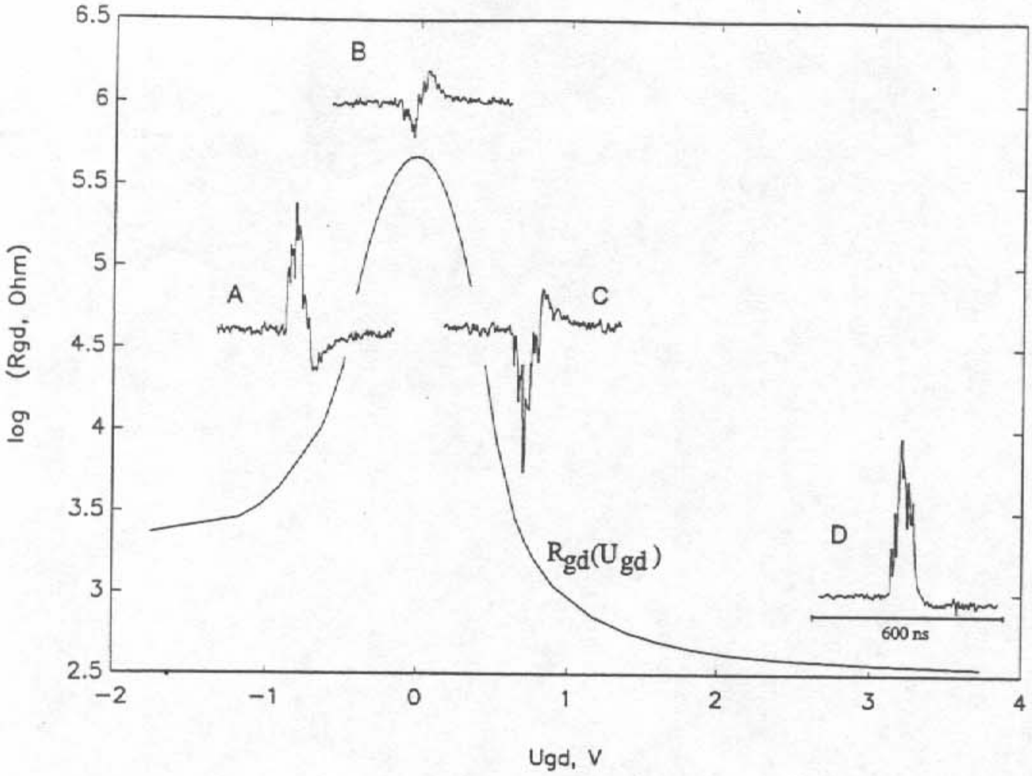

Fig. 2. Gated structure. Photoconductive response (A, C, D) at different gate voltages and photo-e.m.f. (B) due to the FIR laser pulse (duration 100 ns, λ=250 μm). The sample temperature is 77 K. Corresponding gate voltages are U_{gd} = -0.48 V (A), 0 V (B), 0.45 V (C), and 3.73 V (D). The resistance R_{gd} versus the gate voltage is also shown. The same results were observed for λ=90.55 μm.

A fast response has been observed with a time constant smaller than the laser pulse duration. Signal pulses are displayed in Fig. 2 for different gate voltages U_{gd}. Note that the response in the unbiased case (U_{gd} = 0) is a voltaic signal inducating a spatial redistribution of free charges.

The response at $U_{gd} \neq 0$ changes its sign when the sign of the bias voltage is changed. This means that the response is due to a change in the conductance of the structure at $U_{gd} \neq 0$, i.e., it is a photoconductivity effect. The sign of the photoconductivity reveals that during the laser pulse the conductance decreases at low bias and increases at high bias. Radiation heating of 2DEG in δ-doped layer would result in an increase of the tunnel junction conductivity, since the latter rises about ten times with increasing sample temperature from 77 to 300 K.

Thus, we conclude that the low-bias response is of non-thermal origin. However, it must be noted that at low bias the dominant negative component of photoconductivity is followed by a small positive tail, which may be due to electron heating effects.

At low bias voltage, U_{gd} < 0.5 V, the resistance R_{gd} between the gate and the δ-layer is about 100 times higher than the channel resistance measured directly. Thus, the response at low bias should be considered as the result of a decrease of the tunnel conductance during the laser pulse. Such a sign of the observed photoconductivity in the gate-channel tunnel junction is completely different from what has been observed in usual tunnel junctions with Schottky barriers where the photoconductivity is always positive [2-3].

The change in the sign of the photoconductivity with the increase of the bias voltage may be related to the crossover from the tunnel junction resistance, decreasing exponentially with the bias, to the channel resistance. This can be seen from the resistance-voltage characteristic shown in Fig. 2, where the resistance assumes an approximately constant value for bias voltages U_{gd} > 2 V.

To clear up the origin of the response of the gated structure at high bias voltage, the photoresponse of the structure without gate has been measured. It turned out that the response observed in the gateless structure is very similar to the response of the tunnel structure at large bias voltages and both should be related to an increase of the channel conductance.

This fast positive photoconductivity of the channel could qualitatively be explained by electron heating. To check this assumption, the temperature dependence of the channel resistance must be known. We have measured the channel resistance as a function of the lattice temperature under different conditions: a) in the dark, b) the sample permanently illuminated by visible light, c) after illumination switched off (persistent photoconductivity). It is of interest that a long-time signal tail of opposite sign occurs under the condition of steady-state illumination with visible light, in addition to the fast positive photoresponse (Fig. 2, curve D). However, this will not further be considered here since the fast channel response related to 2DEG mobility change does not depend on the illumination conditions which affect mainly the 2DEG density.

To test the assumption about the thermal origin of the fast photoresponse of the δ-layer, measurements of the dependence of the channel photoconductivity on the intensity of laser radiation have been carried out at various sample temperatures in the range of 77-300 K. The illumination by external visible light was rejected with a black polyethylene film, when it was necessary. It was found that the values of the fast photoresponse in darkness and under persistent photoconductivity condition are identical despite the large difference of the temperature dependencies of the channel resistance in these two cases. Therefore, in the following the data obtained under dark conditions are discussed only.

Fig. 3 shows the temperature dependence of the response. The magnitude of the response drops by two orders of magnitude in a range where the temperature increases about by a factor of three. This behaviour can be attributed to an exponential factor like $\exp(-\hbar\omega_0/kT)$ in the electron energy loss rate ($\hbar\omega_0$=36.5 meV is the energy of longitudinal optical (LO) phonons in GaAs). As known, such a term is present in the expressions for the electron energy loss rate due to scattering by LO phonons irrespectively of the possible heating of the LO phonons (see for example [6]).

To analyze the heating effects in 2DEG it is necessary to know the electron distribution in two dimensional subbands. Following [5] we have obtained the value of the Fermi energy, E_F = 93 meV for the lowest subband and 17 meV for first excited subband. A rigorous treatment of hot 2D electrons, taking into account the subband filling, is quite cumbersome. Therefore as a first approach, we have analyzed the measured photoresponse in a one-subband approximation. Effective parameters of the 2DEG were taken from Hall measurements.

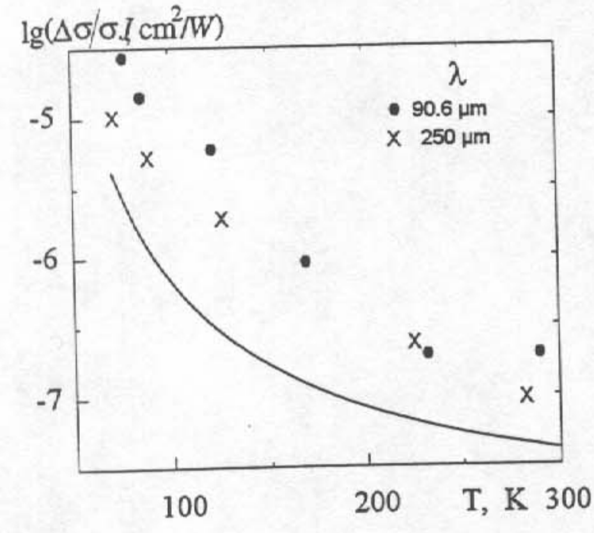

Fig. 3. Gateless structure. Temperature dependence of the relative photoconductivity Δσ/σ normalized to the intensity J at two wavelengths. The solid line shows the $\exp(\hbar\omega_0 / kT)$ behavior.

The density of 2DEG in our samples is high enough that the electron temperature approximation can be applied. As known, in GaAs at temperatures > 50 K the energy of hot electrons is transferred to the lattice due to the emission of LO phonons. In this case the expression for the energy loss rate per electron can be written in the form:

$$P = \hbar\omega_0 \nu_e [\exp(-\frac{\hbar\omega_0}{kT_e}) - \exp(-\frac{\hbar\omega_0}{kT})] \quad (1)$$

where ν_e is the effective emission frequency of LO-phonon by electrons, T_e and T are the temperature of electrons and the lattice at equilibrium, respectively. It can be rigorously proved that Eq. (1) is valid in the case of LO-phonon heating, too.

Using the data shown in Fig. 3, we have determined the magnitude and temperature dependence of the emission frequency ν_e. It takes a value of the order of $10^{12}s^{-1}$ at 77 K and of $10^{13}s^{-1}$ at room temperature. It could be verified that these values of ν_e give the correct order of the measured electron energy loss rate in GaAs as a function of T_e (see, for example, [7]) and the cooling rate of hot LO phonons due to the coupling with acoustical phonons [8]

Hence, the presented data show that the channel photoconductivity of δ-layers is stipulated by electron heating owing to the absorption of radiation by free carriers but the photoresponse of the tunnel junction is not due to hot-electron effects.

It seems likely that the decrease in tunnel conductance observed under the action of radiation can be related to a change in the shape of the self-consistent barrier-well potential due to the ponderomotive force of the electromagnetic wave, just as it was found in the case of tunnel Schottky-barrier junctions [3]. However, the momentum transfer from the radiation to electrons of the δ-layer may be provided here by the magnetic field of the free carrier current (like pinch-effect) instead of the free carrier plasma reflection of the radiation in the bulk of the semiconductor. To explain the observed phenomena, the change in the shape of the δ-layer potential well must be taken into aacount. This change is caused by ponderomotive forces in the nonuniform field of the reflected electromagnetic wave near the GaAs surface.

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