Photoresistive effect in δ-doped GaAs/metal tunnel junctions

I. N. Kotel'nikov, A. Ya. Shul'man,[1)] and N. A. Varvanin
Institute of Radio Engineering and Electronics, Russian Academy of Science, 103907 Moscow, Russia

S. D. Ganichev
Universität Regensburg, Institut für Angewandte Physik, 93040 Regensburg, Germany; A. F. Ioffe Physicotechnical Institute, 194021 St. Petersburg, Russia

B. Mayerhofer, and W. Prett
Universität Regensburg, Institut für Angewandte Physik, 93040 Regensburg, Germany

(Submitted 26 May 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 1, 48–53 (10 July 1995)

An increase of the resistance of a tunnel junction, formed by a two-dimensional electron gas of δ-doped GaAs and a metal film (gate) on a semiconductor surface, was observed under the action of pulsed submillimeter laser radiation. This response is opposite in sign to that expected from heating of two-dimensional electrons by radiation. It was found that the electrons in the δ-layer are heated and this heating is responsible for the positive photoconductivity due to the change in the resistance of the δ-layer itself. A comparison is made with the photoresistive effect in volume-doped tunnel junctions with a Schottky barrier and possible mechanisms of the formation of ponderomotive forces from the field of the electromagnetic wave which influence the tunneling resistance in the case of a two-dimensional electron gas are discussed. © *1995 American Institute of Physics.*

Previous investigations of the response of tunnel junctions with a Schottky barrier, which are formed by volume-doped GaAs and a metal on its surface, to submillimeter laser pulses have shown that under the conditions of plasma reflection the change in the resistance of the tunnel junctions is associated with the deformation of the self-consistent potential of the Schottky barrier.[1–3] This deformation of the barrier is produced by the radiation pressure acting on the free-electron plasma in the semiconductor. For tunnel junctions with a Schottky barrier, as observed in Refs. 2 and 3, the fast photoresistive effect was observed only for radiation whose wavelength lies in the plasma-reflection range.

The two-dimensional electron gas (2DEG) in the potential well of a δ-doped layer, grown near the surface of a semiconductor, is a similar system with a self-consistent potential barrier. The properties of such a system depend on the spatial distribution of the free carriers in a direction perpendicular to the plane of the δ-layer.[4] It can therefore be expected, on the one hand, that if the interaction of intense laser radiation with the 2DEG

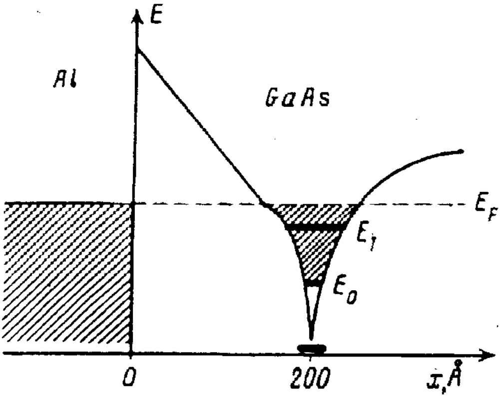

FIG. 1. Schematic representation of the potential well and the energy spectrum of a tunnel junction formed by the 2D electron gas of a δ-doped semiconductor and a metal gate. The bias voltage is 0.

changes the profile of the self-consistent potential in the tunnel structure δ-GaAs/metal, as in the case of junctions with a Schottky barrier, then this will be manifested as a change in the tunneling resistance between the δ-layer and the metal electrode. On the other hand, plasma reflection does not occur in a quasi-two-dimensional electron gas, since the thickness of the conducting layer is much smaller than the skin depth. Therefore, tunnel structures based on a δ-doped layer should make it possible to check the importance of plasma reflection for the manifestation of an effect of the transverse electromagnetic field on the tunneling.[3] In the present paper we report the first results of an experimental study of the photoresponse of structures with a δ-doped layer in GaAs in the temperature range 77–300 K.

The samples, prepared by the method of molecular-beam epitaxy, consisted of a structure with a δ-doped layer grown 200 Å from the GaAs surface. The concentration of the donor atoms (Si) in the δ-layer was equal to 6×10^{12} cm^{-2}. The Hall concentration of the two-dimensional electron gas was found to be 3×10^{12} cm^{-2} as a result of the redistribution of carriers between the δ-layer and the surface states. Two types of samples were employed in the experiments: structures with an aluminum gate, which were deposited in the molecular-epitaxy apparatus immediately after epitaxial growth of GaAs was completed (δ-GaAs/Al tunnel junctions), and structures with a free GaAs surface (δ-GaAs samples). The gate was 2000 Å thick.

Investigations at 4.2 K have shown[4] that the data from tunneling spectroscopy and magnetotransport measurements agree well with the results of self-consistent calculations of the energy structure of the two-dimensional subbands in a δ-doped layer of width 50 Å. According to the data obtained, the position of the Fermi level E_F relative to the bottom of the lowest filled two-dimensional subbands E_0 and E_1 were 93 and 20 meV, respectively, and the height of the barrier at the GaAs/Al boundary was 0.9 eV. The energy diagram of the δ-GaAs/Al tunnel structure is shown schematically in Fig. 1, and the scheme for measuring the photoresponse is shown in Fig. 2.

Analysis of the current-voltage characteristics showed that for relatively low bias

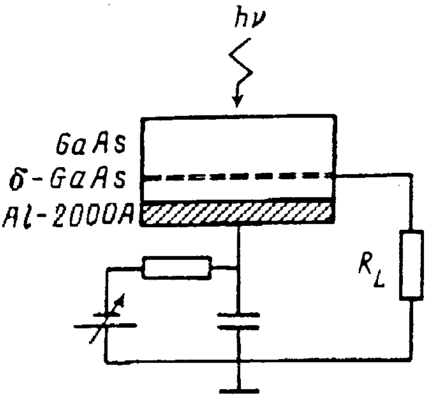

FIG. 2. Arrangement of the tunnel structure and measurements.

voltages $U_{gd} < 0.5$ V in such a structure the resistance R_{gd} between the aluminum gate and the channel is determined by the tunneling transparency of the potential barrier, and that at high voltages U_{gd}, because the tunneling transparency decreases exponentially with increasing bias, the resistance R_{gd} approaches a constant value — resistance R_{ch} of the channel with the two-dimensional electron gas (see Fig. 3). For low voltages U_{gd} the

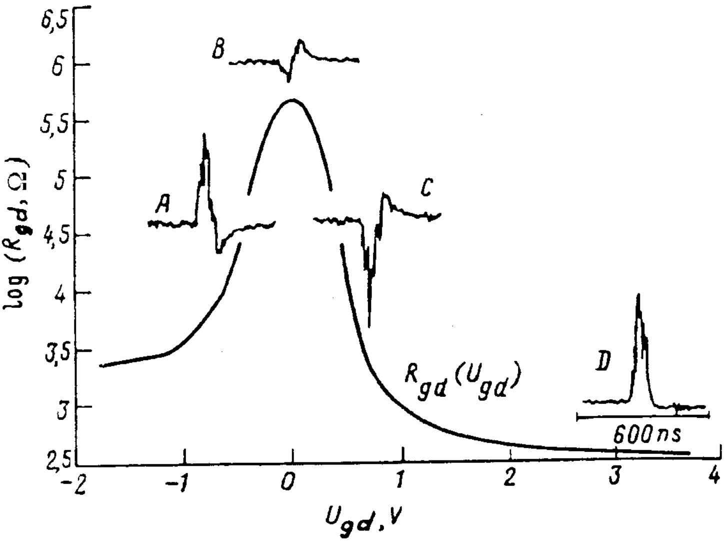

FIG. 3. Photoconductivity (A,C,D) and photoemf (B) produced by submillimeter laser pulses in 2DEG/metal a tunnel junction. The wavelength of the radiation is $\lambda = 250$ μm, the pulse duration is 100 ns, and the temperature of the sample is $T = 77$ K. A similar picture was observed for $\lambda = 90.6$ μm. The resistance R_{gd} of the junction as a function of the bias voltage U_{gd} is also shown. U_{gd} for different response curves: -0.48 V (A), 0 V (B), 0.45 V (C), 3.73 V (D). The bias for which the electrons tunnel out of the semiconductor into the metal is assumed to be positive.

tunneling resistance is approximately 100 times greater than R_{ch}.

To estimate the contribution of the heating effects to the photoresponse of the experimental δ-GaAs/Al tunnel structures, it is necessary to know the behavior of R_{gd} as a function of the temperature. In our samples, as the temperature increased from 77 to 300 K, the tunneling resistance of the junction decreased by approximately a factor of 10, while the resistance of the channel with the two-dimensional electron gas decreased by only 15%. In both cases, the heating of the electrons in the δ-layer by the radiation should therefore result in a decrease of the resistance. The effect of heating on the tunneling resistance should be much stronger.

We have investigated the photoresponse of δ-doped structures to pulsed submillimeter laser radiation (wavelengths 90.55 and 250 μm) with optical pumping by a CO_2 laser. The duration of the submillimeter radiation pulse was equal to 100 ns. The pulsed signal, which is proportional to the change in the resistance of the sample under the action of the laser radiation incident from the substrate side, was measured using the standard arrangement with a load resistance $R_L = 50\ \Omega$ to measure the photoresponse. A fast photoresponse, which is not delayed relative to the laser pulse, was observed. The results of the measurements at 77 K and with different bias voltages U_{gd} on the δ-GaAs/Al tunnel junction are shown in Fig. 3. For zero bias $U_{gd}=0$ a sign-alternating photovoltage was observed. This indicates that, just as in the case of junctions with a Schottky barrier based on volume-doped GaAs, under the action of a laser pulse the free charges are redistributed between the δ-layer and the metal gate.[2] For $U_{gd} \neq 0$ the photosignal changed sign when the sign of the bias voltage changed. This revealed that the irradiation changes the resistance of the structure. In addition, for small biases the resistance increased and for large U_{gd} the resistance decreased. Therefore, the sign of the photoresistive effect in the case of a small bias indicates unequivocally that the photoresponse of a δ-GaAs/Al tunnel junction is of a nonthermal nature. We note that submillimeter radiation always decreased the resistance in the case of tunnel junctions with a Schottky barrier.[2]

In the case of large biases on the experimental structure (i.e., when the resistance of the structure was close to R_{ch}) the sign of the photoresistive effect corresponds to a decrease of the resistance and it can therefore be associated with heating of the two-dimensional electron gas by the laser radiation. The measurements showed that the photoresponse of δ-GaAs/Al structures with large biases is identical to that of δ-GaAs (no gate) structures. To clarify the nature of the photoresponse in a channel with a two-dimensional electron gas, measurements of the temperature dependence of the transport characteristics and the photoresistive response of δ-GaAs samples were therefore performed in the temperature range $T=70-300$ K. The results of these investigations will be published separately. Here we note that the data obtained confirm the assumption that the two-dimensional electron gas is heated as a result of the absorption of radiation by free carriers. Figure 4 shows the increase of the electron temperature $\Delta T_e = T_e - T$ in a δ-GaAs structure versus $1/T$, as calculated from the measured values of $\Delta R_{ch}/R_{ch}$ for a wavelength of $\lambda = 90.6\ \mu$m, with low laser radiation intensity ≈ 50 W/cm^2. Similar results were also obtained for $\lambda = 250\ \mu$m. The figure also shows the function $\exp(\hbar\omega_{LO}/kT)$, where ω_{LO} is the frequency of the longitudinal optical (LO) phonons. Since the exponential dependence in Fig. 4 describes virtually completely the change in

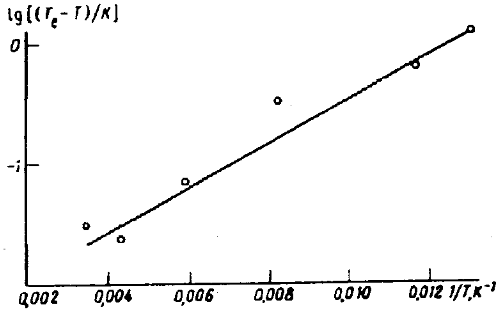

FIG. 4. Lattice temperature dependence of the heating of a 2D electron gas by radiation with intensity $J = 50$ W/cm^2 ($\lambda = 90.6$ μm). Structure — δ-doped GaAs with no gate. The solid line represents an exponential dependence with a characteristic energy (36.5 meV), equal to the energy of a longitudinal optical phonon in GaAs (see text).

the observed heating with a change in the lattice temperature, this indicates that in our structures the LO phonons play a large role in the relaxation of the energy of the hot 2D electron gas. The rate of loss of the energy by electrons as a function of T_e can also be determined from our data. This estimate in the temperature range 80–100 K agrees well in order of magnitude with the results of measurements, obtained in Refs. 5 and 6, of the rate of cooling of a 2D electron gas of quantum wells and with theoretical calculations, performed in Ref. 7, of this process, taking into account the energy transfer from the electrons to LO phonons (see also the review of the effects of hot electrons in low-dimension structures[8]). These facts, taken together, show that the response of structures with no gate is determined by the heating of the 2D electron gas in the channel.

We now return to the response of the tunnel structure shown in Fig. 3, with small biases and we shall compare it to the response of a standard tunnel junction with a Schottky barrier, investigated in Refs. 2 and 3. In Ref. 3 it was shown that the presence of an electromagnetic field decaying in a direction into the semiconductor plasma leads to the apperance of ponderomotive forces, which move the plasma boundary toward the semiconductor surface. As a result, the thickness of the Schottky barrier at the Fermi level decreases and, correspondingly, the tunneling resistance decreases. This gave a qualitative explanation for the observed positive photoconductivity. A number of factors which were ignored in the theory were indicated to explain the quantitative discrepancy between the measured response and its theoretical estimate. Specifically, it was noted that the vector potential of the transverse electromagnetic field in the depleted layer (in the barrier region) can act directly on the structure of the wave functions of the electrons under the barrier. Apparently, the results of this study suggest that this mechanism cannot be responsible for the observed response, since the response in a tunnel structure with a two-dimensional electron gas has the opposite sign from the response of a junction with a Schottky barrier, although a transverse electromagnetic field in the barrier region which is classically forbidden for electrons is present in each case.

It should be noted that the direction of incidence of the radiation relative to the metal-coated semiconductor surface is opposite in our case to the direction in the preceding investigations. In investigations of the response of tunnel junctions with a Schottky barrier, the radiation penetrated into the semiconductor through the semitransparent metal electrode. Structures with a two-dimensional electron gas were irradiated from the opposite side, since the aluminum gate is too thick to pass submillimeter laser radiation. In the region near the metal-coated surface, where the conducting δ-layer with the 2D electron gas is located, a standing wave was produced with a node at the middle of the gate, such that the gradient of the energy density is directed opposite to the gradient of the density of the electromagnetic field incident from the surface side and decaying as a result of the plasma reflection by the electrons in the semiconductor. This fact can be regarded as a qualitative explanation of the difference in the signs of the response of the two types of tunneling structures. However, the characteristic scale of the spatial nonuniformity of the field of the standing wave, which is of the order of the wavelength of the incident radiation in the semiconductor, is much greater than both the size of the δ-layer itself and the distance of the δ-layer from the surface. A more quantitative analysis of this mechanism must therefore be carried out.

The conduction current excited in the 2D electron gas by an alternating field of the wave is another source of the ponderomotive forces that change the tunneling resistance of 2DEG/metal structures. The magnetic field of this current can compress the gas, as happens in the pinch effect. This should be accompanied by a narrowing of the self-consistent potential well of the δ-layer (see Fig. 1). This narrowing results in an increase in the thickness of the barrier and an increase in the tunneling resistance.

We thank V. G. Mokerov and B. K. Medvedev for preparing the samples of δ-doped structures and V. A. Kokin for performing a numerical calculation of the energy spectrum and the occupancy of the two-dimensional subbands. One of us (A. Ya. Sh.) thanks S. Das Sarma for a reprint of Ref. 7. Financial support for this work was provided by a NATO program (Grant HTECH.LG 9931585) and by the Russian Fund for Fundamental Research (Grant 94-02-05712-a).

e-mail:ash@cplire.ru

---

[1] I. N. Kotel'nikov, N. A. Mordovets, and A. Ya. Shul'man in *Conference Digest of 9th International Conference on IR and MM Waves*, Takarazuka, Japan, 1984, p. 137.
[2] S. D. Ganichev, I. N. Kotel'nikov, N. A. Mordovets *et al.*, JETP Lett. **44**, 301 (1986).
[3] S. D. Ganichev, K. Yu. Glukh, I. N. Kotel'nikov *et al.*, Zh. Éksp. Teor. Fiz. **102**, 907 (1992) [Sov. Phys. JETP **75**, 495 (1992)].
[4] I. N. Kotel'nikov, V. A. Kokin, B. K. Medvedev *et al.*, Fiz. Tekh. Poluprovodn. **26**, 1462 (1992) [Sov. Phys. Semicond. **26**, 821 (1992)].
[5] J. Shah, A. Pinczuk, A. C. Gossard *et al.*, Phys. Rev. Lett. **54**, 2045 (1985).
[6] C. H. Yang, J. M. Carlson-Swindle, S. A. Lyon *et al.*, Phys. Rev. Lett. **55**, 2359 (1985).
S. Das Sarma, J. K. Jain, and R. Jalabert, Phys. Rev. B **37**, 4560 (1988).
[8] B. K. Ridley, Rep. Prog. Phys. **54**, 169 (1991).

Translated by M. E. Alferieff