Effect of FIR Pulsed Laser Radiation
on Tunnel and Channel Resistance of δ-Doped GaAs

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An increase in the tunneling resistance between a two-dimensional electron gas (2DEG) in δ-doped GaAs and a metal gate has been observed in response to pulsed submillimeter laser radiation. The sign of this response is opposite to that expected from radiation heating of 2DEG. The strength of the signal increases strongly when a double-gate structure is used. This enhancement of the response may be attributed to near-field effects at the edges of the gates and in the slit between the gates. The results are compared with the photoresistive effect in the bulk tunnel junction with a Schottky barrier. In addition, it is shown that radiation heating of electrons in the δ-layer results in channel photoconductivity in the 2DEG.

1. Introduction

Previous studies of the response of tunnel Schottky-barrier junctions formed by bulk δ-doped GaAs and a metal gate on its surface to pulsed submillimeter laser radiation have shown that under the conditions of plasma reflection the change in the resistance of a tunnel junction is caused by the deformation of the self-consistent potential of the Schottky barrier [1–3]. The barrier deformation arises due to radiation pressure on the free electron plasma in the semiconductor. This fast photoresistive effect was only observed for the radiation with wavelength in the spectral range of the plasma reflection [2–3].

A two-dimensional electron gas (2DEG) in the potential well of a δ-doped layer grown near the semiconductor surface represents a similar system with a self-consistent potential barrier. The properties of such a system depend on spatial distribution of free carriers in the direction perpendicular to the δ-layer [4]. Therefore, it may be expected that, like in the case of the Schottky barrier junctions, intense laser radiation
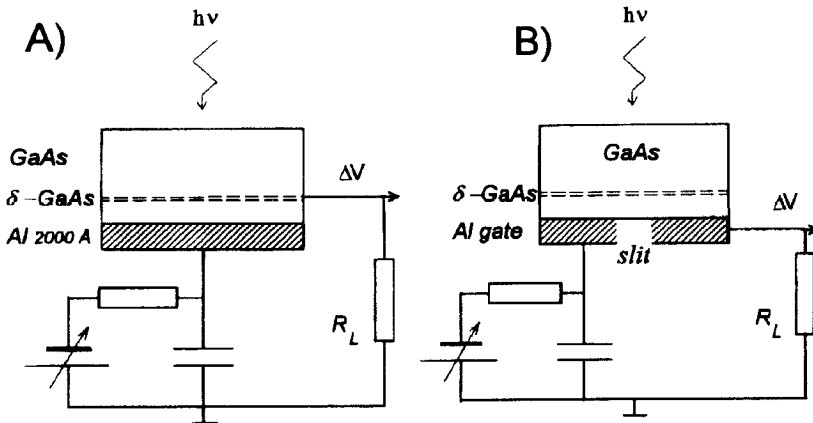
Figure 1. Tunnel structures δ-GaAs/Al and measurement circuits. a) A single-gate structure and the connection "gate-channel". b) A double-gate structure and the connection "gate-gate".

will reconstruct the 2DEG self-consistent potential yielding a change in the tunnel resistance between the δ-layer and metal electrode. On the other hand, a quasi-two-dimensional electron gas cannot lead to plasma reflection because the thickness of the conducting layer is much less than the skin depth. Hence, tunnel structures on the basis of δ-doped layers should allow to find out how essential plasma reflection is with respect to the influence of transverse electromagnetic field on tunneling [3]. In the present work first results on the photoresponse of the structures with δ-doped layers in GaAs are presented. The measurements were carried out in the temperature range of 77–300 K.

2. Experimental

Samples with δ-doped layers grown 200 Å below the GaAs surface were prepared by the molecular-beam epitaxy (MBE). The concentration of donor atoms (Si) in a δ-layer was $6 \cdot 10^{12}$ cm^{-2} giving a Hall density of the 2DEG of $3 \cdot 10^{12}$ cm^{-2} due to the carrier redistribution between the δ-layer and surface states. The tunnel junctions were formed in MBE chamber by depositing an aluminium film of about 2000 Å thickness immediately after epitaxial growth. Two types of the samples with aluminium gates were used in experiments. The first type has one continuous gate of 1 mm width and 4.5 mm length located above the 2DEG channel with the same dimensions. The second type has two identical gates (g1 and g2) 2.25 mm long each and separated by a thin (20 μm) slit (see Fig.1). In addition, the structures with free GaAs surface were investigated.

Tunneling spectroscopy and magnetotransport measurements performed at a temperature of 4.2 K are in good agreement with the results of self-consistent calculations
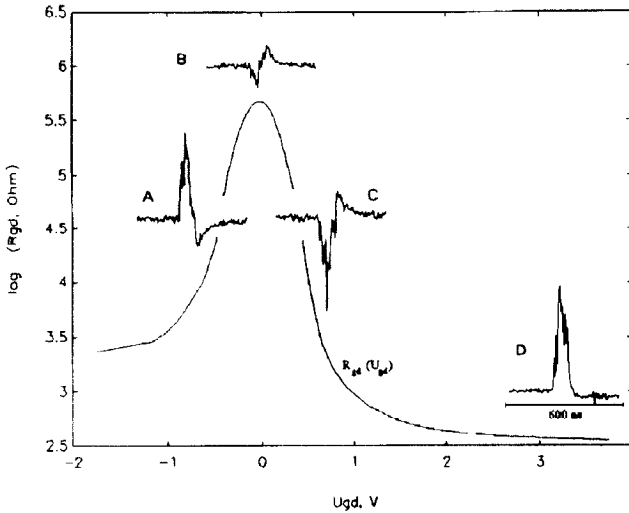
Figure 2. Single-gate structure. Photoconductive response (A, C, D) at different gate voltages and photo-e.m.f. (B) due to the FIR laser pulse (duration 100 ns, $\lambda = 250$ μm). The sample temperature is 77 K. Corresponding gate voltages are $U_{gd} = -0.48$ V (A), 0 V (B), 0.45 V (C), and 3.73 V (D). The resistance R_{gd} versus the gate voltage is also shown. The same results were observed for $\lambda = 90.55$ μm. The positive bias corresponds to electron tunneling from the semiconductor into the metal.

of the energy structure of two-dimensional subbands in δ-doped layers of 50 Å width [4]. These results show that two lowest subbands are filled. The Fermi level is 93 and 20 meV above the bottom of these subbands, respectively, and the barrier height at the GaAs/Al interface is 0.9 eV.

The analysis of current-voltage characteristics has shown that the resistance R_{gd} of the tunnel structures is determined by the tunnel transparency of the potential barrier between the gate and the channel (see. Fig.1A) for bias voltages U_{gd} below a characteristic value. At higher U_{gd} the main contribution to R_{gd} stems from the finite conductivity of the 2DEG channel (see Fig.2). At low U_{gd} the tunnel resistance exceeds the channel resistance approximately by a factor of 100 at a temperature of 77 K and a factor of 10 at 300 K.

To evaluate the contribution of heating effects to the photoresponse, the temperature dependence of R_{gd} has been measured. The junction tunnel resistance increases approximately by a factor of 10 upon cooling the sample from 300 K to 77 K, whereas the channel resistance of 2DEG grows only by about 15%. Thus, heating of electrons in the δ-layer by radiation should lead to a decrease in both resistances; however, the influence on the tunnel resistance should be considerably stronger.

The photoresponse of δ-doped structures has been measured by 100 ns submillimeter laser pulses of the 90.55 μm and 250 μm wavelength. The signal proportional to the

lg[($T_e - T$)/K]
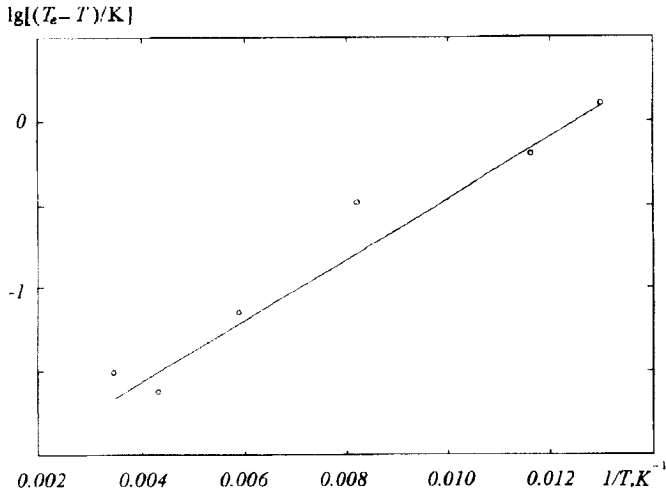
Figure 3. Dependence of the radiation heating of the two-dimensional electron gas in δ-doped GaAs without a gate on the lattice temperature. The radiation intensity is 50 W/cm^2 ($\lambda = 90.55$ μm). Solid line represents the exponential expression with the characteristic energy of 36.5 meV equal to the energy of longitudinal optical phonons in GaAs (see text).

irradiation induced change in the sample resistance was recorded with the standard scheme with a load resistor of $R_L = 50$ Ohm in series with the sample (Fig.1).

Signal pulses measured with the continuous gate structure (Fig.1A) at 77 K are shown in Fig.2 (A,C,D) for three bias voltages U_{gd} applied to the δ-GaAs/Al tunnel junction. The position of the pulses on the voltage scale in Fig.2 corresponds to the bias. At high bias voltages the signal is determined purely by photoconductivity and reproduces the temporal structure of the laser pulse with resolution better than 100 ns. At small bias voltages a discrepancy between the laser pulse and the signal pulse occurs. This discrepancy is due to a mixture of the photoconductive signal and a photo-e.m.f. which is observed at zero bias in Fig.2B (note that the e.m.f was subtracted from the low-bias pulses A and C in Fig.2). This e.m.f. changes its sign during the laser pulse and is similar to the case of bulk δ-doped GaAs Schottky barrier junctions [2]. The occurrence of the e.m.f. indicates a redistribution of free charges between the δ-layer and the gate due to the laser pulse.

At large bias voltages U_{gd}, when R_{gd} is determined by the channel conductivity, the sign of the photoresistive effect is reversed. This response corresponds to a decrease in the structure resistance (Fig.2D) and can be associated with heating of the 2DEG by laser radiation. This conclusion is also supported by measurements of the channel photoconductivity on gateless structures which basically gave the same result. From the magnitude of the photoconductivity the electron temperature T_e has been determined in the lattice temperature range $T = 70 \div 300$ K. In Fig.3 the electron

heating $\Delta T_e = T_e - T$ in a δ-GaAs structure is shown as a function of the reciprocal lattice temperature $1/T$. The electron temperature in this figure is a result of heating by the 90.55 μm wavelength radiation with the 50 W·cm^{-2} power. The dependence of ΔT_e on $1/T$ can be well fitted by the expression $\exp(\hbar\omega_{LO}/kT)$ (solid line in Fig.3) where ω_{LO} is the frequency of longitudinal optical (LO) phonons. Since the exponential dependence in Fig.3 almost completely describes the change in the observable heating with the lattice temperature T, it shows that LO phonons determine the energy relaxation of hot 2DEG. In the temperature range of 80–100 K the energy loss rate estimated from the measurements agrees well with the cooling rate of 2DEG in quantum wells [5–6]. Theoretical calculations taking into account the energy transfer from the electrons to LO phonons give the same results [7,8]. More details of FIR laser heating of 2DEG in δ-doped GaAs and the energy relaxation are given in Ref.[9].

At small bias voltages, where the tunneling process determines the voltage drop across the structure, the resistance of the sample increases upon irradiation. This result unambiguously proves the non-thermal nature of the photoresponse of the δ-GaAs/Al tunnel junction. In the case of heating of 2DEG, rising temperature and, thus, a decrease in the resistance with irradiation is expected.

In bulk δ-doped tunnel junction with a Schottky barrier, non-thermal signals have also been observed with submillimeter radiation indicating a decrease in the resistance in contrast to our case [2,3]. The analysis carried out in Ref.[3] showed that the electromagnetic field acts with a ponderomotive force on electrons. Measurements of the response of the tunnel Schottky barrier junctions were carried out by irradiating the sample through a semitransparent metal electrode. The radiation field is attenuated in the semiconductor due to plasma reflection by the electrons yielding a gradient of the density of electromagnetic field energy. As a result, the thickness of the Schottky barrier at the Fermi level and, accordingly, the tunnel resistance decreases due to the displacement of the plasma boundary.

In 2DEG δ-doped structures, high electron density is concentrated in a layer thinner than the skin depth; therefore, the situation is essentially different from the bulk tunnel junctions. Neglecting absorption, the electromagnetic field energy density gradient is zero in this configuration and, hence, there are no ponderomotive forces. There is also no plasma reflection and illumination from the semiconductor side is possible. This permits to apply thick, non-transparent gates as have been used here. This results in a different electromagnetic field configuration at the location of the δ-layer close to the metal-covered semiconductor surface. The conducting δ-layer with 2DEG is in a standing electromagnetic wave which has a node of the electric field and an oscillation loop of the magnetic field at the metal gate. This might suggest conclusion that the transverse magnetic filed component of the radiation causes the observed non-thermal signal [10]. To verify this suggestion, samples were irradiated from the gate side which allows only the radiation diffracted at the edges of the gate to penetrate into the tunneling region. It turned out that the same photoresistive response occurs in this case, too.

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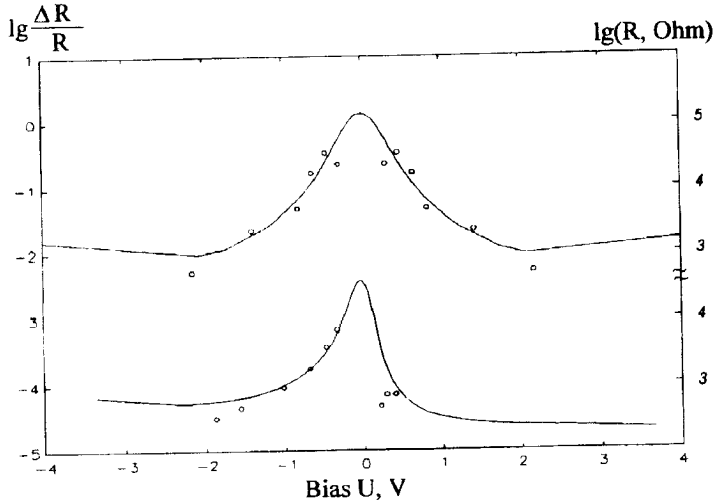
Figure 4. Comparison between the photoresistive response of the tunnel δ-GaAs/Al structure with a double gate at two connections (circles). Solid lines represent the dependence of the resistance on the bias for each connection. This dependence indicates the bias range where the resistance is determined by the tunnel junction. Upper and lower curves show the $R_{gg}(U_{gg})$ and $R_{gch}(U_{gch})$ dependences for "gate-gate" and "gate-channel" connections, respectively. Note a similarity of the structure photoresponse and resistance dependences on the bias. Temperature is 300 K, radiation wavelength is 90.55 μm, radiation intensity is of the order of 20 kW/cm^2.

The only explanation of this result is that diffraction effects at the edges of the gate cause the observed signal in all cases. The 2DEG is located in the near-zone field of the diffracted radiation which has a substantial potential electric field component. To amplify these effects, the double gate structure shown in Fig.1B has been used. The width of the slit between the gates was 20 μm which is less than the incident radiation wavelength and the gate size. The sample was biased across the two gates which corresponds to two junctions of opposite polarity in series. In fact, a significant increase in the response has been observed. The relative irradiation induced change of the resistance $\Delta R_{gg}/R_{gg}$ is approximately 300 times larger than that of the single-gate structure (see Fig.4) and does not depend on which side of the structure is irradiated. This implies that the area of the sample where the effective interaction of the radiation with the tunnel current takes place is located in the vicinity of the slit. Measurements with polarized radiation showed that the signal is mostly determined by the component of the electric field of the incident wave perpendicular to the slit. Furthermore, Fig.4 shows that the dependence of the radiation induced relative change in the resistance is similar for both structures at negative bias. In the case of the double-gate tunnel junction (upper curve in Fig.4) the response is a symmetric function of the bias voltage

because for any polarity of the bias one of the diodes is reverse biased.

The enhancement of the response in the double-gate configuration may be understood considering the distribution of both the static bias field and the high-frequency electric field in the vicinity of the slit. The δ-layer is located very close to the metal gate in comparison with all other spatial scales of the sample. Therefore, both electric fields are tangential in the area of the slit, i.e. directed along the δ-layer. Under the gate, the electric fields have only components normal to the surface and, hence, also to the δ layer. Close to the edges of the slit, the normal components of the fields assume very high values (infinitely high in the limit of a thin ideally conducting screen, as it is required by the well-known "edge conditions", see, e.g. Ref.[11], Sec.3.3). The enhancement of the static field near the edges produces a highly inhomogeneous dc current distribution concentrated near the edges and overlapping with the high-frequency field due to the near-zone effects caused by diffraction. This overlap of both fields should be expected to enhance the response. To prove this assumption, the photoresponse of a double-gate sample has been measured with electrically shortened gates in the biasing configuration of Fig.1A. In this case the gates are at the same electrostatic potential and the enhancement of the normal component of the dc field close to the slit edges disappears. On the other hand, distribution of the high-frequency field does not change. The measurements showed that the photosignal amplitude of this electrically shortened double-gate structure is small and practically the same as in the case of the structure with a single continuous gate. Thus, enhancement of the dc field normal component in the region where the diffracted field is present is important for the amplification of the response.

From the microscopic point of view the mechanism of the photoresistive effect in the 2DEG tunnel junction is still not well understood. The physical phenomenon of signal generation differs essentially from the case of photoresistive response in bulk tunnel Schottky barrier junctions due to plasma reflection where the tunnel current is controlled by the transverse electromagnetic field. On the other hand, it cannot be described as a simple rectification of the time-dependent electromagnetic field by means of the nonlinear current–voltage characteristic of the structure. The frequency of the incident radiation is too high with respect to the large capacity of the structures and the sign of the response should be opposite to the observed one because of the superlinearity of the current-voltage characteristic.

3. Conclusion

In conclusion, the influence of far-infrared radiation on the tunnel resistance of δ-GaAs/Al structures is substantially affected by the near-zone electric field component normal to the δ-layer and the gate. This field arises close to the edges of the gate due to the diffraction of the normally incident electromagnetic wave and is directed along the tunnel current. Our results demonstrate that the near-zone field effects must be taken into account in all far-infrared investigations of microscopic structures.

The observed enhancement by two orders of magnitude of the detection sensitivity by the near-zone field effects is of great practical importance in the development of two-dimensional detector arrays of high spatial and temporal resolution based on microscopic single elements. It can also be interesting from the point of view of other investigations and applications of the near-field effects [12].

Acknowledgements

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