Oscillations of the tunnel conductance of an *n*-GaAs:Te/Au junction with a Schottky barrier

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An n-GaAs(Te)/Au tunnel junction with a free-electron density $n = (7\text{–}9)\times 10^{18}\ \text{cm}^{-3}$ was illuminated at 77 K using a GaP light-emitting diode. Oscillations of the dependence of the tunnel conductance on the applied bias voltage were observed. A typical period was $\geqslant 40$ mV and the amplitude was $\leqslant 1\%$. These oscillations were retained for a long time after the end of illumination. Earlier information about the influence of filling of DX centers on the tunneling in Schottky-barrier junctions under pressure was used to explain the overall profile of the oscillations and the nature of their pressure dependence by perturbation of the space charge region caused by activation of the DX centers in GaAs as a result of photoexcitation.

Tunnel spectroscopy is one of the methods for investigating the energy spectrum of quasiparticles in a semiconductor. A combination of this method with a high-pressure technique was used in Ref. 1 and it was found that the behavior of the tunnel conductance of Schottky-barrier junctions made of heavily doped n-GaAs can be explained by the influence of the DX centers. One of the manifestations of the influence of the DX centers on the bulk conductance of n-GaAs is the frozen photoconductivity effect. Therefore, it seemed of interest to carry out tunnel investigations of heavily doped GaAs under pressure when the DX centers are activated by photoexcitation.

With this in mind we measured the tunnel current as a function of the bias voltage applied to a Schottky-barrier n-GaAs(Te)/Au junction in which the semiconductor was characterized by a free-electron density $n \approx (7\text{–}9)\times 10^{18}$ cm^{-3}. The measurements were carried out under pressures up to 10 GPa at liquid nitrogen temperature (77 K).

The tunnel junctions were made by a method described in Ref. 2 and the stability of a sample under high pressures was ensured by hf sputtering of an SiO film $\approx 0.2\ \mu$m thick on the GaAs surface coinciding with the (100) plane; this film was deposited around a semitransparent gold electrode 0.25 mm in diameter. Next, two copper contacts with the gold electrode were deposited by evaporation. When this contact formation technology was used, the junction current-voltage characteristics recorded after removal of the pressure were found to be identical with the initial curves.

Investigations under pressure were made by a method described in Ref. 3. The junction was illuminated with a GaP light-emitting diode placed alongside a sample in a high-pressure zone. Under normal conditions a current of ≈ 20 mA corresponded to an emission wavelength of about 530 nm (green light). Cooling of the diode to 77 K at atmospheric pressure shifted the emitted light to the yellow part of the spectrum, but the initial color was recovered when the current through the diode was increased to ≈ 50 mA. Bearing in mind that GaP is an indirect-gap semiconductor, so that the minimum of the conduction band corresponds to the [100] direction and that the gap depends weakly on the pressure ($dE_g/dp \approx -1.1$ meV/kbar—see, for example, Ref. 4), we assumed that in our measurements under pressure the emission wavelength remained close to the initial value.

A direct influence of the illumination on the tunnel characteristics was manifested by an increase in the conductance by a few percent, a change preserved after the end of illumination. A more subtle effect of such illumination was an oscillatory structure, which was exhibited by the dependence of the ratio of the differential conductances $S(V) = dI/dV$ on the bias voltage V (Fig. 1). These dependences were

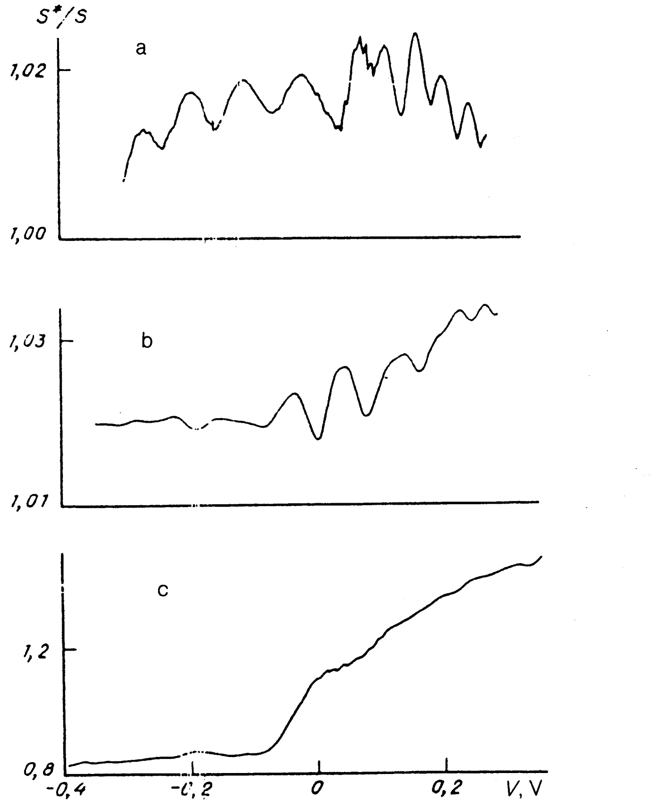

FIG. 1. Ratio of the tunnel conductance of an n-GaAs(Te)/Au junction after illumination (S^*) to the dark conductance (S), plotted as a function of the bias voltage V and recorded at different pressures: a—$p = 0$; b—$p = 7$ kbar; c—$p = 10$ kbar.

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obtained by numerical calculations based on the tunnel-current values measured before and after illumination. The states of the tunnel junction responsible for the observed nonmonotonic behavior were identified by plotting, for each pressure, a series of curves representing the logarithmic derivative of the tunnel conductance $d(\ln S)/dV$ before, during, and after illumination with a light-emitting diode (one of these curves is plotted in Fig. 2). It is clear from this figure that at high bias voltages there were small variations of the conductance against the background of a near-exponential tunnel spectrum $S(V)$. Figure 3 shows strongly smoothed-out curves representing the logarithmic derivative of the ratio of the persistent photoconductance S^* and the dark conductance S exhibiting the oscillations of interest to us, which were revealed by numerical analysis. The oscillations grew for a certain finite time after the beginning of illumination and retained a considerable amplitude after illumination throughout the duration of the experiment (~ 1 h), as demonstrated in Fig. 4. Application of a pressure of 7 kbar changed little the oscillation period, compared with the initial value, but the amplitude decreased. At $p \sim 10$ kbar the oscillation period increased significantly.

Several types of oscillations of the tunnel conductance, observed in the absence of a magnetic field, had been reported and they differ in respect of their nature and energy scale.[5]

The first of them is known as the Stark ladder, which appears as a result of interband tunneling in a strong homogeneous electric field, when the finite width of the allowed band makes the carrier motion finite and this gives rise to a discrete energy spectrum. Such a mechanism cannot account for the oscillations observed by us since under a posi-

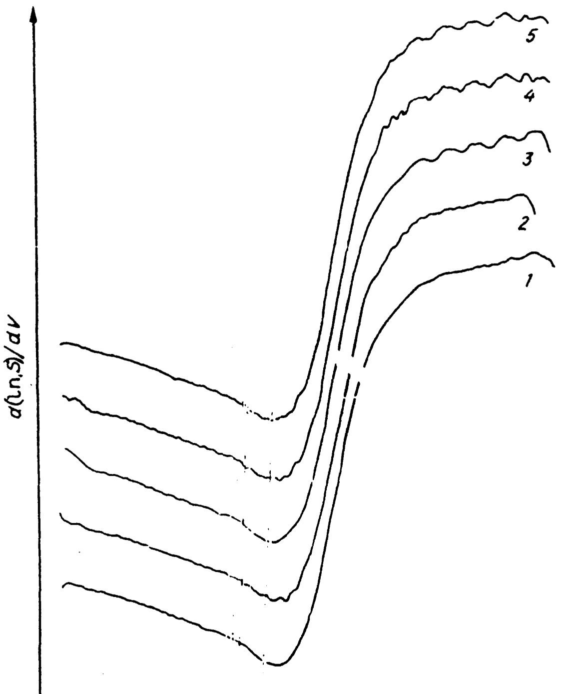

FIG. 2. Influence of illumination on the tunnel spectrum at $p = 7$ kbar: *1,2*—before illumination; *3,4*—during illumination; *5*—~ 30 min after the end of illumination.

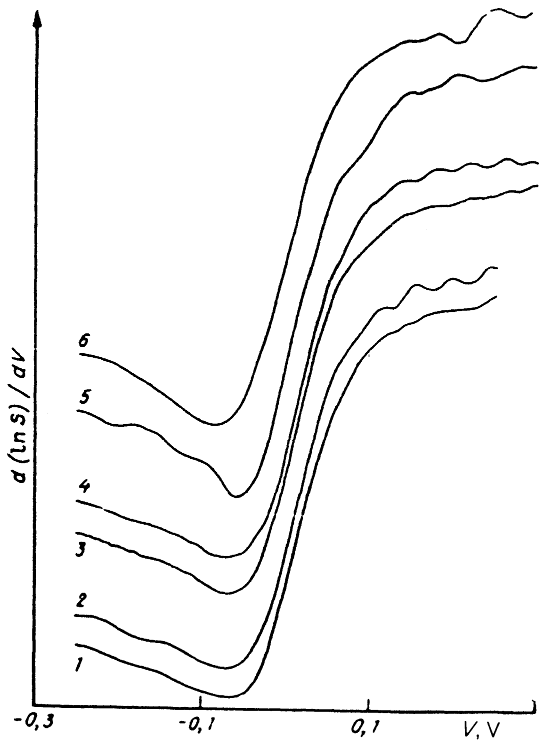

FIG. 3. Influence of illumination on the logarithmic derivative of the conductance at different pressures: *1,2*—$p = 0$; *3,4*—$p = 7$ kbar; *5,6*—$p = 10$ kbar; *1,3,5*—before illumination; *2,4,6*—after illumination.

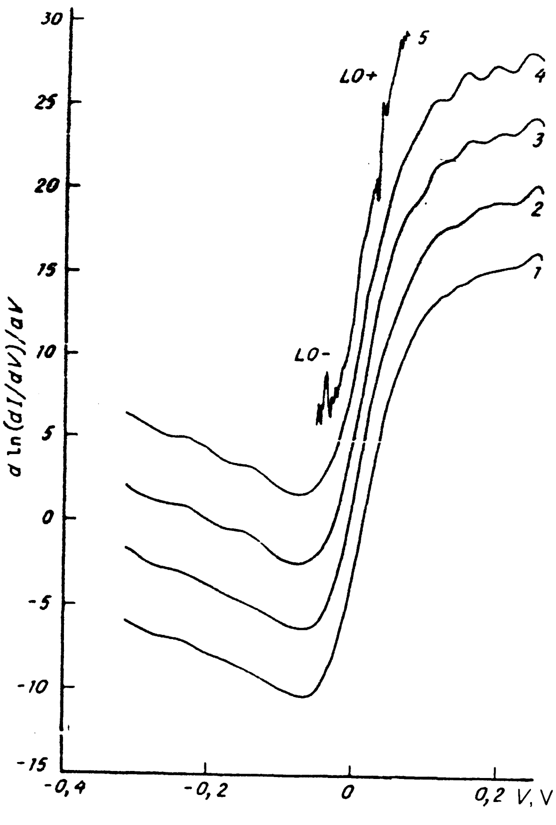

FIG. 4. Evolution of oscillations in time at $p = 0$: *1*—before illumination; *2*—9 min after illumination; *3*—19 min after illumination; *4*—35 min after illumination; *5*—phonon singularities shown for the sake of comparison and recorded at $T = 4.2$ K (LO^+ represents characteristic singularities of the tunnel spectrum at energies equal to the energy of a longitudinal optical phonon in GaAs).

tive bias the Schottky-barrier field can only retard and not accelerate the tunneling electrons.

Another type of the conductance oscillations is associated with the appearance of geometric resonances and is known as the Tomasch effect,[5] in which the occurrence of superconducting pairing is of fundamental importance, but it is difficult to expect this in our case.

The third type of oscillations of the tunnel conductance was predicted in Ref. 6 as a consequence of the influence, on the tunnel current, of random inhomogeneities of the field of impurities, which had been investigated intensively by Raĭkh and Ruzin.[7] However, in this case we could not expect a definite periodicity, which was a clear feature of our data.

We shall attempt to interpret our observations as follows. We shall assume that the presence of a substitutional impurity (such as Te in GaAs) at an As lattice site alters the potential energy of an electron. This may be associated both with the real charge of an impurity center localized at this site or with a deformation potential, created by perturbation of the main lattice in the vicinity of the Te atom, as postulated in current models of the DX centers.[8,9] In any case if in each atomic plane parallel to the junction plane we average the contribution of randomly distributed impurities to the potential energy of electrons over a sufficiently large macroscopic area of the junction, then as a result of such averaging the profile of the barrier should exhibit a more or less regular component which varies periodically with the coordinate along the normal to the surface. The periodicity of this component in space should correspond to a system of atomic planes containing As and having a period equal to half the lattice constant.

A semiclassical model of the tunneling across a Schottky barrier, in which the behavior of the potential is described by a self-consistent solution of the Poisson equation, predicts that the tunnel current observed for $V > 0$ is governed primarily by the semiconductor electrons with an energy of the order of the Fermi energy, i.e., by those electrons which are close to the boundary of a depletion layer. The position of this layer depends on the applied bias V:

$$L = L_0[1 - eV/(E_b + \mu_F)]^{1/2},$$

where E_b is the barrier height, μ_F is the Fermi level in a degenerate semiconductor with an electron density n, $L_0 = [\varepsilon(E_b + \mu_F)/2\pi N_d e^2]^{1/2}$, ε is the permittivity of the semiconductor, and N_d is the density of charged impurities in the depletion layer. If we now relate the position of the conductance oscillations on the scale V to the change in the characteristic scale L, representing the Schottky-barrier width by a value of the order of one half of the lattice constant $a = 5.65$ Å due to a change in the applied bias voltage, then the period $5.65/2 \approx 2.8$ Å should correspond to conductance oscillations with the characteristic voltage scale $(2/e)(E_b + \mu_F)\Delta L/L \approx 40$ mV, which was close to the values observed at $p = 0$.

We tried to calculate more accurately the positions of the conductance oscillation maxima on the bias voltage scale V (Fig. 5) converting them into the spatial coordinates of the turning points of electrons that dominate the tunnel current at various pressures. At positive bias voltages $V > 0$ the tunnel current is governed by the energy states near the Fermi level of the semiconductor, whereas at negative voltages

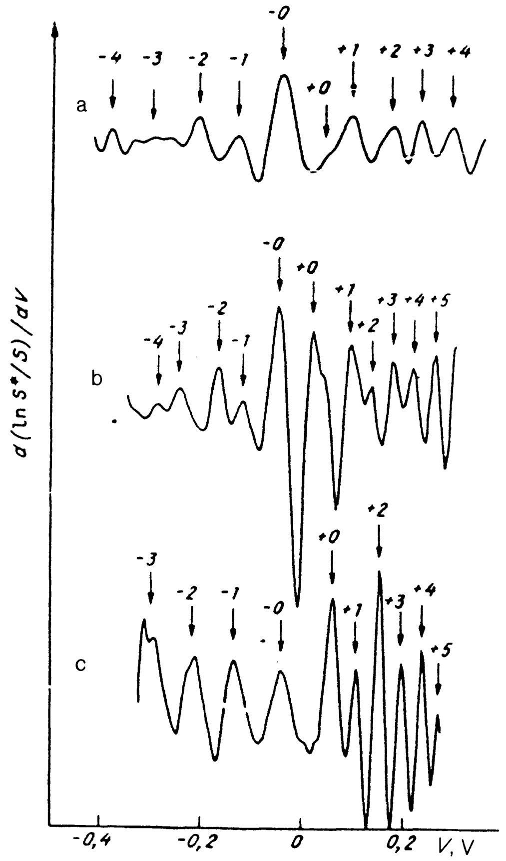

FIG. 5. Oscillation peaks of the logarithmic derivative of the ratio of the conductances at different pressures: a—$p = 10$ kbar; b—$p = 7$ kbar; c—$p = 0$.

it is governed by the states near the Fermi level of the metal (Fig. 6).

Let μ_F be the Fermi energy of a gas of free electrons with the density n_e and an effective mass $m^* = 0.068 m_e$ for the electrons in the Γ valley of GaAs. The density of free electrons in the depletion layer is zero and at energies above the Fermi level the barrier is parabolic. In this region the behavior of the potential $\Phi(x)$, measured from the bottom of the semiconductor conduction band and expressed in units of μ_F, can be found explicitly by solving the Poisson equation in which an allowance is made for the screening effect of free electrons.[10,11] For positive bias voltages the coordinate of the turning point l_+ for electrons at the Fermi level of the semiconductor is governed by the condition $\Phi(l_+) = 1$, which gives the following expression for the tunneling length:

$$l_+ = 2L_s\{[(E_b - eV)/\mu_F + 3/5]^{1/2} - (3/5)^{1/2}\}, \quad V \geq 0, \tag{1}$$

and at negative bias voltages we have to use the corresponding condition for electrons at the Fermi level of the metal $\Phi(l_-) = 1 - eV/\mu_F$, which leads to

$$l_- = 2L_s\{[(E_b - eV)/\mu_F + 3/5]^{1/2} - (3/5 - eV/\mu_F)^{1/2}\}, \quad V < 0, \tag{2}$$

where V is the bias voltage regarded as positive when the Fermi level is located in the semiconductor above the Fermi level of the metal electrode and $L_s = (\varepsilon\mu_F/8\pi N_d e^2)^{1/2}$.

The results of calculations using Eqs. (1) and (2) are presented in Fig. 7 which gives the dependence of the relative

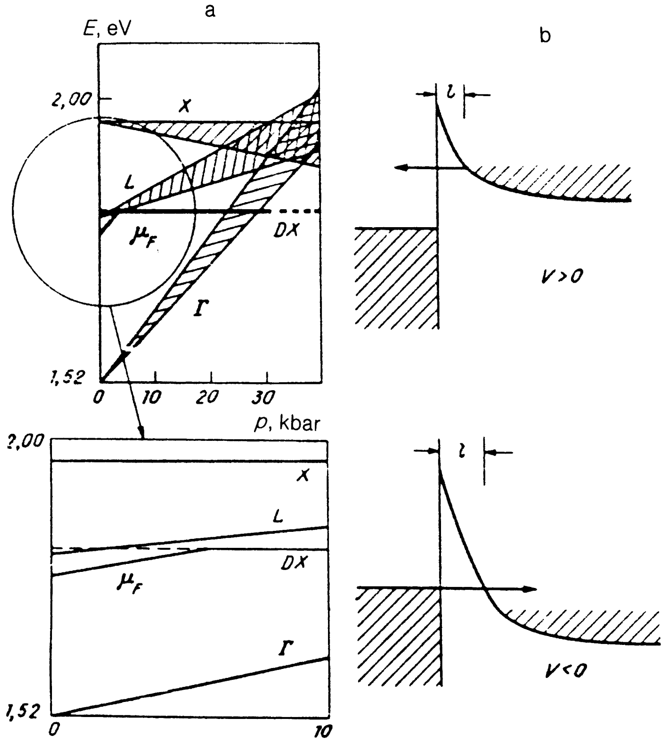

FIG. 6. a—Influence of the applied pressure on the structure of the conduction band of GaAs and the position of the Fermi level of electrons in a sample with $N_d = 1.6 \times 10^{19}$ cm^{-3}. b—Model of a Schottky barrier used in calculations of the screening length l.

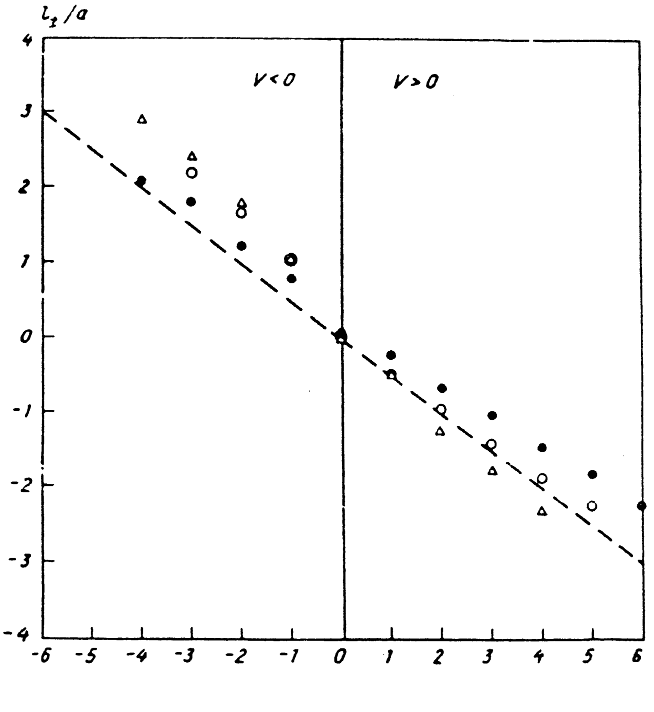

FIG. 7. Correlation of the oscillations with the position of the turning point for electrons at the Fermi of a semiconductor ($V>0$) or a metal ($V<0$; O–$p=0$; ●–$p=7$ kbar; Δ–$p=10$ kbar; the dashed line corresponds to the slope $-1/2$). The abscissa gives the serial numbers of the peaks corresponding to those used in Fig. 5.

(in units of a) separation between the adjacent turning points (l_+ if $V>0$ and l_- if $V<0$) on the serial number of an oscillation peak, deduced from the dependences of the positions of the corresponding oscillation maxima of the curves on the bias voltage $d\ln(S^*/S)/dV$ plotted in Fig. 5. The abscissa serial number of the peak in Fig. 7 represents the oscillation number and the first oscillation for each sign of the bias voltage corresponds to the peak 0. Since the characteristic tunneling length decreases on increase in the absolute value of the bias voltage, a linear dependence is obtained when the left-hand branch is plotted with the sign reversed. In this representation the expected periodicity with the lattice half-period should be represented by a straight line with the slope $-1/2$.

The model presented in Fig. 6 was used and it was assumed that if the Fermi energy of electrons does not exceed the energy level of the DX centers, then in the interior of a semiconductor the density of free carriers n may not be equal to the total donor concentration N_d. This circumstance reflects the fact that cooling results in a disequilibrium of the population of the DX levels at temperatures below ≈ 120 K because of the existence of a potential barrier separating an electron captured by a DX level from delocalized states, as demonstrated in Ref. 9 for the case of GaAs(Si). In this sense we could regard the density of free carriers as a free parameter. If however the Fermi energy, found on the assumption that all the electrons are free, was located above the DX level (after allowance for the influence of pressure on the energy band structure of GaAs), it was concluded that the Fermi level was pinned by the latter and the fraction of the electrons captured by the DX centers could be calculated. On the other hand, all the DX centers in the depletion layer were regarded as ionized by the strong Schottky-barrier field, so that the density of the positive background charge was eN_d.

The influence of pressure on the relative position of the DX level and on the width of the band gap, governing the barrier height E_b, was allowed for in the calculations based on the known pressure coefficients and on the dependence of the DX level on the free-electron density.

The calculations were carried out for a wide range of values of the free-carrier density (from $n_e = 6 \times 10^{18}$ cm^{-3} to N_d), of the impurity concentration [$N_d = (11\text{–}19) \times 10^{18}$ cm^{-3}], and of the barrier height at zero pressure ($E_b = 0.6\text{–}1.5$ eV); the slope of the straight line approximating (in the least-squares sense) the dependences plotted in Fig. 7 was determined. The sets of the parameters for which the absolute value of the slope was within the range 0.4–0.6 at all pressures were selected as possible candidates for the subsequent analysis from the point of view of agreement with the physical sense; this was done allowing for the results of the Hall effect measurements of the density of electrons in GaAs at room temperature and under normal pressure.

We were able to establish a correlation between the oscillation number and an integer representing the number of halves of the lattice constant for both signs of the bias voltage and at all pressures if we assumed the following parameters: $N_d = (16\text{–}19) \times 10^{18}$ cm^{-3}, $E_b(p=0) = 0.7\text{–}0.8$ eV, and $n_e(p=0) = (8\text{–}9) \times 10^{18}$ cm^{-3}. These values agreed well both with the results of the Hall-effect determination of the electron density at room temperature ($\approx 8 \times 10^{19}$ cm^{-3})

and with the direct determination of the concentration of Te in our sample carried out by x-ray microanalysis (this was done after the above calculations by A. B. Ormont, to whom the authors are grateful), which gave 1.85×10^{19} cm^{-3}, and alos with the value $N_d \approx 1.8\times10^{19}$ cm^{-3}, deduced from the tunnel current-voltage characteristics of a similar sample and reported in Ref. 1.

The role of the DX levels formed by the Te atoms in the dependence of the amplitude of the oscillations on the illumination is as follows. Cooling of a heavily doped sample of n-GaAs from room to low temperatures results in metastability of the state of the electrons captured by the DX centers. Illumination of the semiconductor enables these electrons to overcome a potential barrier that separates them from the delocalized states and converts Te into an ordinary positively charged donor. The result is an increase in the amplitude of the fluctuations of the potential so that the oscillations become stronger. This explanation relates the observations to the change in the charge state of the DX centers and their displacement in the lattice on removal of an electron.[8]

In view of the roughness of our model (particularly because we are ignoring the change in the barrier transparency and the energy distribution of the tunneling electrons), the degree of the agreement with the dashed line in Fig. 7 achieved in this way can be regarded as quite satisfactory.

It should be pointed out that the idea of the periodicity of the contribution of randomly distributed substitutional impurities after averaging over a sufficiently large area along crystal planes had been used earlier to account for the oscillatory behavior of the d^2I/dV^2 curves recorded at high bias voltages ($\approx$650–750 mV) for n-GaAs/Au junctions made of a lightly doped material (Ref. 12).[1)] The appearance of the peaks was attributed in Ref. 12 to a major change in the Schottky-barrier transparency when a deep level formed by the impurities located in the barrier region coincides with the Fermi level. However, this mechanism of resonant tunneling is sensitive to the inhomogeneous broadening of the level participating in the resonance by impurity-potential fluctuations (of the type considered in Ref. 7) which should suppress the oscillations completely. Moreover, in the strong field of the barrier the impurity levels should be empty and their filling cannot change under the influence of illumination. Finally, the level positions (70 and 400 meV) calculated in Ref. 12 do not agree with the energy of any known impurity levels in GaAs. Therefore, we do not find sufficient grounds for invoking the resonant tunneling model in interpretation of our results.

On the other hand, we tried to treat the results of Ref. 12 by our method assuming the value $5.65\times3^{-1/2} = 3.38$ Å for the interplanar distances along the [111] direction, in combination with the values of the electron density given in Ref. 12. We varied the barrier height between the permissible limits 0.8–1.3 eV. However, this failed to give satisfactory results.

In view of this, we are justified in assuming that a new type of oscillations of the tunnel conductance had been observed and these oscillations are stimulated by illumination and are related to the nature of the DX centers in n-GaAs.

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[1]A. Ya. Shul'man, I. N. Kotel'nikov, A. N. Voronovsky *et al.*, *Proc. Twentieth Intern. Conf. on Physics of Semiconductors, Thessaloniki*, 1990 (ed. by E. M. Anastassakis and J. D. Joannopoulos), Vol. 2, World Scientific, Singapore (1990), p. 1242.

[2]I. N. Kotel'nikov, I. L. Beĭnikhes, and A. Ya. Shul'man, Fiz. Tverd. Tela (Leningrad) **27**, 401 (1985) [Sov. Phys. Solid State **27**, 246 (1985)].

[3]A. N. Voronovskiĭ, E. M. Dizhur, and E. S. Itskevich, Zh. Eksp. Teor. Fiz. **77**, 1119 (1979) [Sov. Phys. JETP **50**, 564 (1979)].

[4]Y. F. Tsay, S. S. Mitra, and V. Bendow, Phys. Rev. B **10**, 1476 (1974).

[5]*Tunneling Phenomena in Solids (Proc. NATO Advanced Study Institute, Risø, Denmark*, 1967, ed. by E. Burstein and S. Lundqvist), Plenum Press, New York (1969).

[6]I. M. Lifshitz and V. Ya. Kirpichenkov, Zh. Eksp. Teor. Fiz. **77**, 989 (1979) [Sov. Phys. JETP **50**, 499 (1979)].

[7]M. É. Raĭkh and I. M. Ruzin, Zh. Eksp. Teor. Fiz. **92**, 2257 (1987) [Sov. Phys. JETP **65**, 1273 (1987)].

[8]P. M. Mooney, *Proc. Twentieth Intern. Conf. on Physics of Semiconductors, Thessaloniki*, 1990 (ed. by A. M. Anastassakis and J. D. Joannopoulos), Vol. 3, World Scientific, Singapore (1990), p. 2600.

[9]J. C. Portal, D. K. Maude, T. J. Foster *et al.*, Superlattice Microstruct. **4**, 33 (1988).

[10]J. W. Conley and G. D. Mahan, Phys. Rev. **161**, 681 (1967).

[11]A. Ya. Shul'man and V. V. Zaitsev, Solid State Commun. **18**, 1623 (1976).

[12]A. P. Kovchavtsev, G. L. Kuryshev, K. O. Postnikov *et al.*, Fiz. Tekh. Poluprovodn. **21**, 1944 (1987) [Sov. J. Semiconductors **21**, 1178 (1987)].

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