Tunneling, accompanying plasma reflection of radiation, in metal-semiconductor junctions with a self-consistent Schottky barrier

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The previously discovered [Pis'ma Zh. Eksp. Teor. Fiz. **44**, 234 (1986)] photoresistive effect in n-GaAs/Au tunnel junctions, which arises as a result of the laser-radiation pressure exerted on the free-carrier plasma in the semiconductor in the presence of plasma reflection, was investigated experimentally. Under these conditions the tunneling conductivity increases and the photoresponse duplicates the form of the laser pulse with characteristic times $\leqslant 10^{-8}$ sec. Comparative analysis of the pulsed photoresponse at wavelengths of 10, 90, and 385 μm in n- and p-GaAs tunnel junctions made it possible to prove that the presence of plasma reflection is a necessary condition for the existence of the effect. The fast photoresistive response was measured as a function of the bias voltage on the tunnel junction with different electron densities [$(2\text{–}4)\cdot 10^{18}$ cm^{-3}] in n-GaAs. It follows from this dependence, in particular, that the heating of the electrons by the radiation can be eliminated. Formulas are derived for the response of a tunnel junction due to deformation of the Schottky barrier by the ponderomotive force of the electromagnetic wave. It is shown that the bias-voltage dependence of the photoresponse and other characteristic features of the observed effect can be understood on the basis of this theoretical model.

INTRODUCTION

A metal-semiconductor tunnel junction with a Schottky barrier is a structure in which the form of potential barrier and therefore the tunneling current depend significantly on the profile of the self-consistent distribution of electrons in the semiconductor.[1,2] Under ordinary conditions this distribution is established by the electric field generated by charged impurities and surface states at the boundary with the metal, and the equilibrium position of the boundary of the electron gas corresponds to the balance of forces acting on each element of volume of the electron plasma due to the presence in the plasma of a gradient of the electron pressure and of the electric field. When this balance is disrupted by an external perturbation, the plasma boundary is displaced and the shape of the potential barrier changes. The change in the shape of the potential barrier can be recorded from the change in the tunneling conductivity of the junction. The external perturbation can be the radiation-pressure force arising in the case of plasma reflection of light from the electrons of the semiconductor. Together with the change in the conductivity of the tunnel junction (photoresistive effect), there should also arise a nonstationary photo-emf owing to charge transfer between the semiconductor and the metallic electrodes, which accompanies the displacement of the plasma boundary and is equivalent to a change in the capacitance of the depletion layer.

The effect described above was predicted in Ref. 3, and the observation of the photoresistive effect in n-GaAs/Au tunnel junctions under the action of radiation in the region of the plasma reflection at the wavelength $\lambda = 90.55$ μm, which was greater than the wavelength λ_p corresponding to the plasma minimum in the reflection spectrum of n-GaAs, was reported in Ref. 4.

The present work is devoted to an experimental investigation and analysis of the observed photoeffect as well as to qualitative experiments confirming the photoresponse mechanism under study. The samples and experimental procedure are described in Sec. 1. In Sec. 2 the possible mechanisms leading to the appearance of the photoresistive effect in metal-semiconductor tunnel junctions are discussed and qualitative experiments confirming that the observed photosignal is related to deformation of the self-consistent Schottky barrier accompanying plasma reflection of the incident radiation are described. The results of an experimental investigation of the photoeffect in n-GaAs/Au junctions under the conditions of plasma reflection are presented in Sec. 3. In Sec. 4 the basic elements of the theoretical analysis of the photoresistive effect in a model of a radiation-pressure-deformed self-consistent Schottky barrier are presented and a theoretical estimate of the response is given. In Sec. 5 the experimental data on the effect of the carrier density and wavelength of the incident radiation on the photoresistive effect and the experimental data on the dependences of the photoresponse on the bias voltage on the junction and the radiation intensity are compared with the theory.

1. SAMPLES AND EXPERIMENTAL PROCEDURE

We investigated GaAs/Au tunnel junctions prepared by vacuum ($\approx 10^{-10}$ mm Hg) sputtering of metal on clean n- and p-GaAs substrate surfaces. Prior to sputtering the surface of the substrates was cleaned by heating at 550 °C and checked using Auger spectra.[2] The impurity concentration in GaAs was varied in the range $(1\text{–}7)\cdot 10^{18}$ cm^{-3}. As should happen at such free-carrier densities, a pronounced plasma minimum was observed in the reflection spectra of n-

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TABLE I. Parameters of substrates for GaAs/Au tunnel junctions.

Sample	Type of conductivity	Impurity concentration, 10^{18} cm^{-3}	λ_p, μm
3094	n	1,8	20
ГМ-1	n	2,2	– *
180,5	n	3,7	16,5
1446	n	7,0	11,5
К-1-18	p	1,0	– *
4031	p	6,0	– **

*The reflection spectrum was not measured.
**The plasma minimum was not present in the reflection spectrum.

GaAs substrates, while the spectra of p-GaAs did not have a plasma minimum. Table I gives the Hall data on the impurity concentrations and the experimental values of λ_p for the samples studied. The samples were $\approx 10\times 10$ mm^2 GaAs wafers ≈ 1 mm thick. An ohmic and a gold electrode were placed on opposite sides of the substrate (see Fig. 1). The semitransparent gold electrode was $\leqslant 200$ Å thick and 1 or 0.25 mm in diameter (as a rule, three to five tunnel junctions were prepared on a single substrate). The measurements of the tunneling spectra (performed at liquid-helium temperatures) of the junctions prepared showed that tunneling charge transfer between GaAs and Au occurs in the samples.[2]

Discrete laser lines in the range $\lambda \approx 10$–400 μm were utilized in order to realize in the same n-GaAs sample the conditions of presence of absence of plasma reflection in the investigations of the photoresponse. The radiation source in the region $\lambda > \lambda_p$ was an optically pumped, pulsed, submillimeter NH_3 and D_2O vapor laser (pulse width $\tau_d \approx 40$ ns, $\lambda = 90.55$ and $385\,\mu$m);[5] in the region $\lambda < \lambda_p$ ($\lambda = 9.2$–10.8 μm) a Q-switched CO_2 laser ($\tau_d \approx 500$ ns) and a TEA-CO_2-laser ($\tau_d \approx 100$ ns) were used as the radiation sources. In the measurements of the photoresponse the shape and intensity of the laser pulse in both ranges were checked with the help of fast detectors based on the photon drag effect.[6,7]

The photo-emf and photoconductivity of GaAs/Au tunnel structures were studied at 300 and 78 K. The measuring channel had a time resolution of ≈ 7 ns. The radiation was directed from the side of the semitransparent gold electrode along the normal to the surface of the sample, which was inserted into the photoconductivity-measuring circuit (see Fig. 1). In this scheme the change $\Delta\sigma$ in the conductivity $\sigma = I/V$ of the tunnel junction during the action of the laser pulse results in a change ΔV_L in the voltage V_L on the load resistor R_L. Since the experimental junctions have nonlinear current-voltage and capacitance-voltage characteristics, a special analysis was required in order to determine from the measured pulsed signal ΔV_L the quantity $\Delta\sigma/\sigma|_{V=\text{const}}$, of interest to us, at a specified voltage V. This problem is solved in Appendix 1 in the linear approximation for the case $\Delta\sigma/\sigma \ll 1$.

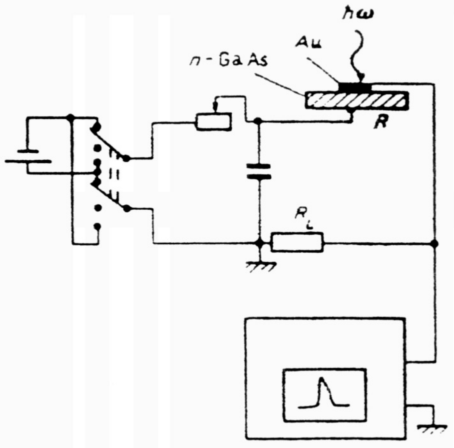

FIG. 1. Setup for measuring the photoresponse of GaAs/Au tunnel junctions to pulsed laser radiation.

2. DETERMINATION OF THE PHYSICAL NATURE OF THE PHOTORESPONSE. QUALITATIVE EXPERIMENTS

As we have already mentioned in the Introduction, the fast photoresistive effect occurring when n-GaAs/Au tunnel junctions are exposed to far-IR radiation was discovered in Ref. 4. The junction conductivity can be changed under these conditions by several possible mechanisms. We first discuss the change induced in the shape of the barrier by the light pressure. A necessary condition for this mechanism to appear is plasma reflection of the incident radiation in the region of formation of a self-consistent barrier. This leads to the appearance of a force acting on the free-carrier plasma in a direction perpendicular to the junction plane. The electrons are redistributed in space in this process in a time of the order of the inverse plasma frequency ω_p^{-1} of the semiconductor (for n-GaAs $\omega_p^{-1} \approx 5\cdot 10^{-15}$ sec for the electron densities employed), and a photoresponse should appear for any polarity of the bias voltage.

The conductivity of the tunnel junction can also change as a result of transfer of radiation energy to the electrons and the lattice upon absorption by free carriers, and as a result the temperature of the entire junction (or only of the electrons in the semiconductor) changes. The kinetics of this process, in contrast to the previously discussed mechanism, in the case of lattice heating, should be determined by the time within which the temperature of the illuminated region is established by heat conduction. In our case this time should be of the order of $\tau_{\text{th}} \approx 10^{-4}$–$10^{-2}$ sec,[8] while in the case when the electrons are heated the kinetics of the process is determined by the electron energy relaxation time ($\tau_e \approx 10^{-11}$–10^{-12} sec).[9] For lattice heating, a photosignal should appear for any polarity of the bias voltage on the junction. For electron heating, the photoresponse $\Delta\sigma/\sigma$ should be significant only at positive bias $V \geqslant 0$ and should drop off rapidly for $V < 0$, when the carriers tunnel from the metal electrode into the semiconductor and the dependence of the junction conductivity on the electron temperature in the semiconductor becomes much weaker, since $\Delta\sigma/\sigma \propto \exp(eV/E_0)$ for $V<0$ (see Appendix 2). According to these estimates, in the case of n-GaAs/Au with $N=2\cdot10^{18}$ cm^{-3} the quantity $\Delta\sigma/\sigma$ with $V=-300$ mV should be $\exp(10)$ times smaller than with $V\geqslant0$.

Thus is can be expected that by using in the experiment narrow radiation pulses with width $\tau_d<\tau_{th}$ it will be possible to separate the lattice heating mechanism from electronic processes. The change in σ with heating of the electrons should differ from the response due to barrier deformation under radiation pressure by the dependence on the bias voltage in the region $V<0$.

The experiments showed that the fast photoresponse, duplicating the shape of the laser pulse with $\tau\approx40$ nsec, was observed only in structures based on n-GaAs under the action of radiation with $\lambda>\lambda_p$ ($\lambda=90.55$ and 385 μm) for both polarities of the bias voltage, i.e., when plasma reflection occurred. In all other cases, i.e., in the case of n-GaAs with $\lambda<\lambda_p$ ($\lambda=9.2$–$10.8\,\mu$m) or for tunnel junctions based on p-GaAs, for which plasma reflection did not occur, only a slow response with $\tau\gg\tau_d$ was observed at all wavelengths.

We note that the fast photoresponse was observed only under conditions when a region of n-GaAs bounded by the area of the gold electrode (see Fig. 2) was irradiated, and the fact that the existence of a fast response for $\lambda>\lambda_p$ is not related with the illumination of the boundary of the gold electrode was specially checked. It follows from these data that the fast response exists only under conditions of plasma reflection in the region of the tunnel junction. The fact that the fast response is not related to lattice heating follows from its kinetics, since $\tau\ll\tau_{th}$. Electron heating can also be excluded, since the observed photosignal has a significant strength for $V<0$, when the electrons tunnel from the metal into the semiconductor. For example, the experimentally observed decrease of the signal when the bias voltage changes from $V\approx0$ to -300 mV is by a factor of ≈5, while according to the formulas of Appendix 2, in the case when the electrons are heated it should be equal to $\approx2\cdot10^4$.

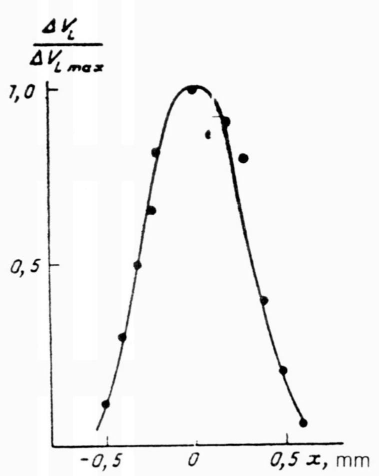

FIG. 2. Amplitude of the photoresistive response, normalized to its maximum value, as a function of the coordinate x of the position of the center of a focused 0.7 mm in diameter Gaussian beam relative to the center of the gold electrode (diameter 1 mm). n-GaAs/Au sample with $N=2\cdot10^{18}$ cm^{-3}, $\lambda=90.55$ μm.

Thus the data presented make it possible to exclude heating effects and associate the observed fast response to deformation of the self-consistent Schottky barrier accompanying transfer of the radiation momentum to the electron plasma.

3. CHARACTERISTICS OF THE PHOTORESISTIVE EFFECT

As we have already mentioned, a photoresistive response in n-GaAs/Au junctions is observed in the case of plasma reflection of light with $\lambda>\lambda_p$. The sign of the photoresponse corresponds to an increase in the tunneling conductivity of the junction under the action of the radiation. This does not fit into the simple picture in which the light pressure displaces the electron plasma of the semiconductor away from the surface. We measured the dependence of the photoresistive effect on the bias voltage and we also studied the effect of the impurity concentration, the temperature, and the wavelength and intensity of the light on the effect. The dependence of ΔV_L on the bias voltage V was measured at relatively low radiation intensities (≈40 kW/cm^2), when there was no nonstationary photo-emf signal with $V=0$ (see below). We investigated n-GaAs/Au junctions with donor concentration $N=(2$–$3.7)\cdot10^{18}$ cm^{-3} at temperatures 78 and 300 K and laser-radiation wavelengths 90.55 and 385 μm. The measured values of ΔV_L were converted to $\Delta\sigma/\sigma_{V=\text{const}}$ according to the formula

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{V=\text{const}}=\frac{\Delta V_L}{V_L(1+R_L/r_d)}$$

[see Eq. (A1.8) from Appendix 1].

The dependence of the relative response on the bias voltage V_b in the fixed-voltage regime for a sample with $N\approx2\cdot10^{18}$ and $3.7\cdot10^{18}$ cm^{-3} at $T=300$ K and with $\lambda=90.55$ μm is presented in Fig. 3. One can see that in the region $V<0$ the quantity $\Delta\sigma/\sigma_{V=\text{const}}$ decreases as $|V|$ increases, and for positive biases this quantity remains virtually constant. The character of the dependences of $\Delta\sigma/\sigma$ on V and the strength of the response do not change significantly as the temperature decreases and the wavelength increases.

Measurements of the amplitude of the photoconductivity signal as a function of the intensity J ($\leqslant2$ MW/cm^2) of laser radiation with $\lambda=90.55$ μm showed that the amplitude of the signal increases somewhat more rapidly than the first power of the intensity. The characteristic curve of $\Delta\sigma/\sigma_{V=\text{const}}$ versus J was not determined, because the fact that $\Delta\sigma/\sigma$ increases up to values of the order of unity with increasing intensity makes the linear relation, which we employed, between $\Delta\sigma/\sigma$ and the measured signal ΔV_L inapplicable, while our measurement scheme made it impossible to fix the bias voltage V during the pulse because of the low resistance of the tunnel junctions.

Besides the photoconductivity, a nonstationary sign-alternating photo-emf was also observed. Its observation was possible with zero bias or small values of V, when the photoconductivity signal is weak. Characteristic oscillograms are presented in Figs. 4b–d. One can see that there is a great diversity of shapes of the signal observed in the region $V\approx0$. A possible explanation of this phenomenon is the combined effect, studied in the Appendix 1, of the change in the charge

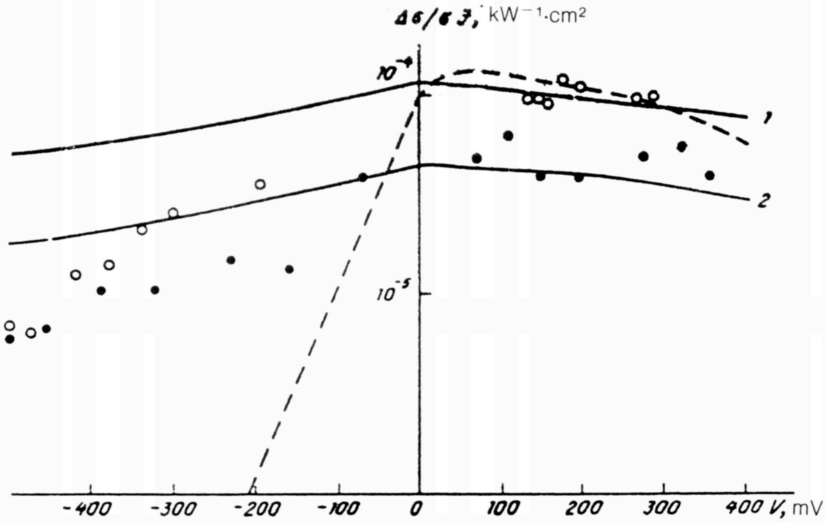

FIG. 3. $\Delta\sigma/\sigma J$ in the fixed-voltage regime as a function of the bias voltage V on the n-GaAs/Au junction at $T = 300$ K for $\lambda = 90.55$ μm; $N = 2\cdot 10^{18}$ cm^{-3} (○) and $N = 3.7\cdot 10^{18}\,\text{cm}^{-3}$ (●). Solid lines—calculation of $\Delta\sigma/\sigma$ as a function of V for the photoresistive effect under conditions of plasma reflection using the formula (4.7). Parameters used in the calculation: $\Phi_s = 0.9$ eV, $T = 300$ K, $N = 2\cdot 10^{18}$ cm^{-3} (curve *1*), and $3.7\cdot 10^{18}$ cm^{-3} (curve *2*). In constructing the plots both theoretical curves were multiplied by 60. Dashed line—the response (in arbitrary units) for the case when the semiconductor electrons are heated by the incident radiation, as calculated according to Eq. (A2.8).

of the depletion layer and the tunneling conductivity under the action of the radiation on the form of the response. In order to check this proposition, we approximated the shape of the laser pulse as follows (see Fig. 4a′):

$$J(t) = \begin{cases} J_0 \dfrac{1-\exp(-t/\tau_1)}{1-\exp(-t_0/\tau_1)}, & 0\leqslant t\leqslant t_0 \\ J_0 \exp[-(t-t_0)/\tau_2], & t\geqslant t_0 \end{cases},$$

and we employed Eq. (A1.6) to obtain the form of the response for small biases on the junction. Figures 4b′–d′ show

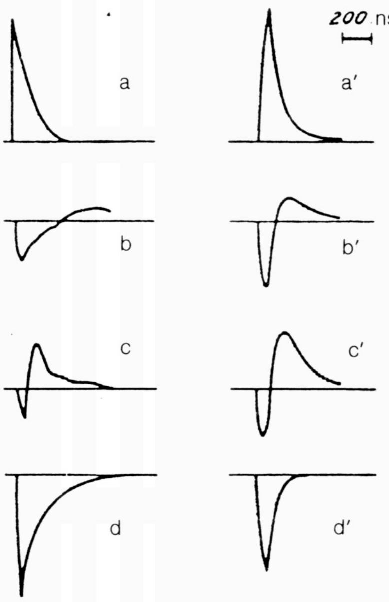

FIG. 4. Pulsed photoresponse under conditions of plasma reflection (n-GaAs/Au sample, $\lambda = 90.55$ μm) for bias voltage on the tunnel junction $V \approx 0$ (a–d, experiment; a′–d′, calculations). a) Shape of the radiation pulse, measured with the help of a photodetector based on photon drag of electrons;[6] b–d) experimentally observed oscillograms of photosignals from the sample with $V = 0$; a′) shape of the pulse $J(t)$ employed in the calculation (see text); b′–d′) model calculation of the response of the J-dependent nonlinear resistor and capacitor connected in parallel to a weak perturbation $J(t)$ (see text) with bias voltages on the nonlinear element $U = 0$, 0.5, and -0.5 mV, respectively. The parameters employed in the calculation are: $\Phi_s = 0.9$ eV, $C_d = 3\cdot 10^{-9}\,\Phi$, $R_L = 50\,\Omega$, $R = r_d = 100$ Ω, $(1/\sigma)(\partial\sigma/\partial J) = 1\cdot 10^{-4}\,\text{kW}^{-1}\cdot\text{cm}^2$, $(1/Q)(\partial Q/\partial J) = -1.4\cdot 10^{-8}$ $\text{kW}^{-1}\cdot\text{cm}^2$.

the computed form of the response for bias voltages on the junction $V = 0$, 0.5, and -0.5 mV, respectively. The experimentally determined values of the parameters C_d, V', R, r_d, and

$$\frac{1}{\sigma}\frac{\partial\sigma}{\partial J} \approx \frac{\Delta\sigma}{\sigma}\frac{1}{J}.$$

were utilized in the calculation. The value of the parameter $(1/Q)(\partial Q/\partial J)$ was adjusted to obtain the best description of the observed pulse shape and was equal to $\approx -1.5\cdot 10^{-8}$ $\text{kW}^{-1}\cdot\text{cm}^2$. One can see from Fig. 4 that the shape of the pulses which were observed in the experiment in the absence of a prescribed bias is in good agreement with the curves calculated in the presence of a small bias. From this it follows that the diversity of pulse shapes observed in the experiment in the absence of bias could be related to the presence of random potentials of small amplitude and different polarity, caused, for example, by rectification of the electric interference, thermal relaxation, etc., on the junction during the action of the light pulse. Since the constant bias on the junction during the period of action of the laser pulse was measured with an accuracy of ≈ 1 mV, the available experimental data are consistent with the proposed explanation of the diversity of pulse shapes at zero bias.

For large biases $|V| > 100$ mV the computed shape of the response is identical to the shape of the laser pulse, as in the experiment.

Thus the phenomenological theory proposed in Appendix 1 for the response of a tunnel junction to laser radiation made it possible not only to derive formulas for quantitative analysis of measurements, but also to explain qualitatively the experimentally observed large spread in the shape and strength of the response with zero bias.

4. THEORETICAL CALCULATION OF THE RESPONSE IN THE MODEL OF DEFORMATION OF A SELF-CONSISTENT SCHOTTKY BARRIER BY RADIATION PRESSURE

We now present, following Ref. 10, the basic elements of the theoretical analysis of the photoresistive effect in the model of a radiation-pressure-deformed self-consistent Schottky barrier. Let a degenerate electron gas (see Fig. 5) occupy the half-space $x < 0$ to the left of the semiconductor-metal boundary. The point x_0, determined by the condition

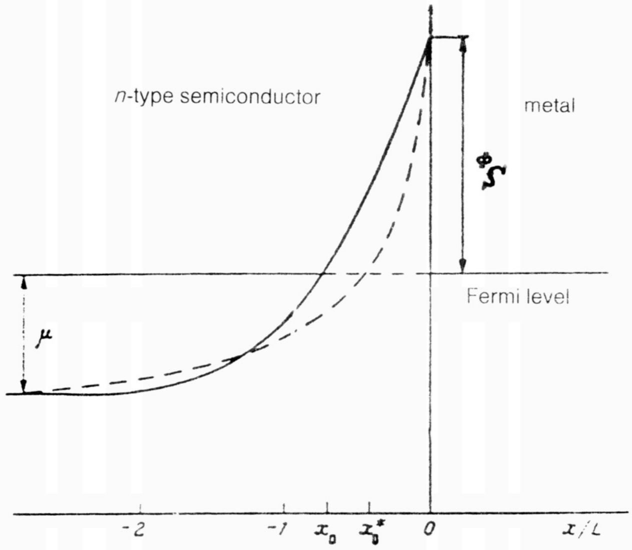

FIG. 5. Schematic diagram of the scalar potential in the depletion layer of a tunnel junction with a Schottky barrier. The solid line corresponds to the case of no radiation; x_0 is the distance from the boundary of the plasma to the surface of the semiconductor. The dashed line corresponds to the case when plasma reflection of the radiation occurs; x_0^* is the new position of the boundary of the degenerate plasma and corresponds to an increase in the tunneling conductivity under the action of the radiation.

$\Phi(x_0)=\mu$, where $\Phi(x)$ is the potential energy of an electron and μ is the Fermi energy, is the equilibrium position of the boundary of the electron gas, corresponding to the balance of forces acting on each element of the volume of the electron plasma. If an electromagnetic plane wave, whose frequency ω is much smaller than the plasma frequency ω_p of the electrons, is incident on the electron gas from the right, then reflection of radiation is accompanied by transfer of momentum to the electronic subsystem. This should result in the appearance of an additional force acting on the plasma, which in turn is accompanied by displacement of the equilibrium position and perturbation of the shape of the plasma boundary. As a result, the shape of the potential barrier changes and correspondingly the resistance of the tunnel junction should change.

In order to find this change, we consider the condition of equilibrium of the plasma in a static electric field of the depletion layer, taking into account the pressure of the electron gas and of the radiation incident in a direction normal to the surface. Neglecting scattering of electrons (under the conditions of the experiment the frequency ω is quite high) the decay depth of the alternating field in the semiconductor under conditions of plasma reflection is determined by the screening of the vector potential of the wave by the induced current (skin effect) and is equal to $L_\perp = c^*/\omega_p$. It is significantly greater than the characteristic length of the depletion layer

$$L=(\varkappa\Phi_b/2\pi Ne^2)^{1/2}\equiv v_b/\omega_p,$$

and all the more than the characteristic Thomas–Fermi linear-screening length for the longitudinal field

$$l_{TF}=(\varkappa\mu/6\pi Ne^2)^{1/2}\equiv 3^{1/2}v_F/\omega_p,$$

where $\varkappa$ is the lattice permittivity of the semiconductor, N is the concentration of ionized impurities, v_F is the Fermi velocity of free carriers in the semiconductor, v_b is the velocity of an electron with energy $\Phi_b=\Phi_s+\mu$ (see Fig. 5), and $c^*=c/\varkappa^{1/2}$ is the velocity of light in the semiconductor. For $N=2\cdot 10^{18}$ cm^{-3} we have $\mu\approx 80$ meV, $v_F\approx 5\cdot 10^7$ cm/sec, $\varkappa=12.5$, and, setting $\Phi_b=1$ eV, we obtain

$$\frac{L_\perp}{L}=\frac{c^*}{v_F}\frac{\mu}{\Phi_b}\approx 14,\qquad \frac{L_\perp}{l_{TF}}=\frac{c^*}{3^{1/2}v_F}\approx 100.$$

Therefore it can be assumed that the amplitude of the electric field E_1 of the wave in the depletion region is constant and that in the bulk of the semiconductor $E_1\to 0$ as $x\to-\infty$.

We obtain the condition of equilibrium of the electron plasma from the hydrodynamic equation of momentum balance for electrons:[11]

$$mn\frac{d\mathbf{u}}{dt}=-\nabla p-ne\mathbf{E}-n\frac{e}{c}[\mathbf{uH}]-mn\frac{\mathbf{u}}{\tau}. \qquad (4.1)$$

Here $\mathbf{H}$ is the magnetic field of the wave, m is the effective mass, $n(x)$ is the density, $p(x)$ is the pressure, $\mathbf{u}(x,t)$ is the drift velocity, and τ is the momentum relaxation time of the electrons. We utilize the fact that the expression for the density of the force $\mathbf{F}_{em}(\mathbf{r},t)$, exerted by the electromagnetic field on charges with density $\rho(\mathbf{r},t)$ and currents with density $\mathbf{j}(\mathbf{r},t)$, can be represented as a divergence of the Maxwell stress tensor $T_{ik}(\mathbf{r},t)$:[12]

$$F_{em,i}(\mathbf{r},t)\equiv\rho E_i(\mathbf{r},t)+\frac{1}{c}[\mathbf{jH}(\mathbf{r},t)]_i\equiv\frac{dT_{ik}}{dx_k}. \qquad (4.2)$$

Here we dropped the term

$$\frac{\varkappa}{4\pi c}\frac{\partial}{\partial t}[\mathbf{EH}],$$

which under our conditions is $(\omega/\omega_p)(L_\perp/c^*\tau_d)\approx 10^{-6}$ times smaller than the term retained (for radiation pulse widths $\tau_d>1$ nsec, $L_\perp\approx 0.5\ \mu$m and $\omega/\omega_p\leqslant 1/4$).

Setting $\rho=e[N-n(x)]$ and $j=-en\mathbf{u}$ and using Eq. (4.2), the right-hand side of Eq. (4.1) can be put into the form

$$mn\frac{d\mathbf{u}}{dt}=\mathbf{F}(x,t)-mn\frac{\mathbf{u}}{\tau}, \qquad (4.3a)$$

where

$$F_i(x,t)=-\nabla_i p-eNE_i+\frac{dT_{ik}}{dx_k}. \qquad (4.3b)$$

Setting now

$$\mathbf{E}(x,t)=\mathbf{E}_{st}(x)+\mathbf{E}_1(x)\cos(\omega t),\quad \mathbf{H}(x,t)=-\mathbf{H}_1(x)\sin(\omega t)$$

and averaging Eq. (4.3a) over the period of the high-frequency field, we obtain the condition of equilibrium of a collisionless plasma in the form $\overline{F}_x=0$ (the overbar indicates time-averaging). Integrating this equality from $-\infty$ up to the point x in the depletion layer ($x_0\leqslant x\leqslant 0$) we find that the total force acting on the plasma is equal to zero:

$$p(-\infty)-N\Phi(x)+\overline{T}_{xx}(x)=0. \qquad (4.4)$$

Here we took into account the fact that $p(x)=\overline{T}_{xx}(-\infty)=0$ and $-eE_{st}(x)=-d\Phi/dx$, where $\Phi(x)=-e\varphi(x)$ is the potential energy of an electron in the electrostatic potential $\varphi(x)$. Since for the geometry chosen ($\mathbf{E}_1\|0y$, $\mathbf{H}_1\|0z$)

$$\bar{T}_{xx}(x)=\frac{1}{8\pi}\left(\varkappa E_{st}^2-\frac{\varkappa}{2}|E_1|^2-\frac{1}{2}|H_1|^2\right),$$

and the amplitude H_1 of the magnetic field, decaying as $\exp(kx)$ with $k=(\omega/c)[\varkappa(\omega_p^2/\omega^2-1)]^{1/2}$ into the plasma, can be expressed with the help of the first Maxwell equation

$$\operatorname{rot}E=-\frac{1}{c}\frac{\partial H}{\partial t}$$

in terms of E_1 by the relation

$$H_1=[\varkappa(\omega_p^2/\omega^2-1)]^{1/2}E_1,$$

we obtain

$$\bar{T}_{xx}(x)=\frac{\varkappa}{8\pi}E_{st}^2(x)-\frac{\varkappa}{16\pi}\frac{\omega_p^2}{\omega^2}|E_1(x_0)|^2.$$

It should be noted that in order to obtain the last formula we utilized the relation between the amplitudes H_1 and E_1, valid in the region where the field decays exponentially into the plasma. However, since the transverse components of the electromagnetic field are continuous and the thickness L of the depletion layer is small compared with the characteristic scales over which the radiation field alters $L_\perp$ and $\lambda/\varkappa^{1/2}$, this expression can be continued into the depletion layer; this, by the way, is also confirmed directly in the approximation of a sharp plasma boundary.

An equation for the static field E_{st} in the depletion layer in the presence of an electromagnetic wave can be derived from Eq. (4.4):

$$\frac{\varkappa}{8\pi}E_{st}^2(x)=N\Phi(x)-\frac{2}{5}N\mu+\frac{\varkappa}{16\pi}\frac{\omega_p^2}{\omega^2}|E_1(x_0)|^2. \quad (4.5a)$$

It is convenient to rewrite the balance equation (4.5a) by introducing the dimensionless energy $w=\Phi/\mu$ and length $\xi=x/l_s$, where $l_s=(v_F/\omega_p)/2$. We have

$$\left(\frac{dw}{d\xi}\right)^2\equiv w'^2(\xi)=w(\xi)-\frac{2}{5}+\frac{u(\xi)}{\mu}, \quad (4.5b)$$

where $u=e^2|E_1|^2/4m\omega^2$ is the high-frequency potential.[11]

In order to understand the consequences of the change in the field E_{st} in the Schottky barrier owing to the action of the radiation pressure, we examine the expression for the tunneling current[2]

$$I\propto\int_0^\infty dE[f(E)-f(E+V)]\exp\left[-\frac{2(2m)^{1/2}}{\hbar}\int_{x_E}^0 dx(\Phi(x)-E)^{1/2}\right].$$

Here x_E is the turning point of the trajectory of an electron incident with energy E on the barrier. We denote the argument of the exponential by $-G$ and transform it by switching to dimensionless variables and using Eq. (4.5b):

$$G(\varepsilon,w_b,u)\equiv\frac{2(2m)^{1/2}}{\hbar}\int_{x_E}^0 dx(\Phi(x)-E)^{1/2}$$

$$=\frac{2(2m)^{1/2}}{\hbar}\int_E^{\Phi_b} d\Phi\frac{(\Phi-E)^{1/2}}{\Phi'}$$

$$=2k_Fl_s\int_\varepsilon^{w_b} dw\left(\frac{w-\varepsilon}{w-2/5+u(x_0)/\mu}\right)^{1/2}. \quad (4.6)$$

In Eq. (4.6) k_F is the Fermi wave vector and $\varepsilon\equiv E/\mu$. The last expression in Eq. (4.6) is written for the energy range of $\varepsilon\geqslant1$.

The change occurring in the current I when the tunnel junction is irradiated is related to the change in the argument of the exponential $\delta G=G(\varepsilon,w_b,u)-G(\varepsilon,w_b,0)$:

$$\Delta I=\int_0^\infty dE[f(E)-f(E+eV)][\exp[-(G+\delta G)]-\exp(-G)],$$

so that in the approximation linear in δG the relative response can be written as

$$\left.\frac{\Delta I}{I}\right|_{V=\mathrm{const}}=\left.\frac{\Delta\sigma}{\sigma}\right|_{V=\mathrm{const}}=\frac{-\int_0^\infty dE\,\delta G(f(E)-f(E+eV))e^{-G}}{\int_0^\infty dE(f(E)-f(E+eV))e^{-G}}, \quad (4.7)$$

where $\sigma=I/V$.

In order to make an analytical estimate we utilize the fact that at low temperatures the tunneling integrals are determined mainly by the values of the integrands at the energy of the highest filled state. For this reason, the function $\delta G(E)$, which is not an exponential function of the energy, can be taken outside the integral sign in Eq. (4.7) at

$$E_{max}=\begin{cases}\mu, & V>0\\ \mu-eV, & V<0\end{cases}.$$

If it is assumed that in the presence of radiation the surface barrier Φ_s for electrons in the metal remains constant, then at a constant bias voltage V the barrier height $\Phi_b=\Phi_s+\mu-eV$ remains constant. Then, since the high-frequency potential remains virtually constant in the region of the depletion layer ($L_\perp\gg L$), we obtain from Eq. (4.6) an estimate of the change δG of the barrier transparency in the linear approximation in u:

$$\delta G(E_{max})\approx-k_Fl_s\frac{u}{\mu}\int_{\varepsilon_{max}}^{w_b} dw\frac{(w-\varepsilon)^{1/2}}{(w-2/5)^{3/2}}. \quad (4.8)$$

After integrating in Eq. (4.8) we find

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{V=\mathrm{const}}\approx-\delta G(\varepsilon_{max})\approx2k_Fl_s\frac{u}{\mu}\psi(\varepsilon_{max}), \quad (4.9)$$

where

$$\psi(\varepsilon)=\ln\frac{(w_b-\varepsilon)^{1/2}+(w_b-2/5)^{1/2}}{(\varepsilon-2/5)^{1/2}}-\left(\frac{w_b-\varepsilon}{w_b-2/5}\right)^{1/2}. \quad (4.10)$$

We now estimate the order of magnitude of the relative response $\Delta\sigma/\sigma$, normalized to the intensity of the incident wave J. The relation between the high-frequency potential u at the boundary of the semiconductor plasma and the intensity J of the incident wave is found by solving the linear electrodynamic problem (for $\omega<\omega_p$):

$$u=\frac{1}{N}\frac{|E_{in}|^2}{4\pi}=\frac{1}{N}\frac{J}{c},$$

where E_{in} is the amplitude of the electric field of the incident wave.

Calculating $\psi(\varepsilon_{max})$ in Eq. (4.10) with $\varepsilon_{max}=1$, we find for the case of n-GaAs/Au and $N=2\cdot10^{18}$ cm^{-3}

$$\frac{\Delta\sigma}{\sigma J}\approx0{,}7\frac{m^{1/2}}{e\hbar c}N^{-1/2}\approx5\cdot10^{-6}\ \frac{\mathrm{cm}^2}{\mathrm{kW}}.$$

The obtained response is approximately 20 times weaker than the experimentally measured response. As shown in Ref. 13, the function $\psi(\varepsilon_{max})$ conveys the basic qualitative singularities of the dependence of the response on the bias voltage V. However, in order to determine more accurately the T and N dependence of $\Delta\sigma/\sigma$ which follow from the theoretical model examined above, we performed a numerical calculation of $\Delta\sigma/\sigma$ as a function of V according to the formula (4.7). The results of this calculation are also presented in Fig. 3. The nonparabolicity of the dispersion law of the electrons was taken into account in the two-band approximation. This is achieved by modifying appropriately the formula (4.6) (Ref. 2). In calculating the integrals in Eq. (4.7) the lower limit of integration over E was determined by the condition $E \geqslant \mu$ in order to exclude the contribution to the tunneling current from states lying below the Fermi level of the electrons in the semiconductor (see Fig. 5), where the problem of the perturbation of the barrier by the field of the radiation is more complicated and was not solved. We note also that the calculation for temperatures ≈ 50 K and below gives results which are practically identical to the analytical expression (4.9) for $\Delta\sigma/\sigma$.

5. DISCUSSION OF RESULTS AND CONCLUSIONS

The following qualitative singularities of the response follow from the theoretical expression for the response (4.9), derived in the model of deformation of the Schottky barrier by the radiation pressure: 1) the transparency of the barrier should increase under the action of the radiation, since in the formula (4.9) $\psi > 0$ for the physically admissible values of the parameters; 2) the magnitude of the response does not depend on the frequency of the radiation (if $\omega < \omega_p$); 3) the relative response depends weakly on the free-carrier density N, approximately as $1/N^{3/2}$. All these results are in agreement with the measurements. The computational result obtained for the response $\Delta\sigma/\sigma$ as a function of the bias V from the expression (4.7) in the model of a deformed Schottky barrier is shown in Fig. 3 (solid lines). One can see that the agreement with experiment here is much better than in the case of the calculation of the response as a function of the bias voltage according to the formulas (A2.8) with the electronic heating mechanism (dashed line).

It is helpful to shed more light on why the transparency of the tunneling barrier increases in the presence of radiation pressure, pushing the plasma of free carriers away from the surface. The point is that the force acting on an element of volume of the plasma is not a simple sum of the forces exerted by the external electro magnetic field on each electron. It includes also the interaction of the electrons through the self-consistent field. The existence of the plasma reflection is itself due to this interaction. For this reason, one can expect that although the radiation-pressure force acts on the entire carrier plasma as a whole in the direction away from the illuminated surface of the semiconductor, separate parts of the transitional layer of the plasma, where the electron density drops from the value in the bulk to zero, can move in the opposite direction, giving rise to deformation of the Schottky barrier and not simply increasing the width of the barrier. A detailed analysis of the behavior of the electrons and the radiation field in the transitional layer would require solving the nonstationary Vlasov kinetic equation in the nonuniform field of the barrier, which is a quite difficult problem. At the same time, the use of the momentum-balance equation and the Maxwell stress tensor makes it possible, as was shown above, to find exactly the change in the Schottky barrier in the depletion layer for energies $E \geqslant \mu$ without calculating explicitly the distribution of the fields and electrons in the volume of the semiconductor and to obtain a qualitative understanding of the nature of the effect.

As one can see from the expression (4.5a), the static electric field of the barrier $E_{st}(x)$ in the depletion layer increases everywhere in absolute magnitude in the presence of an electromagnetic wave. This relation is also valid at the semiconductor-metal interface, where we assume that always $\Phi(0) = \Phi_b$. Naturally, in the metal $E_{st} = 0$ always, and therefore in the presence of radiation the jump in the longitudinal field at the semiconductor-metal interface increases. Gauss' theorem implies that the surface charge increases at this boundary, and because the system as a whole is electrically neutral (the field in the bulk of the semiconductor is likewise always equal to zero) the positive space charge on the semiconductor side of the junction should increase by a corresponding amount. The latter increase is possible only if the majority of the electrons in the region of the space charge are pushed away from the surface of the semiconductor. This is in complete accord with the intuitively expected effect of radiation pressure. However, the increase in $E_{st}(x)$ at the point $x = x_0^*$ with a constant height Φ_b of the Schottky barrier results in a decrease of the thickness of the barrier at the Fermi level, since in the presence of radiation the point x_0^* where $\Phi(x_0^*) = \mu$ approaches the surface. This result can be easily derived explicitly from Eq. (4.5):

$$|x_0^*| \approx |x_0| - {}^5/_3{}^{1/2} l_s u/\mu.$$

The corresponding modification of the Schottky barrier by the radiation pressure is shown schematically in Fig. 5. Since the states near the Fermi level make the main contribution to the tunneling current, the resulting change in the tunneling conductivity is positive. We underscore the fact that the derivation of the expression (4.5a) rests on very general relations, whose validity requires only that the dynamics of the electrons in the field of a quasiclassical Schottky barrier and the incident electromagnetic wave be describable with the help of classical mechanics. The approximation of a sharp boundary of the semiconductor plasma enters only into the solution of the linear electrodynamic problem which relates the field in the incident wave to the field in the semiconductor. Making this solution more accurate, however, can affect only the quantitative estimate and not the sign of the effect.

It follows thus from the results presented that the main qualitative features of the observed fast photoresponse can be understood on the basis of the idea that the Schottky barrier becomes deformed when the laser radiation is reflected by the plasma of free carriers in the semiconductor.

It should be noted, however, that, as one can see from Fig. 3, the quantitative estimate of the magnitude of the response $\Delta\sigma/\sigma J$ according to the formula (4.7) gives for $V > 0$ a much smaller value than experiment. The variation of the response $\Delta\sigma/\sigma J$ for $V < 0$ likewise is not described completely correctly in the model of a deformed barrier (see Fig. 3).

It is possible that in order to understand the reasons for these discrepancies one would have to examine theoretically the effect of the field of the radiation not only on the shape of the Schottky barrier but also on the tunneling process itself. The theoretical calculation likewise ignores the fact that the Schottky barrier can be deformed not only by the transverse (vertical) electric field of the wave but also by the longitudinal field of the wave. The latter field can arise either because the angle of incidence deviates from normal or because the gold film adsorbed on the surface of the semiconductor is not uniform. It is well known that in experiments on second-harmonic generation when radiation is incident on the surface a metal (a phenomenon that is physically related to the photoresistive effect which we have investigated, since it is also quadratic in the amplitude of the wave; see, for example, Ref. 14), the normal component of the electric field is intensified at the adsorbate-vacuum interface. This could also increase the measured photoresponse.

The investigations performed indicate that the photoresistive effect can be used to detect intense pulsed far-IR and submillimeter laser radiation. Estimates of the sensitivity of such a detector on the basis of the experimental data obtained give the value $\approx 3\cdot 10^{-5}$ V·cm²/kW, which is comparable to the sensitivity of detectors based on the drag of carriers by photons,[6,7] while the planar technology for fabricating such junctions makes it possible to obtain small-diameter detecting elements, which could be very useful in applications.[15]

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APPENDIX 1

The stationary effect of radiation on a tunnel junction can change the total conductivity $\sigma(U,J)$ of the junction and the charge of the depletion layer $Q(U,J)$. In addition, the change in the charge of the depletion layer includes changes in both the capacitance of the junction and the height of the Coulomb barrier. If the intensity J of the radiation changes with characteristic time τ_d, then under the condition $\tau_d > \omega_p^{-1}$, which is known to hold in our case (radiation with frequency $\omega < \omega_p$ is employed), the quasistatic approximation can be used for $\sigma(t)$ and $Q(t)$, since the characteristic charge redistribution time in the junction with a fixed bias voltage is of the order of ω_p^{-1}. Then, in the linear approximation in the signal strength $v = U - U_0$ and the radiation intensity J we can write

$$\sigma(U,J) = \sigma_0 + \frac{\partial\sigma}{\partial U} v + \frac{\partial\sigma}{\partial J} J, \tag{A1.1}$$

$$Q(U,J) = Q_0 + \frac{\partial Q}{\partial U} v + \frac{\partial Q}{\partial J} J. \tag{A1.2}$$

Here U is the voltage on the junction, U_0 is the value of the voltage at $J=0$, $Q_0 = Q(U_0,0)$, and $\sigma_0 = \sigma(U_0,0)$. Representing the equivalent circuit of the tunnel junction in the form of a resistor and capacitor connected in parallel and assuming that the sum of the voltages on the junction (U) and the load resistor (V_L) is equal to the emf of the source of the constant bias voltage $U + V_L = \varepsilon$, we obtain for the circuit shown in Fig. 1:

$$I = \frac{\varepsilon - U}{R_L} = \frac{U}{R} + \frac{dQ}{dt} = U\left(\sigma_0 + \frac{\partial\sigma}{\partial U} v + \frac{\partial\sigma}{\partial J} J\right) + \frac{dQ_0}{dt} + \frac{\partial Q}{\partial U}\frac{dv}{dt} + \frac{\partial Q}{\partial J}\frac{dJ}{dt}. \tag{A1.3}$$

Here I is the total current in the circuit, R_L is the resistance of the load, and $R \equiv 1/\sigma$. Substituting Eqs. (A1.1) and (A1.2) into Eq. (A1.3) and confining ourselves to the linear approximation in v and J, we obtain the following equation for the response to the action of the radiation $J(t)$:

$$\frac{dv}{dt} + \frac{v}{\tau} = \gamma_1 J - \gamma_2 \frac{dJ}{dt}. \tag{A1.4}$$

Here $\tau = C_d(1/R_L + 1/r_d)^{-1}$ is the characteristic response time, $C_\partial \equiv \partial Q/\partial U$ is the differential capacitance, and

$$\gamma_1 = \frac{-U_0}{C_d R}\left(\frac{1}{\sigma}\frac{\partial\sigma}{\partial J}\right), \qquad \gamma_2 = \frac{1}{C_d}\frac{\partial Q}{\partial J}$$

determine the effect on the junction associated with the sensitivity of the junction resistance and the charge of the depletion layer, respectively, to the radiation. In the derivation of Eq. (A1.4) we utilized the relation for the differential resistance r_d:

$$r_d \equiv \frac{\partial U}{\partial I} = \left(U\frac{\partial\sigma}{\partial U} + \sigma\right)^{-1}. \tag{A1.5}$$

In order to express γ_2 in terms of the relative change in the charge under the action of the radiation, we take into account the fact that $Q \equiv C(V' + U)$, where V' is the height of the barrier for semiconductor electrons at $U = 0$, i.e., the "built-in" charge which produces the potential barrier is also taken into account. From the relation

$$C_d \equiv \frac{\partial Q}{\partial U} = (V'+U)\frac{\partial C}{\partial U} + C$$

and the known form of the dependence of C_d on the voltage on the junction, $C_d = C_d(0)(1 + U/V')^{1/2}$, it is possible to derive a relation between C and C_d: $C = 2C_d$. Then we obtain for γ_2

$$\gamma_2 = \frac{1}{C_d}\frac{\partial Q}{\partial J} = \frac{C(V'+U)}{C_d}\left(\frac{1}{Q}\frac{\partial Q}{\partial J}\right) = 2(V'+U)\left(\frac{1}{Q}\frac{\partial Q}{\partial J}\right).$$

The general solution of Eq. (A1.4) with the initial condition $v = 0$, $J = 0$ at $t = 0$ has the form

$$v(t) = -\gamma_2 J(t) + \left(\gamma_1 + \frac{\gamma_2}{\tau}\right)\exp\left(-\frac{t}{\tau}\right)\int_0^t \exp\left(\frac{t'}{\tau}\right) J(t')\,dt'. \tag{A1.6}$$

The character of the response to the impulsive perturbation will be determined by the ratio of the time constant τ and the pulse width τ_d, as well as by the ratio of γ_1 and γ_2. Since τ, γ_1, and γ_2 depend significantly on the voltage U_0, situations in which the response of the same junction under different bias voltages is determined mainly either by the resistive or charge component are possible. Thus, in the case of a short time constant, $\tau/\tau_d \ll 1$, and for sufficiently large bias voltages, such that $\gamma_1\tau_d \gg \gamma_2$, the solution of Eq. (A1.4) has the form

$$v(t) \approx \gamma_1 \tau J(t) = -\frac{U_0}{R(1/R_L + 1/r_d)}\left(\frac{1}{\sigma}\frac{\partial\sigma}{\partial J}\right) J(t), \tag{A1.7}$$

and the time dependence of the signal has the same form as radiation pulse. This makes it possible to relate the measured strength of the signal ΔV_L on the load to the relative conductivity change $\Delta\sigma/\sigma|_{U=\mathrm{const}}$ in the regime of fixed constant voltage on the sample (in the case of weak signals). Since

$$\frac{1}{\sigma}\frac{\partial\sigma}{\partial J}\approx\frac{\Delta\sigma}{\sigma}\frac{1}{J}, \qquad \Delta V_L=-v$$

and the current associated with charge redistribution is negligibly small in this case, we obtain the formula employed in the analysis of the experimental data to express the change in the conductivity of the junction in terms of the measured response:

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{U=\mathrm{const}}=\frac{\Delta V_L}{V_L(1+R_L/r_d)}. \tag{A1.8}$$

APPENDIX 2

We now estimate the change in the conductivity of a metal-semiconductor tunnel junction with a Schottky barrier under the assumption that the temperature T of the electrons in the semiconductor is different from the temperature T_0 of the metal. In this case the expression for the tunneling current can be written in the form

$$I(V,T,T_0)\propto\int_0^\infty dE[f(E,T)-f(E+V,T_0)]D(E,V), \tag{A2.1}$$

where $f(E,T)$ is the Fermi distribution function, $D(E,V)$ is the barrier factor of the Schottky barrier, and V is the bias voltage on the junction, which is assumed to positive when the carriers tunnel from the semiconductor into the metal and the energy E is measured from the bottom of the conduction band in the interior of semiconductor. Here we neglect the weak, as shown in Ref. 2, dependence of the self-consistent barrier and therefore the barrier factor D on the electron temperature.

For the current increment ΔI resulting from the change in the electron temperature in the semiconductor with $V=\mathrm{const}$ we have

$$\Delta I(V)=I(V,T)-I(V,T_0)$$

$$\propto\int_0^\infty dE[f(E,T)-f(E,T_0)]D(E,V).$$

Hence it follows for the case of weak heating ($\Delta T=T-T_0$) that

$$\Delta I\propto\Delta T\frac{\partial}{\partial T}\int_0^\infty dEf(E,T)D(E,V). \tag{A2.2}$$

The last integral is identical to the standard expression for the tunneling current with large positive bias voltages, when the back flow of the carriers from the metal into the semiconductor can be neglected. But the formula (A2.2) is valid for all values of V only in this case.

For bias voltages not too close to zero, such that $|eV|>T$, the asymptotic expression obtained by Stratton by the saddle-point method (Ref. 16, p. 134) can be used to estimate the integral in (A2.2):

$$\int_0^\infty dEf(E,T)D(E,V)\propto I_s^+(T)\exp[eV/E_0(T)], \tag{A2.3}$$

where the characteristic energy scale is

$$E_0(T)=E_{00}\,\mathrm{cth}(E_{00}/T),\quad E_{00}=\hbar\omega_p/2,$$

ω_p is the plasma frequency of the electrons in the semiconductor, and the expression for $I_s^+(T)$ is presented below [see Eq. (A2.5)].

In order to estimate the relative response

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{V=\mathrm{const}}=\left.\frac{\Delta I}{I}\right|_{V=\mathrm{const}},$$

it is also necessary to obtain analogous approximate formulas for the current I through an unheated junction. The asymptotic expressions for this case for large V are well known,[16] and they are somewhat different for positive and negative bias voltages:

$$I^\pm(V)=I_s^\pm(T)\exp[eV/E_c(T)], \tag{A2.4}$$

where for $V>0$

$$I_s^+(T)\propto\frac{[E_{00}(\Phi_s+\mu-eV)]^{1/2}}{T\,\mathrm{ch}(E_{00}/T)}\exp\left[\frac{\mu}{T}\left(1-\frac{T}{E_0}\right)-\frac{\Phi_s}{E_0}\right], \tag{A2.5}$$

and for $V<0$

$$E_c(T)=E_0(T).$$

$$I_s^-(T)\propto\frac{E_{00}^{1/2}[(eV+\mu)\mathrm{ch}^2(E_{00}/T)+\Phi_s]^{1/2}}{T\,\mathrm{ch}(E_{00}/T)}\exp\left[-\frac{\Phi_s}{E_0}\right]. \tag{A2.6}$$

$$E_c=E_{00}\left(\frac{E_{00}}{T}-\mathrm{th}\frac{E_{00}}{T}\right)^{-1}.$$

The conditions under which these formulas are applicable are discussed in detail in Ref. 16. They correspond to the case of the so-called thermionic field emission, when states lying above the Fermi level in the corresponding electrode but appreciably below the top of the barrier $\Phi_s+\mu-eV$ make the main contribution to the tunneling current.

When the inequalities $T<\mu\leqslant E_{00}<\Phi_s$ are satisfied, as happens in our case, substituting Eqs. (A2.3) and (A2.5) into Eq. (A2.2) we obtain:

$$\Delta I(V)=\frac{\Delta T}{E_0}\frac{\Phi_s-eV}{E_0}\left(\frac{E_{00}/T}{\mathrm{sh}(E_{00}/T)}\right)^2\exp\left[\frac{eV-\Phi_s}{E_0}\right]. \tag{A2.7}$$

Hence we have, using also Eq. (A2.6),

$$\left.\frac{\Delta\sigma}{\sigma}\right|_{V=\mathrm{const}}=\frac{\Delta I}{I}=\frac{\Delta T}{T\,\mathrm{sh}^2(E_{00}/T)}\frac{\Phi_s-eV}{T}F,$$

where

$$F=\begin{cases}1, & \\ \left[\dfrac{\Phi_s-eV+\mu}{\Phi_s-(eV-\mu)\mathrm{ch}^2(E_{00}/T)}\right]^{1/2} & V>0 \\ \times\exp\left[\dfrac{eV}{E_0}\left(1+\dfrac{E_0-E_{00}}{T}\right)\right], & V<0\end{cases} \tag{A2.8}$$

Both formulas are obviously valid outside the neighborhood for zero $-T\leqslant eV\leqslant\mu$ and give close values near the limits of this region for parameters corresponding to the measurement conditions. This can be seen, in particular, from the behavior of the dashed curve in Fig. 3 in the region of the transition from negative values of V to positive values, where the calculation was also performed using the formulas (A2.8).

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