Magnetooscillations and anisotropy of the zero-voltage anomaly in an *n*-GaAs/Au tunnel junction in a quantizing magnetic field

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Tunneling spectra of *n*-GaAs/Au junctions have been measured in magnetic fields $B \leqslant 140$ kG at a temperature of 4.2 K. When the magnetic field B is parallel to the tunneling current I, the anomaly at a zero bias voltage changes with increasing B by a factor several times larger than in the case $B \perp I$. Magnetooscillations and a line structure in the tunneling spectrum are also observed in the vicinity of the zero-voltage anomaly in the configuration $B \perp I$.

Tunneling spectroscopy of metal–semiconductor junctions is a powerful method for studying multiparticle effects in the electron plasma of semiconductors.[1] Recent years have seen a significant increase in interest in tunneling effects in semiconductor structures, since technological advances have made it possible to realize several model tunneling systems in reduced-dimensionality structures (Refs. 2 and 3, for example). These devices open up some opportunities for experimentally testing the basic ideas underlying tunneling theory. Even in "classical" tunneling systems, however, the zero-voltage anomaly observed in the tunneling spectra of junctions with a Schottky barrier based on heavily doped *n*- or *p*-type GaAs remains a subject of debate. This anomaly corresponds to a peak in the tunneling resistance of the junction, for which the doping level of the semiconductor is much higher than the critical concentration corresponding to a Mott transition. Carruthers[4] has shown that none of the mechanisms which have been proposed in the literature as possibly responsible for a peak in the tunneling resistance at zero voltage can explain experimental data on *p*-GaAs/metal tunnel junctions. As Harrison has pointed out,[5] the expression for the tunneling current in the case of semiclassically smooth barriers, e.g, a Schottky barrier, does not contain the density of states. For this reason, Al'tshuler and Aronov's suggestion[6] that the density of states near the Fermi energy of the semiconductor electrode changes because of an electron–electron interaction also fails to qualify as the reason for the zero-voltage anomaly in junctions of heavily doped GaAs with a metal.

Another approach to the problem was developed in Ref. 7, where a numerical calculation on a self-consistent Schottky barrier incorporating an exchange-correlation potential revealed a structural feature in the form of a barrier near the Fermi energy of the semiconductor. This result led Shul'man and Zaĭtsev[7] to link the zero-voltage anomaly with an effect of an electron–electron interaction in the free-carrier plasma of the semiconductor electrode on the shape of the Schottky barrier.

In an analysis[8] of the tunneling spectra of *n*- and *p*-GaAs/Au junctions it was

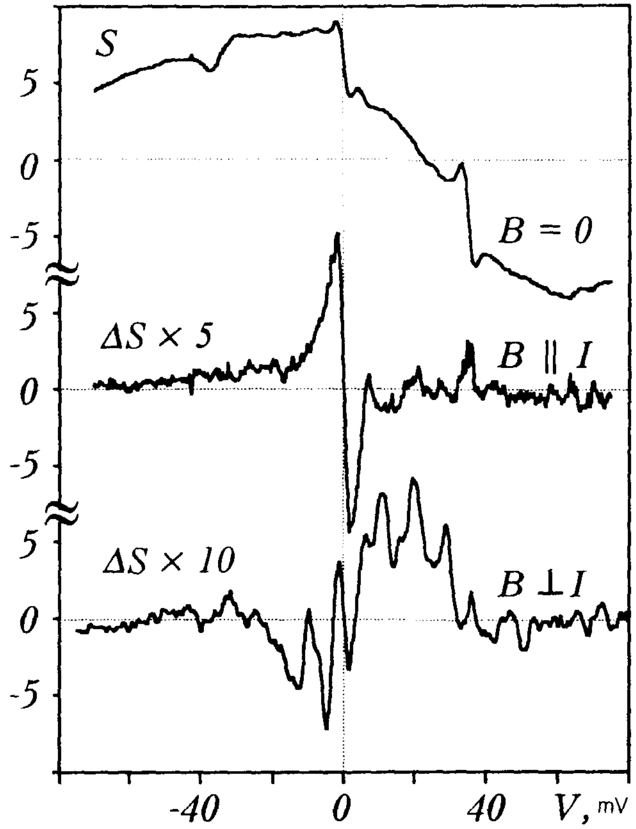

FIG. 1. Tunneling spectrum $S(V) = d^2V/dI^2(V)$ of an n-GaAs/Au junction at $B=0$ and change in the tunneling spectrum, $\Delta S(V) = S(V)_B - S(V)_0$, in a magnetic field $B = 120$ kG ($B \parallel I$ and $B \perp I$).

found that the structure of the zero-voltage anomaly in such systems is more complex than was generally expected. This structure includes, in addition to the peak in the tunneling resistance R, a sharp change in the slope of the $R(V)$ characteristics at a bias voltage $V=0$. It was also shown that the area under the peak corresponding to the zero-voltage anomaly is not conserved during thermal broadening of the spectral line. It has also been observed[9] that the amplitude of the zero-voltage anomaly in n-GaAs/Au junctions falls off exponentially with increasing temperature. These aspects of the behavior of the anomaly suggest an interpretation of the anomaly as a manifestation of a distortion of the self-consistent Schottky barrier due to an electron–electron interaction. However, in order to resolve the nature of the anomaly in such systems, it was necessary to find a way to alter the structure or height of the anomaly by means of some external interaction, e.g., a quantizing magnetic field. In this letter we are reporting preliminary results of a study of the effect of a magnetic field $\leqslant 140$ kG on the tunneling spectra of n-GaAs/Au junctions with a donor concentration $\simeq 7 \times 10^{18}$ cm^{-3} in the GaAs.

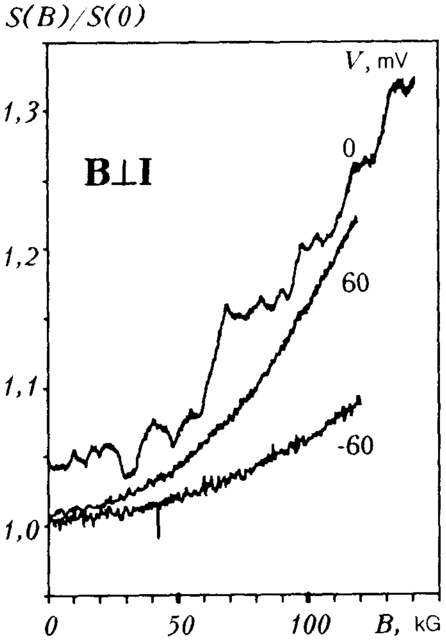

FIG. 2. d^2V/dI^2 versus at points along the V scale in the tunneling spectrum for the case in which the magnetic field is oriented along the surface of the junction ($B\perp I$) for $V=0$, $V\simeq 60$, and -60 mV. The $V=0$ curve is shifted upward by 0.05 for clarity.

Test samples and measurement procedure. In fabricating the n-GaAs/Au tunnel junctions, we used n-GaAs platelets ($9\times9\times0.5$ mm) with a (100) surface and a donor (Te) concentration $\simeq 7\times10^{18}$ cm^{-3} (according to Hall-effect measurements at room temperature). A Au:Ge:Ni ohmic contact was brazed on the backside of the substrate. A thin Au film (100–200 Å) was deposited in a vacuum $\simeq 10^{-10}$ torr on the front of the n-GaAs platelet after this surface had been purified by heating.[10] The composition of the GaAs surface was monitored by Auger spectrometry before the Au deposition; all that was found was some contamination by carbon atoms, in an amount less than a monolayer. Tunnel junctions with a gold electrode 0.2 mm in diameter were fabricated by photolithography on Au-coated n-GaAs substrates. Two copper contacts to this electrode were brought out to a SiO layer (0.2 μm thick) deposited by rf sputtering around the gold electrode. The resulting tunnel junctions had a differential resistance dV/dI (at a bias voltage $V=0$ across the junction) ranging from $\simeq 30$ to $\simeq 50$ Ω at $T=4.2$ K.

The first and second derivatives of the tunneling current-voltage characteristics with respect to V (dV/dI and d^2V/dI^2) were measured by a four-contact method through lock-in detection of sinusoidal signals at the tunnel junction (with frequencies f and $2f$) in the regime of a given current, modulated at a frequency $f\simeq 200$ Hz. The amplitude of the modulating voltage across the junction did not exceed 1 mV. The test samples were in a helium cryostat with a superconducting solenoid. Measurements were carried out in the orientations $B\perp I$ and $B\|I$.

I. Results and discussion. These measurements revealed two interesting aspects of the behavior of the tunneling spectra in a strong magnetic field: (a) their dependence

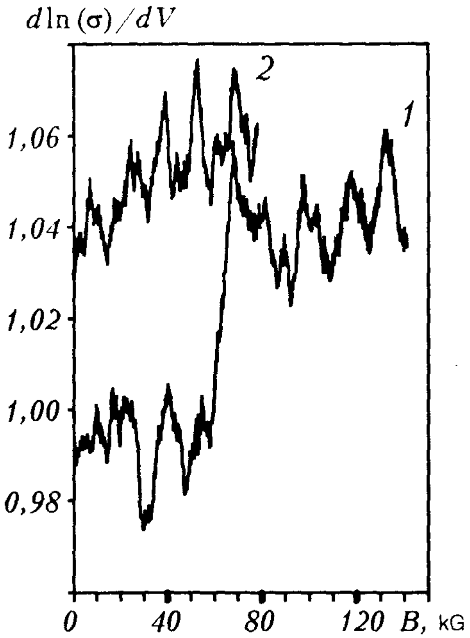

FIG. 3. Reproducibility of the magnetooscillations upon repeated measurements after the junction has been heated to room temperature. *1*—The same as in Fig. 2 for $V=0$, but replotted in the coordinates $d\ln(\sigma)/dV$, in which the magnetooscillations can be seen more clearly; *2*—repeated measurements on the same junction (see the text proper), shifted upward by 0.03.

on the orientation of the magnetic field B with respect to the tunneling current I; (b) the oscillations in $d^2V/dI^2(B)$ as a function of B at $V=0$.

Figure 1 shows a tunneling spectrum $S(V)=d^2V/dI^2$ at $B=0$ and the difference $\Delta S=S_B-S_0$ at $B=120$ kG for the two orientations of the magnetic field. In the orientation $B\|I$ there is a significant increase in the amplitude of the zero-voltage anomaly with the magnetic field, while the spectral lines of the phonon features at $V=\hbar\omega_{LO}/e=\pm 36.5$ mV remain basically constant. This amplification of the anomaly at a zero voltage in a quantizing magnetic field is consistent with the expected increase in the role of the exchange-correlation interaction under these conditions.

The picture is different in the $B\perp I$ orientation (Fig. 1). The height of the zero-voltage anomaly is nearly independent of B. The changes caused by the magnetic field in the tunneling spectrum, which are smaller in magnitude by a factor of nearly 2.5, are concentrated at bias voltages ± 40 mV and take the form of nearly equally spaced peaks against a smooth background. The measurements showed that only the height of these peaks—not their position along the V scale—depends on the magnetic field. At $V=0$ the measurements of d^2V/dI^2 as a function of V revealed an unexpected oscillatory behavior, while the corresponding curves at high bias voltages $V\simeq\pm 60$ mV are monotonic (Fig. 2). The magnetooscillations arise in fairly weak magnetic fields, $B\simeq 20$ kG, at which the quantization of the electron spectrum in the interior of the semiconductor is still suppressed by momentum scattering of the carriers. For the structures studied, the condition $\omega_c\tau\simeq 1$ corresponds to $B\simeq 70$ kG, since the Hall mobility in n-GaAs is $\simeq 1.5\times 10^3$ cm^2/(V·s), where ω_c is the cyclotron frequency, and τ is the time scale of the scattering of the electron momentum in n-GaAs.

The measurements showed that the structure of the curve at $V=0$ in Fig. 2 is reproducible well upon repeated scans of the magnetic field. After the sample is heated to room temperature, however, the structure is reproducible only in its general features. The situation is illustrated by Fig. 3, which is a plot of not d^2V/dI^2 but normalized curves $d\ln\sigma/dV$ (σ is the tunneling conductance of the junction). The latter curves show the oscillations better, since they eliminate the monotonic trend associated with the magnetoresistance of the tunnel junction. Curve 2 was measured 3 months after curve 1, with the help of a different solenoid.

At this point it is difficult to offer a definite interpretation of these oscillations. We might mention their quasimesoscopic nature. We can find a rough estimate of the linear dimensions of the closed trajectories of the tunneling electrons by assuming that the oscillations stem from a quantization of the magnetic flux linked by these trajectories. Taking the oscillation period to be on the order of 20 kG, we find linear dimensions on the order of 100 Å. This figure is comparable to the width of the Schottky barrier at the Fermi level under our conditions.

We should also point out that even at $B=140$ kG, and for both orientations of the magnetic field, the tunneling spectra show no traces of a splitting of the electron spectrum in GaAs into Landau levels, although the condition $\omega_c\tau\simeq 2$ holds at these fields. This result should have been expected in view of the semiclassical nature of the Schottky barrier which, according to Ref. 5, rules out a manifestation of features in the density of electron states of the semiconductor in the tunneling current.

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