Tunneling in a quantizing magnetic field and many-particle featuresin the tunneling spectra of Schottky-barrier junctions

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The differential tunneling resistance R and the tunneling spectra Rd^2I/dV^2 of n-GaAs/Au junctions have been studied as a fun ction of the magnetic field B in longitudinal $(B\|I)$ and transverse $(B\perp I)$ fields up to 23 T at 4.2 K. A quantizing magnetic field alters the various $R(V)$ curves in a similar way. It leaves the tunneling spectra essentially unchanged, except at bias voltages V at which there are manifestations of many-particle effects in the tunneling: an anomaly at a zero voltage and phonon features in the tunneling spectra. These results suggest that the behavior of R as a function of V and B can be described by the multiplicative expression $R\propto f(V)g(B)$ within contributions of many-particle interactions (an exchange–correlation interaction and a polaron interaction). Expressions are derived for the behavior $R(B)$ at $V=0$. Theoretical curves are compared with experimental data. The discrepancies found indicate that it is necessary to consider the change caused in the shape of the self-consistent Schottky barrier by the effect of the quantizing magnetic field on screening. In the case of a longitudinal field, the only possible cause of a magnetoresistance of tunnel junctions would be Landau quantization of the spectrum of free carriers. A comparison of the R curves with Shubnikov–de Haas oscillations of the bulk resistivity of n-GaAs indicates that scattering processes which suppress magnetic quantization in the interior of the semiconductor, when the condition $\omega_c\tau\geqslant 1$ does not hold, do not prevent quantization of electrons near the Schottky barrier in far weaker fields.

The effect of quantizing magnetic fields on tunneling systems has attracted considerable research interest in recent years. For the most part, however, this research has focused on extremely complex semiconductor heterostructures with a high tunnel barrier (Refs. 1 and 2, for example) and has consisted primarily of studies of the energy spectrum of 2D electrons and phonons (magnetic-tunneling spectroscopy). In contrast, metal–semiconductor tunneling junctions with a Schottky barrier—these are fundamental and relatively simple systems—have not been studied adequately from this point of view. Since the electrostatic potential of a Schottky barrier is semiclassical, the mechanism by which the magnetic field affects tunneling characteristics should be quite different from

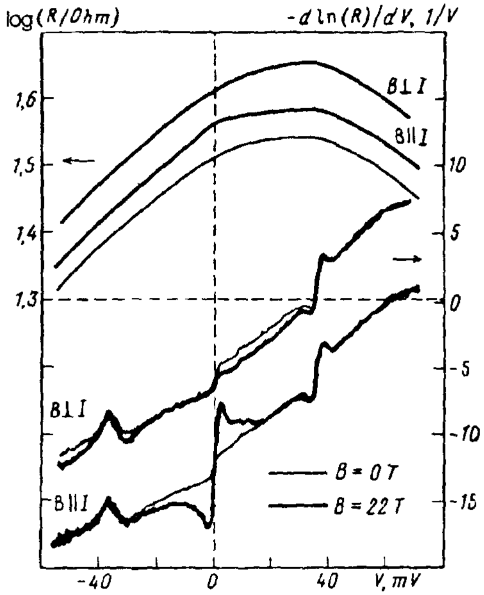

FIG. 1. Effect of a magnetic field, in two orientations, on the tunneling resistance $R(V)$ (the three upper curves; scale at left) and the tunneling spectrum $d\ln\sigma/dV$ (the lower curves; scale at right). Light curves—$B=0$; heavy curves—$B=22$ T. For clarity, the two lowest curves have been shifted by $-7\ \mathrm{V}^{-1}$. The orientation of the magnetic field B with respect to the tunneling current I is indicated near the curves. The tunneling spectrum is insensitive to the presence of a magnetic field except near the zero-voltage anomaly in the $B\|I$ case and between the phonon features in the $B\perp I$ case.

that in systems with a high barrier. As Harrison[3] has shown (for the case without a magnetic field), the expression for the tunneling current through a semiclassical barrier does not contain the density of electron states in the interior of the electrodes. However, the self-consistent nature of the barrier opens up a new possibility for manifestations of the energy spectrum of free carriers in the tunneling characteristics in this case.[4,5] It seemed worthwhile to study magnetic tunneling in Schottky-barrier junctions, since the electron energy spectrum can be tuned quite simply under these conditions.

Test samples and experimental procedure. The tunnel junctions were fabricated on n-GaAs wafers [the (100) surface] in a vacuum on the order of 10^{-10} torr (see Refs. 6 and 7 for a more detailed description). The bulk density of free electron in the substrates was $5.85\times10^{18}\ \mathrm{cm}^{-3}$ according to the period of the Shubnikov–de Haas oscillations. We measured the differential resistance $R=dV/dI$ and the second derivative d^2V/dI^2 by synchronous detection of the first and second harmonics of the voltage across the junction during sinusoidal modulation of the current I through the junction at a frequency ≈200 Hz.

Experimental results. Figure 1 shows the results on $R(V)$ from measurements in a zero magnetic field and in the maximum field, for two orientations. The magnetoresistance in the case of the transverse orientation is considerably higher than that in the case of the longitudinal orientation, although in both cases the curves undergo a nearly parallel shift with respect to the curve for $B=0$. To demonstrate this effect more clearly, we show (in the same figure) tunneling spectra for the same magnitudes and orientations of the magnetic field. Specifically, these are plots of $(d\sigma/dV)/\sigma$, where $\sigma=1/R$ is the tunneling conductance of the junction. The logarithmic derivative of σ (and thus of R) is evidently nearly independent of B, except near the anomaly at a zero voltage and the phonon features at $V=\pm 37$ meV. The differences in the behavior of the zero- voltage anomaly for different orientations of B has been discussed previously,[7] so here we will simply show that the sensitivity of the logarithmic derivative to the magnetic field is far weaker than that of the resistance itself away from the features in the tunneling spectra associated with many-particle (electron–electron and electron–phonon) interactions. It follows that if we write R (or equivalently, σ) in the form $\exp[G(V,B)]$ then we can write $G(V,B)=G_1(V)+G_2(B)$ for the argument. Consequently, R can be written as the product $f(V)g(B)$.

The shape of the B dependence of R established above means that the analysis can be limited, in a first approximation, to a study of the behavior of the resistance as a function of the magnetic field at $V=0$. Corresponding results are shown in Fig. 2. This figure shows a plot of the logarithm of the ratio $R(B)/R(0)$, which characterizes the change in the argument of the tunneling exponential function as the magnetic field is varied. We see that this change is proportional to B^2 over nearly four orders of magnitude. Interestingly, the difference between the values of the longitudinal and transverse magnetoresistances is comparatively small. While the presence of a magnetoresistance in the transverse case can be associated at a qualitatively level with the Lorentz force acting on a tunneling electron, a longitudinal magnetoresistance should arise only as a result of Landau quantization, as in the bulk case. However, measurements of the bulk Shubnikov–de Haas oscillations carried out on the same substrate (see the lowest curve in Fig. 2) show that quantization of the electron spectrum in the interior sets in at $B \geqslant 8$ T, i.e., when the cyclotron frequency ω_c and the momentum scattering time τ (determined from the mobility) satisfy the known condition $\omega_c\tau \geqslant 1$. At weaker fields, the electrons in the interior are thus not quantized. Nevertheless, no fundamental differences in the behavior are seen on the B dependence of the tunneling resistance at fields below 8 T. This is true even of the longitudinal case, in which the magnetoresistance should be a consequence of Landau quantization.

Theoretical analysis. To determine whether electron quantization can be responsible for the longitudinal magnetoresistance observed here, we have derived an expression for the tunneling conductance of a junction with a Schottky barrier. Incorporating a magnetic field directed normal to the surface of the junction (along the z axis) in the Hamiltonian, and following Refs. 4, 6, and 8, we find

$$\sigma(0,B)=\frac{e^2}{\pi\hbar\lambda_B^2}\sum_{N=0}^{N_{\max}} D_N(\mu), \tag{1}$$

where μ is the Fermi energy, $\lambda_B^2=\hbar c/eB$, $N_{\max}=[(\mu/\hbar\omega_c)-1/2]$, $[\ldots]$ means the greatest integer, and

$$D_N(\mu)=\exp\left[-2\,\frac{\mu}{\hbar\omega_c}\int_{1-(\hbar\omega_c/\mu)(N+1/2)}^{\Phi_b} d\Phi\,\frac{\sqrt{\Phi-[1-(\hbar\omega_c/\mu)(N+1/2)]}}{\Phi'(\Phi)}\right] \tag{2}$$

is the transmission of the barrier in the Nth Landau level. Here $\Phi'(\Phi)$ is the electric field at the barrier, i.e., the derivative of the potential with respect to the coordinate. An expression for it in the absence of a magnetic field can be found in Ref. 6. All the energies and lengths in these expressions have been put in dimensionless form as in Ref.

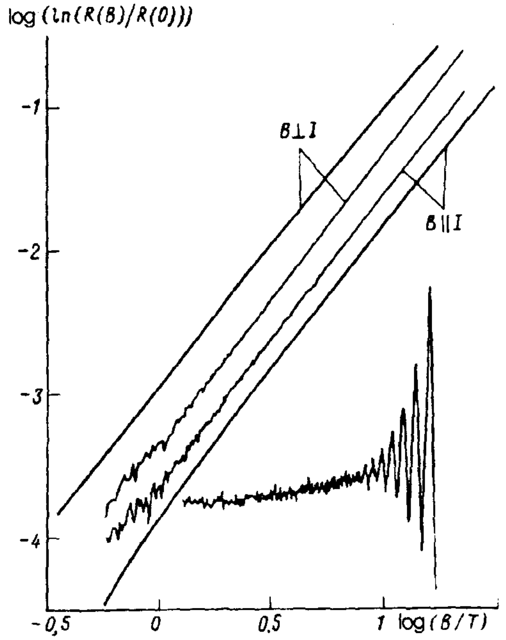

FIG. 2. Experimental and theoretical curves of the argument of the tunneling exponential function, $\ln[R(B)/R(0)]$, versus B in the case $V=0$ for two orientations of the magnetic field (as indicated in the figure). The lowest curve shows the Shubnikov–de Haas oscillations of the bulk resistivity, according to measurements carried out on a sample with a tunnel junction (the results are not drawn to scale). All four curves have an approximately B^2 behavior.

6. Figure 2 shows results calculated from Eqs. (1) and (2). In order of magnitude and also in terms of the nature of the B dependence, the calculated magnetoresistance agrees well with the measurements. From this agreement we conclude that the basic reason for the longitudinal tunneling magnetoresistance is Landau quantization and that the contribution of electron states with the given N to the tunneling current decreases with increasing B. There are some quantitative discrepancies, possibly because the effect of quantization on the shape of the self-consistent Schottky barrier (i.e., on the screening of magnetized electrons) has been ignored. At a formal level, this circumstance is reflected in the fact that we used a relationship between the potential Φ and the derivative Φ' which was derived without consideration of the magnetic field. The decrease in the kinetic pressure of electrons with increasing B should lead to an increase in the width of the barrier and to an increase in the magnetoresistance (cf. the discussion in Ref. 8 for the case in which the shape of a Schottky barrier is changed by radiation pressure during plasma reflection). We might also point out that under our conditions the ratio $\mu/\hbar\omega_c$ is greater than 4, so the change in the Fermi energy in the magnetic field can be ignored.

The case $B\perp I$ is more difficult to deal with theoretically. In this case we found an even cruder estimate of the transverse magnetoresistance. Specifically, we used the standard expression for the tunneling transmission, in which we incorporated (in addition to the electrostatic potential of the barrier) a parabolic magnetic potential. The parabola had a minimum at the semiconductor–metal interface. (This situation corresponds to the case $K_y=0$. In other words, it corresponds to the highest transmission of the barrier as a function of the momentum K_y, directed along the interface in the Landau gauge.) Nevertheless, the result of the calculations (also shown in Fig. 2) demonstrates that even in such a crude approximation it is possible to see the basic features of the transverse magnetoresistance (i.e., the order of magnitude and the type of B dependence), although the numerical differences here are larger than in the longitudinal case (and go in the opposite direction). Estimates show that incorporating the contribution of states with $K_y \neq 0$ should reduce the calculated transverse magnetoresistance, although a comprehensive theory of this effect should incorporate both a derivation of the actual expression for the tunneling current and the incorporation of a change in the shape of the self-consistent barrier under conditions of a quantization of the electron spectrum.

This study shows that the magnetoresistance of tunnel junctions with a semiclassical, self-consistent barrier exhibits a behavior quite different from that of the bulk magnetoresistance and quite different from that in the case of tunneling structures with a high barrier. Another important circumstance is that a quantizing magnetic field intensifies many-particle effects in the tunneling spectra of Schottky-barrier junctions, opening up the possibility of a quantitative study of such effects under magnetic-quantization conditions.

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