Influence of High Magnetic Fields on the Classical and Quantum-Mechanical Transport in Point Contacts

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On spear-anvil-type point contacts of As both positive and negative d^2V/dI^2 spectra are observed, corresponding to respectively an increase and a decrease in the contact resistance at characteristic phonon energies. Contacts with positive electron-phonon-interaction spectra show a positive magnetoresistance indicating ballistic metallic transport, while contacts with negative spectra give a negative magnetoresistance indicating the presence of a localization area inside the contact. The spectral intensity depends on the applied magnetic field (≤ 20 T) due to the magnetic-field-induced one-dimensional current spreading through the contact and the magnetic breakdown of weak localization.

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Point-contact spectroscopy is a very effective tool for the direct study of the energy dependence of the interaction between conduction electrons and low-energy excitations (especially phonons) in a metal.[1,2] Usually, an increase in the contact resistance is observed at voltages V corresponding to characteristic (phonon) energies eV, which results from the backflow of ballistically injected electrons through the contact via inelastic scattering (e.g., spontaneous emission of phonons). This nonlinear current-voltage characteristic allows a direct determination of the Eliashberg function α^2F for the electron-phonon interaction from the measurement of the second derivative d^2V/dI^2 of the metallic contact.

For point contacts with antimony[3] and graphite,[4] an anomalous decrease in the point-contact resistance has been observed at voltages corresponding to the relevant phonon energies. To examine the character of the electronic transport in small constrictions with semimetals, we have investigated point contacts with arsenic in high magnetic fields (≤ 20 T). Both types of point-contact spectra (positive and negative d^2V/dI^2 signals) occur in our point-contact experiments for As. The observed magnetic-field dependence of the point-contact resistance of As illustrates the interplay between ballistic transport and localization phenomena for the two types of spectra, depending on the local purity in the contact area. In addition, the measured d^2V/dI^2 spectral intensity is found to depend on the magnetic field; this can be ascribed to the suppression of localization effects in a field and to the change in the dimensionality of the current spreading through the contact in a strong field. For magnetic fields B where the orbital radius $r_B = m^* v_F/eB$ (effective mass m^* and Fermi velocity v_F) is much smaller than the contact diameter d, the transport in the three-dimensional ballistic constriction becomes effectively one dimensional.[5]

The point contacts with As were formed using the spear-anvil technique[2] by touching at liquid-He temperatures a copper tip to the surface of single-crystalline As. Prior to mounting and cooling down, the surface of As (perpendicular to the c_3 axis) and the Cu tip were chemically etched. The current-voltage characteristics (differential resistance dV/dI and second derivative d^2V/dI^2) were recorded with conventional phase-sensitive detection methods. All measurements have been performed at 4.2 K. The negative d^2V/dI^2 spectra occurred more often (90%) after repeatedly adjusting the contact, while the positive ones were usually observed after the

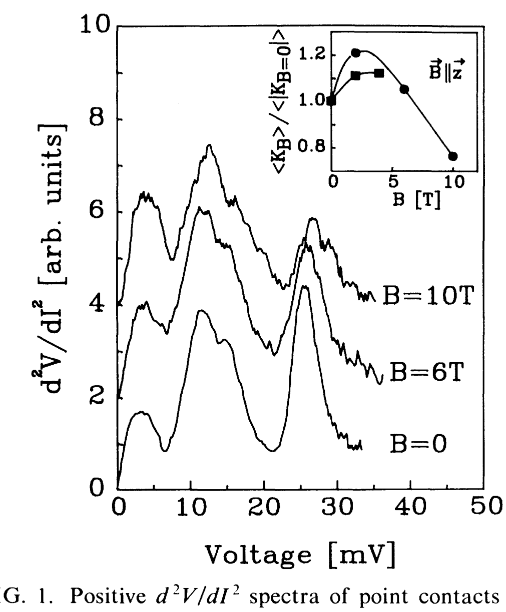

FIG. 1. Positive d^2V/dI^2 spectra of point contacts with an As single crystal against a Cu tip as a function of the applied voltage in different magnetic fields, applied perpendicular to the c_3 axis of As and parallel to the contact axis z. For clarity, the curves have been shifted two units on the vertical axis with respect to each other. Inset: The relative spectral intensity $\langle K_B\rangle/\langle|K_{B=0}|\rangle$ for two different contacts.

first touch on a freshly prepared As surface. We will discuss the magnetic-field dependence of the spectra in a qualitative way for both types of contacts. For a quantitative understanding of the data in a magnetic field, both phenomena related to positive and negative spectra play a role simultaneously.

Figures 1 and 2 show typical positive and negative point-contact spectra of As-Cu heterocontacts in different magnetic fields. Because of the higher Fermi velocity of the electrons in Cu, in these spectra only features due to As are visible.[6] Besides the nonreproducible low-energy structure around zero bias, one can distinguish two broad peaks in Fig. 1 (or valleys in Fig. 2) at 10–15 meV and at 25 meV. The two peaks in the spectrum can be ascribed to the acoustic- and optic-phonon branches of As. The energy position in the spectra can be compared to the phonon density of states $F(eV)$ obtained from inelastic-neutron-scattering experiments.[7]

The negative spectrum as shown in Fig. 2 can be explained as follows. After repeated mechanical adjustment of the contact, the elastic mean free path l_i can become substantially shorter inside the contact and reaches a value comparable with the de Broglie wavelength λ_{dB} ($\simeq 2$ nm for As). In this case, the phase coherence along electron trajectories leads to weak localization,[8] resulting in a backscattering echo of electrons at zero bias. If the inelastic diffusion length $\Lambda_\epsilon = (l_i l_\epsilon)^{1/2}$ (with l_ϵ the inelastic-scattering length) is larger than the contact diameter d, the excess energy $\epsilon = eV$ of the electrons is still determined by the voltage across the contact. The inelastic scattering between electrons and phonons destroys the phase coherence and eliminates the backscattering echo. This effectively results in a *decrease* of the point-contact resistance at the characteristic phonon energies, instead of an *increase* as usually observed in clean ballistic contacts. This demonstrates the fact that point-contact spectroscopy is possible in highly disordered materials where the quantum localization is significant.

The observed magnetoresistance is positive for a contact with a positive spectrum (Fig. 3, curve a) while the magnetoresistance can be negative for a contact with a negative spectrum (Fig. 3, curve b). The positive magnetoresistance indicates a metalliclike ballistic transport in the contact. The negative magnetoresistance supports the interpretation of negative spectra in terms of localization phenomena, while the weak-localization regime is destroyed by a magnetic field. Neglecting the effect of spin-orbit coupling, a negative magnetoresistance is expected[8] as observed in the contacts. The observed positive magnetoresistance has two origins which can play a role simultaneously: a bulk effect or a local-contact effect in a strong magnetic field. As a result of the Corbino-type point-contact geometry, the magnetoresistance of the bulk contributes to the point-contact resistance[9] (note that the magnetoresistance of bulk As is positive). However, the linearity in the magnetoresistance is an indication for one-dimensional current spreading through the contact. In magnetic fields with $r_B < d$, the region of

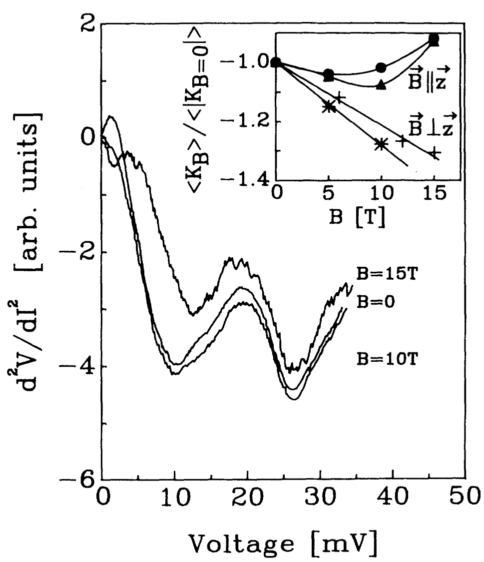

FIG. 2. Negative d^2V/dI^2 spectra of point contacts with an As single crystal against a Cu tip as a function of the applied voltage in a magnetic field parallel to the contact axis z. Inset: The relative spectral intensity $\langle K_B\rangle/\langle|K_{B=0}|\rangle$ for four different contacts with a magnetic field parallel (circles and triangles) and perpendicular (crosses and asterisks) to the contact axis z.

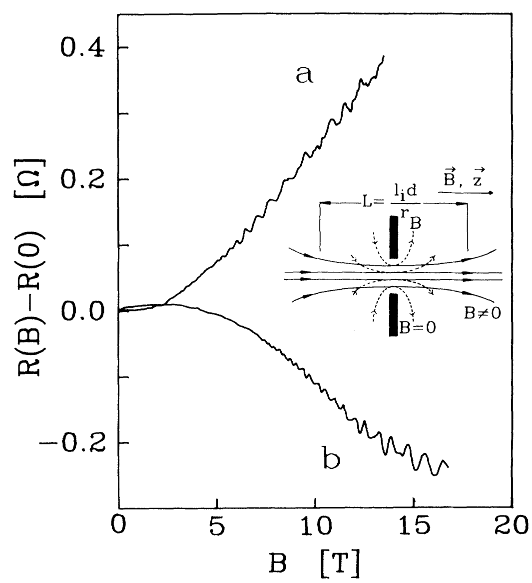

FIG. 3. Point-contact resistance at zero bias as a function of the magnetic field for a contact with a positive spectrum (curve a) and a contact with a negative spectrum (curve b). Inset: Schematically, the current spreading through the constriction without a magnetic field (dashed lines) and in a strong magnetic field ($r_B < d$) parallel to the contact axis z (solid lines).

current spreading parallel to the field is not given by the size of the contact (diameter d) but is controlled by a diffusional process with a mean length r_B and diffusion constant $D_\perp = r_B^2/\tau$ perpendicular to the field and a mean length l_i and diffusion constant $D_\parallel = l_i^2/3\tau$ parallel to the field. The characteristic volume of the current spreading is then given by a cylinder of cross section d^2 and length $L = l_i d/r_B$. The zero-bias resistance $R_0(B)$ of such a ballistic contact depends on the magnetic field as

$$R_0(B) \simeq \rho L/d^2 = \rho l_i/dr_B \text{ with } r_B \ll d\,, \tag{1}$$

i.e., is increasing linearly with magnetic field.[5] For the semimetal As it is quite possible to obtain the region $r_B < d$, as one has typical values of $d = 10$–100 nm and $r_B \simeq 10$ nm at $B = 10$ T. The point-contact magnetoresistance curves in Fig. 3 also show magnetic quantum oscillations (Shubnikov-de Haas effect), as already observed in point-contact experiments with other (semi)metals.[10]

In the standard theory of point-contact spectroscopy,[1,2] the measured point-contact spectrum is a convolution of the Eliashberg function α^2F with an efficiency function $K(\mathbf{k},\mathbf{k}')$, taking into account the efficiency of a backflow process in the contact geometry for an electron scattered from wave vector $\mathbf{k}$ to $\mathbf{k}'$. In an applied magnetic field, the observed change in intensity is difficult to explain in terms of the backflow efficiency for each of the two phonon peaks in the spectra because of the strong anisotropy. The backflow efficiency depends on whether the excited phonons are longitudinal or transverse with respect to the field and the complicated Fermi surface of the electron system. Such anisotropy effects have been studied in Sb point contacts in magnetic fields up to 5 T.[3] To simplify the analysis of the magnetic-field dependence of the spectra, we calculated the integral of each spectrum (after subtraction of the background[1,2]) with respect to the energy eV and divided this quantity by the result in zero field, yielding the normalized spectral intensity $\langle K_B\rangle/\langle|K_{B=0}|\rangle$.

For point contacts with positive d^2V/dI^2 spectra, the integrated point-contact spectral intensity first increases for low fields, reaches a maximum, and then decreases for higher fields (see the inset of Fig. 1). The change in current spreading in high magnetic fields as discussed before also affects the efficiency of inelastic-scattering events in the point-contact spectra. The decreased diffusion perpendicular to the magnetic field enlarges the volume of nonequilibrium electrons near the contact, thus increasing the spectral intensity.[5] For even stronger magnetic fields with $r_B < d$, the elastic scattering in this efficiency volume has to be taken into account, resulting in an efficiency factor[5]

$$K(\mathbf{k},\mathbf{k}') = \frac{9\pi}{128}\frac{l_i}{d}\left\{2(n_z - n_z')^2 + \frac{1-(\omega_c\tau)^2}{1+(\omega_c\tau)^2}(n_\perp - n_\perp')^2\right\}, \tag{2}$$

where $\mathbf{n} = (n_\perp, n_z) = \mathbf{v}/v_F$ and $\mathbf{n}'$ are the normalized velocities belonging to initial and final electron states $\mathbf{k}$ and $\mathbf{k}'$ with the magnetic field parallel to the z axis and perpendicular to the contact surface, and $\omega_c = eB/m^*$ is the cyclotron frequency for electrons with effective mass m^*. The first term in Eq. (2) gives a positive contribution to the K factor describing the contribution of scattering processes along the contact axis. The second term becomes negative in high magnetic fields due to the fact that the scattering in the x-y plane helps the carriers to leave the enlarged volume of nonequilibrium carriers. For very high fields ($\omega_c\tau \gg 1$) these terms cancel each other and the K factor goes to zero. The maximum in the inset of Fig. 1 marks the field where $r_B \simeq d$.

For point contacts with negative spectra, the magnetic-field dependence of the spectra is plotted in Fig. 2 for the field parallel to the contact axis together with the integrated spectral intensity $\langle K_B\rangle/\langle|K_{B=0}|\rangle$. As a result of the destruction of the quantum interference in the electronic transport by the magnetic field on a length scale given by the magnetic length $\Lambda = (\hbar/eB)^{1/2}$ (8.1 nm for 10 T), we see a decrease of the intensity of the spectrum with increasing fields above 10 T.

A rather surprising effect occurs with the field perpendicular to the contact axis (see the inset of Fig. 2). Instead of a decrease of the (negative) intensity of the spectra with the magnetic field, a strong (negative) linear increase is observed. This cannot be explained by considering the diffusional transport inside the contact area only, because a magnetic field, applied in any direction, will destroy the quantum interference but never enhance it. To understand this effect, we have to consider the quantum interference in the dirty contact area as well as the classical trajectory effects in the clean adjacent sides. In zero magnetic field, the effective volume of the phonon generation for a dirty contact is given by the contact dimension; this means that the efficiency function is dominated by localization phenomena (i.e., $\langle K_{B=0}\rangle = \langle K_{\text{loc}}\rangle$) resulting in a negative spectrum. However, in a magnetic field the increased region of current spreading parallel to the field causes inelastic processes in the nearby contact region to be involved in the spectrum. Then, the total $\langle K\rangle$ factor is then a sum of two contributions (i.e., $\langle K_B\rangle = \langle K_{\text{loc},B}\rangle + \langle K_{\text{class},B}\rangle$), related to localization phenomena in the contact area and classical trajectory effects in the nearby (more clean) electrodes. In the efficiency function of Eq. (2), the effect of one-dimensional current spreading has been derived for a circular orifice perpendicular to the magnetic field. For a noncircular geometry (i.e., elliptical orifice), the resulting two terms in Eq. (2) do not cancel each other in the high-field limit; the negative contribution is more important as the nonequilibrium electrons can easily escape the efficiency volume (now a flattened tube) in the direction with the shortest axis.[11] A magnetic field perpendicular to the contact axis yields a flattened tube as the effective phonon-generation volume with an elliptical (asymmetrical) cross section perpendicular to the magnetic field. Then the geometry (field parallel to the contact surface) resembles the elliptical orifice, which would explain the linearly increasing negative spectra with increasing magnetic fields.

In conclusion, the anomalous negative d^2V/dI^2 spectra in As point contacts are due to weak-localization effects in the transport through the constriction, enhanced in semimetals. Both the observed negative magnetoresistance of the contact and the decreasing spectral intensity in a magnetic field support this interpretation. For a full account of the magnetic-field dependence of the point-contact data two phenomena play a role, their relative importance depending on the local contact purity: the localization phenomenon inside the contact area and the one-dimensional current spreading in the adjacent, more clean regions near the contact.

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