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Electric field effects and screening in mesoscopic bismuth wires

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Abstract. Large time-independent conduction fluctuations were observed as a function of transverse electric field in thin (25 nm) and narrow (60 nm) bismuth wires. The conduction of leads far away from a gate capacitor was influenced by changes in the gate voltage. The effects are interpreted as being due to a variation in the Fermi wavelength caused by gate-induced changes in the charge concentration of the leads rather than an electrostatic Aharonov–Bohm-type interference. The screening of charge is strongly reduced in narrow wires.

Electron quantum interference effects give substantial corrections to the conductance of a mesoscopic system when the system's extension is less than or comparable with both the electron phase-breaking length L_ϕ and the coherence length L_T [1]. Conduction electrons within an energy range of $k_B T$ from the Fermi level are coherent in such a system and any changes in the electron wave phase ϕ caused by applied fields or shifts in positions of scatterers result in conductance fluctuations [2, 3]. We have studied the effect of a transverse electric field on the conductance of mesoscopic bismuth wires having transverse dimensions of the order of the bulk screening length. The results indicate that an oscillatory variation in conductance with an applied electric field is due to a variation in the Fermi wavelength, λ_F, of the conduction electrons caused by a changed charge-carrier concentration that was induced capacitively, rather than to a conventional Aharonov–Bohm effect. Furthermore, we had the possibility of studying the effects of screening in a narrow conductor. A charge distortion is effectively screened within a short distance in a 3D metal. A low electron concentration extends the screening length. One expects a decreased screening in low dimensional systems compared with 3D ones. We find that a charge imbalance is much less effectively screened in a narrow conductor so that conductance fluctuations are present well outside the region of the gate capacitor.

We have used an Aharanov–Bohm type configuration, see figure 1. A small metal loop is connected to current and voltage leads and electric fields can be applied via gate capacitors. Periodic variations of the conductance with magnetic field as well as conduction fluctuations have been studied intensively in both metals and semiconductors, i.e. the magnetic Aharonov–Bohm effect [4] is well established. The fourth component of the field vector potential, the electrostatic potential U, should influence the interference (by $\Delta\varphi = \int(eU/\hbar)\,dt$) and, hence, the conductance. However, this effect has been studied less extensively than that resulting from the magnetic field components. Washburn *et al* [5] reported the effects of transverse electric fields on the magnetoconductance of Sb loops. An electric field could tune the position (or phase) of magnetic Aharonov–Bohm h/e oscillations as well as alter the aperiodic conductance fluctuation patterns. The result was not understood unambiguously. One explanation was based on an electric potential Aharonov–Bohm effect but the influence of the electric field was several orders of magnitude less than expected. This was interpreted as being due to the width of the Sb wires being much larger than the screening length meaning that only a small part of the conducting electrons would be affected. Another mechanism stressed the spatial shifting of electron trajectories by the electric field. The latter cause of modifying the phase of the electron wavefunction (or, alternatively, a phase variation induced by a local change in electron density or by a field-induced modification of scattering) was also stressed by de Vegvar *et al* [6], who studied the magnetoresistance of rings in a 2D electron gas (GaAs/AlGaAs heterojunction) subjected to an electric field.

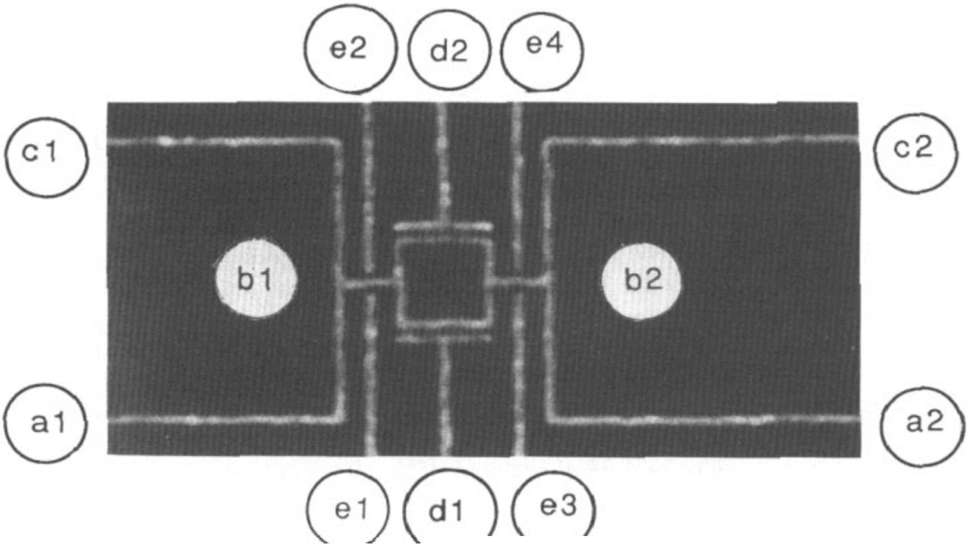

Figure 1. A SEM picture of the microstructure, in this case fabricated in Bi. The widths of the lines are about 60 nm and the thicknesses 25 nm. The lengths of the loop sides and the adjacent capacitor probes are 600 nm. Gate voltages can be supplied to d_1 and/or d_2. e_1–e_4 may be used for screening.

A scanning electron microscope picture of one of the samples is shown in figure 1. Semi-metallic Bi was thermally evaporated onto a Si substrate kept at room temperature and patterned using electron lithography and a 'lift-off' technique. The widths, L_y, are about 60 nm, the thickness L_z about 25 nm for Bi to have a metallic type of conductance [7]. A square loop, with a side length of 0.6 μm, is defined. Two of its leads are coupled capacitively to the probes d_1 and d_2 ('gates'). The centre-to-centre distance between a gate electrode and the adjacent loop lead is about 100 nm. The structure is similar to the one referred to in [5], but it has the additional electrodes e_1–e_4. These could be used as electric screens or as needle (pointed) gates. The loop is connected to the outside world via the electrodes a_1, c_1, a_2 and c_2. The semiconducting substrate helped to protect the samples against electric shocks at room temperature but was insulating at liquid helium temperatures (1.3–4.2 K).

Measurements were performed (at 31 Hz) using the bridge configurations shown in the insets of figures 2 and 3. DC potentials ranging from -8 to $+8$ V were applied to the capacitive probes d_1 and/or d_2. Special attention was paid to work at sufficiently low gate voltages that leakage currents were absent.

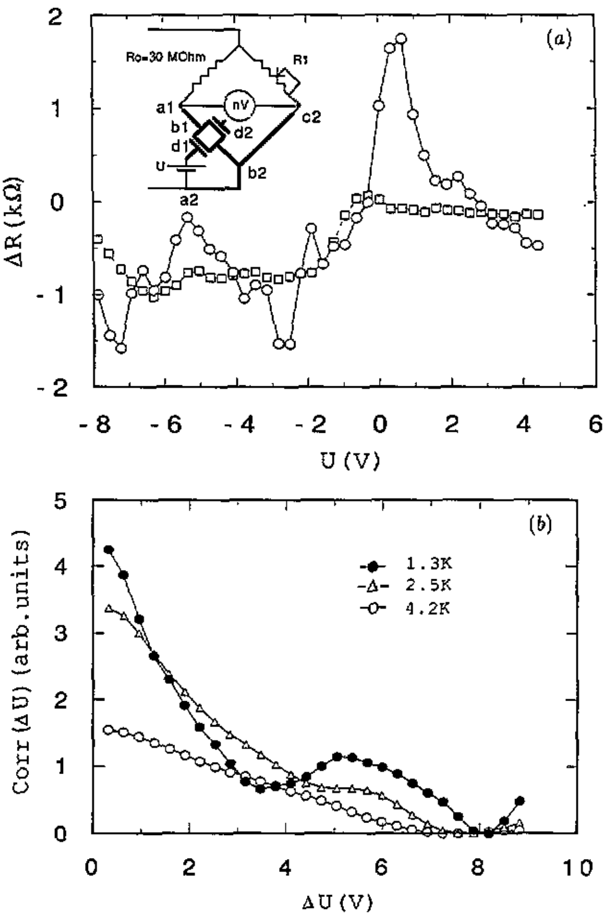

Figure 2. (*a*) The gate voltage dependence of the fluctuations of the resistance of the Bi leads in the loop and its connections. Data are given for $T = 1.3$ (circles) and 4.2 K (squares). The inset shows the configuration. The gate voltage is applied capacitively via d_1, screening electrodes e_1–e_4 are not shown. (*b*) The autocorrelation function of the resistance fluctuations (see the text for its definition) as a function of voltage difference at different temperatures. The same circuit as in (*a*).

The sheet resistance of the Bi film was $R_\square \approx 700\ \Omega$. From magnetoresistance and resistivity measurements in the absence of an electric field, we estimate L_ϕ and L_T to be of the order of 100 nm in Bi at 1.3 K. They would decrease to about 70 nm at 4.2 K. This means that the effective dimensionality of our samples with respect to interference effects is close to the 1D limit ($L_x > L_T, L_\phi > L_z, L_y$). Our Bi wires have transverse dimensions of the order of the screening radius r_s (≈ 40 nm, see [8]), thus the electric field almost completely penetrates into the wires. For comparison, experiments were

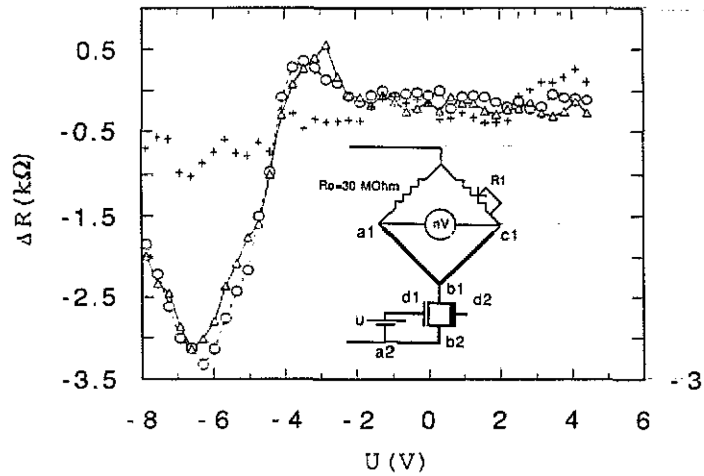

Figure 3. Gate voltage dependence of the difference in resistance between arms a_1–b_1 and b_1–c_1 as shown in the inset. Circles (o) denote a voltage applied between d_1 and a_2, triangles (Δ) when the gate voltage is applied between d_2 and a_2, crosses (+) between d_1 and d_2. Data were taken at $T = 1.3$ K.

also made using Ag strips which have completely different parameters. r_s is expected to be two orders of magnitude smaller for Ag when compared with Bi, while L_ϕ is about 15 times larger.

To check for interference effects we investigated the magnetic field response. For the Bi samples, we saw no magnetoresistance periodic oscillations with period corresponding to either the flux quantum $\Phi_0 = h/2e$, as for weak localization [9], or $2\Phi_0$, for mesoscopic Aharonov–Bohm oscillations [10]. This is expected as L_ϕ and L_T are smaller than the loop dimensions. The arms of the loop will give independent resistance contributions. The Ag circuits, on the other hand, displayed $h/2e$ oscillations in the magnetoresistance. L_ϕ is sufficiently long (about 1.5 μm) in Ag. However, the Ag samples showed no response above the noise level (which in this case was $\Delta R/R \approx 10^{-5}$) to electric fields whereas the Bi ones did.

The magnetoresistance of the Bi leads changed drastically upon the application of an electric field [11]. In this report, however, we will concentrate on the electric field response in zero magnetic field.

An example of the experimental resistance variation with voltage applied to gate d_1 is shown in figure 2. Time independent resistance fluctuations are seen. The curves are reproducible for repeated sweeps using a given sample, but they vary from sample to sample ('electric fingerprints'). The field effects were seen in all four samples that were measured. The amplitude of the oscillations was unexpectedly large ($\Delta R/R \approx 10^{-1}$, R is the resistance of the loop arm close to the capacitor) and it decreased strongly with increased temperature (a dependence $\langle \Delta R^2 \rangle^{1/2} \sim T^{-1/2}$ could be fitted to the temperature dependent data).

Another experiment with the same Bi sample but with a somewhat changed circuit configuration suggests very weak screening in narrow wires. We measured the resistance of a section of the connecting leads while applying a gate voltage as shown in the inset of figure 3. If the resistance changes were to be localized in the loop arms close to the capacitor, the bridge would be insensitive to the applied electric field. On the contrary, we see changes in the bridge balance indicating a resistance change in the wire section a_1–b_1–c_1. The gate voltage dependence of the difference in resistance between arms a_1–b_1 and b_1–c_1 is shown in figure 3. It occurs because the resistance of both arms changes due to fluctuations that are uncorrelated. It is hard to explain this result by non-local quantum effects [12] as L_ϕ and L_T for Bi are too small in this temperature range. It is also unlikely that the effect is due to fringe electric fields from the capacitor edges through vacuum. The field component perpendicular to a_1–c_1 (figure 1) should be negligibly small. We changed the configuration of the electric field by using the other gate. If the effect were due to the fringe field or non-local quantum effects, the fluctuation pattern should differ as different parts of the wires would be exposed to the field. On the contrary, the curves almost coincide, see figure 3. This suggests that the resistance fluctuations are due to the injection of charge via the junction b_1, the effect being symmetric relative to gates d_1 and d_2. We also applied a voltage between the gates d_1 and d_2 letting the potential of the rest of the loop circuit float. No field effect was seen in that case as there is no injection or extraction of charge into the microcircuit. The experiment was also repeated using the leads a_2–b_2–c_2 as parts of the bridge giving similar results.

We propose the following explanation based upon a change in charge carrier concentration. When a voltage U is applied to the gate, the electron concentration in the vicinity will change to keep the electrochemical potential constant. Consequently the Fermi wavenumber and electron wavelength will change. An estimate of the latter change can be derived from the free electron relation:

$$\Delta\lambda/\lambda_F = -(CU/3neV) \tag{1}$$

where C is the capacitance between the gate and the adjacent wire, n is the charge carrier concentration and V the volume of the wire. We ignore small corrections due to the effects of spatial quantization of the electron energy. To change the conduction electron interference pattern it is necessary for the electrons to acquire a relative phase shift of the order of unity over a certain correlation distance L_c. Using this condition, we estimate the value of the voltage needed to change the interference pattern:

$$U_c = (3ne\lambda_F V)/(CL_c). \tag{2}$$

The energy correlation range, which is the typical scale of spacing between peaks and valleys in R as a function of chemical potential, is equal to $\mu_0 = h/\tau_{in}$ for an 1D conductor in the case $L_T < L_\phi < L_x$ (instead of $\mu_0 = k_B T$ for 2D and 3D conductors, dimensionality with respect to interference effect, L_x is the conductor length in the current direction, $\tau_{in}^{-}1$ is inelastic scattering rate) [13]. This leads to $L_c = L_{in} = (\tau_{in} D)^{1/2}$. With $n = 1.5 \times 10^{18}$ electron cm^{-3} (for the 25 nm thick Bi film [7]), the wavelength of conduction electrons, λ_F, of the order of 10 nm [8], $C = 2 \times 10^{-17}$ F and $L_{in} = L_\phi$ (in the absence of magnetic scattering, $\tau_{in} \approx \tau_\phi$), we obtain $U_c(1.3\ \mathrm{K}) \approx 3.2$ V, $U_c(4.2\ \mathrm{K}) \approx 4.6$ V.

We can compare these values with those which we extract from the experiments. The autocorrelation function of fluctuations $\mathrm{Corr}(\Delta U) = \langle(R(U + \Delta U) \cdot R(U)\rangle - \langle R(U)\rangle^2$ (where $R(U)$ is the circuit resistance at gate voltage U) is plotted in figure 2(*b*). If we use U_c as the value at which $\mathrm{Corr}(\Delta U) = \frac{1}{2}\mathrm{Corr}(0)$, we obtain U_c ($T = 1.3$ K) ≈ 2 V, U_c ($T = 4.2$ K) ≈ 4 V. These estimates are in good agreement with the calculated values.

We can also calculate values of U_c for the Sb wires used in [5] to see if we get reasonable values there. In the case of Sb, the screening is more effective than for

Bi (screening radius $R_s \approx 15$ nm for Sb, see [14]) and the electrons sense the electric field only during a fraction of $\tau_\varphi, \tau'_\varphi = \tau_\varphi P$, where $P = r_s/L_y$ is the probability of finding an electron in the layer of thickness of r_s. Furthermore, changes in the charge carrier concentration take place only in the volume $(r_s/L_y)V$. Hence, after averaging over L_y the value of r_s does not enter into the final formula for U_c in the 1D case. With $n = 5 \times 10^{19}$ cm^{-3},$\lambda_F \approx 5$ nm and the rest of the parameters taken from [5] ($C = 5 \times 10^{-17}$ F, phase-breaking length equal to the perimeter of the loop, $V = (75$ nm $\times$ 75 nm $\times$ 800 nm) we obtain $U_c = 3.6$ V. This rough estimate is of the same order as the experimental value $U = 0.8$ V.

For silver, formula (2) would give U_c about 70 V. This would be too large to be observed in our experiments.

To calculate the absolute value of the change in conductance $\Delta G = -\Delta R/R^2$ we need to know the value of the total resistance R of the region of the wire where the change in charge concentration, Δn, occurs. A question then arises as to how fast Δn drops with distance from the gate along the wires, i.e. the question about screening in 1D wires. Intuitively we expect that the screening in narrow wires is highly reduced and that significant changes in n can exist at long distances from the gate.

To show why changes in the charge concentration are not rapidly screened in narrow wires ($L_x > r_s > L_y L_z$), we solve Poisson's equation for a wire and its environment here. At long distances, x, from an added charge, the potential $\phi(0, x)$ on the axis of the wire:

$$\phi(x) \to 1/x \ln^2 x \qquad \text{as } x \to \infty.$$

(We consider a wire with radius R and axis along the x-direction. A test charge, Q, is homogeneously distributed over the area πR^2 in the $x = 0$ plane.

$$\nabla^2\phi - (1/r_s)^2\phi = -(4\pi/\epsilon)\rho \qquad r < R$$
$$\rho = (Q/\pi R^2)\delta(x) = \sigma\delta(x)$$
$$\nabla^2\phi = 0 \qquad r > R.$$

The solution for the Fourier component $\Psi_q(r = 0)$, of the potential $\phi(r, x)$ may be written as

$$\psi_q(0) = (4\pi\sigma/\epsilon s^2)/(1 + 1/F(q))$$
$$F(q) = (s/q)I_0(sR)K_0(qR)/(K_0(qR) - I_0(sR))$$
$$s^2 = q^2 + r_s^{-2}$$

where I_0 and K_0 are reduced Bessel and Hankel functions of zeroth order. At distance x, far from the additional charge, the potential $\phi(0, x) -> 1/x\ln^2 x$.)

Compared with a 3D geometry (dimensionality with respect to screening, $r_s \ll L_x, L_y, L_z$) where charges are screened exponentially, the screening in a narrow enough wire is much less pronounced. It is similar to an unscreened Coulomb law, but with an additional $\ln^2 x$ factor at long distance. This explains the weak screening discussed in connection with figure 3.

An alternative explanation of the quasi-periodic resistance variations may be single electron charging of a segment of the 1D wire defined by two weak spots as recently reported for GaAs nanostructures [15]. The resistance of the wire is higher than $R_Q \approx 6.5$ kΩ. However, a few observations do not support such an interpretation. The large gate voltage period would imply that only a very small segment of the wire would determine the variations, the variations were stable in time instead of shifting character from sweep to sweep which often is the case when trapped charges move, and the variations were the same when a gate voltage was applied to either d_1 or d_2 which would not be expected if the charging part were close to one of the electrodes.

Summarizing, we note that we have observed pronounced field effects in the resistance of metallic nanostructures. However, we argue that the resistance oscillation with electric field in a loop, and the resistance fluctuation in adjacent leads caused by the same field, are not due to the electrostatic four-vector component as in an Aharonov–Bohm type effect. Rather they are due to electron interference caused by a change in the Fermi wavelength from a field induced variation of the charge concentration. The change in the charge distribution is spread out along a narrow wire over a sizeable distance as 1D screening is much weaker than in 3D.

Acknowledgments

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