Electron-electron interaction effects in a diffusive Cu nanobridge

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The electron-electron interaction (EEI) in diffusive metals has been widely investigated in the 1980s. Aronov and Altshuler presented a detailed theory of this effect, which results in a small dip in the electronic density of states close to the Fermi surface [1]. However, there are only few experiments which give spectroscopic information of the resulting modification of the density of states by tunneling spectroscopy. To our knowledge the energy dependence of the conductance has not been studied. Very recently, new interest has focused on EEI in mesoscopic systems. EEI appears in the temperature dependence of the electrical resistivity of thin metallic films, causing a logarithmic increase of the resistance towards lower temperatures. These effects have also often been observed in metallic mesoscopic bridges. However, spectroscopical resolution of the conductance is not possible in such geometries, because the voltage drop takes place all along the leads and heating effects at higher current densities are present.

We present experimental data of the conductance of a Cu bridge which is very short (80 nm), about 80 nm wide and 10 nm thick and placed in good metallic contact between two resevoir-like electric leads which are about 70 times thicker than the bridge and extend over a rather large area of of about 1 mm^2 (see Fig. 1). Hence the voltage applied to the sample drops only along the bridge, and the arising heating power is reliably conducted away by the large Cu leads. The mean free path in the sample is about 10 nm, i.e. equal to the thickness, but much shorter than the lateral lengths (80 nm). Therefore, the electrons in the bridge obey the rules of a 2D diffusive motion. The sample was produced

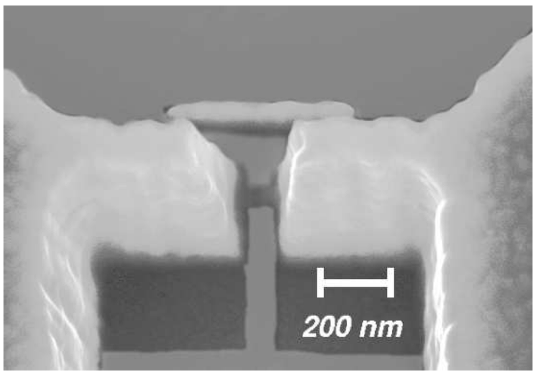

Figure 1: SEM picture of the sample. The Cu bridge is embedded between two considerably thicker Cu leads.

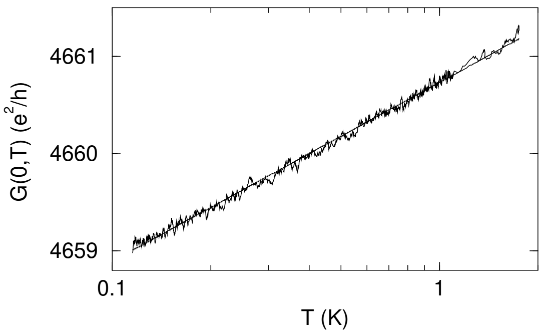

Figure 2: Zero bias conductance of the Cu bridge. The straight line is a fit according to (1)

by the shadow-evaporation technique [2]. Cu was deposited at two different angles under UHV conditions through a PMMA mask patterned with e-beam lithography. We deposited 10 nm Cu for the bridge at one angle (-13° off the normal direction of the surface) and 700 nm for the reservoirs (+13°) at the opposite angle without breaking the vacuum (in the 10^{-9} mbar region during evaporation). The transport measurements were performed in a ^{3}He/^{4}He-dilution refrigerator in a temperature range between 100 mK and 2 K. The differential resistance was measured with a LR 700 resistance bridge, which was capacitively coupled to a DC-circuit through the sample. Raw data of the zero-bias resistance as a function of temperature are shown in Fig. 2. We observe a logarithmic T dependence

$$G(0,T) = G(0,T=1\ \mathrm{K}) + \tilde{\mathrm{B}} \cdot \ln(\mathrm{T/K}) \qquad (1)$$

This logarithmic behavior has often been observed in thin metallic films and metallic nanobridges and is usually attributed to weak localization (WL) and/or EEI.

When applying a bias voltage, small deviations from Ohmic behavior are observed at low voltages. Fig. 3 shows data of the conductance of the bridge as a function of applied voltage V at two different temperatures. A voltage-symmetric dip in the conductance appears which is rather broad at higher temperatures ($T = 2$ K) and becomes more pronounced at lower T ($T = 0.11$ K). We call this anomaly zero-bias anomaly (ZBA). Taking also into account the sweeps at intermediate T (not shown), where the observed behavior develops continuosly, one can observe an interesting scaling property: If one subtracts the zero bias conductance of each sweep and plots $G(V,T) - G(0,T)$ as a function of V/T, all conduc-

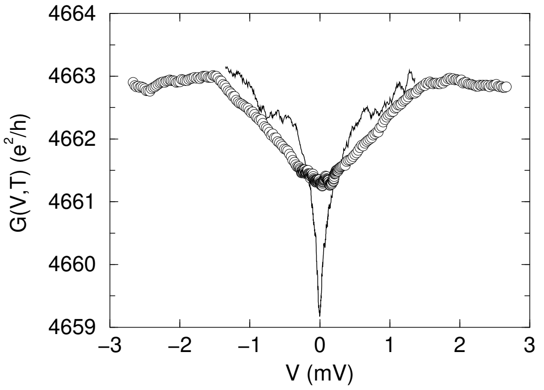

Figure 3: Two voltage-dependences of the conductivity at $T = 110$ mK (line) and $T = 2$ K (circles). A nonlinearity appears as a dip around $V = 0$. At lower T, the dip is narrower, but deeper than at higher T.

tance sweeps collapse onto a single curve. Comparison with results of several Cu samples of the same geometry and for Cu samples doped with Au (with a considerably shorter mean free path) yields that $(G(V,T) - G(0,T))/\tilde{B}$ is identical for all samples.

We propose the following scaling law:

$$G(V,T) = G(0,T) + \tilde{B} \cdot \phi(eV/kT) \tag{2}$$

Fig. 4 shows the function ϕ extracted from conductivity measurements on one sample at seven different temperatures as a function of $y = eV/kT$ on a semi-logarithmic scale (data of positive and negative voltages are included). Within some scatter, all sweeps collapse onto one single curve. At $|y| < 1$, the conductance is essentially constant, which corresponds to thermal smearing. At $|y| > 1$, the behavior is logarithmic, and for larger values of V/T, the curves deviate from this behavior. The low-T data follow the logarithmic behavior up to $y \simeq 100$, while the high-T data deviate at lower y.

We attribute this ZBA in the conductance to EEI in our nanoscopic Cu bridge. Electrons passing from one reservoir through the bridge into the opposite reservoir feel during their diffusive, but energy-conserving trajectory through the bridge the reduction of the density of states at low energies due to EEI. The electronic diffusive motion is two-dimensional, but the Fermi body is three-dimensional. The density of states calculated for this special case (which has not been treated in literature yet) obeys indeed the scaling law Eq. (2). The circles in Fig. 4 show a numerical calculation of ϕ without any free parameter. We obtain very good agreement with the experimental data.

When a magnetic field of $B = 8$ T is applied parallel to the quasi 2D bridge of the sample, the effect remains qualitatively the same, but is reduced

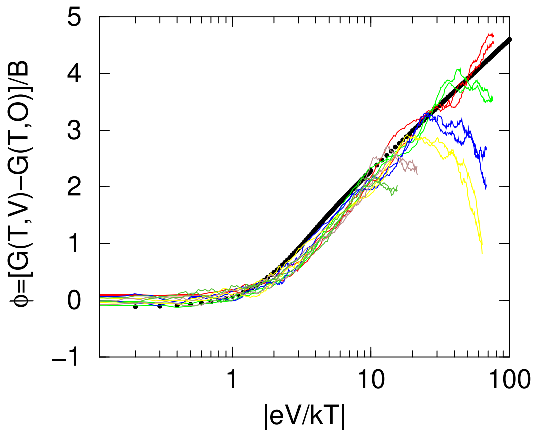

Figure 4: Scaling plot of the conductance data for T=110 mK, 245 mK, 500 mK, 750 mK, 1000 mK, 1450 mK, 2000 mK . The voltage sweeps collapse well onto a single curve, when the data are scaled according to Eq. (2). The black symbols correspond to theoretical calculations.

in amplitude. The zero-bias resistance as a function of T shows still logarithmic behavior obeying Eq. (1), but the coefficient $\tilde{B}$ has approximately half of the value for B=0. The ZBA is also reduced. However, the data do well fit in the scaling law Eq. (2) and the resulting function ϕ is within some scatter the same as shown in Fig. 4, again without any free parameter. Our picture of this reduction is the following: independent of magnetic field, the diffusive motion causes the ZBA due to EEI as discussed above. In zero magnetic field, the interaction of time-reversible paths causes supplementary mechanism for EEI, which is referred to as Cooper-channel contribution to EEI [1]. Both mechanisms obey the observed scaling law eq.(2) and simply add in amplitude for B =0. The latter mechanism is closely related to WL, but as WL affects the effective diffusion constant, it is not energy dependent.

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