Electron-electron interaction in quasi-one-dimensional cobalt nanowires capped with platinum: Low-temperature magnetoresistance measurements

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We have measured the low-temperature magnetoresistance of single cobalt nanowires with various widths ranging between 40 nm and 2 μm prepared by electron beam lithography. The wires are protected *in situ* with 2 nm platinum to prevent oxidation. The temperature dependence of the resistance shows a logarithmic increase to low temperatures which is attributed to enhanced electron-electron interactions in two dimensions. The strength of interaction effects increases with decreasing width of the wires and a transition to a quasi-one-dimensional behavior is observed. We do not find any contribution due to weak electron localization in agreement with previous results on similar carbon covered nanowires.

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I. INTRODUCTION

The nature of the quantum mechanical wave character of conduction electrons affecting the low-temperature electrical resistance has been intensively investigated during the past decades for one-, two- and three-dimensional systems. Essentially, there exist two different physical models that explain the quantum corrections to the electrical resistance. One is phase coherent backscattering of noninteracting electrons in the presence of weak disorder which causes weak electron localization (WEL).[1] The other model describes an enhanced electron-electron interaction (EEI) which originates from a modified screening of electrons due to diffuse electron scattering.[2] Both effects result in a logarithmic resistance increase with decreasing temperature at low temperatures. One can, however, distinguish between WEL and EEI effects by simply applying large enough external magnetic fields oriented perpendicular to the film plane. The vector potential $\vec{A}$ acts on the phase of the electron waves and leads to a phase shift of the time reversed paths of electron waves via the Aharonov-Bohm effect.[3,4] Already, small magnetic fields of the order of $B=0.01$ T begin to destroy the phase coherence between electron waves on length scales of the order of $L_\phi=(\hbar/4eB_\phi)^{1/2}$ and thus modify the observed resistance correction. It leads to a low-field negative magnetoresistance (MR) if no spin-orbit interactions have to be taken into account.[5] On the other hand, EEI effects are hardly affected by the influence of small external magnetic fields, and a corresponding MR effect only occurs for rather large magnetic fields of $B>1$ T (at $T=4.2$ K).[6] Consequently, the slope of the logarithmic resistance versus temperature behavior is sensitive to rather small magnetic fields of the order of $B=0.01$ T if WEL is the relevant mechanism responsible for the observed resistance correction.[7] If EEI is the dominant mechanism, the slope remains almost independent of the applied magnetic field up to large magnetic fields of at least 1 T. Thus, investigating the temperature dependence of the resistance in the presence of various *perpendicular* magnetic fields allows one to differentiate experimentally between the two relevant resistance contributions.[8,9]

So far, many groups have addressed the question both experimentally and theoretically as to whether or not WEL effects also survive in magnetic systems[10–18] since internal magnetic fields in *ferromagnetic* films or wires may or may not influence the phase coherence between conduction electrons even in the absence of external magnetic fields.

With our results of an earlier investigation we have shown that EEI is the dominant contribution for two-dimensional (2D) platinum covered cobalt wires with widths of about 2 μm. Effects resulting from WEL could not be observed.[19] This leads to the question as to whether WEL effects are unobservable due to experimental resolution problems. To overcome this problem we reduce the widths of the wires and thereby increase their resistance. Since quantum corrections based on WEL as well as EEI scale with the total resistance, their observability can be improved. Moreover, this offers the possibility to observe the crossover from 2D to 1D behavior in platinum capped nanowires.

In this paper we report on resistance measurements of Co nanowires with wire widths as small as $w=32$ nm prepared by electron beam lithography (EBL) which are protected by a thin Pt layer to prevent oxidation. Within the accuracy of our measurements we do not observe yet any resistance contribution resulting from WEL. Instead, from the temperature dependence of the resistance at low temperatures we find that only EEI effects are present. Thereby, with respect to the quantum corrections the wires undergo a transition to a quasi-one-dimensional behavior for widths smaller than 100–200 nm.

II. EXPERIMENT

The cobalt nanowires are prepared by high-resolution electron beam lithography (HR-EBL) onto Te-doped GaAs substrates with lateral dimensions of 3.9 mm × 3.9 mm × 0.5 mm, subsequent evaporation of cobalt in an UHV chamber with a base pressure of $p_B=1\times10^{-8}$ mbar and lift-off technique. Details of the sample preparation can be found in Ref. 20. Using customized resist systems which provide resist masks with an undercut in combination with an appropriate lift-off technique, allows us to produce wires of high quality with widths as small as 32 nm. All cobalt wires have thicknesses of 10 or 30 nm and they are capped with a 2 nm platinum layer to prevent oxidation. Figure 1 shows an im-

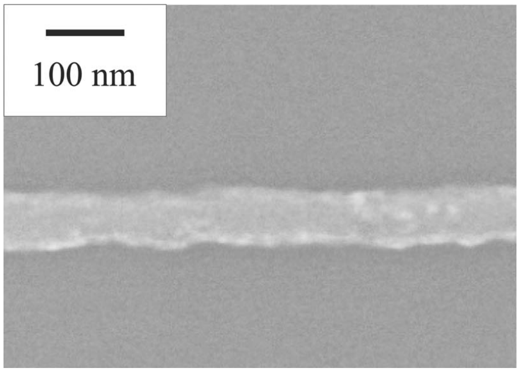

FIG. 1. Scanning electron microscopy (SEM) image of a cobalt nanowire with 12 nm thickness (2 nm platinum cap layer) and 65 nm width. The wire has an edge roughness of about 7 nm which is of the order of the grain size. Nearly no tear-off edges are observed.

age obtained with scanning electron microscopy (SEM) of a typical nanowire with a width of 65 nm and with a thickness of 12 nm (10 nm cobalt and 2 nm platinum). The length of the wires varies between 10 and 200 μm and their width ranges between 32 and 2160 nm. The edge roughness of the cobalt wires is of the order of the grain size which is $\phi = 7 \pm 2$ nm. Structural investigations were performed with SEM and transmission electron microscopy (TEM) for which arrays of nanowires were also prepared onto NaCl substrates, precoated with a carbon layer of about 15 nm thickness.

For the resistance measurements the wires were electrically contacted by using a second EBL process with *nonmagnetic* Au contact pads which do not modify the magnetic configuration of the wires. We have carried out magnetoresistance measurements with a ^{4}He bath cryostat in a temperature range between 1.5 K and room temperature. Magnetic fields up to $B=5$ T can be applied in a direction longitudinal, transverse as well as perpendicular to the wire axis. In order to minimize heating effects only small electrical currents ranging between 5 nA and 1 μA were chosen. This allows us to determine the resistance with an accuracy of about $\Delta R/R \sim 10^{-5}$. The total resistance R contains two contributions, one originating from the 10–30 nm thick cobalt wires, the other from the 2 nm thin platinum capping layer. Measuring the resistance behavior of a single 2 nm thin platinum wire yields a resistivity of $\rho_{Pt} \approx 52$ $\mu\Omega$ cm. By assuming a parallel connection between cobalt and platinum this leads to an additional conductance contribution from the platinum capping layer of about 2–8 % depending on the cobalt wire thickness [$\rho_{Co} \approx 20$ $\mu\Omega$ cm (Ref. 20)]. Structural investigations show the predominance of hexagonal closed packed (hcp) cobalt with a number of stacking faults. Magnetic force microscopy measurements for cobalt wires with a thickness of 32 nm and various widths reveal that Co wires having a width smaller than 1–2 μm always return to a monodomain-like remanent state after saturation in a magnetic field of $B = 2$ T applied along the long wire axis.

III. RESULTS AND DISCUSSION

A. Magnetoresistance behavior

The dominant shape anisotropy of the wires forces the easy axis in a direction parallel to the long wire axis.[21] In longitudinal magnetic fields one, therefore, observes a rather sharp switching behavior of the magnetization, which reflects a switching behavior that originates from the nucleation of domain walls.[22] With increasing *transverse* magnetic field the resistance decreases proportional to B^2, which can be explained as resulting from a coherent rotation of the magnetization in the direction of the external magnetic field. This then results in a negative MR due to the anisotropic magnetoresistance (AMR).[23] In perpendicular magnetic fields the MR is also dominated by the AMR since, when the magnetization rotates into the direction of the external magnetic field, it is again oriented perpendicular to the current direction. The AMR is of the order of 1% and it is thus larger in magnitude as compared to the effects stemming from WEL and EEI.[21] A contribution from the Lorentz magnetoresistance is not observed which corresponds to the small electron mean free path in Co wires of about $l_e = 7$ nm.

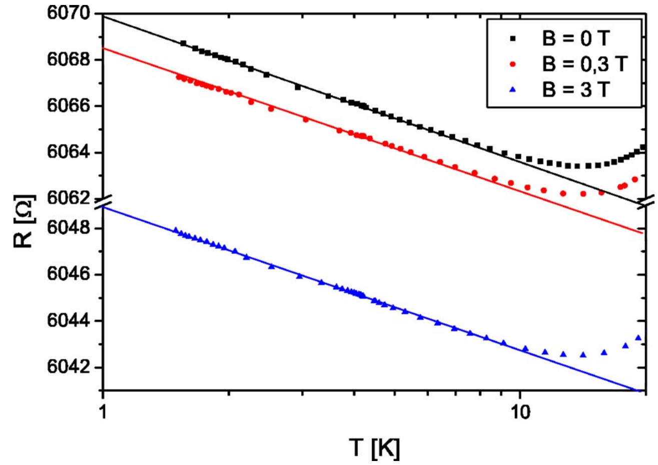

FIG. 2. (Color online) Temperature dependence of the resistance of a cobalt wire of 2160 nm width and 30 nm height capped with 2 nm platinum in zero magnetic field and in the presence of a magnetic field up to 3 T oriented perpendicular to the plane. The wire has a sheet resistance of $R_S = 34$ $\Omega/\square$.

B. Temperature dependence

Any possible contribution of the quantum corrections to the magnetoresistance from both WEL and EEI are largely obscured by the AMR effect, which clearly dominates the magnetoresistance of the Co wires. In order to observe any of such contributions, it is therefore necessary to analyze their impact on the temperature dependence of the resistance, as has been discussed before.[19,21] Figure 2 shows the resistance as a function of temperature for a cobalt wire with a width of 2160 nm and a cobalt thickness of 10 nm capped with a 2 nm thin platinum layer in zero magnetic field and with external magnetic fields up to 3 T applied perpendicular to the film plane.

As one can see, the resistance exhibits a minimum at a temperature of about $T = 14$ K and it shows a logarithmic increase with decreasing temperature in all cases. Upon increasing the magnetic field at a constant temperature the resistance decreases according to the AMR effect,[23] by which

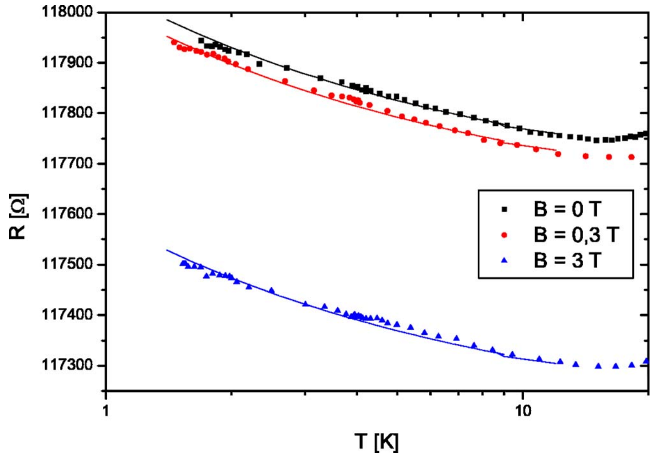

FIG. 3. (Color online) Temperature dependence of the resistance of a cobalt nanowire with a width of 65 nm and a cobalt thickness of 10 nm capped with 2 nm platinum. The full line is a fit according to the model of Neuttiens for enhanced electron-electron interaction (Ref. 24). The wire has a sheet resistance of R_S=40.4 Ω/□.

the magnetization rotates into the direction perpendicular to the current direction. The logarithmic increase of the resistance can be characterized by $\Delta G(10)$,[21] where

$$\Delta G(10) = G(10K) - G(1K) = \frac{R_S(1K) - R_S(10K)}{R_S(10K)^2}. \quad (1)$$

R_S is the sheet resistance of the wire. For a Co wire with R_S=34 Ω/□ we obtain $\Delta G(10) = 2.88 \times 10^{-5}$ □/Ω which is in good agreement with earlier measurements for the case of electron-electron interaction in a two-dimensional system.[21] If WEL effects were present one would expect that the slope $\Delta G(10)$ would change when a magnetic field is applied. However, since the slope remains constant within the accuracy of our measurement, we thus conclude that WEL effects are not present, at least not observable. This is in agreement with our earlier measurements on micrometer wide ferromagnetic wires.[19]

Figure 3 shows the resistance versus $\log_{10}(T)$ of a Co nanowire with a width of w=65 nm in a zero magnetic field and with two different magnetic fields applied perpendicular to the film plane. As one can see—in comparison to the resistance behavior presented in Fig. 2—here, the resistance increase is not purely logarithmic. Note, however, that also for this Co nanowire with a smaller width the slope of the logarithmic resistance increase does not change upon application of magnetic fields perpendicular to the film plane. The experimental data are only shifted to smaller values due to the AMR effect. This again implies that WEL effects are not present such that only contributions of EEI seem to be relevant for the resistance increase. To check this in more detail we have analyzed the data in Fig. 3 by using a formula derived by Neuttiens *et al.* for the case of enhanced electron-electron interactions within the transition regime between one- and two-dimensional behavior.[24]

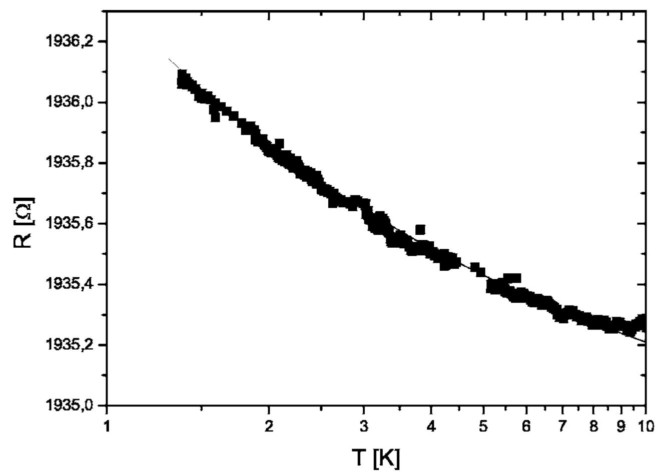

FIG. 4. Temperature dependence of the resistance of a cobalt nanowire with a width of 40 nm and a cobalt thickness of 30 nm capped with 2 nm platinum. The full line is a fit according to the model of Neuttiens (Ref. 24). The wire has a sheet resistance of R_S=7.7 Ω/□.

$$\delta G_{EEI}^{1d-2d}(T) = \frac{\alpha}{\frac{\pi\hbar}{e^2}} \sum_{n=0}^{\infty} \frac{1}{\sqrt{w^2/L_T^2 + (n\pi)^2}} - \frac{1}{\sqrt{w^2/L_{T_0}^2 + (n\pi)^2}}. \quad (2)$$

Here, w is the wire width, α=0.95 (Ref. 24) is a screening parameter, and $L_T = \sqrt{D\hbar/k_B T}$ the thermal diffusion length with $D = \frac{1}{3}\, v_F\, l_e$ the electron diffusion constant. By fitting the experimental data in Fig. 3 with Eq. (2) using $v_F = 1.5 \times 10^6$ m/s (full lines in Fig. 3) we find that the temperature dependence of the resistance is well described by the model of Neuttiens *et al.* The resistance increase over one decade of temperature $\Delta G(10) = 5.41 \times 10^{-5}$ □/Ω is larger as compared to the two-dimensional case. This can be attributed to

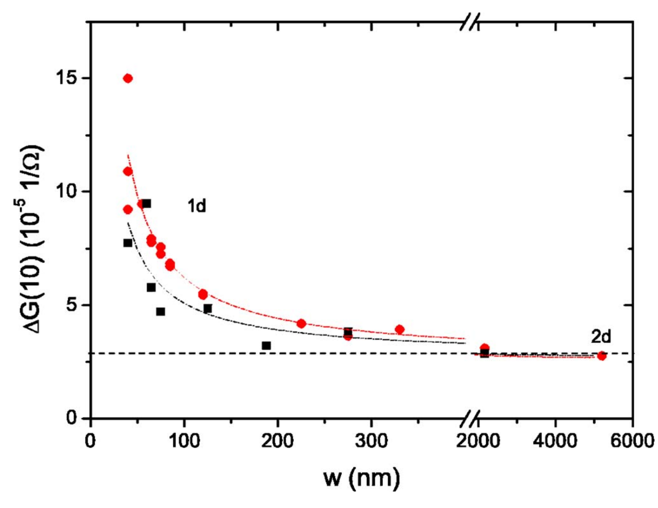

FIG. 5. (Color online) $\Delta G(10)$ as obtained from the resistance increase over one decade in temperature as a function of the wire width for cobalt wires capped with a 2 nm thick platinum layer (squares) in comparison to earlier results for cobalt wires capped with carbon (dots) (Ref. 21).

the reduced dimensionality of the system which enhances quantum corrections to the resistance.[25]

Figure 4 shows the resistance versus $\log_{10}(T)$ for a cobalt wire with a width of $w=40$ nm and a cobalt thickness of 30 nm in zero magnetic field. The resistance increase $\Delta G(10)=7.64\times10^{-5}\ \square/\Omega$ is even larger as compared to the case as shown in Fig. 3. This corresponds well to the theoretical prediction that quantum transport effects become more pronounced with decreasing dimensionality.[25] The full line represents a fit according to the model of Neuttiens *et al.*[24]

In order to investigate the 1D/2D transition with respect to EEI in greater detail we have prepared and measured the low-temperature resistance of Co nanowires with various widths ranging between $40\text{ nm} < w < 2160\text{ nm}$. Figure 5 shows $\Delta G(10)$ as a function of the wire widths. For comparison we have included some data of our previous investigation on Co wires capped with carbon (dots), which have been published earlier.[21] As one can see from Fig. 5, $\Delta G(10)$ continuously increases with decreasing wire width in accordance with our earlier results, indicating the gradual change from 2D to 1D behavior upon reduction of the wire width. In comparison to the carbon covered cobalt nanowires the platinum capped wires exhibit slightly reduced values of $\Delta G(10)$. This might be due to additional spin-disorder effects in the proximity of the Co/Pt interface induced by the polarization of platinum.[21] Note that for the analysis of our data we have used the formula derived by Neuttiens *et al.* for EEI in the transition regime between 1D and 2D,[24] where we kept $\alpha=0.95$ constant and fixed relying on its determination for the 2D case. This then also allows us to determine the electronic diffusion constant D by fitting the experimental data by using Eq. (2). We find that D decreases from $D=3.5\times10^{-3}\ \text{m}^2/\text{s}$ in the 2D case by about one order of magnitude, which indicates that electron diffusion is largely reduced when the wire widths are reduced. Surface scattering effects are most likely responsible for this reduction of electron diffusion. In conclusion, we have shown that WEL effects are not observed in platinum capped cobalt wires with wire widths ranging between 40 nm and 2 μm. The experimentally obtained resistance increase with decreasing temperature can be fully explained by a model of Neuttiens *et al.* for enhanced electron-electron interaction within the transition regime between one- and two-dimensional behavior. We would like to point out that capping the Co nanowires with platinum or carbon has no significant influence in these findings.

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