Magnetoresistance study of a thin α-tungsten film

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The resistance of an α-tungsten film was measured in the temperature range 0.35–30 K and in the magnetic field up to 2.5 T. The obtained dependences of the magnetoresistance are interpreted in terms of the Maki-Thompson-Larkin superconducting fluctuation effect; however, the magnitude of the magnetoresistance exceeds the theoretical value by an order of magnitude. From the magnetoresistance data the dephasing scattering length was determined and the contributions of magnetic impurities, electron-electron, and electron-phonon scatterings were extracted. The experimental electron-electron and electron-phonon scattering lengths are satisfactorily described by the existing theory.
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I. INTRODUCTION

In cryogenic particle detectors tungsten films are used as a sensitive thermometer operating at its superconducting transition temperature.[1,2] For example, due mainly to its very low critical temperature ($\sim$15 mK) the massive sapphire-tungsten detectors used in the dark matter search experiment CRESST show superior energy resolution and sensitivity (per mass of the detector).[3] Furthermore, tungsten films, as all superconducting phase transition thermometers operating in the millikelvin temperature range, are sensitive to nonthermal phonons created in a detector by a particle interaction.[4] The detection of this nonequilibrium response is important for the identification of scattering events and for the further detector development aimed to increase the detector mass without substantial deterioration of parameters. This may be achieved by investigating the energy transfer in these detectors including the tungsten-film thermometer.

For the past two decades weak localization magnetoresistance studies have been established as a powerful tool for investigating relaxation mechanisms of conduction electrons in many materials including various metal films and semiconductors. However, to date only limited data are available for tungsten. Tungsten films are found in three crystallographic modifications, α, β and γ, from which only the first one is stable and has a superconducting transition at low temperature ($\sim$15 mK).[5] The other two modifications are superconducting at substantially higher temperatures ($T > 1$ K).[6] In addition to the crystal structure effects, the critical temperature may be also influenced by disorder. Up to now only the study of ''high-T_c'' films has been carried out. These films show a strong spin-orbit scattering as well as the scattering on superconducting fluctuations.[7] To our knowledge, magnetoresistance of ''low-T_c'' α-tungsten films has not been investigated yet.

In this paper we report the magnetoresistance study of an α-tungsten film with $T_c = 28$ mK. The magnetoresistance data are interpreted according to the Maki-Thompson-Larkin mechanism of superconducting fluctuations in resistivity. Electron-electron and electron-phonon scattering lengths are satisfactorily described by the existing theory.

II. EXPERIMENT

The W film used in this work was prepared at the Max-Planck-Institut für Physik, Munich by using the same technique and methods as for the tungsten-sapphire cryogenic detectors.[1] The tungsten film was evaporated in a dedicated ultrahigh vacuum system (base pressure 2×10^{-11} Torr) from a tungsten single crystal (99.99%) by electron-beam evaporation. After outgasing the single crystal the film was sublimated in a background pressure of about 2×10^{-9} Torr at the rate of 0.15 nm/s on an epipolished c-plane surface of a sapphire plate held at 600 °C. The film thickness of 20 nm was measured with the Surface Profiler Tencor Instruments P-10 device. The x-ray diffraction analysis show the bcc structure of α-tungsten predominantly aligned along the [110] direction orthogonal to the film's surface. A superconducting transition was measured in a dilution refrigerator using a SQUID readout system.[1] A sharp transition with the width of 2 mK was measured at 28 mK. A possible reason for the T_c which is higher than that in the bulk crystal can be disorder in the film. In the bulk crystal the Fermi level lies near the minimum of the density of states; the disorder-induced smearing of the density of states leads to its increase on the Fermi level and to an increase of T_c. The same situation is observed in molybdenum films.[8]

The resistance was measured by a four-probe technique using a dc digital voltmeter ($5\frac{1}{2}$ digits, 100 nV resolution). To decrease the Joule heating the film was photolitographically patterned into a 28 cm long and 0.1 mm wide meander stripe which has the total resistance of $\sim 3\ \mathrm{k}\Omega$ at liquid He temperature. To check the etching quality, the resistance and magnetoresistance of a 1 mm long segment of the meander structure was measured at 4.2 K. The result compared with the full meander scales precisely with the length of the segment thereby excluding possible shorts in the structure due to the unetched remainder of the film.

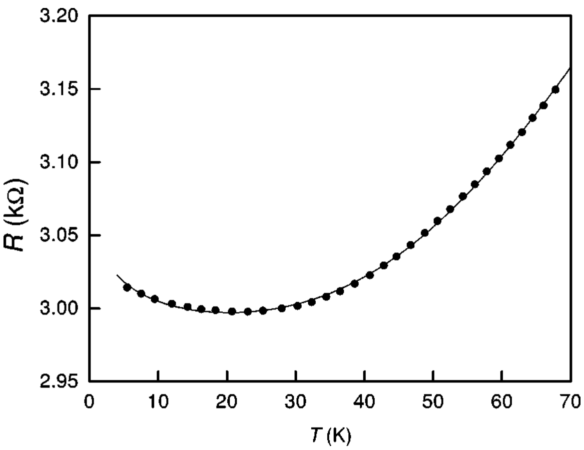

FIG. 1. The temperature dependence of the resistance. The solid line is the best fit of Eq. (1) with parameters $a=-2.21$ kΩ, $b=2.41\times10^{-5}$ kΩ K^{-2}, $c=1.21\times10^{-10}$ kΩ K^{-5}, and $R_0=3.053$ kΩ.

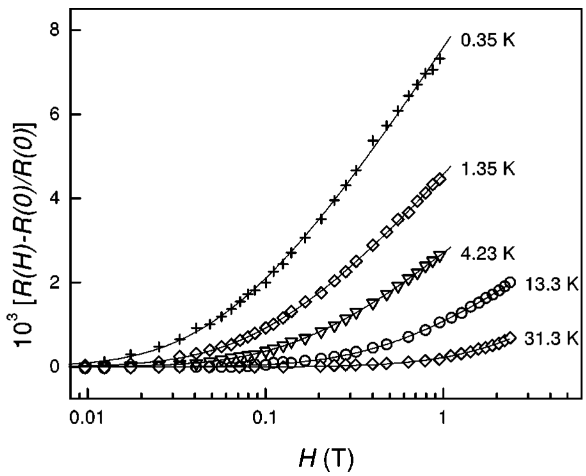

FIG. 2. The normalized magnetoresistance $[R(H)-R(0)]/R(0)$ versus the magnetic field H for selected temperatures. The symbols are experimental data and the solid lines are fits with the use of Eq. (2).

For magnetoresistance measurements the sample was mounted in a ^{3}He cryostat in the magnetic field produced by a superconducting solenoid, perpendicular to the plane of the film. Magnetoresistance dependences were measured by stabilizing the temperature at a certain value between 0.35–30 K. At temperatures below 1 K the measuring current was kept near 0.4 μA to avoid the self-heating of electrons.

III. RESULTS AND DISCUSSION

Figure 1 demonstrates the measured resistance as a function of temperature. As usual for metallic films, with decreasing temperature the resistance decreases, reaches minimum at 20 K, and then increases logarithmically for smaller temperatures. This dependence can be fitted by the formula[9,10]

$$R(T)=a\ \ln(T)+bF_{\rm RS}(T)+cF_{\rm BG}(T)+R_0, \tag{1}$$

where the first term describes the weak localization and Kondo effect, $bF_{\rm RS}(T)$ is the interference between electron-phonon and electron-impurity scattering,[11] $cF_{\rm BG}(T)$ is the Bloch-Grüneisen law, and R_0 is the temperature independent term. In the low-temperature limit $(T<\theta_{\rm Debye}/5)$ $F_{\rm RS}(T)=T^2$ and $F_{\rm BG}(T)=T^5$.[11,12]

Figure 2 demonstrates a semilogarithmic plot of the resistance as a function of the magnetic field H for selected temperatures. With decreasing temperature the magnetoresistance effect increases and is positive in the considered range of magnetic field. As known,[12] the classical low-field magnetoresistance of a two-band conductor is characterized by the H^2 rise with the subsequent saturation in stronger fields. The observed magnetoresistance in classically weak magnetic fields with asymptotic logarithmic dependence differs from this behavior and can be attributed to weak localization effects in two-dimensional systems.[13,14]

In this case contributions to the magnetoresistance from potential, inelastic, magnetic, and spin-orbit scatterings are described by the terms $A_i\psi(\frac{1}{2}+\hbar/4e\tau_k DH)$, where ψ is the digamma function, A_i are the respective weights, $\hbar$ is the Planck constant, e is the electron charge, D is the diffusion constant, and τ_k^{-1} are the linear combinations of inelastic τ_φ^{-1}, spin-orbit $\tau_{\rm so}^{-1}$, and elastic τ_0^{-1} scattering rates.[15] At low fields in the presence of a strong spin-orbit scattering, $\tau_{\rm so}^{-1}\gg\tau_\varphi^{-1}$, the relative change of the resistance is expressed by the formula

$$\frac{R(H)-R(0)}{R(0)}=A\left[\psi\left(\frac{1}{2}+\frac{\hbar}{4eL_\varphi^2H}\right)+\ln\left(\frac{4eL_\varphi^2H}{\hbar}\right)\right], \tag{2}$$

with only two parameters A and L_φ. The dephasing length L_φ is related with the phase-braking time τ_φ by the relation $L_\varphi=\sqrt{D\tau_\varphi}$, and $A=R_\square e^2/4\pi^2\hbar$, where $R_\square$ is the sheet resistivity. If $\tau_{\rm so}^{-1}>\tau_\varphi^{-1}$ Eq. (2) still approximates satisfactory the magnetoresistance, however in this case A depends on the ratio $\tau_\varphi/\tau_{\rm so}$ and on the temperature via τ_φ.

The contribution of the scattering on superconducting fluctuations (the Maki-Thompson-Larkin mechanism)[16] to the resistivity is also described by Eq. (2) with $A=(R_\square e^2/2\pi^2\hbar)\beta(T/T_c)$, where β is the function tabulated in Ref. 16 and T_c is the temperature of the superconducting transition.

As seen in Fig. 2, Eq. (2) gives a good fit to the measured data for different temperatures and in a wide range of magnetic fields that spans over two orders of magnitude. The fitting parameters as functions of temperature are given in Figs. 3 and 4.

The temperature dependence of L_φ is shown in Fig. 3, where the fitting curve corresponds to the formula

$$L_\varphi^{-2}=L_0^{-2}+K_{e\text{-}e}T+K_{e\text{-ph}}T^2, \tag{3}$$

with L_0, $K_{e\text{-}e}T$, and $K_{e\text{-ph}}T^2$ being the contributions of magnetic impurities, electron-electron, and electron-phonon interactions, respectively. Taking into account the observed low T_c, and that magnetic impurities with a concentration of a few parts per million (ppm) can reduce T_c by 1–10 mK,[17] we conclude that this concentration is less than several ppm

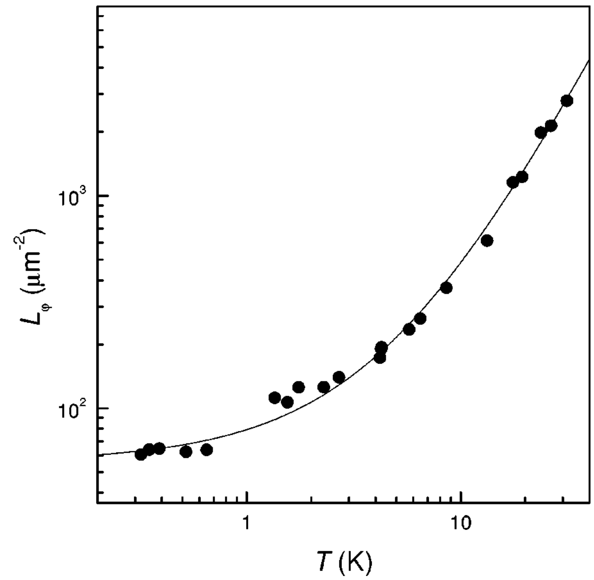

FIG. 3. The squared inverse of the dephasing length L_φ vs temperature. The symbols are the experimental data and the solid line is the best fit of Eq. (3). Fitting parameters are $L_0=0.133$ μm, $K_{e\text{-}e}=21$ $\mu\text{m}^{-2}\,\text{K}^{-1}$, and $K_{e\text{-ph}}=2.2$ $\mu\text{m}^{-2}\,\text{K}^{-2}$.

in the considered film. This value is in agreement with the lower estimate of magnetic impurity concentration of 0.03 ppm that follows from $L_0=133$ nm.

The inelastic scattering length due to electron-electron interaction is described by the formula[18]

$$K_{e\text{-}e}=\frac{k_B e^2}{2\pi D^2 \nu d\hbar^2}\ln\left(\frac{\pi D\nu d\hbar}{e}\right), \tag{4}$$

with only three material parameters: the electron density of states on the Fermi level ν, the film thickness d, and D. As follows from the heat capacity data[19] $\nu=2.7\times10^{22}$ $\text{eV}^{-1}\,\text{cm}^{-3}$, in good agreement with the band structure calculations.[20] With the fitted value $K_{e\text{-}e}=21$ $\mu\text{m}^{-2}\,\text{K}^{-1}$, from Eq. (4) we find $D=4.0$ cm^2/s, that is six times larger than the diffusion constant in tungsten films used in Ref. 7 This points to a larger mean free path 1 $=3D/v_F$ in the considered film. With the Fermi velocity[21] $v_F=3.15\times10^7$ cm/s, we get $l=3.8$ nm which is four times smaller than the film thickness.

We use quadratic temperature dependence of the electron-phonon scattering rate in Eq. (3) following a large number of works where this dependence was observed both in ''clean'' and ''dirty'' limits in two- and three-dimensional metals.[22] Recent results[10] for ''clean'' systems (the wave length of thermal phonons $\lambda_T \gg l$) attribute clearly the T^2 dependence to the interaction with transverse phonons. For these phonons in the considered tungsten film the condition of the ''clean'' limit is satisfied in the temperature range 10–30 K where the T^2 term is the largest one in L_φ^{-2}. To check the validity of the obtained values of D and l we use them to estimate $K_{e\text{-ph}}$ in Eq. (3). For this purpose we use the formula[10]

$$K_{e\text{-ph}}=1.125(b/R_0)\tau_0^{-1}D^{-1}, \tag{5}$$

where b and R_0 are the parameters of the resistance temperature dependence [see Eq. (1)] and τ_0 is the elastic scattering time. In a large number of metallic films electron-phonon scattering rates estimated from Eq. (5) agree well with results of weak localization and electron heating experiments.[10] Using $\tau_0=1.2\times10^{-14}$ s which follows from the value of l given above, $b=2.41\times10^{-5}$ kΩ K^{-2} and $R_0=3.053$ kΩ (see the caption of Fig. 1), we receive from Eq. (5) $K_{e\text{-ph}}=1.84$ $\mu\text{m}^{-2}\,\text{K}^{-2}$, that is close to 2.2 $\mu\text{m}^{-2}\,\text{K}^{-2}$, the result obtained from fitting the magnetoresistance data in Fig. 3.

The temperature dependence of the prefactor A in Eq. (2) is shown in Fig. 4. With decreasing temperature A increases monotonously. In the range $T<2$ K, where A rises steeply, L_φ is nearly constant. The opposite behavior of these quantities is observed for $T>2$ K: L_φ changes sharply while A is almost constant. This indicates that the observed dependence $A(T)$ is not connected with the interplay of spin-orbit and inelastic scatterings. Another possible source of this dependence and the observed positive magnetoresistance is the scattering on superconducting fluctuations described by the Maki-Thompson diagram. Really, the formula

$$A=L[\beta(T/T_c^*)+M], \tag{6}$$

with the fitting parameters L and M and $T_c^*=28$ mK describes satisfactorily the experimental data (see Fig. 4). From the Maki-Thompson-Larkin theory it follows that $R_\square=2\pi\hbar L/e^2=625$ Ω for the fitting value $L=7.7\times10^{-3}$. However, this $R_\square$ is 22 times larger than that calculated from the Drude formula $1/R_\square=e^2D\nu d$ using the diffusion constant estimated above. Moreover, if we take $R_\square=1.08$ Ω, the value obtained by direct measurement of the resistance of the meaner structure, the difference becomes even larger. The agreement with the theory is not improved by varying T_c^*—as follows from Fig. 4, an increase of T_c^* leads to a decrease of L but the fitting curve starts to deviate from experimental points, while L is still too large.

Thus, in spite of the possibility to describe the experimental results with Eq. (6), the effect appears to be amplified in comparison with the Maki-Thompson-Larkin theory. Notice

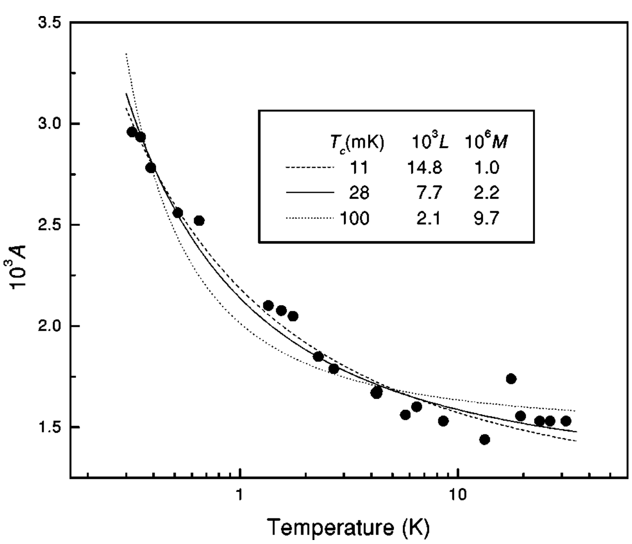

FIG. 4. The amplitude of the magnetoresistance A as a function of temperature. The curves represent the best fit of Eq. (6) for $T_c^*=11$, 28, and 100 mK. The values of fitting parameters are shown in the inset.

that previously an analogous amplified magnetoresistance has already been observed in a number of studies. For example, in Ref. 23 a low-field positive magnetoresistance was observed in a small structure of serially overlaid superconductor-normal metal-superconductor sheets. As in our experiment, the effect was substantially larger than that expected from the weak localization theory. To our knowledge there is no satisfactory explanation for this amplified effect which points to the necessity of close theoretical examination in this field.

In conclusion, we studied the magnetoresistance and electron relaxation processes in the α-tungsten film. Experimentally determined electron-electron and electron-phonon scattering lengths are satisfactorily described by the existing theory. The quantum interference contribution to the magnetoresistance is interpreted in terms of the Maki-Thompson-Larkin superconducting fluctuation effect, however its magnitude exceeds the theoretical value by an order of magnitude.

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