International Journal of Modern Physics B
Vol. 27, No. 8 (2013) 1350026 (8 pages)

DOI: 10.1142/S0217979213500264

1D AND 2D QUANTUM INTERFERENCE EFFECTS IN ELECTRON TRANSPORT IN Au FILM

B. I. BELEVTSEV*, E. Yu. BELIAYEV† and Yu. A. KOLESNICHENKO

B. Verkin Institute for Low Temperature Physics and Engineering,
Kharkov, 61103, Ukraine
** belevtsev@ilt.kharkov.ua*
† beliayev@ilt.kharkov.ua

Received 9 August 2012
Revised 21 December 2012
Accepted 7 January 2013
Published 13 February 2013

We present transport properties of quench-condensed Au film with nominal thickness ≈ 3.56 nm and $R_\square \approx 5$ kΩ for $T > 10$ K. This film has weak nonmetallic temperature dependence of resistance with logarithmic behavior above 10 K and somewhat stronger dependence at low temperatures. Above 3 K only two-dimensional (2D) quantum interference effects in electron transport have been found; whereas, below 3 K both one-dimensional (1D) and 2D effects of weak localization (WL) and electron–electron interaction (EEI) can be distinguished. This reflects inhomogeneous structure of the film near the thickness-controlled metal-insulator transition (MIT).

Keywords: Quantum interference effects; electron transport in low-dimensional systems; metal-insulator transition; quench-condensed ultrathin films.

1. Introduction

The film with size 2×0.1 mm^2 has been prepared by thermal evaporation of 99.99% purity Au from a Mo boat onto a properly prepared single-crystal sapphire plate. The film deposition and subsequent measurement its transport properties were carried out *in situ* in a high-vacuum oil-free ($\sim 10^{-7}$ Pa) cryostat with ^{3}He refrigerator and superconducting solenoid. A system of sliding masks was used for deposition of gold contacts (at room temperature) and subsequent deposition of the gold film (at $T \approx 70$ K with the rate 0.05 nm $\cdot$ s^{-1}). Resistance of the film during its growth has been followed (at applied voltage $U_{\text{appl}} = 1$ V), and deposition was stopped when $R_\square$ had reached 4.4 kΩ. The sample was held at the preparation temperature during 12 h up to stopping of small resistance variation due to structural relaxation inherent for cold deposited films. The measurements were carried out in the range $T = 0.4 - 30$ K and magnetic fields from -0.05 to $+5$ T. The resistance was determined by measuring currents in conditions of preset applied voltages U_{appl}. For

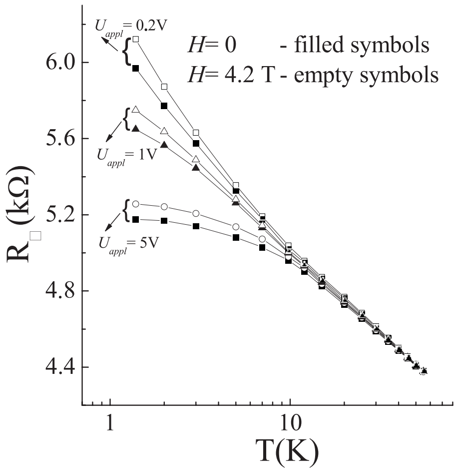

Fig. 1. The influence of electric and magnetic field on $R_\square(T)$.

our film the temperature dependence of resistance above 10 K and at high enough applied voltage (Fig. 1) follows logarithmic dependence ($\Delta R \propto \ln T$) and Ohm's law is obeyed to a good approximation. In the low temperature range (below 5 K) the exponential increase in resistance with decreasing voltage is seen.

According to our previous studies,[1] Au films with $R_\square \approx 5$ kΩ deposited at similar conditions formed percolation structure consisting of metallic islands separated by tunnel barriers — vacuum gaps and/or narrow and thin constrictions (bridges), and can be regarded as a 2D granular metal being on the threshold of the thickness controlled MIT. Small effective thickness of the investigated film (3.56 nm), high values of $R_\square$ (≥ 6 kΩ) and nonohmic behavior of its conductivity in low temperature range indicate that the film is partially discontinuous. These suggestions are fully in line with results of other authors, where it was found that for quench-condensed Au films the critical nominal thickness, marking the onset of conductivity $d_{\rm cr} \approx 2$ nm and for thicknesses moderately greater than $d_{\rm cr}$ they form a 2D disordered array of weak-connected islands with grain diameter,[2,3] d_G, in the range 10–20 nm.

The logarithmic law ($\Delta R \propto \ln T$) found in the film studied implies the presence of WL and EEI effects in conductivity of 2D systems.[4,5] The 2D conditions of manifestation of these effects are: $d < L_\varphi$, L_T, where d is the film thickness, $L_\varphi = (D\tau_\varphi)^{1/2}$ is the diffusion length of phase relaxation, $L_T = (\hbar D/kT)^{1/2}$ is the thermal coherence length in a normal metal, D is the electron diffusion coefficient and τ_φ is the electron phase relaxation time. The lengths L_φ and L_T are attributed to WL and EEI effects, respectively. Macroscopic disorder (percolating and/or granular structures) can induce a dramatic influence on these effects[4] up to their total depression. At the same time, a weak macroscopic disorder has no significant influence on WL and EEI unless the relevant lengths [$L_\varphi(T)$ and L_T] are larger than grain diameter, d_G, in 2D granular metal.

For homogeneous 2D system the contributions of WL and EEI effects lead to well-known logarithmic corrections to conductivity which can be rewritten as[4]:

$$\frac{\Delta R}{R} = -a_T \frac{e^2 R_\square^{\exp}}{2\pi^2\hbar} \ln\left(\frac{kT\tau_\varphi}{\hbar}\right), \tag{1}$$

where a_T is the constant order of unity, determined by dominating mechanism of phase relaxation in a specific system. For highly disordered Au films, taking into account strong spin–orbit interaction and neglecting spin–spin interaction, $a_T = 1/2$ is to expect theoretically. Experimentally we obtained the values of $a_T \approx 1$. So it looks like that only EEI makes contribution to logarithmic $R(T)$ dependence. We suggest that in the film studied the WL correction is significantly suppressed for some reasons so that EEI contribution has dominant effect on $R(T)$ which results in $a_T \approx 1$. The total suppression of WL is possible, for example, by application of strong enough magnetic field[5] ($H > H_\varphi = \hbar c/4eL_\phi^2$). As it is seen from Fig. 1, the application of field $H = 4.2\ T$, which is far larger than H_φ causes only weak effect on a slope of the linear part of dependence ΔR versus $\ln T$ above $T \approx 8$ K, so that it seems that WL is already significantly suppressed in the film even in zero field. This situation is possible in inhomogeneous (percolating or granular) 2D films.[6] In a system consisting of rather large grains separated by weak tunnel barriers appearance of the WL correction is determined by closed electron trajectories with self-intersections that increase the probability of back-scattering.[5] The size of these trajectories is about L_φ. The EEI correction is determined by length L_T. Since, generally, the relation $L_T \ll L_\varphi$ holds,[5] closed electron trajectories that determine WL effect should include more grains (and more intersections with grain boundaries) than those connected with EEI effect, so that weak intergrain connections can induce more depressing effect on WL correction than that on EEI one.

It is seen in Fig. 1 that ΔR begins to deviate from $\ln T$ dependence for $T \leq 5$ K at $U_{\mathrm{appl}} = 5$ V, and seems to go to saturation at low enough temperature. In this case an overheating effect cannot be excluded. The overheating should be, however, diminished with decreasing voltage. Really, the saturation has disappeared at $U_{\mathrm{appl}} = 1$ V, and for the lower voltage $U_{\mathrm{appl}} = 0.2$ V even an increased rate of the $R(T)$ growth with decreasing temperature is observed in low temperature range (Fig. 1). The latter case is presented more clearly in Fig. 2. Below 9 K a deviation from $\ln T$-law appears, which is presented in the inset as $\Delta R = f(T^{-1/2})$. This will be discussed in detail below.

Except for low field ($H \leq 0.02\ T$) and low-temperature ($T \leq 3.1$ K) ranges, the magnetoresistive curves correspond to the known expression describing MR due to WL effect for 2D systems (contribution of EEI to MR is negligible[5]). Positive MR was previously found[1] at and near percolation threshold in 2D discontinuous Au films. For low field range ($H < 1\ T$) the experimental MR data in the film studied (the same as in Ref. 1) can be described by[5]

$$\frac{\Delta R(H)}{R} = R_\square^{\mathrm{MR}} \frac{e^2}{4\pi^2\hbar} f_2\left(\frac{4eHL_\varphi^2}{\hbar c}\right), \tag{2}$$

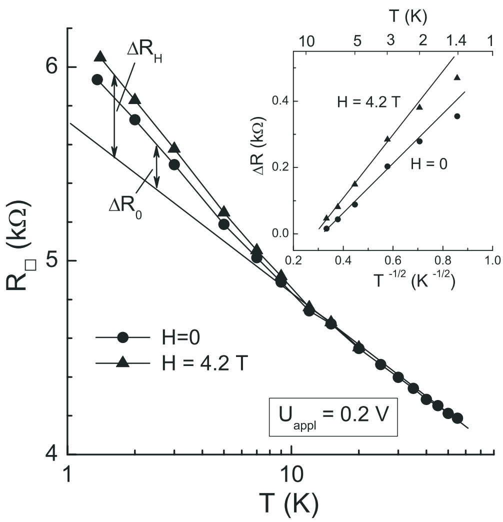

Fig. 2. Deviations of $R(T)$ from logarithmic behavior in low temperature range and the influence of magnetic field.

where $f_2(x) = \ln(x) + \psi(1/2 + 1/x)$, ψ — is digamma function, $R_{\square}^{\mathrm{MR}}$, used as a fitting parameter, is the resistance on the scale L_φ and for all our MR curves it was 20% less than "directly" measured $R_\square$ values reflecting inhomogeneous structure of the film studied. However, this difference is not crucial, and we have not found a significant effect of it on calculated values of L_φ. Generally $L_\varphi(T)$ is not essentially dependent on the applied voltage. In the range 3–10 K, the data for different U_{appl} practically coincide.

In low temperature range we have found a weak but quite distinct anomaly of MR behavior in low-field range Fig. 3, which is shown on a large scale in Fig. 4. This anomaly disappears with increasing field and is depressed with increase in temperature up to $T \geq 3.1$ K. The field at which the MR anomaly comes to saturation (and transition to 2D MR behavior takes place) increases with decreasing temperature being in the range $0.01 - 0.03\ T$. At low field ($H \leq 0.004\ T$) MR in the range of this anomaly follows the quadratic law $\Delta R(H)/R(0) \propto H^2$.

Results obtained permit us to assert that this low-temperature MR anomaly together with the above-mentioned deviations of $R(T)$ from logarithmic behavior at low temperature range (Fig. 2) are indications of 1D effects in film conductivity caused by inhomogeneous (granular) film structure near the percolation threshold. Indications of mixed 1D–2D conductivity in percolating gold films were first suggested to be seen in Ref. 4 and had been studied in specially made narrow films.[7–11] The theory of WL and EEI effects in 1D conductors has been developed in Refs. 5, 12 and 13.

As was mentioned above, a film near the thickness-controlled percolation threshold consists of weakly connected islands (grains). The intergrain connections are

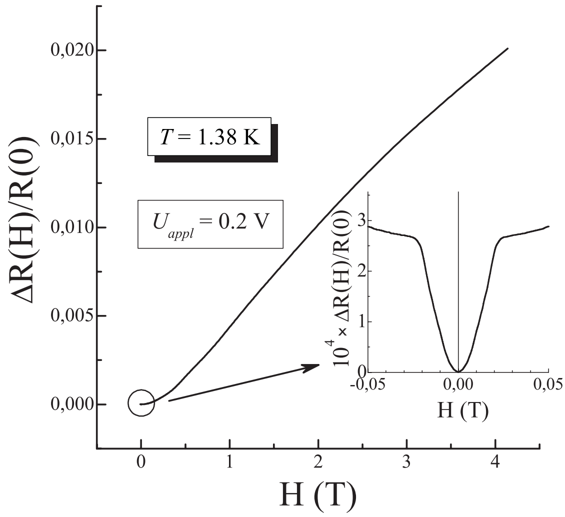

Fig. 3. Low temperature anomaly in low-field magnetoresistance.

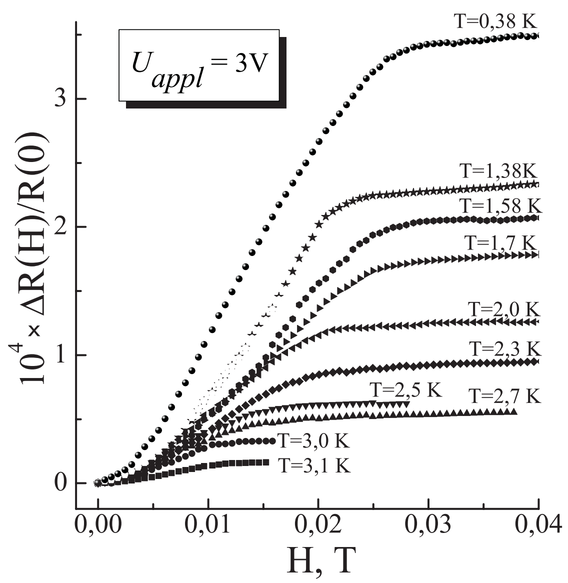

Fig. 4. The temperature dependence of low-field magnetoresistance.

determined by narrow constrictions, which can make tunnel junctions (like point contacts). These intergrain constrictions (contacts) are not the same throughout the system, thus, the conductivity is percolating. It is determined by the presence of optimal chains of grains with maximum probability of tunneling for adjacent pairs of grains forming the chain. At low enough temperature the tunneling can become activated. In conditions of activated conductivity, the number of conducting chains decreases with decreasing temperature, so that at low enough temperature a percolation network can consist of a few conducting channels or even come to a single conducting path.[14] It follows from the aforesaid that thin enough percolating film can manifest a mixed (1D and 2D) behavior of the interference effects in conductivity. In this case, similar as in Ref. 12, it can be suggested that quantum correction to conductivity has two contributions. Relative contribution of each term is temperature and magnetic-field dependent, so that, for example, the 1D term can disappear at high enough T or H.

For the appearance of 1D interference effects in electron transport both L_T and L_φ, must be greater than width, W, and thickness, d, of the 1D wire. It is known[5,8,10,11] that 1D effects become apparent only at low temperatures where the main contribution to the phase breaking gives the EEI with small energy transfer.[5,12,13] This is, so called, Nyquist phase-breaking mechanism which is especially important for low-dimensional systems.[5,10,11,13] For 1D systems characteristic time is denoted by τ_N, and corresponding phase relaxation rate is given by[5,13]:

$$\tau_N^{-1} = \left[\left(\frac{e^2 R_\square}{\hbar}\right)\left(\frac{kT}{\hbar}\right)\left(\frac{\sqrt{2D}}{W}\right)\right]^{2/3} \propto T^{2/3}\,. \tag{3}$$

The phase-relaxation length for this process is $L_N = (D\tau_N)^{1/2} \propto T^{-1/3}$. In line with our suggestion about mixed (1D and 2D) behavior of the film conductivity at low temperature we have compared the deviations of $R(T)$ from logarithmic 2D behavior at low temperature range (Fig. 2) with known 1D expressions. EEI correction to the resistance of a single film strip where $R_\square^{\rm str}$ is the sheet resistance of the strip (at $W < L_T$) is[5]:

$$\frac{\Delta R_{\rm int}(T)}{R} = \frac{e^2}{2\hbar}\frac{R_\square^{\rm str}}{W} L_T \propto T^{-1/2} \tag{4}$$

that functionally agrees rather well with $\Delta R(T)$ behavior shown in the inset of Fig. 2.

The dependence $\Delta R \propto T^{-1/2}$ in the film studied takes place also at high magnetic fields which depress completely WL effect, so this behavior should be attributed solely to EEI effect. Of course, WL effect can also influence quantum 1D transport.[5,13] However since gold is characterized by strong spin–orbit scattering (antilocalization), the corresponding WL correction, $\Delta R_{\rm loc}(T)$, is negative with $dR/dT < 0$ and its absolute value should decrease with decreasing temperature. So the EEI effect gives dominating contribution to the 1D quantum correction.[7,10,11]

Consider now in more detail the low-field anomaly of MR in low-temperature range (Fig. 3), which we have attributed to 1D effect as well. MR of 1D system in low magnetic field is determined exclusively by WL.[5] At low enough temperature the phase relaxation is determined by Nyquist mechanism. For strong spin–orbit scattering, the increase in resistance of 1D film due to WL correction in low magnetic fields ($L_N^2 \ll D\tau_H$) perpendicular to the film plane is[5,10–12]:

$$\frac{\Delta R_{\rm loc}(T,H) - \Delta R_{\rm loc}(T,0)}{R_0} \approx \frac{0.31}{2}\frac{e^2 R_\square^{\rm str}}{\hbar W}\frac{L_N^3}{D\tau_H} = \frac{0.31}{2}\frac{e^2 R_\square^{\rm str}}{\hbar}\frac{L_N^3 W}{12 L_H^4} \propto H^2/T\,, \quad (5)$$

where $\tau_H = 12L_H^4/DW^2$ and $L_H = \sqrt{\hbar c/2eH}$.

The amplitude of MR attributed to 1D WL found in this study ($\Delta R(H)/R \sim 10^{-4}$) agrees well with those found for other 1D Au films.[10,11,15–17] In order to determine the temperature and magnetic field dependence of the observed effect, we have fitted the experimental data $\Delta\sigma_{\rm exp}(H,T)$ by the function of the form $\alpha_T \times H^\beta$. The results of this fitting are shown in Fig. 5. Due to the lack of accuracy of the measurements and the limited temperature range of manifestations of the effect we cannot state the complete agreement between theory and experiment. However, for the most of the available experimental curves the values of the exponent β are in the range $\beta \approx 1.7 \div 1.91$, and the temperature behavior of coefficient α_T does not contradict to the proposed interpretation.

Obtaining values of L_N from Eq. (5) requires values of sheet resistance, $R_\square^{\rm str}$, of 1D strip and its width W. Macroscopic film resistance $R_\square^{\rm exp} \approx 5.2$ kΩ can be substituted for $R_\square^{\rm str}$. Rough estimate of W can be done from the values of transition field, $H_{\rm tr}$, at which the MR anomaly saturates (if to take magnetic lengths L_H for these values of $H_{\rm tr}$ as values of W). Taking nominally the estimated values of W ($\approx 160 \div 100$ nm) and $R_\square^{\rm exp} \approx 5.2$ kΩ, we have calculated L_N values at different temperatures with the help of Eq. (5) for low-field MR and in the range 1.5–3 K, we get the dependence $L_N \propto T^{-0.386}$ which is close enough to theoretical prediction $L_N = (D\tau_N)^{1/2} \propto T^{-1/3}$. It is important to mention as well that obtained values

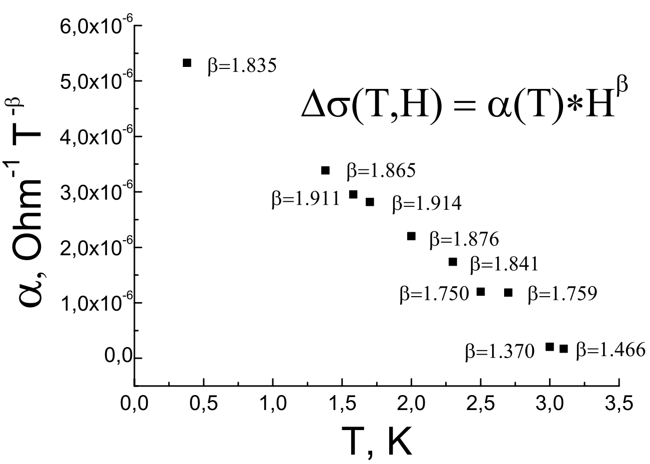

Fig. 5. Fitting experimental results for low-field magnetoresistance.

of L_N exceed the characteristic inhomogeneity scale — the grain size — which, according to Refs. 2 and 3, is between 10 nm and 20 nm in quench-condensed ultrathin gold films. This is the necessary condition for observation of WL effects in granular or island films.

2. Conclusion

The film studied is characterized by low-dimensional quantum interference effects in electron transport. Above 3 K only 2D effects in transport have been found; whereas, below 3 K both 1D and 2D effects in transport properties can be distinguished. This reflects inhomogeneous structure (and corresponding electron transport) of the film near the thickness-controlled MIT in ultrathin metallic films.

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