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QUANTUM TRANSPORT IN ULTRATHIN $CoSi_2$ POLYCRYSTALLINE FILMS

Z.D. Kvon [a], Kijoon Kim [b], Nam Kim [b], Hu Jong Lee [b], M.V. Budantsev [a] and M.R. Baklanov [a,c]
[a] Institute of Semiconductor Physics, 630090 Novosibirsk, Russia
[b] Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea
[c] IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

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Quantum transport in ultrathin $CoSi_2$ polycrystalline films was studied for the first time. The temperature corrections to the conductivity of these films and their anomalous magnetoresistance have been observed and investigated. It is shown that they are determined by the effects of interaction and weak localization with the strong spin-orbit and spin scattering taken into account. Unlike the epitaxial crystalline films reported previously our films including one with the thickness larger than 10 nm show no superconductivity down to the lowest temperature (0.2 K). In the thinnest film we used an unusual dimensional crossover from one dimensional behavior of quantum corrections to two dimensional have been observed with lowering temperature, supposedly due to changes of the characteristic correlation length in the sample, which consisted of meandrous conducting paths caused by the presence of pin-holes. © 1997 Published by Elsevier Science Ltd

Thin silicide films have been a subject of research for many years. Studies of their properties are stimulated by practical importance of these films for the operation of silicon-based devices (see [1], for example). In the earlier years much attention has been focused on the quantum transport properties of the films, since they have a number of characteristic features such as the hole type conductivity, the appearance of superconductivity at temperatures lower than 1 K, strong spin-orbit and spin scattering which provide useful means to investigate various quantum interference effects. Quantum transport experiments on $CoSi_2$ films have been reported by several authors previously [2–4]. However, all the experiments have been done with epitaxial crystalline $CoSi_2$ thin films.

In this article we report, for the first time, the results of experimental studies on the quantum transport in ultrathin $CoSi_2$ polycrystalline films. It is shown that quantum corrections to the conductivity is determined by the effects of interaction and weak localization with a strong spin-orbit and spin scattering taken into account. Unlike the epitaxial crystalline films reported previously our films including the thickest one showed no superconductivity down to the lowest temperature (0.2 K). In the thinnest film we used an unusual dimensional crossover of quantum corrections from one dimension (1D) to two dimensions (2D) was observed with lowering temperature, supposedly due to changes of the characteristic correlation length in the sample, which consisted of meandrous conducting paths caused by the presence of pin-holes.

The polycristalline cobalt-disilicide layers were fabricated by depositing pure metallic Co films on the silicon substrate using the solid state reaction. The initial thickness of the films was about 10–20 nm. In order to make the films thinner a number of additional plasma chemical etching was employed, which allowed us to get ultrathin films down to 1 nm in thickness with the initial composition of material intact. It should be noted that plasma etching does not change the material properties of the films because low energy ions in plasma do not penetrate into the film.

The samples used in the measurements had a Hall-bridge-type geometry where the samples were 50 μm wide and Hall bar contacts were 100 μm apart. The measurements were carried out at temperatures $T = 0.2 - 15$ K in magnetic fields in the range $B = 0 - 2$ T. We studied the three films, N1, N2, and N3, with the thickness of 12 nm, 2 nm and less than 1nm respectively. The major parameters of the films are listed

Table 1. Parameters of polycrystalline $CoSi_2$ films

N	Film thickness, nm	$\sigma_{\square}$, Ω^{-1}	D, cm^2/s	T_c, K
1	12	1.3 10^{-1}	46	<0.2
2	2	1.3 10^{-3}	3	<0.2
3	<1	1.2 10^{-4}	—	<0.2

in Table 1. It is necessary to note that the diffusion coefficient D was determined on the basis of the free electron model using expression $\sigma = e^2\nu D$(ν is the density of state). The D in the thinnest film (N3) was not determined because we could not find its thickness. The lack of the superconductivity in our samples down to 0.2 K, in contrast to the observed superconducting transition at about 1 K in epitaxial films with thickness even down to 2 nm, may have been caused by the enhanced structural disorder due to the polycrystallity of our films.

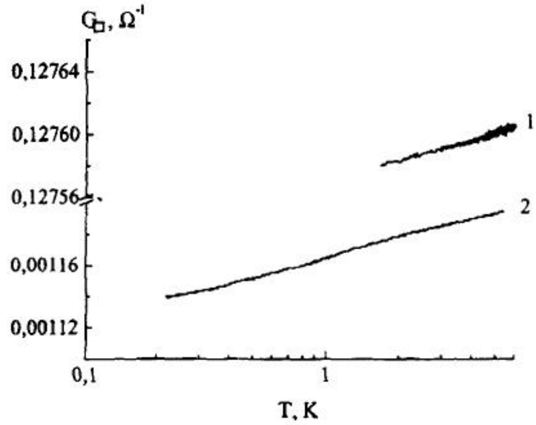

Fig. 1. ΔG vs $\ln T$ for the samples N1(1) and N2 (2). For both samples $A = 1.4 \pm 0.1$.

Figure 1 shows the typical sheet conductivity G for two thicker films, N1 and N2, as a function of temperature. As the temperature is lowered the values of G of both samples decrease logarithmically at the temperatures below 10 K. It should also be noted that the temperature dependencies of the films are not affected by the magnetic field up to 2 T. The logarithmic decrease of the conductivity indicates to the effects of the weak localization and interaction in quasi two-dimensions, the category to which the films in this study are supposed to belong. According to the theory of these effects the change of the conductivity is [5]

$$G(T) = \frac{e^2}{2\pi^2\hbar} A \ln \frac{T\tau}{\hbar}, \tag{1}$$

where $A = -\alpha p + (p-1)\beta(T) - 4 + 3 \cdot \frac{2+F}{F}\ln(1+\frac{1}{2}F)$.

The first term in the coefficient A is due to the weak localization [5] and depends on the phase relaxation (p is the exponent in the temperature dependence of the phase relaxation time $\tau_{\varphi} \propto T^{-p}$) , spin-orbit and spin scattering processes through the coefficient α. The second term in A is the contribution of carriers scattered by superconducting fluctuations ($\beta(T)$ is the constant of electron–electron interaction in the Copperon channel) [6]. The rest terms, together, are due to the interaction in the diffusion channel [7,8], where F corresponds to the contribution of the Hartree-like term. It is necessary to note that F also depends on the spin-orbit and spin scattering. For instance, if $\min\{\tau_{so}, \tau_s\} \sim \tau_p$ (τ_{so} is the time of spin-orbit scattering, τ_s is the time of spin scattering, τ_p is the time of elastic scattering) $F << 1$ [9, 10]. The spin-orbit and spin scattering rates in our films were obtained from the anomalous magnetoresistance (AMR). The typical results are shown in Fig. 2(a) for the film N2 at three different temperatures. The figure shows that the AMR in our films is positive as that of epitaxial films. As well-known, a positive AMR is caused by the strong spin-orbit scattering as the spin-orbit scattering time $\tau_{so} \sim \tau_p$. The theory gives the following expression for AMR in this case:

$$\Delta G(T) = -\frac{1}{2}\frac{e^2}{2\pi^2\hbar} f(x), \tag{2}$$

where $f(x) = \ln(x) + \Psi(\frac{1}{2} + x)$ and $x = 4DeH\tau_{\varphi}/\hbar c$.

Here $\Psi(x)$ is the logarithmic derivative of the gamma-function and τ_{φ} is the phase relaxation time due to inelastic collisions or spin scattering at paramagnetic impurities.

The solid curves in Fig. 2(a) illustrate the best fits of the data to the expression in Eq. (2). One can see good fits of the data to the theoretical expectations at all temperatures. Figure 2(b) shows the temperature dependence of the phase coherence time τ_{φ} determined from the fit. It is seen that the temperature dependence of τ_{φ} is weak at temperatures in the range of 2 K< T <8 K and even weaker at 0.6 K< T <2 K. It indicates that the main phase-breaking factor in the films gives a rather temperature-insensitive contribution. It is quite likely that, as in the epitaxial films investigated previously [3], this temperature insensitivity of τ_{φ} is from dominant spin scattering at paramagnetic defects in our polycrystalline samples. We also believe the logarithmic temperature dependence of our samples was not sensitive to an eternal magnetic field due to the strong spin orbit and spin scatterings as illustrated in the AMR of our samples. This observation leads to a conclusion that A should be close to 1 in Eq. (1), because $\alpha p << 1$ and $F << 1$ under the above scattering condition. The best fit (not shown) to the data in Fig. 1 gives $A = 1.4 \pm 0.1$. Thus, it follows that the temperature dependence of quantum corrections to conductivity of ultrathin polycrystalline $CoSi_2$ films is mainly due to the exchange

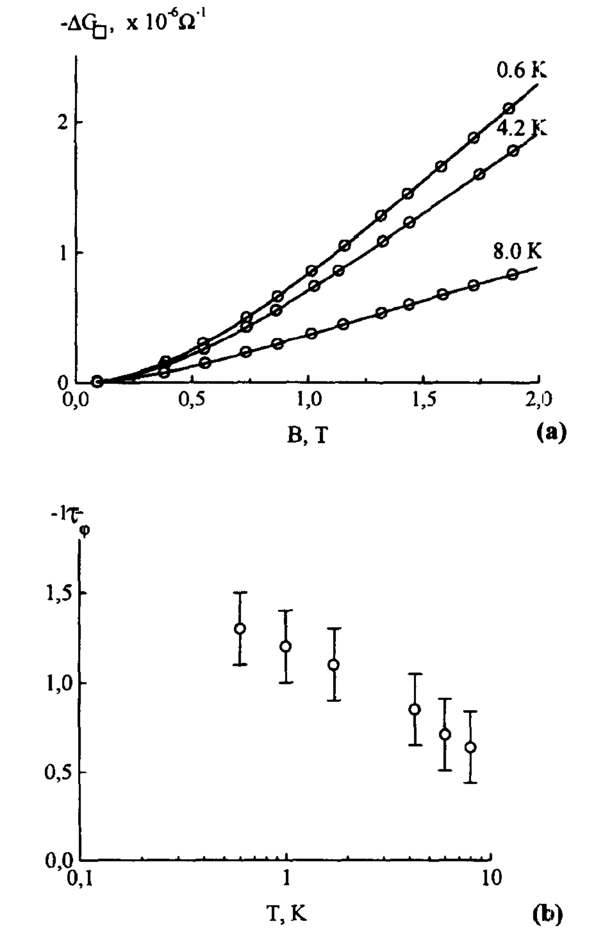

Fig. 2. (a) AMR $\Delta G(B)$ for sample N2 at three temperatures (points are the experiment, solid lines are the theory). (b)τ_φ vs T.

interaction term in Eq .(1). But we do not understand clearly yet why the value of A, in slight contradiction to the results of epitaxial films and theory, is larger than unity. As seen in Fig. 3(a), a noticeable unique feature of the thinnest film ($d \sim 1$ nm) is that the temperature dependence of the conductivity $G(T)$ is more complicated. The conductivity shows a logarithmic temperature dependence at temperatures below 2 K. Above 2 K, however, $G(T)$ deviates from the logarithmic temperature dependence, where it rather fits better to $T^{-1/2}$ temperature dependence. As mentioned above the logarithmic temperature dependence of ΔG reflects the behavior of quantum corrections to the conductivity due to electron-electron interaction in 2D, where the relation $d << L_T < \min\{W, L\}$ should be satisfied ($L_T = \pi[D/kT]^{1/2}$, L and W are the length and width of the sample, respectively). On the other hand , the square root temperature dependence of ΔG is valid in 1D, where the relation $\max\{d, W\} < L_T < L$ should be hold. Thus, the change in the temperature dependence of ΔG as observed only in the thinnest film N3 indicates an unusual dimensional crossover from 1D to 2D with lowering temperatures from 10 K to 0.2 K. We suppose that this behavior is closely related with the existence of the pin-hole structure as observed previously in similar films [11]. At higher temperatures ($T > 2$ K) we believe that a relation $L > L_T > W$ holds between the characteristic length scales of the samples. Thus we identify that W should be characteristic width of conducting channels between the holes and L is the size of the holes. The interaction term in G is, thus, due to quasi-one-dimensional nature of the conducting channels between the holes. In this case $\Delta G(T) \propto T^{-1/2}$ should be observed as in the experiment. At temperatures below 2 K however L_T becomes larger than L and the interaction effects give a logarithmic temperature dependence which corresponds to a two-dimensional case, and $\Delta G(T) \propto \ln T$ occurs as in Fig. 3(a). As shown in [11] $L \sim 100$ nm in the films with $d \sim 1$ nm. If we take the smallest measured value of the diffusion coefficient $D = 3$ cm^2/s we will obtain $L_T \approx 100$ nm at 2 K. Thus this estimate supports the observed exis-

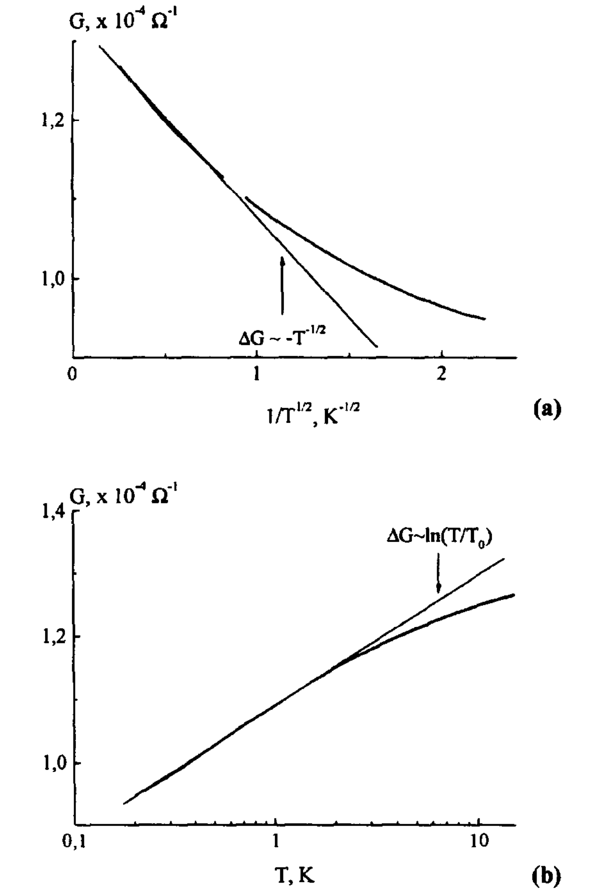

Fig. 3. (a) G vs $T^{-1/2}$ and (b) G vs $\ln T$ for sample 3.

tence of 1D-to-2D crossover of quantum corrections to conductivity in the $CoSi_2$ with thickness $d \sim 1$ nm with lowering temperature.

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