Antilocalization and electron-electron interaction in thin granular palladium-carbon mixture films

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We report measurements of the temperature dependence of the resistance in zero field and magnetic fields up to $B = 4$ T for thin granular Pd_xC_{1-x} films with various compositions x ($0.45 < x < 1$). The films have been prepared by codeposition of pure palladium and high-purity carbon onto quartz-crystal substrates at room temperature. The low-temperature resistance behavior of the Pd_xC_{1-x} mixture films clearly exhibits contributions from weak antilocalization (WAL) and electron-electron interaction (EEI) effects in two dimensions. The experimental results are analyzed by theoretical predictions due to WAL and EEI theories, using electron scattering times as obtained from magnetoresistance measurements. It is shown that the analysis yields a consistent description of the low-temperature dependence of the resistance in zero field as well as in magnetic fields up to 4 T.

I. INTRODUCTION

The resistance behavior of thin metallic films at low temperatures has attracted great interest, since theoretical calculations predicted additional contributions to the conductance based on weak localization (WL) and/or electron-electron interaction (EEI) in two dimensions.[1,2] The temperature dependence as well as the magnetic field dependence of these contributions is influenced by elastic, inelastic, spin-orbit, and spin-flip electron scattering processes.[3] Numerous experiments impressively confirmed the theoretical predictions for homogeneous films[4,5] and even for films of complex structures such as granular[6] or amorphous films.[7]

For *homogeneous* thin films a quantitative analysis of the resistance behavior as a function of both the temperature and the magnetic field in terms of explicit theoretical predictions[8] can be obtained. This has been shown, e.g., for Mg thin films by Gijs *et al.*,[9] who consistently described the magnetoresistance (MR) measurements as well as the temperature dependence of the resistance by the same set of electron scattering times. Recently Lin and Giordano[10] conducted extensive measurements of the low-temperature MR for Au-Pd films [two-dimensional (2D)] as well as Au-Pd wires [one-dimensional (1D)] to investigate the influence of the dimensionality on the various scattering times. The magnetic scattering time τ_s and the spin-orbit scattering time $\tau_{s.o.}$ are found to be consistent in one and two dimensions, whereas the inelastic phase-breaking time τ_Φ depends on the dimensionality of the samples.[11] However, there are still open questions. Lin and Giordano[11] found that for sputtered Au-Pd films the inelastic electron scattering time well agrees with theoretically predicted ones, whereas for evaporated Au-Pd films the experimentally determined scattering times are quite different.

We recently have reported results for the inelastic electron phase-breaking time $\tau_\Phi(T)$ of Pd_xC_{1-x} mixture films as obtained from MR measurements at low temperatures.[12] To check the magnitude of the scattering times $\tau_\Phi(T)$ we also investigated the resistance behavior of these films up to $T = 300$ K, from which $\tau_i(T)$, the inelastic scattering time, has been determined for $20 < T < 300$ K. We found $\tau_\Phi(T) = \tau_i(T)$ at temperatures, where τ_Φ, τ_i can be obtained by different methods, proposing that this gives an additional check for the determination of the absolute magnitude of τ_Φ. Using these data we analyze, in the present paper, the low-temperature dependence of the resistance in the presence of magnetic fields for the same Pd_xC_{1-x} samples as discussed in the previous paper.[12] It is well known that magnetic fields applied perpendicularly to the film plane allow one to separate localization and electron-electron interaction effects. At "large" magnetic fields only electron-electron interactions contribute to the temperature dependence of the resistance, since localization effects are suppressed. At zero field the anomalous resistance behavior is caused by both electron-electron interaction and localization effects. As to be expected from the observed positive MR for the Pd_xC_{1-x} films—due to strong spin-orbit scattering processes—weak antilocalization effects result in a much weaker logarithmic resistance increase in zero field than in finite magnetic fields. To obtain reliable data for the scattering times, it is necessary to check the consistency of the experimental data with respect to the temperature and magnetic field dependence of the resistance in two dimensions. It will be shown that the temperature dependence of the resistance of the Pd_xC_{1-x} mixture films in magnetic fields as well as in zero field can be well explained within the framework of theoretically predicted 2D contributions to the resistance.

II. THEORY

Additional logarithmic contributions to the resistance of thin films can be explained as resulting from weak electron localization (Refs. 1 and 3) and electron-electron interactions (Ref. 2) in two dimensions. Thin films of finite thickness t (quasi-2D films) are treated as to be two dimensional, if the inelastic diffusion length of the electrons L_i (Thouless length) becomes larger than the film thickness t. In the case of WL the diffusion length is given by $L_{\mathrm{WL}}=(D\tau_i)^{1/2}$ with $D=(v_F l_e)/3$ the diffusion constant, l_e the elastic electron mean free path, and τ_i the inelastic electron scattering time. For EEI the cutoff is defined by $L_{ee}=(D\hbar/k_B T)^{1/2}$ with D as given before. L_{ee} as well as L_{WL} increase with decreasing temperature. Thus, 2D contributions to the resistance of thin films occur below distinct temperatures $T_{2\mathrm{D}}\approx T_{\min}$ which are defined through $L_{ee}=t$ ($L_{\mathrm{WL}}=t$).

The temperature dependence of the 2D resistance due to WL in zero field is given by[3]

$$\delta\sigma^0(T)|_{\mathrm{WL}}=\frac{e^2}{2\pi^2\hbar}\left[\tfrac{1}{2}\ln\left[\frac{\tau_3}{\tau_1}\right]-\tfrac{3}{2}\ln\left[\frac{\tau_2}{\tau_1}\right]\right], \quad (1)$$

with

$$\tau_1^{-1}=\tau_i^{-1}(T)+\tau_e^{-1}+\tau_{\mathrm{s.o.}}^{-1},$$

$$\tau_2^{-1}=\tau_i^{-1}(T)+\tfrac{2}{3}\tau_s^{-1}+\tfrac{4}{3}\tau_{\mathrm{s.o.}}^{-1},$$

$$\tau_3^{-1}=\tau_i^{-1}(T)+2\tau_s^{-1},$$

where τ_e, $\tau_i(T)$, $\tau_{\mathrm{s.o.}}$, and τ_s are the mean electron scattering times for elastic, inelastic, spin-orbit, and spin-spin scattering, respectively.

Electron-electron interactions in disordered 2D systems lead to the contribution[8]

$$\delta\sigma^0(T)|_{ee}^{\mathrm{DC}}=\frac{e^2}{2\pi^2\hbar}g(F)\ln\left[\frac{k_B T\tau_e}{\hbar}\right] \quad (2)$$

(DC denotes diffusion channel), with

$$g(F)=4-\frac{6}{F}\left[\left[1+\frac{F}{2}\right]\ln\left[1+\frac{F}{2}\right]\right],$$

where F is the screening parameter.

Based on three-dimensional (3D) screening $F_{3\mathrm{D}}=[\ln(1+x)]/x$ with $x=(2k_F/\chi)^2$, k_F being the Fermi wave number and χ the inverse screening length λ. The contribution given by Eq. (2) results from electron scattering with small momentum transfer. If superconducting fluctuations—even far above T_c—have to be taken into account, two more contributions to the resistance as resulting from electron-electron interaction have to be considered.

The first one is given in Eq. (3a) leading from electron-electron interaction with large momentum transfer in the Cooper channel (CC):

$$\delta\sigma^0(T)|_{ee}^{\mathrm{CC}}=-\frac{e^2}{2\pi^2\hbar}\ln\left[\frac{\ln\left[\frac{k_B T_c\tau_e}{\hbar}\right]}{\ln\left[\frac{T_c}{T}\right]}\right]. \quad (3a)$$

The second one is given by

$$\delta\sigma^0(T)|_{ee}^{\mathrm{MT}}=-\frac{e^2}{2\pi^2\hbar}\beta(T)\ln\left[\frac{\hbar}{k_B T\tau_i}\right], \quad (3b)$$

with

$$\beta(T)=\frac{\pi^2}{6[\ln(T_c/T)]^2} \quad \text{for } |\ln(T_c/T)|\gg 1,$$

where MT denotes the so-called Maki-Thomson term, which diverges as the temperature reaches the superconducting temperature T_c.

The total correction to the (static) conductivity in two dimensions in zero magnetic field $\delta\sigma^0(T)$ is simply given by the sum of the contributions mentioned in Eqs. (1)–(3b):

$$\delta\sigma^0(T)=\delta\sigma^0(T)|_{\mathrm{WL}}+\delta\sigma^0(T)|_{ee}^{\mathrm{DC}}+\delta\sigma^0(T)|_{ee}^{\mathrm{CC}}+\delta\sigma^0(T)|_{ee}^{\mathrm{MT}}. \quad (4)$$

In the presence of a magnetic field the weak-localization theory predicts that for magnetic fields $B>B_i$ the WL contribution to the temperature dependence of the resistance becomes independent of temperature:

$$\delta\sigma^B(T)|_{\mathrm{WL}}=\text{const} \quad \text{for } B>B_i(T).$$

This holds below temperatures T_0, as defined by $B=B_i(T_0)$, where $B_i=\hbar/[4eD\tau_i(T_0)]$ is the characteristic magnetic field for inelastic electron scattering. For our samples the absolute magnitude of $B_i\approx 10^{-3}-10^{-2}$ T at T=4.2 K.

On the other hand, the sensitivity of electron-electron interactions to small magnetic fields is quite negligible.[8] Thus, the temperature dependence of the resistance in two dimensions in the presence of small magnetic fields is approximately given by

$$\delta\sigma^B(T)=\text{const}+\delta\sigma^0(T)|_{ee}^{\mathrm{DC}}+\delta\sigma^0(T)|_{ee}^{\mathrm{CC}}+\delta\sigma^0(T)|_{ee}^{\mathrm{MT}}. \quad (5)$$

The variation of the different contributions $\delta\sigma^0(T),\delta\sigma^B(T)$ over one decade of temperature is given by $\Delta\sigma=\delta\sigma(10\text{ K})-\delta\sigma(1\text{ K})$ where $\Delta\sigma$ can be experimentally determined by

$$\Delta\sigma\equiv\frac{R_\square(1\text{ K})-R_\square(10\text{ K})}{R_B^2},$$

with $R_\square=\rho/t$ the sheet resistance and R_B the (sheet) Boltzmann resistance.

III. EXPERIMENT

Thin granular Pd_xC_{1-x} films are prepared by codeposition of pure palladium (less than 1 ppm magnetic impurities) and high-purity carbon onto quartz-crystal substrates at room temperature in an ultrahigh-vacuum (UHV) system. During evaporation the system pressure is kept below 1×10^{-7} mbar. The total film thickness t is determined by two separate quartz-crystal oscillators, which independently monitor the deposition of carbon and palladium. Both oscillator systems are calibrated by optical interferometry (Tolansky method). In each run three Pd_xC_{1-x} samples with fixed concentration x are deposited simultaneously. One sample is used for the resistance measurements, the others for x-ray, electron-probe-microanalysis (EPMA), and transmission-electron-microscopic (TEM) investigations, respectively. Through a relative variation of the evaporation rates for C and Pd, various films of different compositions ($0<x<1$) and thicknesses of $10<t<60$ nm are prepared. As revealed by TEM investigations the Pd_xC_{1-x} films consist of small Pd clusters with mean diameters of $\Phi=6$ nm which form a well-connected structure in a carbon matrix for concentrations x well above the percolation threshold $x_p=0.3$. Details of the structural analysis of the films are given elsewhere.[13]

The temperature dependence of the resistance (four-terminal dc technique) of the various Pd_xC_{1-x} films is measured within $3<T<300$ K *in situ* as well as in a separate ^{4}He cryostat ($1.7<T<300$ K) where magnetic fields up to 5 T can be applied. Within the accuracy limits, no difference in the resistance behavior is found when using the second setup, i.e., when exposing the films to air. dc currents are used between 1 and 100 μA. In this current range the current-voltage characteristic of the Pd_xC_{1-x} films is found to be linear. The overall resistance behavior of the samples above the percolation threshold is *metallic* as revealed by the linear temperature dependence of the resistance. The low-temperature parts of the resistance of the films clearly exhibit 2D behavior, i.e., logarithmic resistance increase with decreasing temperature. Below the percolation threshold ($x<x_p$) the Pd_xC_{1-x} films show exponential increase of the resistivity[14] according to variable-range hopping following $\ln(R)\sim(T_0/T)^\alpha$.

IV. RESULTS

Figure 1 shows the resistivity versus the logarithm of the temperature for four different Pd_xC_{1-x} films at low temperatures. As one can see from Fig. 1 resistance minima occur at various temperatures T_{min} which shift to higher temperatures with increasing carbon content. Below T_{min} the resistivity logarithmically increases with decreasing temperature. Following the experimental data in Fig. 1 (from bottom to top) the resistance increase becomes more pronounced with increasing carbon content.

The magnitude of the various resistance increases is given by the change of the resistance per square $R_\square(T)$ over one decade of temperature $\Delta\sigma$ as defined above. The zero-field values $\Delta\sigma^0|_{expt}$ are listed in Table I.

Table I also contains other relevant parameters for the Pd_xC_{1-x} films investigated: $R_{\square\,min}$ the resistance per square at T_{min}, t the mean thickness of the Pd_xC_{1-x} films, and τ_e the elastic mean free path of the electrons. Data for τ_e have been evaluated assuming Drude's law with $n=2.45\times10^{28}$ m^{-3} (Ref. 15). The reliability of the determination of τ_e for the present samples has been discussed in a previous paper.[12] Figure 2 typically shows the resistance $R_\square$ versus $\ln(T)$ for a $Pd_{0.45}C_{0.55}$ film at

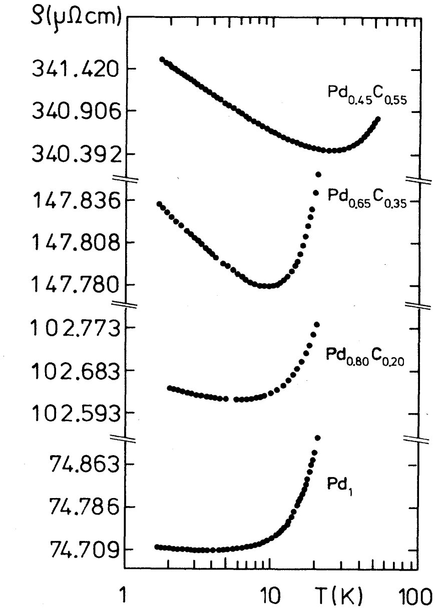

FIG. 1. Resistivity vs logarithm of temperature for four Pd_xC_{1-x} mixture films with $x=1$, 0.8, 0.65, and 0.45.

various magnetic fields between zero and $B=4$ T. As one can see from Fig. 2 the magnetoresistance is positive and becomes larger with decreasing temperature. This has been analyzed in detail in a previous work[12] for the same samples as discussed in the present paper. We found for the phase-coherence time $\tau_\Phi(T)$ a power-law dependence $\tau_\Phi(T)\sim T^{-p}$ with $p=1$ below 5 K and with $p=2$ above 5 K. The absolute values of τ_Φ at 1 K as extrapolated from the experimental data (MR) are given in Table II which also shows the values for p and $\tau_{s.o.}$ the spin-orbit scattering time.

As pointed out above, we concentrate in the present work on the analysis of the temperature dependence of the resistance $R_\square(T)|_{B=\text{const}}$ as a function of magnetic field. As one can see from Fig. 2 the slopes of the $R_\square(T)|_B$ curves slightly increase with increasing magnetic field and completely saturate above a distinct field B_{sat}, which is around $B=1$ T. Figure 3 shows the relative

TABLE I. x is the composition, $R_{\square\,min}$ the resistance per square at minimum temperature, t the film thickness, τ_e the mean elastic electron scattering time, and $\Delta\sigma^0|_{expt}$ the resistance variation over one decade of temperature in zero magnetic field.

x	$R_{\square\,min}$ ($\Omega/\square$)	t (nm)	τ_e (s)	$\Delta\sigma^0_{expt}$ $(\Omega/\square)^{-1}$
1.0	19.4	38.4	3.9×10^{-15}	3.32×10^{-6}
0.8	39.2	26.1	2.8×10^{-15}	9.39×10^{-6}
0.65	21.7	68.1	1.9×10^{-15}	2.52×10^{-5}
0.45	132.5	25.7	8.5×10^{-16}	2.61×10^{-5}

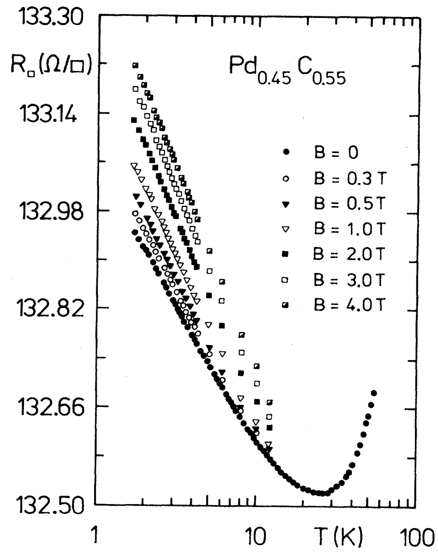

FIG. 2. Resistance per square vs logarithm of temperature for the $Pd_{0.45}C_{0.55}$ mixture film in zero field and various magnetic fields up to $B = 4$ T.

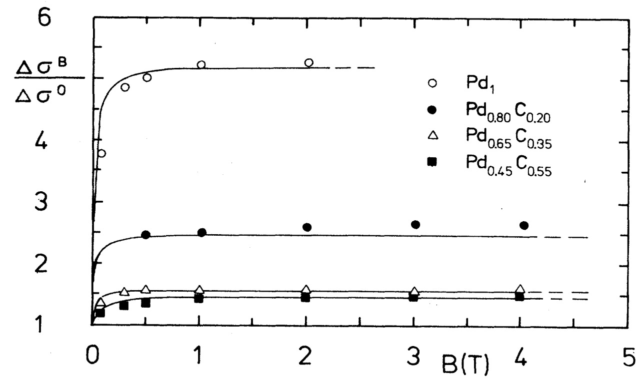

FIG. 3. Relative change of the slopes of the $R_\square(T)$ curves vs magnetic field for Pd_xC_{1-x} mixture films with compositions $0.45 < x < 1$. Dots show experimental data and solid lines are calculated from 2D theory (see text).

change of the slopes, given by $\Delta\sigma^B|_{\rm expt}/\Delta\sigma^0|_{\rm expt}$ over one decade of temperature versus magnetic field B for the present Pd_xC_{1-x} samples. The solid squares denote the data for the $Pd_{0.45}C_{0.55}$ film as shown in Fig. 2; the open triangles, solid circles, and open circles denote the data for the Pd_xC_{1-x} films with $x = 0.65$, 0.8, and 1.0, respectively. The solid lines are calculated using the theoretical predictions as will be discussed in the next section. As one can see from Fig. 3, $\Delta\sigma^B/\Delta\sigma^0$ increases rapidly as a function of B for low magnetic fields ($B < 1$ T) and saturates above approximately $B_{\rm sat} = 1$ T for all the samples investigated (see Table II). The saturation values $\Delta\sigma^{B > B_{\rm sat}}/\Delta\sigma^0$ decrease from 5.2 to about 1.5 with increasing carbon content.

V. DISCUSSION

As shown in Fig. 2 (and for the other Pd_xC_{1-x} samples in Fig. 3), applying a magnetic field perpendicular to the film plane causes the slopes of the low-temperature logarithmic resistance to increase (positive MR) and to saturate above magnetic fields $B > B_{\rm sat} \approx 1$ T. Following WL theory the temperature variation of the 2D resistance in the presence of magnetic fields is expected to be completely suppressed for magnetic fields $B > B_i(T_0) = \hbar/[4eD\tau_i(T_0)]$, at temperatures $T < T_0$.

With $v_F = 5.3\times10^5$ m/s (Ref. 16), we find B_i(1 K)≈ 0.01 T at 1 K and B_i(10 K)≤ 0.4 T at 10 K to be much smaller than $B_{\rm sat}$ for the Pd_xC_{1-x} films. Thus, WL contributions to the resistance of the Pd_xC_{1-x} films are completely suppressed for $B > B_{\rm sat}$, from which it follows that the remaining logarithmic resistance increases in the presence of large magnetic fields are caused by electron-electron interactions (EEI) (as far as $T < 10$ K). According to Eq. (5) there are several contributions from EEI in two dimensions, which are expressively given in Eqs. (2), (3a), and (3b). Since we find from MR measurements $p = 1$ at temperatures $T < 5$ K for the present Pd_xC_{1-x} mixture films (see Table II), the Maki-Thomson term $\delta\sigma^0(T)|_{ee}^{\rm MT}$ becomes zero and can be omitted.[8] Thus, only two contributions are important as resulting from EEI in the diffusion channel [Eq. (2)] and in the Cooper channel [Eq. (3a)]. According to Eqs. (2) and (3a), there are two different parameters, i.e., $g(F)$ and T_c, which determine the absolute magnitude of $\delta\sigma^0(T)|_{ee}$. The function $g(F)$ continuously decreases with increasing F with $0 < F < 1$. For F approaching zero $\lim_{F\to 0} g(F) = 1$ and, hence, $\Delta\sigma^0|_{ee}^{\rm DC} = 2.86\times10^{-5}$ $(\Omega/\square)^{-1}$, which is the maximum value of $\Delta\sigma^0|_{ee}^{\rm DC}$. As one can see from Table III, the experimentally determined values $\Delta\sigma^B|_{\rm expt}$ are smaller than 2.86×10^{-5} $(\Omega/\square)^{-1}$ for the Pd_xC_{1-x} films with $x = 1$ and 0.8.

For the samples with higher carbon content ($x = 0.65$ and 0.45), $\Delta\sigma^B|_{\rm expt} = 3.9\times10^{-5}$ $(\Omega/\square)^{-1}$ is much larger than the maximum value of $\Delta\sigma^0|_{ee}^{\rm DC} = 2.86\times10^{-5}$ $(\Omega/\square)^{-1}$. This means that, at least for these two samples, electron-electron interactions resulting from both the diffusion channel and the Cooper channel also have to be taken into account. Since we did not observe any superconducting transition temperature T_c for the various Pd_xC_{1-x} samples within the temperature region $2 < T < 300$ K, we have no possibility to determine $\Delta\sigma|_{ee}^{\rm CC}$ definitely. However, we can give some approximate con-

TABLE II. x is the composition, τ_i(1 K) the mean inelastic scattering time at $T = 1$ K, $p(T < 5$ K) the exponent for the power law $\tau_i(T) \sim T^{-p}$ from MR measurements, $\tau_{\rm s.o.}$ the mean spin-orbit scattering time, and $B_{\rm sat}$ the saturation field.

x	τ_i (1 K) (s)	$p(T < 5$ K)	$\tau_{\rm s.o.}$ (s)	$B_{\rm sat}$ (T)
1.0	4.75×10^{-11}	1	4.5×10^{-14}	1
0.8	5.4×10^{-11}	1	4.5×10^{-14}	1
0.65	9.0×10^{-11}	1	4.5×10^{-14}	1
0.45	5.0×10^{-11}	1	4.5×10^{-14}	1

TABLE III. x is the composition, $\Delta\sigma^B|_{\rm expt}$ the resistance variation over one decade of temperature in magnetic fields $B > B_{\rm sat}$, $\Delta\sigma|_{ee}^{\rm CC}$ the resistance variation over one decade of temperature arising from the Cooper channel, $\Delta\sigma|_{ee}^{\rm DC}$ the resistance variation over one decade of temperature arising from the diffusion channel, F the screening parameter, and T_c the superconducting transition temperature.

x	$\Delta\sigma_{\rm expt}^B$ $(\Omega/\square)^{-1}$	$\Delta\sigma_{ee}^{\rm CC}$ $(\Omega/\square)^{-1}$	$\Delta\sigma_{ee}^{\rm DC}$ $(\Omega/\square)^{-1}$	F	T_c
1.0	1.72×10^{-5}	0.50×10^{-5}	1.24×10^{-5}	0.85	0.01
0.8	2.32×10^{-5}	0.50×10^{-5}	1.85×10^{-5}	0.50	0.01
0.65	3.92×10^{-5}	1.32×10^{-5}	2.62×10^{-5}	0.10	0.30
0.45	3.93×10^{-5}	1.36×10^{-5}	2.68×10^{-5}	0.05	0.32

clusions. It is well known,[17,18] that pure Pd becomes superconducting at temperatures T_c (up to about $T_c \approx 10$ K) when adding hydrogen (interstitially). Since, we cannot rule out the influence of residual gases on the condensation process during preparation of the Pd_xC_{1-x} samples, it is possible that small amounts of hydrogen are dissolved into the Pd clusters. Thus, the occurrence of superconducting fluctuations above T_c, and its influence on the 2D behavior of the resistance due to electron-electron interaction is very likely, although we cannot determine T_c itself. To estimate $\Delta\sigma|_{ee}^{\rm CC}$ we plotted $\delta\sigma(T)|_{ee}^{\rm CC}$ [Eq. (3a)] versus $\ln(T)$ for various superconducting temperatures $T_c < 1$ K. We found that, for $T_c > 0.35$ K, $\delta\sigma(T)|_{ee}^{\rm CC}$ exhibits an upwardly bent curve at low temperatures which has not been observed for our samples (see, e.g., Fig. 2). Taking much lower values for T_c, $\delta\sigma(T)|_{ee}^{\rm CC}$ shows a "pure" logarithmic behavior as a function of temperature. For values of $T_c \le 0.01$ K we find $\Delta\sigma|_{ee}^{\rm CC} = 5\times10^{-6}$ $(\Omega/\square)^{-1}$ to be independent on the transition temperature. Thus, once assuming that superconducting fluctuations are present at low temperatures for our Pd_xC_{1-x} mixture films, $\Delta\sigma|_{ee}^{\rm CC} = 5\times10^{-6}$ $(\Omega/\square)^{-1}$ gives the lowest limit of this contribution to the resistance. This we take into account for the Pd_xC_{1-x} samples with small carbon content. To explain the experimental data for the samples with $x = 0.65$ and 0.45, it is necessary to take larger values for T_c. The most appropriate values of T_c and the corresponding data of $\Delta\sigma|_{ee}^{\rm CC}$ are listed in Table III. We again emphasize that these values are estimated very roughly. However, the order of magnitude of the estimated T_c seems to be correct. At least the presence of superconducting fluctuations far above T_c appear to be consistent with our experimental findings. With $\Delta\sigma|_{ee}^{\rm CC}$ as estimated above, the DC contribution to EEI, $\Delta\sigma|_{ee}^{\rm DC} = \Delta\sigma^B|_{\rm expt} - \Delta\sigma|_{ee}^{\rm CC}$, can be analyzed. As one can see from Eq. (2), the amplitude of this contribution is given by $g(F)$, which can be determined by fitting $\delta\sigma(T)|_{ee}^{\rm DC}$ to the experimental data. This yields the screening parameter F which is listed in Table III for the various Pd_xC_{1-x} thin mixture films. As one can see from Table III, F becomes gradually smaller with increasing carbon content. For the $Pd_{0.45}C_{0.55}$ sample $F \approx 0$, or $g(F) \approx 1$. Since the screening parameter $F = F_{3d}$ approaches zero for large screening length λ, electron-electron interactions become more important with increasing disorder which has been observed by several authors[10,16,19] for "pure" palladium thin films.

Gijs *et al.*[15] measured the conductance for various Al-Al_2O_3-Pd tunnel junctions. They found the density of states at the Fermi energy to exhibit an inverse cusp with a logarithmic energy dependence, referring to EEI in two dimensions. For Pd thin films with large disorder (sheet resistance R_B) the anomaly at the Fermi energy becomes more pronounced due to enhanced EEI, which clearly demonstrates the influence of disorder on the strength of EEI. Thus, the behavior of the screening parameter F approaching zero with increasing carbon content for the present Pd_xC_{1-x} films appears to be in reasonable agreement with other experimental results.

Table IV shows the logarithmic resistance contribution $\Delta\sigma^0|_{\rm expt}$ in *zero* magnetic field for the present Pd_xC_{1-x} thin mixture films, which are determined from, e.g., Fig. 1. Table IV also shows the values for $\Delta\sigma|_{ee}$ which are given by $\Delta\sigma|_{ee} = \Delta\sigma^B|_{\rm expt}$ (Table III) as discussed above.

$\Delta\sigma|_{\rm WL}$ is experimentally determined, taking the difference of $\Delta\sigma$ for zero magnetic fields and for fields $B > B_{\rm sat}$, according to Eqs. (4) and (5), $\delta\sigma^0(T) - \delta\sigma^B(T) = \delta\sigma^0(T)|_{\rm WL} - \text{const}$; which gives $\Delta\sigma|_{\rm WL} = \Delta\sigma^0|_{\rm expt} - \Delta\sigma^B|_{\rm expt}$ over one decade of temperature. $\Delta\sigma|_{\rm WL}^{\rm MR}$ refer to the values as calculated by Eq. (1) using the MR data (Table II).

As one can see from Table IV, $\Delta\sigma|_{\rm WL} = -1.41\times10^{-5}$

TABLE IV. x is the composition, $\Delta\sigma^0|_{\rm expt}$ the resistance variation over one decade of tempeature in zero magnetic field, $\Delta\sigma|_{ee}$ the resistance variation over one decade of temperature $\Delta\sigma|_{ee} = \Delta\sigma|_{ee}^{\rm CC} + \Delta\sigma|_{ee}^{\rm DC}$, $\Delta\sigma|_{\rm WL}$ the resistance variation over one decade of temperature $\Delta\sigma|_{\rm WL} = \Delta\sigma^0|_{\rm expt} - \Delta\sigma|_{ee}$, and $\Delta\sigma|_{\rm WL}^{\rm MR}$ the resistance variation over one decade of temperature calculated by Eq. (1) with parameters from MR.

x	$\Delta\sigma_{\rm expt}^0$ $(\Omega/\square)^{-1}$	$\Delta\sigma_{ee}$ $(\Omega/\square)^{-1}$	$\Delta\sigma_{\rm WL}$ $(\Omega/\square)^{-1}$	$\Delta\sigma_{\rm WL}^{\rm MR}$ $(\Omega/\square)^{-1}$
1.0	0.33×10^{-5}	1.74×10^{-5}	-1.41×10^{-5}	-1.41×10^{-5}
0.8	0.94×10^{-5}	2.35×10^{-5}	-1.41×10^{-5}	-1.41×10^{-5}
0.65	2.52×10^{-5}	3.94×10^{-5}	-1.42×10^{-5}	-1.41×10^{-5}
0.45	2.61×10^{-5}	4.03×10^{-5}	-1.42×10^{-5}	-1.40×10^{-5}

$(\Omega/\square)^{-1}$ for all the Pd_xC_{1-x} samples investigated. The negative sign of $\Delta\sigma|_{WL}$ indicates that weak-*anti*localization (WAL) effects are present in our samples, as to be expected from the MR measurements due to the occurrence of strong spin-orbit scattering. The magnitude of $\Delta\sigma|_{WL}$ is very close to the theoretically predicted values for the symplectic case, where $\alpha_B=-\frac{1}{2}$, which provides $\Delta\sigma|_{WL}=-1.42\times10^{-5}$ $(\Omega/\square)^{-1}$. As one can see from Table IV, there is an excellent agreement between the experimentally determined values $\Delta\sigma|_{WL}$ and theoretically predicted ones $\Delta\sigma|_{WL}^{MR}$. Here the evaluation of $\Delta\sigma|_{WL}^{MR}$ is based on the data given in Table II, i.e., in the limit for $B>B_{sat}$. For $B<B_{sat}$ we calculate $\delta\sigma(T)|_{WL}^{MR}$ by Eq. (1) for different magnetic fields B using the fact that the magnetic electron scattering time τ_s is correlated to a characteristic field $B_s=\hbar/4De\tau_s$. Taking $B=B_s$ provides the magnetic field dependence of $\delta\sigma(T)|_{WL}^{B}$. Including EEI effects which are found to be independent on small magnetic fields[8] yields the total 2D quantum correction as a function of temperature for various magnetic fields $\delta\sigma(T)|^{B}=\delta\sigma(T)|_{WL}^{B}+\delta\sigma(T)|_{ee}$.

Figure 3 shows $\Delta\sigma^B$ normalized by $\Delta\sigma^0$ as calculated (solid lines) and as experimentally determined (different symbols) from the various slopes of the $R_\square(T)$ curves, e.g., plotted in Fig. 2. As one can see from Fig. 3, $\Delta\sigma^B/\Delta\sigma^0$ strongly increases for low magnetic fields up to about 0.5 T.

As discussed above, we find strong WAL effects to be present in the Pd_xC_{1-x} mixture films which cause a negative contribution to the resistance in 2D $[\Delta\sigma^0|_{WL}=-1.42\times10^{-5}$ $(\Omega/\square)^{-1}]$. With increasing magnetic field, WAL effects are gradually cancelled and completely suppressed for $B>B_{sat}$ $[\Delta\sigma|_{WL}(B=B_{sat})=0]$. Due to the large (positive) 2D resistance contributions as caused by EEI effects, the sum of both contributions, $\Delta\sigma^B=\Delta\sigma|_{WL}+\Delta\sigma|_{ee}$, increases with increasing magnetic field, as shown in Fig. 3.

For $B>B_{sat}\approx 1$ T, $\Delta\sigma^B/\Delta\sigma^0$ saturates. The saturation values correspond to the data as given in Tables III and IV, respectively. As one can see from Fig. 3 the experimental data for the various Pd_xC_{1-x} films can be well fitted by the theoretical predictions (solid lines). We emphasize that for the evaluation of $\Delta\sigma^B/\Delta\sigma^0$ the same set of scattering parameters (see Table II) are used which have been derived from the MR data. This shows that a consistent description of the $R_\square(T)$ as well as $R_\square(B)$ behavior of our various Pd_xC_{1-x} samples within the theoretical concept of 2D resistance can be obtained. The description appears to be complete since also the magnetic field dependence of $R_\square(T)|_B$ can be well explained using the same scattering data.

VI. CONCLUSION

Thin Pd_xC_{1-x} mixture films $(x\geq0.45)$ show anomalous resistance behavior at low temperatures which can *consistently* be explained by 2D theory as resulting from both EEI and weak antilocalization, the latter due to strong spin-orbit scattering. In the presence of magnetic fields, WAL effects are suppressed, leading to a positive MR.[3] The analysis of the experimental data yields a *unique* set of electron scattering times for the present samples. We conclude that the consistency of the data gives an additional check to determine the *absolute* magnitudes of the elastic and inelastic electron scattering times.

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