Large effects due to electron–phonon-impurity interference in the resistivity of Pt/C-Ga composite nanowires

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The temperature-dependent resistivity of highly disordered Pt/C-Ga composite nanowires is shown to be well described by the interference of electron–phonon scattering and elastic electron scattering from boundaries and defects. The strongly disordered nature of these wires, combined with a high value of their Debye temperature, are responsible for the pronounced nature of the interference effects in their resistivity. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1745108]

In Mattheissen's rule, the contributions to the resistivity due to electron scattering from a random potential (the residual resistivity) and from lattice vibrations [the Bloch–Gruneisen (BG) term] are expected to be independent of each other. Even within the framework of the simplest model, however, this rule can be violated due to the *interference* of these scattering mechanisms.[1] The magnitude of this effect is described by the elastic part of the electron–phonon-impurity collision integral, and therefore depends only on the electron temperature.[1] In the quasiballistic limit of electron–phonon scattering (defined as $T>\hbar u/k_B\ell$, where T is the electron temperature, u is the sound velocity, and ℓ is the electron mean free path), the interference term is expected to provide a dominant contribution to the resistivity of disordered conductors.[2] At low temperatures ($T<0.2\theta_D$, where θ_D is the Debye temperature), the interference gives a resistivity variation that is proportional to $T^2\ \rho_o$, where ρ_o is the residual resistivity, while at higher temperatures ($T\sim\theta_D$), a saturation of its magnitude is predicted.[1] In previous work, evidence for the interference term has been observed in studies of the resistivity of thin metal films, fabricated using a variety of methods.[3–9] In this letter, we discuss the contribution of the interference mechanism to the resistivity of highly resistive (40–400 $\mu\Omega$ cm at 4.2 K) Pt/C composite nanowires fabricated by focused-ion-beam (FIB) deposition. Our analysis shows that the interference mechanism remains the dominant contribution to the resistivity of these wires, to significantly higher temperatures than has been noted in other material systems.[3–9] This observation is attributed to strong electronic disorder in these nanowires, combined with their high Debye temperature. We furthermore show the resistivity to be robust to thermal cycling, and insensitive to large magnetic fields, which may suggest the application of these structures as nanoscale thermometers.

Pt/C-Ga nanowires were fabricated on SiO_2 substrates, using the technique of FIB-induced deposition.[10–12] In Fig. 1(a), we show a transmission electron microscope (TEM) micrograph of the end of a freestanding Pt whisker that was deposited by the same process that is used to form the composite nanowires. The Pt tends to form nanocrystals, with an average diameter of the order of 1–2 nm, which are embedded into an amorphous matrix. The polycrystalline nature of this material is confirmed by electron diffraction [Fig. 1(b)], while electron-energy-loss spectroscopy (not shown) reveals the presence of carbon in between the Pt nanocrystals. We have also performed energy-dispersive x-ray spectroscopy and Auger studies of these wires, and our analyses indicate that they consist of approximately 30% Pt and 3% Ga, with the remaining material comprised largely of codeposited C.[12] To allow for electrical measurements of the nanowires, Ti/Au contacts were first formed on the SiO_2 substrates by photolithography and liftoff.[11,13] Results from three different wires are discussed in this letter, and the physical dimensions of these structures are listed in Table I, along with the notation that we use hereafter to refer to these structures. Inspection of similar wires by atomic-force microscopy revealed an approximately square cross section, with a deposited thickness of 60 nm. The wires were mounted in a chip carrier and their resistivity was measured in the range of 4.2–100 K, using

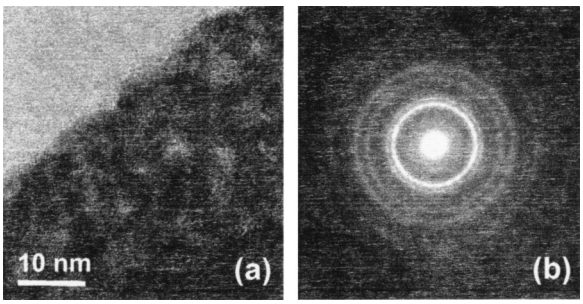

FIG. 1. (a) High-resolution TEM image of a Pt/C-Ga whisker. The darker regions correspond to Pt nanocrystals. (b) An electron diffraction micrograph showing the fcc crystal structure of Pt nanocrystals.

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TABLE I. Various transport parameters of the different nanowires studied here. The notation used to refer to the nanowires is also defined in the table.

Wire	Length (μm)	Width (nm)	$\rho_{300\,K}$ ($\mu\Omega$ cm)	$\rho_{77\,K}$ ($\mu\Omega$ cm)	ρ_o ($\mu\Omega$ cm)	$\rho_{300\,K}/\rho_o$	ℓ_φ (1 K) (nm)
S	5.9	56±14	61.5	47.3	44.4	1.39	91
M	13	60±7	482	377	360	1.34	51
L	20	45±8	545	417	393	1.39	55

low-frequency (11 Hz) lock-in detection with small constant currents (~7 nA). While these measurements were made using a two-probe geometry,[11] the resistivity variations reported here suggest that our analysis is not significantly influenced by contact resistance. The resistance measured between pairs of contacts unbridged by the wires was in excess of 10 MΩ, several orders of magnitude larger than the resistance of the nanowires (Table I).

The nanowires consist of Pt nanocrystals surrounded by doped C. In spite of this, electron transport in these wires does not show any effects that might be expected for an inhomogeneous system. We have studied[11,13] the magnetoresistance of these wires and have found behavior that is largely consistent with that expected for disordered, but homogeneous, conductors. The electron dephasing length (l_φ) has been extracted from the weak-antilocalization magnetoresistance, and was found to saturate at temperatures below 1 K,[11] similar to other disordered wires.[14] Above 1 K, the variation of $\ell_\varphi(T)$ was consistent with the one-dimensional Nyquist dephasing mechanism,[14] for which $\ell_\varphi(T) \propto T^{-1/3}\rho_o^{-1/3}$. In Table I, we list the values of ℓ_φ obtained in the three different wires at ~1 K, and see that these are consistent with the expected scaling of the dephasing length with ρ_o. These different results provide good evidence that transport in these wires in well described by theoretical considerations for homogeneous conductors.

In this letter, we focus on the variation of the resistivity of the nanowires at temperatures well above 4.2 K, where electron transport is dominated by electron–phonon scattering. In the quasiballistic regime of electron–phonon scattering, the correction to the resistivity due to the interference mechanism is given by:[1,5]

$$\rho_{\rm int} = BT^2\rho_o \frac{6}{\pi^2}\int_0^{\Theta_D/T}\left[\frac{xe^x}{(e^x-1)^2} - \frac{1}{(e^x-1)}\right]x\,dx, \qquad (1)$$

where

$$B = \left[2\frac{\beta_t}{u_t} + \left(\frac{\pi^2}{16}-1\right)\frac{\beta_l}{u_l}\right]\frac{2\pi^2 k_B^2}{3\varepsilon_F p_F}. \qquad (2)$$

Here, ε_F and p_F are the Fermi energy and momentum, and u_l and u_t are the speed of sound for longitudinal and transverse phonons, respectively. β_l and β_t are the constants of interaction with longitudinal and transverse phonons, respectively. In the jellium model with the Boom–Staver relation for the sound velocity, $\beta_l = 0.5$ and $\beta_t = (u_l/u_t)^2\beta_l$. Since u_l is typically larger than u_t by a factor of ~2–3, the interference term is dominated by scattering from transverse phonons. At low temperatures ($T < 0.2\Theta_D$), the integral in Eq. (1) approximates to $\pi^2/6$ and, with $\beta_t = 0.5(u_l/u_t)^2$, we may write

$$\rho_{\rm int} = BT^2\rho_o, \quad B \approx \frac{2\pi^2 k_B^2 u_l^2}{3\varepsilon_F p_F u_t^3}. \qquad (3)$$

In the inset to Fig. 2, we show the temperature-dependent variation of the resistivity of the different nanowires. A large spread in resistivity is apparent among the nanowires and presumably reflects their dirty nature. Indeed, the resistivity values shown here represent some of the highest that have been achieved in studies of the electron–phonon-impurity interference mechanism.[3–9] In the main panel of Fig. 2, however, we show that when these data are rescaled in accordance with Eq. (3), they fall on curves that lie very close. In all three wires, the rescaled resistivity shows the predicted [Eq. (3)] quadratic dependence on temperature. By fitting to the form of Eq. (3), we obtain $B = 1.2\times10^{-5}$, 0.9×10^{-5}, and 1.1×10^{-5} K^{-2} for nanowires *S*, *M*, and *L*, respectively. The spread in these values suggests that the variation of the electron density of states and Fermi velocity in the wires does not exceed 25%. Since the electron and phonon parameters for these nanowires are unknown, it is interesting to compare the inferred values of *B* with that expected for bulk Pt. Taking $\varepsilon_F = 5.6$ eV, $p_F = 1.3\times10^{-19}$ g cm/s, $u_l = 4.45\times10^5$ cm/s, and $u_t = 2.27\times10^5$ cm/s,[15] we obtain $B = 1.8\times10^{-6}$ K^{-2}, ~5–6 times smaller than the values inferred from Fig. 2. Previous studies[4–9] have given a value of *B* that typically lies in the range of $1-3\times10^{-6}$ K^{-2}, with the notable exception of Nb,

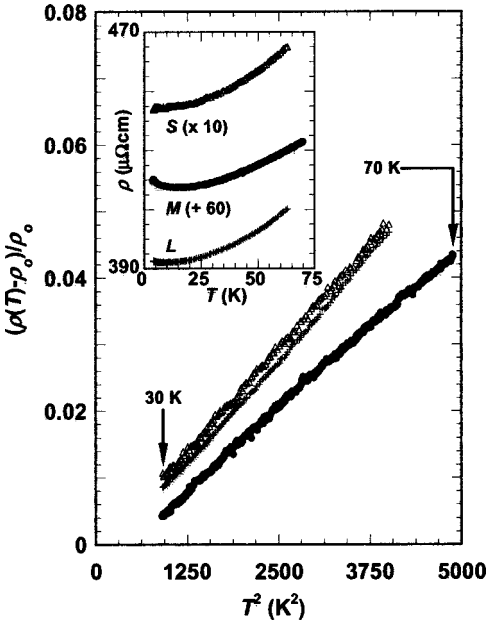

FIG. 2. Main panel: $(\rho(T)-\rho_o)/\rho_o$ vs T^2 for the three different nanowires. Inset: original resistivity variations of the three different nanowires.

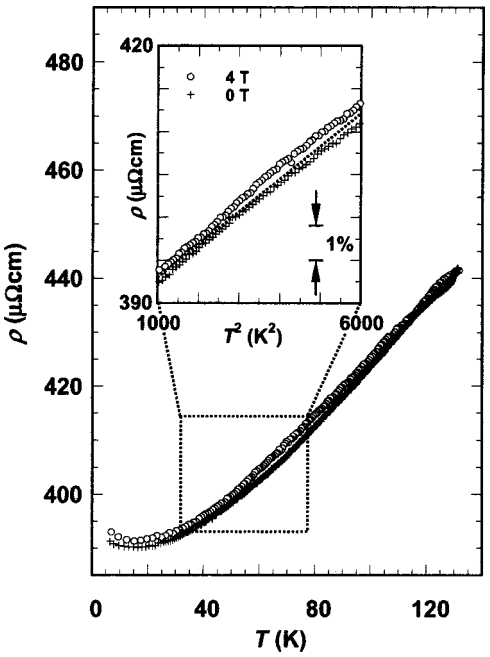

FIG. 3. Main panel: Temperature-dependent resistivity of nanowire L, at zero magnetic field (+) and at 4 T (o). Inset: resistivity ρ is replotted versus T^2. The straight dotted line is a guide for the eye used to indicate the proportionality of ρ to T^2.

which is known as a material with a strong electron–phonon interaction and for which the value of $B=1.5\times10^{-5}$ K^{-2} was reported.[5]

At higher temperatures ($T>0.2\Theta_D$), the resistivity no longer shows a simple quadratic behavior, but is described instead by the Eq. (1). In this regime, it is interesting to use the values of B obtained earlier to extrapolate the interference term to room temperature. Since the only unknown in Eq. (1) is Θ_D, we treat this as a free parameter that we adjust such that the theoretically predicted value $\rho_{int}(300\,\mathrm{K})$ matches $\rho(300\,\mathrm{K})-\rho_o$. In this way, we obtain $\Theta_D=606$, 721, and 639 K for nanowires S, M, and L, respectively, close to the reported Debye temperature for graphite (614 K).[16] While we have neglected the contribution of the BG term to the resistivity in this calculation, we believe this approach to be appropriate. Firstly, our estimates for Θ_D are consistent with the fact that we are able to observe the quadratic temperature dependence of the resistivity to temperatures approaching 100 K. Secondly, the BG term is known to be independent of disorder, and previous studies have shown it to give a resistivity contribution of approximately 10 $\mu\Omega$ cm in Pt films near room temperature (273 K).[17] This corresponds to 1%–2% of the resistivity of the interference term in nanowires M and L, and ~15% of that in sample S. The suggestion, therefore, is that the interference mechanism continues to dominate over the BG term, even at room temperature. This should be contrasted with an earlier analysis,[11] in which we interpreted the resistivity variations as arising solely from the BG mechanism.

In Fig. 3, we compare the results of resistivity measurements at zero magnetic field, and in a static field of 4 T. From this figure, we see that the resistivity is quite robust to thermal cycling, and does not exhibit any significant dependence on magnetic field. These characteristics, combined with the well-defined functional dependence of the nanowire resistivity on temperature (Fig. 2), suggest the potential of exploiting these structures as nanoscale thermometers.

In conclusion, the temperature-dependent resistivity of Pt/C-Ga composite nanowires has been shown to be well described by the interference of electron–phonon scattering and elastic electron scattering. The strong electronic disorder in these wires, combined with their high Debye temperature, are responsible for the pronounced interference effects.

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