Electrical Transport in Rings of Single-Wall Nanotubes: One-Dimensional Localization

H. R. Shea, R. Martel, and Ph. Avouris*
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

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We report low-temperature magnetoresistance (MR) measurements on rings of single-wall carbon nanotubes. Negative MR characteristic of weak one-dimensional localization is clearly observed from 3.0 to 60 K, and the coherence length L_φ is obtained as a function of temperature. The dominant dephasing mechanism is identified as electron-electron scattering. Below 1 K, we observe a transition from *weak* to *strong* localization, and below 0.7 K a weak antilocalization is induced by spin-orbit scattering.

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Carbon nanotubes (NTs) provide ideal model systems to test theories describing transport phenomena in low-dimensional systems. Nanotubes come in two forms: large diameter (typically 10–30 nm) multiwall nanotubes (MWNTs) and smaller diameter (typically 1–2 nm) single-wall nanotubes (SWNTs). The powerful technique of magnetoresistance (MR) has already been used to investigate the transport mechanism in MWNTs [1–3]. Weak localization [4] was observed which allowed the coherence length L_φ in MWNTs to be determined. SWNTs are attracting even more interest, their being closer to ideal one-dimensional (1D) systems. It has been suggested that backscattering is ineffective in SWNTs, but it can be switched on by an external magnetic field leading to a large *positive* magnetoresistance [5], and that transport is ballistic [6–9]. However, recent electrical measurements on semiconducting SWNTs were found to be consistent with diffusive transport [9,10]. The nature of transport in metallic SWNTs is still a matter of debate. MR measurements on metallic SWNTs could in principle determine the transport mechanism and reveal the nature of the inelastic scattering (dephasing) processes involved. Attempts to measure MR in SWNT bundles have not been successful so far [11]; however, negative MR at low fields has been reported from entangled SWNT mats [12]. Recently, we have been able to fabricate rings from SWNTs [13], and we observed MR from some of these rings at low temperatures. Furthermore, unlike past low temperature studies (for example, see Refs. [6] and [14]), our SWNT rings do not exhibit Coulomb blockade even at the lowest temperatures (0.3 K). These studies enable us to determine the transport mechanism, the dominant electron dephasing mechanism, to observe the transition from a weakly to a strongly localized state, and spin-related scattering phenomena.

Figure 1 is an atomic force microscope image of a SWNT ring deposited over two 25 nm thick Ti/Au electrodes. The electrodes are patterned by e-beam lithography on 100 nm of SiO_2 grown on degenerately doped Si. Typical ring resistances range from 20 to 50 kΩ at 300 K.

The magnetoresistance of a 0.82 μm diam and 20 nm thick ring is shown in Fig. 2a for temperatures between 3.0 and 6.0 K. The MR is *negative;* i.e., the resistance decreases with increasing magnetic field. Negative MR is characteristic of materials in a state of weak localization [15], in our case one-dimensional weak localization (1D-WL). WL results from the constructive interference between conjugate electron waves counterpropagating around self-intersecting electron trajectories inside the material [4,16]. The closed ring geometry in principle may provide an additional path for interference. The enhanced backscattering produced by the constructive interference leads to an increased nanotube resistance, the magnitude of which depends on the number and the strength of the dephasing collisions that the electrons experience inside the nanotube. By applying a magnetic field perpendicular to the ring, the conjugate electron waves acquire opposite phases and the constructive interference is destroyed. From the effect of the field on the resistance, the coherence length L_φ can thus be obtained.

The change of the conductance $\Delta G(H)$ of a unit length along the circumference of a metallic ring of radius R and of wall thickness w smaller than L_φ can be written as [17]

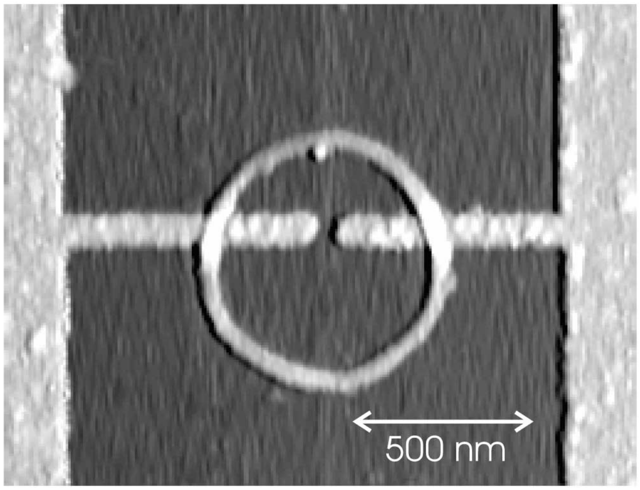

FIG. 1. Atomic force microscope image of a nanotube ring spanning two gold electrodes.

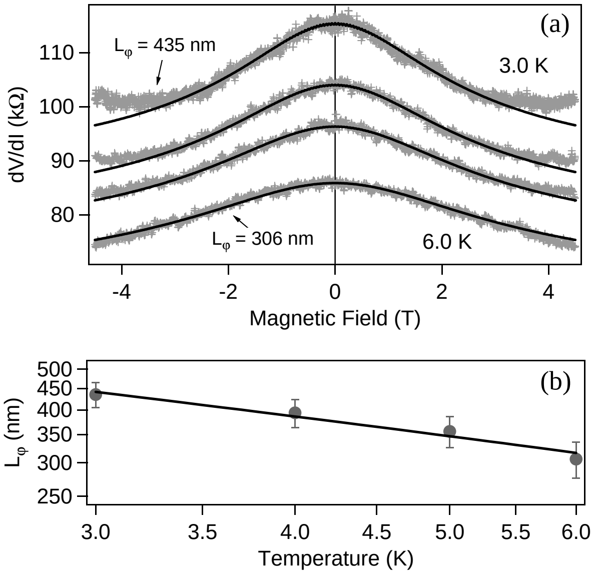

FIG. 2. (a) Differential resistance dV/dI of a nanotube ring as a function of the magnetic field perpendicular to the plane of the ring. The probe current was 10 pA. The four data sets (in gray), from top to bottom, were taken at 3.00, 4.00, 5.00, and 6.00 K and are not offset. The solid black lines are fits to the 1D weak localization theory using $w = 1.4$ nm. Similar fits were performed using different wall thicknesses w between 1.4 and 20 nm. For example, the obtained values of L_φ at 3.00 K are 342 nm for $w = 2$ nm and 216 nm for $w = 3$ nm. (b) Coherence length from Eqs. (1) and (2) vs temperature ($w =$ 1.4 nm). The line is a fit to $L_\varphi \propto T^{-1/3}$.

$$\Delta G(H) = -\frac{2e^2 L_\varphi(H)}{h}\,\frac{\sinh(\frac{2\pi R}{L_\varphi(H)})}{\cosh(\frac{2\pi R}{L_\varphi(H)}) - \cos[2\pi\frac{2\Phi}{\Phi_0}]}\,, \tag{1}$$

where H is the magnetic field perpendicular to the ring through which a flux Φ passes, $\Phi_0 = h/e$ is the flux quantum, and $L_\varphi(H)$ is the magnetic field dependent coherence length [16]:

$$\frac{1}{L_\varphi^2(H)} = \frac{1}{L_\varphi^2} + \frac{1}{3}\left(\frac{2\pi w H}{\Phi_0}\right)^2. \tag{2}$$

L_φ can be determined by fitting the measured MR to Eqs. (1) and (2), with ΔG scaled by a factor A to account for the transmission of the gold electrode–NT barriers. We determined A from fits to the 4 K data to be $A \sim 0.2$, which corresponds to a contact resistance of 22 kΩ. We used the same A to fit the data at other temperatures.

The width w entering Eq. (2) needs careful consideration. It can be argued that the most appropriate value is 1.4 nm, i.e., the diameter of the most abundant nanotube in the SWNT sample. A very good fit of the negative MR data to Eqs. (1) and (2) of 1D-WL theory is obtained as shown by the solid dark lines in Fig. 2(a). The obtained L_φ are plotted in Fig. 2(b) vs temperature, and range from 306 nm at 6 K to 435 nm at 3 K. A possible explanation for the fact that MR was not observed in straight bundles of SWNTs and in some of our ring samples may be that MR requires either a stronger metallic tube-tube coupling (which may be a function of sample processing), or the presence of a larger diameter metallic SWNT in the bundle. Either case leads to a larger effective value of w. Using w as an extra fitting parameter we obtain the best fits for w at around 2 nm. A larger w in the fit gives smaller values of L_φ (see caption of Fig. 1). Therefore, we should consider the above values of L_φ as upper bounds [18]. Our estimates of the coherence lengths are within the range of values reported from MR of MWNTs, which vary from 10 nm at 1.5 K [1] to 250 nm at 3 K [19]. Most importantly, L_φ remains in all cases many times smaller than the ring circumference. This is consistent with a conduction that is not ballistic even at 3 K. Ballistic transport would require a much larger and temperature independent L_φ.

By fitting the coherence length vs temperature to the predictions of different dephasing models, we can determine the dephasing mechanism that is dominant in this temperature range. The relation is best described as $L_\varphi \propto T^{-1/3}$ (Fig. 2b). A good fit to this expression is obtained within the entire range of values of w used to fit Eqs. (1) and (2). This power law temperature dependence of the coherence length is characteristic of dephasing through weakly inelastic electron-electron interactions [20]. The same mechanism has been found to dominate in MWNTs [19] and in many 1D and 2D free electron gas systems at low temperatures [15,21]. Thus, our MR results indicate that transport and dephasing in SWNTs appear to be qualitatively the same as in MWNTs [22].

Finally, we note that if the SWNTs composing the ring could form a closed path along the circumference one may observe Aharonov-Bohm oscillations in the MR of the rings with a period $\Phi = h/2e$ [see Eq. (1)]. We do not observe these oscillations. Because of the size of our rings, the oscillations would correspond to a change in ring resistance of less than 1 part in 100, which is just below our noise level [23].

Figure 3 shows the temperature dependence of the zero-field resistance $R_{H=0}$. From 300 to 0.3 K we observe a monotonic rise in resistance with decreasing temperature. The data between 6 and 60 K can be fit very well by the equation $1/R_{H=0} = \sigma_0 - C_0 T^{-p/2}$ which describes the conductance of a 1D metallic conductor in a weakly localized state [4]. The exponent p has a value of $p = 2/3$ for Nyquist electron-electron scattering induced dephasing, and σ_0 and C_0 are sample specific constants. Given the good fit of both the resistance and the MR to 1D-WL theory and our findings at even lower temperatures (see below) we conclude that coherence effects dominate transport at low temperatures [24].

While the electrical behavior of the nanotube rings seems to be monotonic down to about 2 K (Fig. 3a), a drastic change is observed below ~1 K (Fig. 3b). The resistance within a temperature range of only 1° increases from ~200 kΩ to ~1.5 MΩ. The temperature dependence of the resistance can now be expressed as

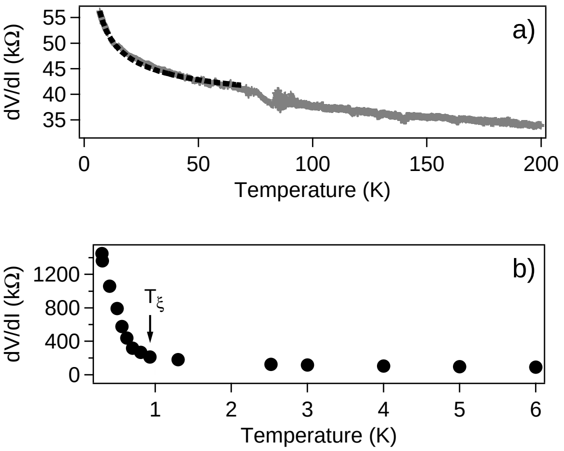

FIG. 3. (a) Temperature dependence of the zero-field nanotube ring resistance from 6 to 200 K (gray scatter), and fit to 1D-WL theory between 6 and 60 K (dashed line). (b) Ring resistance from 0.3 to 6 K.

$R_{H=0} \propto \exp(T_0/T)$, with $T_0 = 0.8$ K. Thus $k_B T_0 \approx k_B T_\xi$, where T_ξ is the transition temperature. This behavior suggests that the electron system has undergone a transition from a weak to a strong localization (SL) state. Below T_ξ transport from one coherent segment to another becomes a thermally activated process with an activation energy $k_B T_0$. According to Thouless [25], this is due to the fact that the width of the coherent states, $\hbar/\tau_\varphi$, has now become smaller than their energy separation. In our case, the localization is the result of both single electron scattering events and electron-electron interactions. The localization length ξ can be obtained as the L_φ at T_ξ ($\sim$1 K), i.e., about 750 nm. A different estimate of ξ can be obtained from $\xi = (h/2e^2)(S/\rho)$ [15], where S ($\sim w^2$) is the active cross-sectional area and ρ the resistivity of the ring. The latter is estimated to be $\rho \approx 20$–30 $\mu\Omega$ cm. The two methods of obtaining ξ yield values of $\sim$560 nm and $\sim$260 nm, respectively. The agreement is quite reasonable given that the approaches used are supposed to give order of magnitude estimates. In all the cases, ξ is smaller than the electrode separation.

Further evidence for a weak to strong localization transition is obtained from the MR data. Figure 4(a) is a plot of dV/dI vs H taken at 0.4 K. The effect of the MR of the ring is much stronger than at $T > 3$ K and cannot be fit by 1D-WL theory. In this SL regime, the field affects the conductance by changing the activation energy for electron hopping via the Zeeman effect [26]. At higher fields, new peaks due to conductance fluctuations appear. Precursors to these peaks in the WL regime are seen in Fig. 2(a) (note the 3 K data). These are universal conductance fluctuations that result from scattering by defects [27]. The stronger fluctuations in the SL regime seem to have a similar origin suggested by the fact that a weak annealing of the sample changes their structure.

Additional information can be obtained by examination of dV/dI vs V plots. Figure 4b shows such a plot for the ring at temperatures between 0.9 and 0.3 K. A clear resistance peak centered at the Fermi energy is observed: a Fermi level singularity (FLS). As the temperature is decreased below $\sim$0.7 K, the resistance peak takes on a cusp shape. In addition to an overall increase in the magnitude of the FLS peak, a local resistance *minimum* is observed around zero bias: a zero-bias anomaly (ZBA). The corresponding dI/dV vs V plot, which is proportional to the density of states, shows a singularity (FLS) around E_F as well as the ZBA.

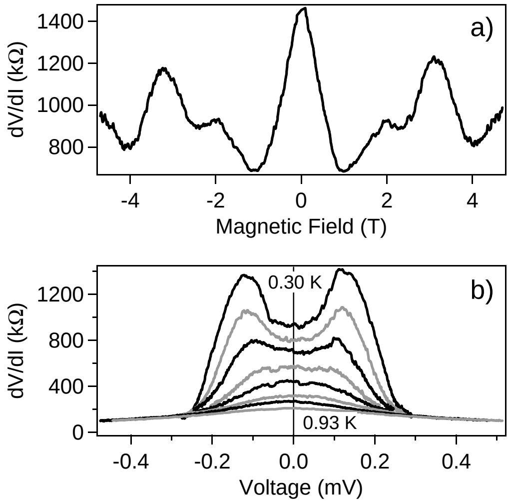

FIG. 4. (a) Ring MR at 0.40 K. (b) Differential resistance of a nanotube ring vs bias V, taken, from top to bottom, at 0.30, 0.40, 0.50, 0.56, 0.63, 0.70, 0.81, and 0.93 K. The curves were taken in zero magnetic field and they are not offset.

Several different interactions can lead to a singularity at E_F. Perhaps the most obvious is Coulomb blockade. However, the absence of any gate effect and the low contact resistances ($\sim$20 kΩ per contact) argue against this possibility. A more likely cause for the observed gap is strong electron-electron interactions. We have already seen that such interactions provide the dominant dephasing process at low temperatures. Electron-electron interactions are strongly enhanced by disorder and can produce a Fermi level singularity similar to the one observed here [28]. Strong electron interaction can also lead to the formation of a Luttinger liquid (LL) phase [29–31]. One characteristic of the LL phase is the power law dependence of the tunneling conductance on the energy of the electrons. Thus, for $eV > k_B T$, $dI/dV \propto V^\alpha$, where for nanotubes $\alpha < 1$ and temperature independent. For $T \geq 1$ K, and $V > 4$ mV, we can fit the dI/dV vs V data to $dI/dV = V^{0.25\pm0.01}$. This suggests that the tubes in the ring may be in a LL state. It is not clear, however, that effects such as the weak localization and the MR behavior described above are compatible with the formation of a LL phase.

We now examine the nature of the ZBA. It appears to involve processes that can compete with electron-electron scattering only at temperatures $T \leq 0.7$ K. The new scattering process(es) leads to a *decrease* in resistance. Such behavior can result from spin-orbit scattering induced by the heavy gold atoms of the electrodes. If the spin of an electron moving in one direction along a self-folding ring trajectory is rotated from σ_+ to σ'_+, i.e., $\sigma'_+ = Q\sigma_+$, then the rotation in the conjugate path will be $\sigma'_- = Q^{-1}\sigma_-$. If the relative rotation is 2π then the electron waves will interefere destructively at the origin leading to a decrease of the backscattering below its statistical value, i.e., to an *antilocalization*. The same behavior was reported in MR studies in which a small amount of gold was deposited on thin films of light metals such as Mg [4,32]. We find that the ZBA is strongly reduced in the presence of weak fields, which hardly affect the main resistance peak, supporting our assignment of the ZBA as due to spin-orbit scattering [33].

In summary, we have used magneto resistance measurements to show that rings of single-wall carbon nanotubes are in a state of 1D weak localization at low temperatures. The upper limit value of the coherence length L_φ is 0.5 μm at 3 K. The dominant dephasing mechanism at low temperatures involves electron-electron collisions. Below $\sim$1 K we observe a transition to a strongly localized state characterized by thermally activated transport. Finally, a magnetic field sensitive zero-bias anomaly is observed and is ascribed to spin-orbit scattering.

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*Email address: avouris@us.ibm.com

[1] L. Langer *et al.*, Phys. Rev. Lett. **76**, 479 (1996).
[2] A. Bachtold *et al.*, Nature (London) **397**, 673 (1999).
[3] A. Fujiwara, K. Tomiyama, H. Suematsu, M. Yumura, and K. Uchida, Phys. Rev. B **60**, 13 492 (1999).
[4] For reviews, see G. Bergmann, Phys. Rep. **107**, 1 (1984); P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[5] T. Ando and T. Nakanishi, J. Phys. Soc. Jpn. **67**, 1704 (1998).
[6] S. J. Tans *et al.*, Nature (London) **386**, 474 (1997).
[7] S. J. Tans, A. R. M. Verschueren, and C. Dekker, Nature (London) **393**, 49 (1998).
[8] C. T. White and T. N. Todorov, Nature (London) **393**, 240 (1998).
[9] P. L. McEuen, M. Bockrath, D. H. Cobden, Y.-G. Yoon, and S. G. Louie, Phys. Rev. Lett. **83**, 5098 (1999).
[10] R. Martel, T. Schmidt, H. R. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. **73**, 2447 (1998).
[11] J. Lefevre, M. Radosavljevic, J. Hone, and A. T. Johnson, in *Electronic Properties of Novel Materials,* edited by H. Kuzmany *et al.*, AIP Conf. Proc. No. 486 (AIP, New York, 1999); H. R. Shea *et al.* (unpublished).
[12] G. T. Kim *et al.*, Phys. Rev. B **58**, 16 064 (1998).
[13] R. Martel, H. R. Shea, and Ph. Avouris, Nature (London) **398**, 299 (1999).
[14] M. Bockrath *et al.*, Science **275**, 1922 (1997).
[15] Y. Imry, *Introduction to Mesoscopic Physics* (Oxford University Press, New York, 1997).
[16] A. G. Aronov and Yu. V. Sharvin, Rev. Mod. Phys. **59**, 755 (1987).
[17] B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak, JETP Lett. **33**, 94 (1981).
[18] Statistically only $\sim 1/3$ of the tubes in a bundle are metallic and only a small fraction of these is in contact with the electrodes. Thus, it is unlikely that a large value of w can arise from strong interaction between neighboring metallic tubes.
[19] A. Bachtold, C. Strunk, C. Schönenberger, J.-P. Salvetat, and L. Forró, in *Proceedings of the 12th International Winterschool on the Electronic Properties of Molecular Nanostructures* (AIP, New York, 1998).
[20] B. L. Altshuler, A. G. Aronov, and D. E. Khmelnitsky, J. Phys. C **15**, 7367 (1982).
[21] B. L. Al'tshuler, A. G. Aronov, M. E. Gershenson, and Yu. V. Sharvin, Sov. Sci. Rev. A, Phys. Rev. **9**, 223 (1987).
[22] C. Schönenberger *et al.*, in Proceedings of the Satellite Conference to LT22, Göteborg [J. Low Temp. Phys. (to be published)].
[23] The $\Phi_0/2$ Aharonov-Bohm oscillations would appear as a modulation of the MR amplitude. This modulation, however, decreases exponentially with increasing R/L_φ.
[24] It is interesting to note that an equation of the form $1/R = A - BT^{-n}$ has been derived to describe tunneling into a Luttinger liquid containing scatterers [R. Egger and A. Gogolin, Eur. Phys. J. B **3**, 281 (1998)]. The exponent of the temperature was predicted to be 0.36, i.e., essentially indistinguishable from the $T^{-1/3}$ behavior discussed above. To our knowledge, interference effects and weak localization have not been discussed within the context of Luttinger liquid theory.
[25] D. J. Thouless, Phys. Rev. Lett. **39**, 1167 (1977).
[26] Yu. B. Khavin, M. E. Gershenson, and A. L. Bogdanov, Phys. Rev. B **58**, 8009 (1998).
[27] P. A. Lee, A. D. Stone, and H. Fukuyama, Phys. Rev. B **35**, 1039 (1987).
[28] B. L. Al'tshuler and A. G. Aronov, Sov. Phys. JETP **50**, 968 (1979).
[29] M. Bockrath *et al.*, Nature (London) **397**, 598 (1999).
[30] R. Egger and A. O. Gogolin, Phys. Rev. Lett. **79**, 5082 (1997).
[31] C. Kane, L. Balent, and M. P. A. Fisher, Phys. Rev. Lett. **79**, 5086 (1997).
[32] G. Bergmann, Phys. Rev. Lett. **48**, 1046 (1982).
[33] Another possible explanation for the ZBA involves Kondo scattering from residual magnetic impurities. See Ph. Avouris, H. R. Shea, and R. Martel, in *Electronic Properties of Novel Materials,* edited by H. Kuzmany *et al.*, AIP Conf. Proc. No. 486 (AIP, New York, 1999).