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
(Received 14 April 1999)

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 \( L_w \) 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.

PACS numbers: 73.61.Wp, 61.48.+c, 72.15.Rn, 73.50.–h

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 \( L_w \) 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 k\( \Omega \) at 300 K.

The magnetoresistance of a 0.82 \( \mu \)m 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 \( L_w \) 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 \( L_w \) can be written as [17]
and 6.0 K and are not offset. The solid black lines are fits (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 \( L_\varphi \) 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 \( L_\varphi \propto T^{-1/3} \).

\[
\frac{1}{L_\varphi^2(H)} = \frac{1}{L_\varphi^2(0)} + \frac{2}{3} \left( \frac{2\pi w H}{\Phi_0} \right)^2.
\]

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

\[
\Delta G(H) = -\frac{2e^2 L_\varphi(H)}{h} \sinh \left( \frac{2\pi K}{L_\varphi(H)} \right) \cosh \left( \frac{2\pi K}{L_\varphi(H)} \right) - \cos \left( \frac{2\pi K}{L_\varphi(H)} \right),
\]

(1)

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 \( L_\varphi \) (see caption of Fig. 1). Therefore, we should consider the above values of \( L_\varphi \) 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, \( L_\varphi \) 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 \( L_\varphi \).

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 \( \sigma_0 \) 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 \( T \) K (Fig. 3b). The resistance within a temperature range of only 1° increases from \( \sim 200 \) k\( \Omega \) to \( \sim 1.5 \) M\( \Omega \). The temperature dependence of the resistance can now be expressed as
of magnitude estimates. In all the cases, given that the approaches used are supposed to give order of the electrode separation. 

The latter is estimated to be \( r \) from \( j \) length and \( r \) active cross-sectional area and yields values of \( 0.3 \) to \( 6 \) K.

\( R_{H=0} \propto \exp(T_0/T) \), with \( T_0 = 0.8 \) K. Thus \( k_B T_0 = k_B T_\xi \), where \( T_\xi \) 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 \( T_\xi \) 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, \( \hbar/\tau_\eta \), 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 \( \xi \) can be obtained as the \( L_\eta \) at \( T_\xi \) (~1 K), i.e., about 750 nm. A different estimate of \( \xi \) can be obtained from \( \xi = (\hbar/2e^2)(S/\rho) \) [15], where \( S \) (\( \sim w^2 \)) is the active cross-sectional area and \( \rho \) the resistivity of the ring. The latter is estimated to be \( \rho = 20-30 \mu \Omega \) cm. The two methods of obtaining \( \xi \) 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, \( \xi \) 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 \( T \) 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.

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 (\( \sim 20 \) k\( \Omega \) 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 \( eV > k_BT \), \( dI/dV \propto V^\alpha \), where \( \alpha < 1 \) 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 $\sigma_+ \to \sigma'_+$, i.e., $\sigma'_+ = Q \sigma_+$, then the rotation in the conjugate path will be $\sigma'_- = Q^{-1} \sigma_-$. If the relative rotation is $2\pi$ then the electron waves will interfere 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 $L_c$ is $0.5 \mu m$ at 3 K. The dominant dephasing mechanism at low temperatures involves electron-electron collisions. Below $-1$ 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.

The authors thank A. Stern, Y. Imry, and J. Appenzeller for very helpful discussions and A. G. Rinzler and R. E. Smalley for providing the nanotubes.

*Email address: avouris@us.ibm.com

[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.
[23] The $\Phi_0/2$ Aharonov-Bohm oscillations would appear as a modulation of the MR amplitude. This modulation, however, decreases exponentially with increasing $R/L_c$.
[24] It is interesting to note that an equation of the form $1/R = A - BT^w$ 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.