Superconductivity in ropes of single-walled carbon nanotubes

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Abstract

We report measurements on ropes of single-walled carbon nanotubes (SWNT) in low-resistance contact to non-superconducting metallic pads, at low voltage and at temperatures down to 13 mK. Large resistance drops and strong non-linearities in the IV characteristics are observed below 0.4K. These features, which disappear in magnetic field in the Tesla range, strongly suggest the existence of superconductivity in ropes of SWNT.

Key words: superconductivity; carbon nanotubes; Luttinger liquids

Since their discovery [1], carbon nanotubes have attracted scientists both for their mecanical and electronic properties [2]. Band calculations [3] find that depending on helicity and diameter the Fermi surface is reduced at most to two points. These calculations were experimentally confirmed by the simultaneous STM determination of the helicity and measurement of the density of states of single wall nanotubes [4]. In metallic nanotubes, due to the strong 1D character of the band structure, electronic correlations lead to a breakdown of the Fermi liquid state. Nanotubes should then be described by Luttinger Liquids theories [5,6], with collective low energy excitations and no long range order. Proof of the validity of Luttinger Liquid description in ropes was given by the measurement of a resistance diverging as a power law with temperature down to 10 K [7]. However, this measurement was done on nanotubes separated from measuring leads by tunnel junctions. Because of Coulomb blockade, the low temperature and voltage regime were not explored.

In contrast, we have developed a technique in which measuring pads are connected through low contact resistance to suspended nanotubes [9]. We have previously shown that when the contact pads are superconducting, a large supercurrent can flow through nanotubes [10]. In this letter, we report experimental evidence of intrinsinc superconductivity in ropes of carbon nanotubes below 0.55 K.

The samples are ropes of SWNT suspended between normal metal contacts (Pt/Au bilayers). The SWNT are prepared by an electrical arc method with a mixture of nickel and yttrium as a catalyst [11,12]. SWNT with diameters of the order of 1.4 nm are obtained. They are purified by the cross-flow filtration method [12].The tubes are usually assembled in ropes of a few hundred parallel tubes. Isolation of an individual rope and connection to measuring pads are performed according to the procedure we previously used [9], where ropes are soldered to melted contacts. The contact resistance is low and the tubes can be structurally characterized with a transmission electron microscope (TEM). For the three samples presented here, the contacts were trilayers of $Al_2O_3/Pt/Au$ of respective thicknesses 5, 3 and 200 nm. These contacts showed no sign of superconductivity down to 50 mK. The samples were measured in a dilution refrigerator, at temperatures ranging from 1 K to 0.05 K, through filtered lines [13]. Magnetic fields up to 5 T could be applied perpendicularly

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to the contacts and the tubes. The resistance was measured by applying a small (1 nA to 10 nA, 30 Hz) AC current though the sample and measuring the AC voltage using lock-in detection.

We select samples with a room temperature (RT) resistance less than 10 kΩ. As is generally observed, we find that the resistance increases as the temperature is lowered between 300 K and 1K . Things change however below 1K, as shown in Fig. 1 for the three samples Pt1, Pt2, and Pt3, measured in magnetic fields ranging from 0 to 2.5 T. At zero field, the zero-bias resistance of Pt3 continues to increase as T is reduced, whereas the resistances of Pt1 and Pt2 decrease drastically below $T_1^* = 140$ mK for Pt1 and $T_2^* = 550$ mK for Pt2. The resistance of Pt1 is reduced by 30% at 70 mK. That of Pt2 decreases by more than two orders of magnitude, and saturates below 100 mK at a value $R_r = 74\ \Omega$. We define a transition temperature T_{C2} by the inflexion point of R(T). T_{C2} is 370 mK at zero field, decreases at higher magnetic fields, and extrapolates to zero at 1.35 T. At fields above 1.25 T, the resistance increases with decreasing temperature, similarly to Pt3, and becomes independent of magnetic field. The resistance of Pt1 follows qualitatively the same trend, but the full transition did not occur down to 70 mK. The differential resistance of the samples at $T < T_c, H < H_c$ is strongly bias-dependent, with lower resistance at low bias. These data suggest that the rope Pt2 (and, to a lesser extent, Pt1) is intrinsically superconducting.

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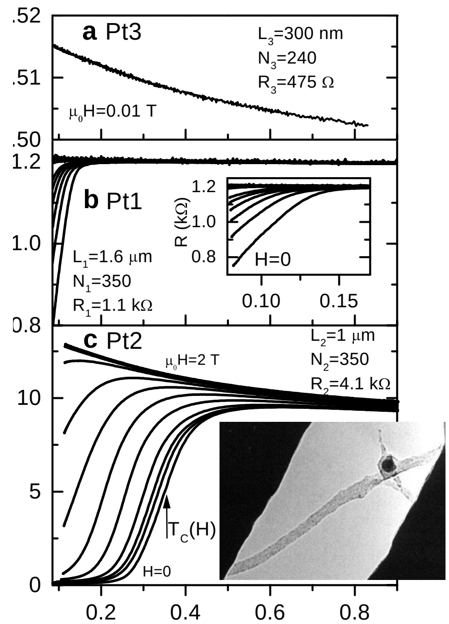

Fig. 1. Resistance as a function of temperature for the three samples. The length L, number of tubes N and room temperature resistance R of each sample are given in the corresponding panel. a: Sample Pt3. b: Resistance of Pt1 at different applied magnetic fields H. $\mu_0 H$= 0, 0.02, 0.04, 0.06, 0.08, 0.1, 0.2, 0.4, 0.6, 0.8 and 1 T from bottom to top. Inset is a zoom of the low temperature region. c: Resistance of Pt2 at $\mu_0 H$=0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1, 1.25, 1.5, 1.75, 2, 2.5 T from bottom to top. Inset: TEM micrograph of sample Pt2, from which we deduce L_2 and N_2. N_2 is estimated from the measured diameter D_2 , through $N_2 = (D_2/(d+e))^2$, where d is the diameter of a single tube (d=1.4 nm), and e is the typical distance between tubes in a rope (e=0.2 nm). The dark spot is a Ni/Y catalyst particle.