Superconductivity in Carbon Nanotube

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Abstract

Since its discovery in 1991,Carbon nanotube has been the subject of intense research both experimentally and theoretically worldwide.Carbon nanotube with its incredible properties have numerous practical appliations.In this paper,superconducting aspect of carbon nanotube has been explored.Carbon nanotube shows both proximity induced and intrinsinc superconductitivity in it.Flux pinning has been enhanced in high-temperature superconductors by embedding them with carbon nanotubes.Recently a model has been proposed for possible room temperature superconductivity in quasi-1D composite of superconducting nanotubes.

Carbon nanotubes are new materials for the twenty-first century.Their exceptional properties can be exploited in wide ranges of application: molecular electronics, nanomanipulation, supersensitive sensor, molecular motors, hydrogen storage, field emitters, flat panel displays, superstrong and multifunctional materials, and many more.Most strikingly, it may be the possible candidate for room-temperature superconductor.With all these and intense research on nanotube throughtout the world, we are heading for Carbon Nanotube Age.

Carbon nanotubes (single-wall) are rolled up cylinders of graphene sheets of sp^2 bonded carbon atoms organized into a honeycomb structure as a flat graphene sheet (see Fig.-1)[1].The conductivity of nanotube depends drastically on both the diameter and the chirality (or twist) of the hexagonal carbon lattice along the tube.A slight change in the winding of hexagon along the tube can transform the tube from metal into a large-gap semiconductor ![2] The indices (n,m) are used to represent a possible tube structure, where $n \geq m$. It can be seen from Fig.-1 that $m = 0$ for all zigzag tubes, while $n = m$ for all armchair tubes.All other tubes are chiral. Tubes for which $n-m = 3i$, with i zero or an integer, are metallic;all others are semiconducting.It turns out that about two-thirds of tubes are semiconducting and one-third are metallic, armchair always being metallic.

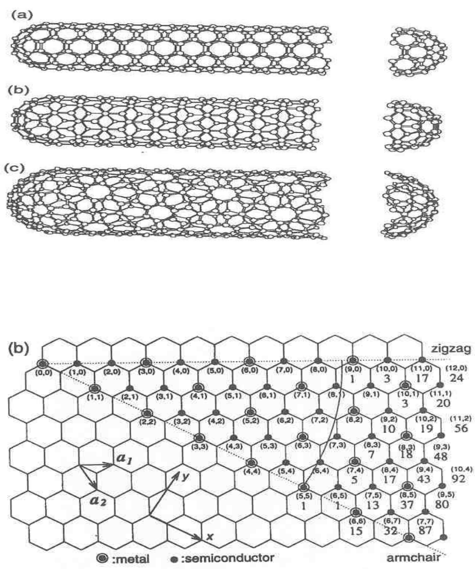


Figure 1: Carbon nanotubes:(a)Armchair(5,5) (b)Zigzag (9,0) (c)Chiral(10,5) (d)Possible chiral vectors.

Because of their very small diameters (down to $\sim$ 0.6 nm) and relatively long lengths (up to $\sim$ several μm),single-wall carbon nanotubes (SWNTs) are good examples of 1D quantum wires.Electron transport along such tubes may be ballistic in nature [3].Ballistic tranport occurs when elctron pass along a conductor without experienceing any scattering from impurities or phonons;effictively,the electrons encounter no resistence, and dissipate no energy in the conductor.Experimentally when a multiwall nanotube was dipped into liquid mercury or gallium and conductance of the tube was measured simultaneously, the conductance was indeed nearly equal to the conductance quantum $G_o = 2e^2/h$ (see Fig.-2).The measured conductance appeared to be independent of the depth to which the tube was inserted into the metal,suggesting that electronic transport occurs ballistically in nanotubes-even at room temperature!As a result no heat is dissipated in the tubes,and an extrordinary current density of about 10^9 A/cm^2 ran through an individual SWNT between two electrodes at room temperature [4].

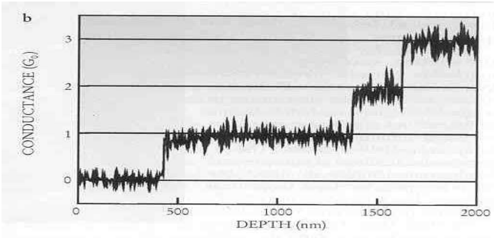


Figure 2: Conductance vs. position of nanotube fiber at room temperature.

1 Proximity-Induced Superconductivity

Superconductivity proximity effect is a phenomenon in which a material (conductor)which by itself is not a superconductor acquires the superconducting state in the presence of a nearby superconductor.If we attach a normal metal (N) with a macroscopic superconductor (S), the superconducting transition temperature T_c and the gap $\triangle$ in N can be on the order of their values in S if the resistance of the SN interface is sufficiently small.Besides, the characterstic length in which the superconductivity occurs should be smaller than both the phase coherence length in the normal metal L_ϕ and thermal length L_t (in a clean metal $L_t = \hbar V_f/k_B T$ and in a dirty metal $L_t = \sqrt{\hbar D/k_B T}$,where D is the electrom diffusion coefficient).

Proximity-induced superconductivity in SWNT below 1 kelvin,both in a single tube 1 nanometer in diameter and in crystalline ropes containing about 100 nanotubes,was observed [4].The rope samples were mounted on superconducting bilayer electrodes Re/Au (30-nm layer of Re,rhenium,;50-nm layers of Au) with a transition temperature $T_c = 1.1k$ (Fig.-3),the resistance became temperature dependent below 1.5k in the region of the superconducting transition of Re/Au contact.Samples $R0_1$ and $R0_2$ are too resistive (1750 ohms and 650 ohms respectively)and do not fulfill the condition $L_T > L$ necessary to achieve superconductivity.In contrast,the resistance of the rope $R03$, which contains approximately 200 tubes, is $R_o = 65$ ohm;the average resistance for each tube is on the order of 13 kilohms.This sample underwent a superconducting transition and exhibited zero resistance below 1k.Taking the Fermi velocity $V_F = 0.8 \times 10^6 ms^{-1}$,the L_T (T=1k) of the sample is on the order of $3\mu m$,larger than its length of $1.7\mu m$.The proximity-induced superconductivity was also observed in isolated SWNT samples like ST_1 (Fig.-3),with $R_o = 27$ kilohms.The tube was mounted on Ta/Au electrodes (5-nm Ta,Tantalum, 100-nm Au) and had a superconducting transition at $T_c = 0.4K$, close to the transition temperature of the contacts.The transition was shifted to lower temperature when a magnetic field was applied in the plane of the contacts (perpendicular to the tube axis).The critical field was surprisingly high (of the order of 1 T) and was 10 times larger than the measured critical field of the contact.Above 2 T, the resistance became field-independent and a small increase was apparent when the temperature was lowered below 0.2 K (Fig.-3B).Similar behavior was observed in $R0_3$ and all the nanotube junctions which exhibit superconductivity.

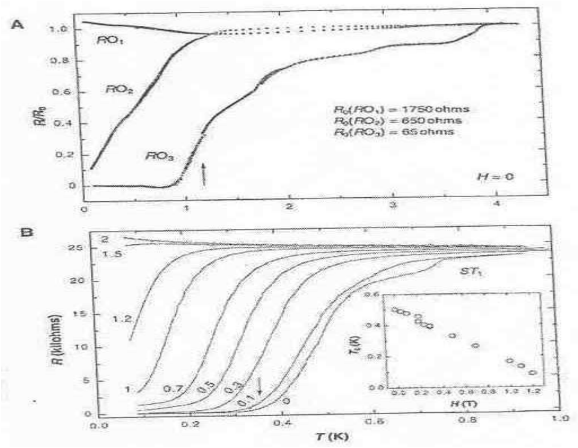
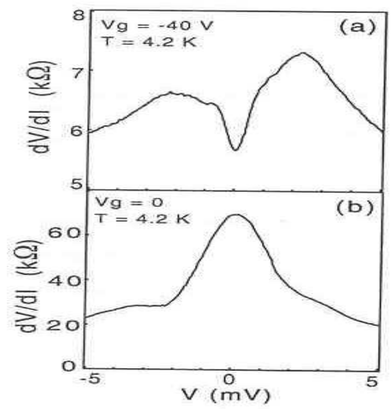


Figure 3: (a)Temperature dependence of the resistance of ropes $R0_1$,$R0_2$,$R0_3$ (b)Temperature dependence of the resistance of the single tube ST_1.

Carbon nanotubes suspended between superconducting contacts constitute a new type of Josephson junction.Because of their low electronic density,the superconducting properties may be controlled by a metallic gate located close to the tube.This possibility was confirmed by making a Nb/nanotube contact in a highly doped Si substrate which is used as back gate [5].Low-temperature transport measurements of differential resistance (dV/dI) versus bias voltage (V) was carried out in a two-lead configuration with a negligible series resistance of $\approx 20ohm$.All five samples,each consisting of either three or four individual SWNTs, exhibited the same qualitative behavior (Fig.-4),including the disappearence of these behaviors at temperature above T_c of Nb.



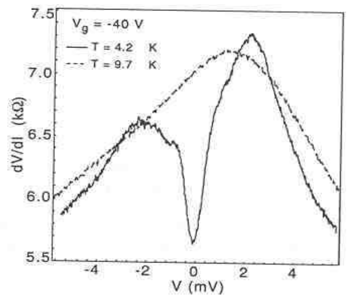


Figure 4: (a) and (b) dV/dI vs. V (c) dV/dI vs.V for same sample,measured with $V_g = -40$ V at 4.2 K (solid) and at 9.7 K (dashed):at $T > T_c$ the Andreev dip disappears.

2 Intrinsinc Superconductivity

Natural superconductivity,i.e.,without having superconducting contact in SWNT is of great interest.Three samples of SWNT ropes were suspended between normal metal contacts of trilayers Al_2O_3/Pt/Au of respective thickness 5,3 and 200 nm.The contacts showed no sign of superconductivity down to 50 mk.As is generally observed,the resistance increases as the temperature is lowered between 300 K and 1 K.Things change however below 1 K,as shown in Fig.-5 for the three samples Pt1,Pt2, and Pt3,measured in magnetic fields ranging from 0 to 2.5 T.In sample Pt2,a two order of magnitude resistance drop was found below 0.55 K,which was destroyed by a magnetic field of the order of 1 T, or by a d.c. current greater than 2.5 μA.Thus the rope Pt2 (and,to a lesser extent, Pt1) is intrinsically superconducting [6].(This was the first observation of intrinsinc supercondcutivity in SWNTs by the same group who first observed the proximity induced superconductivity on them).Since much higher transition temperature were observed in alkali doped fullerenes,a soccer ball shaped carbon molecules similar to nanotbe, because of coupling to higher energy phonons,there is good possibility that transition temperature can be increased in nanotubes by chemically doping them.

3 Possible Room Temperature Superconductivity

Research in high temperature supercondcutivity(HTSC) clearly gives a hint that the room-temperature superconductivity requires a synthesis of new materials.In V.L. Gingburg's opinion,"layered compounds and sandwiches of dielectric-metal-dielectric type are the most perspective in respect to HTSC.To produce them is natural to use an atomic layer-by-layer technique" [7].What all the HTSC ceramics have in common is that they consist of alternated atomic both superconducting layers (CuO_6,MoS_2,NiB_4,etc.) and metallic(La,K,etc.) or dielectric(LuC,etc.) layers,which are the genuine atomic-scale sandwiches.Many years ago,Little and Parks showed that in thin superconducting-cylindric Sn quasi-1D tube of diameter d in comparision with plane Sn 2D film of the same thickness h, a critical temperature T_c raises on some oscillated value $\triangle T_c(H)$ provided that $d < \xi(T)$ and $d < \lambda(T)$,where ξ is the electron correlation length and λ is the field penetration depth [8].This wrapping effect depend on the diameter as

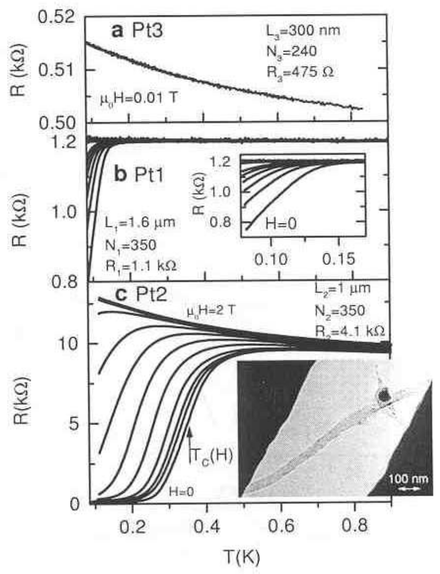


Figure 5: Resistance as a function of temperature for the three samples.The lenght L,number of tubes N and room tempearture resistance R of each sample are given.

$\triangle T \sim 1/d$ pointing on small nanotube as a promising high-T_c superconductor.

An attempt to incorporate carbon nanotube into the superconducting matrix of a high-T_c superconductor was done.Indeed when a $Bi_2Sr_2CaCu_2O_{8+x}$ superconductor was embedded with carbon nanotubes,an enhanced flux pinning was observed [9].Superconducting transition temperature T_c and superconducting fraction were both appreciably higher in the nanotube containing samples than in pure Bi2212.In several respects the superconductor with nanotubes embedded had better superconducting properties than the pure matrix substance.The most reasonable explanation of the result is that the carbon nanotubes embedded in the superconductor act as extended sites for strong,columnar-defect-like pinning.

A leading idea is proposed for the possible room-temperature superconductivity [7].The idea is to combine Little's and Ginzberg's idea to create a novel type of material on a base of a close-packed lattice of quasi-1D superconducting nanotubes.Accounting a geometric similarity between Abrikosov vortex and nanotube ,the superconducting coaxial multilayer nanotubes of the correlation length in diameter is an ideal and natural trap for pinning of such vortex.Nanotube should be layered superconductor,such as LuNiBC.An example of wrapping HTSC sandwich into the cylindric multilayer HTSC nanotube is shown in Fig.-6.Mechanism of superconductivity was proposed on a base of a whispering mode,which is shown to be responsible for a strong enhancement of electron-phonon interaction and for an increase of critical temperature.Basically the whispering mode is precisely the phonon vibration corresponding to lowest frequency of nanotube vibrations associated with the lowest energy transition.Nanocomposite built from such quasi-1D nanotubes when coinciding with vortex lattice provides ideal condition for the pinning,resonance,distortion,ordering,and Little-Parks effects,the joint action of which is guggested to result in synergetic effect increasing the superconductivity.Such quasi-1D or 2D nanotubular crystal is proposed to synthesize by template approach using zeolite-like membrane.The principal distinguishing feature of superconducting nanotube composite is that the quasi-1D or 2D lattice of layered superconducting nanotubes differs fundamentally both from 2D sandwich film and 3D lattice of cylindric superconducting nanorodes.

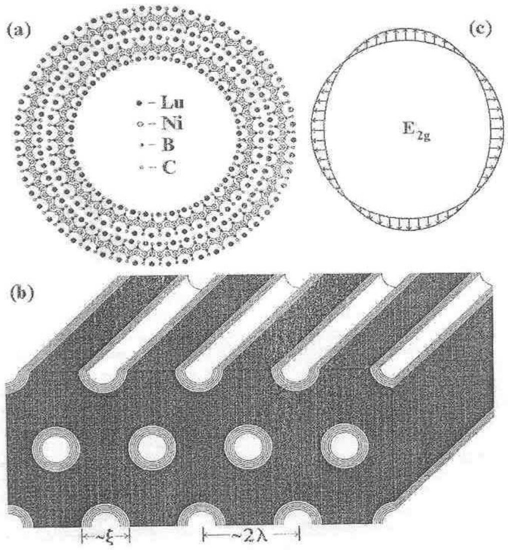


Figure 6: Whispering mode in the superconducting nanotubular lattice.(a) Cross-section of two-layer NT on base of LuNiBC rare-earth borocarbides. (b) Nanocomposite in kind of close-packed triangular lattice. (c) Sketch of whispering mode of vibration in a nanotube.

References

[1] M.S.Dresselhauss,G.Dresselhaus,P.C.Eklund:Science of Fullerenes and Carbon Nanotubes (1996).

[2] Cees Dekker, Physics Today,May 1999

[3] P.J.F.Harris, Carbon Nanotubes and Related Structures (1999)

[4] A.Yu.Kasumov *et al. ,Science,28 May 1999*

[5] A.F.Morpurgo et al.,Science,8 Octorber 1999

[6] M.Kociak,A.Yu.Kasumov et al,arXiv:cond-mat/0010220 v2 9 January 2001

[7] V.V.Pokropivny, Journal of Superconductivity,Vol 13,No.4,2000

[8] P.G.De Gennes,Superconductivity of Metals and Alloys (1966)

[9] K.Fossheim et al.,Physica C 248(1995)195-202