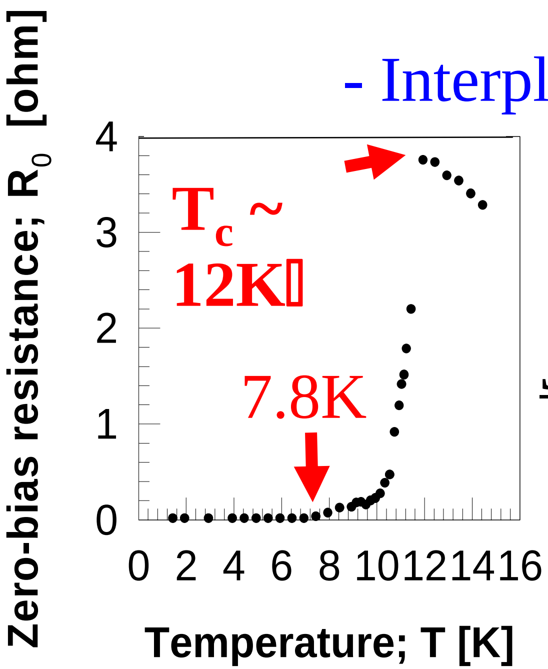
High-T_c Superconductivity in Entirely End-bonded Multi-walled Carbon nanotubes



- Interplay between Tomonaga-Luttinger liquid and superconductivity-

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Outline

1:Backgrounds and motivations

①Superconductivity in 1D conductor

②Two reports of superconductivity in CNTs

③Carbon-related new superconductors

B-doped Diamond

Ca-Intercalated Graphite C_6Ca

2:Experemental results

Sample structures and identifications

Results of electrical and magnetic measurements

3:Two possible mechanisms

4:Application to flux-controlled quantum bit

Back ground and motivation ①

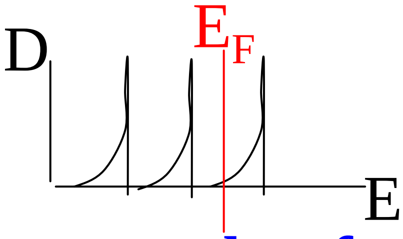
Whether 1D conductor within a ballistic charge transport regime can be superconductive at finite temperatures or not ??

Obstructions for appearance of superconductivity

1: Tomonaga-Luttinger liquid

2: Peierls Transition → Charge-density wave

3: Low density of states due to van-Hove singularity

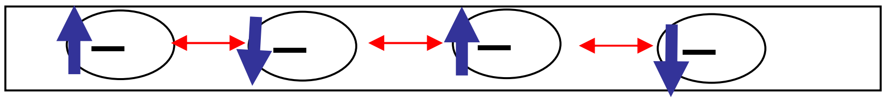


4: Spin fluctuation etc.

→ **Depends on competition between strengths of these phenomena and superconductivity**

CNTs → an ideal 1D conductor

What is Tomonaga-Luttinger liquid(TLL) ?



Non-Fermi liquid

<u>**Repulsive Coulomb interaction**</u> between electrons in a 1D ballistic charge transport regime → Spin-charge separation

Power laws in conductance vs. energy relationships

Semiconductor (2 DEG) : Dirty TLL

Tarucha・ Fukuyama ~1995

In carbon nanotubes

M.Bockrath, D.H.Cobden, R.E.Smalley, Nature **397**, 598 (1999)

Bachtold, et al., PRL 87, 166801 (2001)

R.Egger, Phys.Rev.Lett. 83, 5547 (1999)

R.Egger, et al., Phys.Rev.Lett. **87**, 066401 (2001)

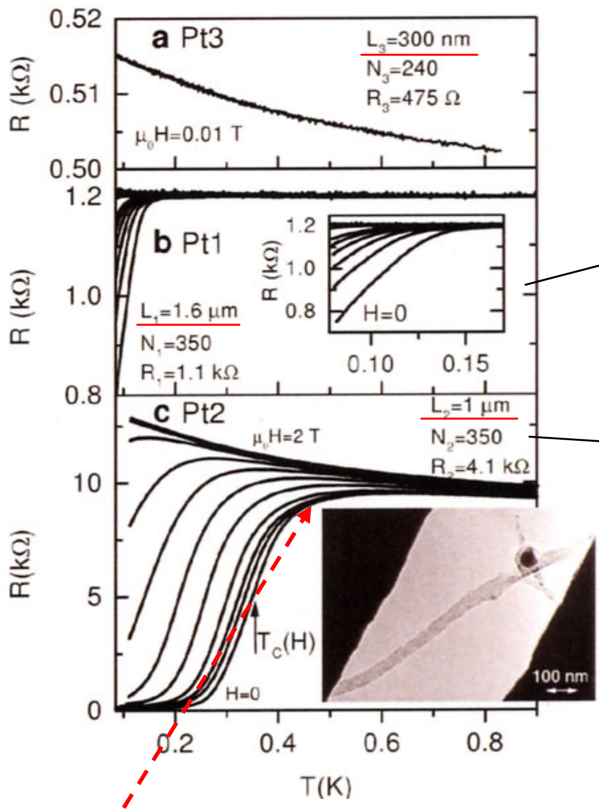
H.Ishi, H.Kataura, et al., Nature **426**, 540 (2003)

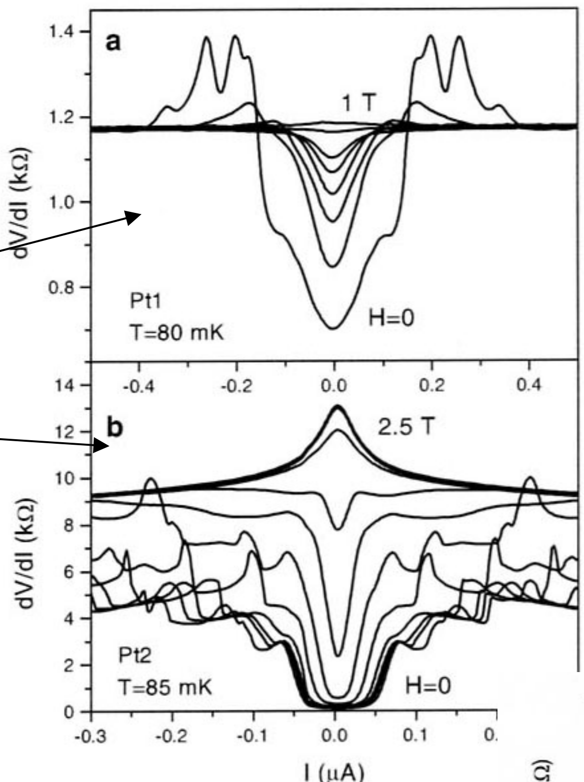
H.W.Ch Postma, C.Dekker et al., Science **293**, 76 (2001)

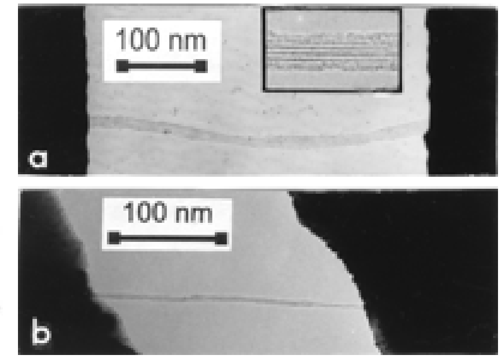
Back ground and motivation ②

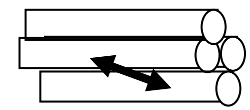
Bouchiat
Phys. Rev. Lett. 86, 2416 (2001)

In SWNT **ropes**

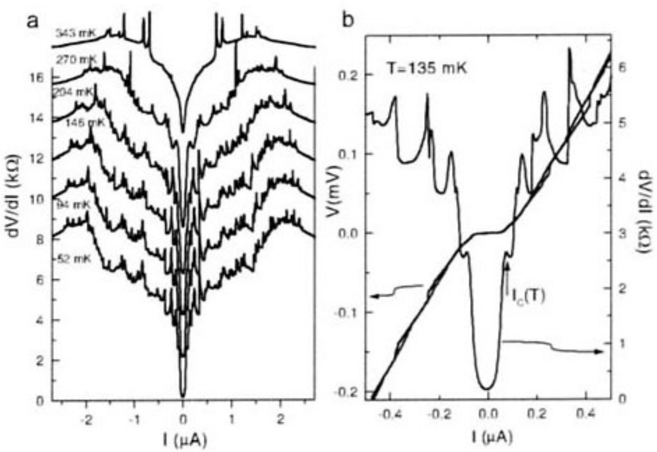


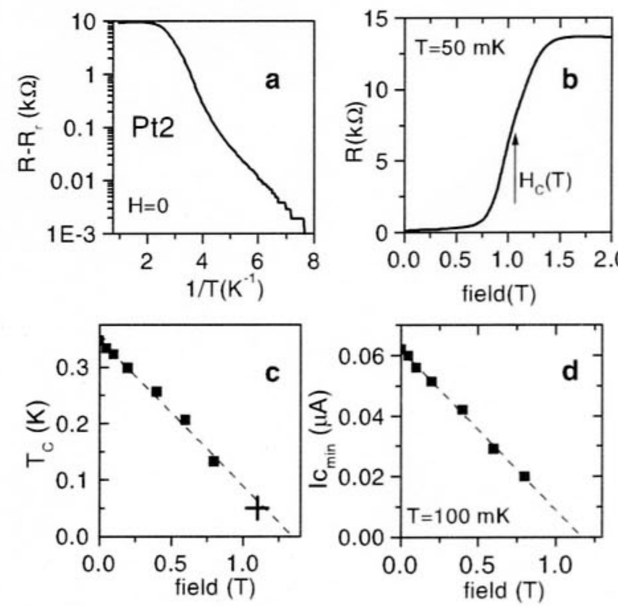






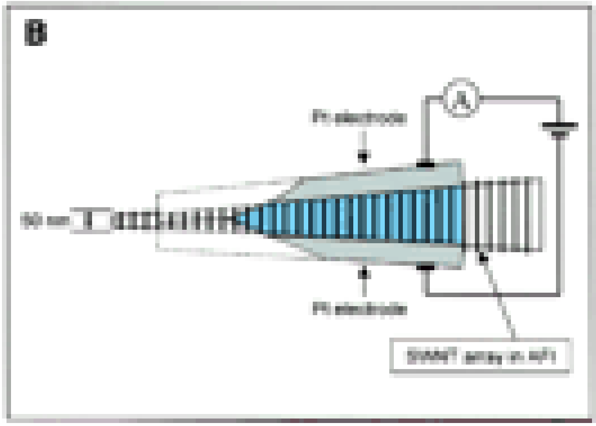
$T_c \approx 0.4K$

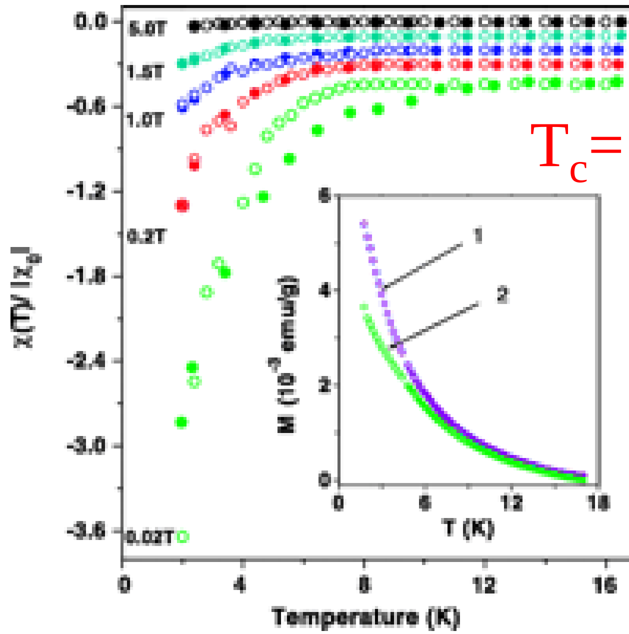




Tang

Science 292, 2462 (2001)

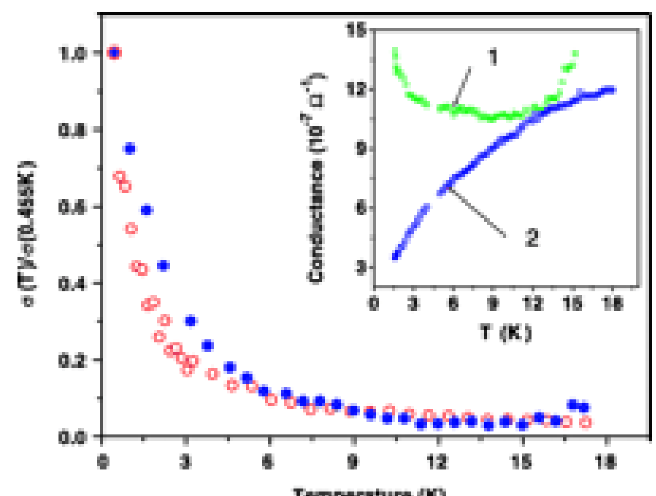




T_c=15K

Meissner effect

SWNTs with **Φ= ~0.4nm**
embedded in zeolite matrix



Non-zero resistivity

Our case

In third type CNT

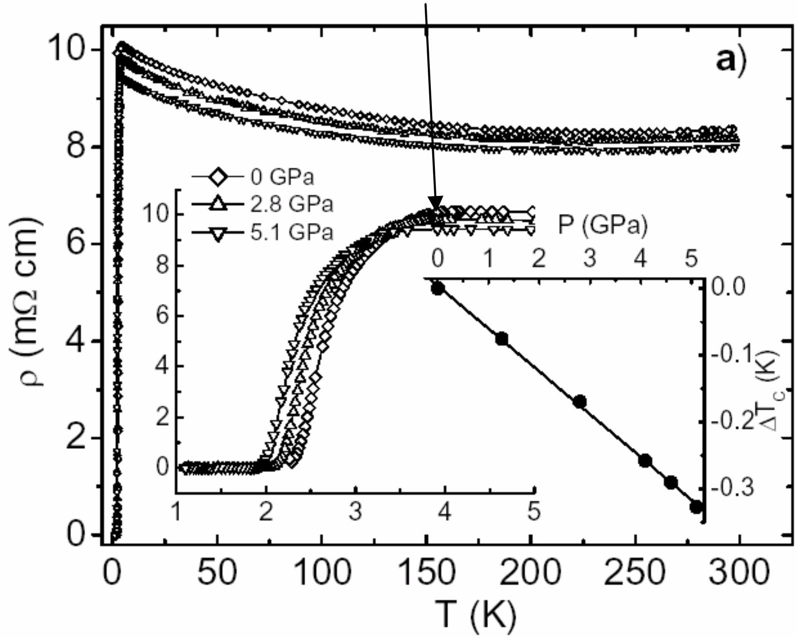
↓

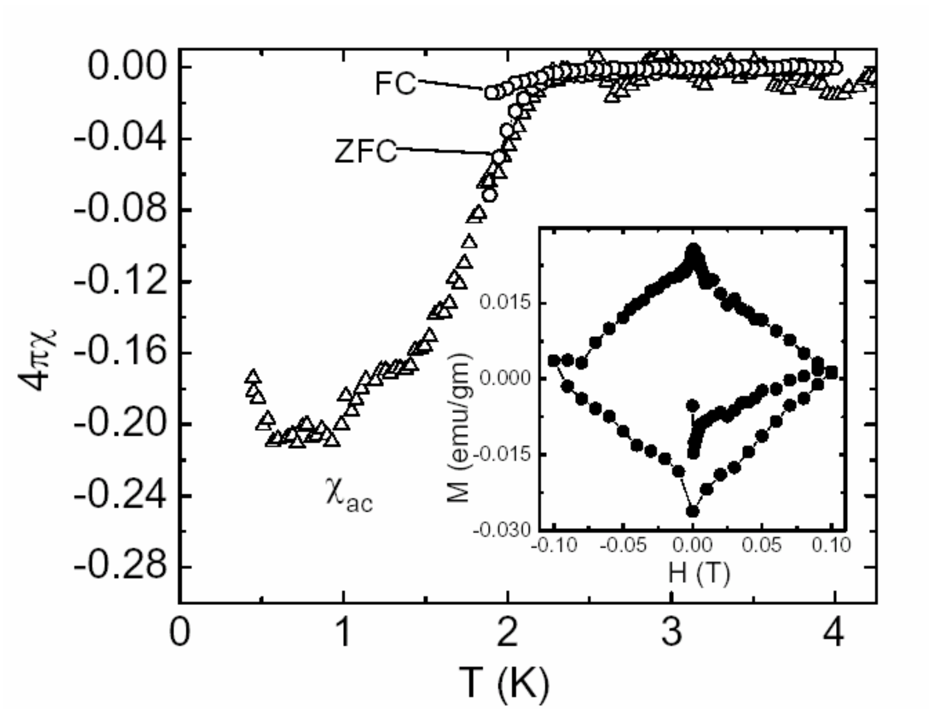
Multi-walled CNTs

Superconductivity in highly B-doped Diamond

E.A.Ekimov, et al., Nature 428, 542 (2004)

$T_c \approx 4K$





High pressure 8 ~ 9 GPa

2500 ~ 2800 K

$n = 4 \times 10^{21}$ (cm^{-3})

Current T_c=11.4K

On (1,1,1)

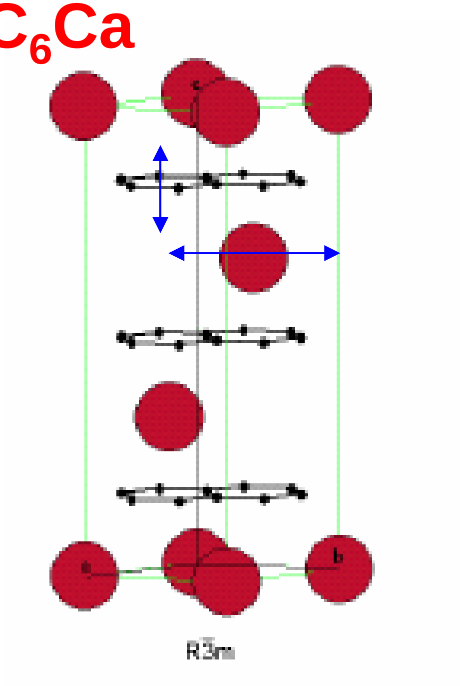
$n = \sim 10^{22}$ (cm^{-3})

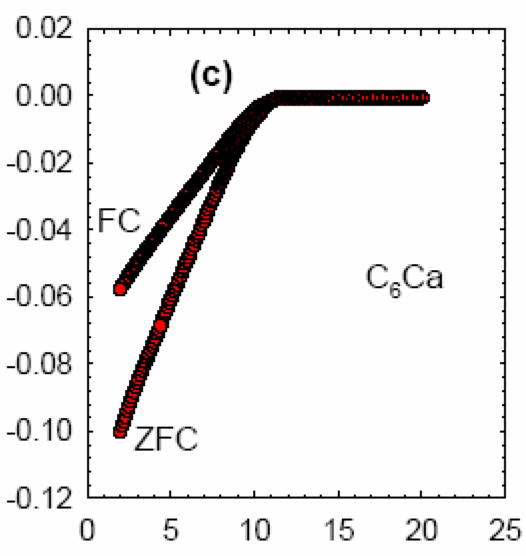
Superconductivity in C_6M

Weller et al., Nature Phys 1, 39 (2005)

N.Emery, G.Loupias et al.,PRL 95, 87003 (2005)

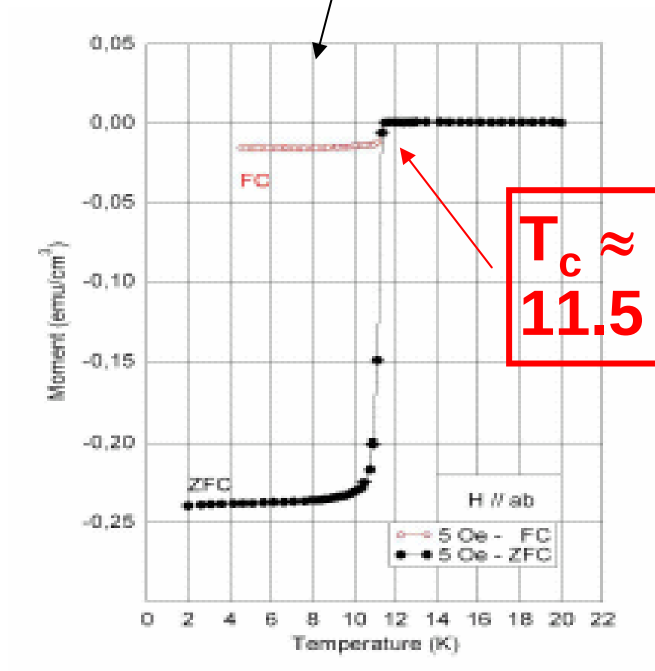
C_6Ca





Only surface

In bulk

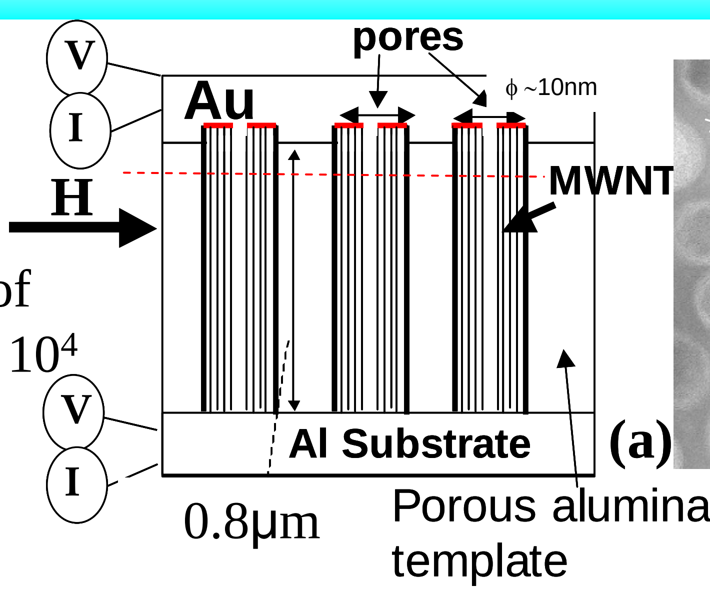


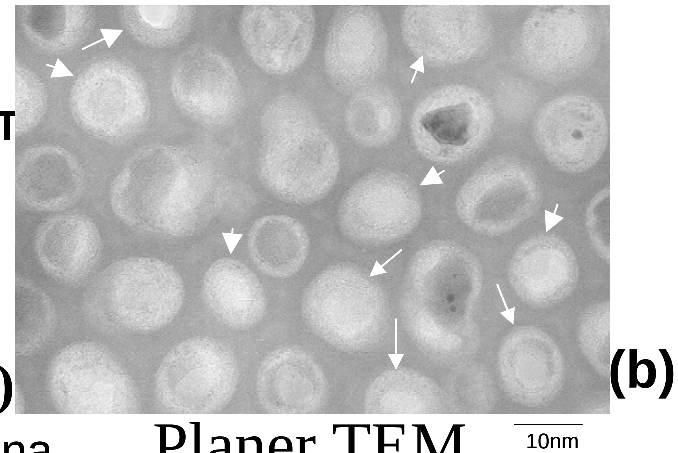
$T_c \approx$ 11.5 K

Non-carrier doping into CNTs

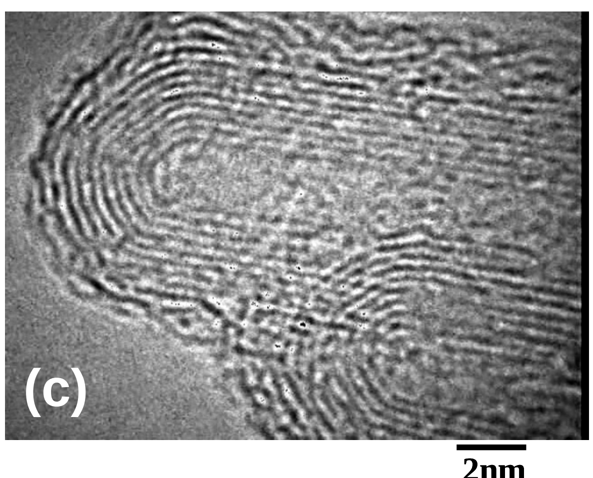
Sample structures (Au/MWNTs/Al) and identifications

Number of pores ~10^3, 10^4

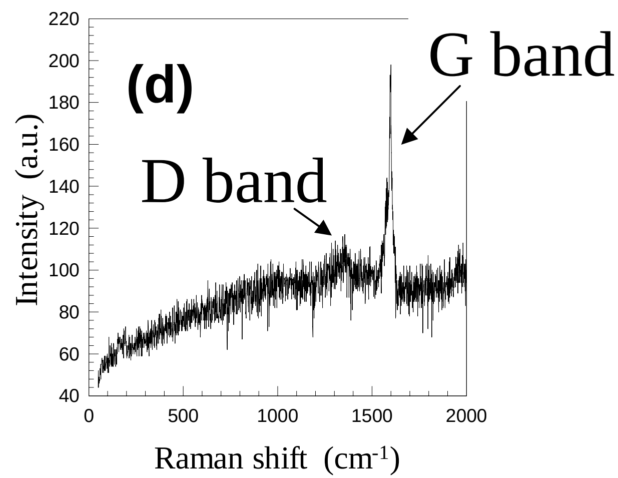




Planer TEM

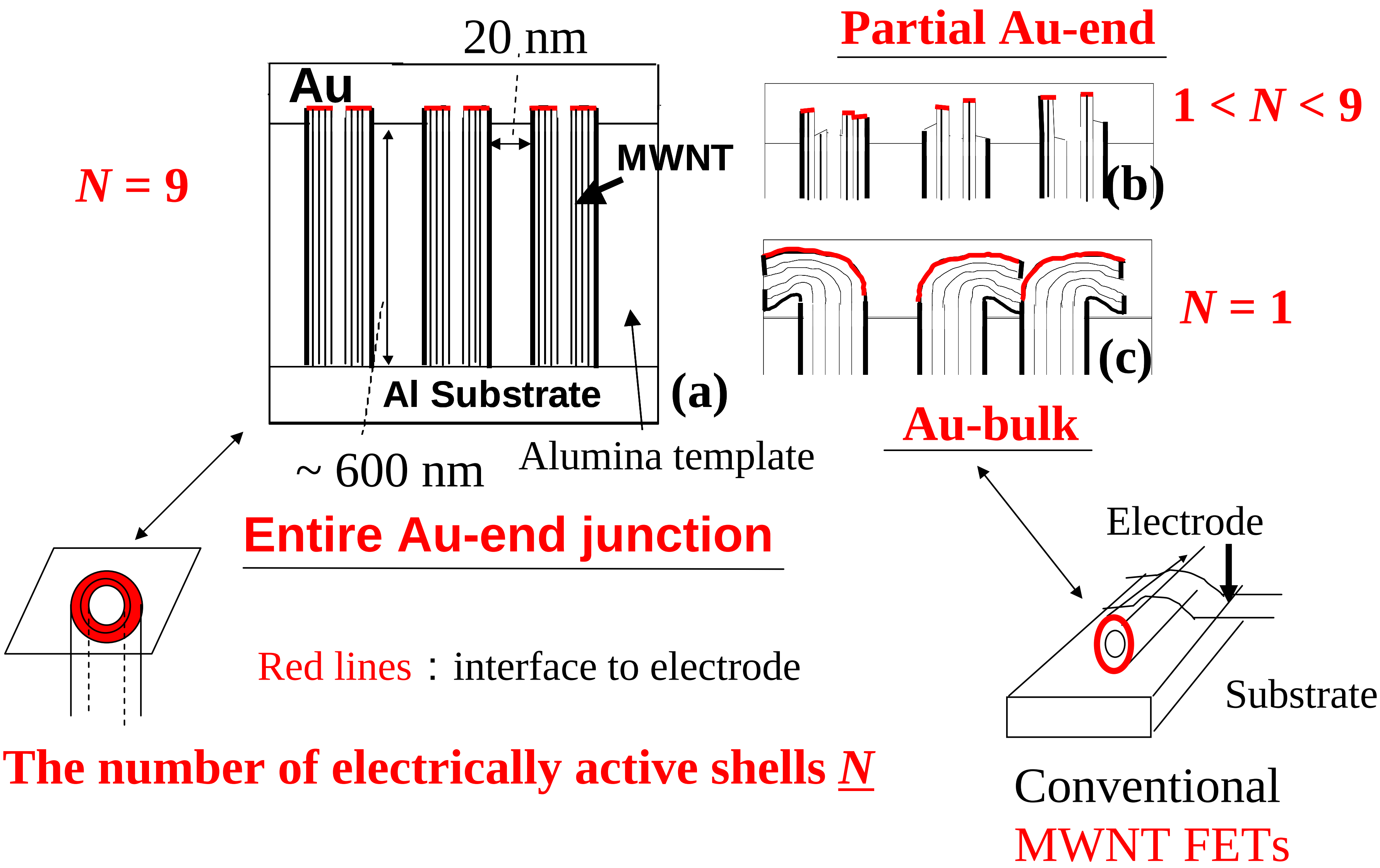


N=9, Φ_O= ~7nm, Φ_I=2nm



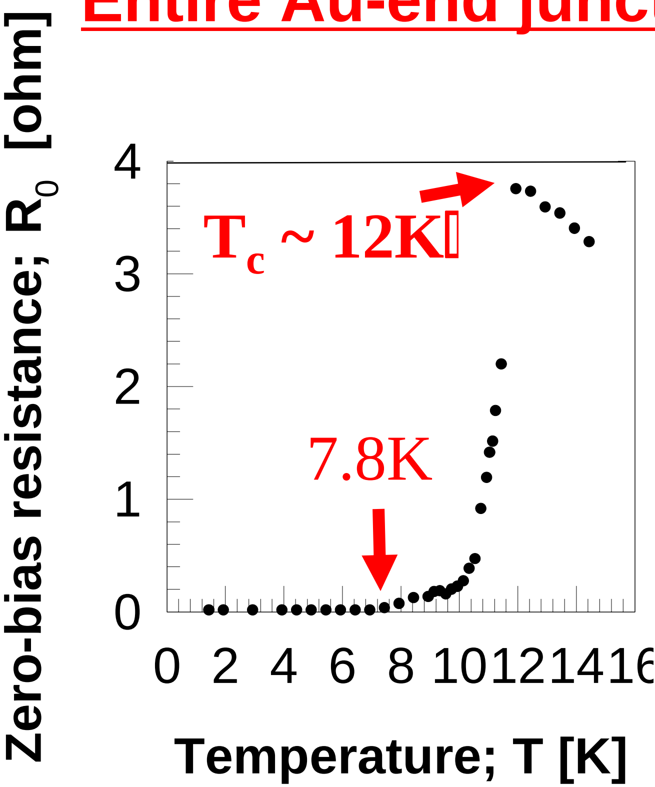
High quality

Three different types of Au/MWNTs junctions

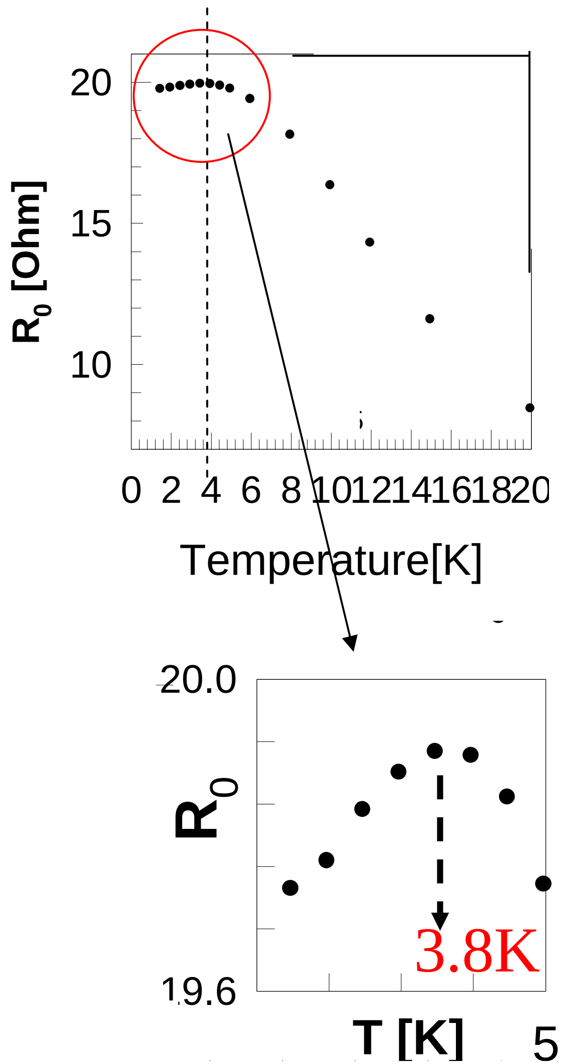


Observation of zero-bias resistance

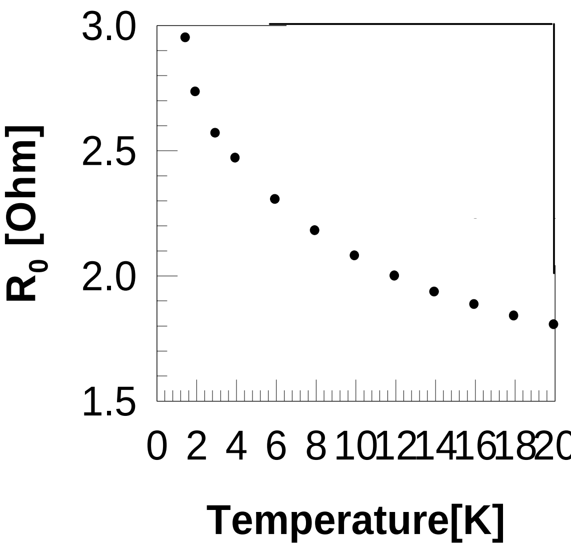
Entire Au-end junction



Partial Au-end



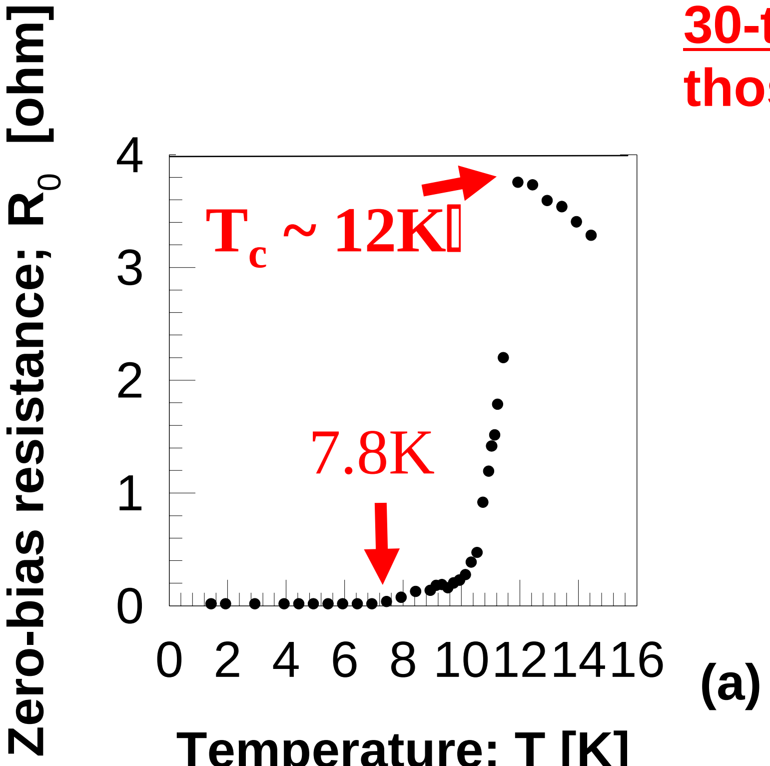
Au-bulk



Observation of resistance drop

Entire Au-end junction

30-times larger than those in SWNT ropes



Residual resistance ≈ 1Ω

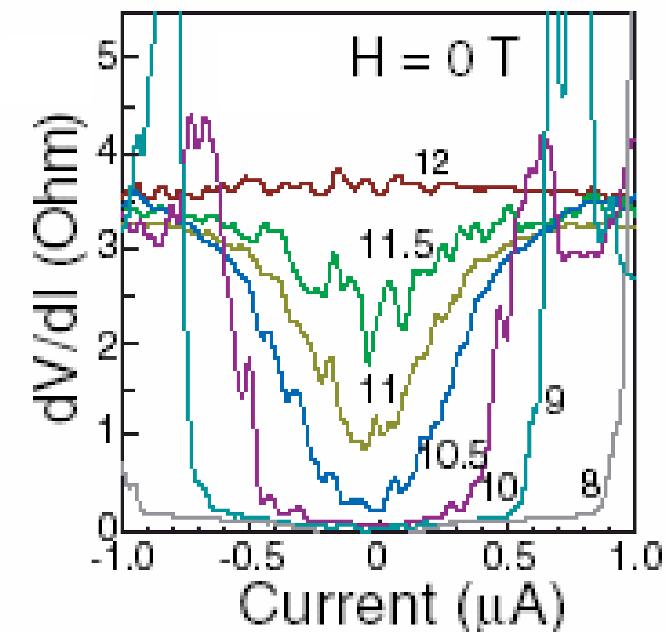
Au + Al ≈ 0.5Ω

Total quantum resistance R_Q, $h/2(2e)^2$ $/2/9/N_{SC} \approx 0.5\Omega$ → N_{SC} ~100

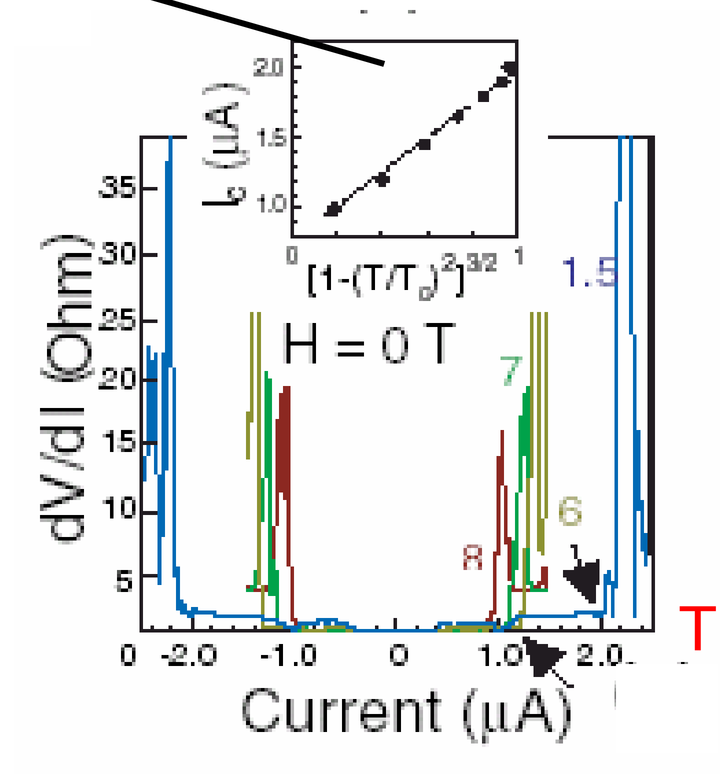
Temperature dependence of dip and critical currents

Entire Au-end

$I_c \propto [1-(T/T_c)^2]^{3/2}$ → **G-L theory**



$T > T_c$



$T < T_c$

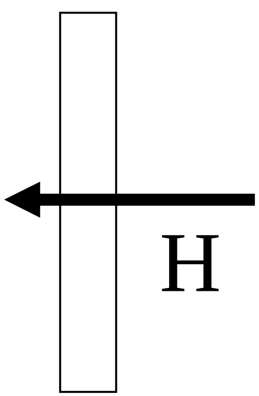
Coupling of neighboring MWNTs?

Screening of repulsive e-e interaction → High T_c

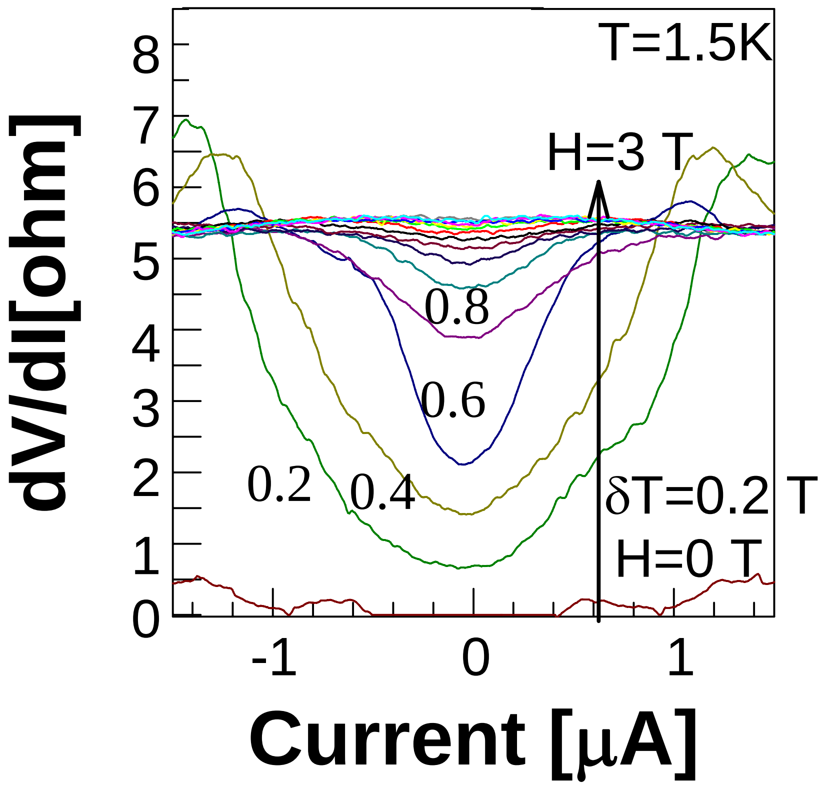
Field dependence of resistance dip and R_0

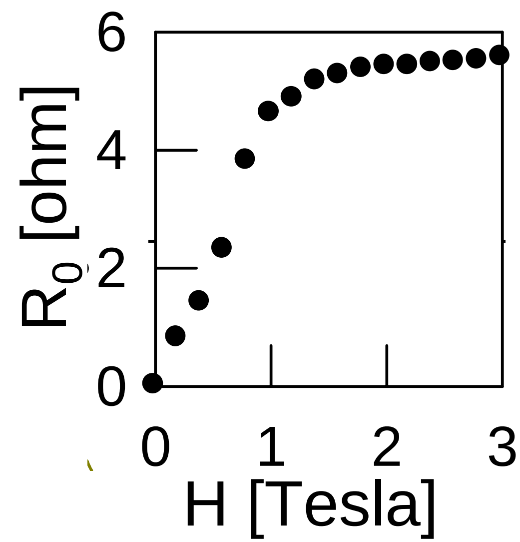
Entirely Au-end

Upper H_c = ~1T ➔ Magnetic penetration length >> 10nm ➔ Type II



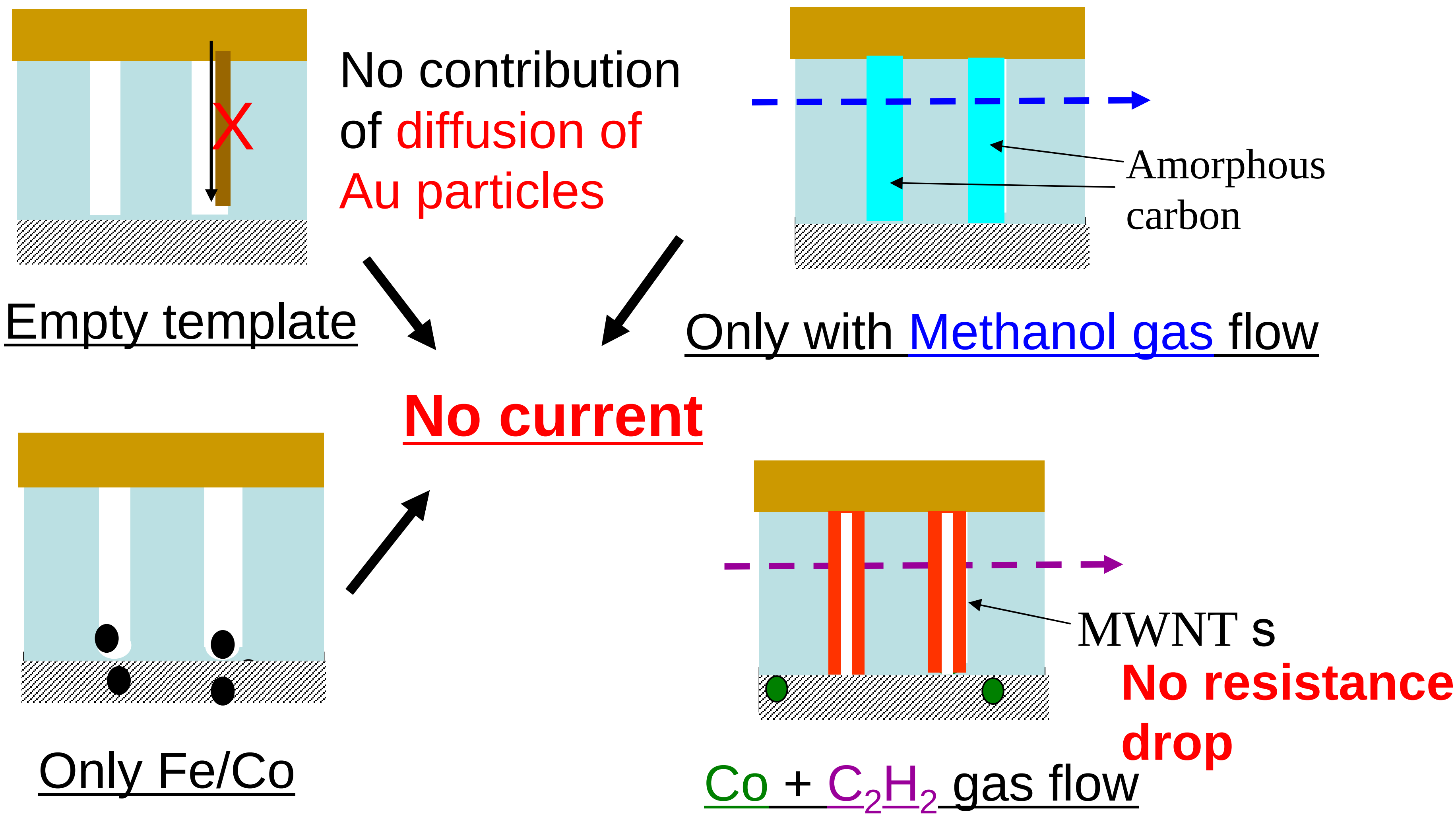
MWNT



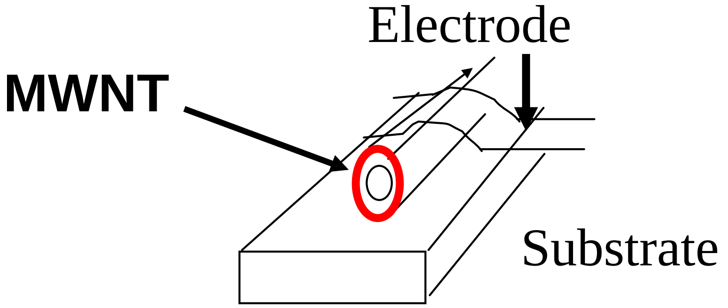


$H_c \approx 2T$

Rejection of parasitic effects

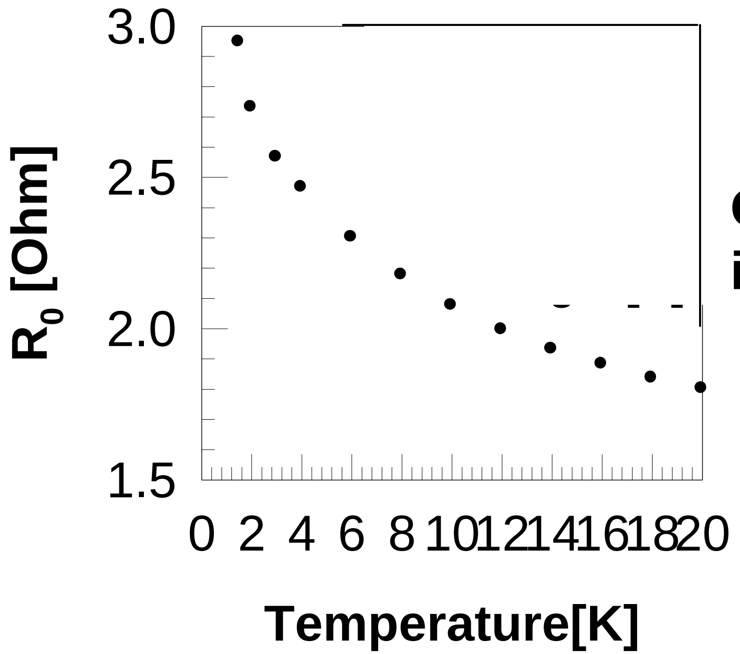


Au-bulk junction



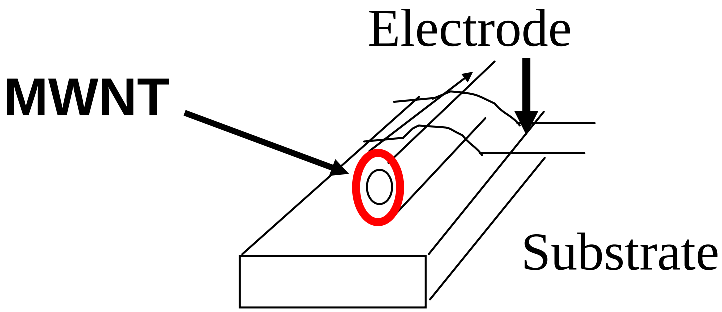
Conventional
MWNT FETs

Only the outermost shell is electrically active



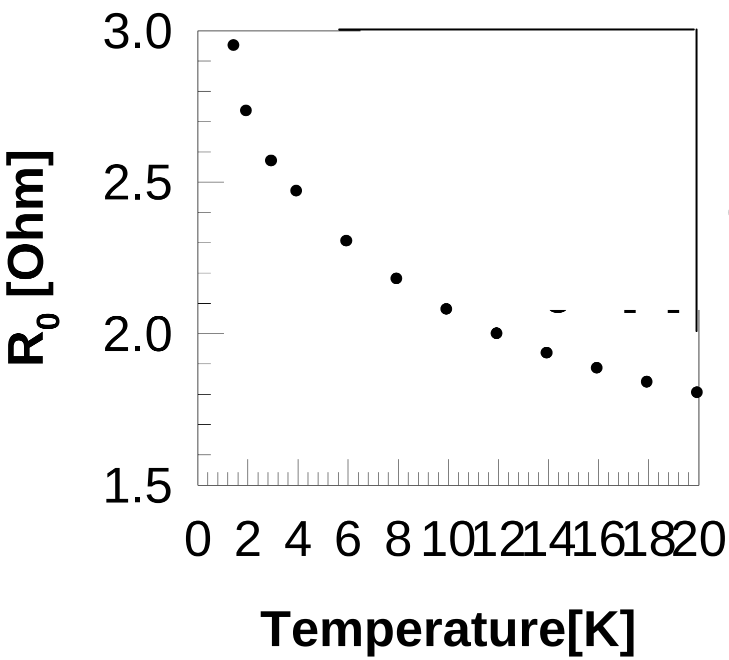
No superconducting transition

Au-bulk junction



Conventional
MWNT FETs

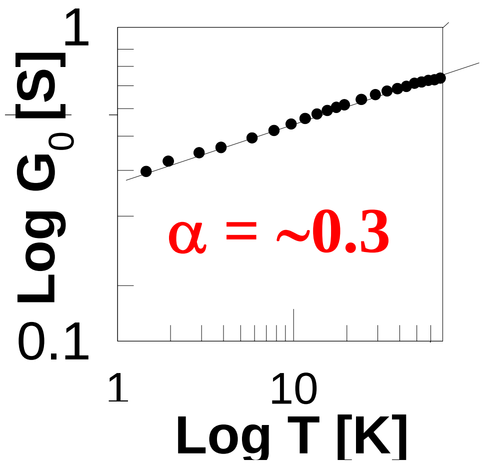
Only the outermost shell is electrically active

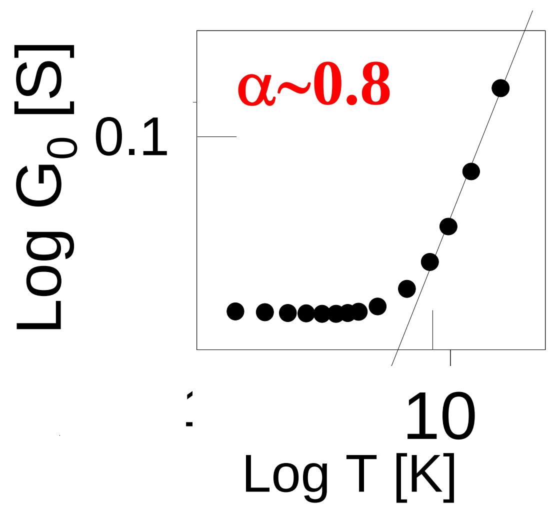


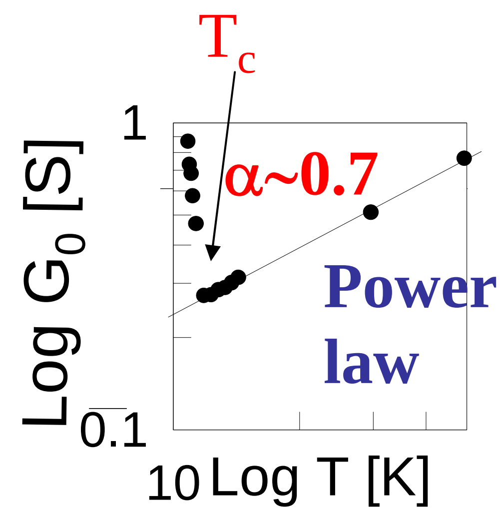
(c)

No superconducting transition

Interplay between TLLs(power laws) and superconductivity(R_0 drop)







<u>**Au-bulk junction**</u> | <u>**Partial Au-end**</u> | <u>**Entire Au-end**</u>

TLLs >> SC | TLLs ≈ SC | TLLs << SC

PRL 96, 057001 (2006)

(Feb. 10th)

PRL 96, 057001 (2006) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2006

Superconductivity in Entirely End-Bonded Multiwalled Carbon Nanotubes

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We report that entirely end-bonded multiwalled carbon nanotubes (MWNTs) can exhibit superconductivity with a transition temperature (T_c) as high as 12 K, which is approximately 30 times greater than T_c reported for ropes of single-walled nanotubes. We find that the emergence of this superconductivity is highly sensitive to the junction structures of the Au electrode/MWNTs. This reveals that only MWNTs with optimal numbers of electrically activated shells, which are realized by end bonding, can allow superconductivity due to intershell effects.

DOI: 10.1103/PhysRevLett.96.057001 PACS numbers: 74.70.Wz, 74.78.Na

One-dimensional (1D) systems face some obstructions that prevent the emergence of superconductivity, such as (1) Tomonaga-Luttinger liquid (TLL) states consisting of a repulsive electron-electron (*e*-*e*) interaction [1–3], (2) a Peierls transition (charge-density waves), and (3) a small density of states, which becomes significant when the Fermi level is not aligned with van Hove singularities (VHSs). A carbon nanotube (CN), an ideal 1D molecular conductor, is one of the best candidates for investigating

synthesized in nanopores of alumina templates. Further, we recently realized proximity-induced superconductivity (PIS) in Nb/MWNTs/Al junctions, which were prepared using the same method [13,14]. They proved that Cooper pairs could be effectively transported through the highly transparent interface of the CNs/metal junctions obtained by this end bonding. Such entire end bonding has never been carried out in conventional field-effect transistor (FET) structures using CNs as the channels.

IOP Physics Web Feb.14th

Physorg.com NEWS March 11th

Superconductor NEWS May

Conclusion

Entirely end-bonded multi-walled carbon nanotubes
can take a superconducting transition
with T_c as high as 12K

↓

Interplay with 1D phenomena

Intentional B-doping → $T_c \approx 40K$?

↓

Application to molecular quantum computation

Carbon Nanotubes can have high potentiality for quantum physics and applications