Carbon Nanotubes, The Future?

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Introduction

- **Basic Principles**
  - **Brief History.**
  - **Structure of the Carbon Nanotubes**
  - **Comparison to Conventional Electronics.**
  - **Challenges**
  - **Summary**

Brief History of Carbon Nanotubes

- **1970s by Morinobu Endo**
  - **Part of Phd. Project at University of Orleans in France**
  - **7nm diameter**
  - **Not recognized as Nanotubes so not studied**
- **1991 Sumio Iijima**
  - **NEC Lab in Tsukuba**
  - **Used high-resolution transmission electron microscope to observe carbon nanotubes.**
  - **Field took off**

Brief History of Carbon Nanotubes

- **1996 Richard Smalley synthesized bundles**
- **1997 Metallic Properties discovered**
- **1998 Semi-conducting Properties Discovered**

Structure of Carbon Nanotubes

- **Single Walled Carbon Nanotubes (SWNT).**
  - **1 nm width**
- **Can be either metallic or semiconductor.**
  - **Depends on how tube is rolled.**
  - **Semi-metal(zero band gap semiconductor).**
- **2-dimensional graphene.**
- **1-dimensional analogs of the MOSFETs.**
- **Long Scattering Lengths**
- **Better than best metals or the best semiconductors**

Structure of Carbon Nanotubes

McEUEN *et al.*: SWNT ELECTRONICS 79

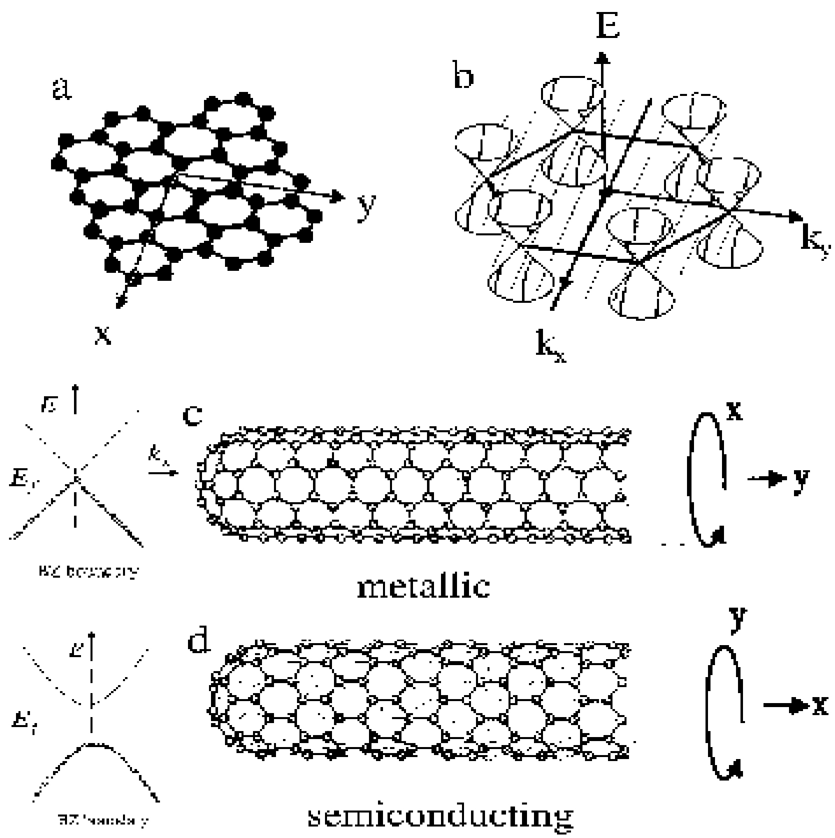

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Fig. 1. (a) Lattice structure of graphene, a honeycomb lattice of carbon atoms. (b) Energy of the conducting states as a function of the electron wavevector k. There are no conducting states except along special directions where cones of states exist. (c), (d) Graphene sheets rolled into tubes. This quantizes the allowed ks around the circumferential direction, resulting in 1-D slices through the 2-D band structure in (b). Depending on the way the tube is rolled up, the result can be either (c) a metal or (d) a semiconductor.

Structure of Carbon Nanotubes

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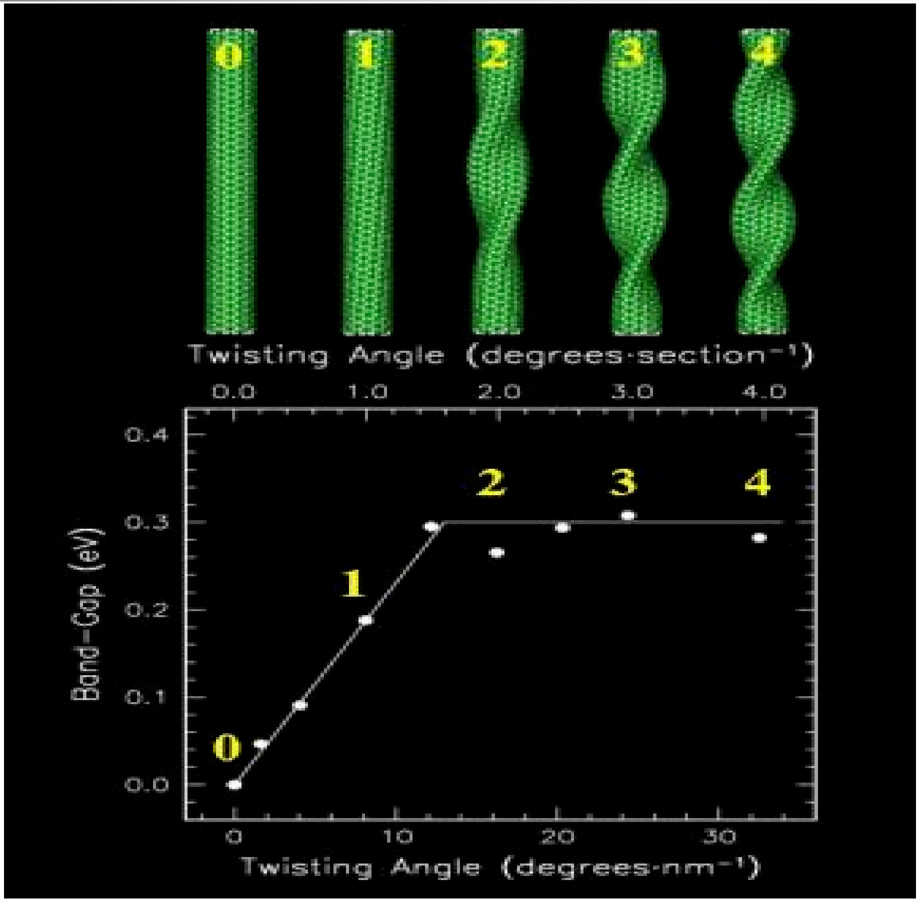
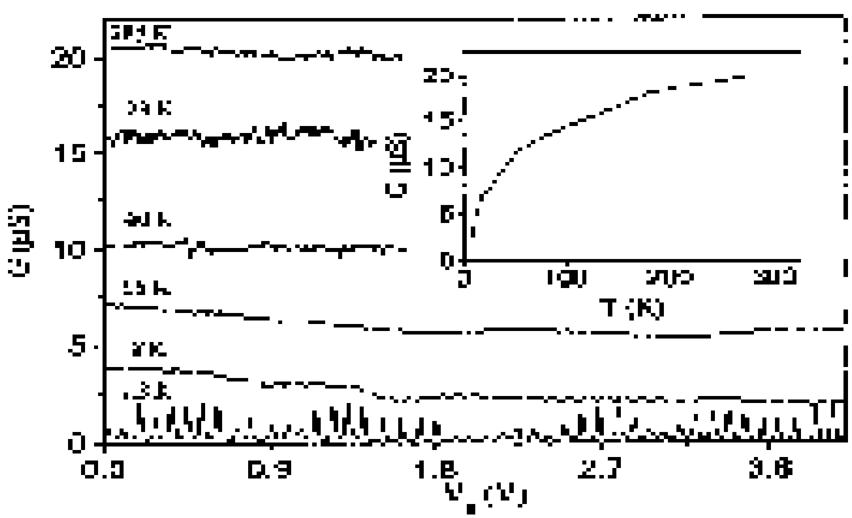


Comparison to Conventional Electronics

- **Surface States.**
  - **No surface states.**
  - **Surface states degrade devices.**
  - **When a 3-dimensional crystal is interrupted by a boundary.**
- **Conductance**
  - **Ballistic SWNT with perfect contacts**
    - **$G = 4e^2 / h$ = 155 uS (approx. 6.5 k ohm)**
    - **Total Resistance = $h/4e^2 + R_c + R_t$**
      - **Where R_c extra contact resistance**
      - **$R_t = (h/4e^2)(L/1)$ L is length of tube**

Comparison to Conventional Electronics

- **Conductance is 6Kohm range switching speeds of 10 THz.**
- **Gate Voltage change of 10V a increase of 10^6 change in conductance.**



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Comparison to Conventional Electronics

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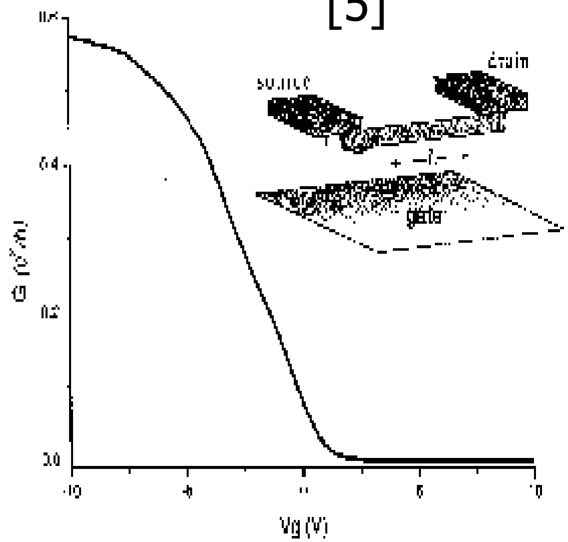

Fig. 5. Conductance G versus gate voltage V_g of a p-type semiconducting SWNT field effect transistor. The device geometry is shown schematically in the inset.

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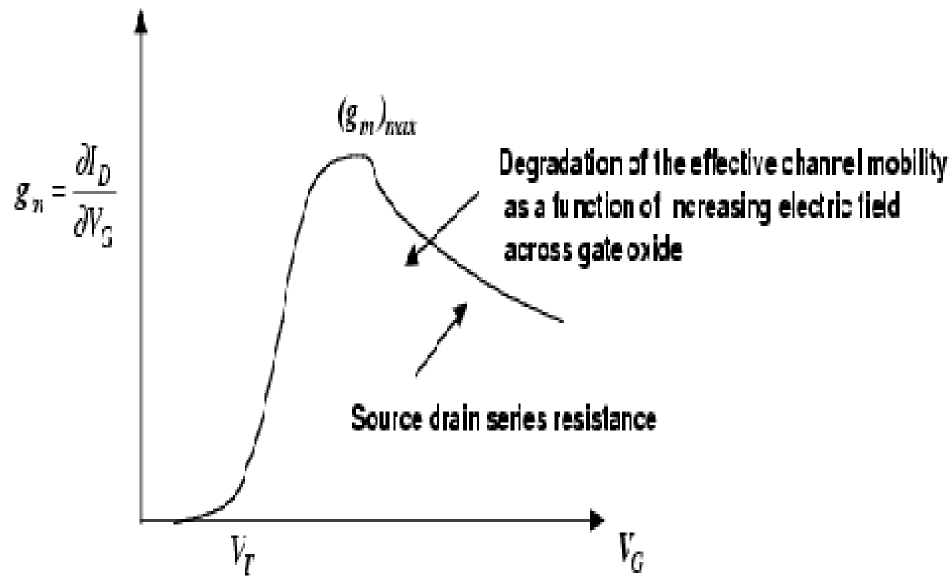

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Comparison to Conventional Electronics

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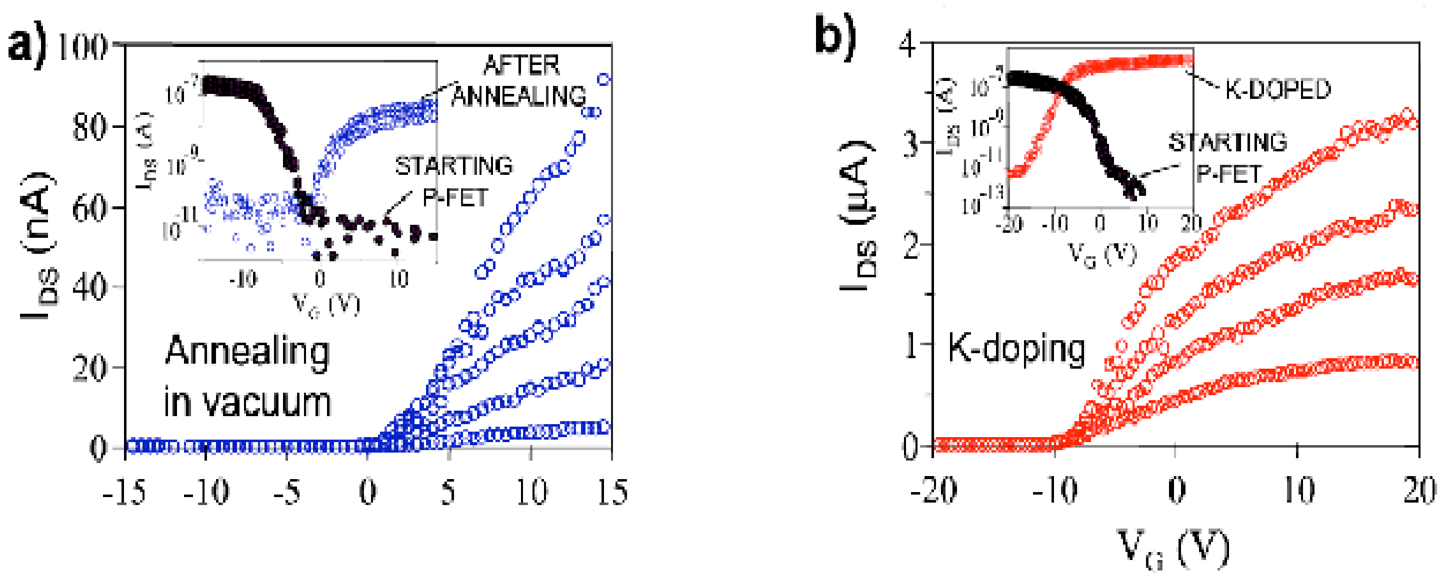

Figure 1. Electrical characteristics of n-type nanotube FETs made by (a) annealing the device in a vacuum at 700 K for 10 min and (b) doping with potassium. The curves are obtained at different values of V_{DS} starting at (a) 300 mV, step size 200 mV and (b) 200 mV, step size 200 mV.

Comparison to Conventional Electronics

- **Mobility**
  - **Typically 1000- 10,000 cm^2/Vs**
  - **As high as 20,000 cm^2/Vs**
  - **Get mobility from:**
    - **$G = C_g (V_g - V_{go}) \mu / L$**

Challenges

- **Purity of the contacts.**
- **Absorption of Atoms.**
- **Controlling whether metal or semiconductor.**
- **Placement of Tubes.**

Summary

- **Are Carbon Nanotubes the future of Electronics?**
- **There are no fundamental barriers to this technology.**
- **1000 times faster and much smaller than Si devices.**