Analysis of Carbon Nanotube-Semiconductor Diode Device

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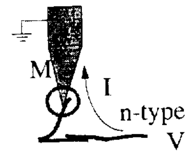
Two experiments

Berkeley: metallic (M)-STM & semiconducting (S)-NT



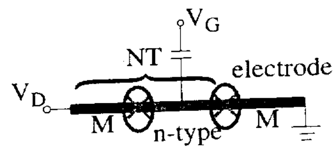
Science '97

I-V measurement

Two modes proposed: vacuum-gap & touching

NT shown to be n, not p

Delft: MS-NT & M-electrode with V_G



Nature '99

gated I_D-V_D measurement

Gate modulation effects explained

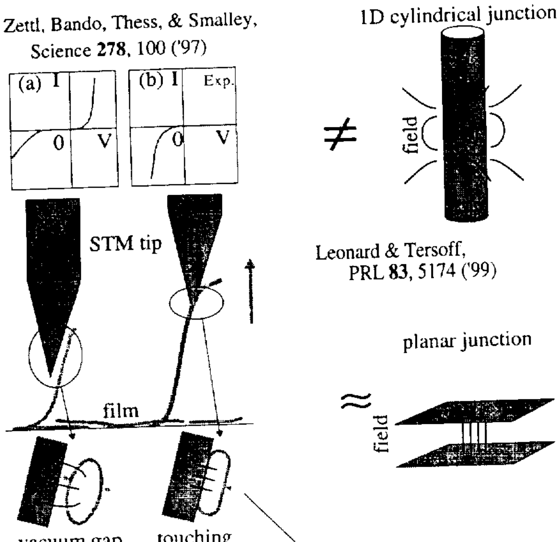
Nature of MS and SM junctions clarified

NT shown to be n, not p

Tip (metal) - nanotube (semiconductor) contact experiment

Collins, Zettl, Bando, Thess, & Smalley, Science **278**, 100 ('97)

1D cylindrical junction



Leonard & Tersoff, PRL **83**, 5174 ('99)

planar junction

band alignment (BA) variable

BA fixed

Hertel, Walkup, & Avouris, PRB **58**, 13870 ('98)

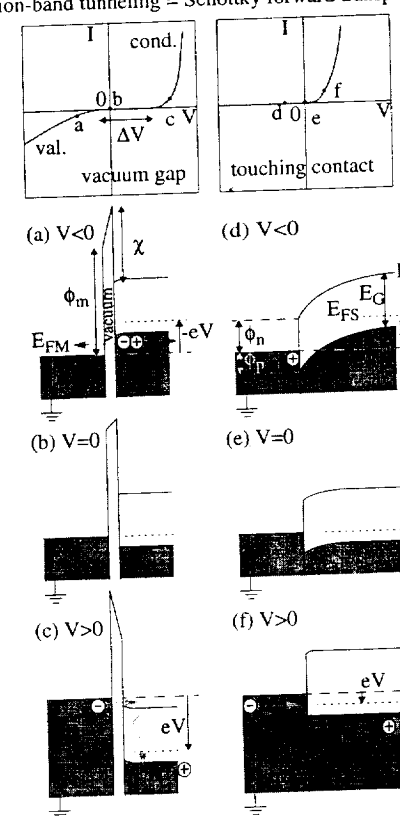
(against metal)

T. Yamada, APL **78**, 1739 ('01)

(against H-Si)

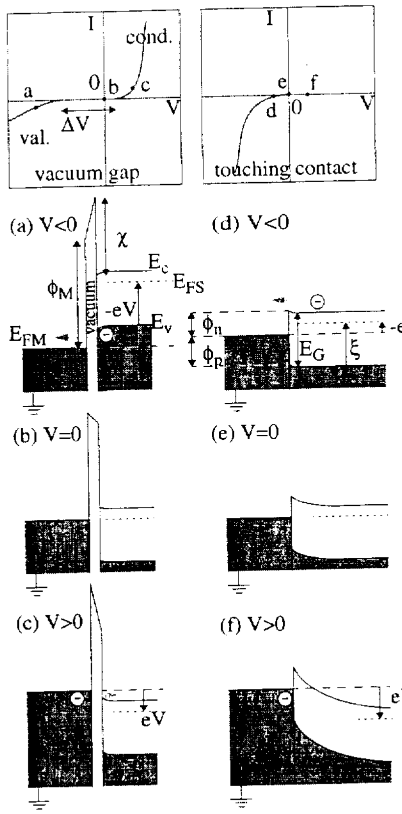
p-type nanotube

conduction-band tunneling = Schottky forward transport - contradictory

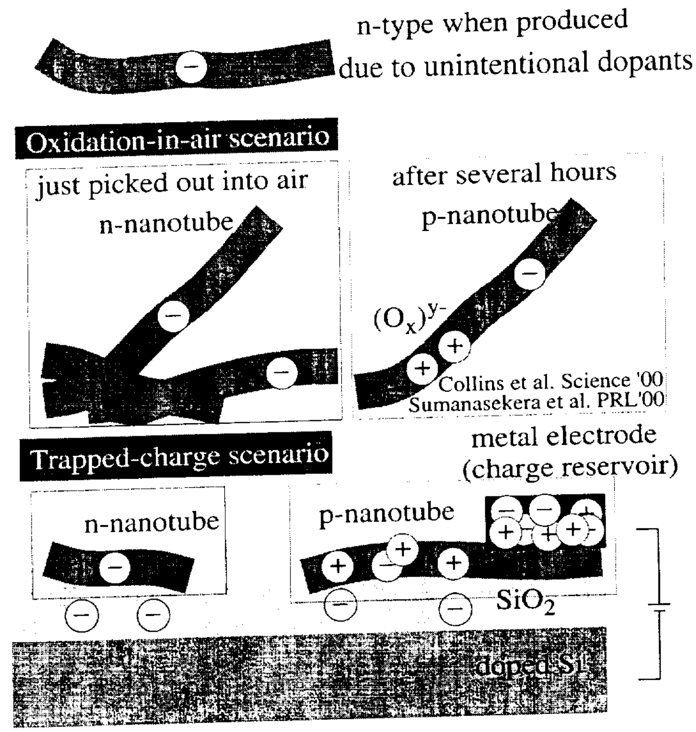


n-type nanotube

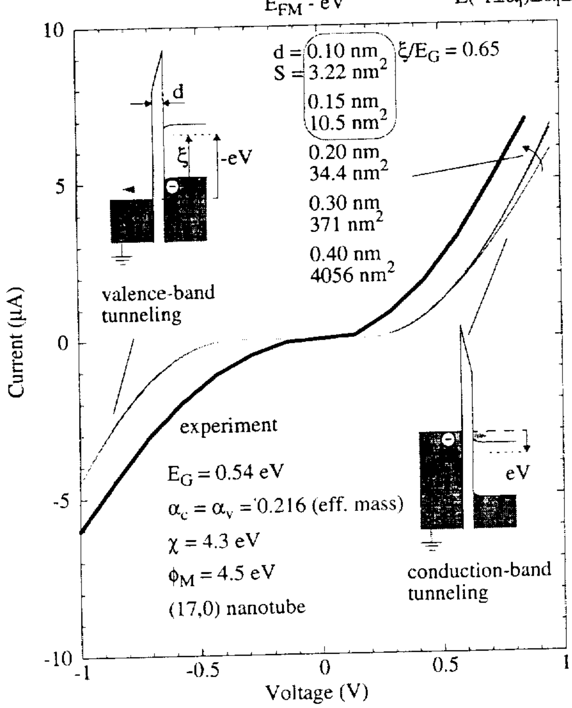
valence-band tunneling = Schottky forward transport - consistent



Why n-type, not common p-type?

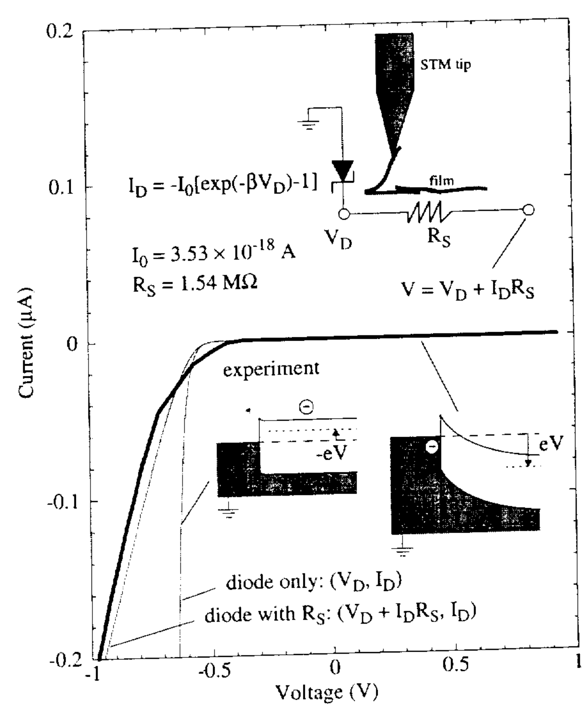


tunneling $I_i = \frac{4\pi meS}{h^3} \int_{E_{FM} - eV}^{E_{FM}} dE\, \theta[\pm\{E - E_i(V)\}] \int_{-E(-1\pm\alpha_i)\pm\alpha_i E_i(V)}^{E} dW\, D(W)$

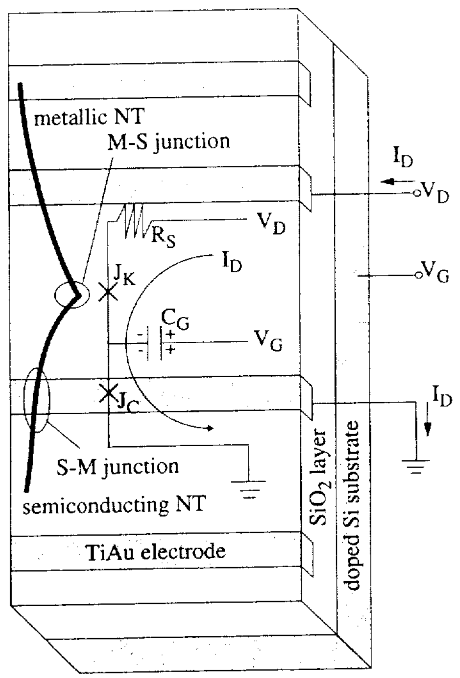


continuum approx. with 17 subbands, no band bending, parallel-momentum conserv. (wide tube limit), T = 0, WKB, no image potential

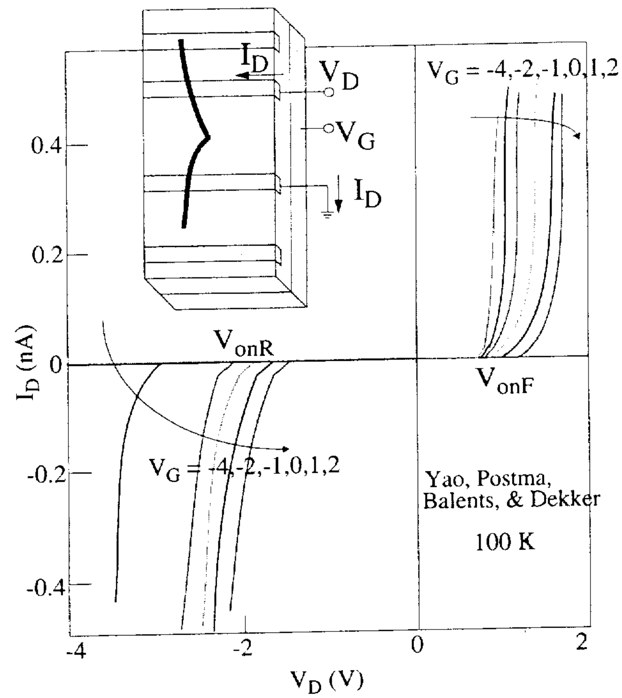
Schottky formula



Monolithic NT Schottky diode

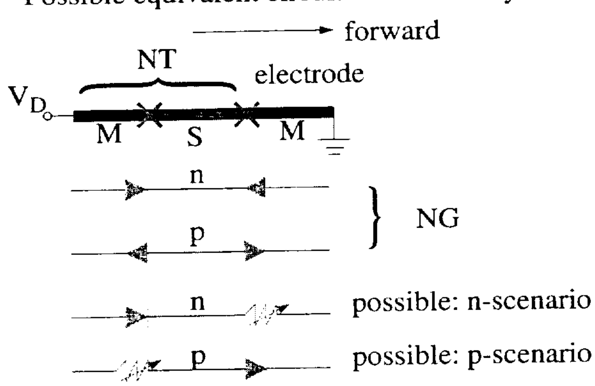


Yao, Postma, Balents, & Dekker, Nature **402**, 273 ('99)



For V_G ↗ , V_{onF} ↗ and $|V_{onR}|$ ↘

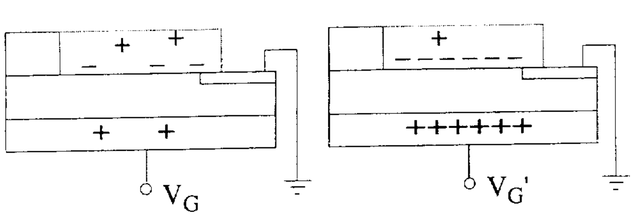
Possible equivalent circuit with Schottky diodes

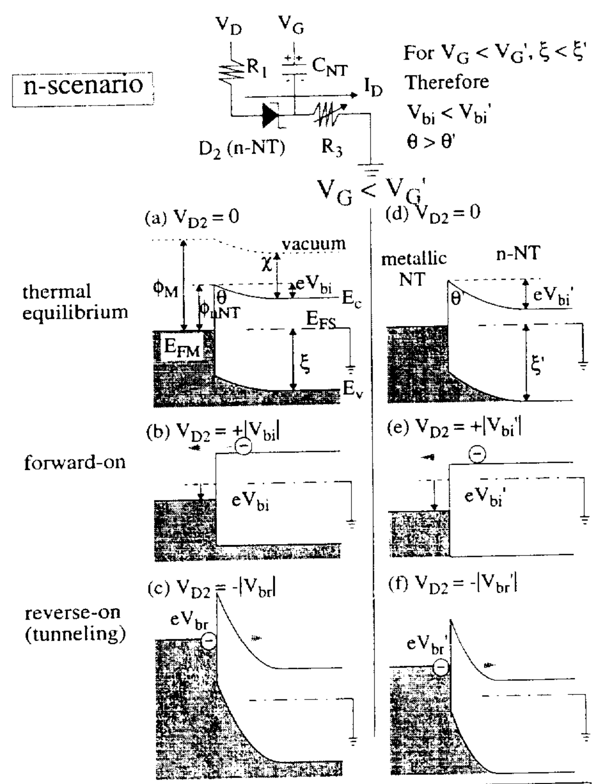


Increasing V_G

=> increase $\xi = E_F - E_v$, regardless of p or n

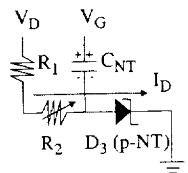
=> not change the Schottky barrier





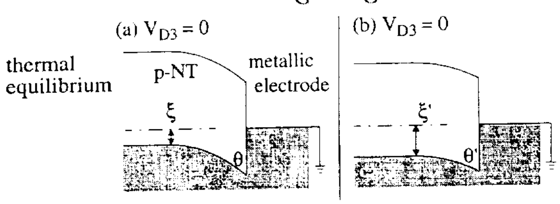
For V_G ↗ , V_{onF} ↗ and $|V_{onR}|$ ↘
- consistent to the experiment

p-scenario



For $V_G < V_G'$, $\xi < \xi'$
Therefore
$V_{bi} > V_{bi}'$
$\theta < \theta'$
opposite of n-scenario

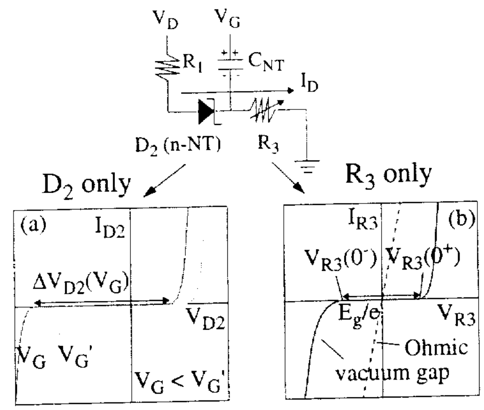
$V_G < V_G'$



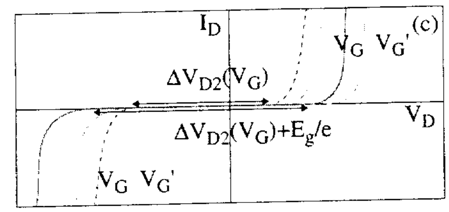
For $V_G \nearrow$, $V_{onF} \searrow$ and $|V_{onR}| \nearrow$
- contradictory to the experiment

Why n, not common p?
monolithic Schottky NT
low T ($e^{-5000/100}/e^{-5000/300} \sim 3 \times 10^{-15}$)

Effect of contact to electrode at R_3

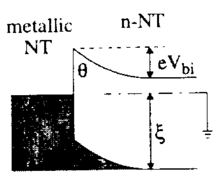


I_D-V_D for series of D_2 and R_3



With R_3, ΔV_{D2} is extended by E_g/e

V_{onF} and V_{onR} as a function of V_G



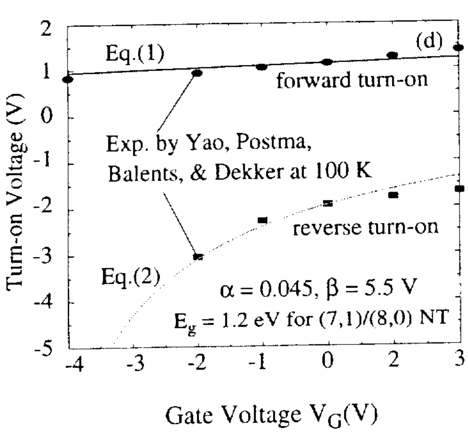
V_{bi} modulated by V_G at the forward-on

$$V_{onF}(V_G) = V_{onF}(0) + \alpha V_G \qquad (1)$$

the same θ realized for different V_G at the reverse-on

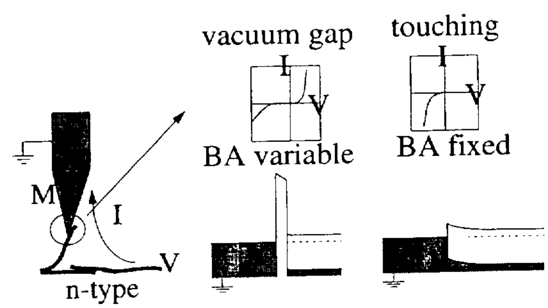
$$V_{onR}(V_G) = V_{onR}(0) + \alpha V_G + \frac{(V_{onF}(0) + |V_{onR}(0)| - E_g/e)V_G}{V_G + \beta} \qquad (2)$$

where α and β are parameters.

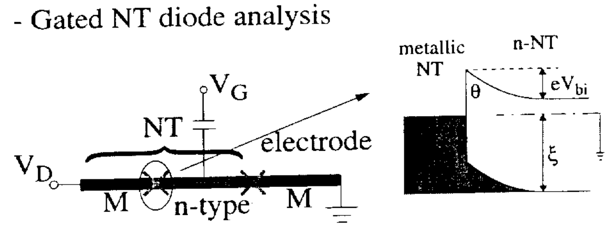


Summary

- STM (M) - NT (S) junction modele



- Gated NT diode analysis



- Both are n-NT
  STM - NT
  Before air oxidation (p-doping)
  gated kink NT diode at 100 K
  monolithic kink NT
  low T ($e^{-5000/100}/e^{-5000/300} \sim 3 \times 10^{-15}$)