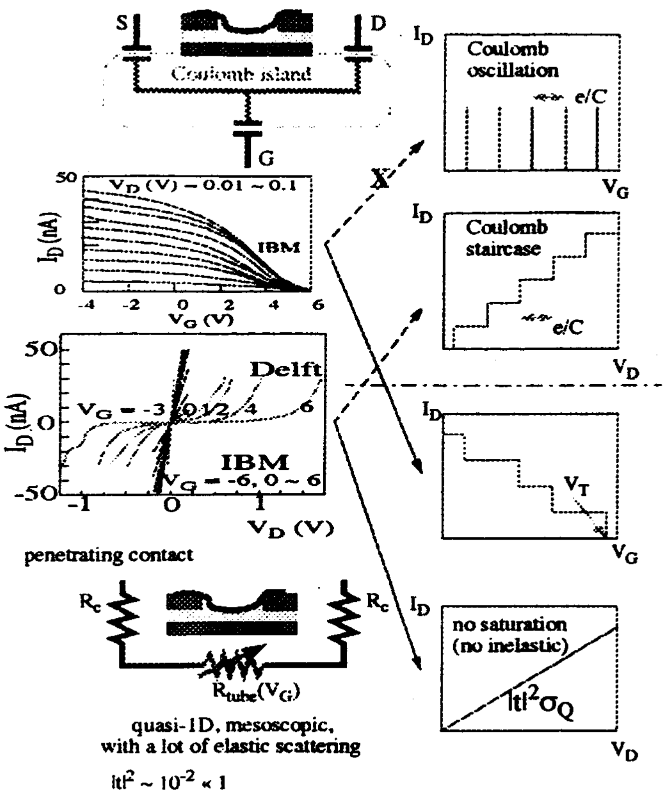
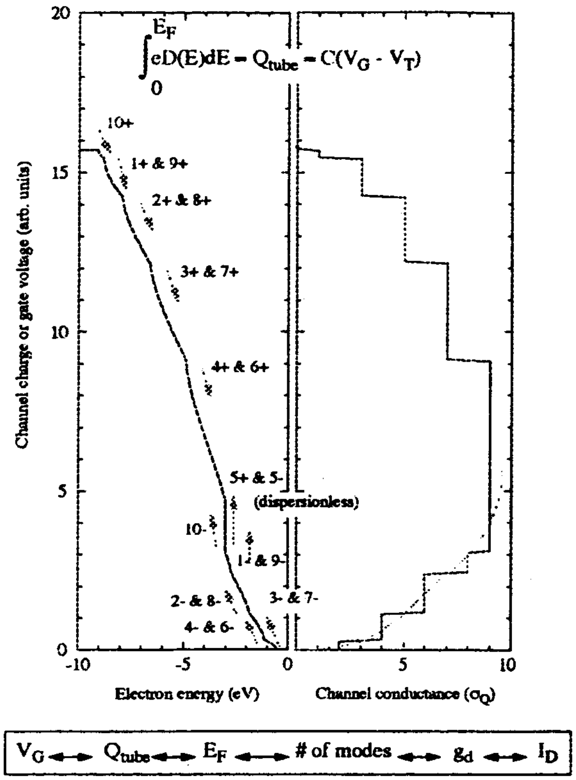
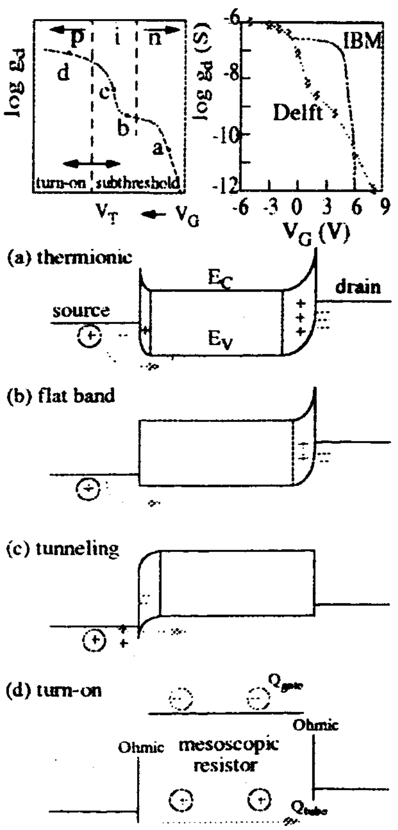
theoretical nanotube FET characteristics

isolating contact



Gate voltage channel charge modulation
and channel conductance for (10,0) nanotube FET





Analysis of submicron carbon nanotube field-effect-transistors

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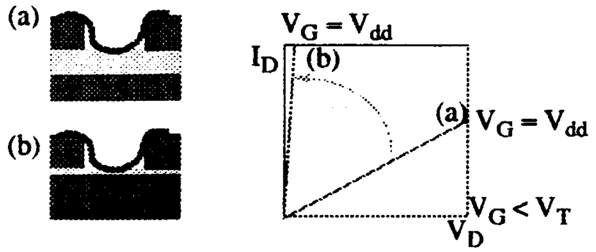
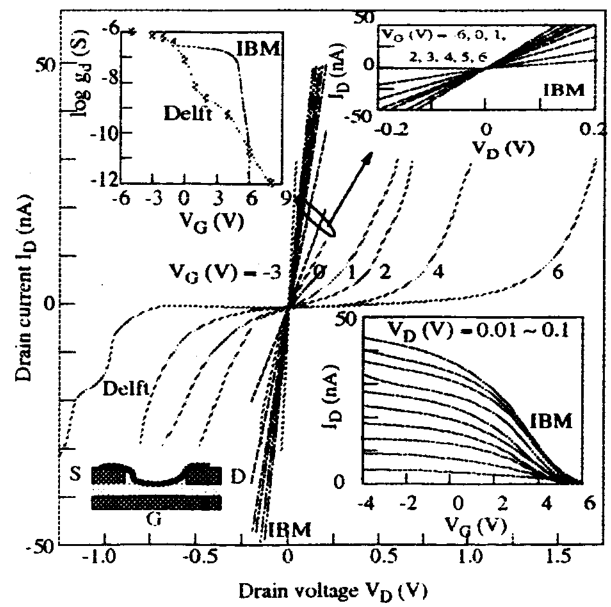
Summary

Delft & IBM nanotube FET analysis

- $I_D(V_D)$ at fixed V_G
  - saturationless I_D in Delft & IBM
  - no carrier-carrier scattering
  - weak localization regime
- $I_D(V_G)$ or $g_d(V_G)$ at fixed V_D
  - transport across metal-semiconductor contact
    - Delft (Pt): thermionic → flat band → tunneling → on
    - IBM (Au): tunneling → on
- For circuit applications
  - saturationless I_D for submicron or less
  - maximize g_m (thinner oxide)





[Delft] S.J. Tans, A.R.M. Verschueren, and C. Dekker. Nature **393**, 49 ('98)
[IBM] R. Martel, T. Schmidt, H.R. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. **73**, 2447 ('98)

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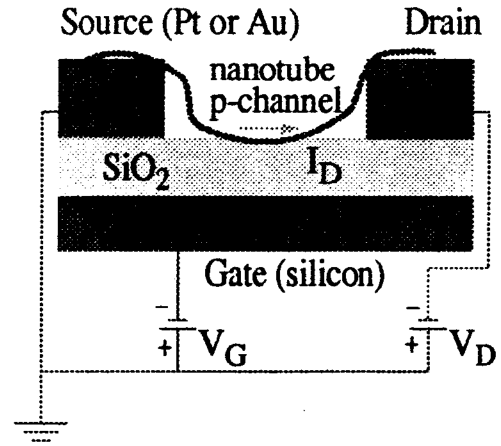
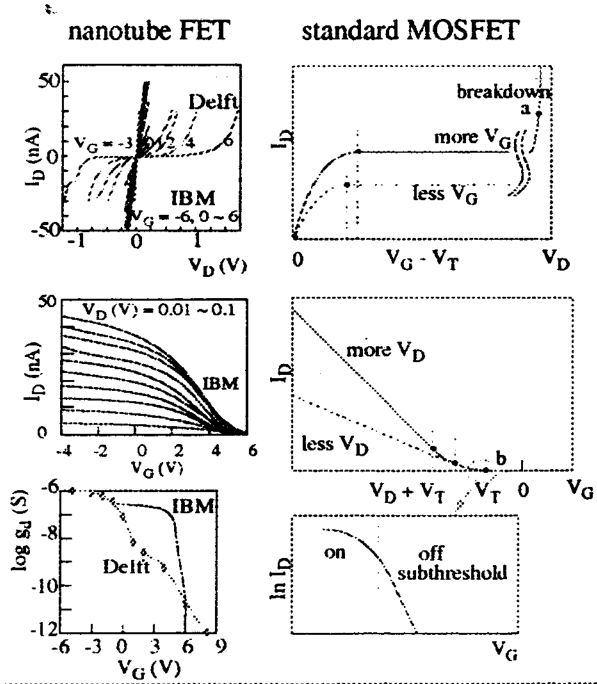
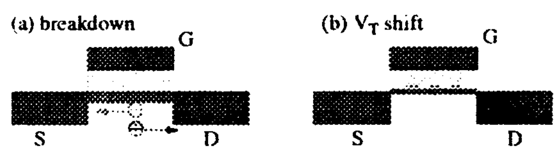
Nanotube FET by Delft, IBM

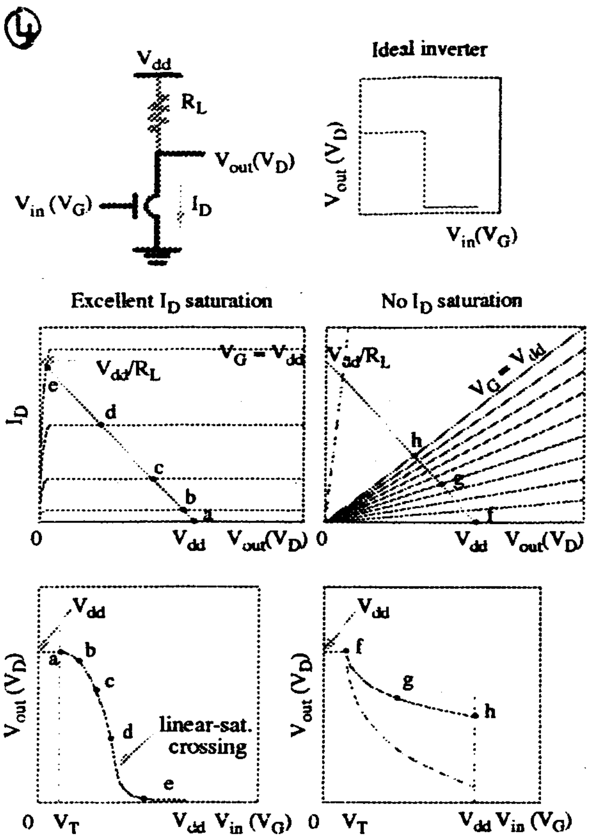
[Delft] S.J. Tans, A.R.M. Verschueren, and C. Dekker, Nature **393**, 49 ('98)
[IBM] R. Martel, T. Schmidt, H.R. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. **73**, 2447 ('98)

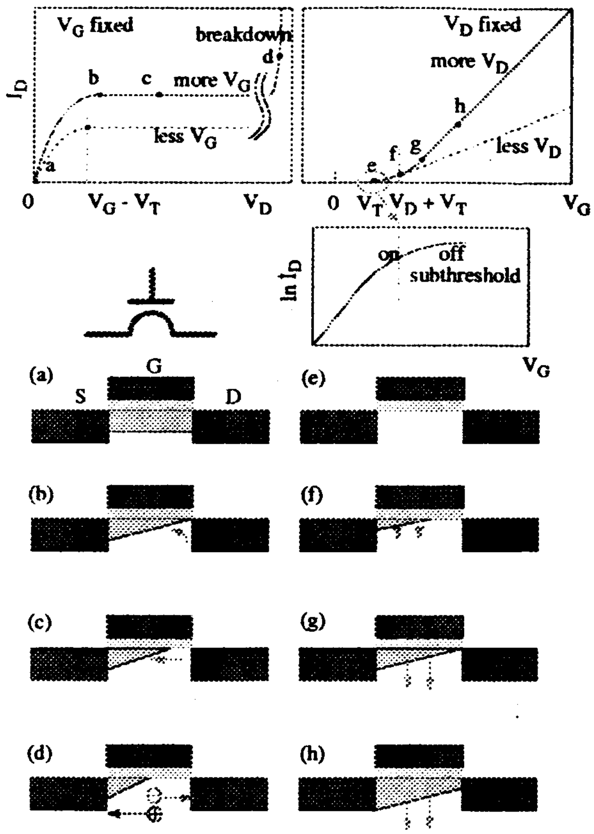


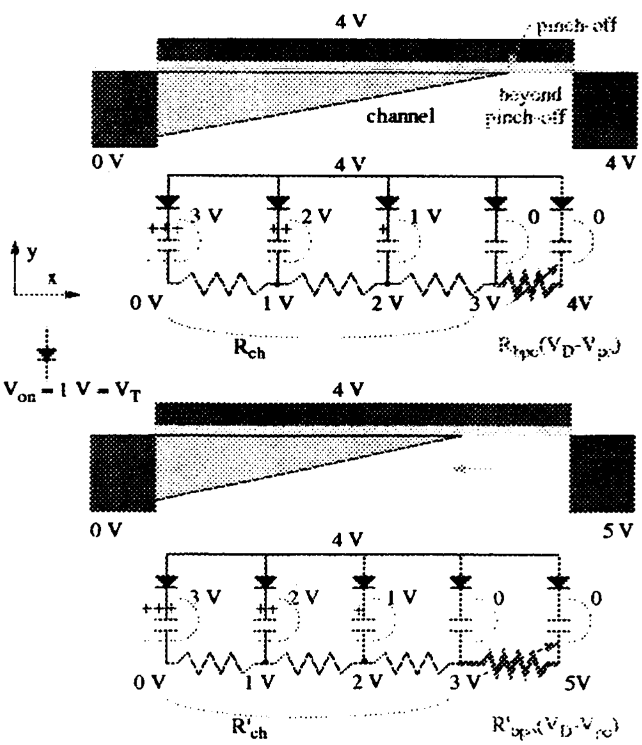
measure	channel conductance $g_d = \partial I_D/\partial V_D$
$I_D(V_D)$ at fixed V_G	transconductance
$I_D(V_G)$ at fixed V_D	$g_m = \partial I_D/\partial V_G$





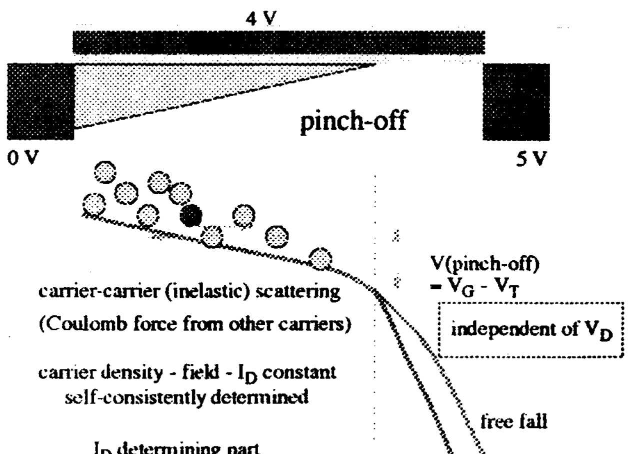






$R'_{bpo} > R_{bpo} \sim R_{ch} \geq R'_{ch}$

$I_D = 3\,(V)/R_{ch}\,(\Omega) \sim 3\,(V)/R'_{ch}\,(\Omega) = I'_D$



If we can write

$\boxed{I_D = G[V(x)]\, dV(x)/dx}$

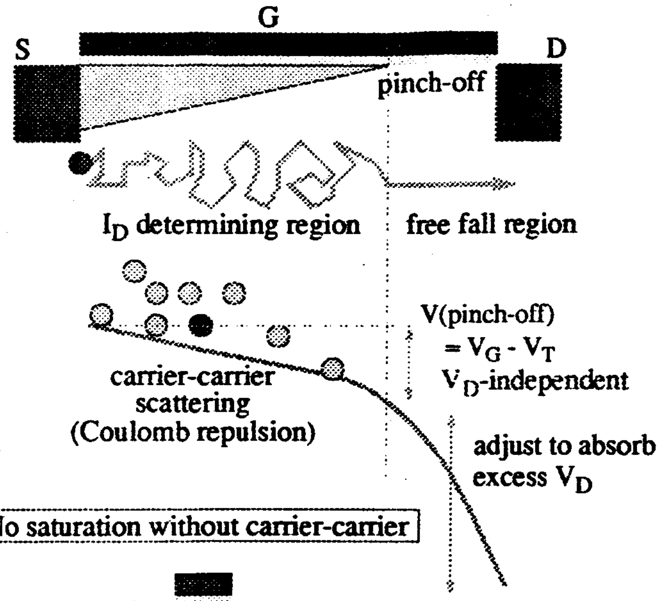
1. local field $dV(x)/dx$ ~ long channel
2. depending only on $V(x)$ ~ thin gradual channel

then I_D saturates.

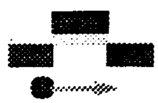
Otherwise, it does NOT.

5

Saturation with carrier-carrier



No saturation without carrier-carrier

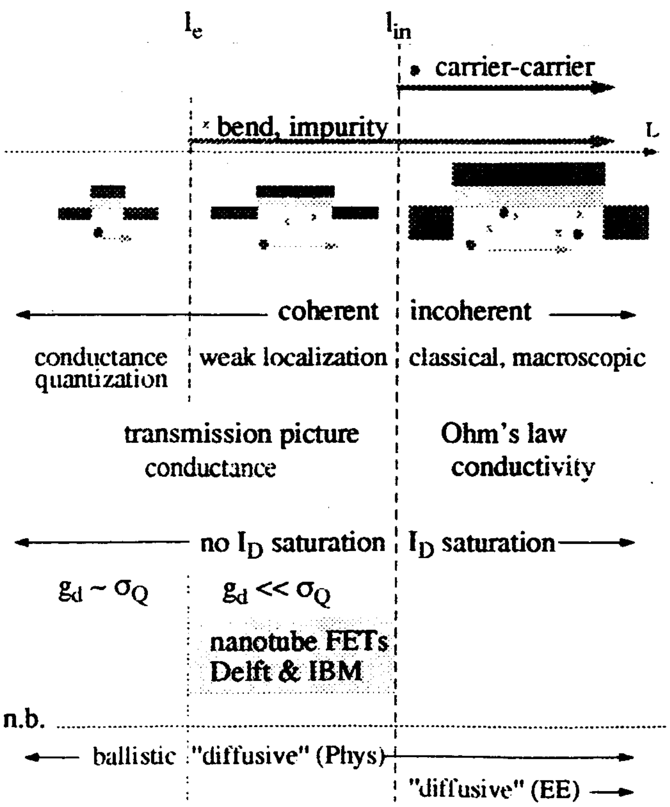


Without carrier-carrier,
no pinch-off, no saturation in $I_D(V_D)$

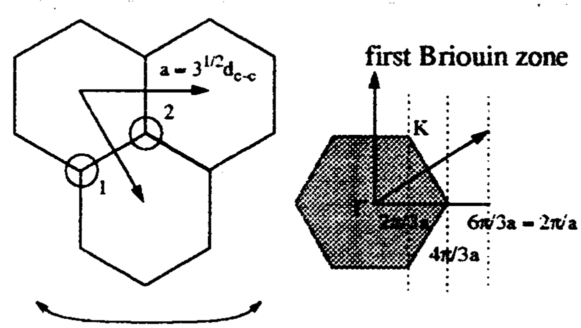
Experimental observations & possible mechanisms:

1. saturationless $I_D(V_D)$ fixing V_G of Delft
   absence of carrier-carrier scattering
   a lot of elastic scattering, low g_d
2. breakdown in $I_D(V_D)$ fixing V_G of Delft
   usual pair creation
3. kink in subthreshold $g_d(V_G)$ of Delft (Pt S & D)
4. smooth subthreshold $g_d(V_G)$ of IBM (Au S & D)
   Schottky barrier effects
5. saturated "on" $I_D(V_G)$ fixing V_D of IBM
   quasi-1D nanotube characteristics
6. large V_G shift in $g_d(V_G)$ of Delft, IBM
   usual Q_{int} effects

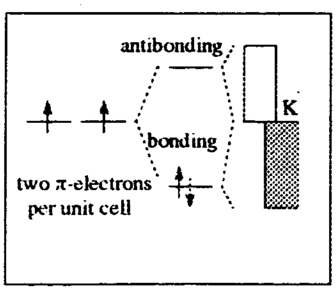
Gate length L, elastic length l_e, & inelastic length l_{in}



Electronic properties of carbon nanotube



$k_i = 2\pi i/aN$ for (N,0) tube



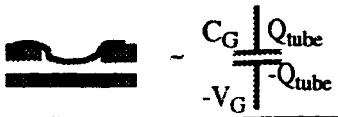
If N = 3, 6, 9, ... , then
the K-point is crossed.

metallic
Otherwise, semiconducting

$$E = \pm V_{pp\pi}[1 \pm 4\cos(3^{1/2}ka/2) \times \cos(k_i a/2) + 4\cos^2(k_i a/2)]^{1/2}$$

$$k_i = 2\pi i/aN,\ i = 1, 2, \ldots, N$$

9



$V_G \leftrightarrow Q_{tube} \leftrightarrow E_F \leftrightarrow$ # of modes $\leftrightarrow g_d \leftrightarrow I_D$

$$\int_0^{E_F} eD(E)dE = Q_{tube} = C_G(V_G - V_T)$$