Scientific Overview: Nanoscale Transistors

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electronics and the world today

The 20th Century was transformed by **electronic and microelectronic** device technologies.

The 21th Century will be transformed by **nanoelectronic** device technologies – especially transistors.

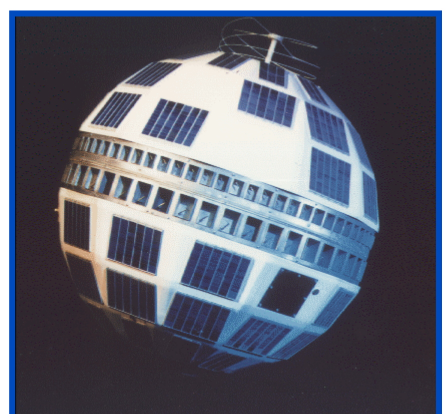
The nanotransistor is the first true, active nanodevice.

transistors (and IC's) created the modern world

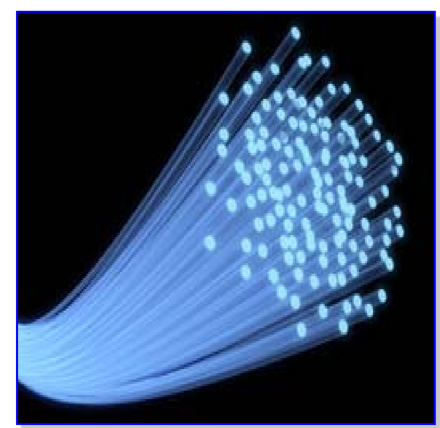
supercomputers

PCs

cell phones



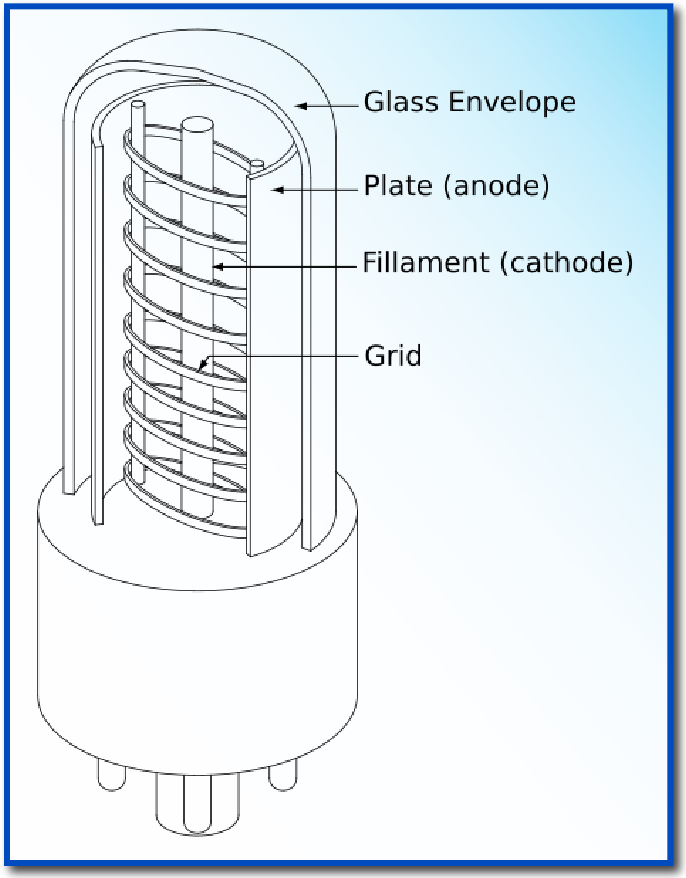
communication satellites



fiber optics / Internet

vacuum tube electronics

Vacuum Tube



http://en.wikipedia.org/wiki/Vacuum_tube

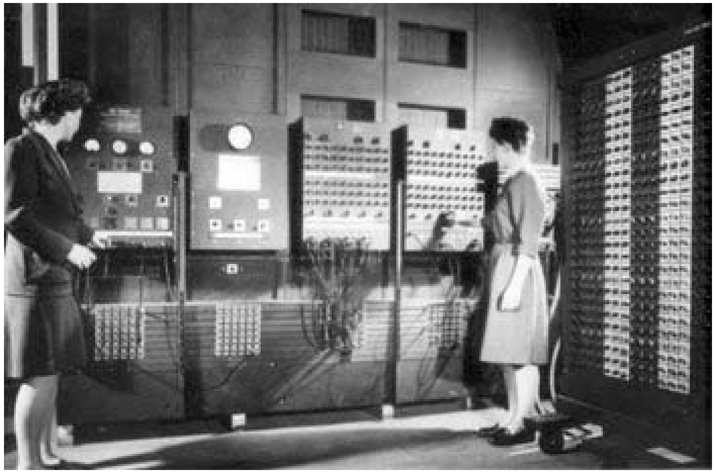
Edison effect (Edison, 1883)
cathode rays (Thompson, 1897)
diode (Fleming, 1904)
triode (De Forest, 1905)

what vacuum tubes enabled

"Golden age of radio"
1935 - 1950

http://history.sandiego.edu/GEN/recording/images5/radio11.jpg

ENIAC
(1945, Mauchly and Echkert, U Penn)



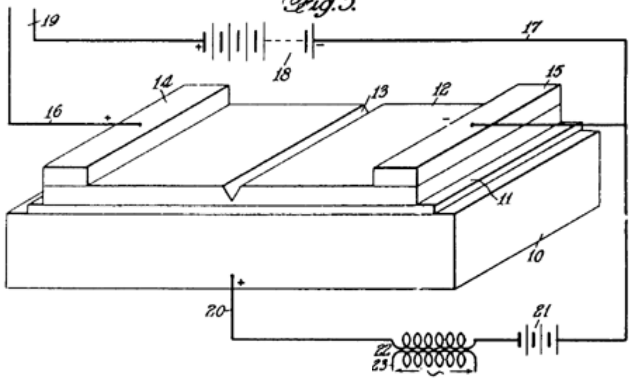
http://en.wikipedia.org

17,468 vacuum tubes
1000 sq. feet of floor space
30 tons
150 KW
~50 vacuum tubes / day

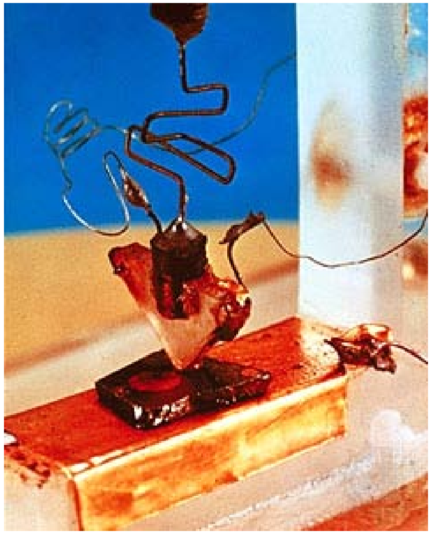
invention of the transistor

Field-Effect Transistor
Lillienfield, 1925
Heil, 1935

Fig.3.



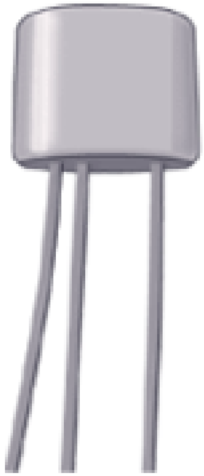
Bardeen, Schockley, and Brattain, 1947



Lucent / Bell Labs

IV characteristics: real current sources

transistors



Sony TR-63
6-transistor
shirt pocket radio
1957

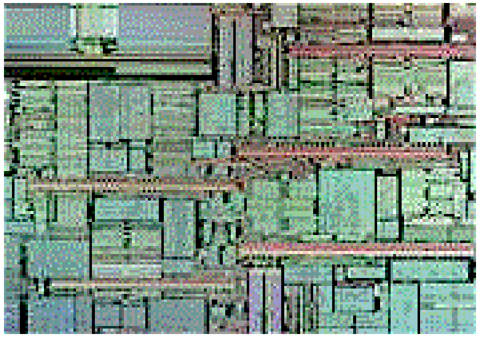
http://www.sony.net/Fun/SH/1-6/h2.html

invention of the integrated circuit

integrated circuit

Kilby and Noyce (1958, 1959)

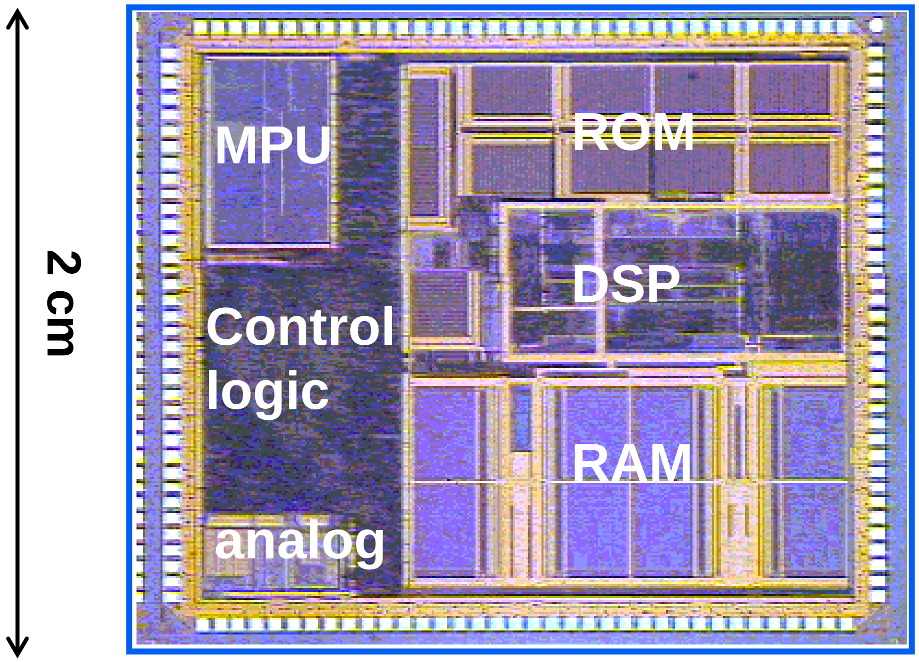
Intel 4004



Hoff and Faggin (1971)

~2200 transistors

modern CMOS chip



Texas Instruments cell phone chip

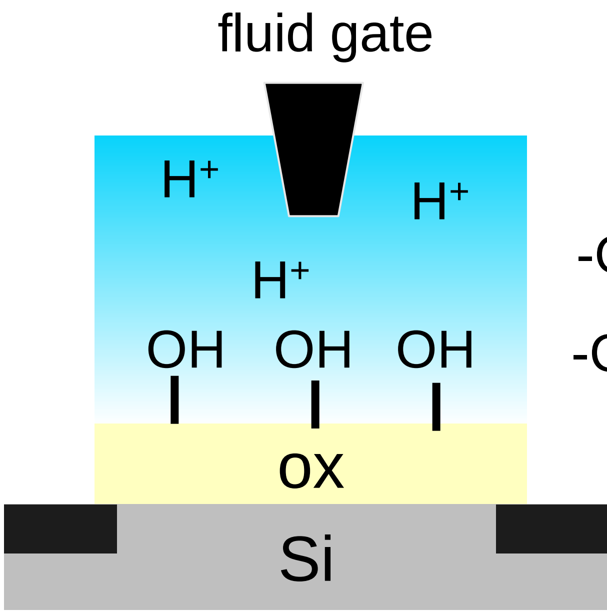
pH sensing with ISFETs

$pH = -\log_{10} [H^+]_B$

$[H^+]_B = 10^{-7}\,M \rightarrow pH = 7$

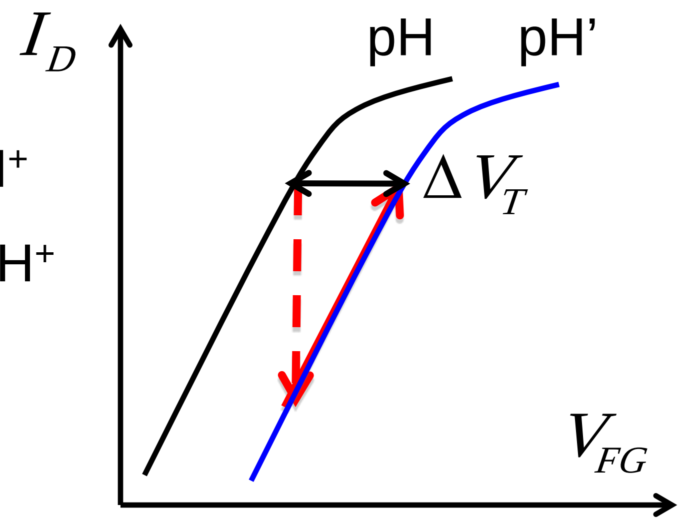
Human blood: $7.35 < pH < 7.45$

pH out of range is fatal!



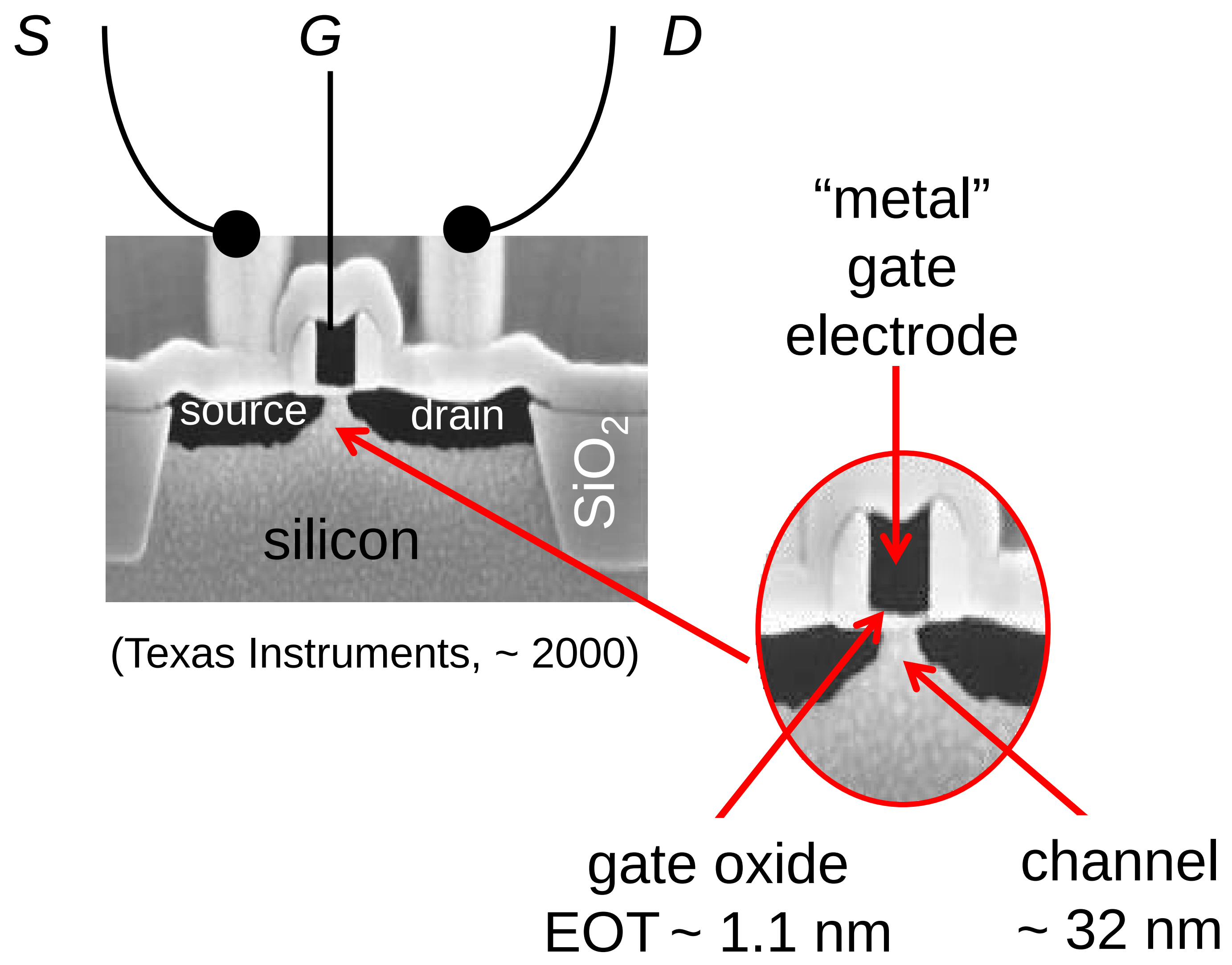
$-OH \longleftrightarrow -O^- + H^+$

$-OH_2^+ \longleftrightarrow -OH + H^+$

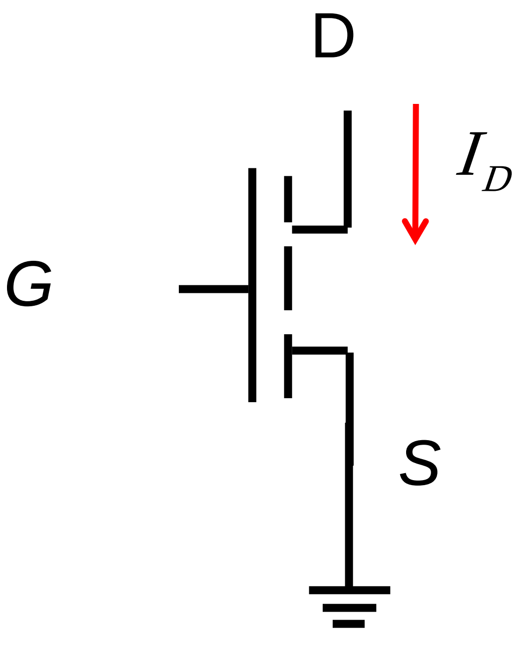


pH sensitivity = $\Delta V_T / \Delta pH < 59$ mV/pH (Nernst limit)

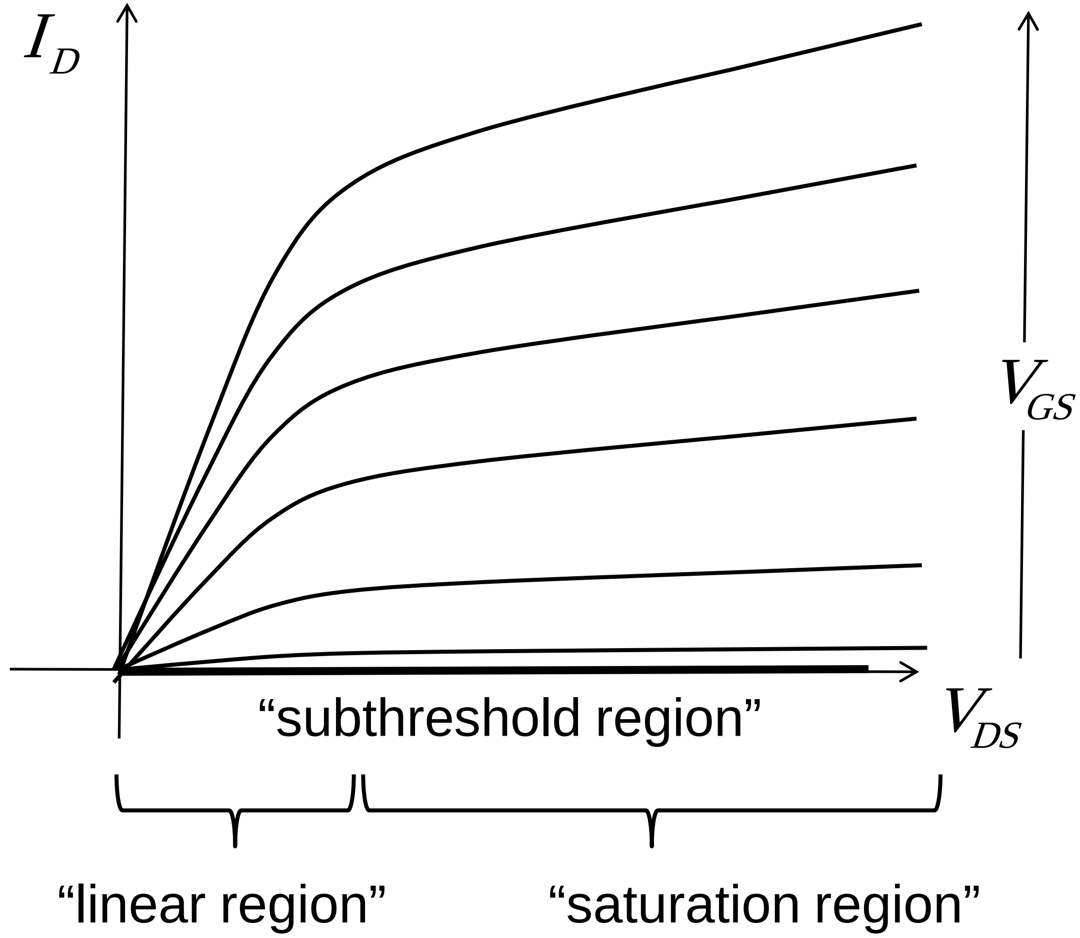
nanoscale MOSFETs



IV characteristics: transistors



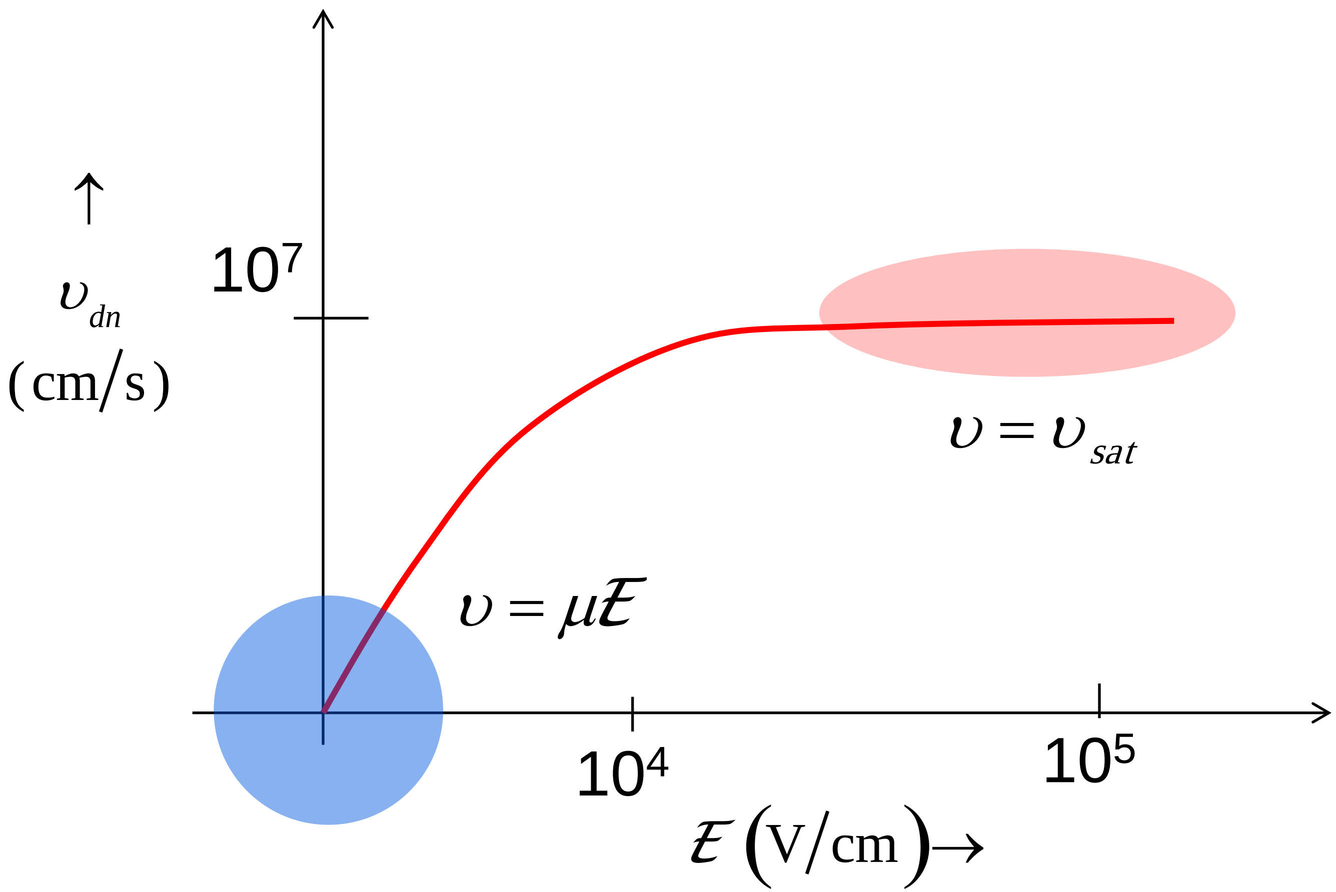
n-channel enhancement mode MOSFET



physics of MOSFETs

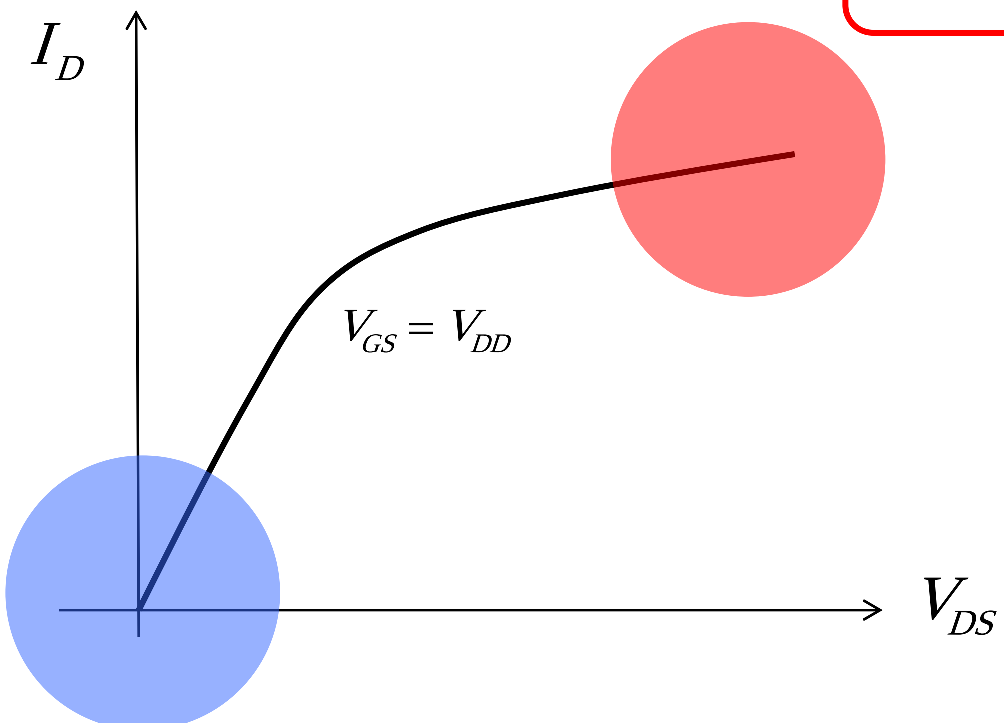
S.R. Hofstein and F.P. Heiman, “The Silicon Insulated-Gate Field-Effect Transistor,” *Proc. IEEE*, pp. 1190-1202, Sept. 1963.

“drift-diffusion” carrier transport



traditional model of a MOSFET

$$I_D = W C_{inv}\left(V_{GS} - V_T\right)\upsilon_{SAT}$$



$$I_D = \frac{W}{L}\mu_{eff} C_{inv}\left(V_{GS} - V_T\right)V_{DS}$$

transport in a "long" device

$$\upsilon_x = \mu_n \mathcal{E}_x$$

$$D_n = \frac{\upsilon_T \lambda}{2}$$

$$\frac{D_n}{\mu_n} = \frac{k_B T}{q} = 0.026$$

$$\upsilon_T \approx 10^7 \text{ cm/s}$$

$$\mu_{eff} \approx 300 \text{ cm}^2/\text{V-s}$$

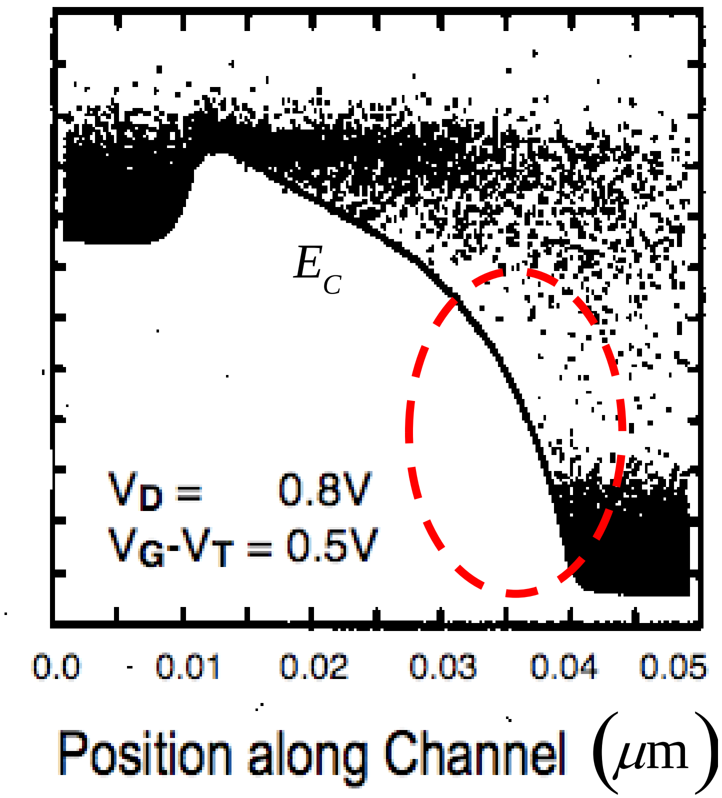
$$\lambda \approx 16 \text{ nm}$$

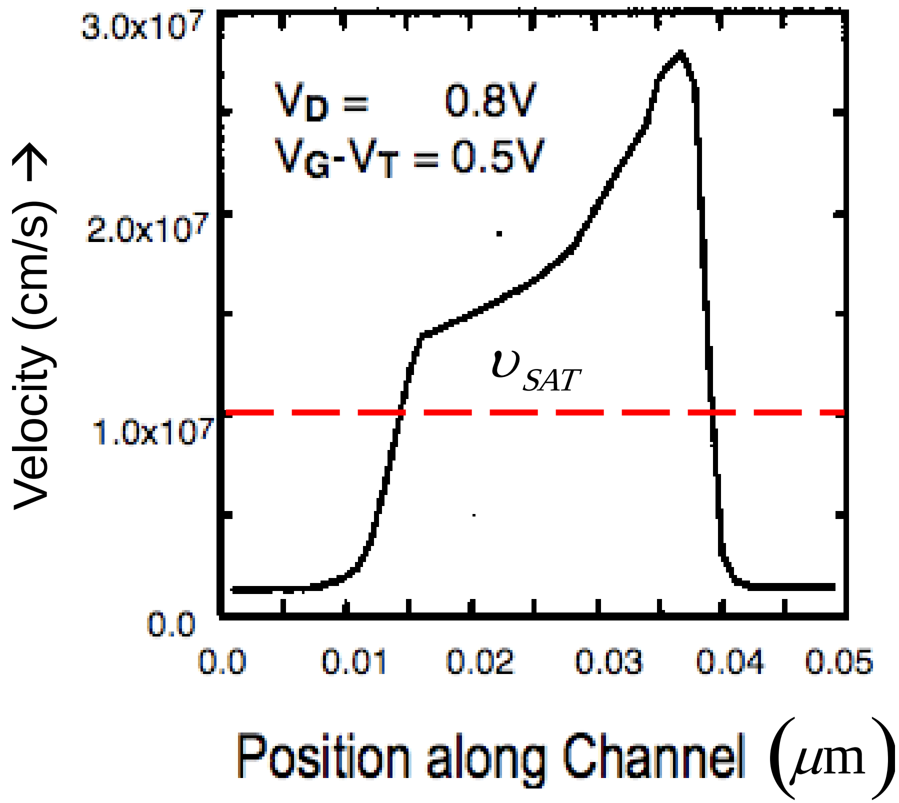
$$D_n \approx 8 \text{ cm}^2/\text{s}$$

$$\upsilon_x = \mu_n \mathcal{E}_x$$

$$L >> \lambda$$

semiclassical transport in nanoscale MOSFETs

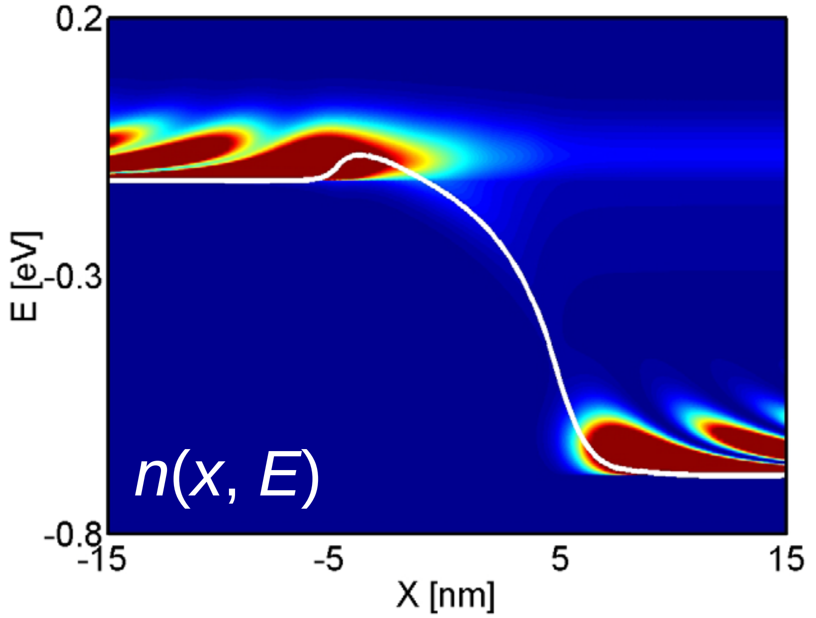




D. Frank, S. Laux, and M. Fischetti, Int. Electron Dev. Mtg., Dec., 1992.

quantum transport

L = 10 nm



nanoMOS (www.nanoHUB.org)

simple models and sophisticated simulations

“It is nice to know that the computer understands the problem," said Wigner when confronted with the computer-generated results of a quantum-mechanics calculation.

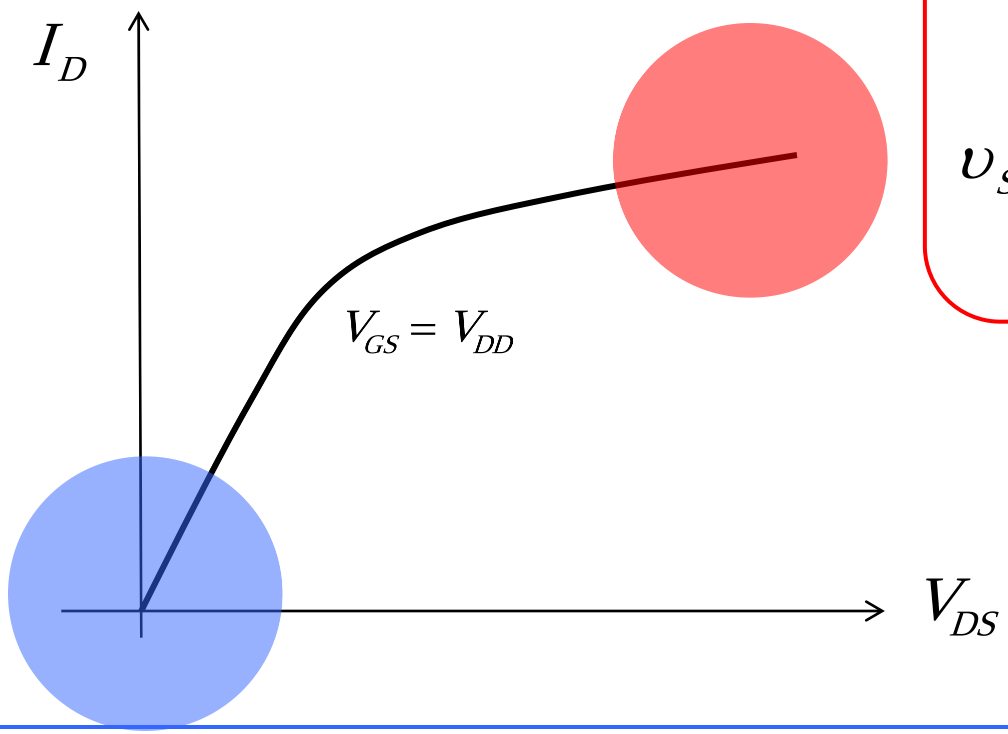
“But I would like to understand it, too.”

(http://www.cs.utah.edu/~crj/quotes.html)

microscale → nanoscale MOSFETS

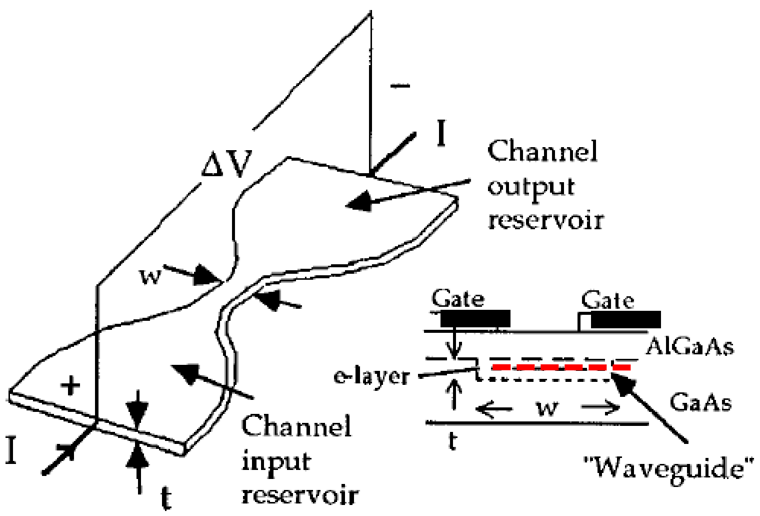
$$I_D = W C_{inv} \upsilon_{SAT} \left(V_{GS} - V_T\right)$$

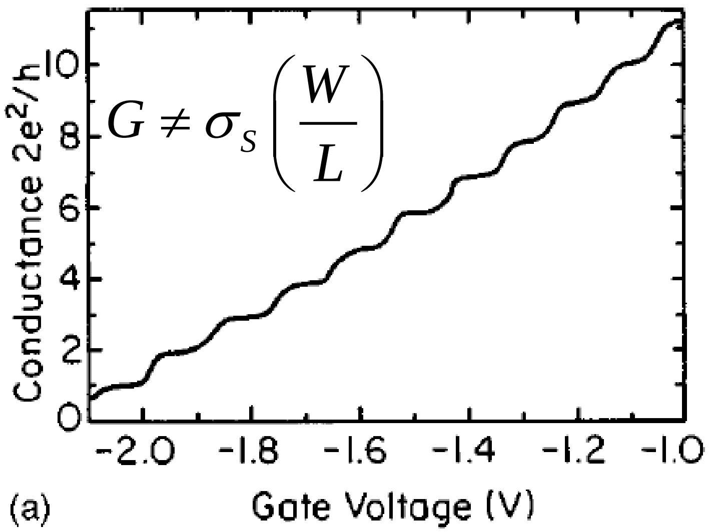
$$\upsilon_{SAT} \rightarrow \left(\frac{T_{sat}}{2 - T_{sat}}\right) \upsilon_{inj}^{ball}$$



$$I_D = \frac{W}{L} \mu_{eff} C_{inv} \left(V_{GS} - V_T\right) V_{DS} \qquad \mu_{eff} \rightarrow \mu_{app} \qquad 1/\mu_{app} = 1/\mu_{eff} + 1/\mu_B$$

ballistic transport and quantized conductance





W -->

B. J. van Wees, et al. *Phys. Rev. Lett.* **60**, 848–851,1988.

$$G = \frac{2q^2}{h} T(E_F) M(E_F)$$

Landauer approach

1) conductance is quantized
2) upper limit to conductance

goals

- Develop a simple, physical understanding of nanoscale MOSFETs.
- Understand why the functional form of the IV characteristic is so similar to MOSFETs of 50 years ago.
- Briefly examine the limits of device scaling.

lectures

1) Introduction to transistors
2) The traditional model
3) The MOSFETs as a barrier controlled device

4) MOS electrostatics
5) Carrier transport

6) Ballistic model
7) Comparison to experiments
8) Relation to traditional model
9) Scattering and transmission
10) Scattering model

11) MOSFET limits and possibilities

nanoHUB-U short course Fall 2012