Nanotechnology 101 Series

Transistors 101

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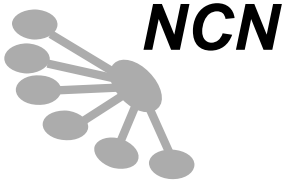

www.nanohub.org

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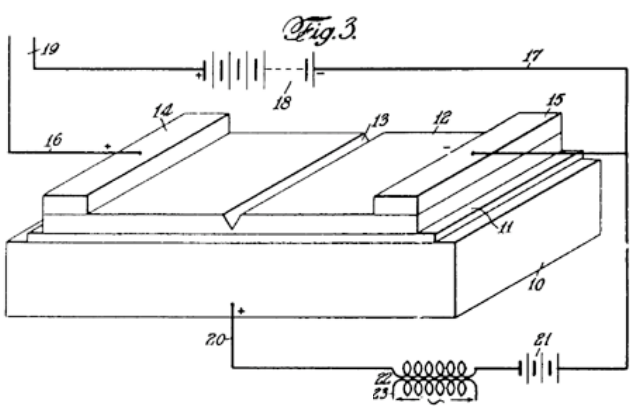
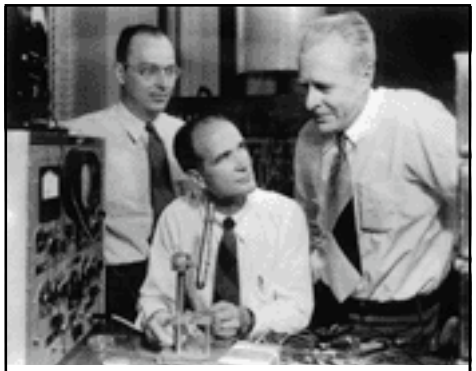
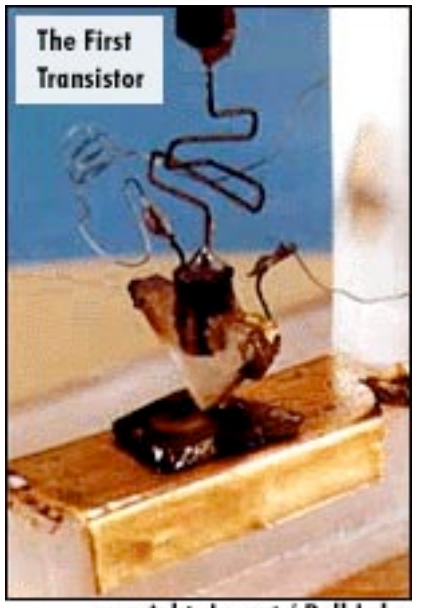
what to transistors do?

Field-Effect Transistor
Lillienfield, 1925
Heil, 1935





Bardeen, Schockley, and Brattain, 1947



copyright: Lucent / Bell Labs

"The transistor was probably the most important invention of the 20th century,"

Ira Flatow, Transistorized!
www.pbs.org/transistor

transistors

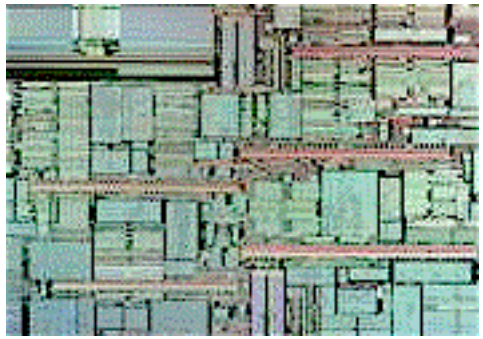
- junction transistor, 1951
- silicon BJT, 1954
- MOSFET, 1960

integrated circuit

Kilby and Noyce (1958, 1959)

- commercial IC's, 1961
- PMOS IC's, 1963
- CMOS invented, 1963
- NMOS IC's, 1970

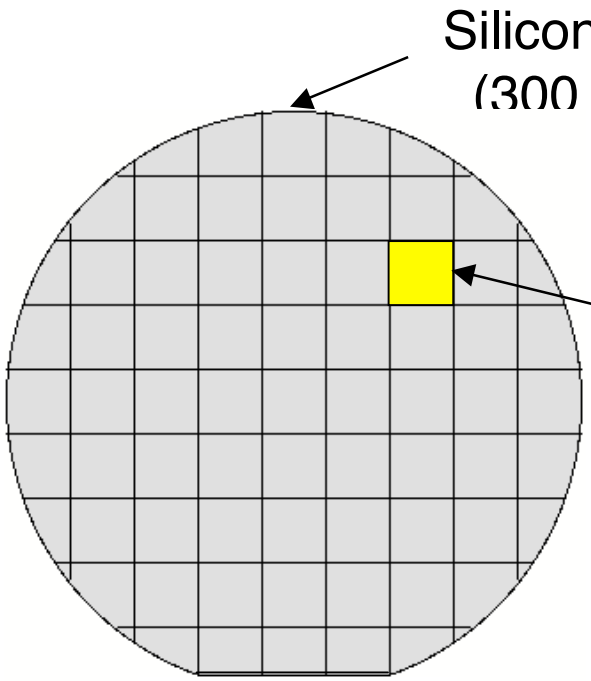
Intel 4004

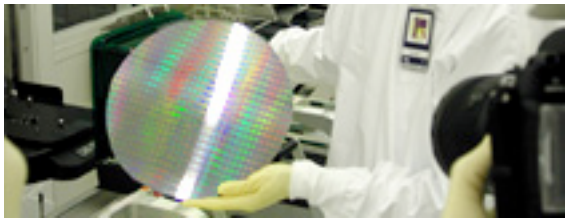


Hoff (1971)

~2000 transistors

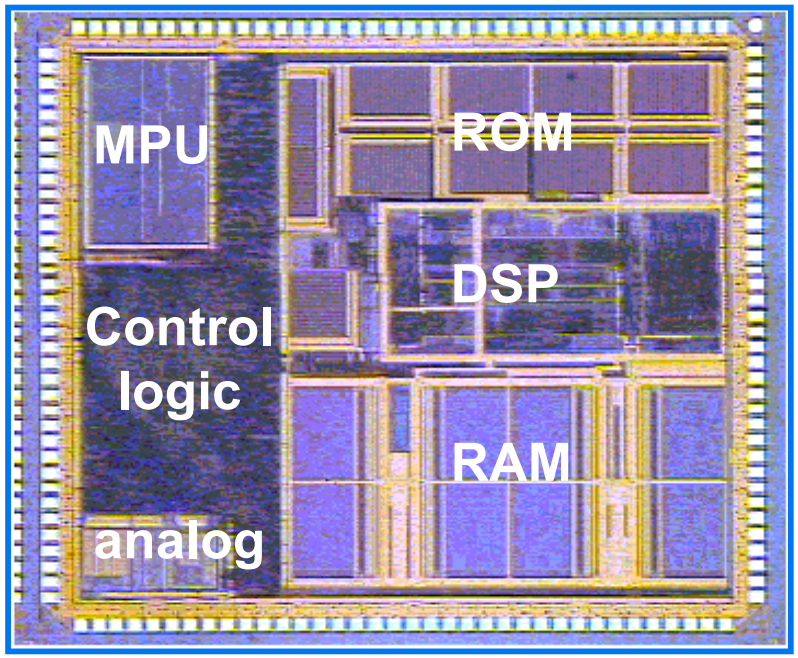
silicon microelectronics





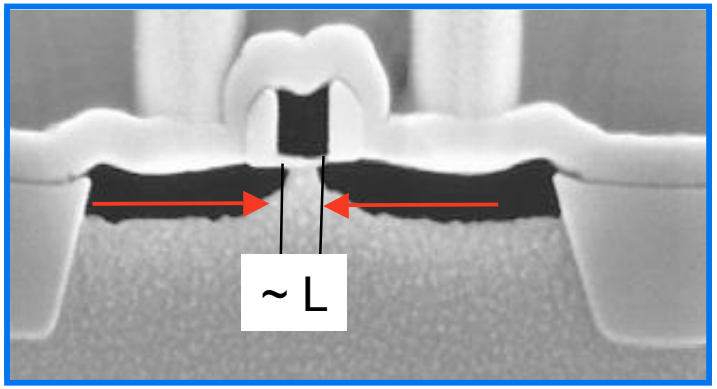
Intel

Silicon “chip”
(~ 2 cm x 2 cm)



TI cell phone chip

Transistor scaling

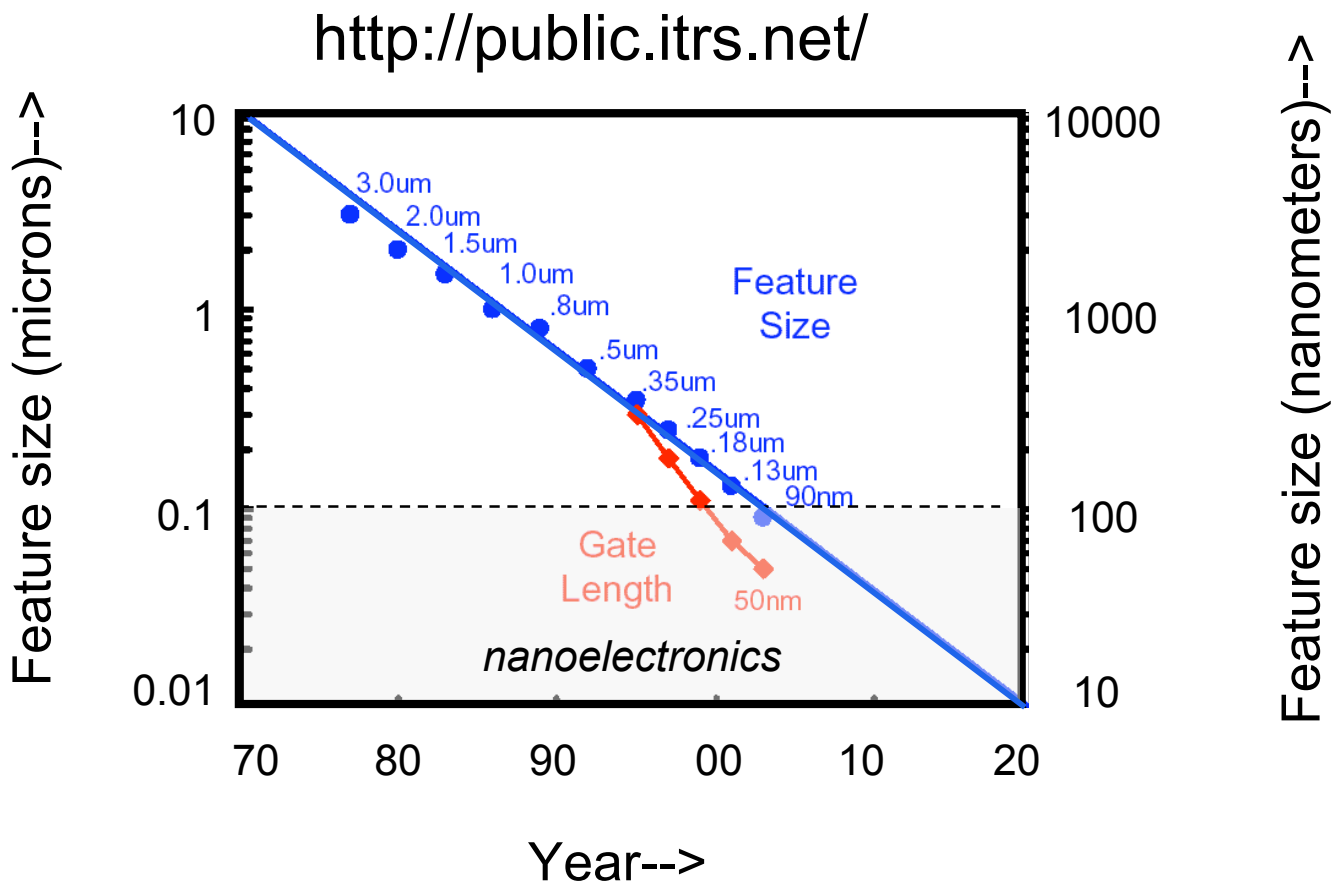


Each technology generation: **(scaling)**

$$L \rightarrow L/\sqrt{2} \qquad A \rightarrow A/2$$

Number of transistors per chip doubles **(Moore's Law)**

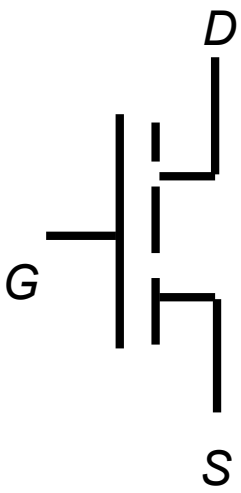
Moore's Law



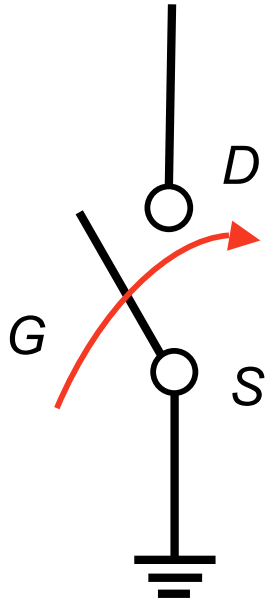
L = 6 nm (IBM, 2002)
L = 5 nm (NEC, 2003)

applications

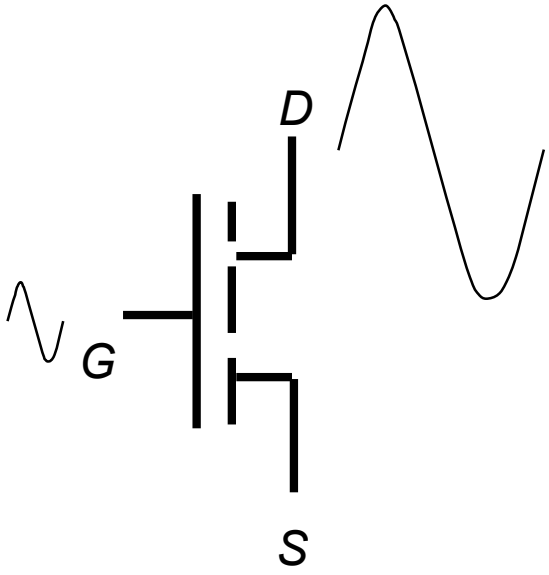
symbo



switch



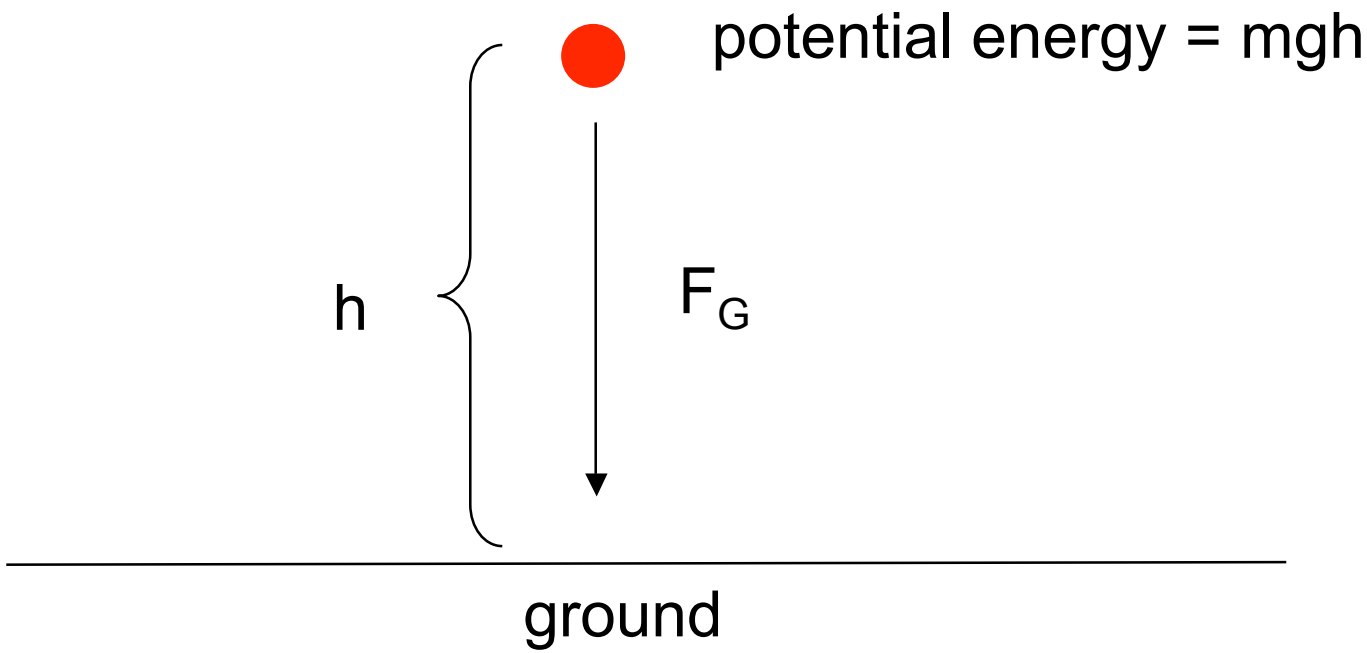
amplifier



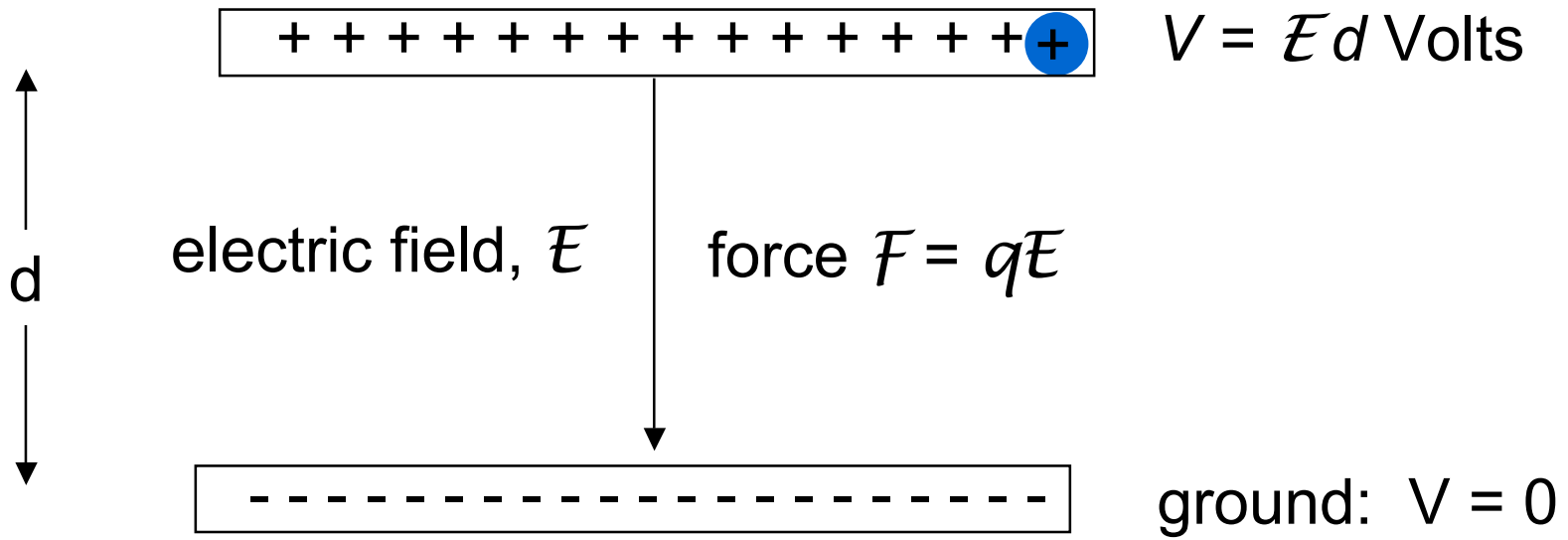
EE fundamentals

1) Voltage
2) Current
3) Resistance
4) I-V characteristics
   - resistor
   - voltage source
   - current source
5) Metals, insulators, and semiconductors

voltage

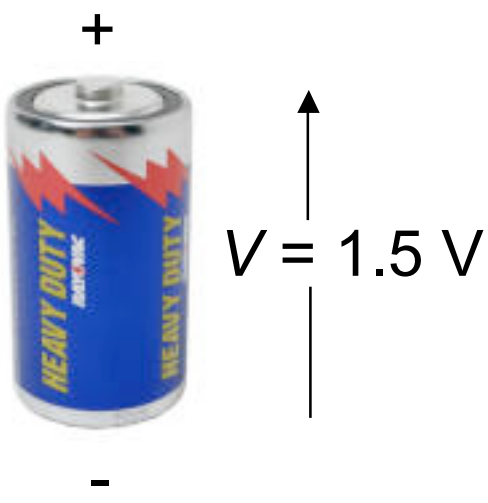


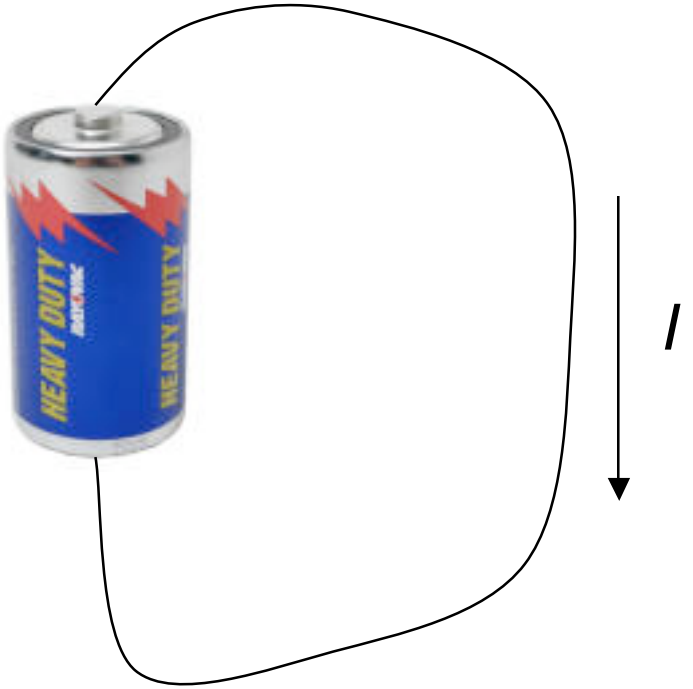
voltage



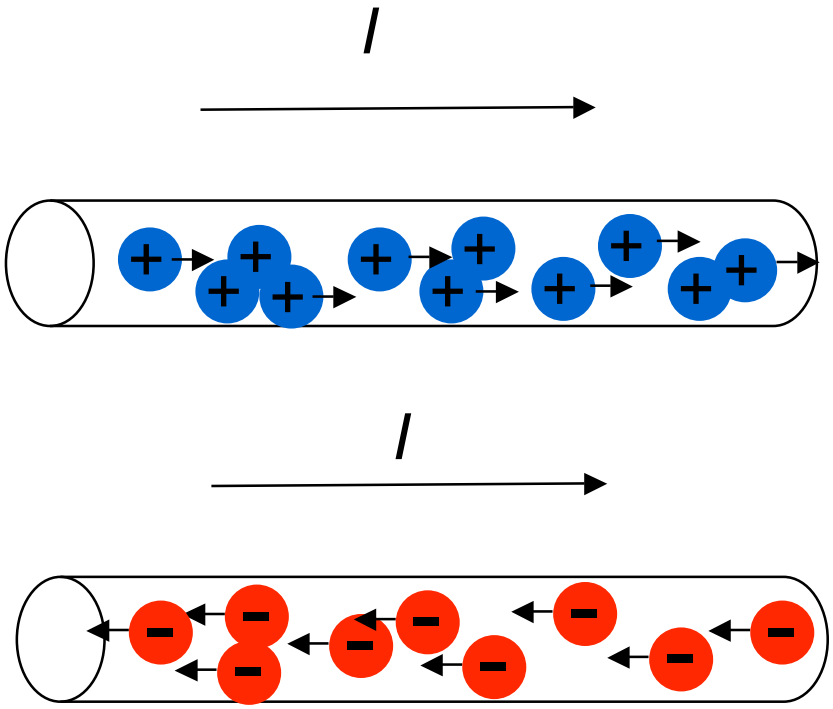
potential energy: E = q$\mathcal{E}$ d Joules

voltage



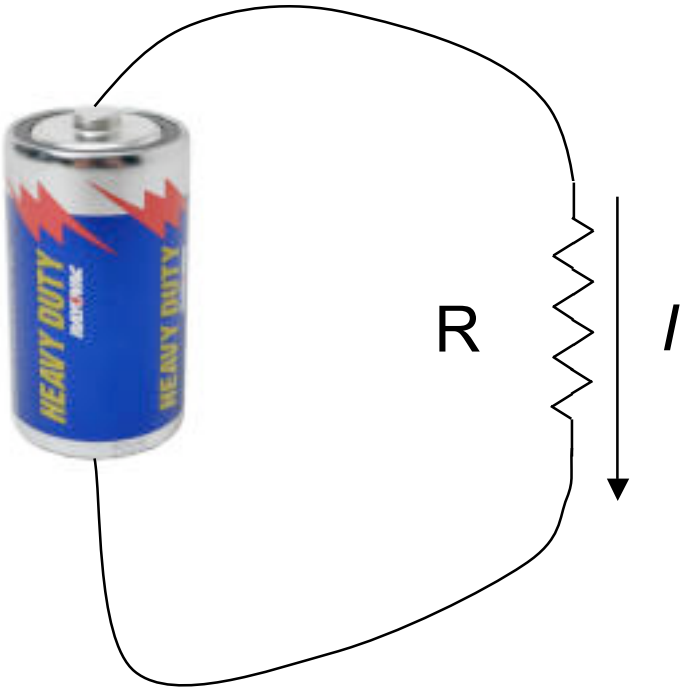


current



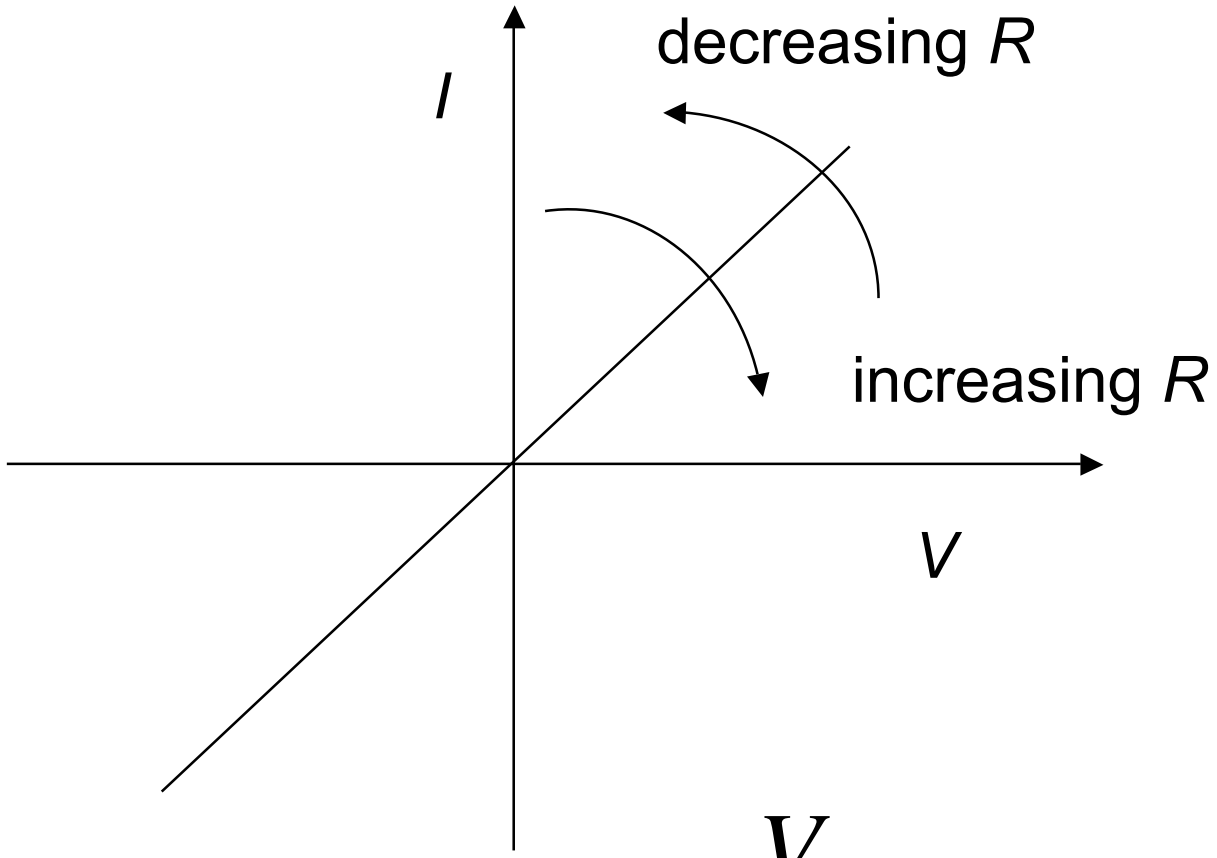
$$I = \frac{Q}{\tau}$$ C/sec = amperes

resistance



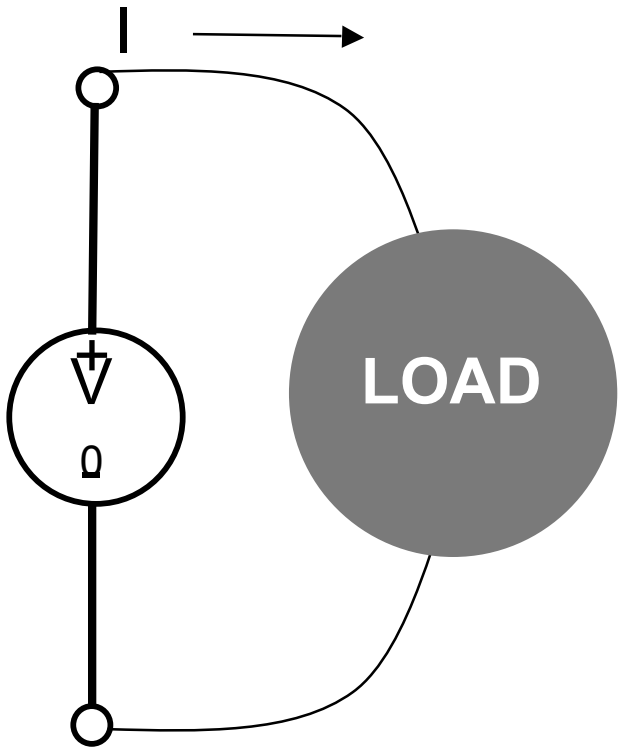
resistance (ohms W)

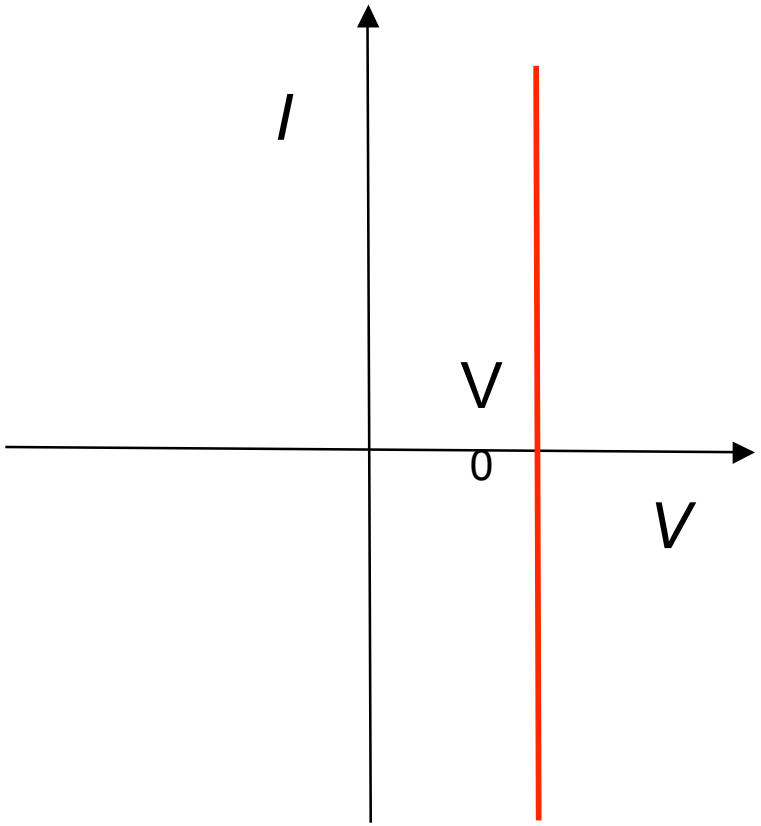
current-voltage characteristic



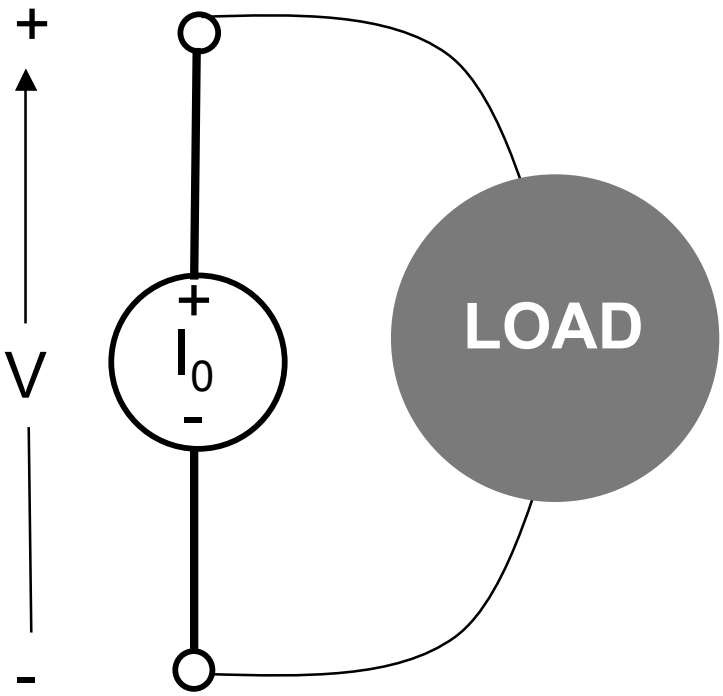
Ohm's Law: $I = \frac{V}{R}$

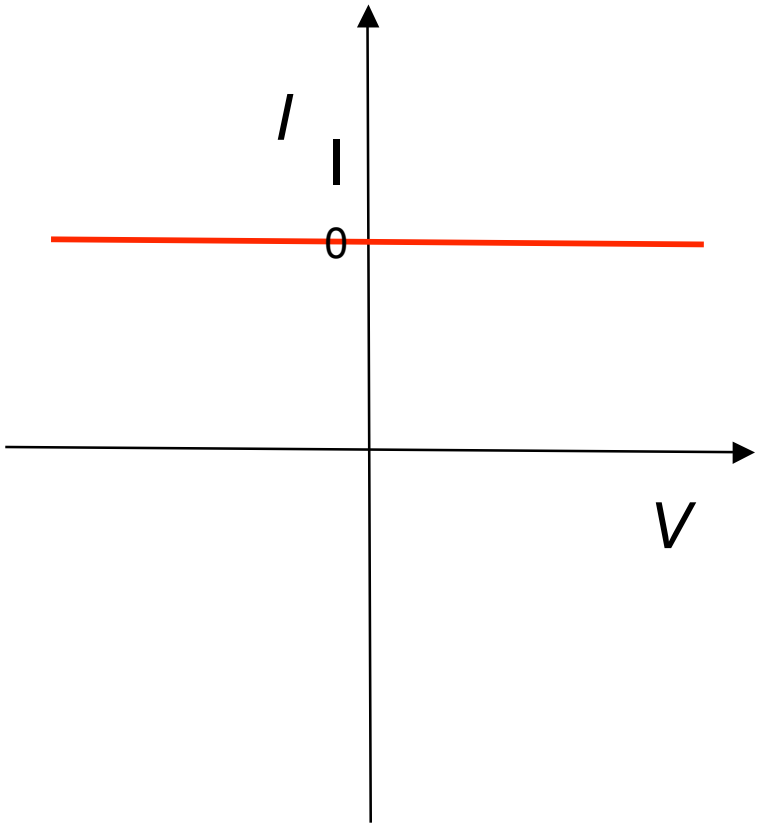
ideal voltage source



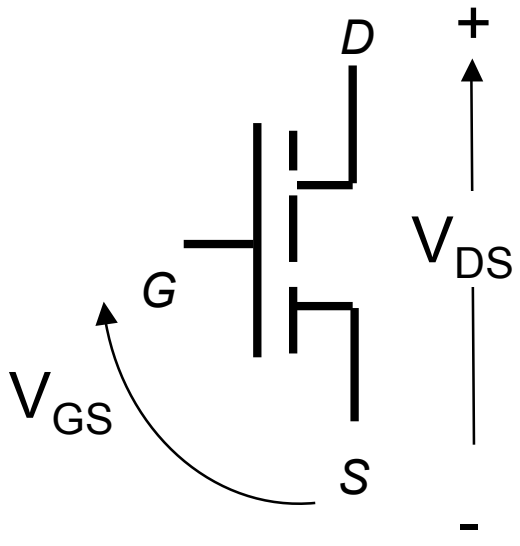


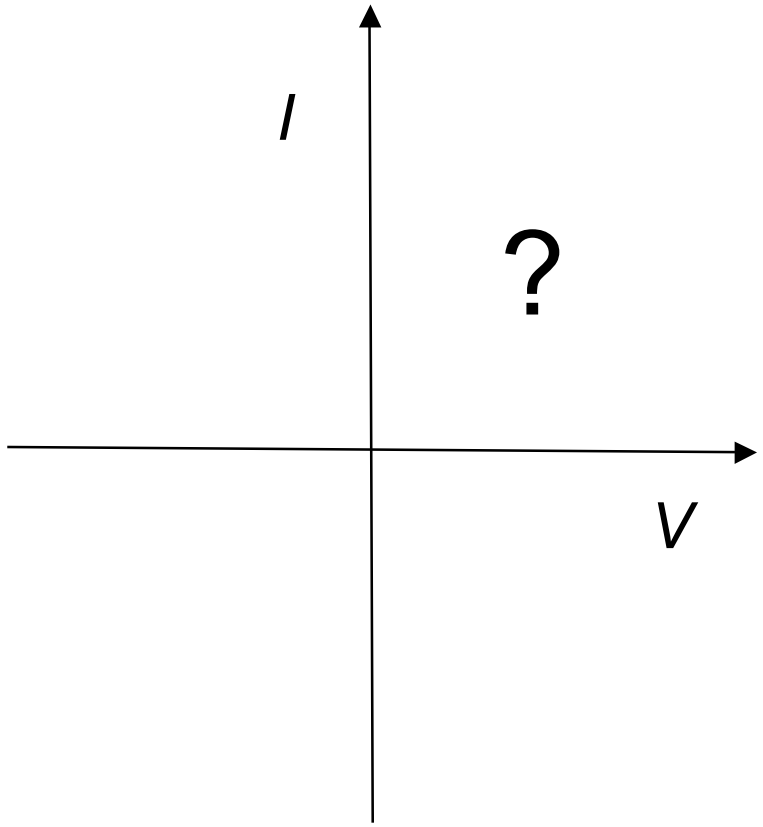
ideal current source



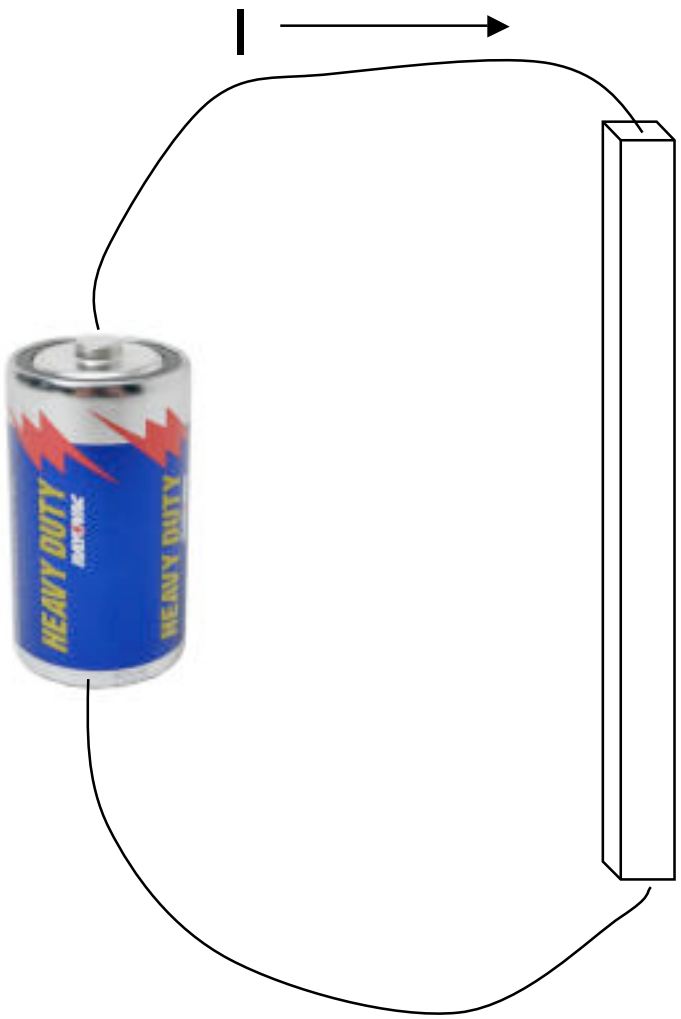


transistor





metal



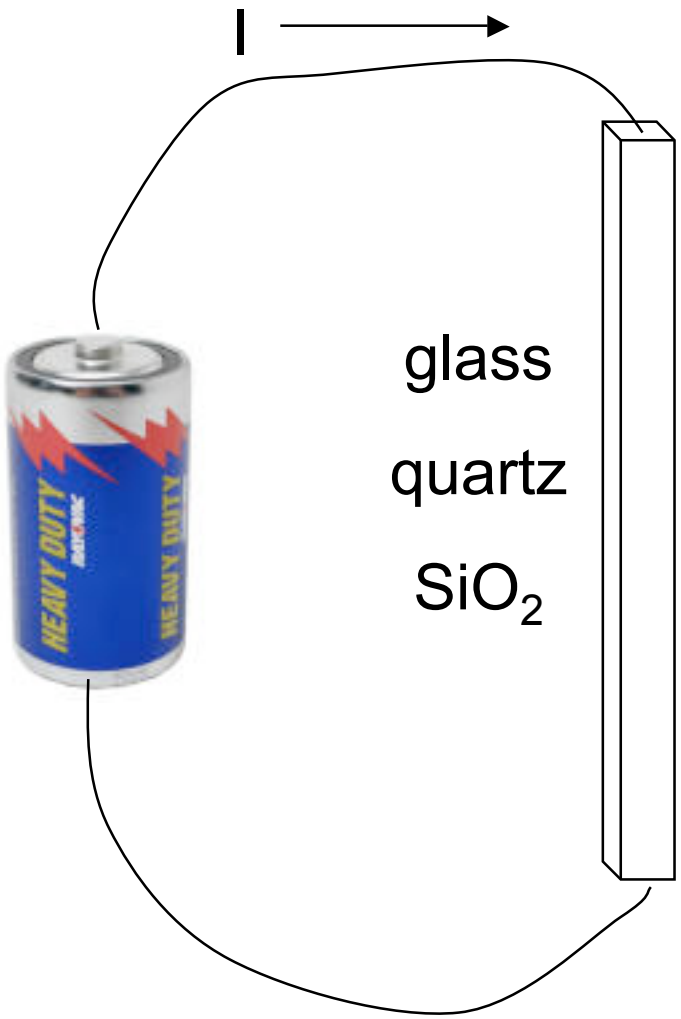
Au

Ag

Cu

- good conductors
- resistance low
- conduction by electrons

insulator



- very poor conductors
- resistance very high

semiconductor

resistance greater than a metal (~ 1 Ω) but less than an insulator (~ 10^6 Ω)

semiconductor doping

intrinsic semiconductor:
e.g. pure Si

doped semiconductor:
< 1% ‘impurities’

p-type:
boron impurities
conduction by + charges

n-type:
phosphorus impurities
conduction by - charges

EE fundamentals

√ 1) Voltage

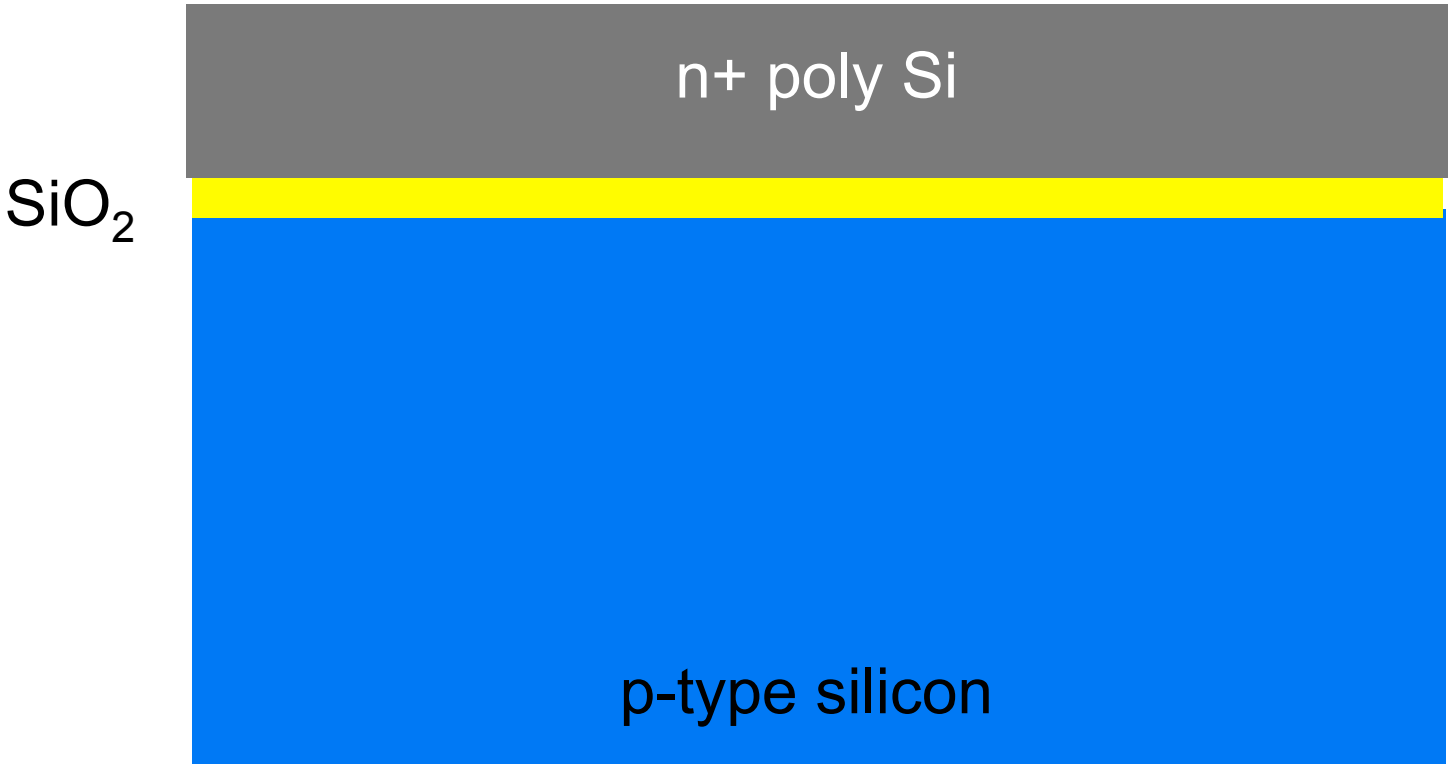
√ 2) Current

√ 3) Resistance

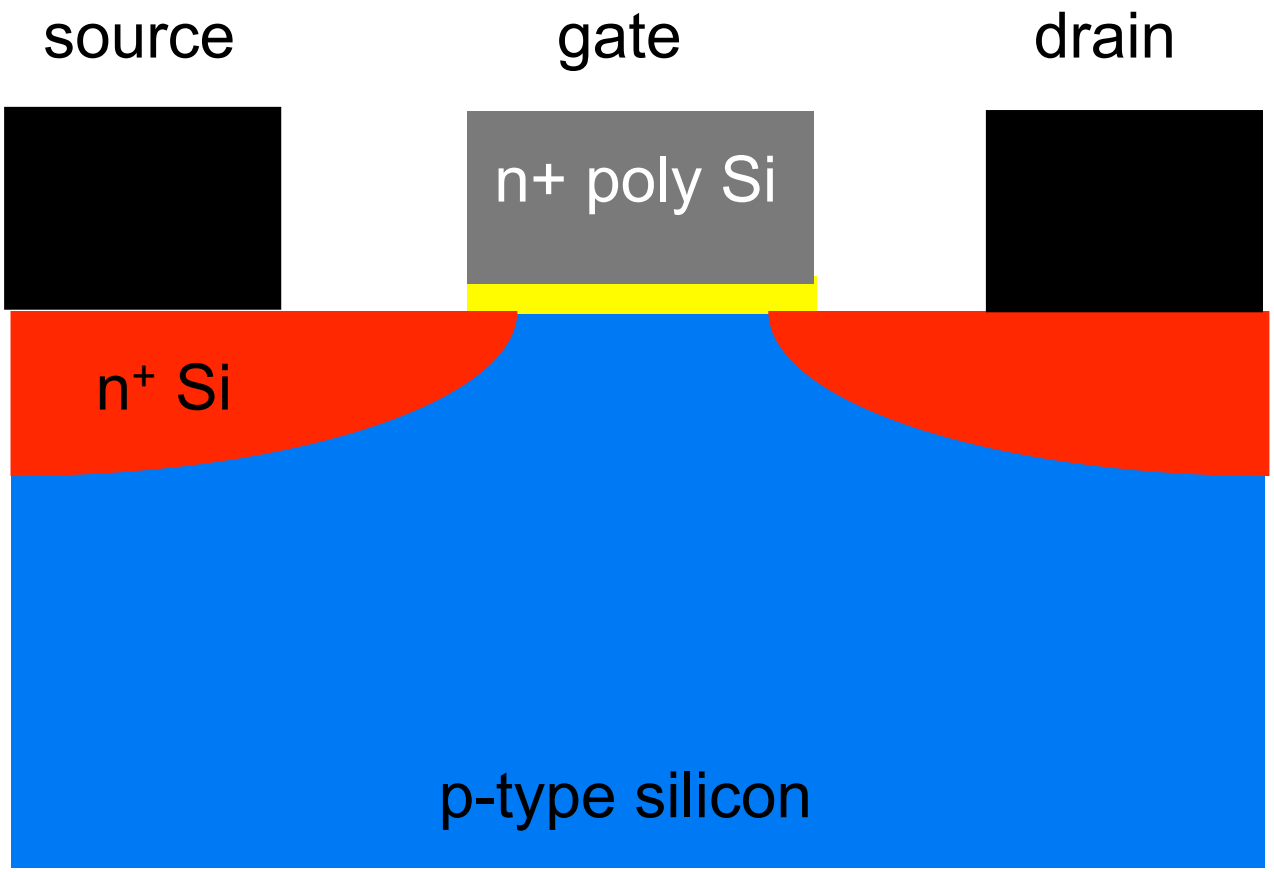
√ 4) I-V characteristics
- resistor
- voltage source
- current source

√ 5) Metals, insulators, and semiconductors

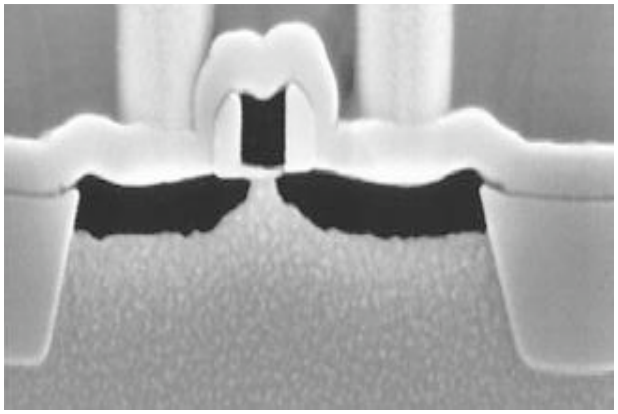
building a transistor



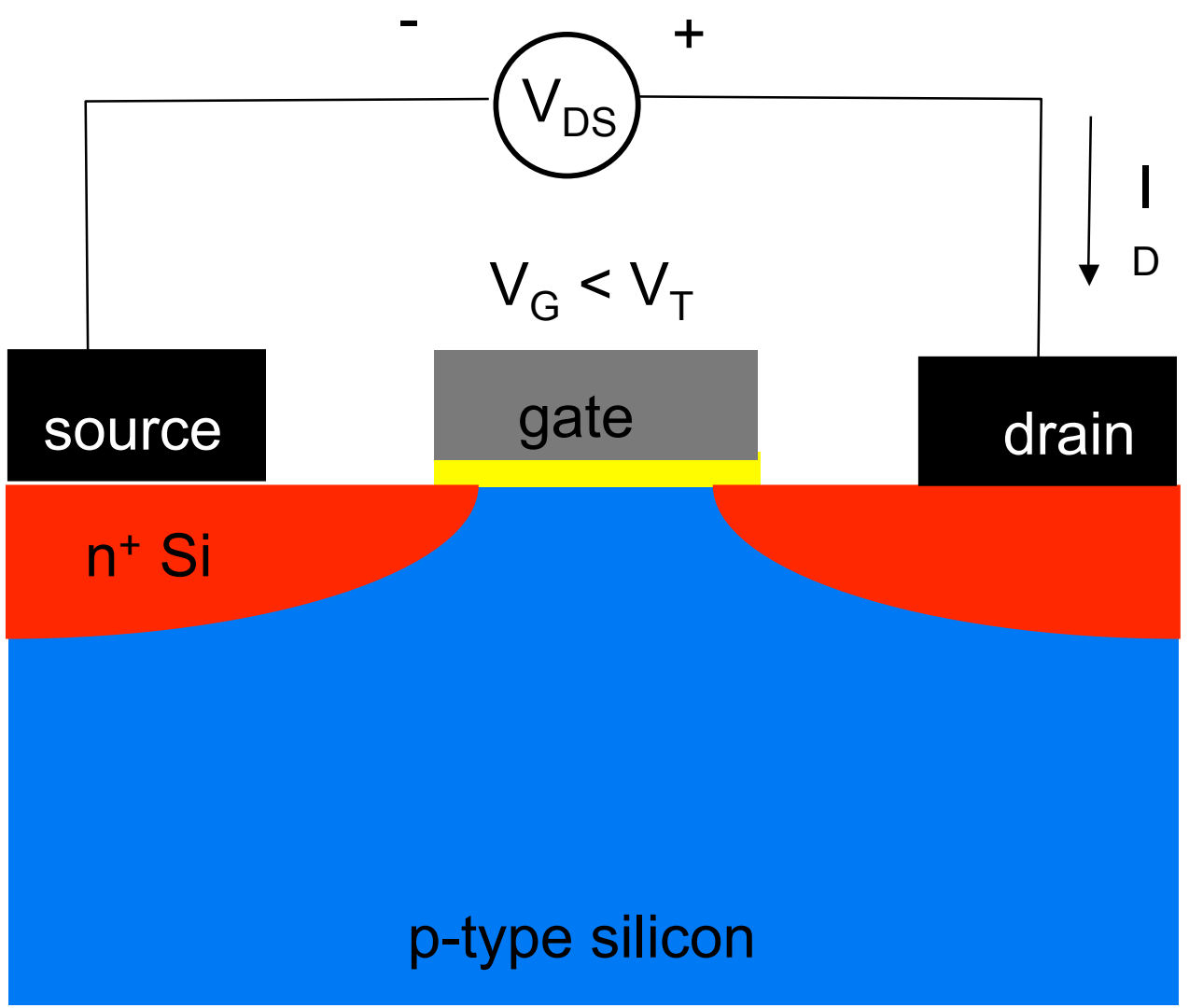
building a transistor



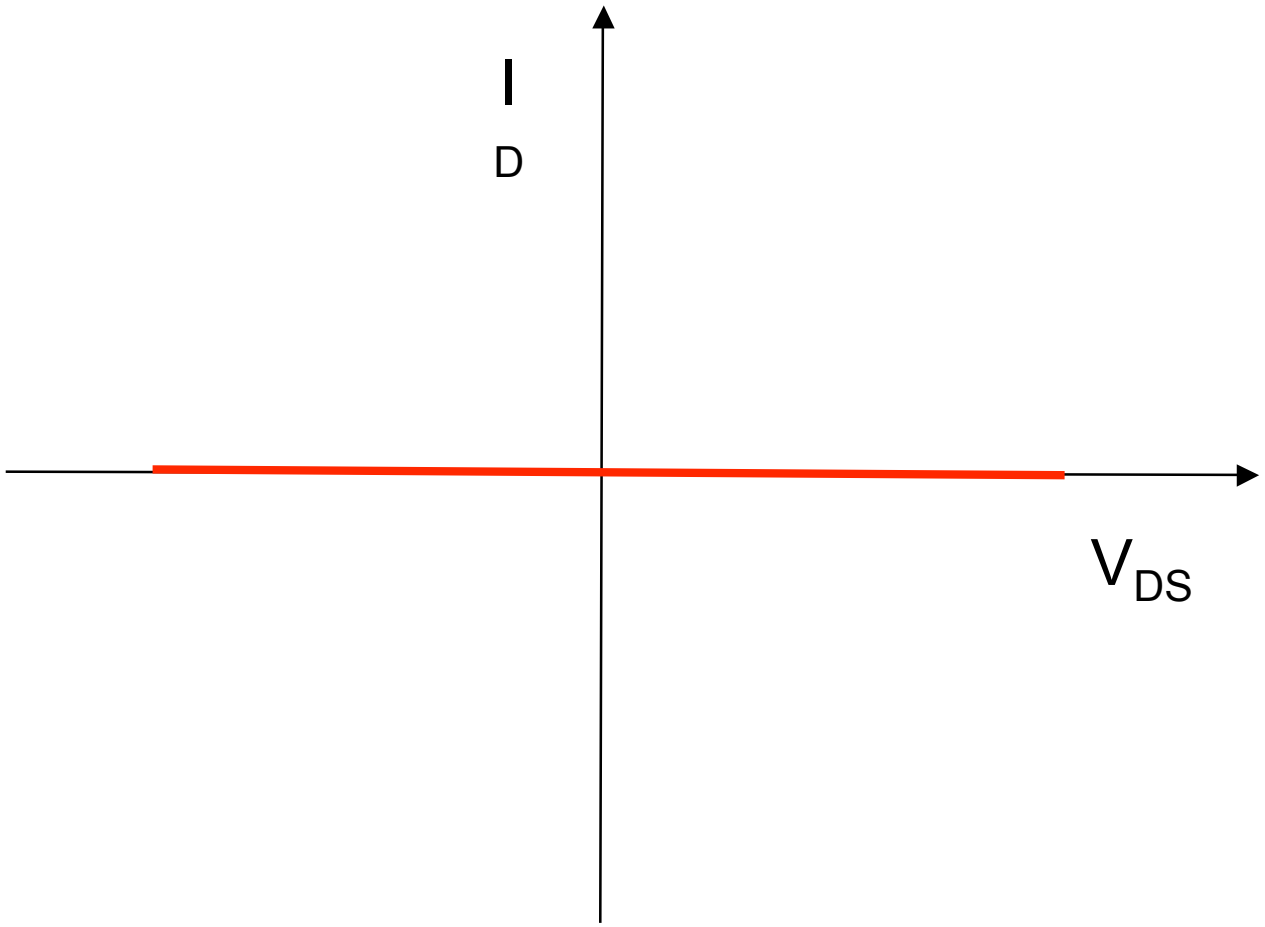
S *G* *D*



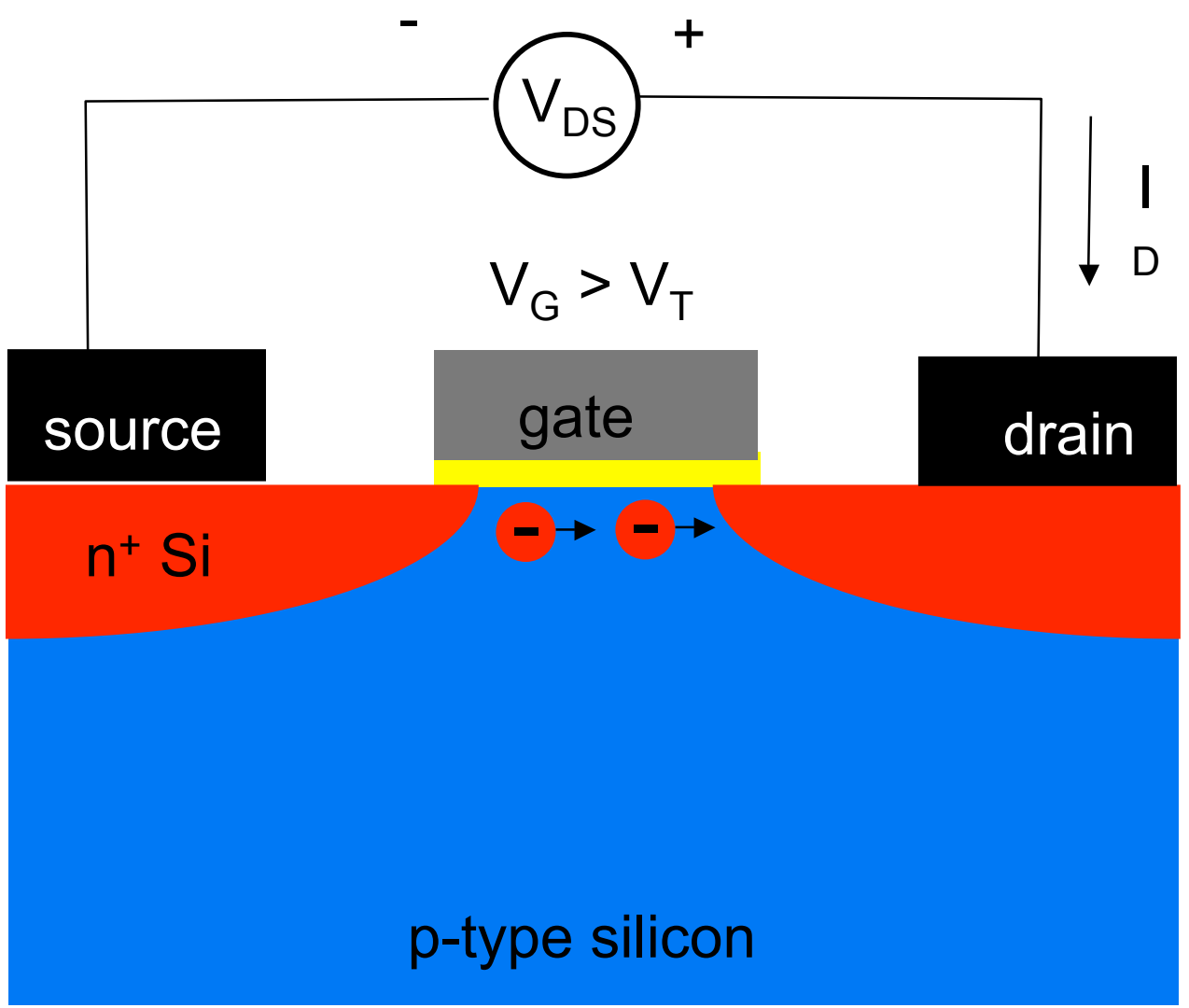
transistor



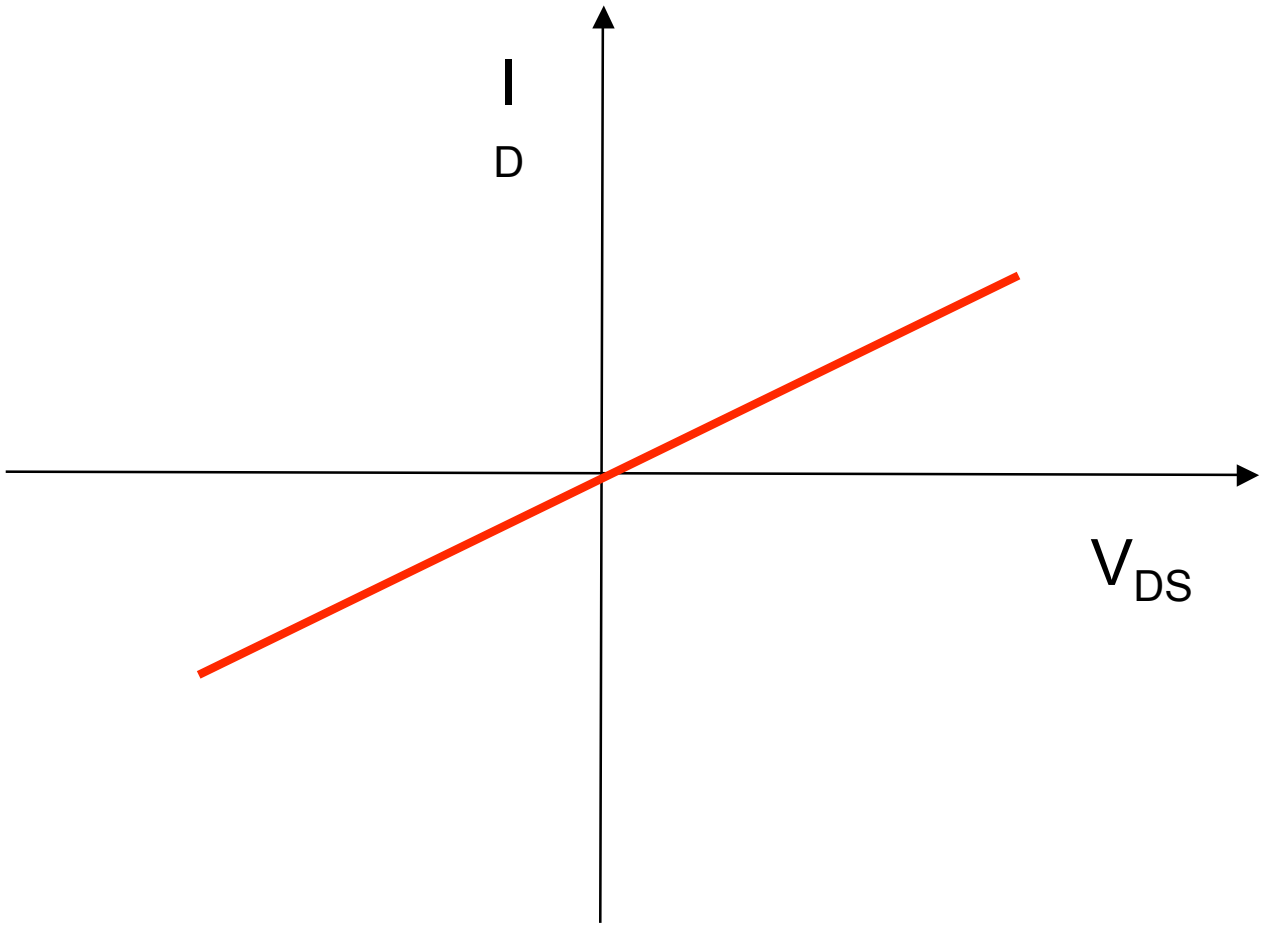
transistor



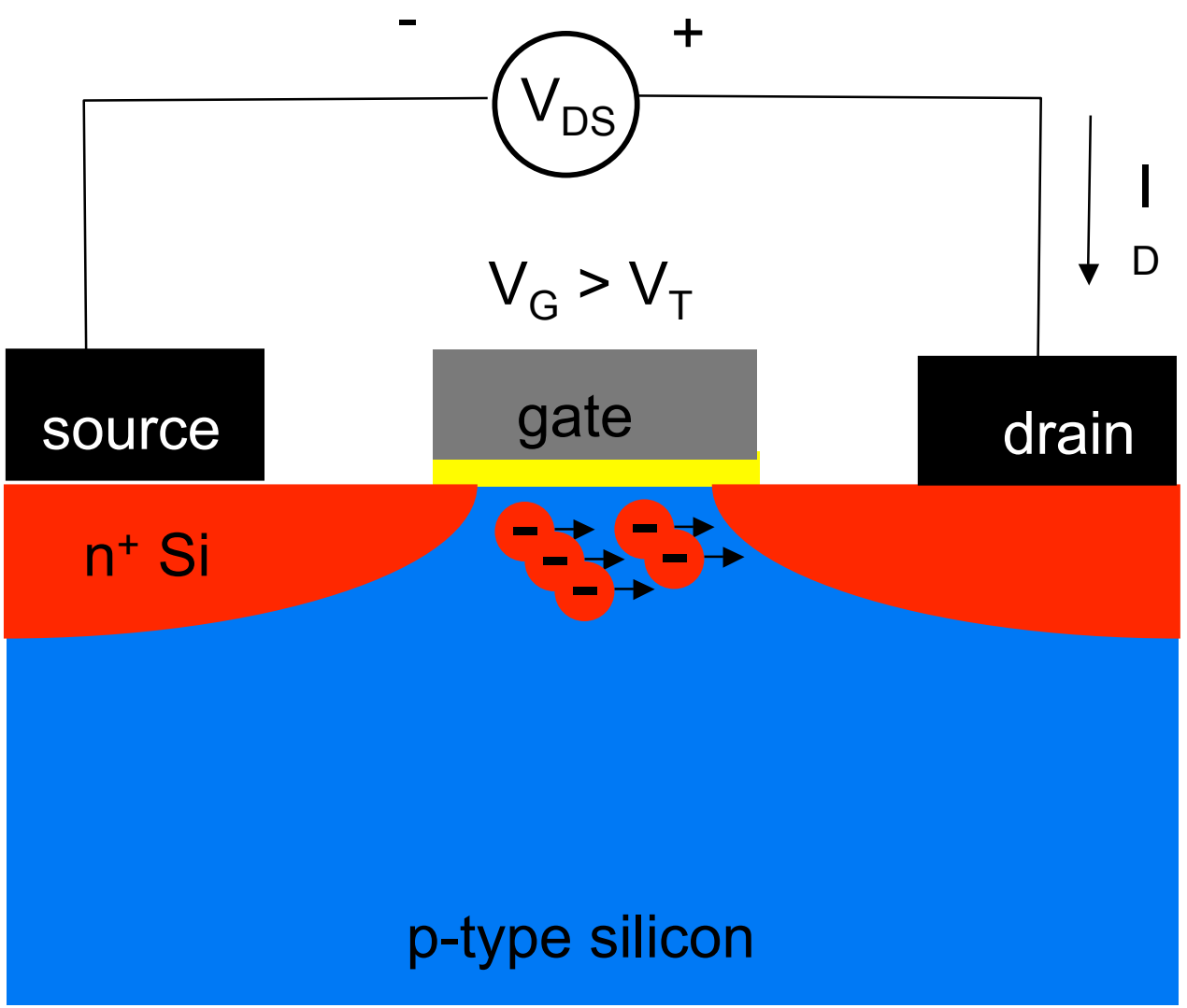
transistor



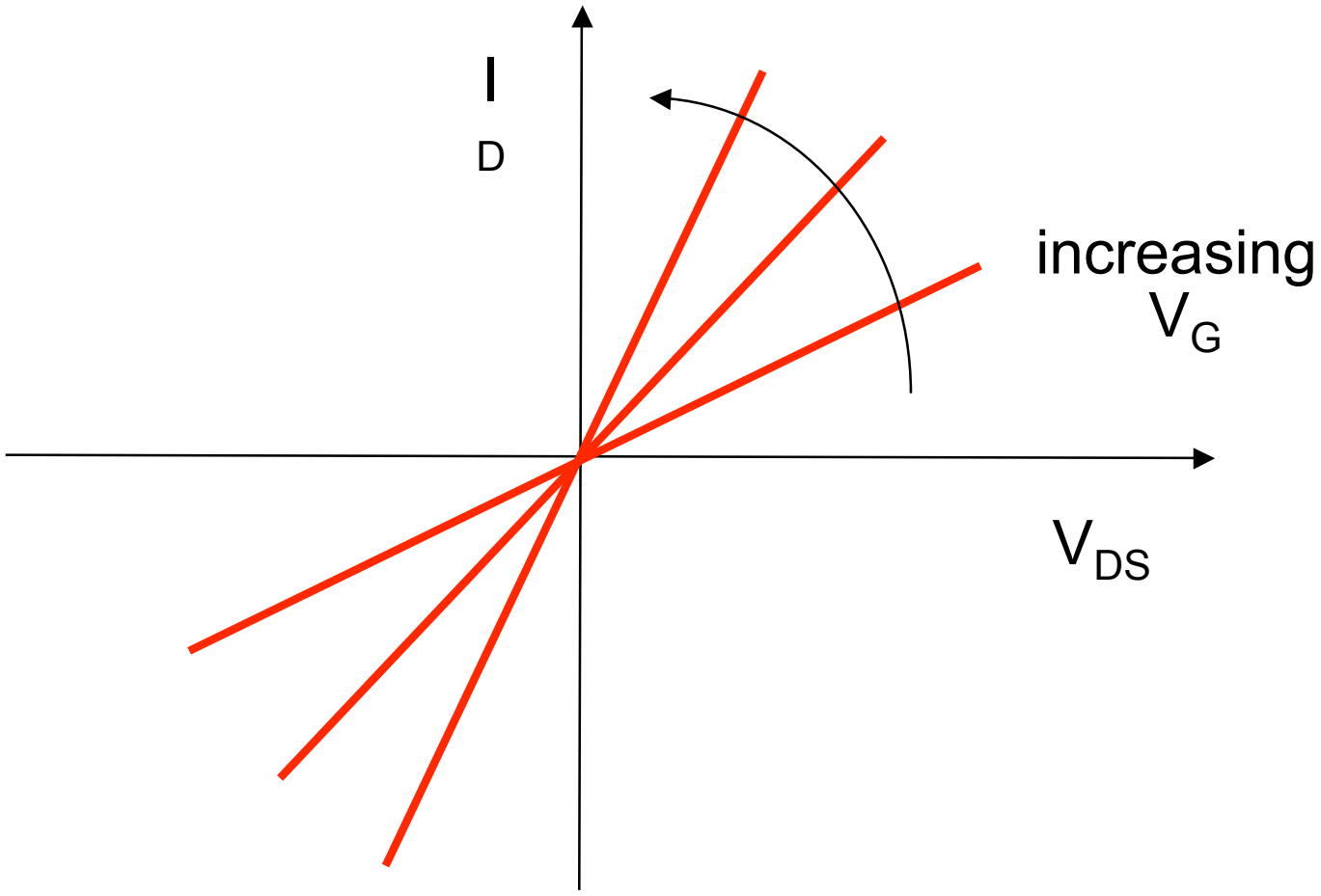
transistor



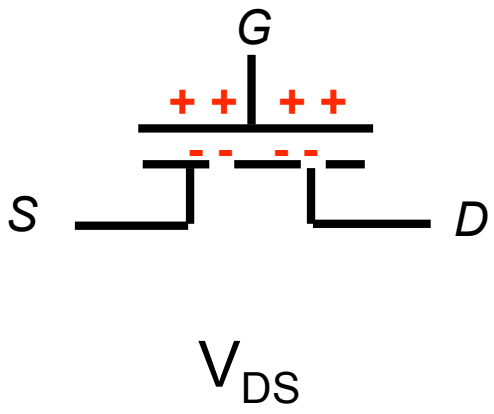
transistor

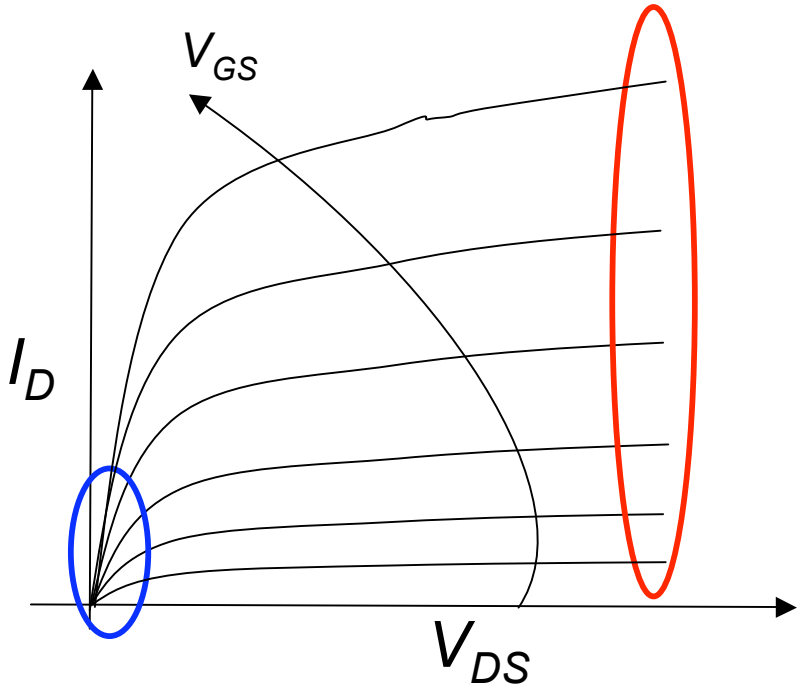


transistor: a voltage controlled resistor?

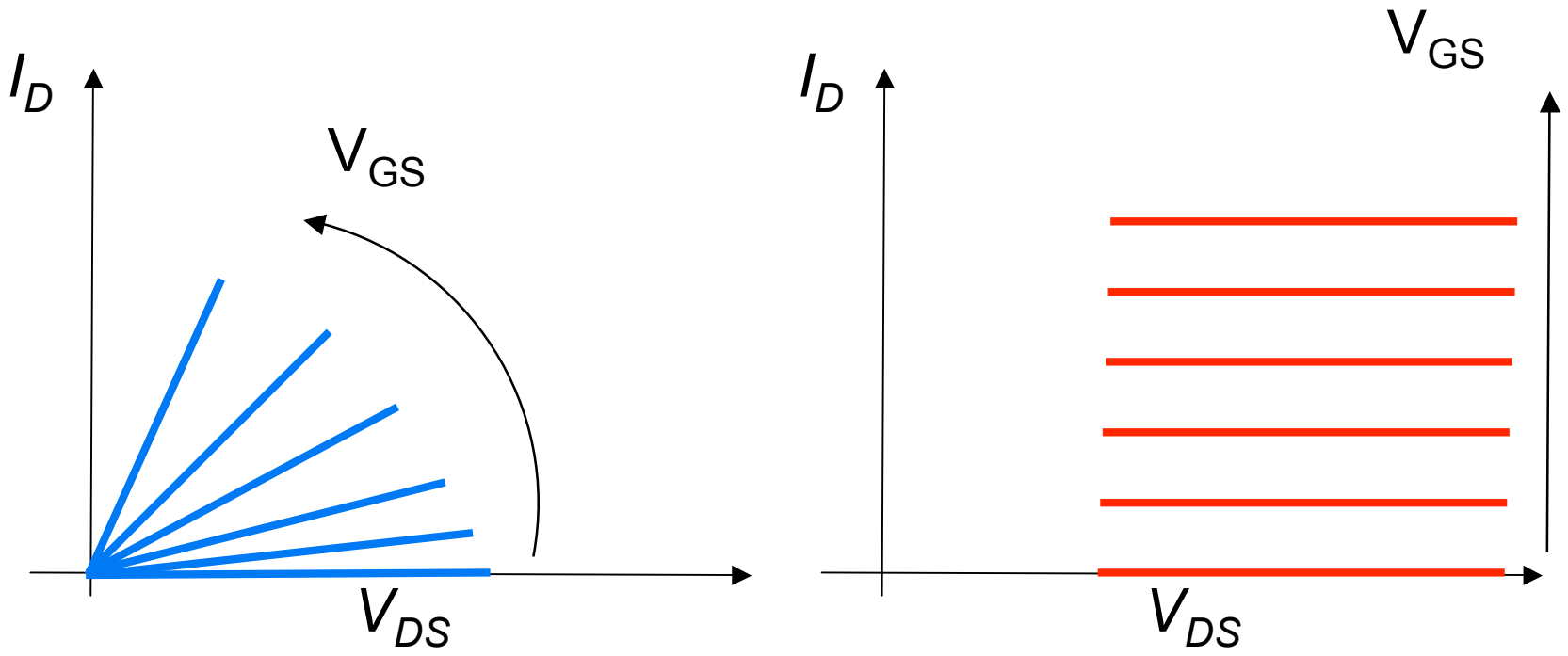


real transistors

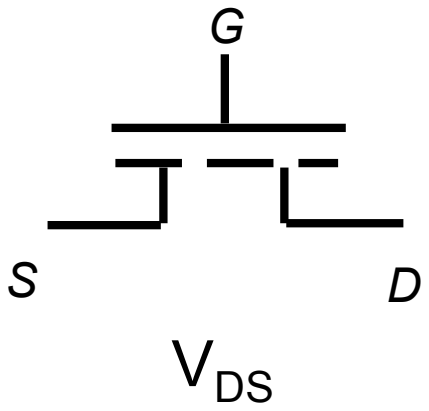


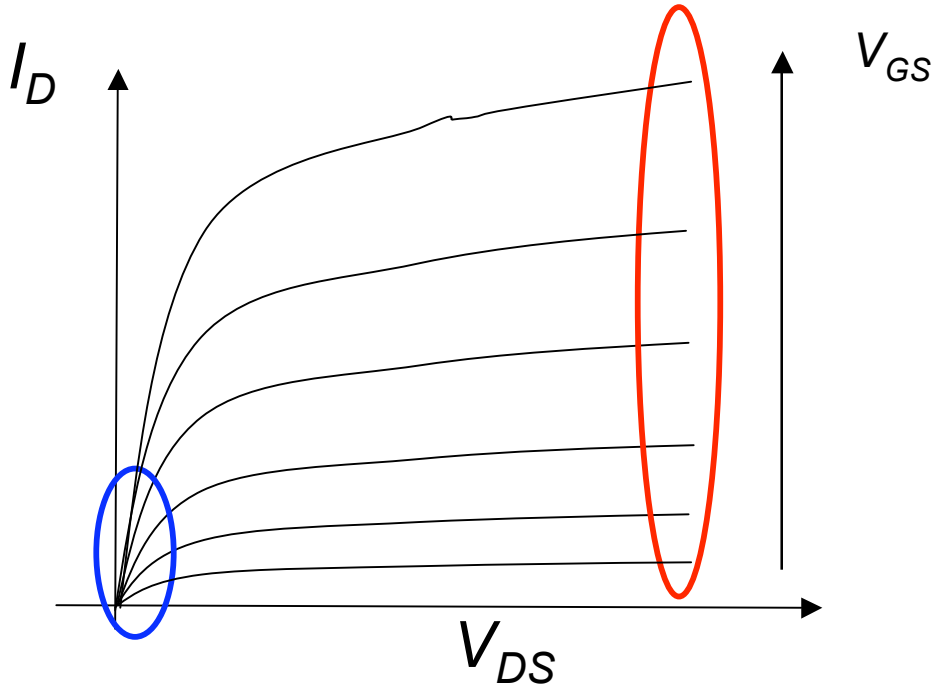


real transistors



real transistors

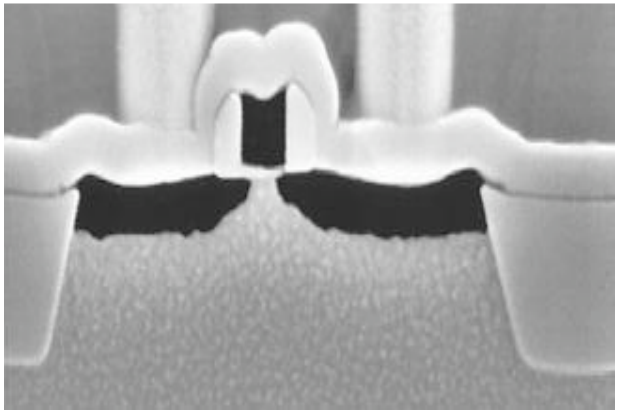




why does the current saturate?

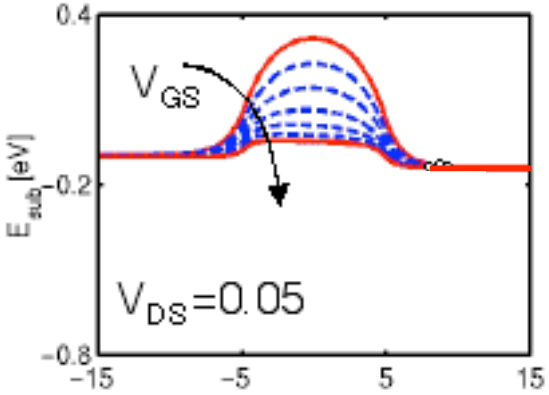
MOSFET energy band diagrams

S G D

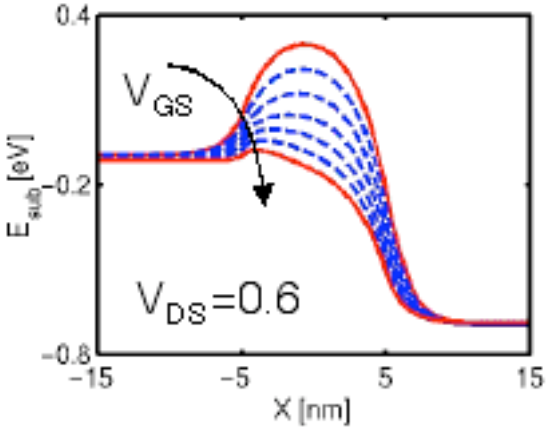


$E = -q\,V$

electron energy vs. position

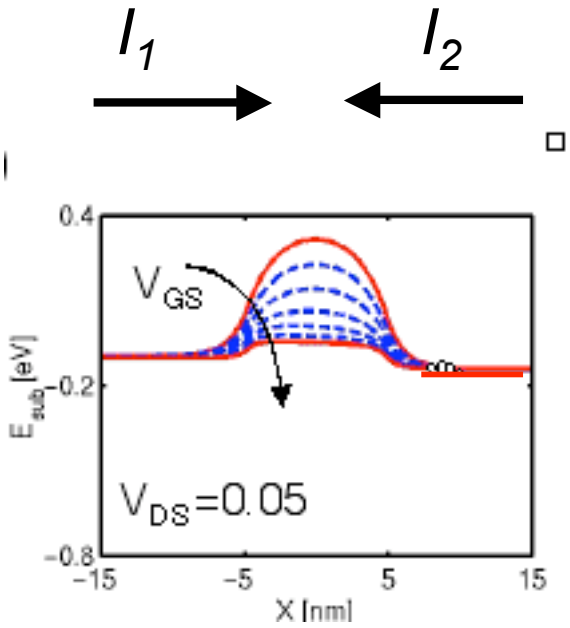


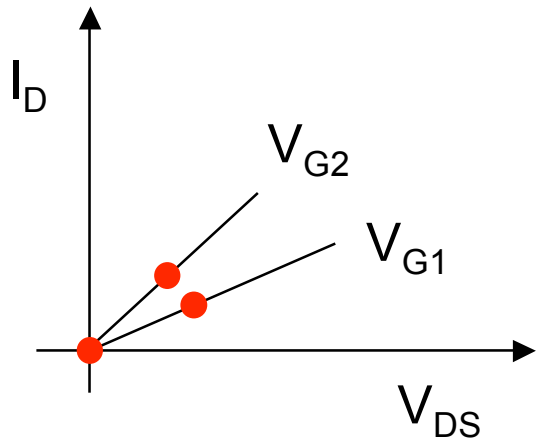
$V_D \approx 0V$



$V_D = V_{DD}$

low V_{DS}





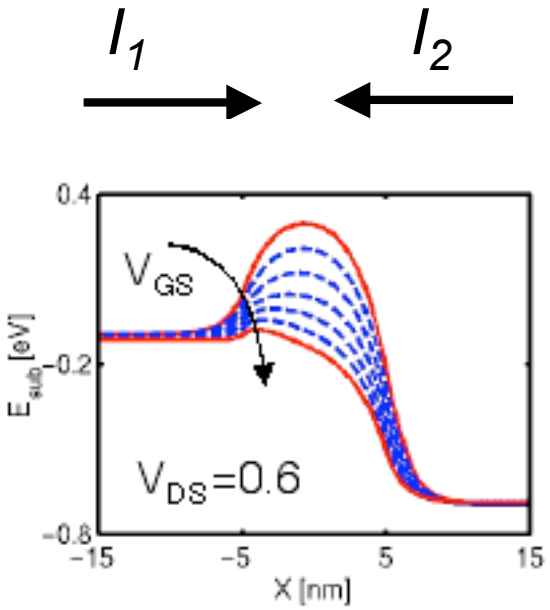
$I_1, I_2 \sim V_G$

$I_D = I_1 - I_2$

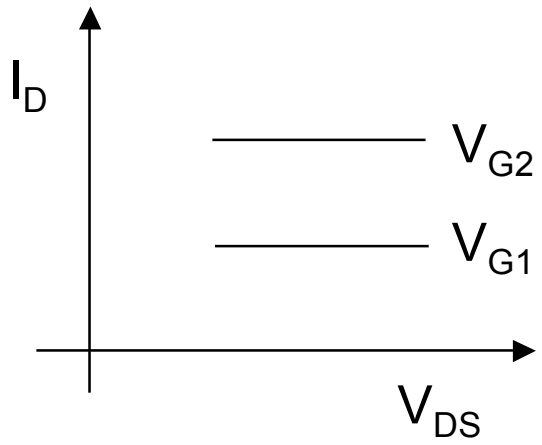
$V_D = 0$:
$I_1 = 1_2$
$I_D = 0$

$V_D > 0$:
$I_1 > 1_2$
$I_D > 0$

high V_{DS}

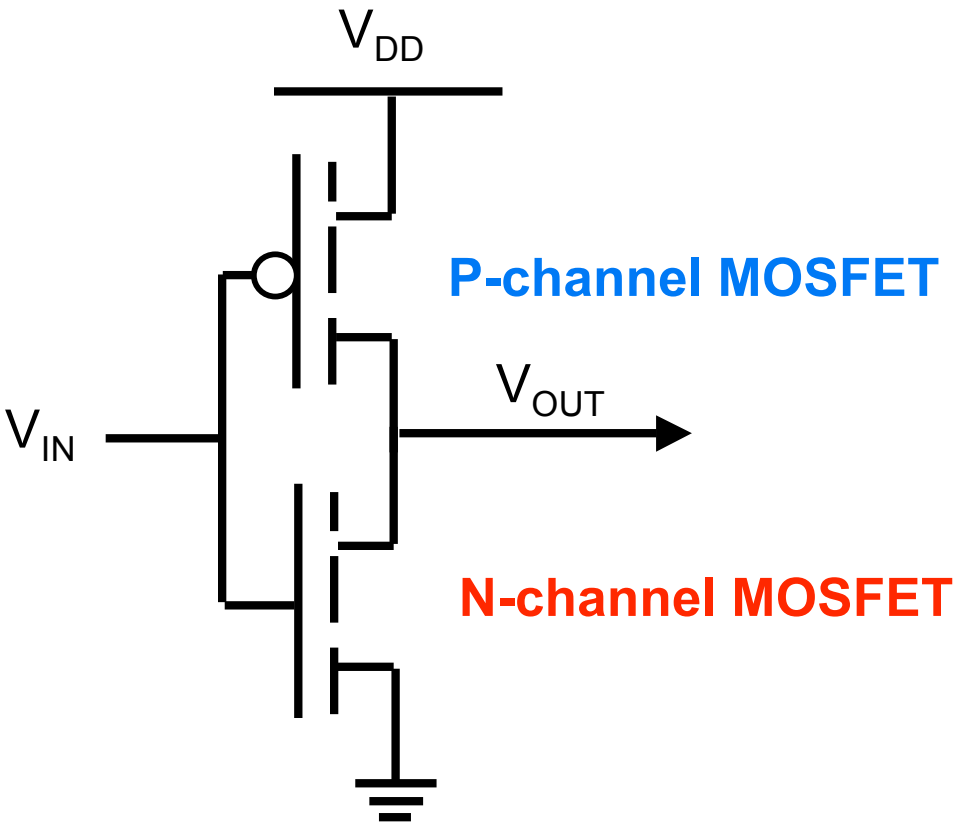


I_1, ~ V_G
I_2 ~ 0

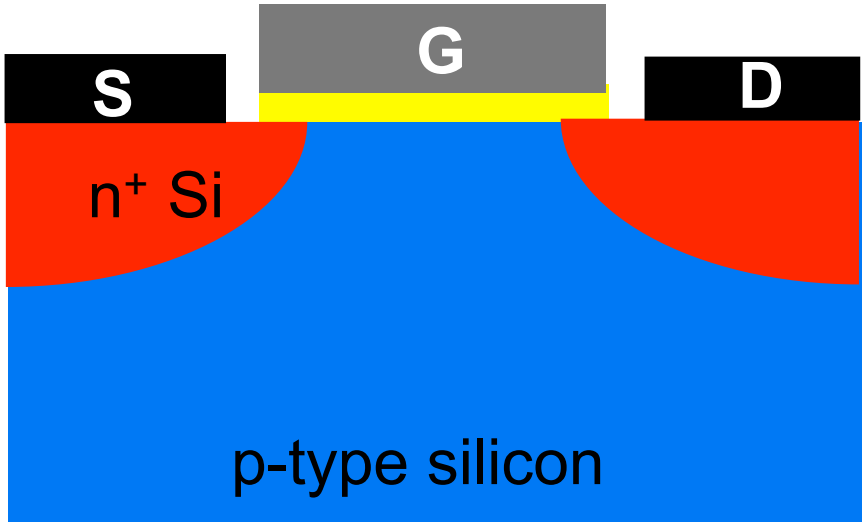


$I_D = I_1 \sim V_G$

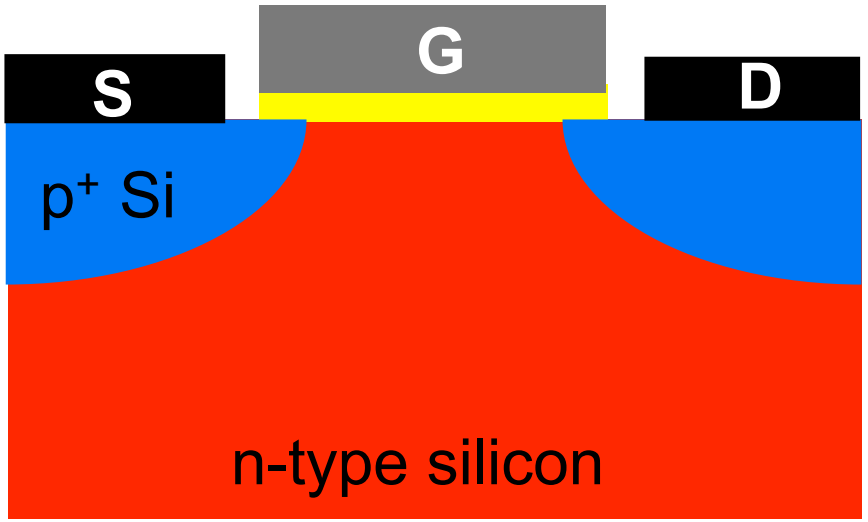
complementary CMOS



CMOS

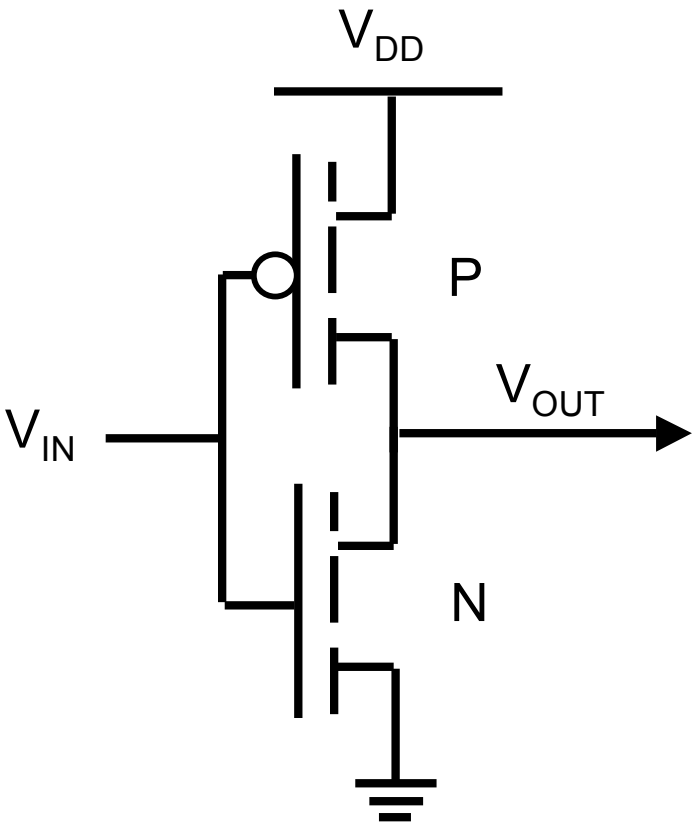


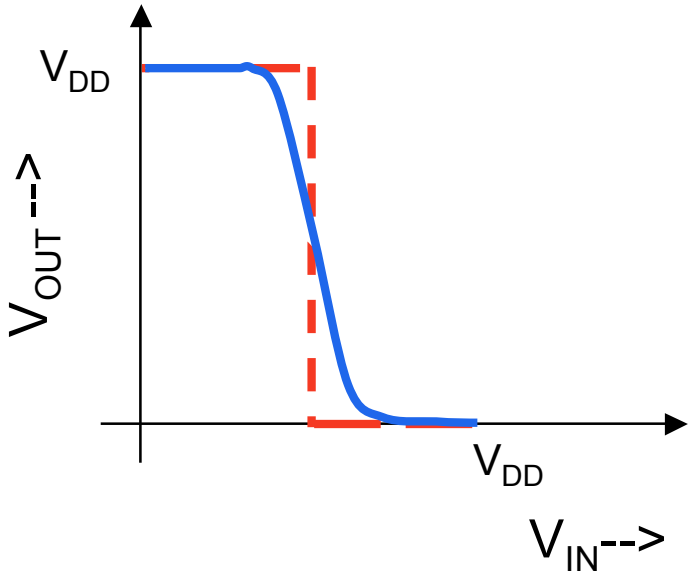
n-MOS: $V_{GS} > 0$



p-MOS: $V_{GS} < 0$

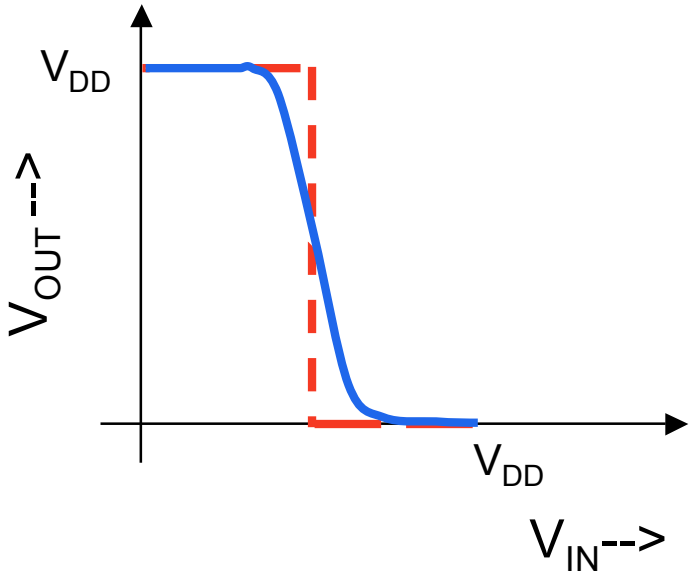
CMOS inverter



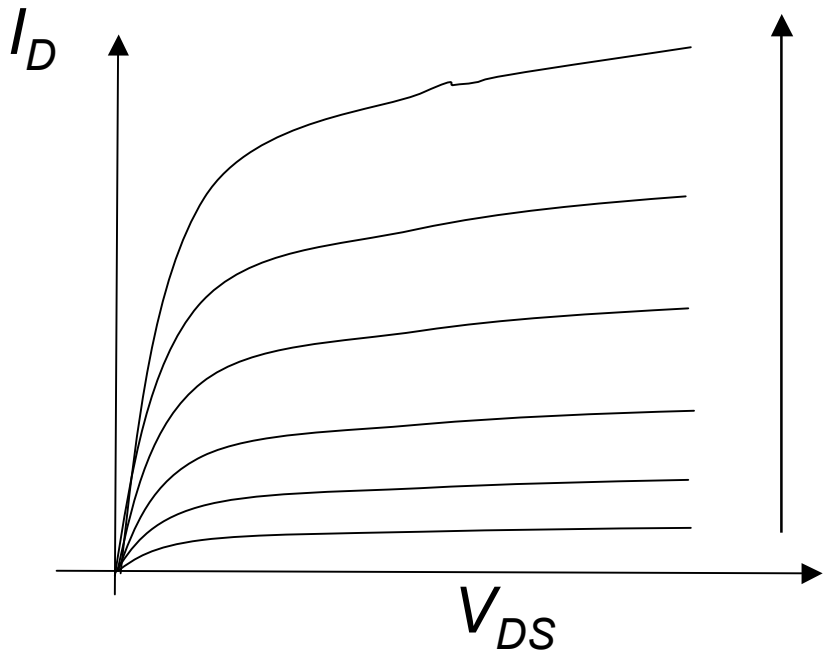


"transfer characteristic"

CMOS inverter



sharp transition
separates zero and one

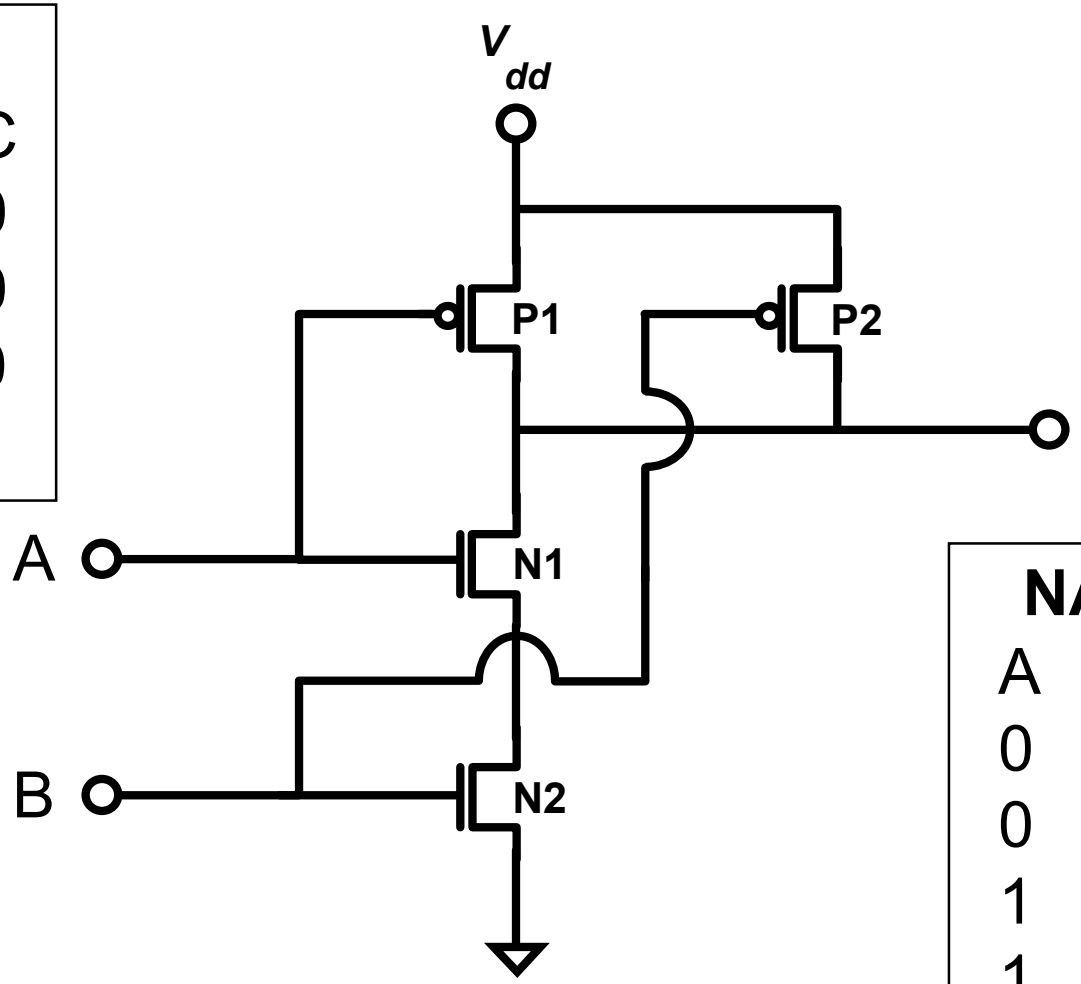


flatter characteristic
(small dependence of I_D on V_{DS})
gives sharp transition

Two input CMOS NAND gate

AND

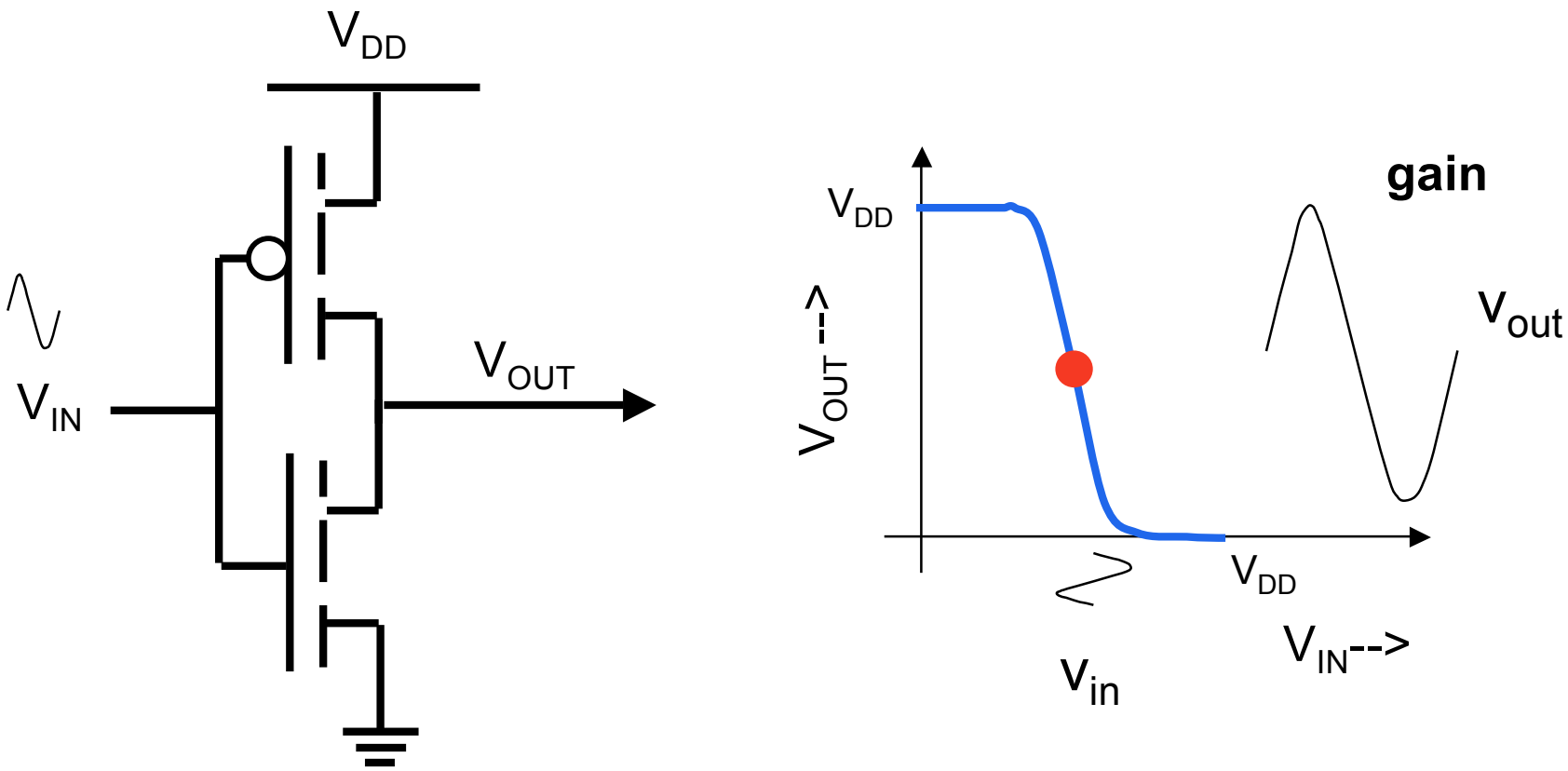
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1



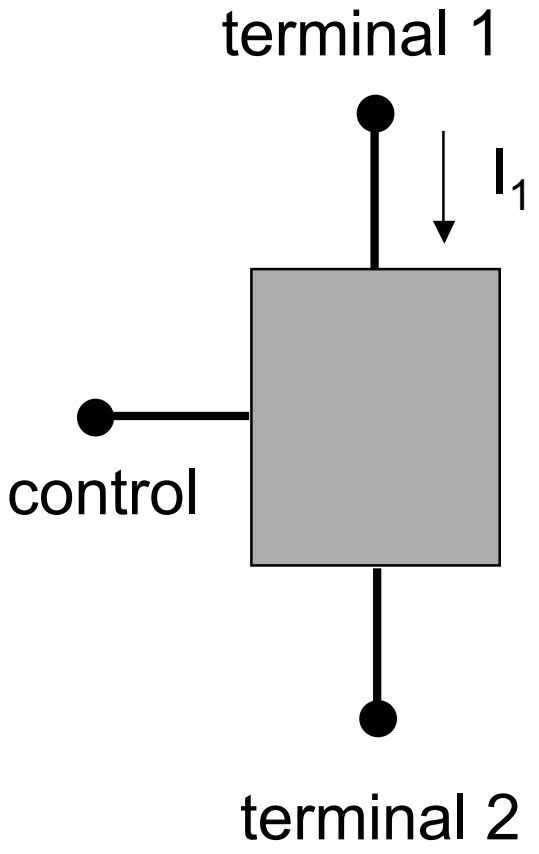
NAND

A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

CMOS Amplifier



transistors



point contact transistor
bipolar transistor
MOSFET
JFET
SOI MOSFET
FinFET

MODFET (HEMT)
heterojunction bipolar transistor
velocity modulation transistor