Where does the power go? The physics

Sommerakademie in Leysin
AG 2 – Effizientes Rechnen

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August 2016

Outline

What is a transistor?

- semiconductor device
- smallest unit in modern electronics
- used to guide the amplitude of electric current
- largest transistor count in a commercially available processor (2016): 7.2 billion (Intel Broadwell-EP Xeon)

Different transistor types

- bipolar junction transistor (BJT)
- field-effect transistor (FET)
- junction field-effect transistor (JFET)
- metal-oxide-semiconductor field-effect transistor (MOSFET)
- complementary metal-oxide-semiconductor (field-effect transistor) (CMOS)

The depletion region

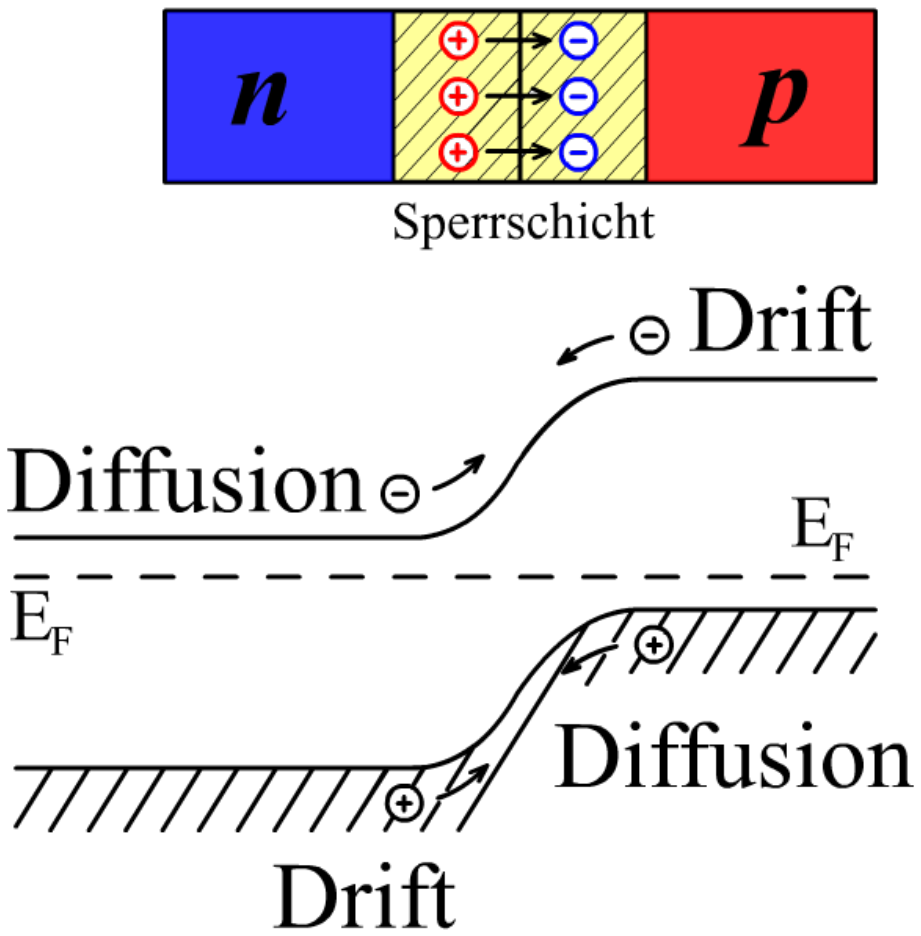

Figure: Scheme of a depletion region

The bipolar junction transistor

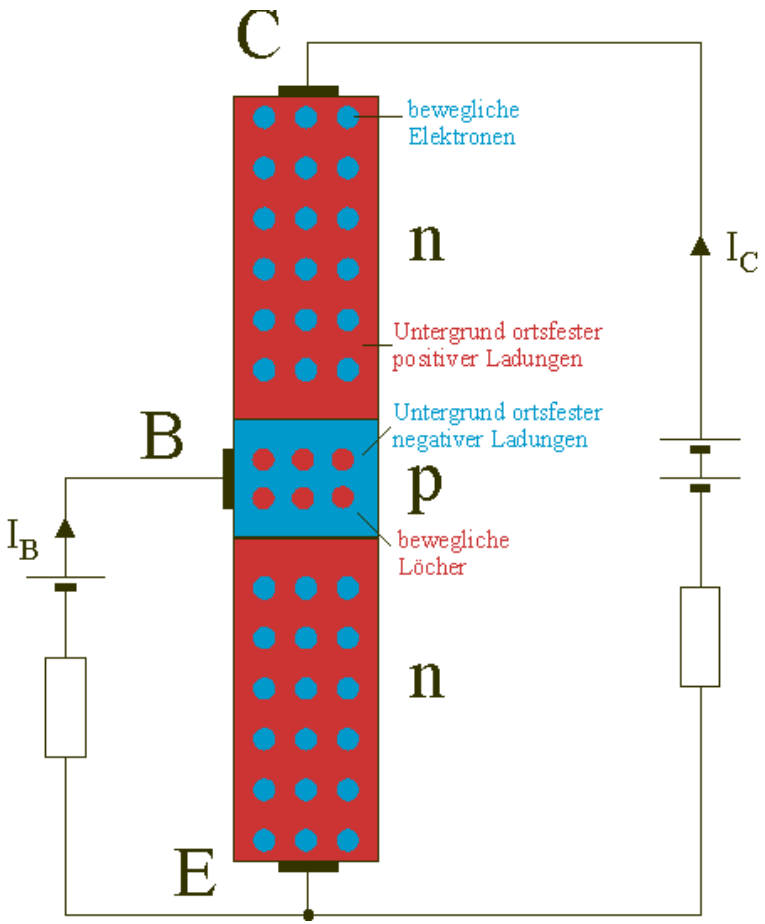

Figure: Scheme of a BJT

The junction field effect transistor

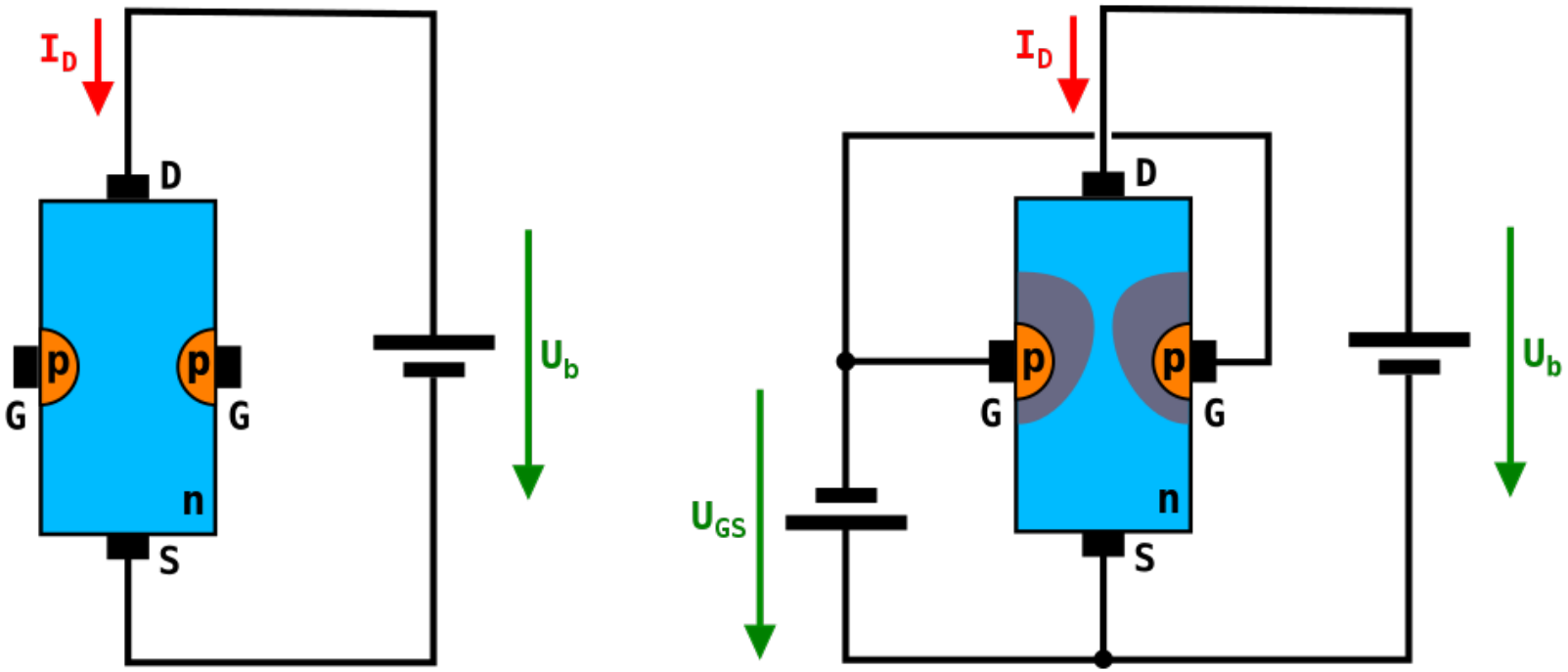

Figure: Scheme of a JFET

The complementary metal-oxide-semiconductor

- technology used for building integrated circuits
- design uses complementary MOSFETs (NMOS and PMOS) to fulfill logic functions
- high noise immunity
- low static power consumption due to complemetary design
- low heat production

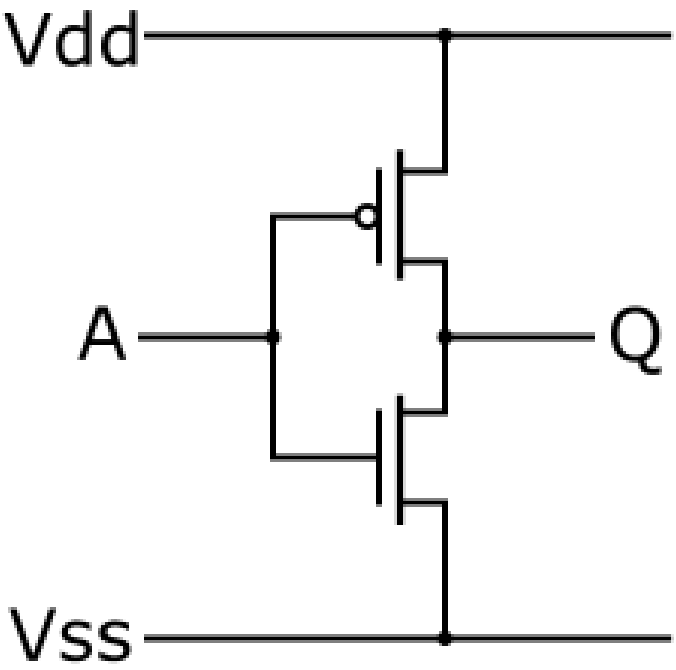

Figure: CMOS NOT gate

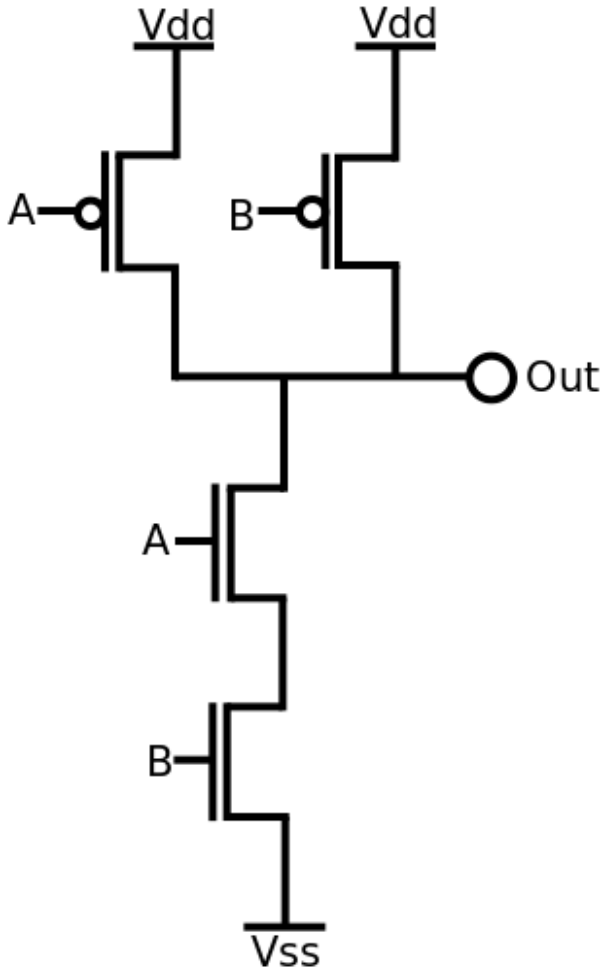

Figure: CMOS NAND gate

The physical layout of a CMOS NAND gate

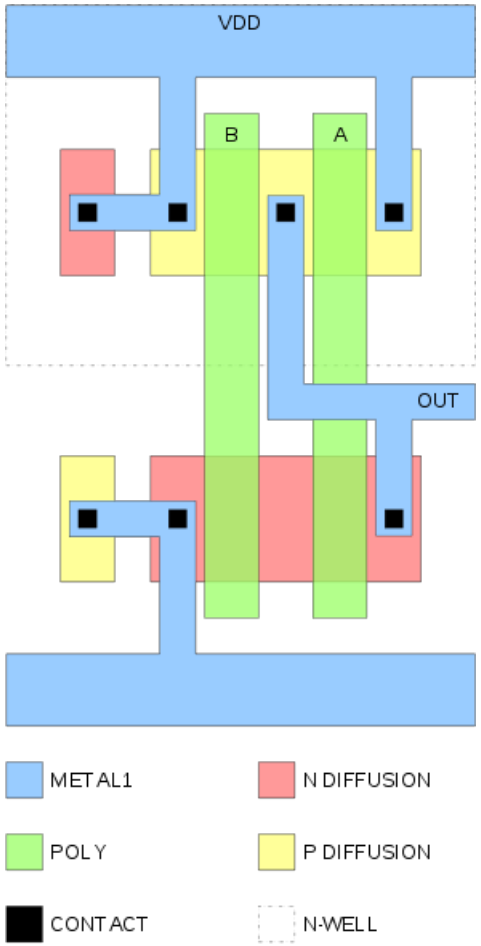

Figure: Physical layout (schematic)

Static dissipation

- subthreshold conduction of MOS components
- Tunneling current through gate oxide (gate leakage)
- Leakage current through reverse-biased diodes

Dynamic dissipation

- Charging and discharging of load capacitances
- Short-circuit power dissipation
  due to finite transition time on/off for both PMOS and NMOS
- *crowbar* power: appears in long, narrow, weakly driven wires

Dynamic power models (dominant for decades)

Dynamic power models

The most important equation:

Dynamic power models

The most important equation:

$$p = A \cdot C \cdot V^2 \cdot f$$

Growing importance in recent years: leakage energy

Leakage energy: causes 20 to 40 % of the power consumption of microprocessors

Leakage energy: the mathematical model

$$I_{\mathrm{leak}} = \mu_0 C_{\mathrm{ox}} V_{\mathrm{T}}^2 \frac{W}{L} e^{1.8 \cdot \frac{V_{\mathrm{gs}} - V_{\mathrm{th}}}{n V_{\mathrm{T}}}} \left(1 - e^{-\frac{V_{\mathrm{ds}}}{V_{\mathrm{T}}}}\right)$$

Dynamic power reduction

- Reducing of output capacitance C
- Reducing of supply voltage V_{dd}
- Reducing of switching activity A
- Reducing of clock frequency f

Static power reduction

- Dual threshold CMOS
- Increasing V_s of NMOS transistors: subthreshold leakage decreases exponentially, due to negative gate-to-source voltage
- stacking transistors