Essentials of MOSFETs

Unit 5: Additional Topics

Lecture 5.7: Unit 5 Recap

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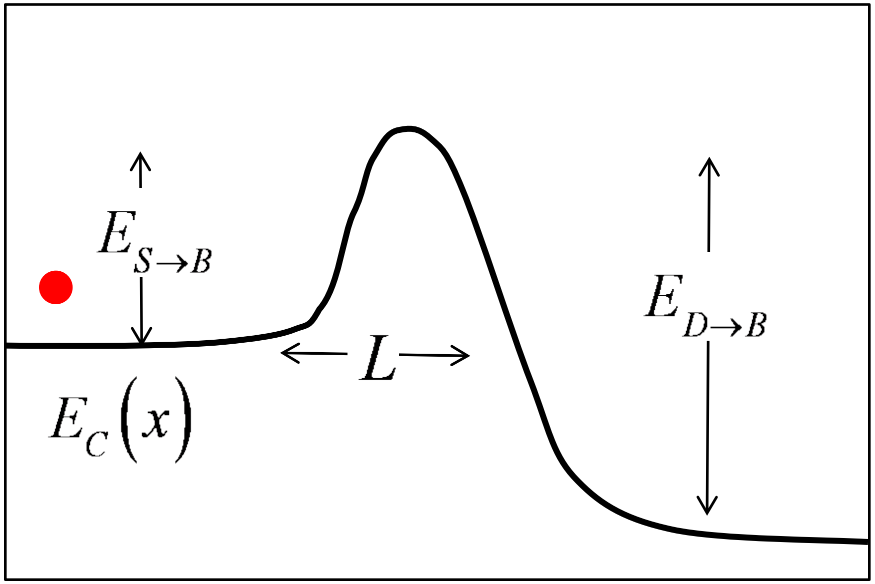
Unit 5 Topics

L5.1: Limits of MOSFETs
L5.2: Power MOSFETs
L5.3: High Electron Mobility Transistors (HEMTs)
L5.4: Review of PN Junctions
L5.5: Heterostructure Bipolar Transistors (HBTs)
L5.6: A Second Look at Compact models

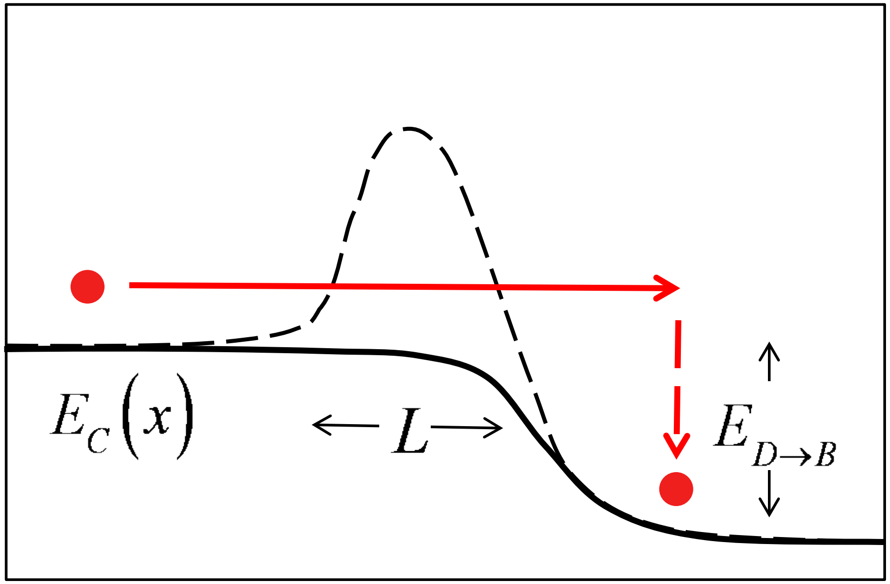
Because we covered so much ground and so many topics, I'll simply mention a few key things that you should take away from Unit 5.

Limits of MOSFETs

Off-state



On-state



Channel length, speed, energy dissipation

Limits

$$E_{\min} = k_B T \ln 2 = 0.017 \text{ eV}$$

$$L_{\min} = \frac{\hbar}{\sqrt{2m^* E_{\min}}} = 1.5 \text{ nm} \qquad \left(m^* = m_0\right)$$

$$\tau_{\min} = \frac{\hbar}{E_{\min}} = 40 \text{ fs}$$

CMOS today

$$\frac{1}{2}C_G V_{DD}^2 \approx 57{,}000 \times E_{\min}$$

$$L = 20\ \text{nm} = 13 \times L_{\min}$$

$$\tau = \frac{C_G V_{DD}}{I_{ON}} \approx 11 \times \tau_{\min}$$

22 nm technology

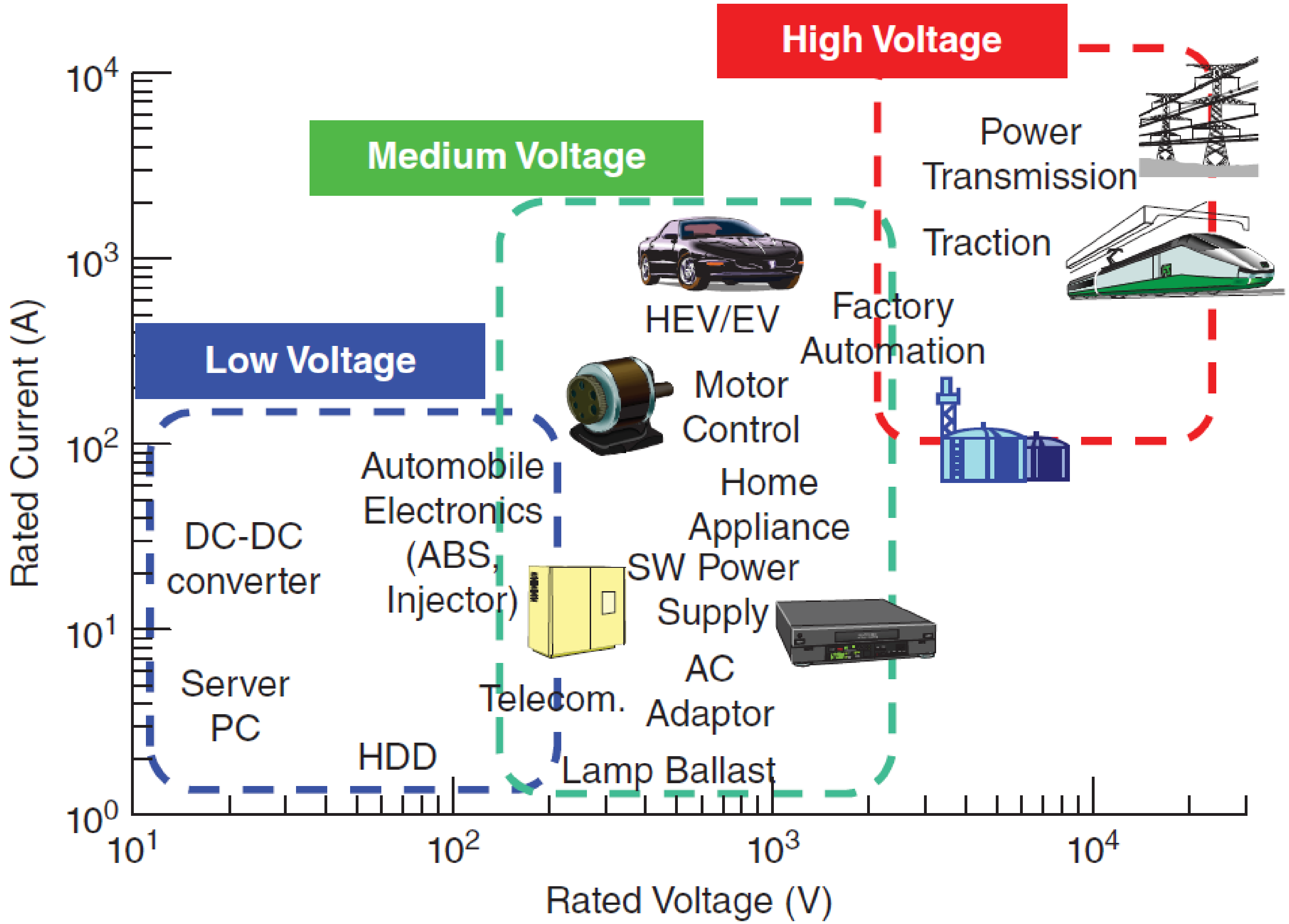
Summary of limits

1) Transistors are approaching some very fundamental limits.

2) Practical, technology considerations such as series resistance, parasitic capacitance, BTBT leakage currents, etc. are likely to set the practical limits.

3) It is unlikely that a digital switching device that is fundamentally better than a MOSFET exists.

Power semiconductor devices



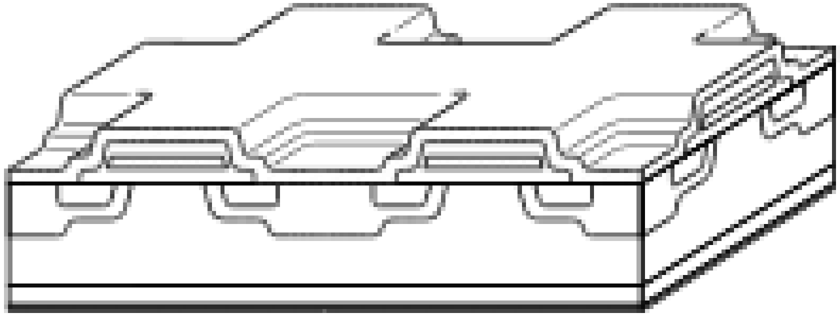
T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology*, Wiley (2014).

Power MOSFET design

High currents require large *W* (MOSFET width)

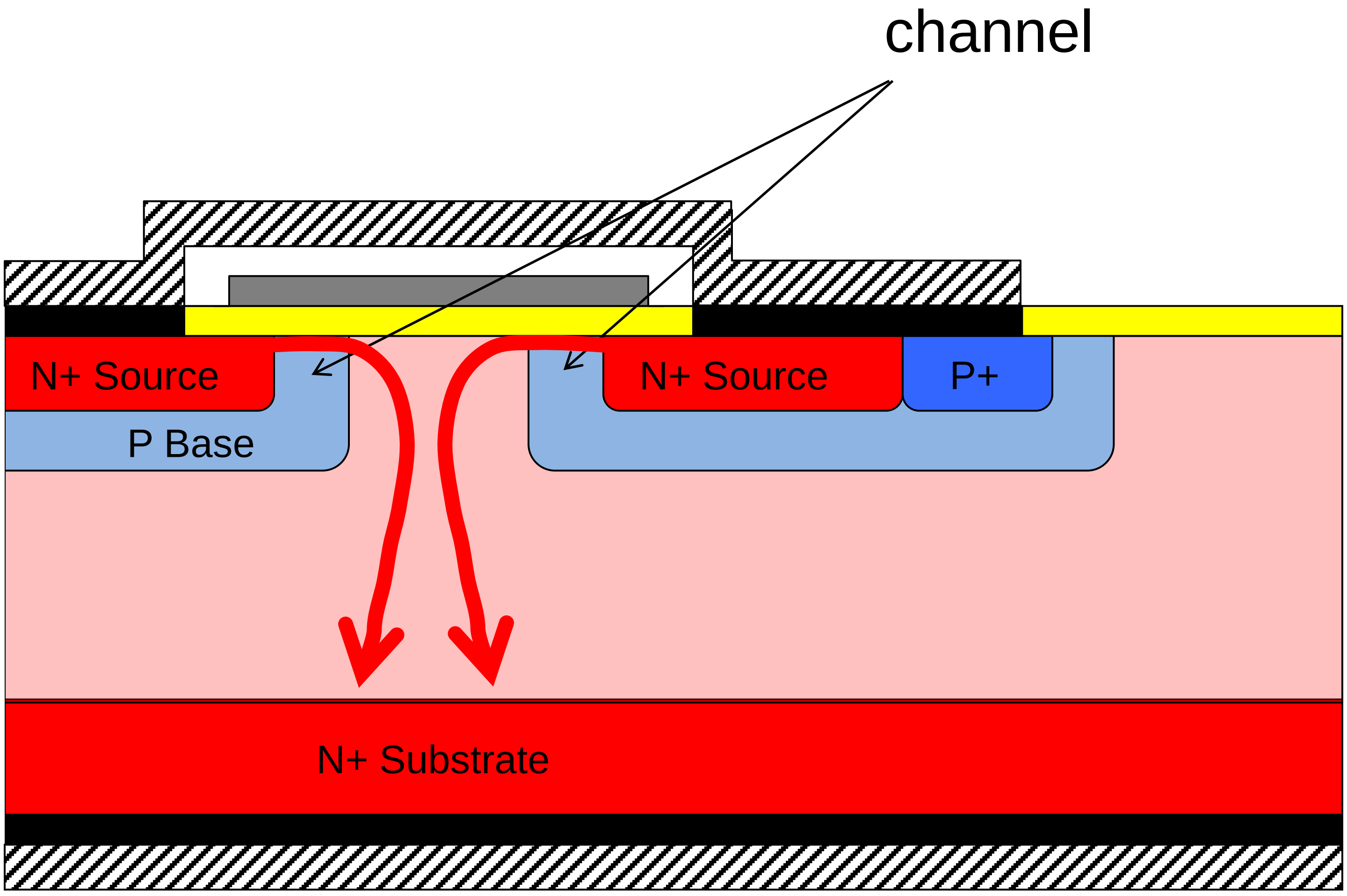
High breakdown voltage requires that we spread he voltage drop out (long channels) to minimize the electric field.

To achieve these goals, power MOSFETs use vertical current flow and cellular structures.

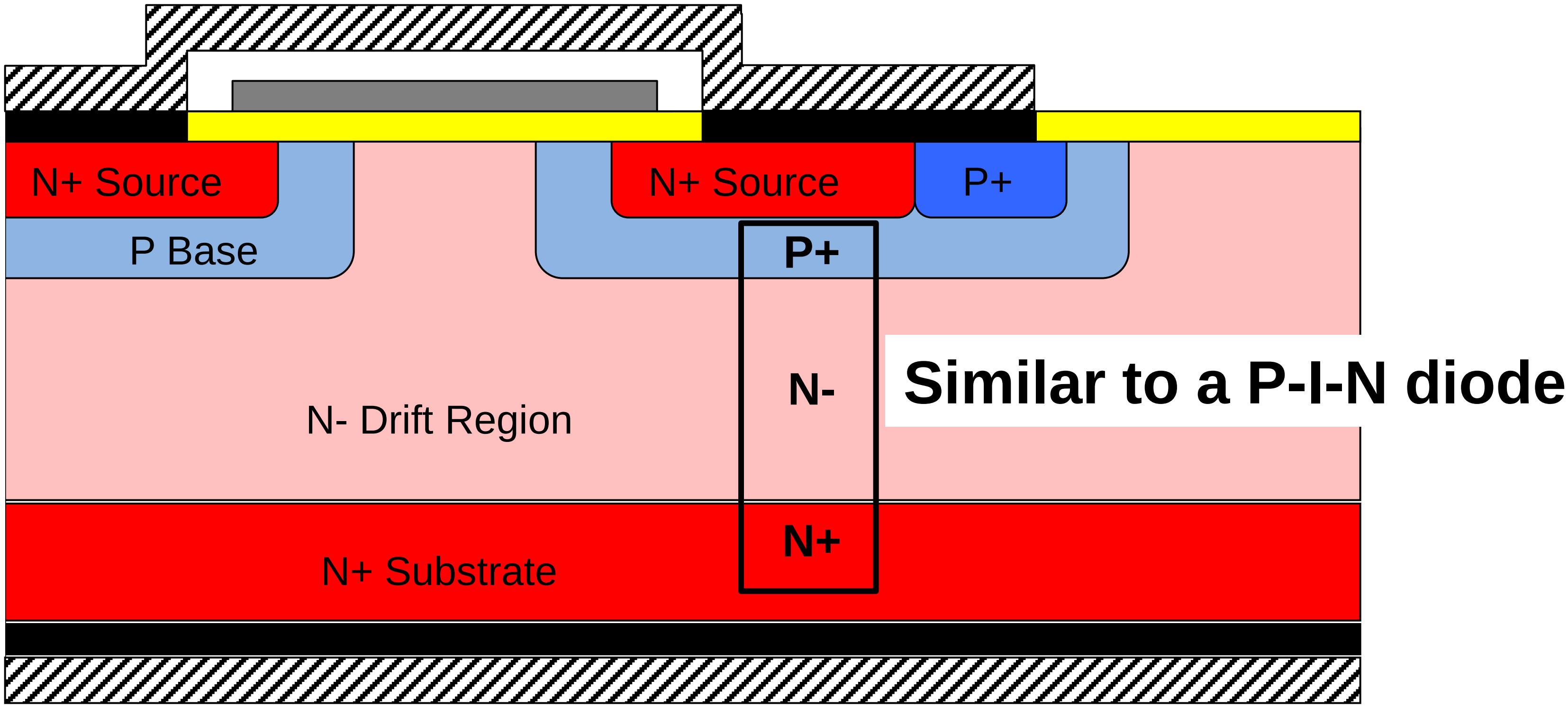


https://en.wikipedia.org/wiki/Power_MOSFET

Diffused MOSFET DMOSFET (ON)

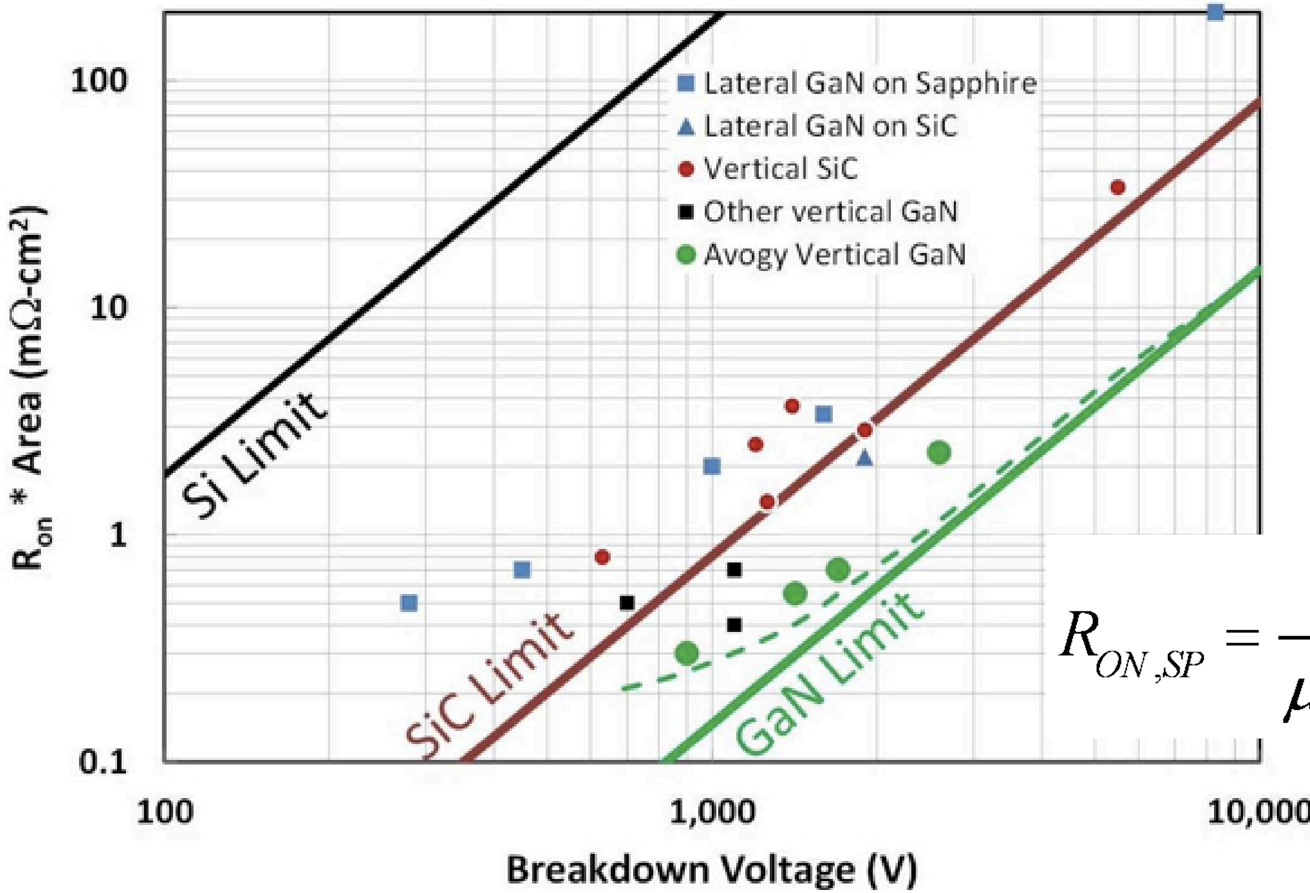


DMOSFET (OFF)



N+ Source
P Base
N+ Source
P+
P+
N-
Similar to a P-I-N diode
N- Drift Region
N+
N+ Substrate

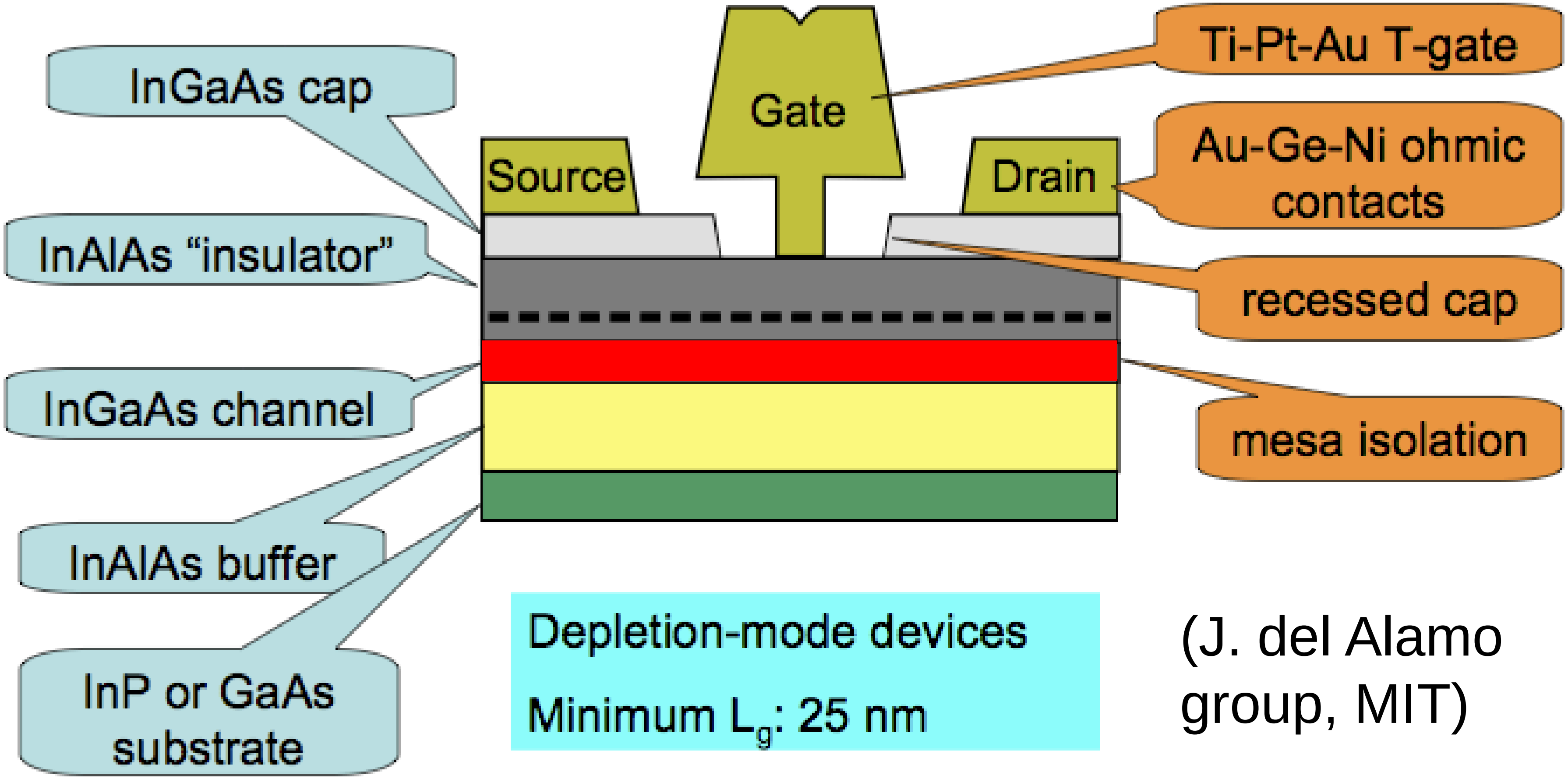
On resistance vs. blocking voltage



$$R_{ON,SP} = \frac{4V_B^2}{\mu_n \varepsilon_S E_C^3}$$

Lundstrom: 2018

InGaAs HEMT

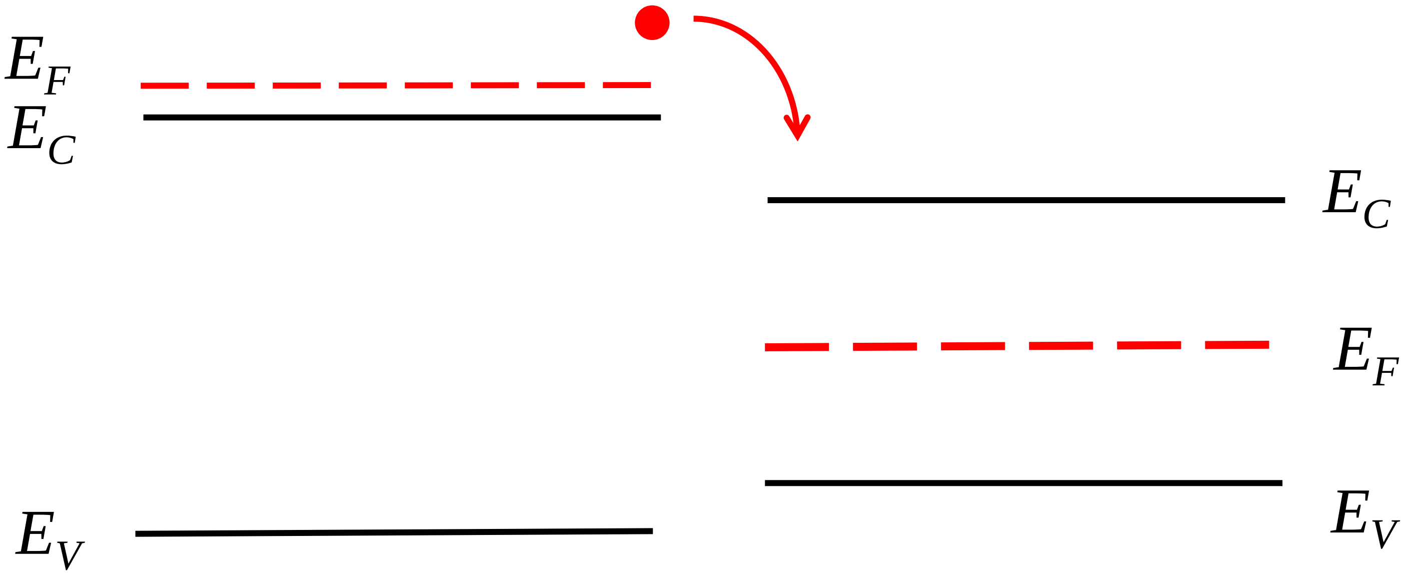


Depletion-mode devices

Minimum L_g: 25 nm

(J. del Alamo group, MIT)

“Modulation doping”

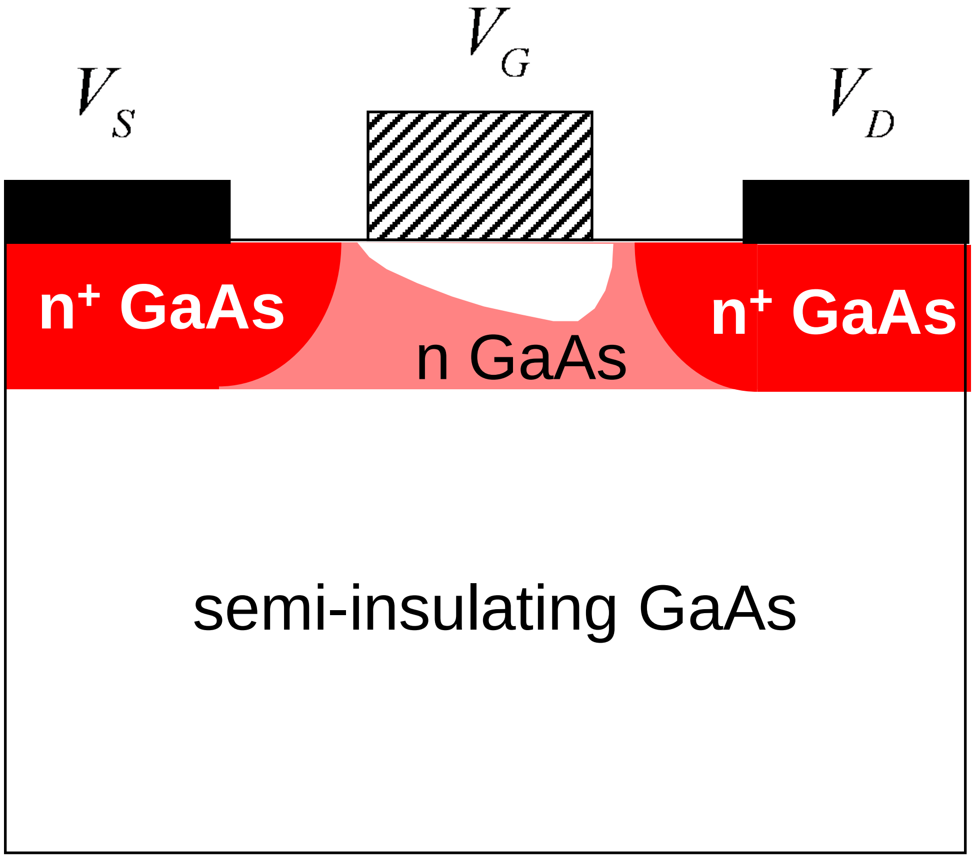


wide bandgap
doped n^+

small bandgap
nominally undoped

R. Dingle, et al., *Appl. Phys. Lett.*, **33**, 665, 1978.

GaAs MESFET



- high mobility
  $\mu_n(10^{14}) \sim 8500\ \mathrm{cm^2/V\text{-}s}$
- mobility and doping
  $\mu_n\,(10^{17}) \sim 4700\ \mathrm{cm^2/V\text{-}s}$
  $\mu_n\,(10^{18}) \sim 2800\ \mathrm{cm^2/V\text{-}s}$
- for high g_m, need both charge **and** velocity
- SB gate limits V_G

HEMT summary

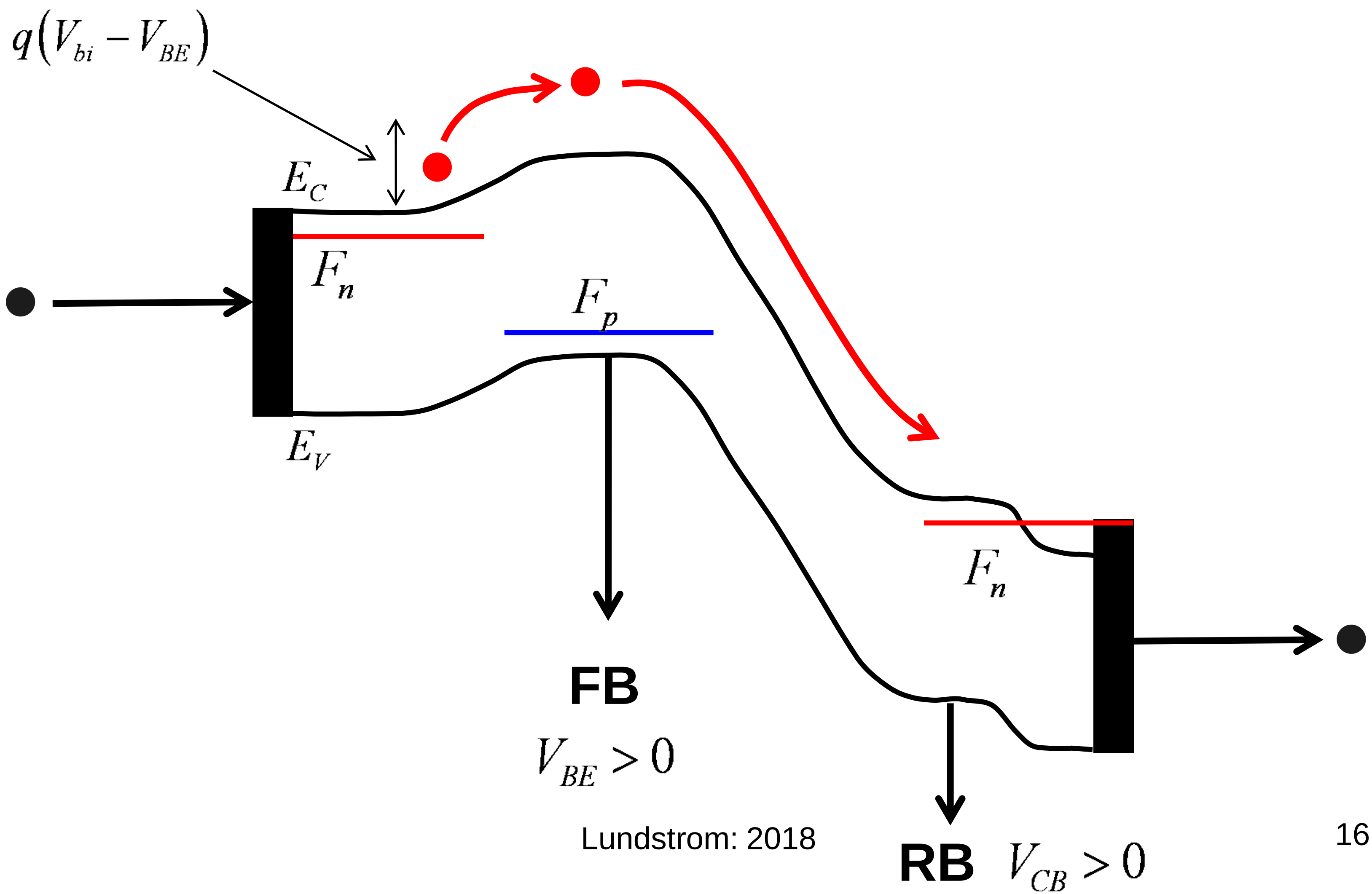
1) III-V FETs are an important technology for high-frequency RF applications.

2) Both HEMTs and HBTs have achieved THz speeds.

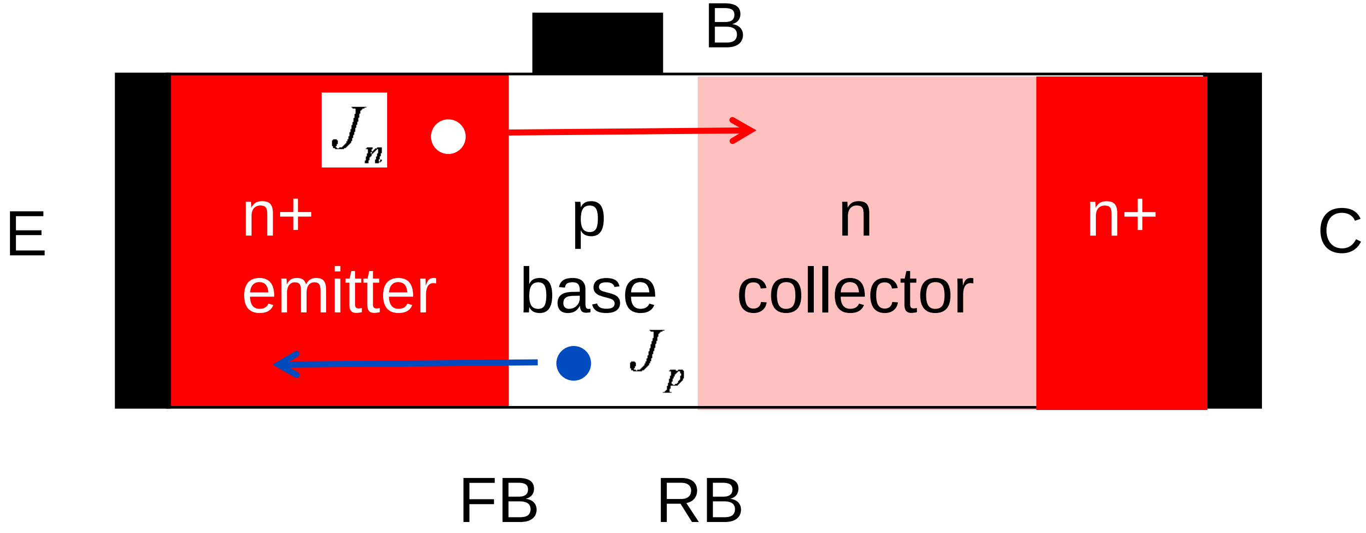
3) HEMTs operate in exactly the same “barrier controlled mode” as Si MOSFETs, so the VS model describes them well.

4) III-V HEMTs operate near the ballistic limit.

BJTs are barrier controlled transistors



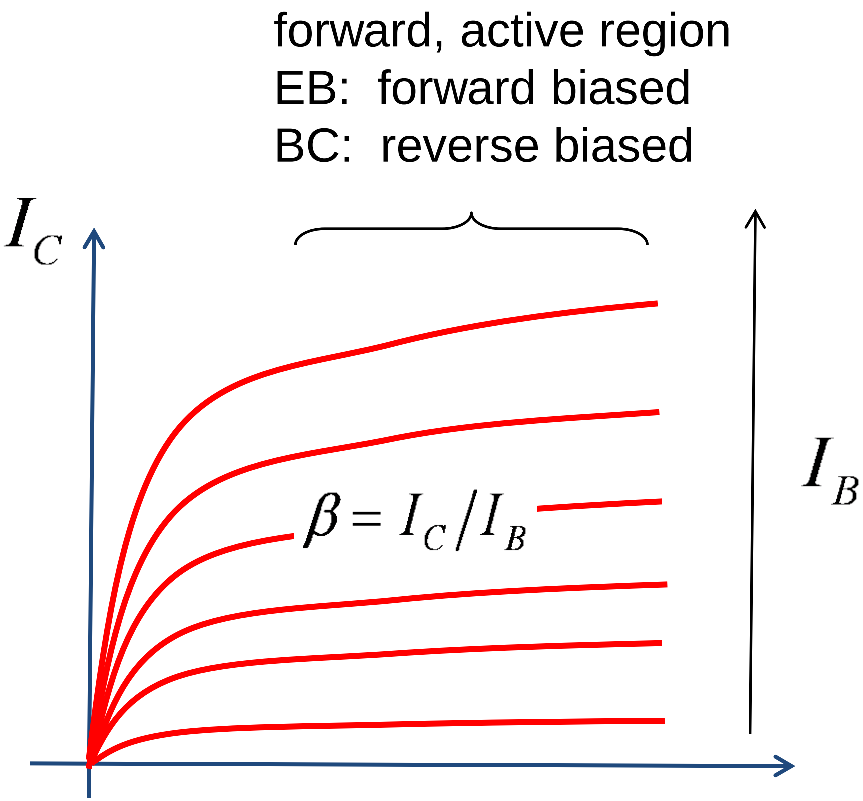
Common emitter current gain



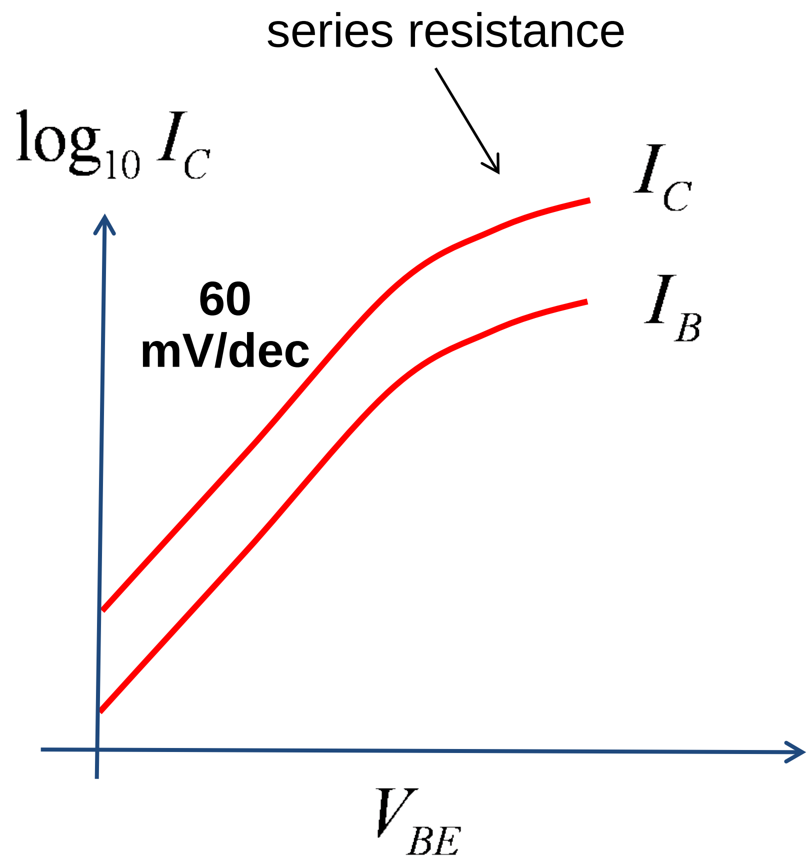
$$\beta = \frac{I_C}{I_B} = \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2}$$

(In the forward active region of operation)

IV characteristics



output characteristic



transfer characteristic

MOSFET vs. BJT (transconductance)

MOSFET

$$g_m = \frac{I_D}{\left(V_{GS} - V_{th}\right)}$$

$$I_D = 1\ \text{mA}$$

$$V_{GS} = 1.0\ \text{V} \qquad V_{th} = 0.2\ \text{V}$$

$$g_m = 2.5\ \text{mS}$$

BJT

$$g_m = \frac{I_C}{V_T}$$

$$I_C = 1\ \text{mA}$$

$$V_T = 0.026\ \text{V}$$

$$g_m = 40\ \frac{\text{mA}}{\text{V}} = 40\ \text{mS}$$

MOSFET vs. BJT (high frequency)

BJTs are superior RF/analog devices. A typical BJT has more than 10X the transconductance of a typical MOSFET.

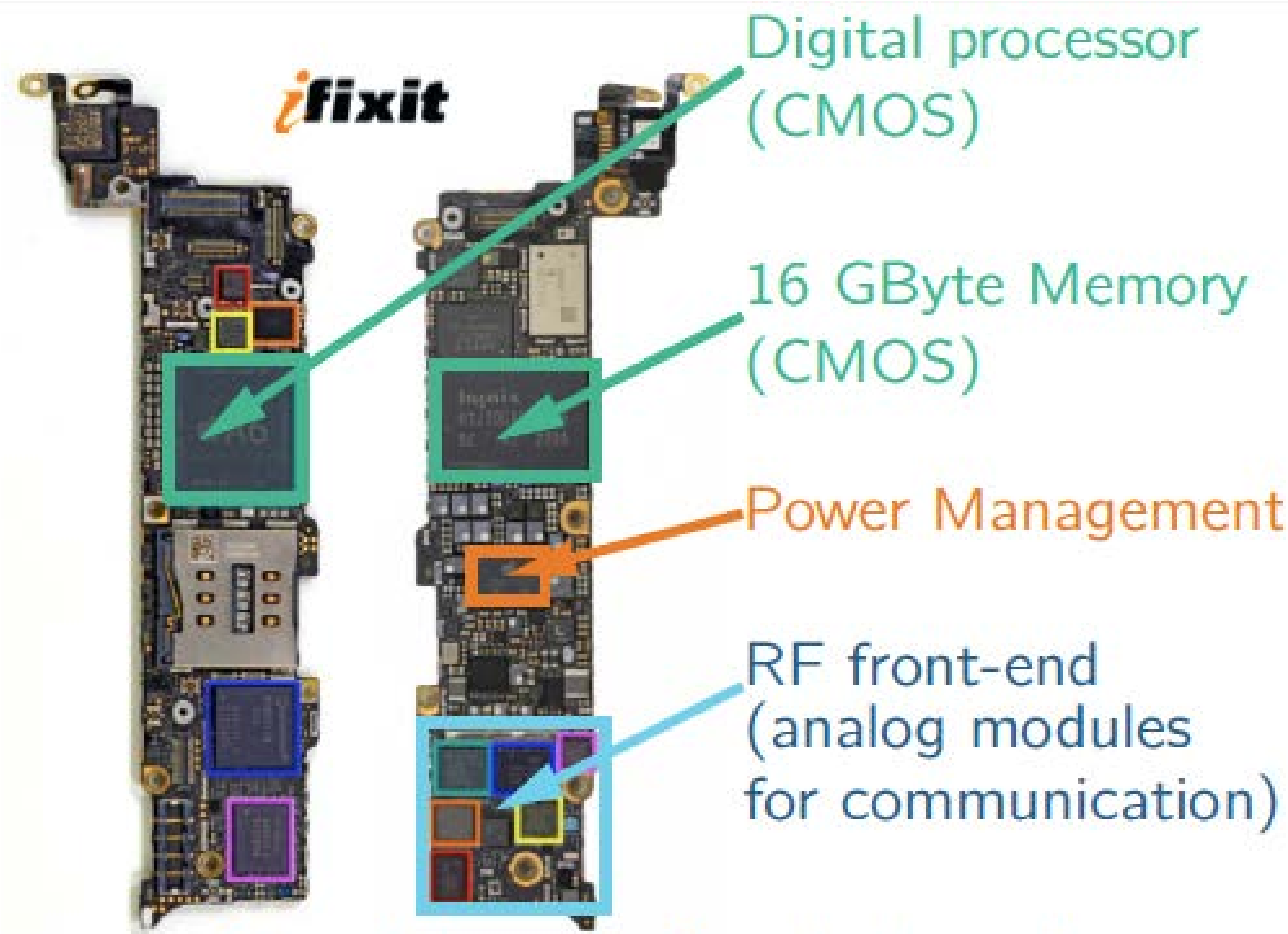
Both devices can achieve high f_T.

$$f_T = \frac{g_m}{2\pi C_{tot}}$$

BJTs offer higher drive currents (higher g_m)

→ Well-suited for RF power amplifiers

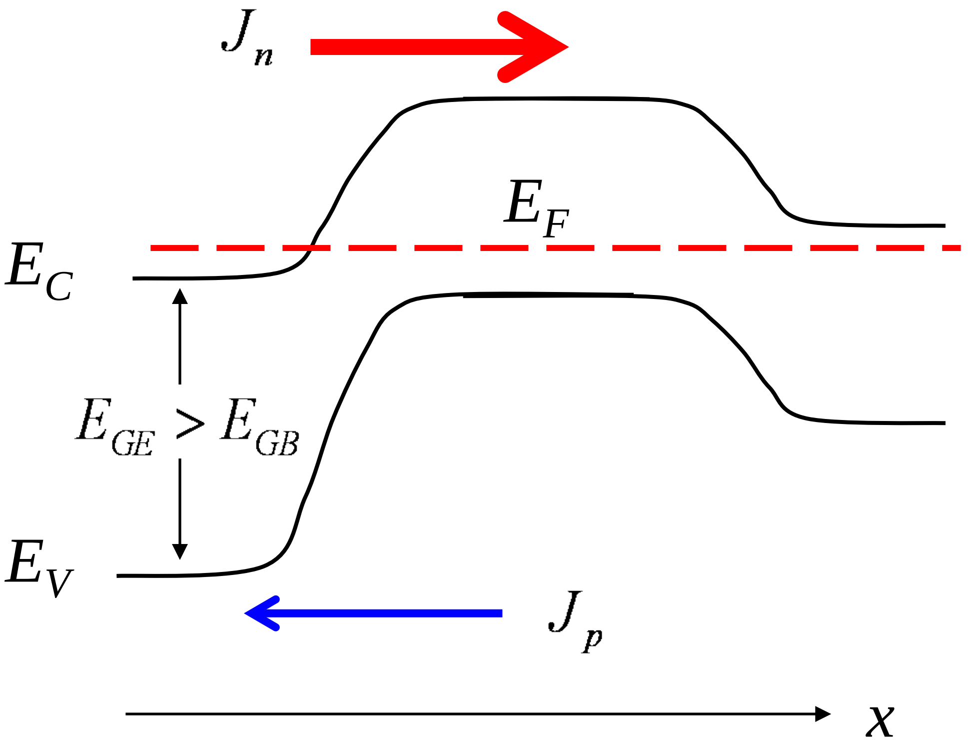
SiGe HBTs



Circuit board of an Iphone 5

Martin Claus
TU-Dresden

HBTs



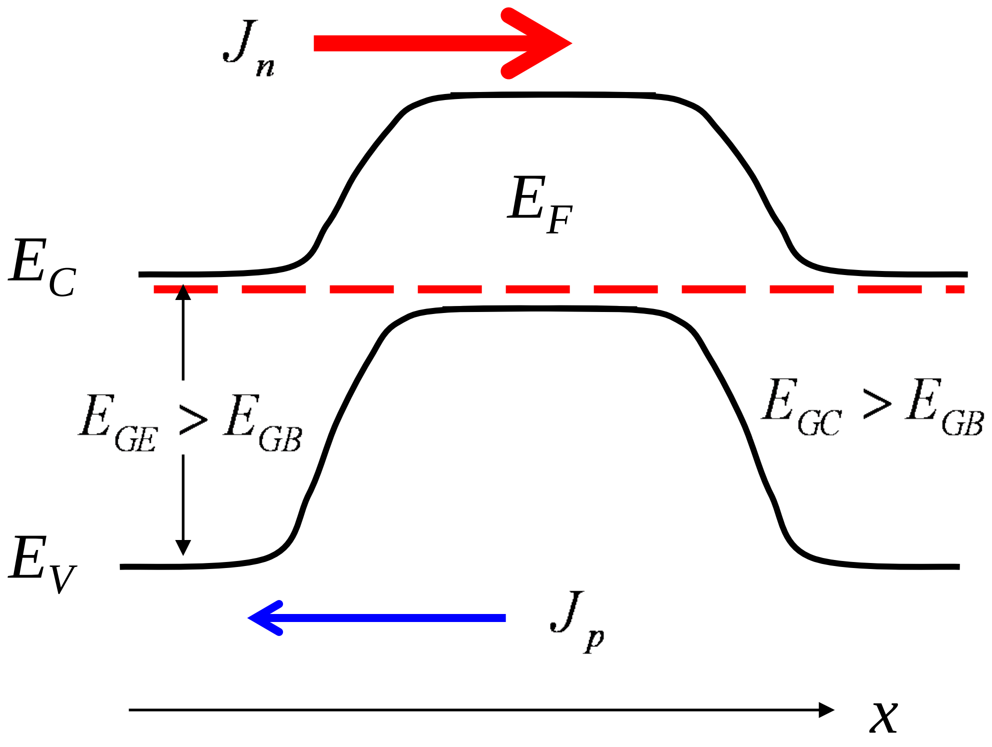
wide bandgap emitter

$$\beta = \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} \frac{n_{iB}^2}{n_{iE}^2}$$

$$n_i^2 = N_C N_V e^{-E_G/k_B T}$$

$$\beta \approx \frac{N_{DE}}{N_{AB}} \frac{D_n}{D_p} \frac{W_E}{W_B} e^{\Delta E_G/k_B T}$$

DHBTs



- symmetrical operation
- reduced collector offset voltage
- higher collector breakdown voltage

HBT summary

1) III-V HBTs are an important technology for high-frequency RF power applications.

2) SiGe HBTs are a critical technology for wireless electronics

3) HBTs offer speeds close to that of HEMTs (f_T = 600 GHz, f_{max} = 1200 GHz).

4) Compared to HEMTs, HBTs deliver higher power and integration density.

5) HBTs operate in the same "barrier controlled mode" as Si MOSFETs.

Compact circuit models

1) Compact circuit models link semiconductor manufacturing and circuit design.

2) Compact circuit models also link device and materials R&D to circuit design and applications.

3) Developing compact circuit models requires a good understanding of the device physics, what goes on inside the circuit simulator, and the intended application.

4) Many of the lessons learned in developing compact circuit models for MOSFETs can be transferred to other devices.

Course Summary

Unit 1: Transistors, compact models, and circuits

Unit 2: Essential physics of the MOSFET

Unit 3: MOS Electrostatics

Unit 4: Transmission theory of the MOSFET

Unit 5: Additional topics