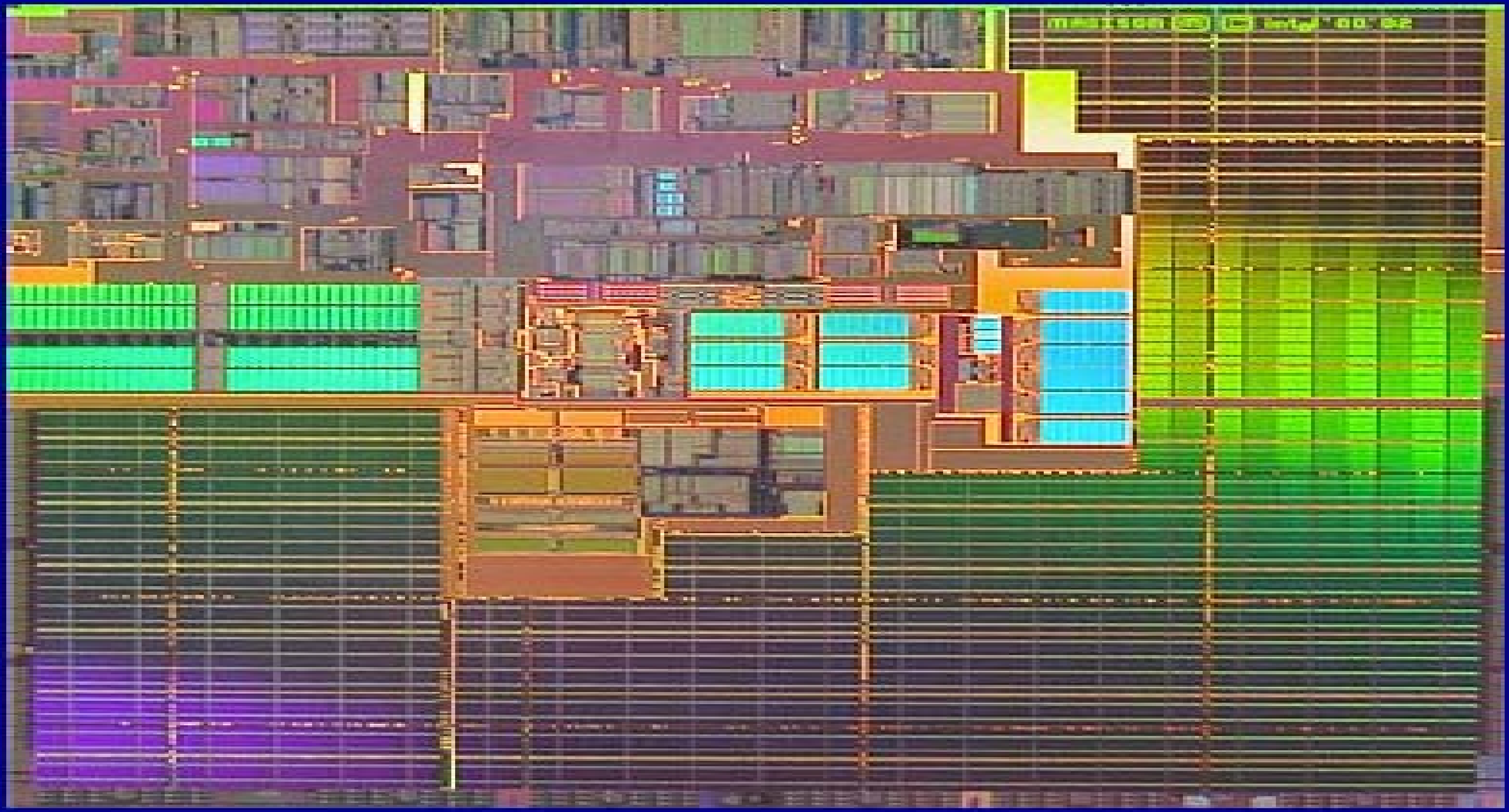
Review

Is a student a vessel to be filled or a torch to be lit?

Itanium Microprocessor 0.13 mm 415 million transistors 1.5 GHz



Even old technology has overwhelming complexity and tremendous performance

We better

learn fundamentals and

to solve problems

in order to work as engineers with advanced degrees in such competitive environment

So what did we cover?

Materials systems discussed

Si

SiGe

III-V

Ternary and quaternary

SiC

III-N

Devices Covered: Building blocks

- Metal-semiconductor contacts
  - Schottky contact
  - Ohmic contact
- p-n junction
- MOS structure
- Heterointerface
- Quantum well
- Superlattice
- Quantum wire Quantum dot Quantum electronic island

Devices Covered: Transistors

BJTs

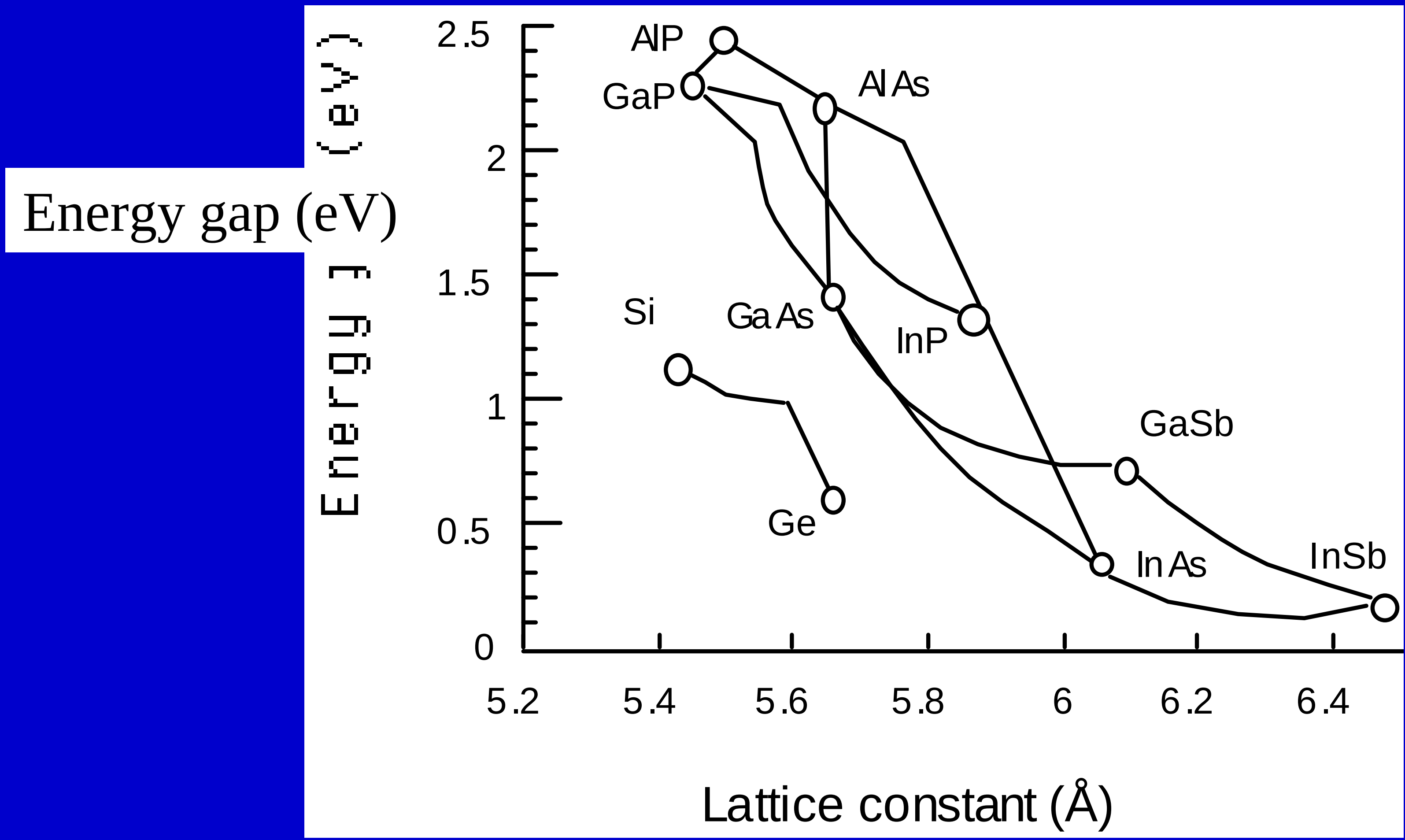
HBTs

MESFETs

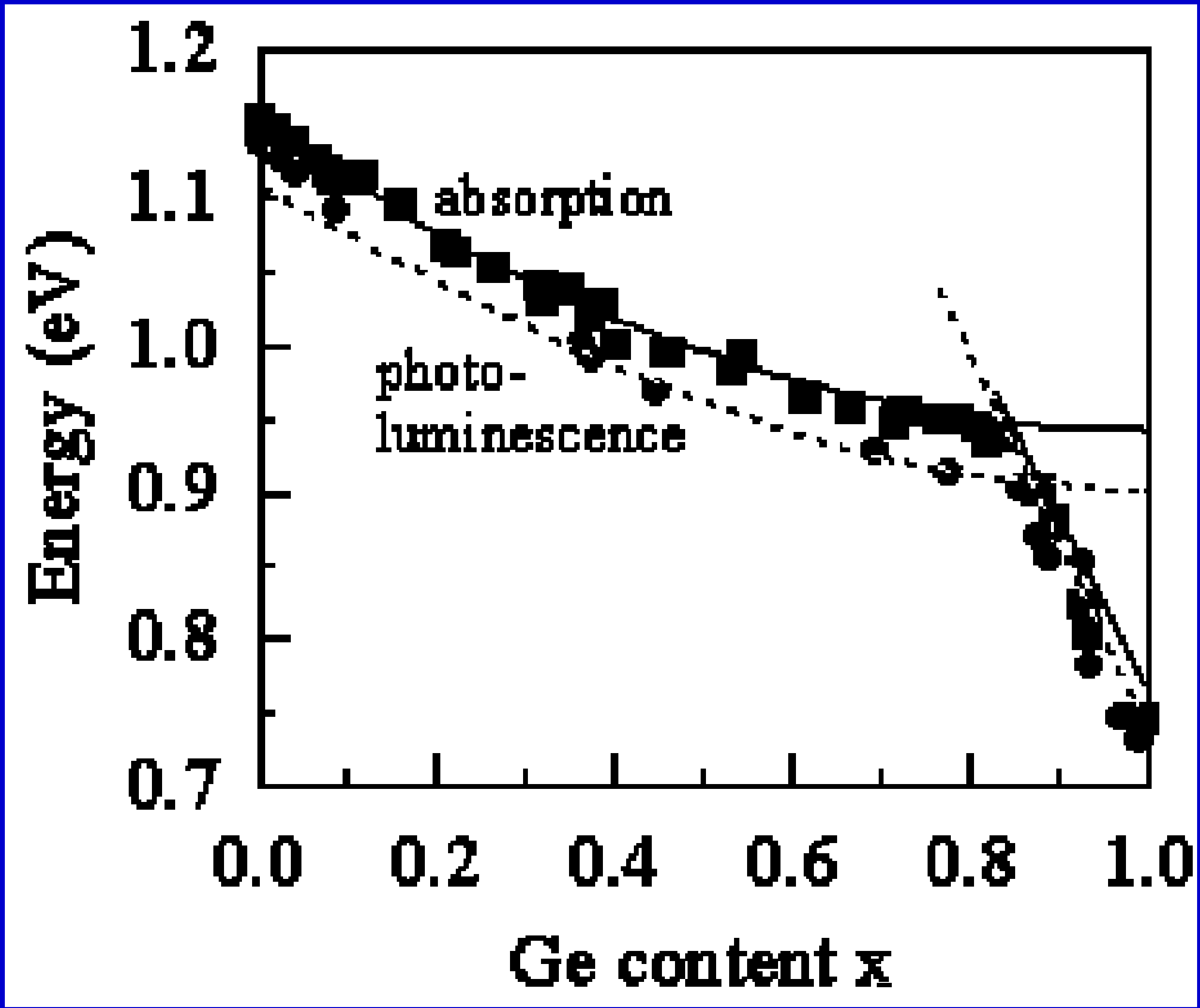
HFETs

Pyroelectric devices

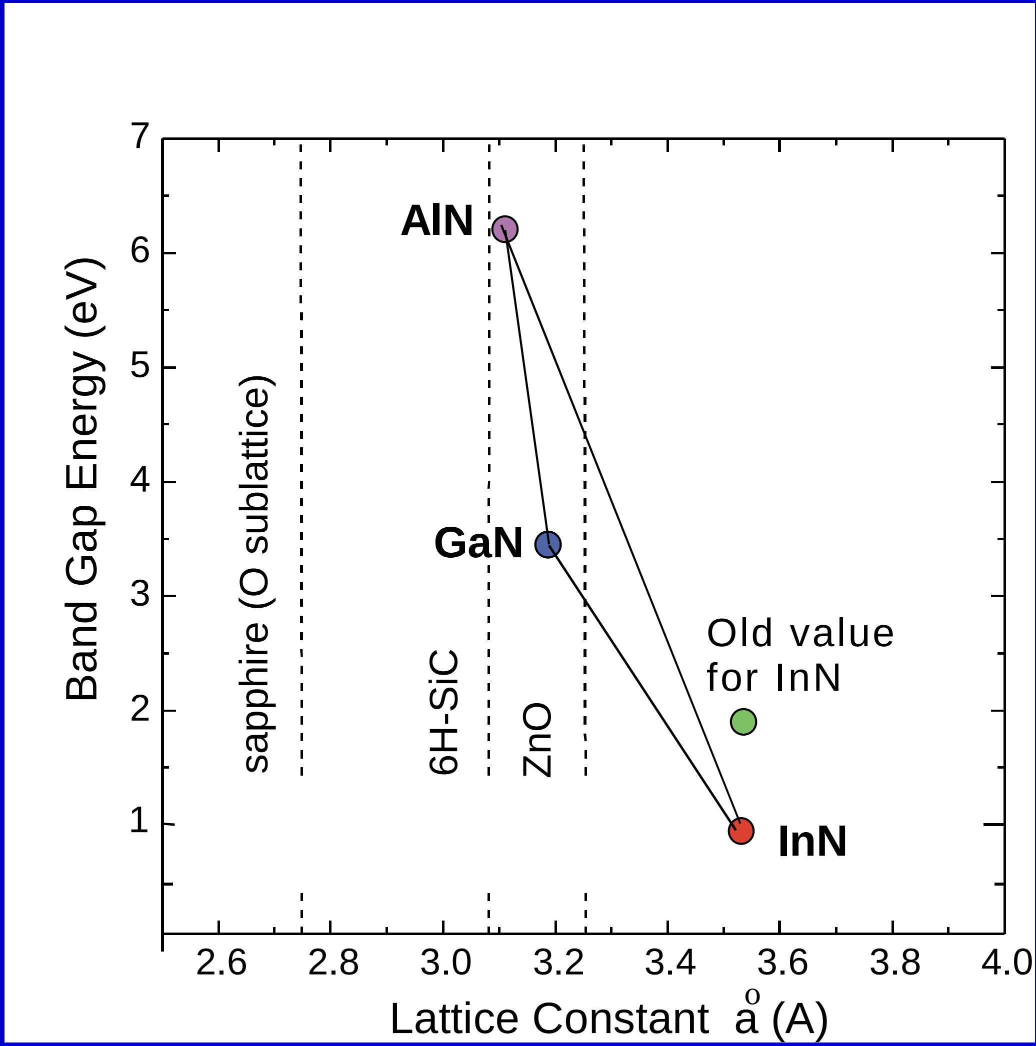
SiGe and III-V Materials Systems



Energy Gap versus Ge content



AlInGaN Materials System

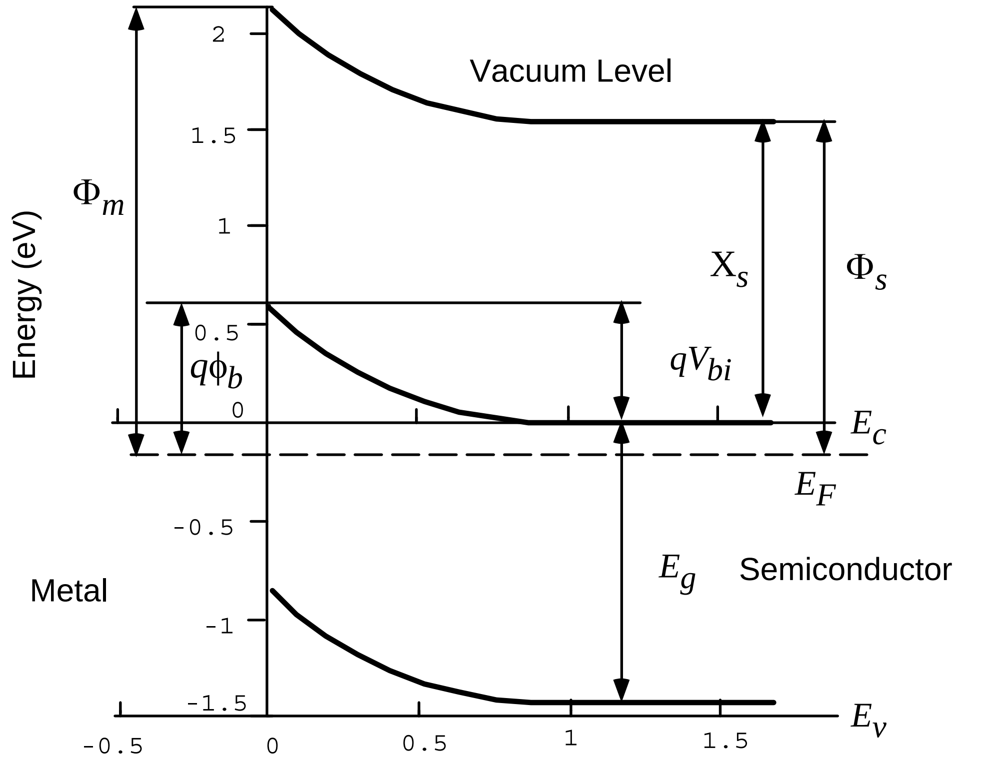


More detailed information

M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur, Editors, “Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, and SiGe,” John Wiley and Sons, December, 2,000

Also please visit http://nina.ecse.rpi.edu/shur/GaN.html

Schottky contact Energy Band Diagram



Energy diagram of GaAs metal-semiconductor barrier.

$q\phi_b$ is the barrier height (0.75 eV)

X_s is the electron affinity in the semiconductor

Φ_s and Φ_m are the semiconductor and the metal work functions

V_{bi} (0.591 V) is the built-in voltage.

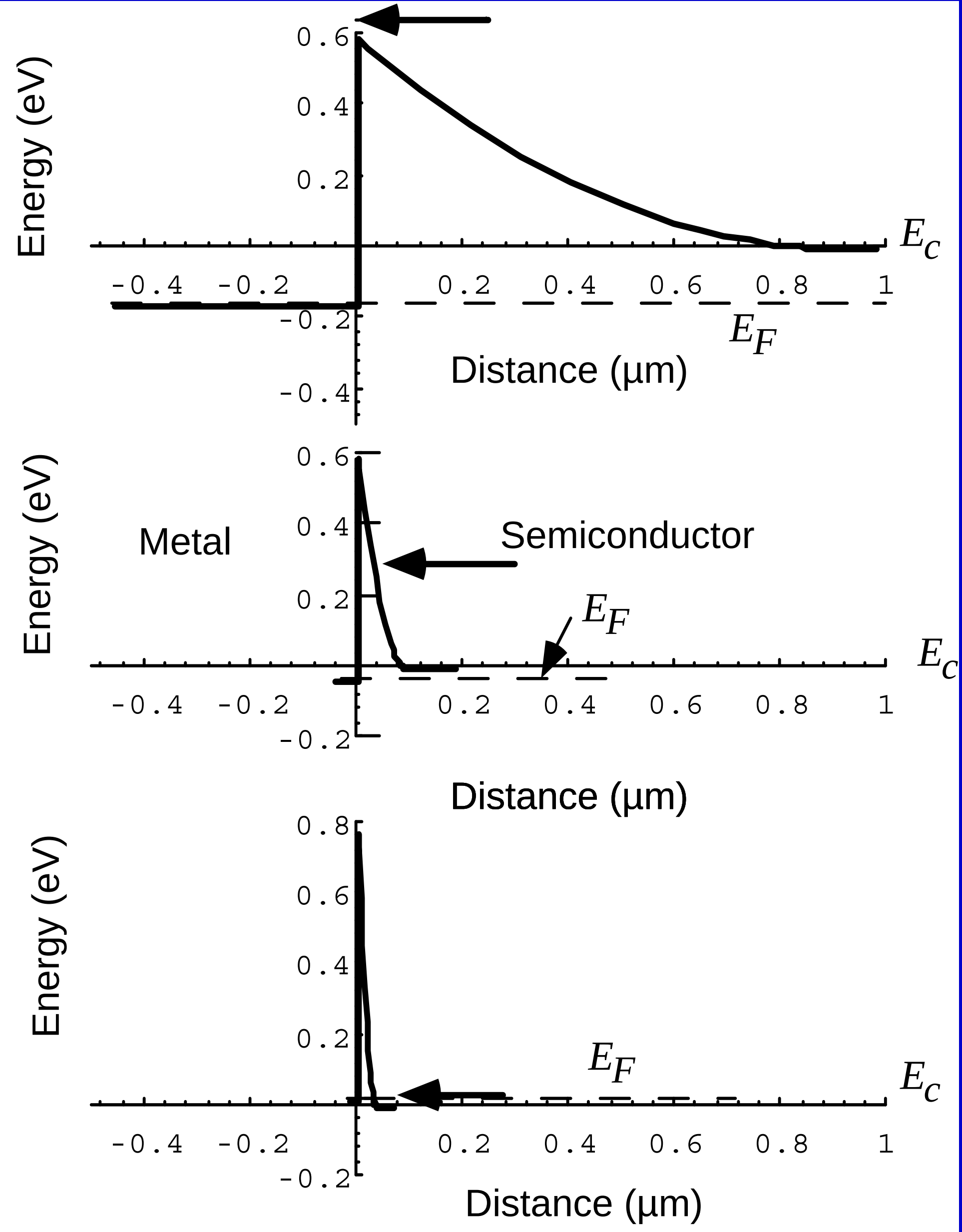
Donor concentration in GaAs is 10^{15} cm^{-3}.

(From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Thermionic, Thermionic Field, and Field Emission

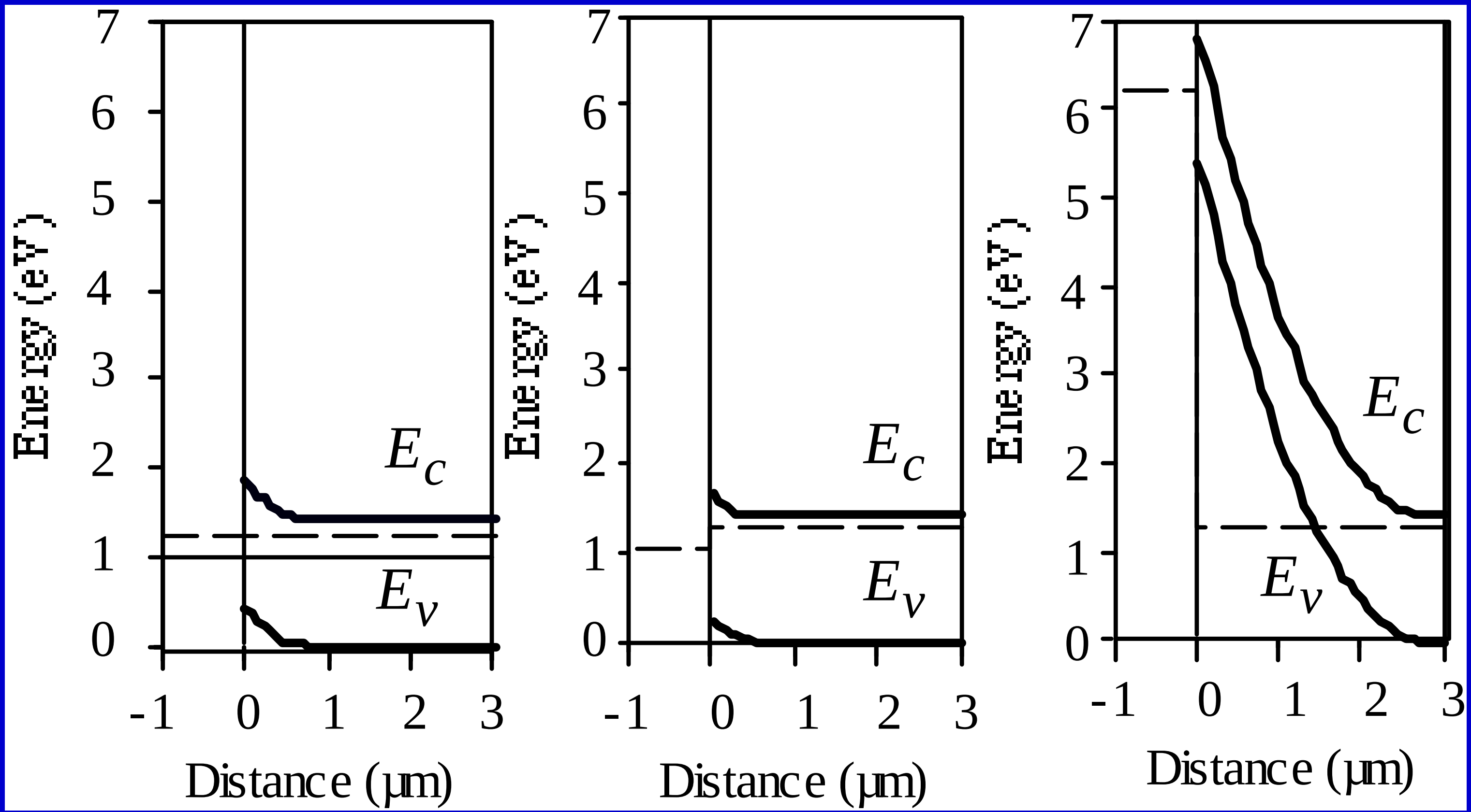
Thermionic emission

$$j_{ss} = A^* T^2 \exp\left(-\frac{\phi_b}{k_B T}\right)$$

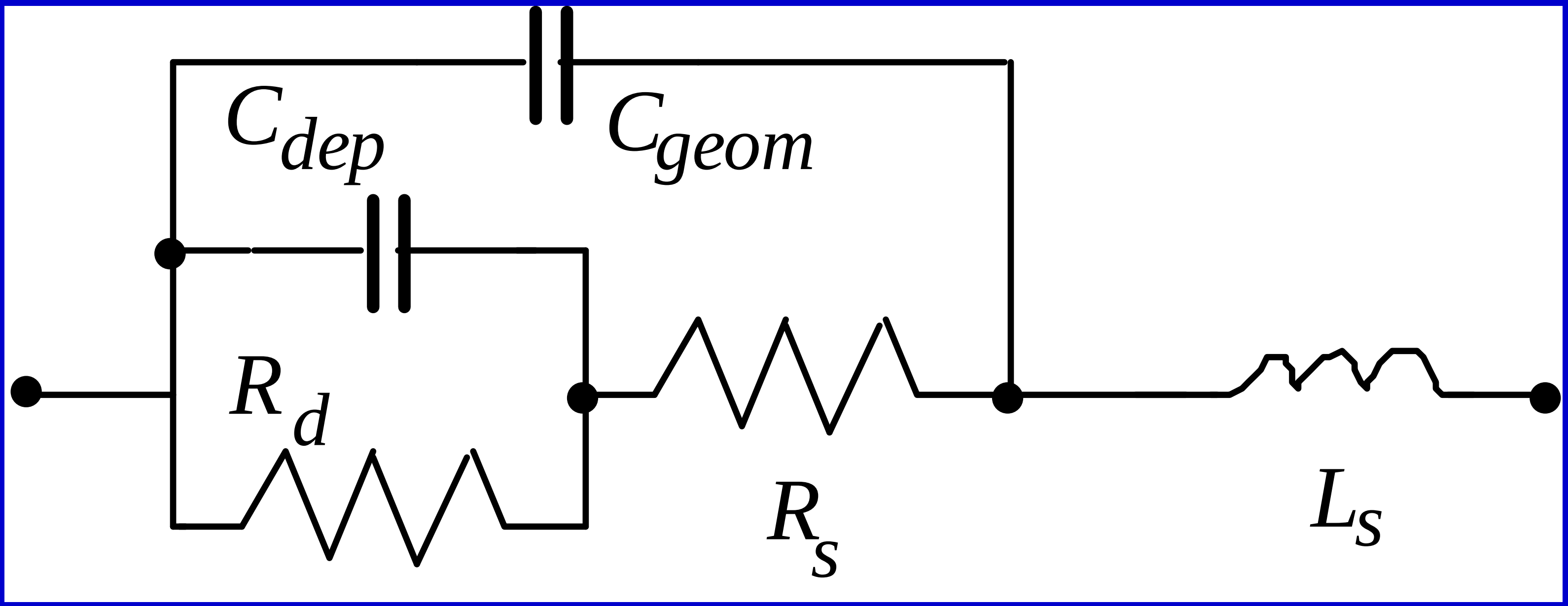


Example:

Estimate the doping density in the GaAs layer from the data in the figure. The dielectric permittivity $\varepsilon = 1.14\times10^{-10}$ F/m. The electronic charge $q = 1.602\times10^{-19}$ C.



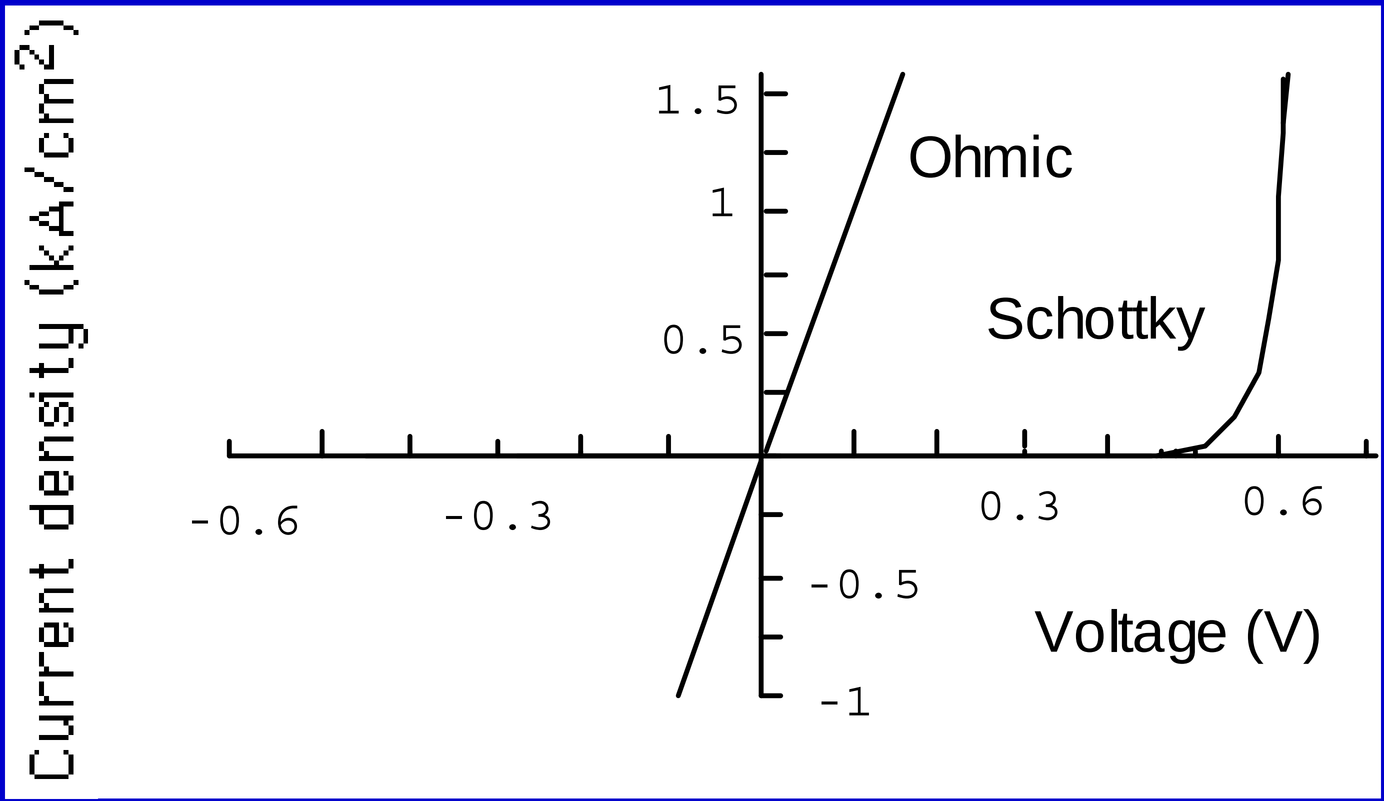
Equivalent Circuit



From M. Shur, Introduction to Electronic Devices, Wiley, 1996

Ohmic Contacts

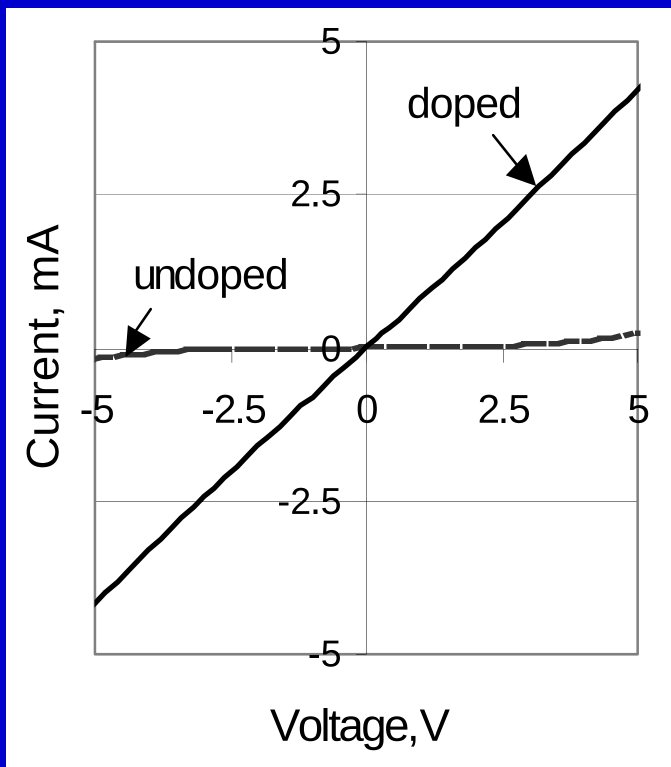
$R_c = 10^{-4}$ ohm cm^2

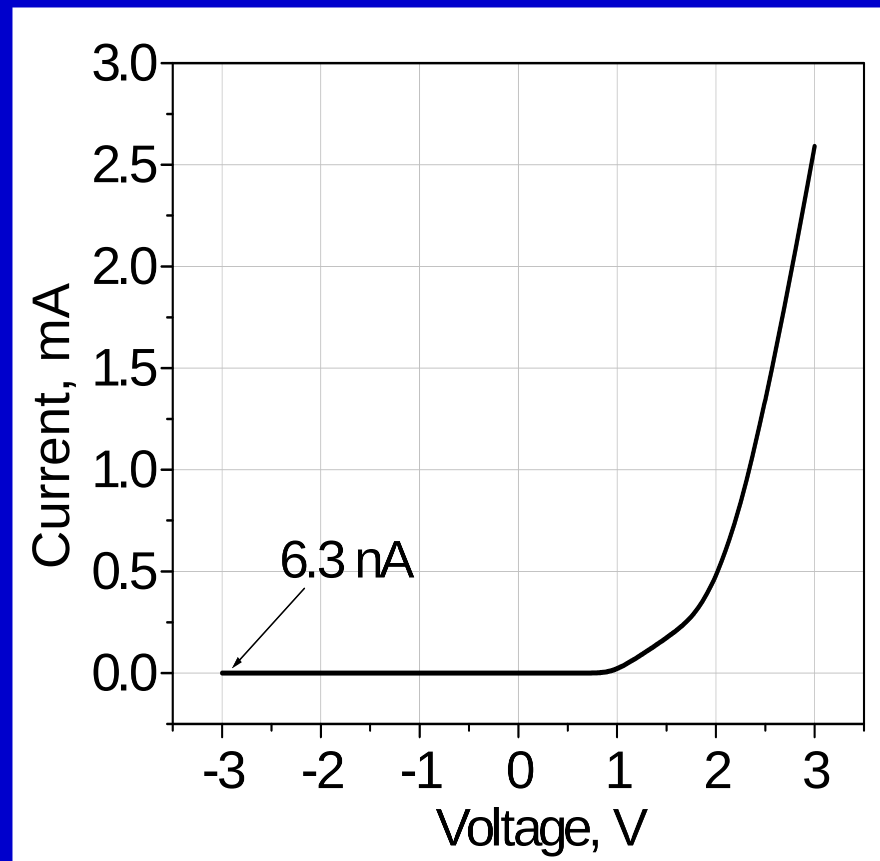


Best $R_c = 10^{-8}$ ohm cm^2

I-Vs of ohmic contacts to n-doped AlGaN (a) and of the AlGaN photodiode (b).

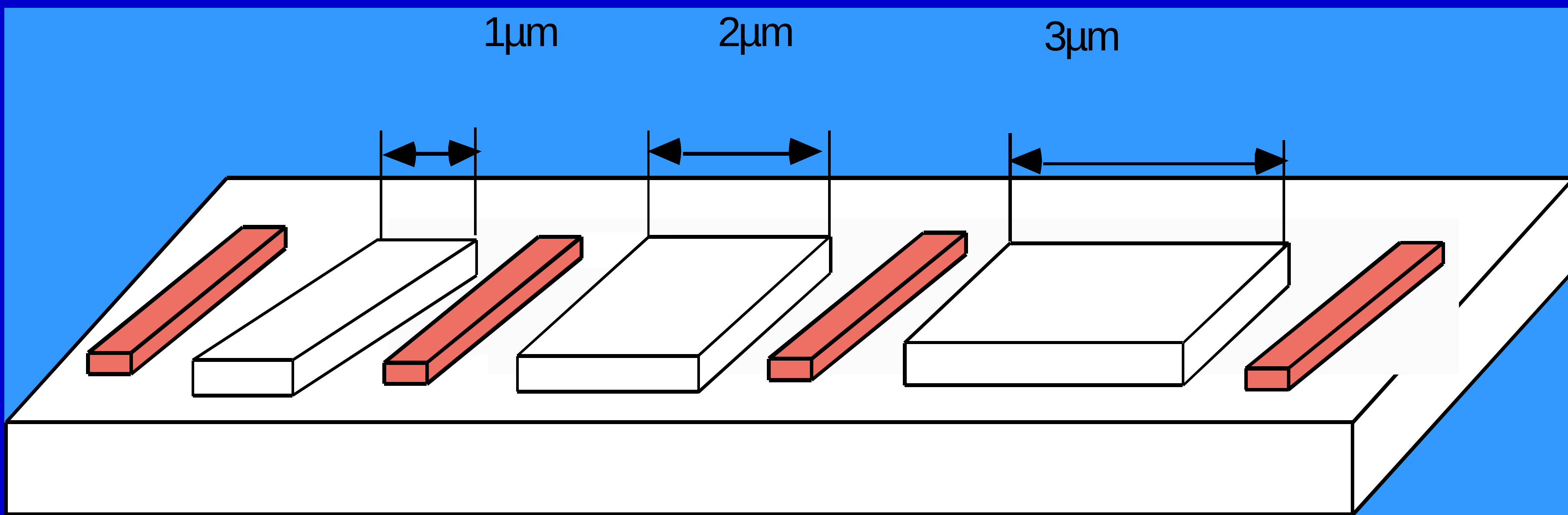
Dashed line in the left figure shows the I-V curve for undoped AlGaN layer.





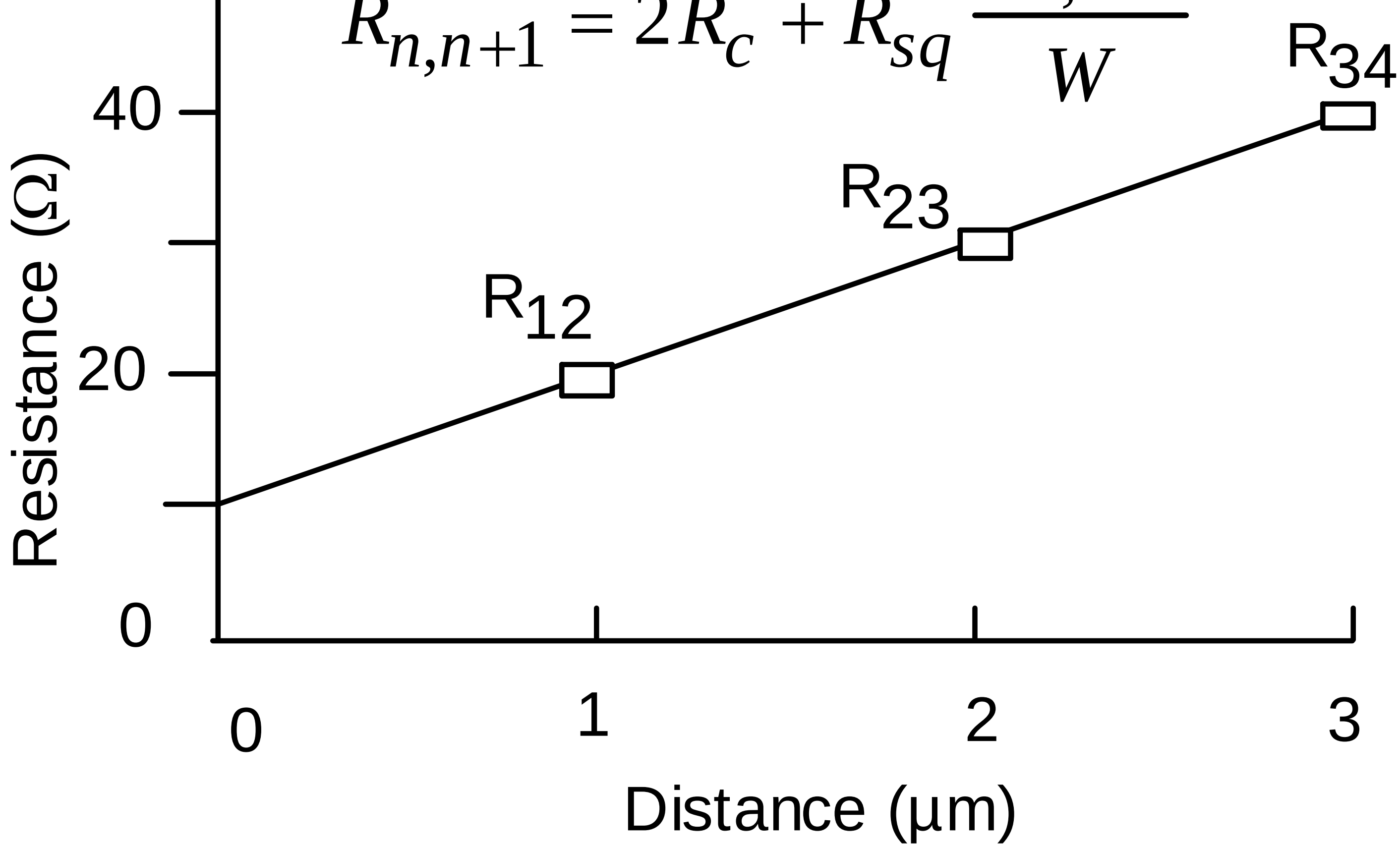
From V. Adivarahan, G. Simin, J. W Yang, A. Lunev and M. Asif Khan, N. Pala, M. Shur, and R. Gaska, SiO2 passivated lateral-geometry GaN transparent Schottky barrier detectors, Appl. Phys. Lett., Vol. 77, No 6, pp. 863-865, August (2000)

Gated Transmission Line Model



Resistance versus distance

$$R_{n,n+1} = 2R_c + R_{sq}\frac{L_{n,n+1}}{W}$$



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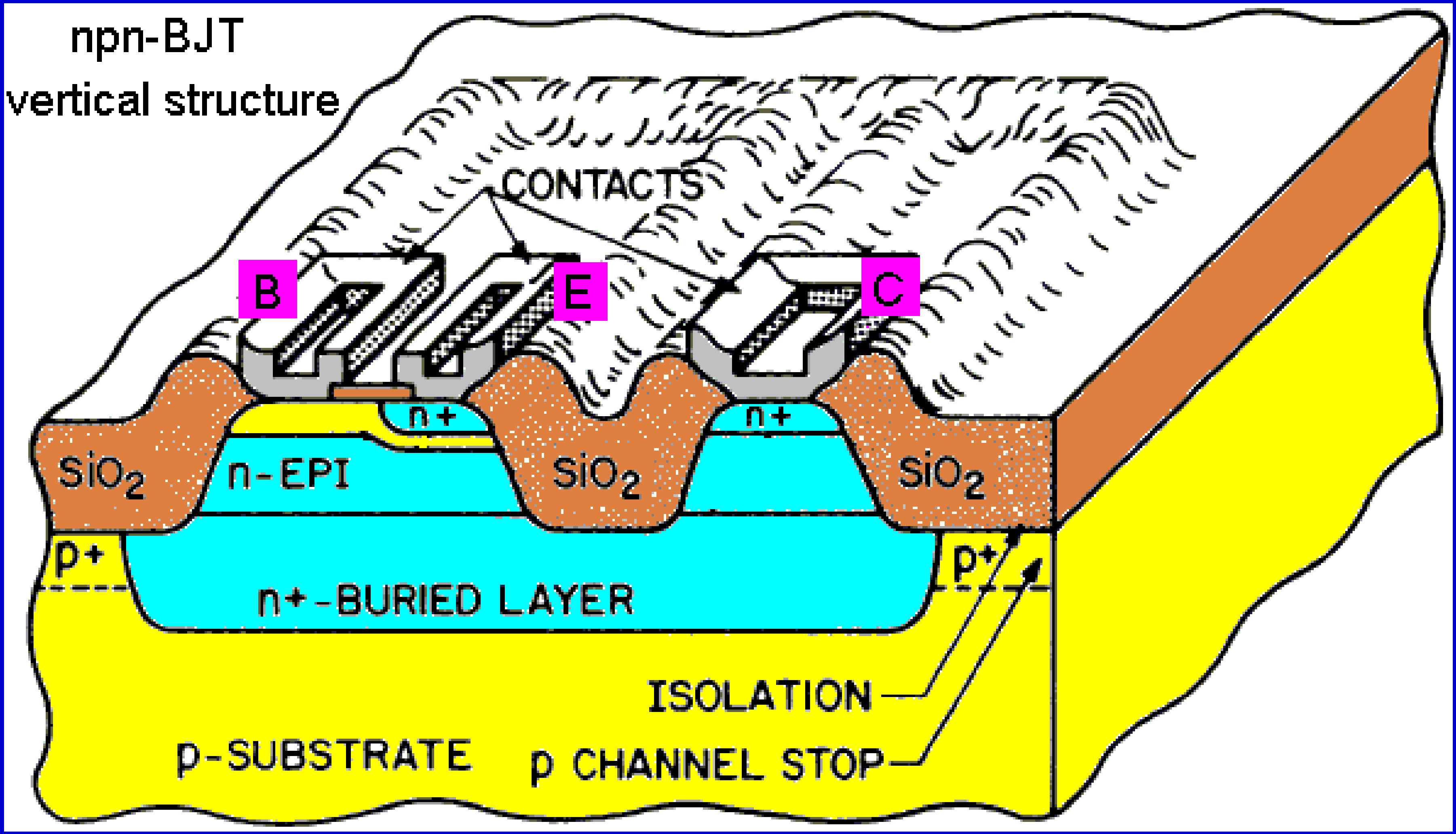
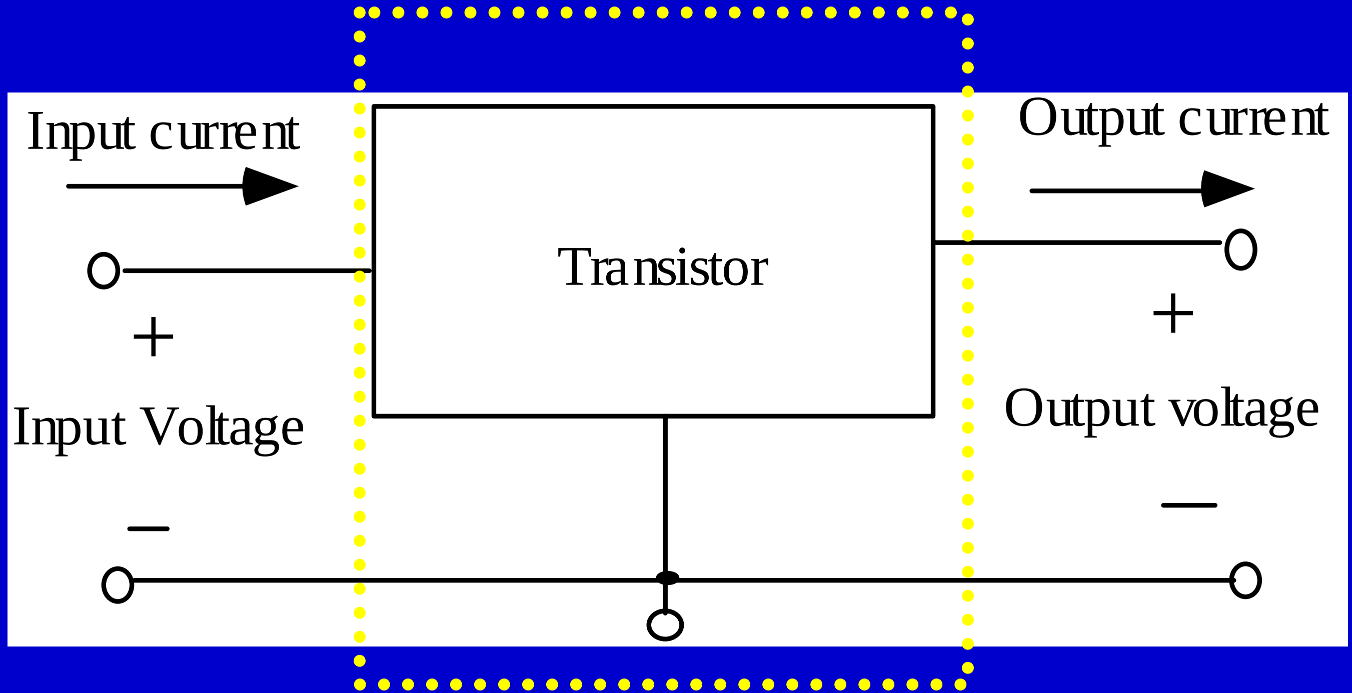
BJT structure

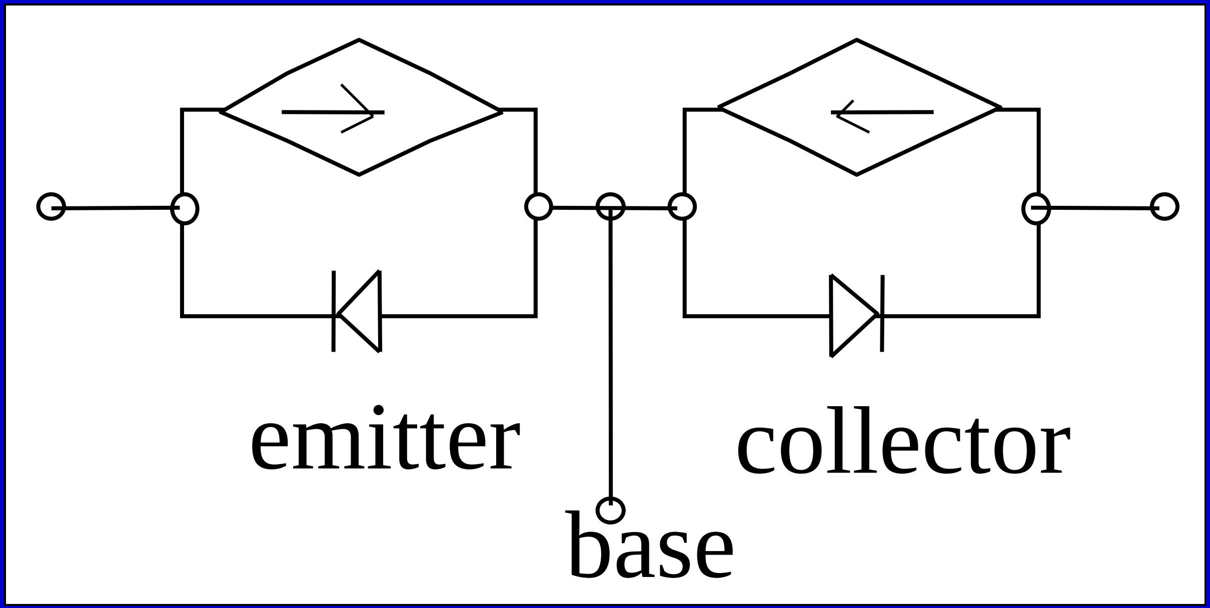


From http://www.hl.pc.uec.ac.jp/~hays/electronics/lecture/chapter5.htm

Input and Output Loops

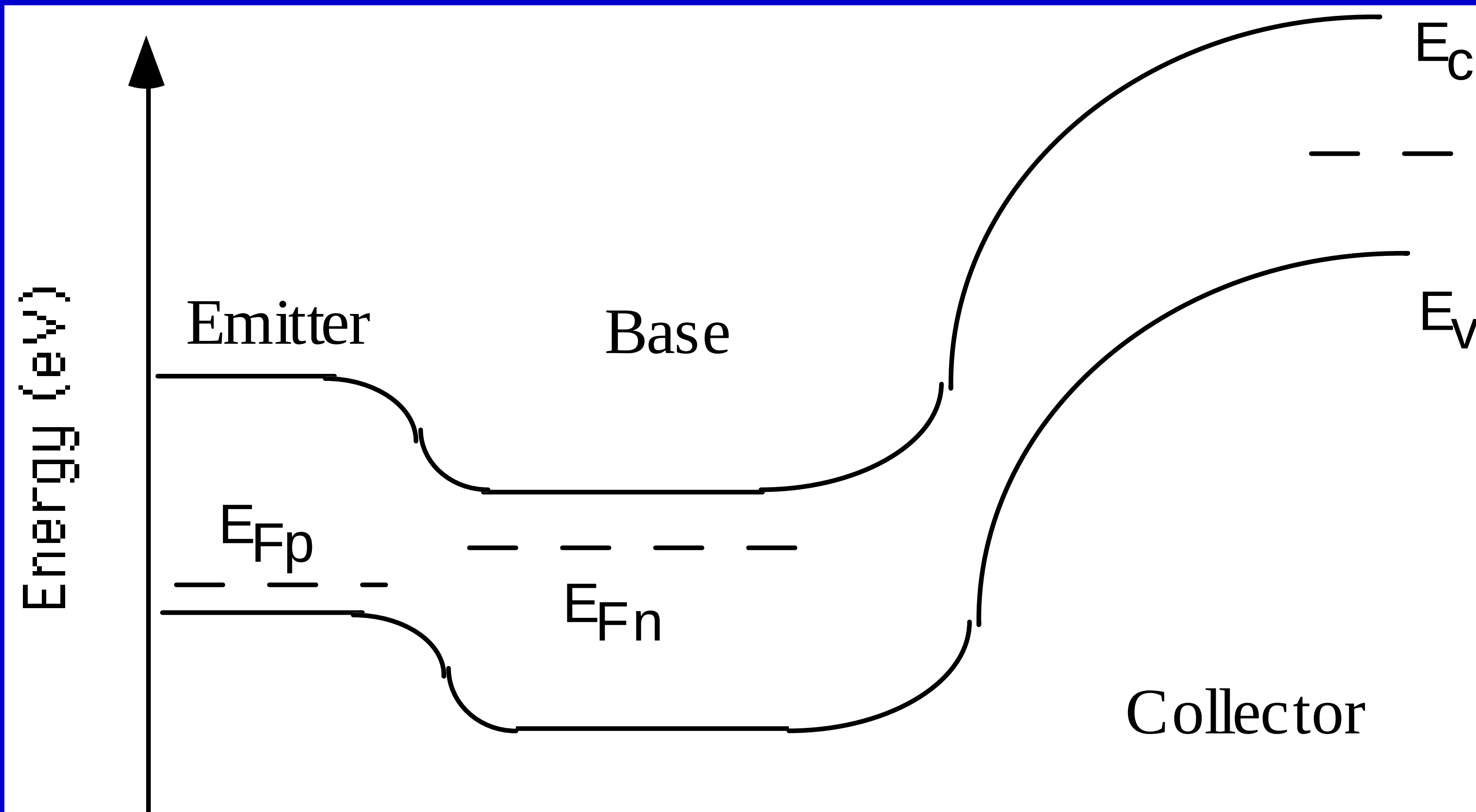


Equivalent circuit

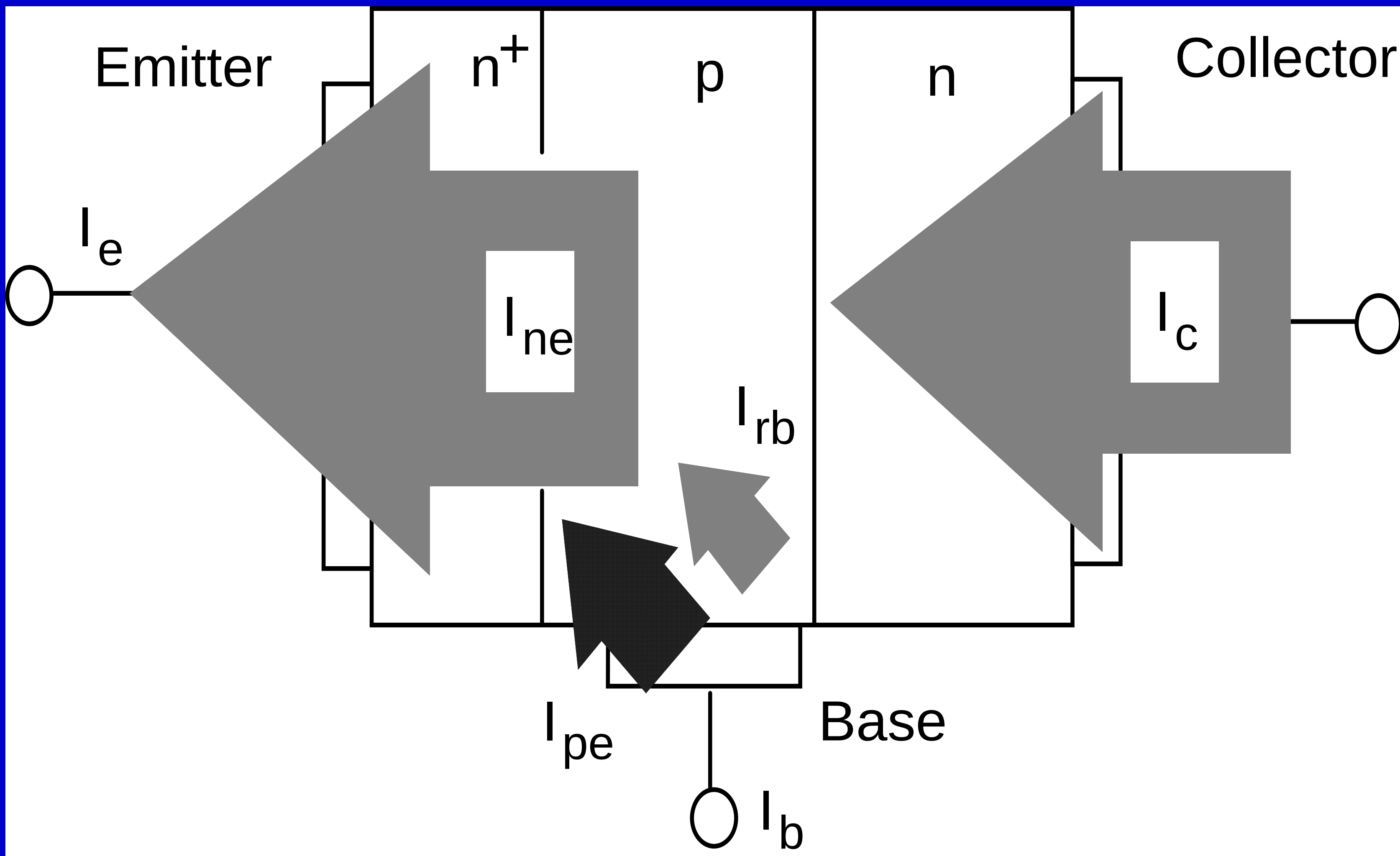


Equivalent circuit of ideal n-p-n BJT

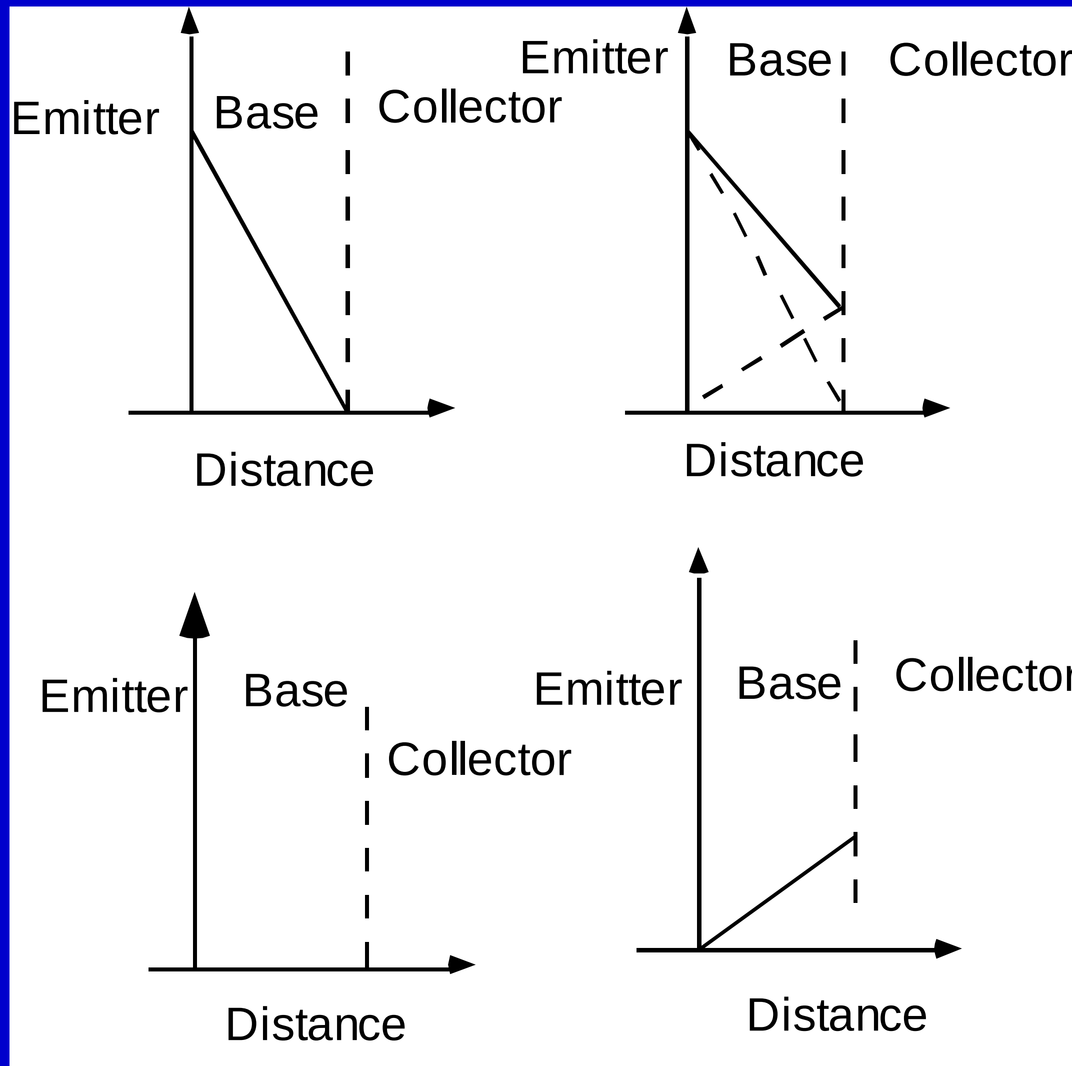
Band diagram of p-n-p transistor



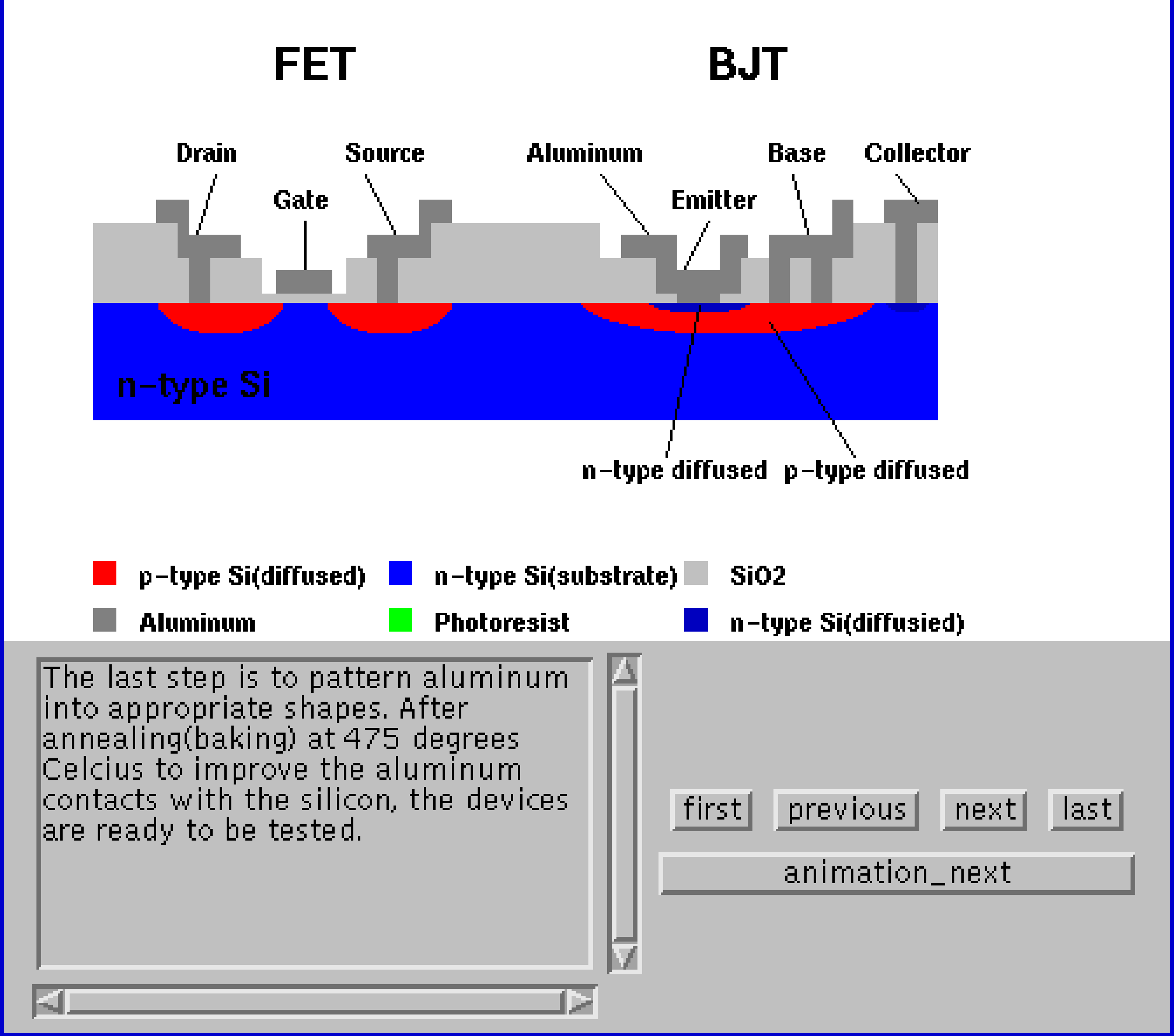
Principle of Operation



Hole distributions in the base of *p-n-p* BJT for active forward mode, saturation, cutoff, and reverse active mode

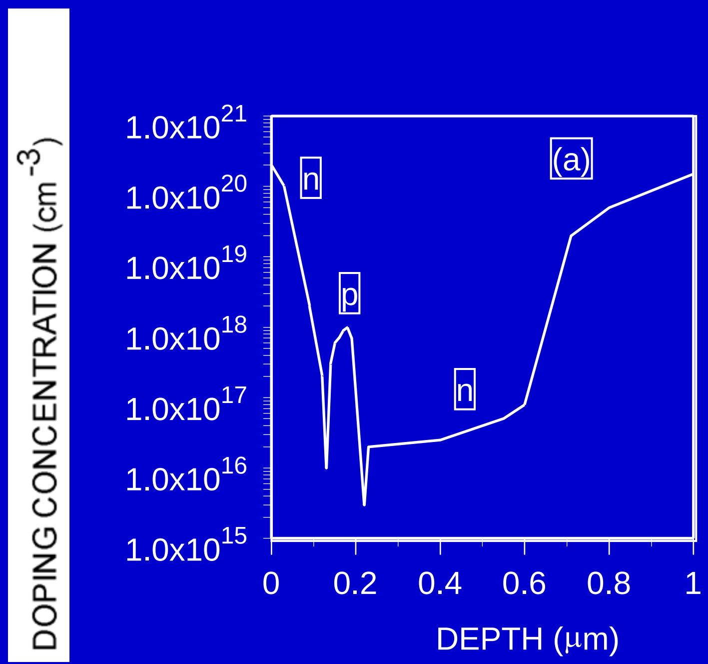


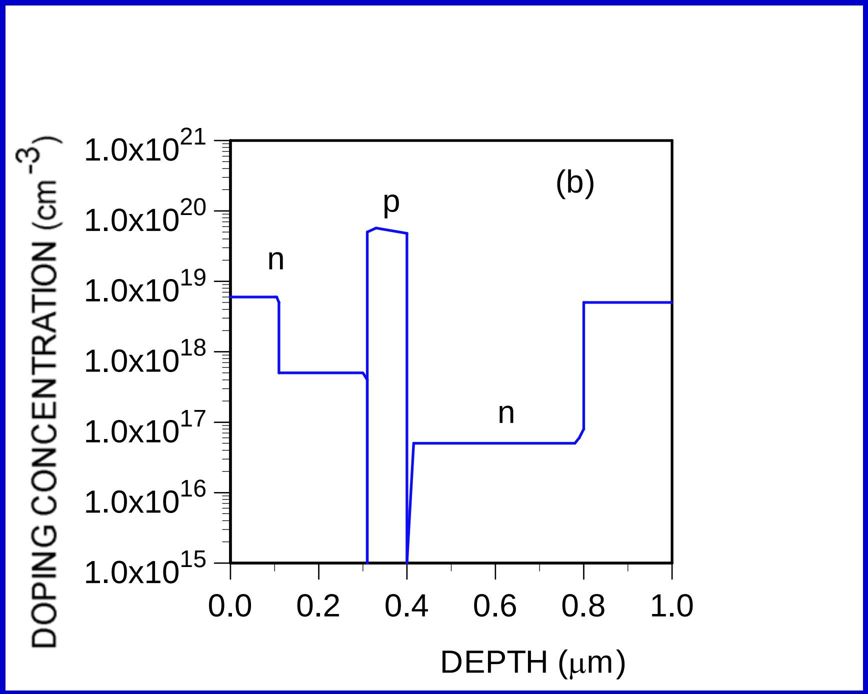
MOSFET/BJT Fabrication



From: http://jas.eng.buffalo.edu/education/fab/BjtFet/index.html

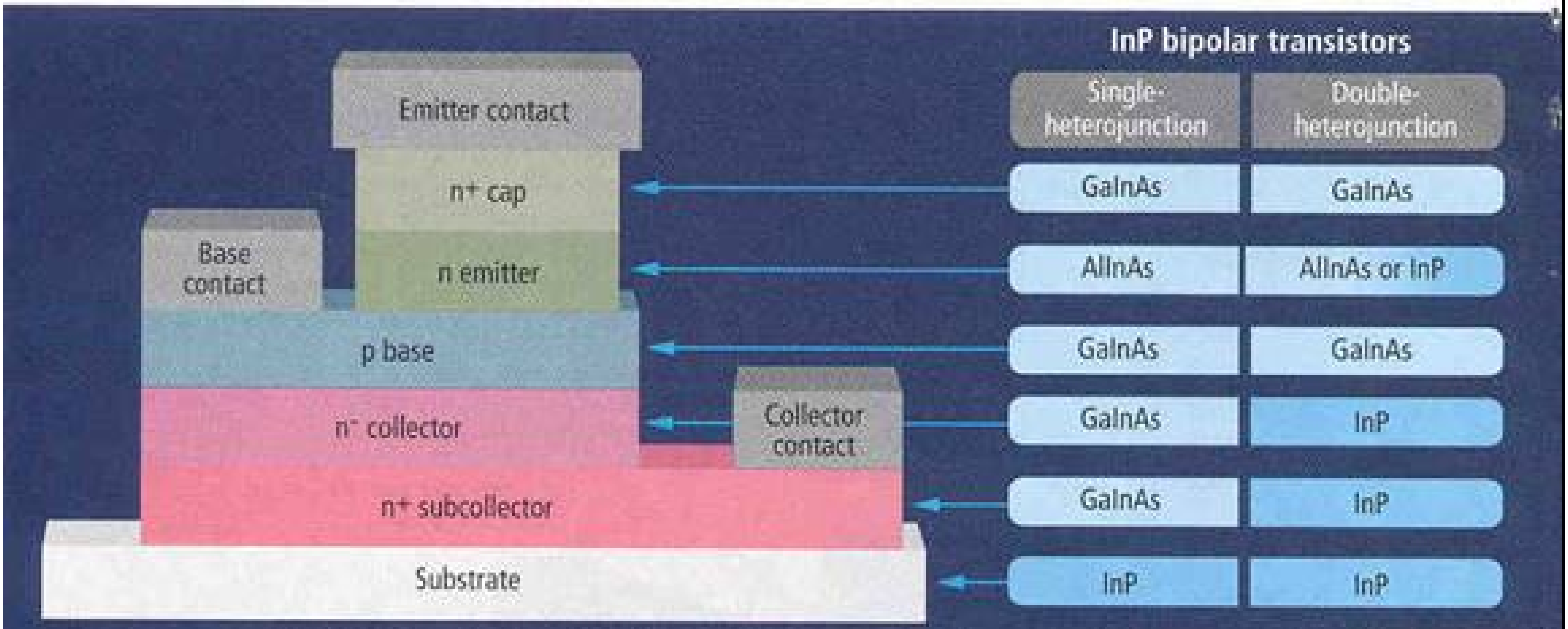
Typical BJT and HBT Doping Profiles





Impurity profile in homojunction (a) and heterojunction (b) bipolar transistors. (After Gao et al., Compound Semiconductor Electronics: The Age of Maturity. Ed. M. S. Shur, (World Scientific, New Jersey, 1996), p. 89.)

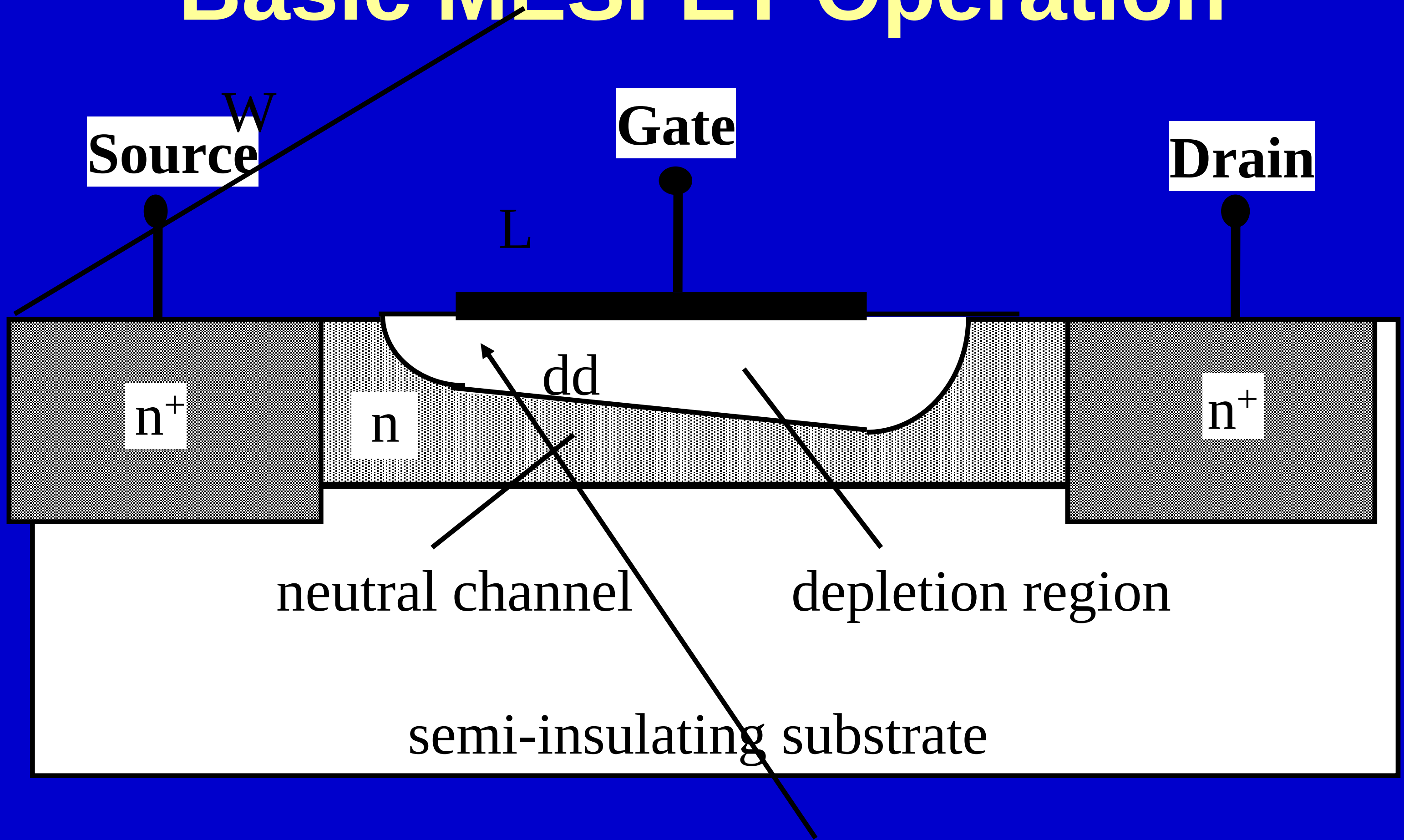
InGaAs/AlInAs and InGaAs/InP HBTs



[2] Single- and double-heterojunction bipolar transistors (SHBTs and DHBTs, respectively) are made using a combination of materials, but start with an indium phosphide substrate. The ratio of gallium to indium in these transistors is 47:53, and the ratio of aluminum to indium is 48:52.

From: Gopal Raghavan, Marko Sokolich, William E. Stanchina, *"Indium Phosphide ICs unleash the high-frequency spectrum"*, IEEE Spectrum, October 2000, p. 47-52.

Basic MESFET Operation



Cdep = ε/dd

Cedge = ε W

S = W L

Capacitance per unit area (F/m^2) Capacitance (F)

MESFET Models

Square-law model: $I_{sat} = \beta V_{GT}^2$

Curtice model (1980): $I_d = I_{sat}(1 + \lambda V_{DS})\tanh(\alpha V_{DS})$

Statz model (1987): $$I_{sat} = \frac{\beta V_{GT}^2}{1 + \alpha V_{GT}}$$

Shur (1987): $$\beta = \frac{2\varepsilon_s v_s W}{d(V_{po} + 3V_L)}$$

UCCM for MESFETs

Below threshold:

$$n_{sb} \approx n_0 \exp\left(\frac{V_{GT} - V_F}{\eta V_{th}}\right)$$

Unified charge density expression:

$$n_s \approx \frac{n_{sa} n_{sb}}{n_{sa} + n_{sb}} = \left[\frac{1}{N_d d}\left(1 - \sqrt{1 - \frac{V_{gte}}{V_{po}}}\right)^{-1} + \frac{1}{n_o}\exp\left(-\frac{V_{gt}}{\eta V_{th}}\right)\right]^{-1}$$

Use same expression for V_{gte} as for MOSFETs

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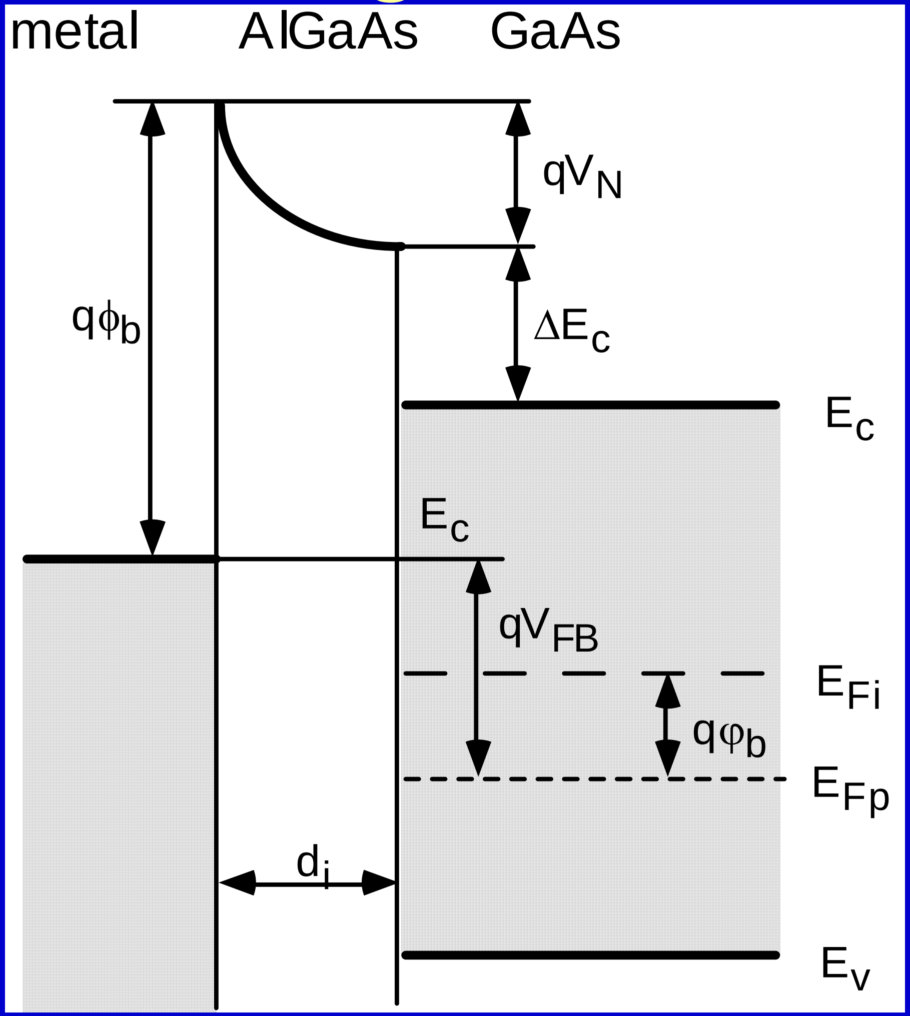
HFET Band Diagram at Flat Band



From T. A. Fjeldly, T. Ytterdal,M. S. Shur, Introduction to Device Modeling and Circuit Simulation for VLSI, Wiley, 1998

Threshold voltage

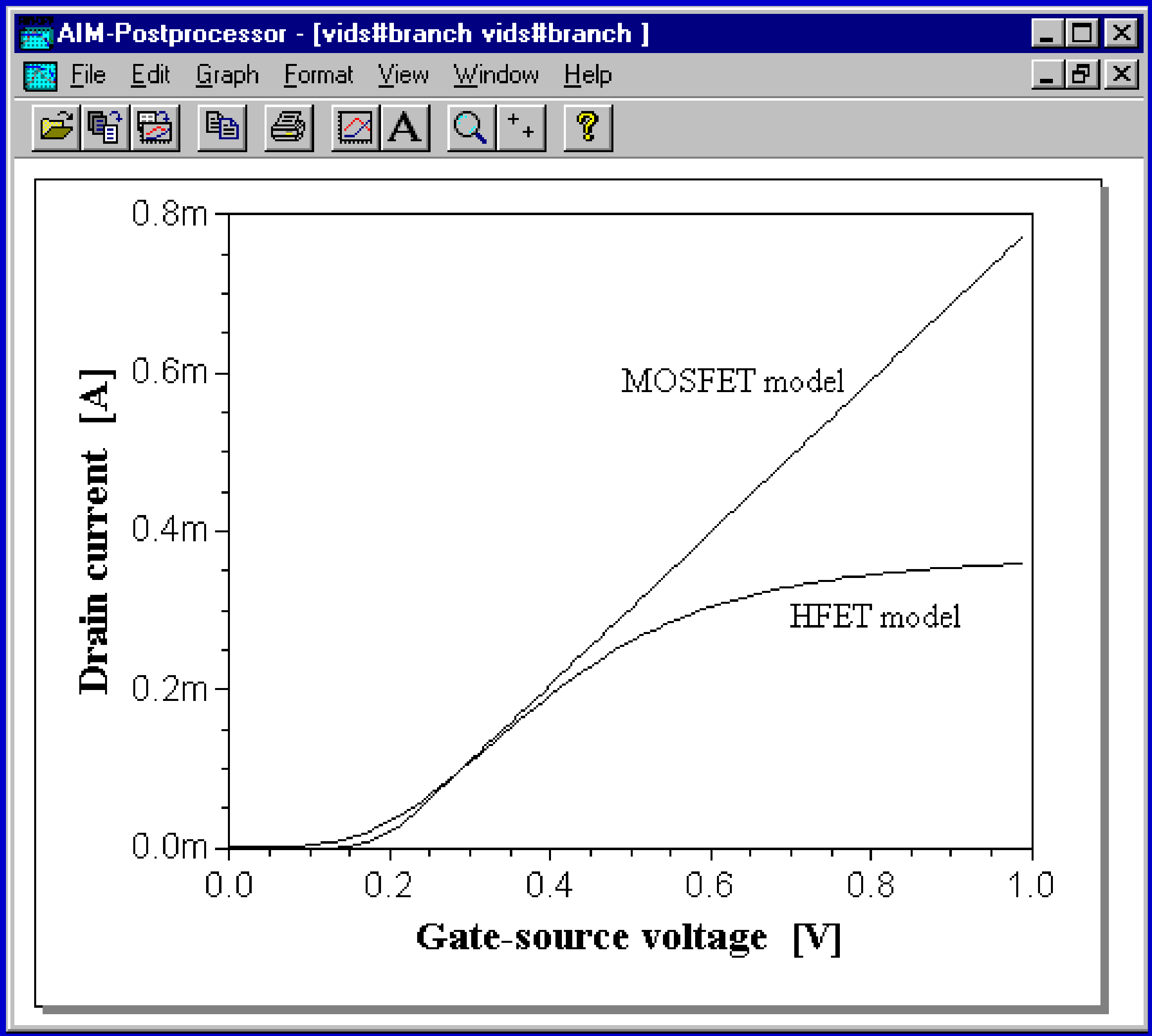
Uniform doping

$$V_T \approx \phi_b - \frac{qN_d d_i^2}{2\varepsilon_i} - \Delta E_c / q$$

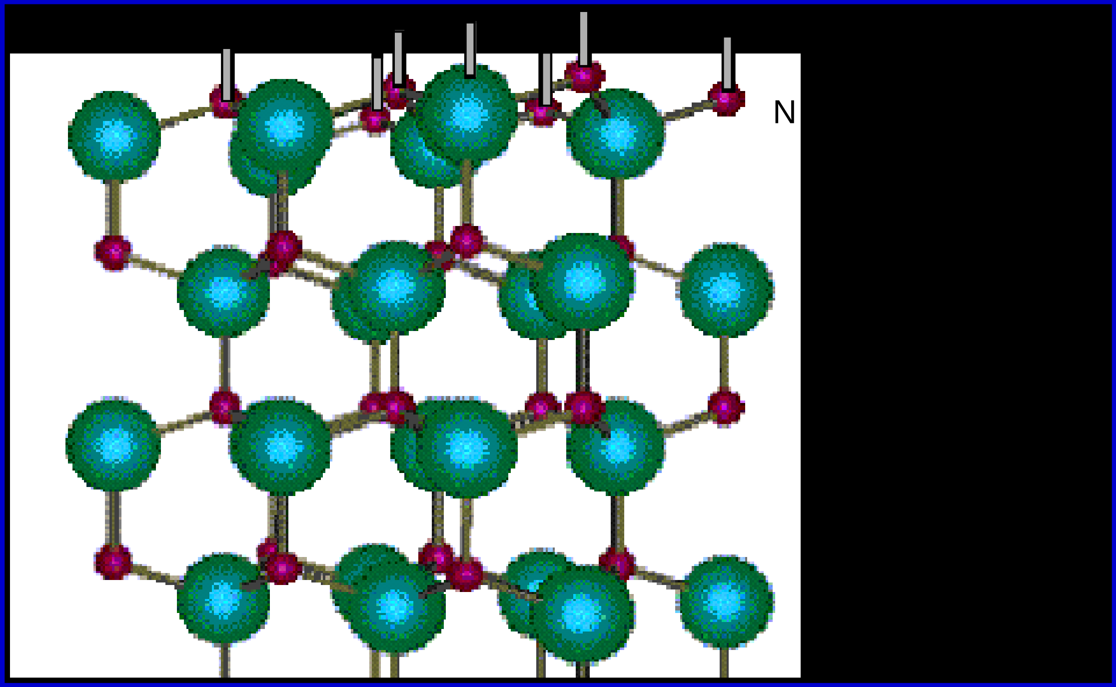
Delta doping

$$V_T \approx \phi_b - qn_\delta d_\delta / \varepsilon_i - \Delta E_c / q$$

Example: HFET Transfer Characteristics



Ga and N faces



After Hellman, E. S., The Polarity of GaN: a Critical Review. MRS Internet J. Nitride Semicond. Res. 3, 11(1998)

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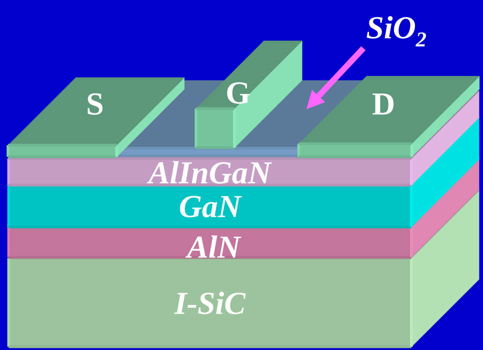
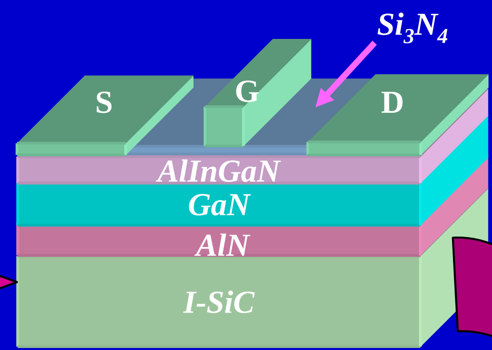
AlN/InN/GaN HFETs



Reducing the gate leakage current (10^4 - 10^6 times)

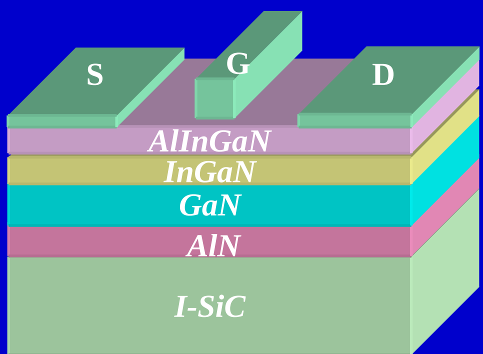
MOSHFET (SiO_2)

MISHFET Si_3N_4

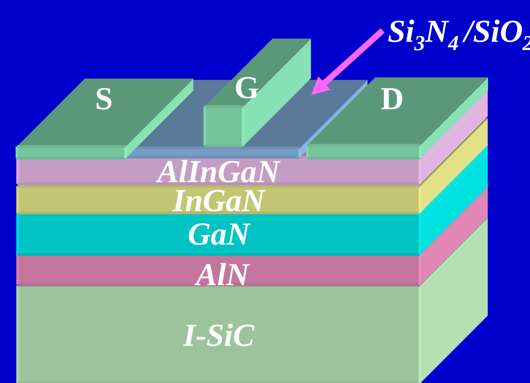


Reducing current collapse,
Improving carrier confinement

Combining the advantages

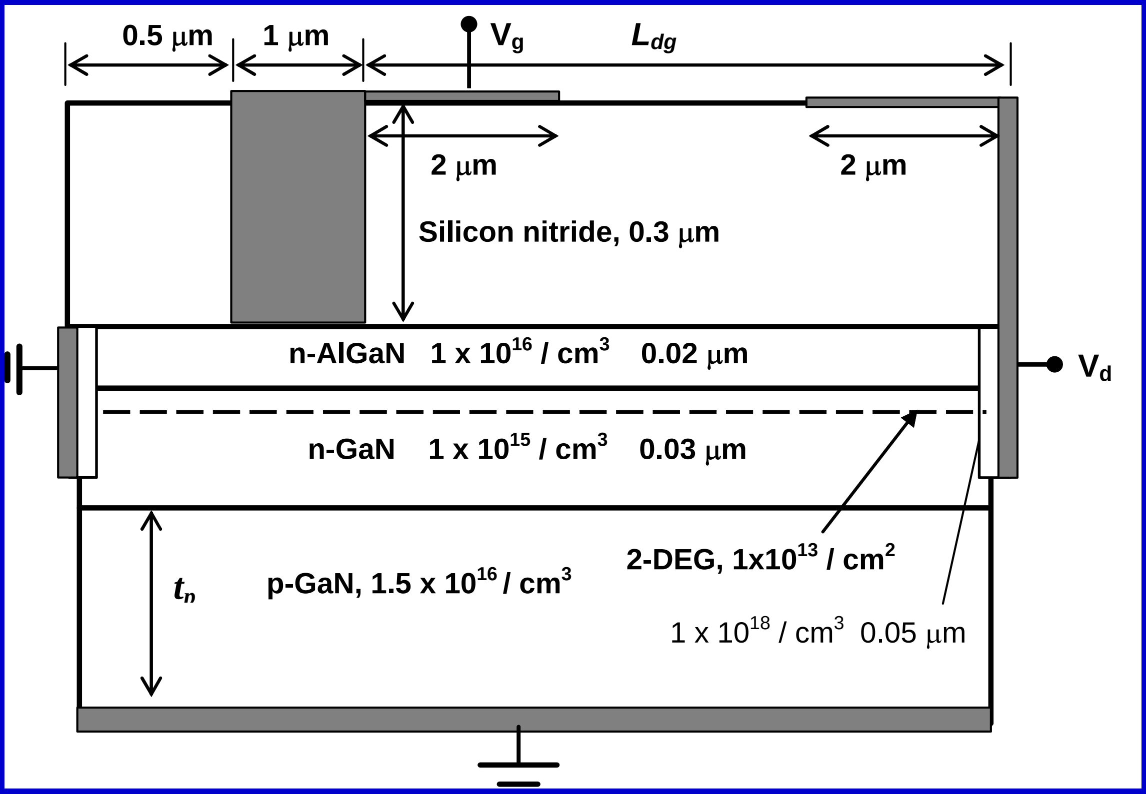


AlGaN/ InGaN GaN DHFET



MISDHFET

RESURF HEMT



From S. Karmalkar, J. Deng, M. S. Shur, R. Gaska, RESURF AlGaN/GaN HEMT for high voltage power switching, IEEE Electron Device Letters, vol. 22, No. 8, pp. 373-375, August (2001)

SDM2 Spring 2009
Thank you for taking my class!