EE-612:
Lecture 26:
Heterostructure FETs

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NCN

www.nanohub.org

outline

I) Introduction

II) Heterojunction review

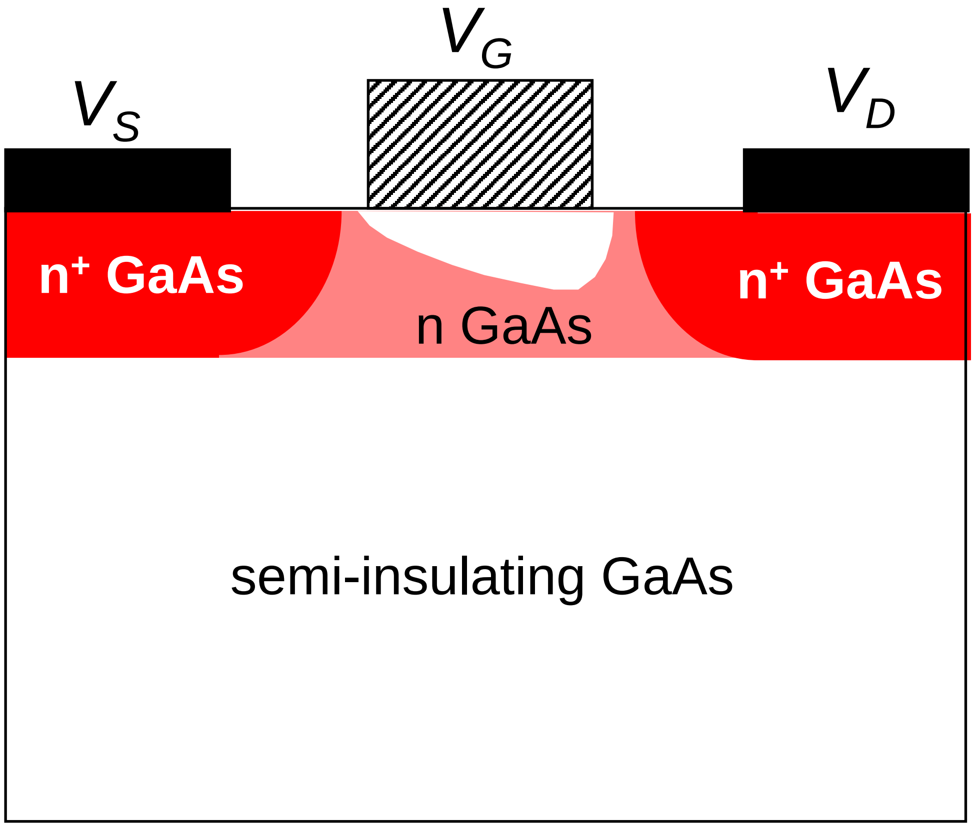
III) Modulation doping

IV) I-V characteristics

V) Device Structure / Materials

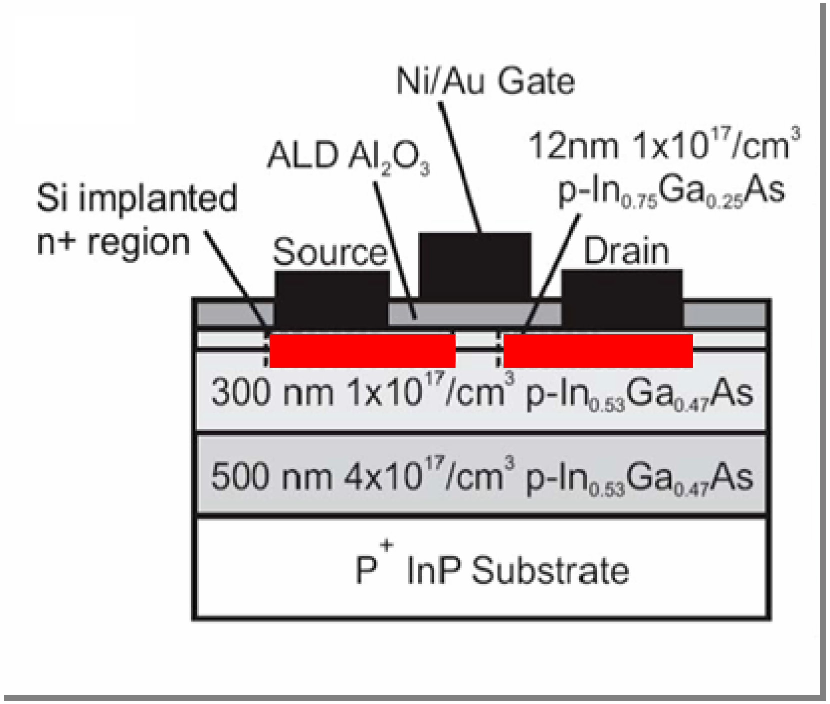
VI) Summary

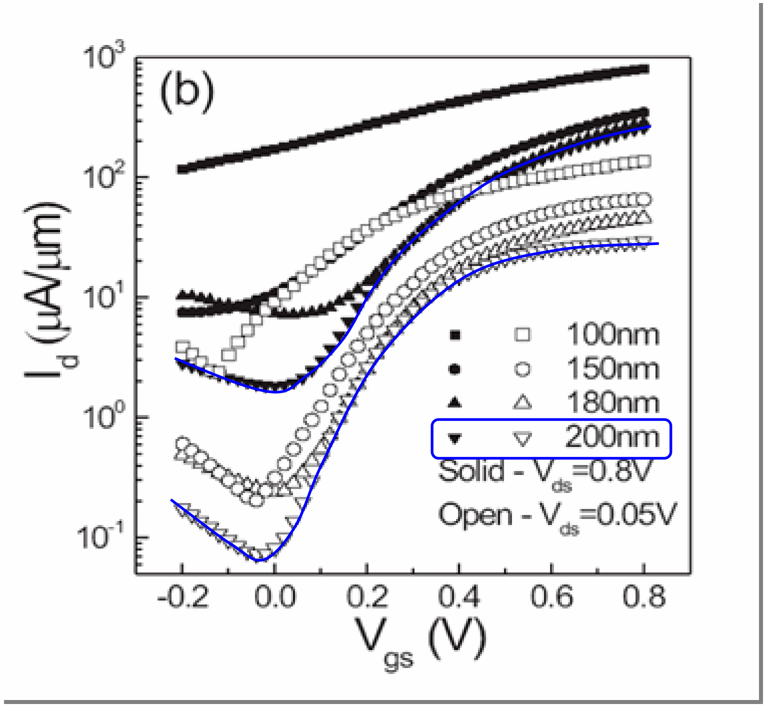
GaAs MESFET



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

InGaAs MOSFETs?





Y. Q. Wu, W. K. Wang, O. Koybasi, D. N. Zakharov, E. A. Stach, S. Nakahara, J. C. M. Hwang, and P. D. Ye, “0.8 V Supply Voltage Deep-Submicron Inversion-Mode In0.75Ga0.25As MOSFET,” submitted for publication, 2008.

Heterostructure FETs

1) Similar to MESFETs and MOSFETs, but different from each.

2) Well-developed commercial technology for high-frequency rf applications.

3) Currently being explored for applications in CMOS logic.

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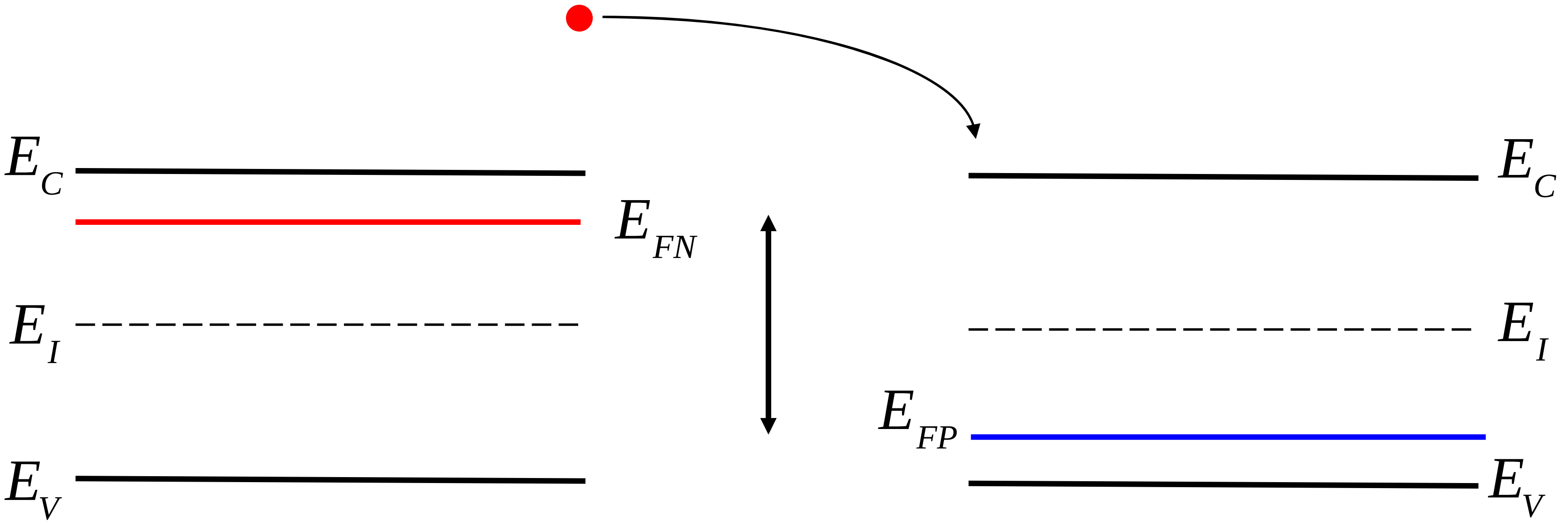
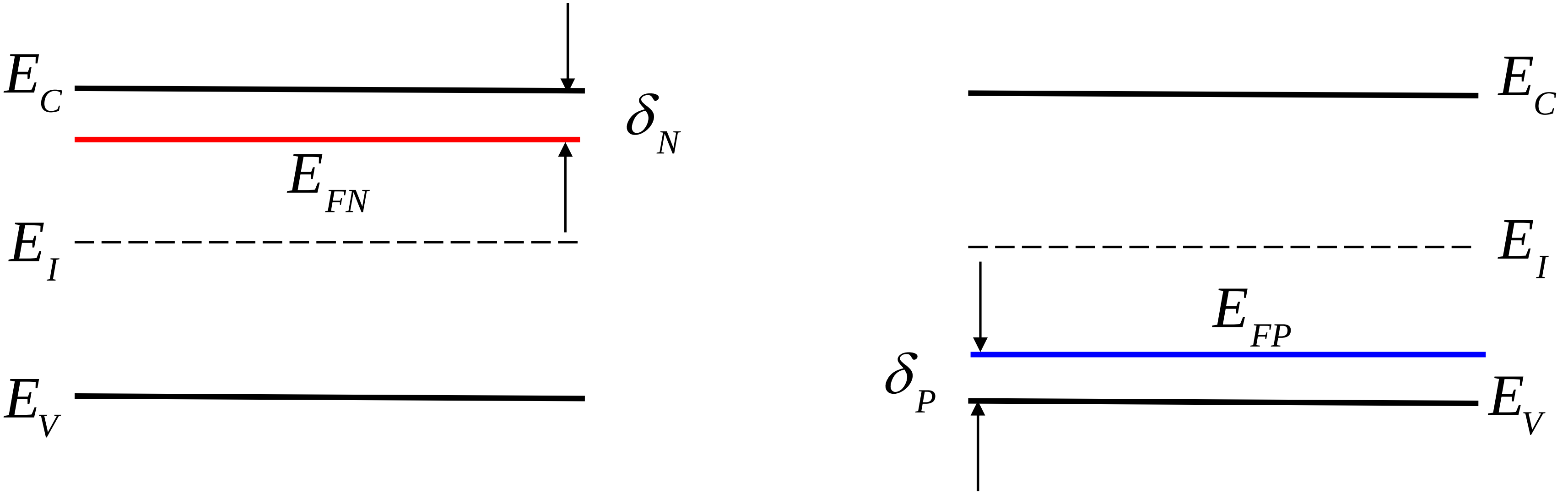
review: pn homojunctions



potential must decrease

$$V_{BI} = \left(E_{FN} - E_{FP}\right)/q$$

built-in potential



$$qV_{BI} = \left(E_{FN} - E_{FP}\right)$$

$$qV_{BI} = \left(E_C - E_V\right) - \delta_N - \delta_P$$

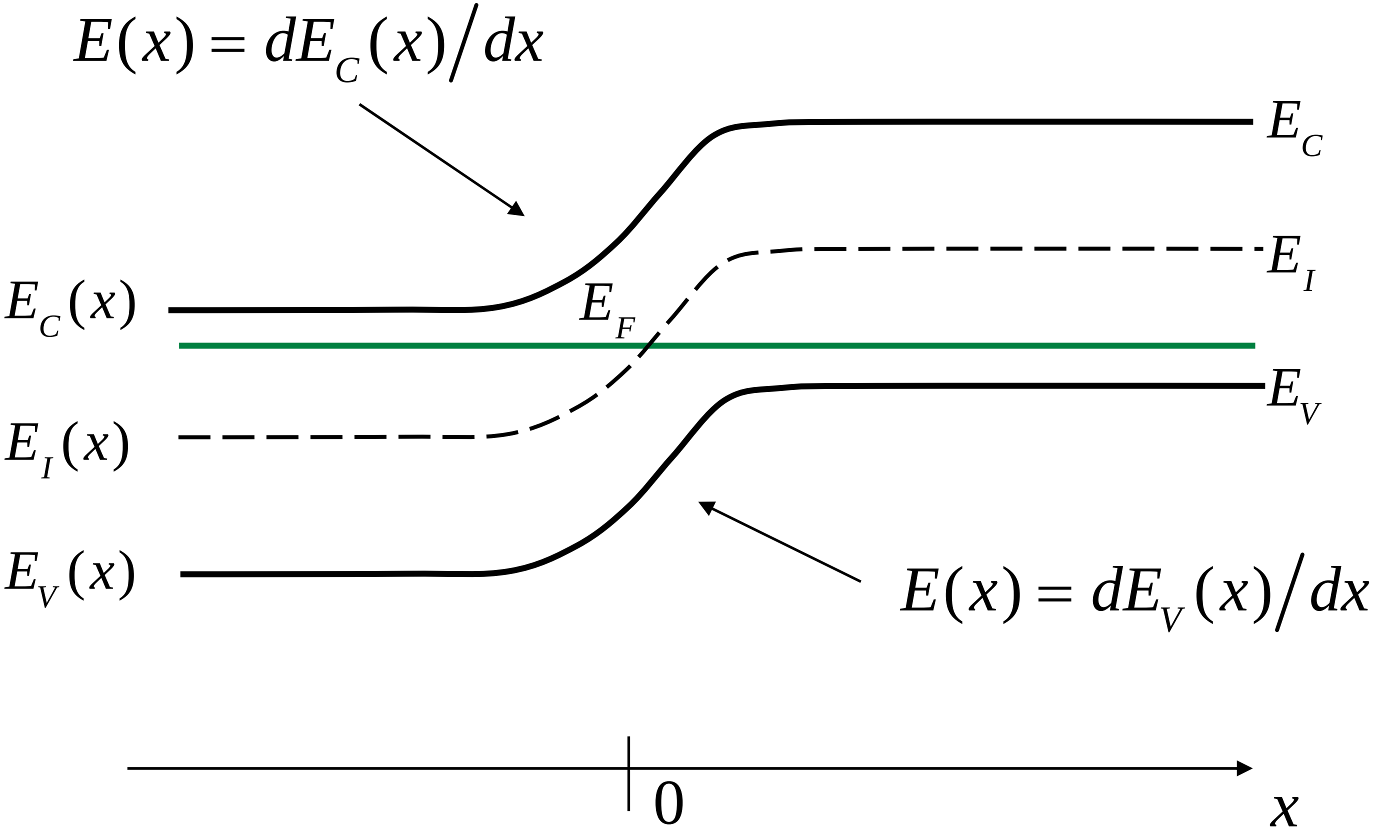
$$qV_{BI} = E_G - \delta_N - \delta_P$$

$$N_D = N_C e^{-\delta_N / k_B T}$$

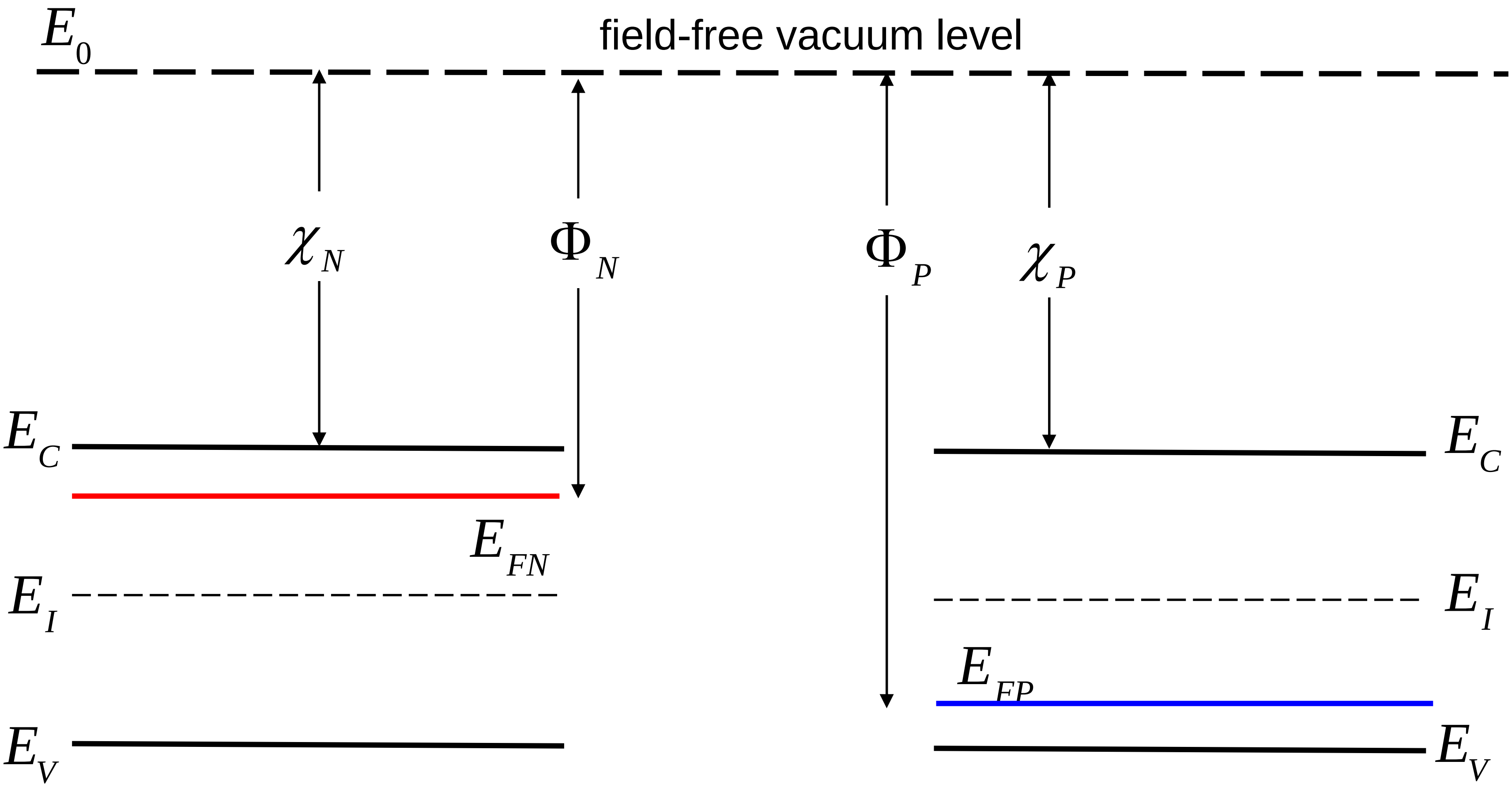
$$N_A = N_V e^{-\delta_P / k_B T}$$

$$qV_{BI} = k_B T \ln\left(N_A N_D / n_i^2\right)$$

review: pn homojunctions



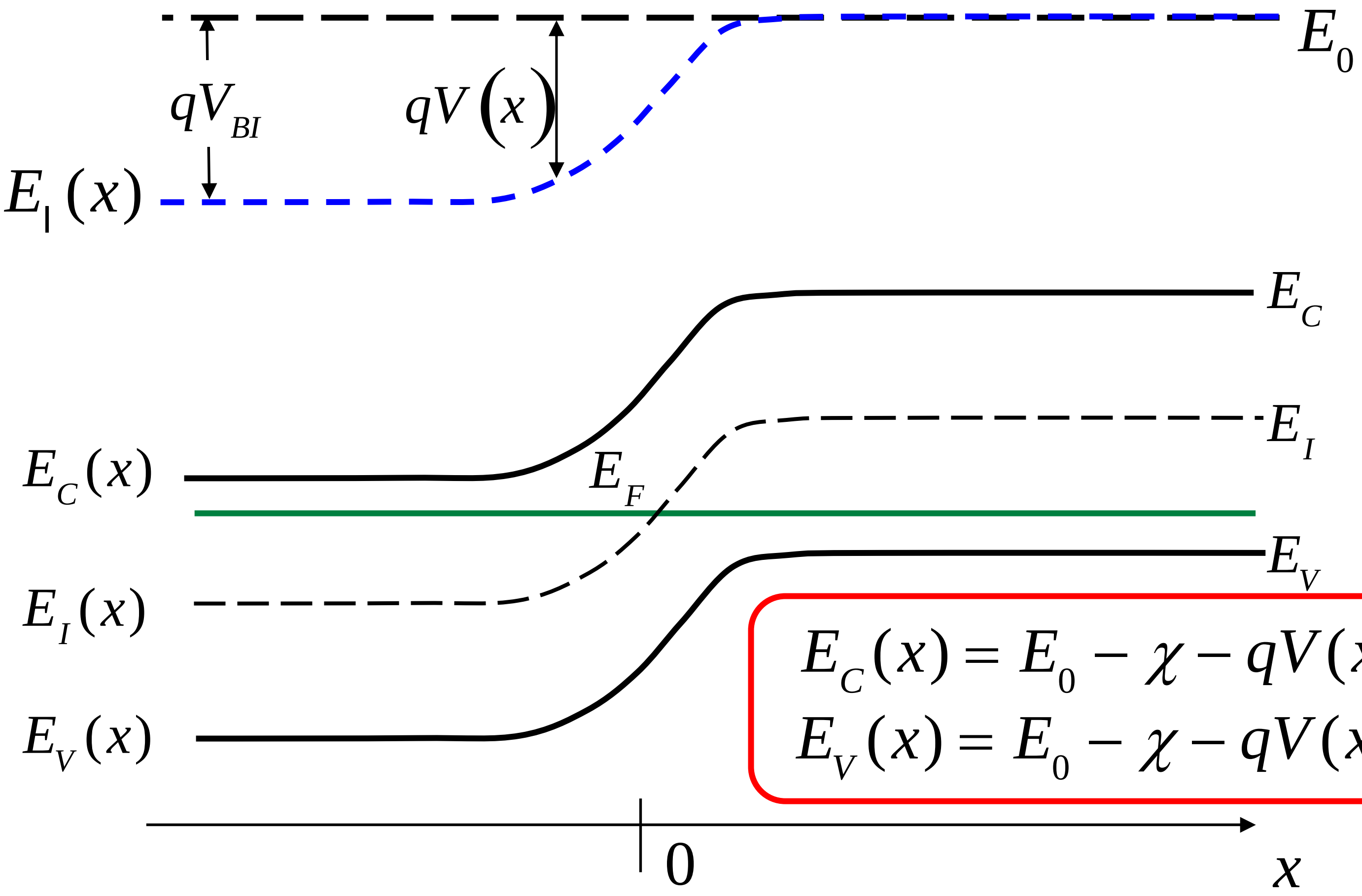
reference for the energy bands?



$$E_C = E_0 - \chi$$
$$E_V = E_0 - \chi - E_G$$

$$qV_{BI} = \left(\Phi_P - \Phi_N\right)$$

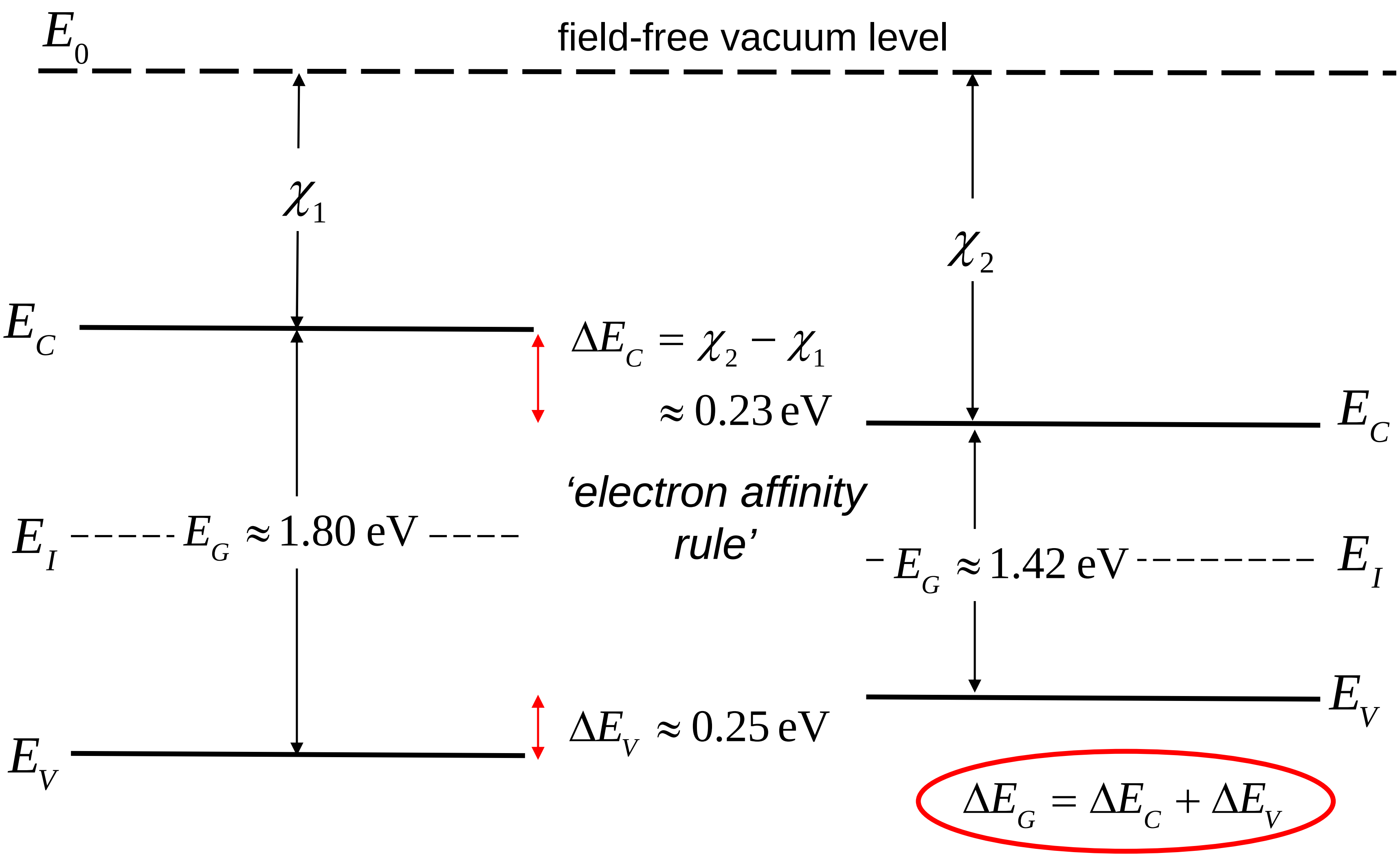
“local” vacuum level



$$E_C(x) = E_0 - \chi - qV(x)$$

$$E_V(x) = E_0 - \chi - qV(x) - E_G$$

$Al_{0.3}Ga_{0.7}As$: GaAs (Type I HJ)



E_0 field-free vacuum level

χ_1

χ_2

E_C

$$\Delta E_C = \chi_2 - \chi_1$$
$$\approx 0.23\,\text{eV}$$

E_C

'electron affinity rule'

E_I $E_G \approx 1.80\,\text{eV}$

$E_G \approx 1.42\,\text{eV}$ E_I

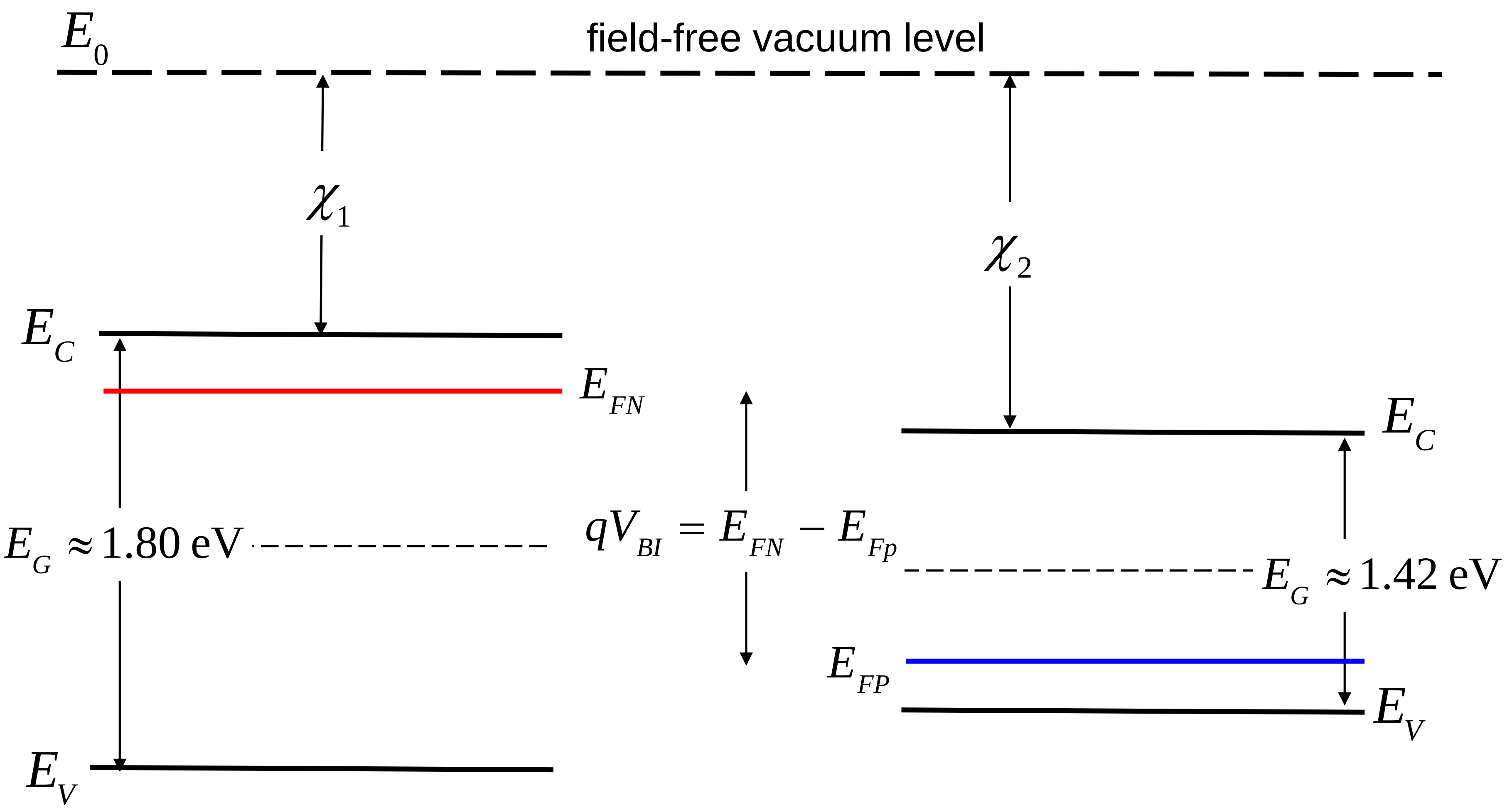
E_V

$$\Delta E_V \approx 0.25\,\text{eV}$$

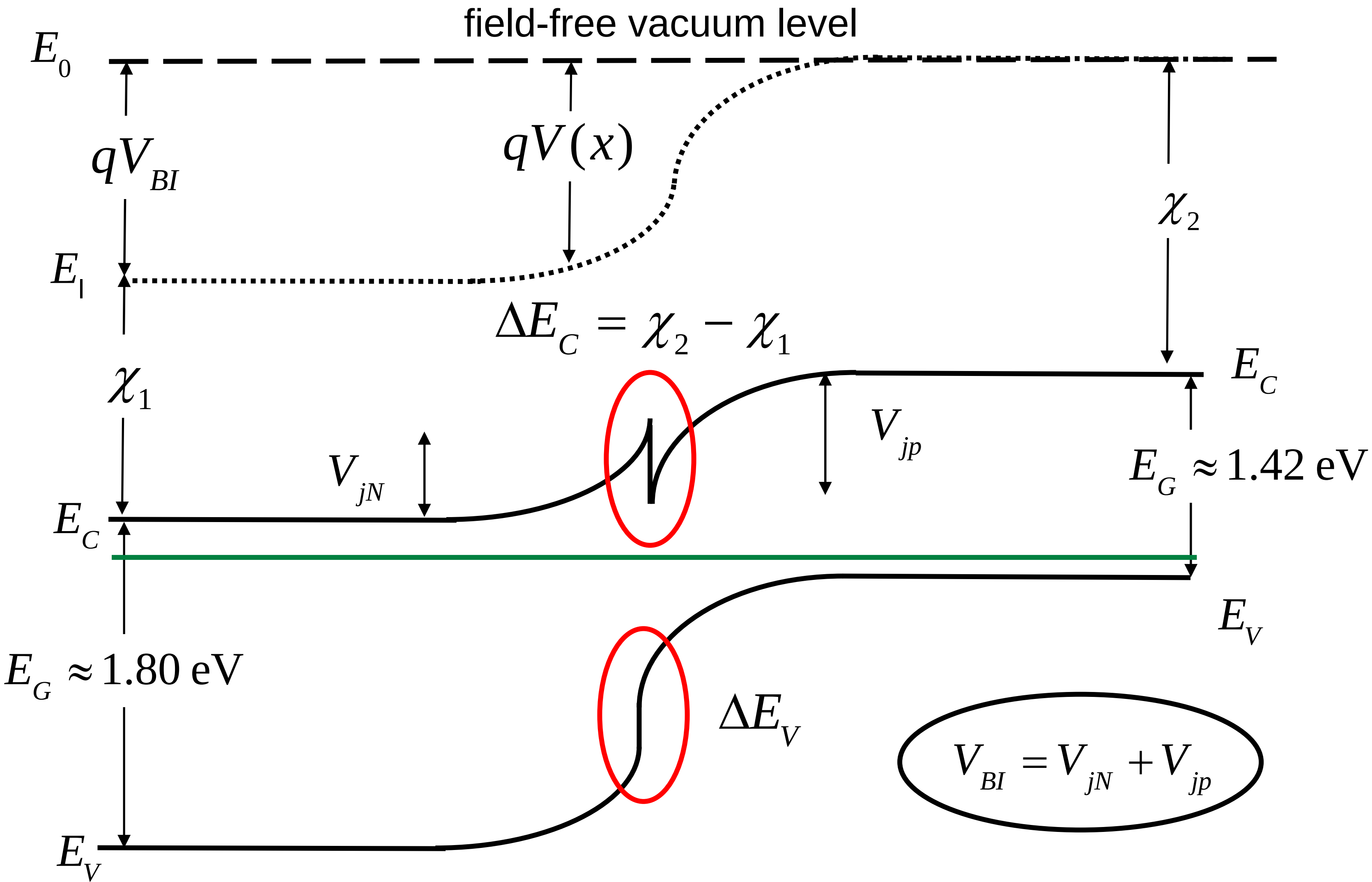
E_V

$$\boxed{\Delta E_G = \Delta E_C + \Delta E_V}$$

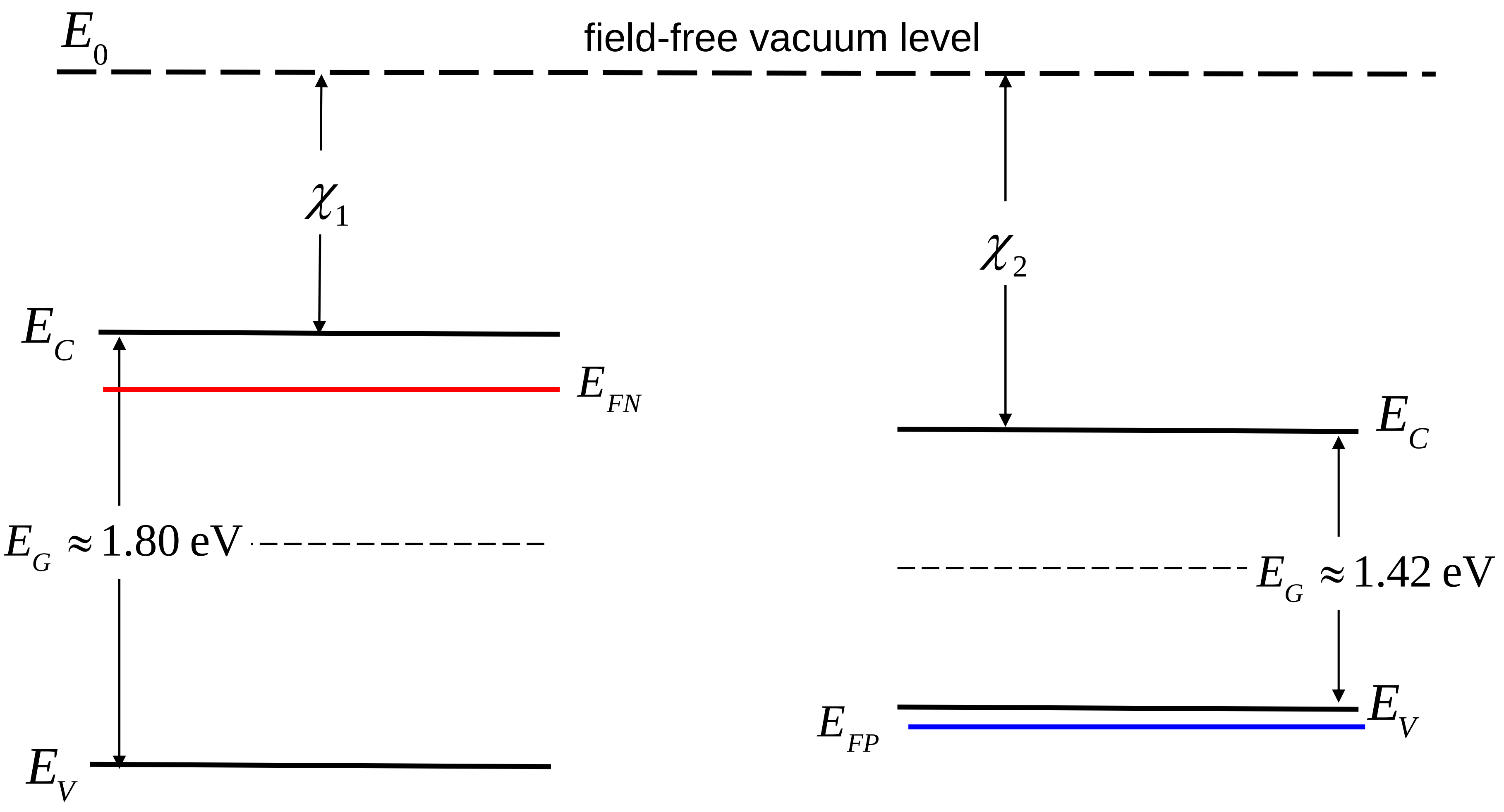
N-$Al_{0.3}Ga_{0.7}As$: p-GaAs (Type I HJ)



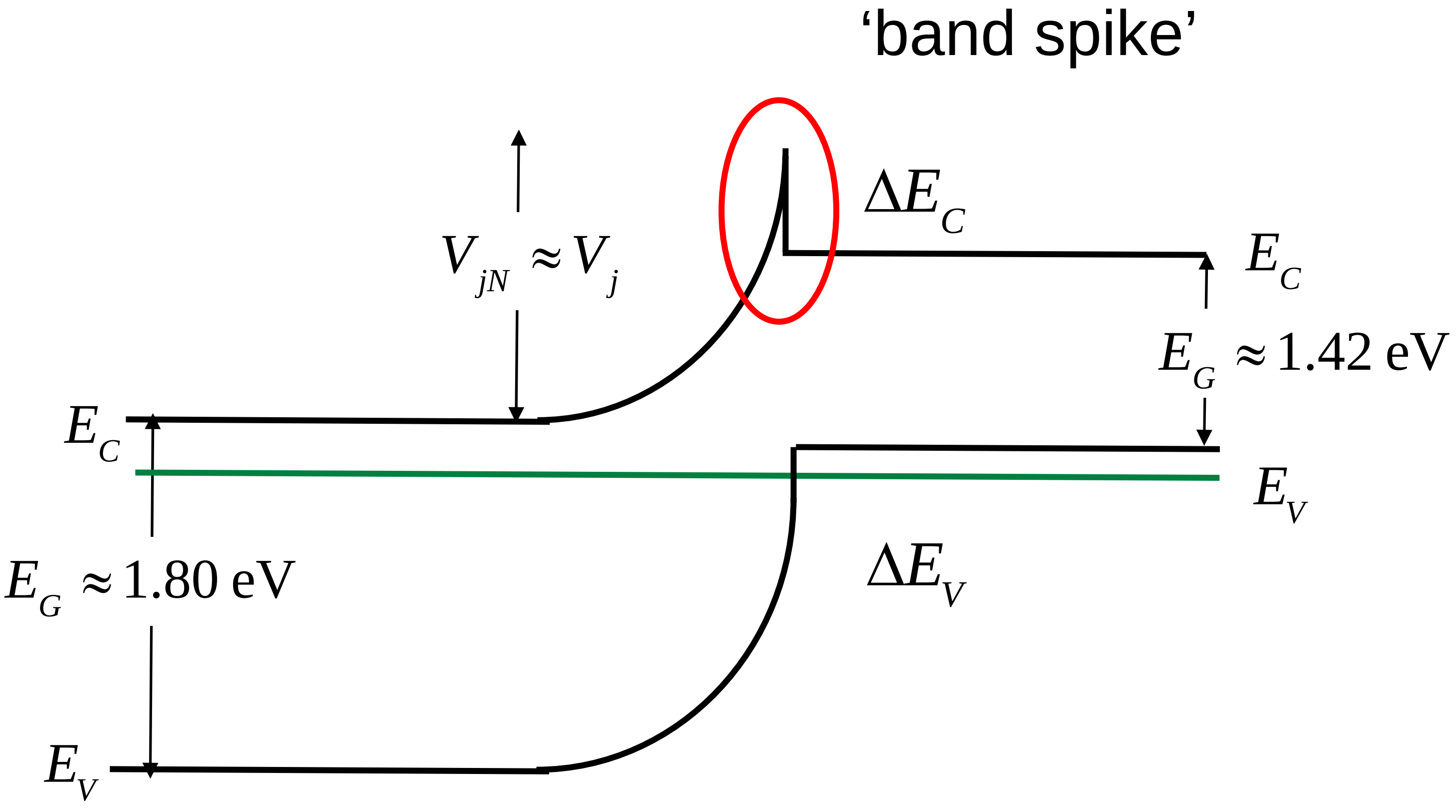
N-$Al_{0.3}Ga_{0.7}As$: p-GaAs (Type I HJ)



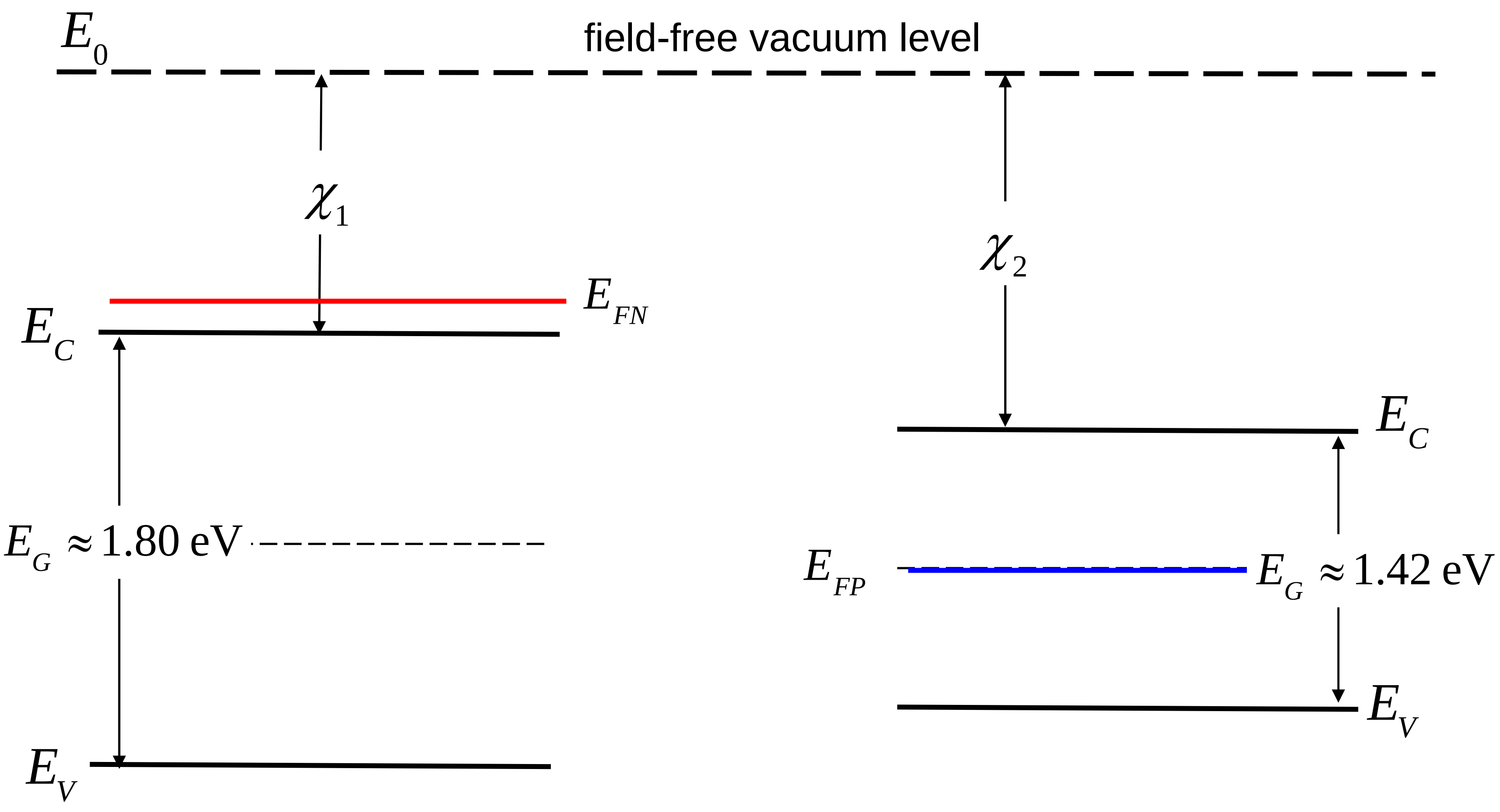
N-$Al_{0.3}Ga_{0.7}As$: p^+-GaAs



N-$Al_{0.3}Ga_{0.7}As$: p-GaAs



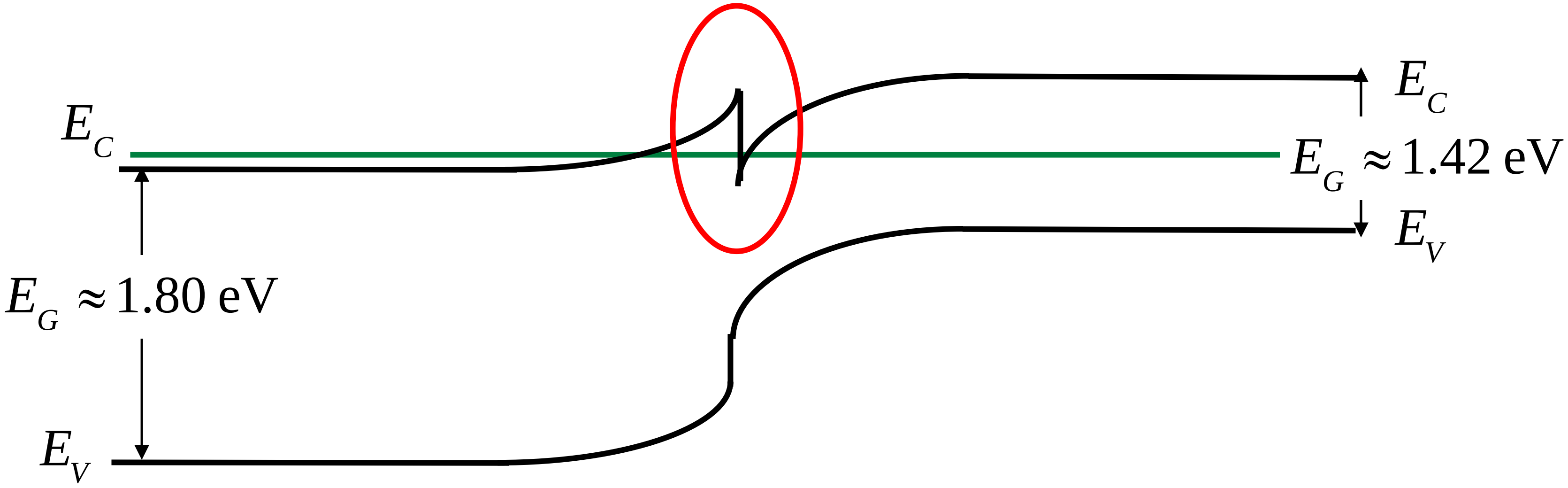
N$^+$-Al$_{0.3}$Ga$_{0.7}$As : i-GaAs



N-$Al_{0.3}Ga_{0.7}As$: i-GaAs

‘modulation doping’

‘2D electron gas’



depletion layer inversion/accumulation layer

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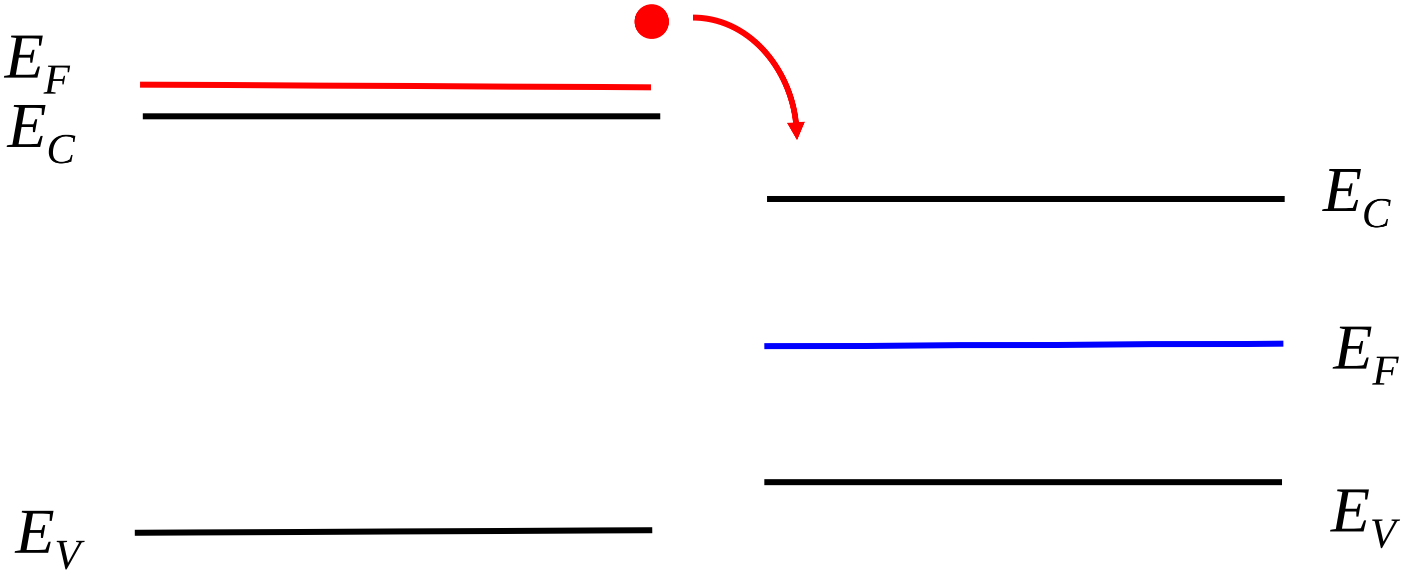
modulation doping

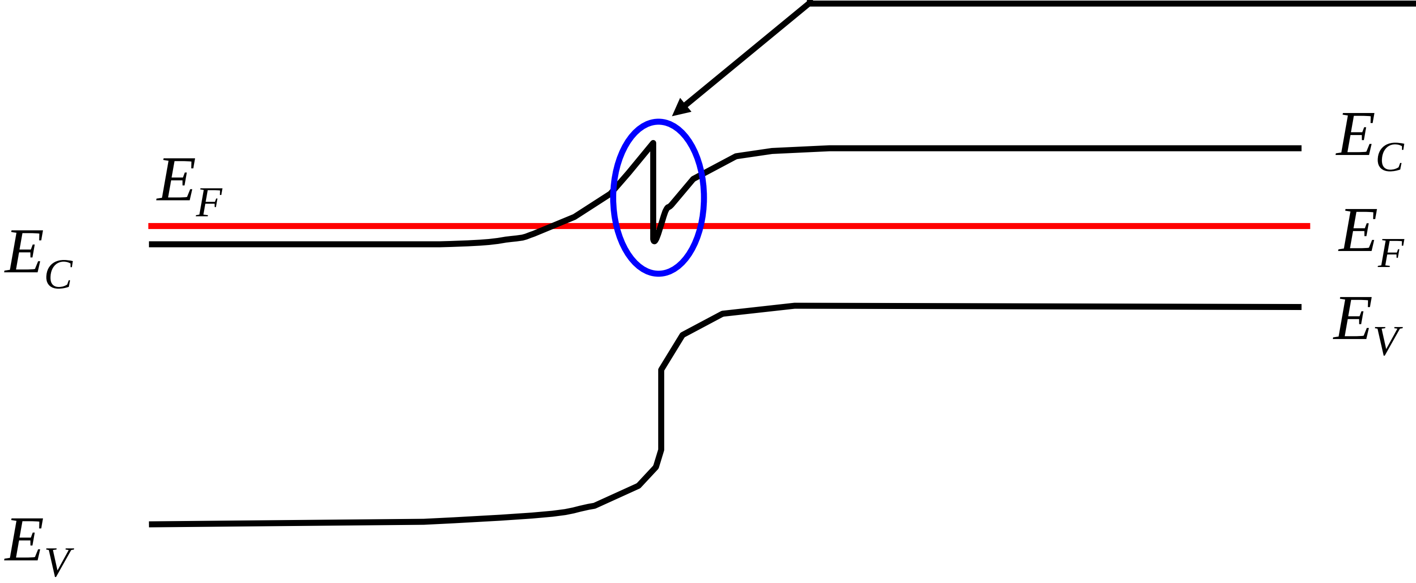


wide band gap
doped n$^+$

small band gap
nominally undoped

modulation doping

“2D electron gas”
(high carrier density ***and*** high μ)

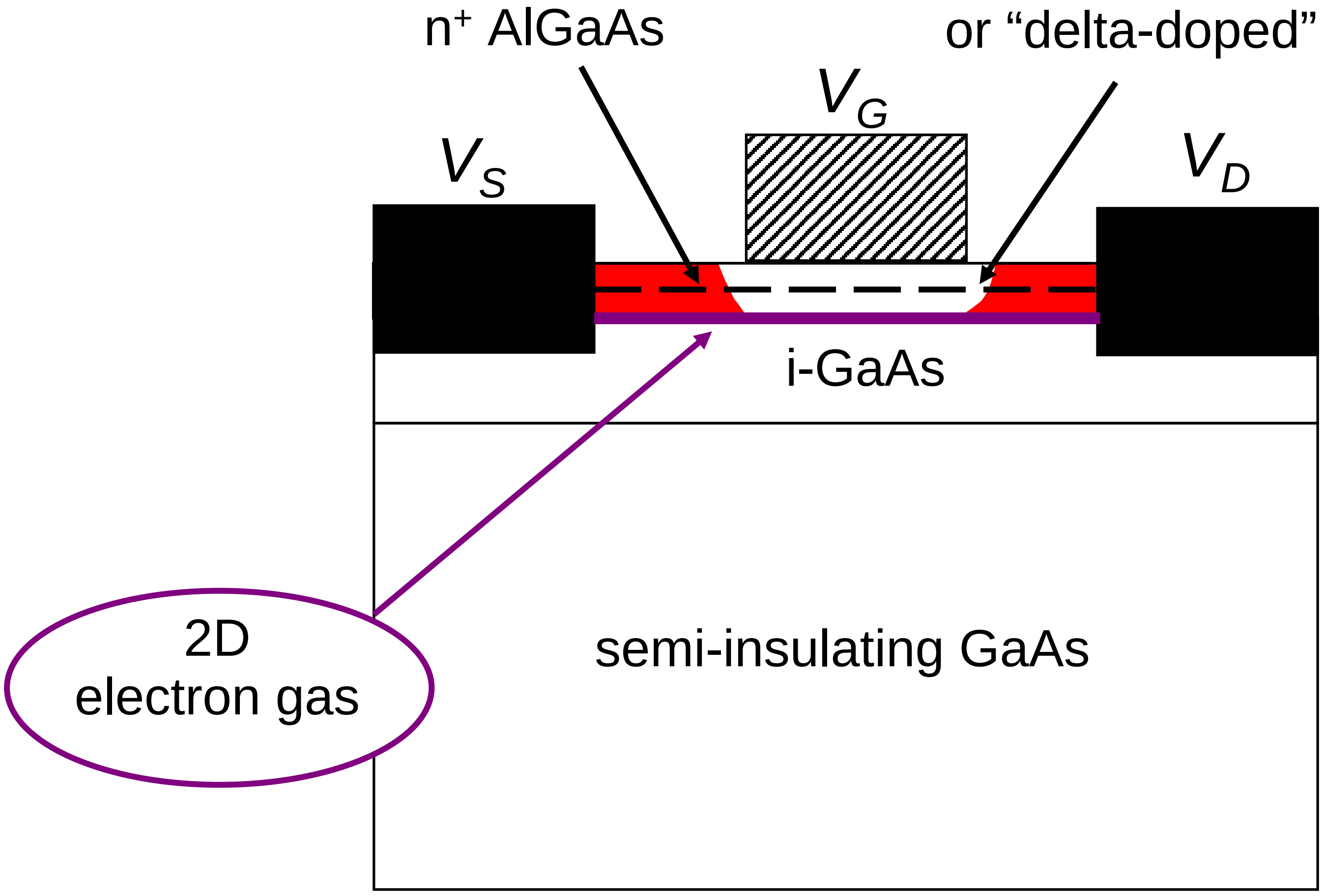


wide band gap
doped n$^+$

small band gap
nominally undoped

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

heterostructure FET



names

MODFET: “**M**odulation-**D**oped **F**ield-**E**ffect **T**ransistor”

HEMT: “**H**igh **E**lectron **M**obility **T**ransistor”

SDHT: “**S**electively-**D**oped **H**eterostructure **T**ransistor”

TEGFET: “**T**wo-dimensional **E**lectron **G**as **F**ield-**E**ffect **T**ransistor”

applications

1) initially driven by high-speed logic

2) Low noise amplifiers (micro/millimeter waves)

-satellite communication, radio astronomy, electronic warfare

3) Millimeter-wave power amplifiers

4) High-speed logic?

references

Modulation doping was discovered by Dingle, who gives a personal account of the work in:

R. Dingle, “New high-speed III-V devices for integrated circuits,” *IEEE Trans. on Electron Devices ,* **31**, pp. 1662-1667, 1984.

For a good discussion of basic principles, see:

P.M. Solomon, and H. Morkoc, “Modulation-doped GaAs/AlGaAs heterojunction field-effect transistors (MODFETs), ultrahigh-speed device for supercomputers,” *IEEE Trans. on Electron Devices,* **31**, pp. 1015-1027, 1984.

For a tutorial on current practice as of 1992, see:

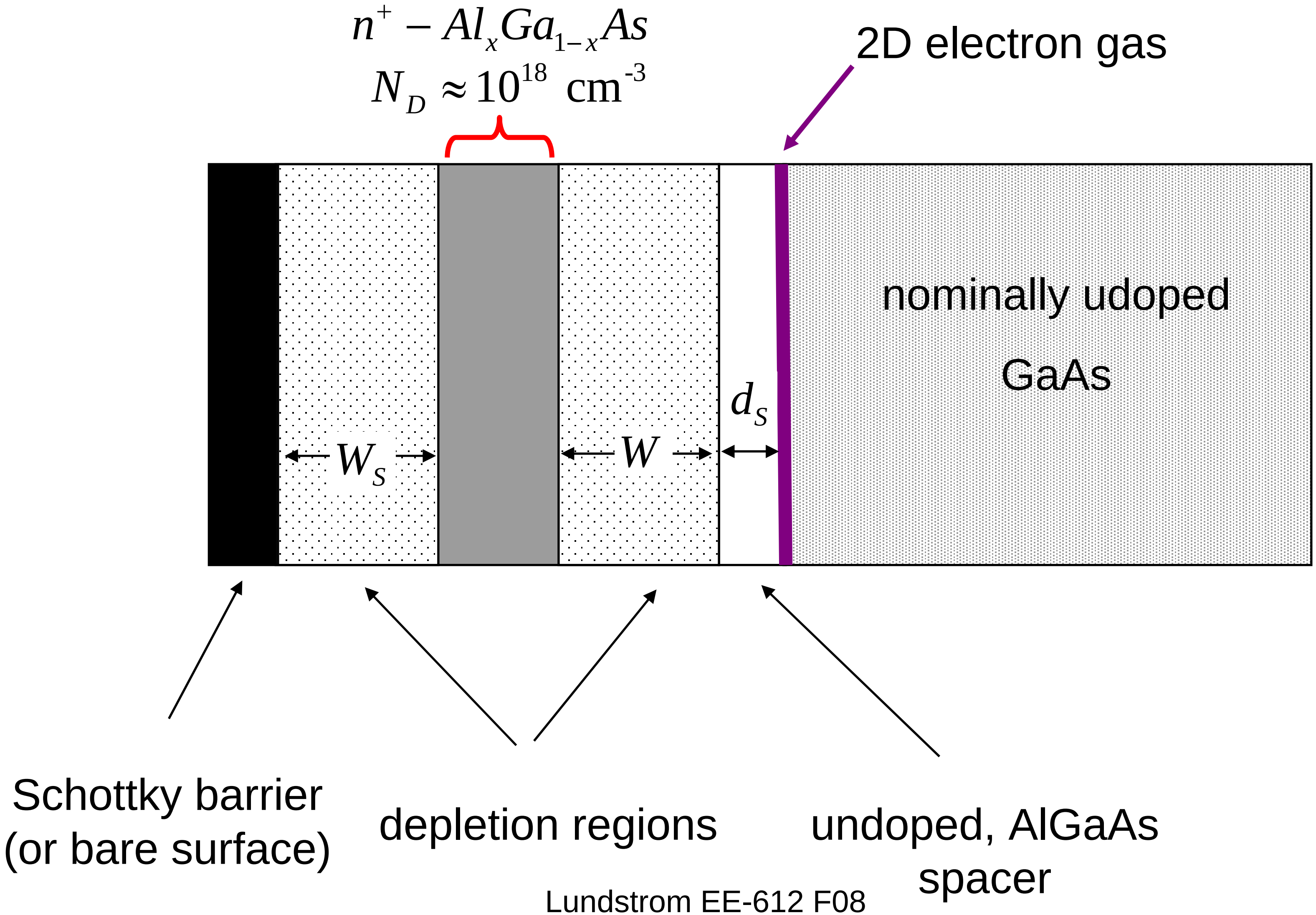
L. D. Nguyen, L.L. Larsen, and U.K. Mishra, “Ultra-high-speed modulation-doped field-effect transistors: A tutorial review,” *Proc. IEEE,* **80**, pp. 494-518, 1992.

references

For a good textbook treatment of modulation doping and MODFETs, see:

K.F. Brennan and A.S. Brown, “Theory of Modern Electronic Semiconductor Devices,” *Wiley, 2002.*

model structure



$n^{+} - Al_xGa_{1-x}As$

$N_D \approx 10^{18}\ \text{cm}^{-3}$

2D electron gas

nominally udoped

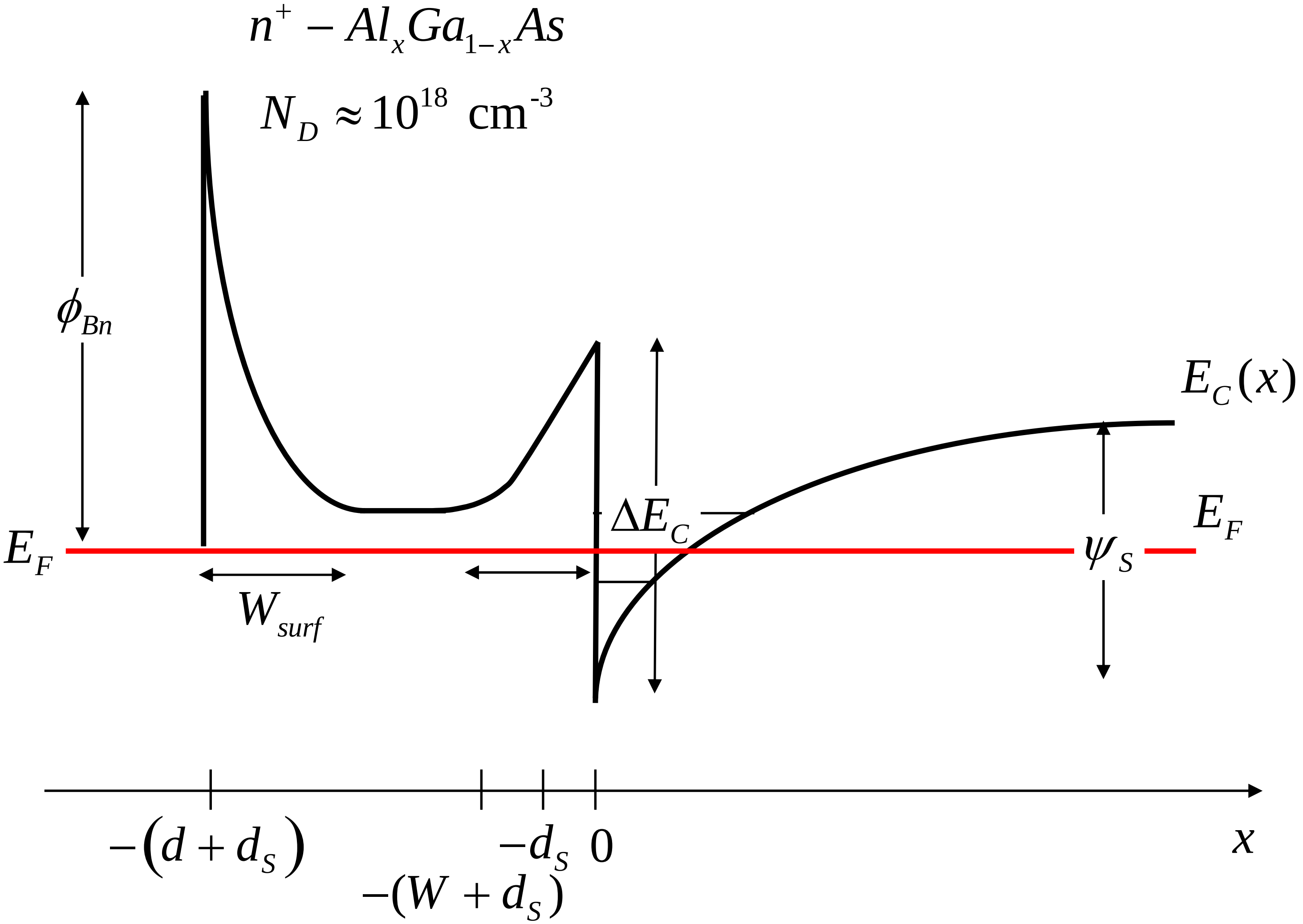
GaAs

Schottky barrier
(or bare surface)

depletion regions

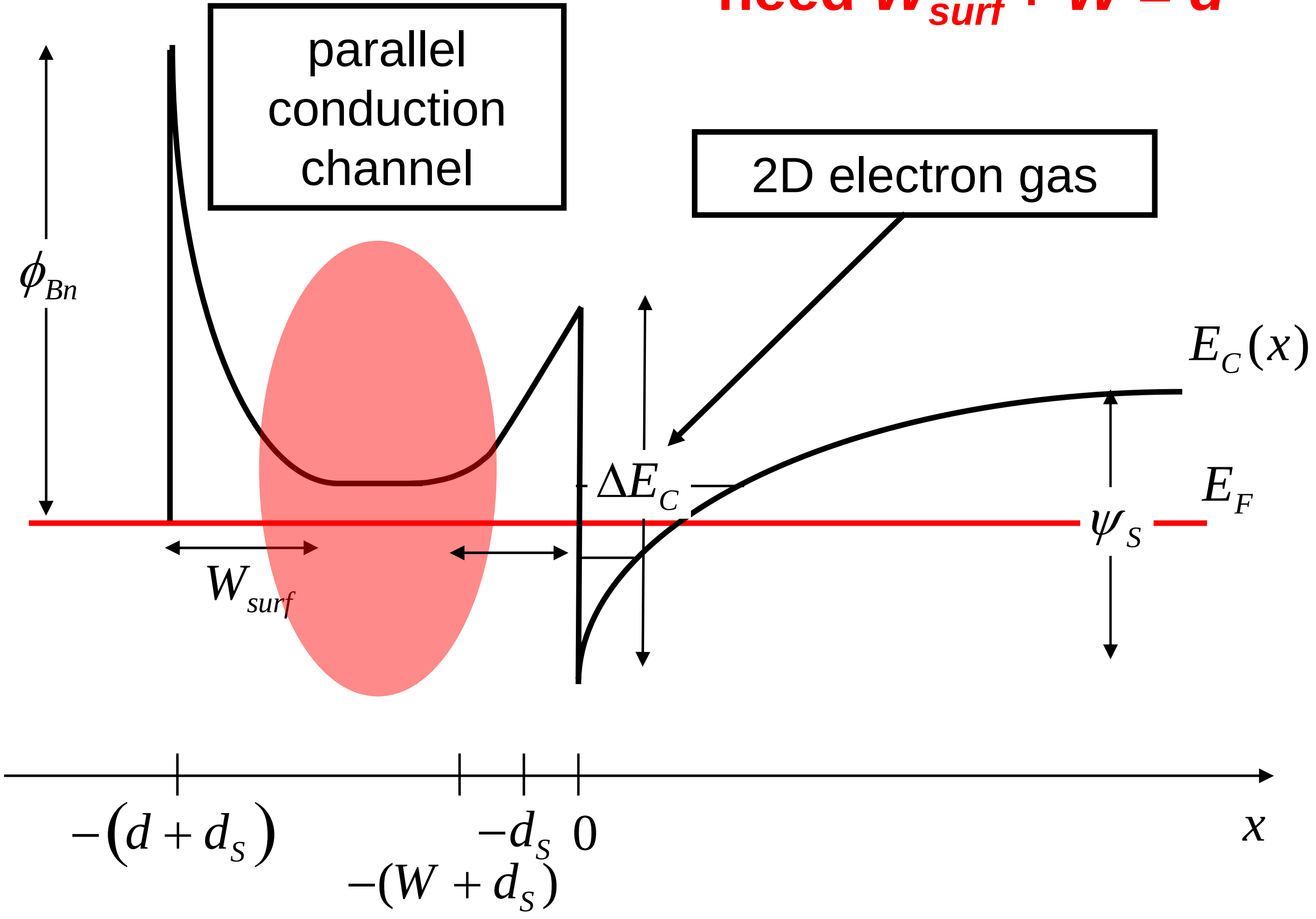
undoped, AlGaAs
spacer

equilibrium energy band diagram



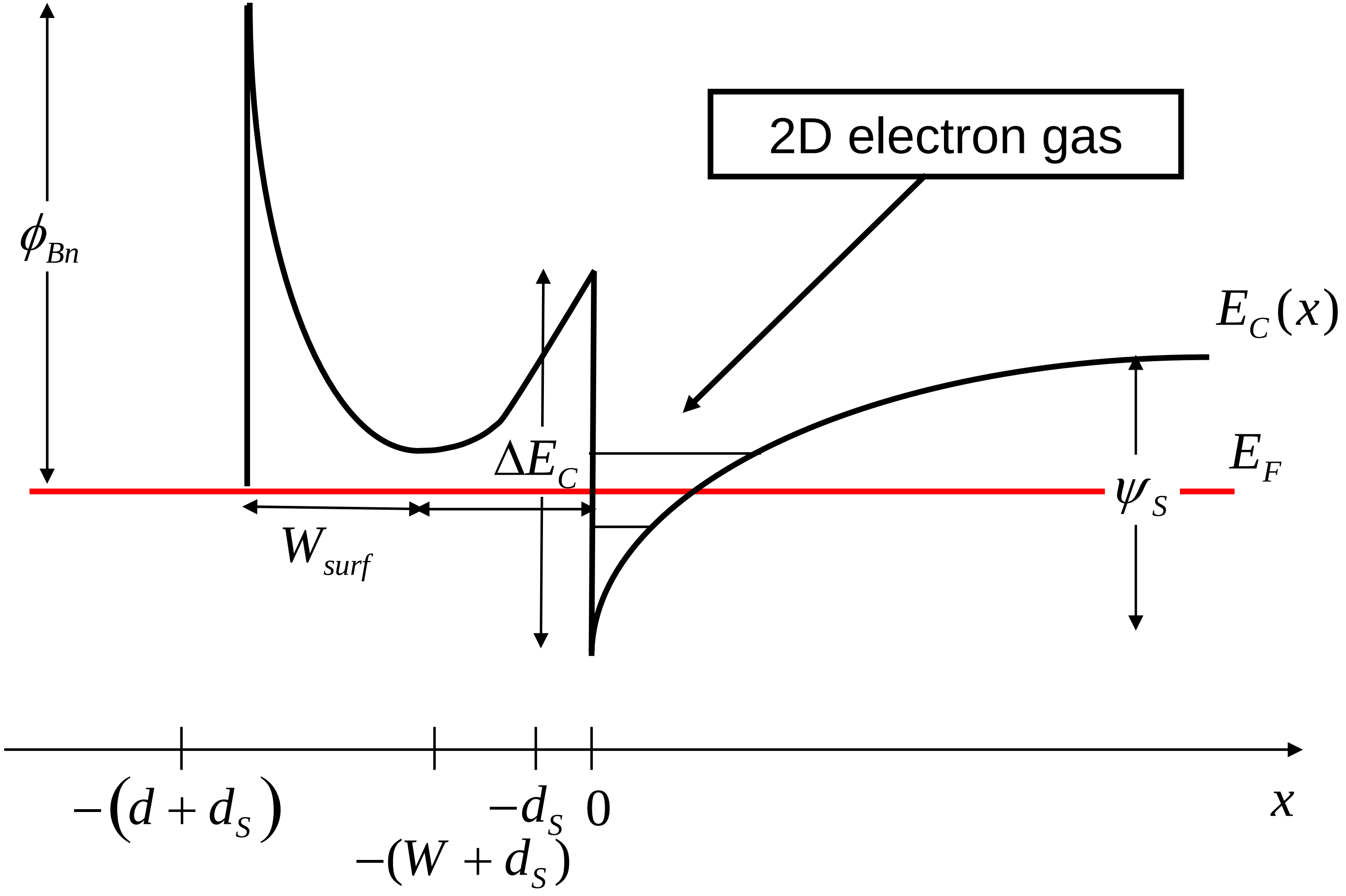
parallel conduction

need $W_{surf} + W = d$



equilibrium energy band diagram

$W_{surf} + W = d$



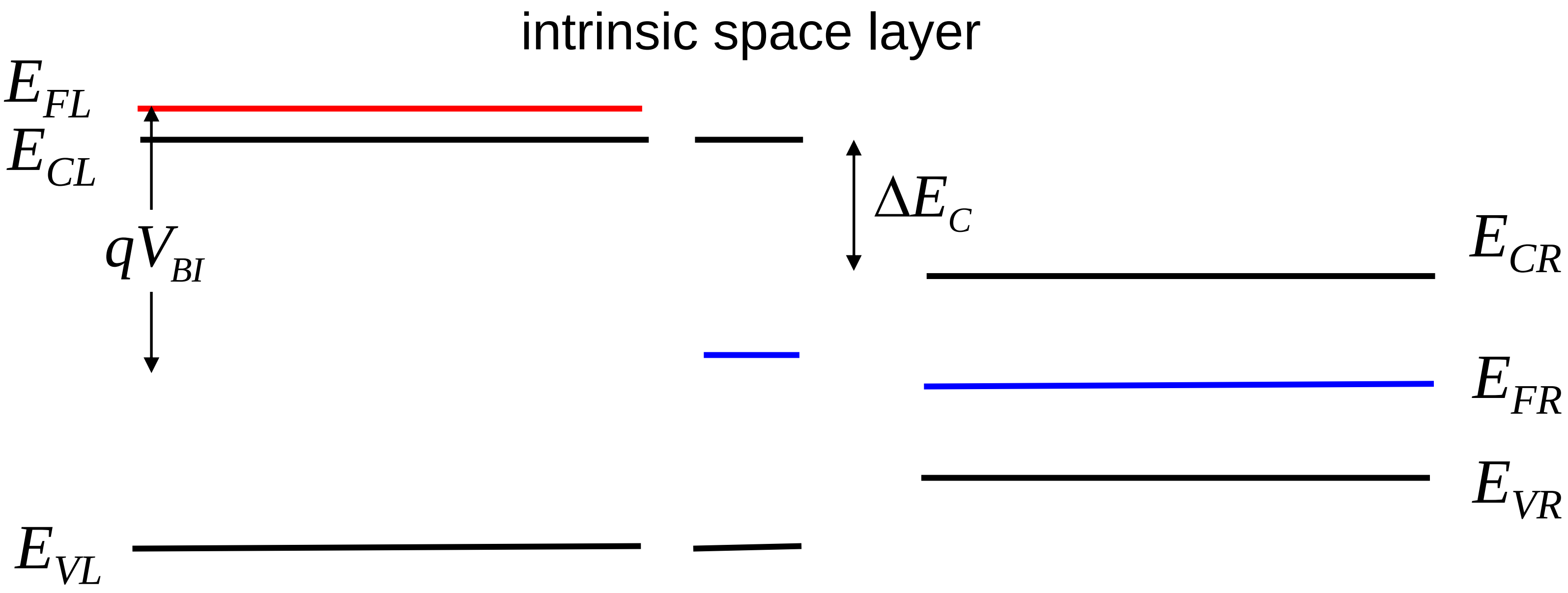
2D electron gas density

How is the the 2DEG density (per cm^2) related to the spacer layer thickness, AlGaAs doping density, conduction band discontinuity?

1) numerical solutions (Schrödinger-Poisson)

2) approximate analytical calculations

charge transfer



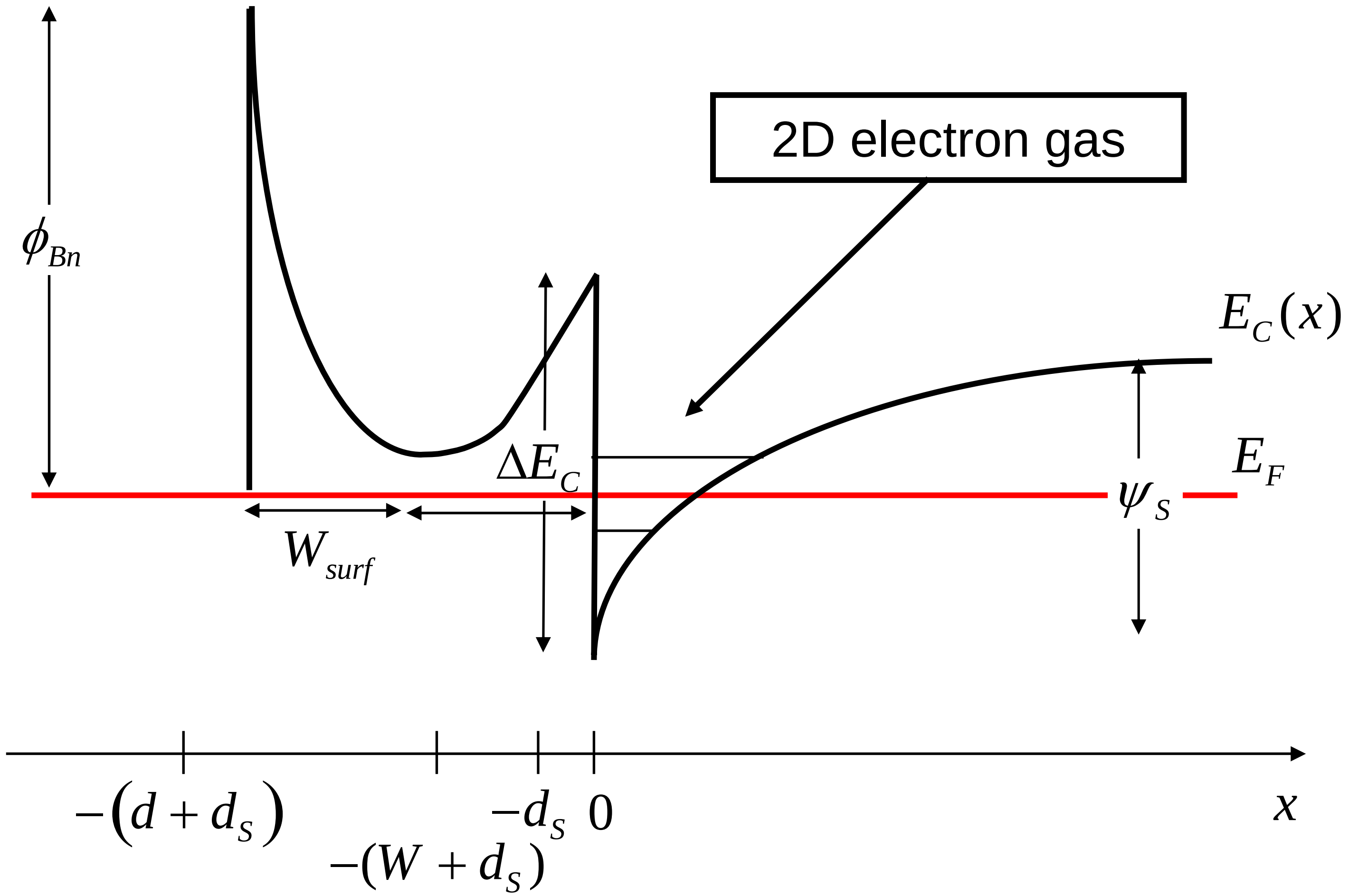
$$qV_{BI} = E_{FL} - E_{FR} \qquad E_{FR} = E_{CL} - \Delta E_C - E_G/2$$

$$qV_{BI} = \underbrace{\left(E_{FL} - E_{CL}\right)}_{\text{doping}} + \underbrace{\Delta E_C}_{\text{band discontinuity}} + \Delta E_G/2$$

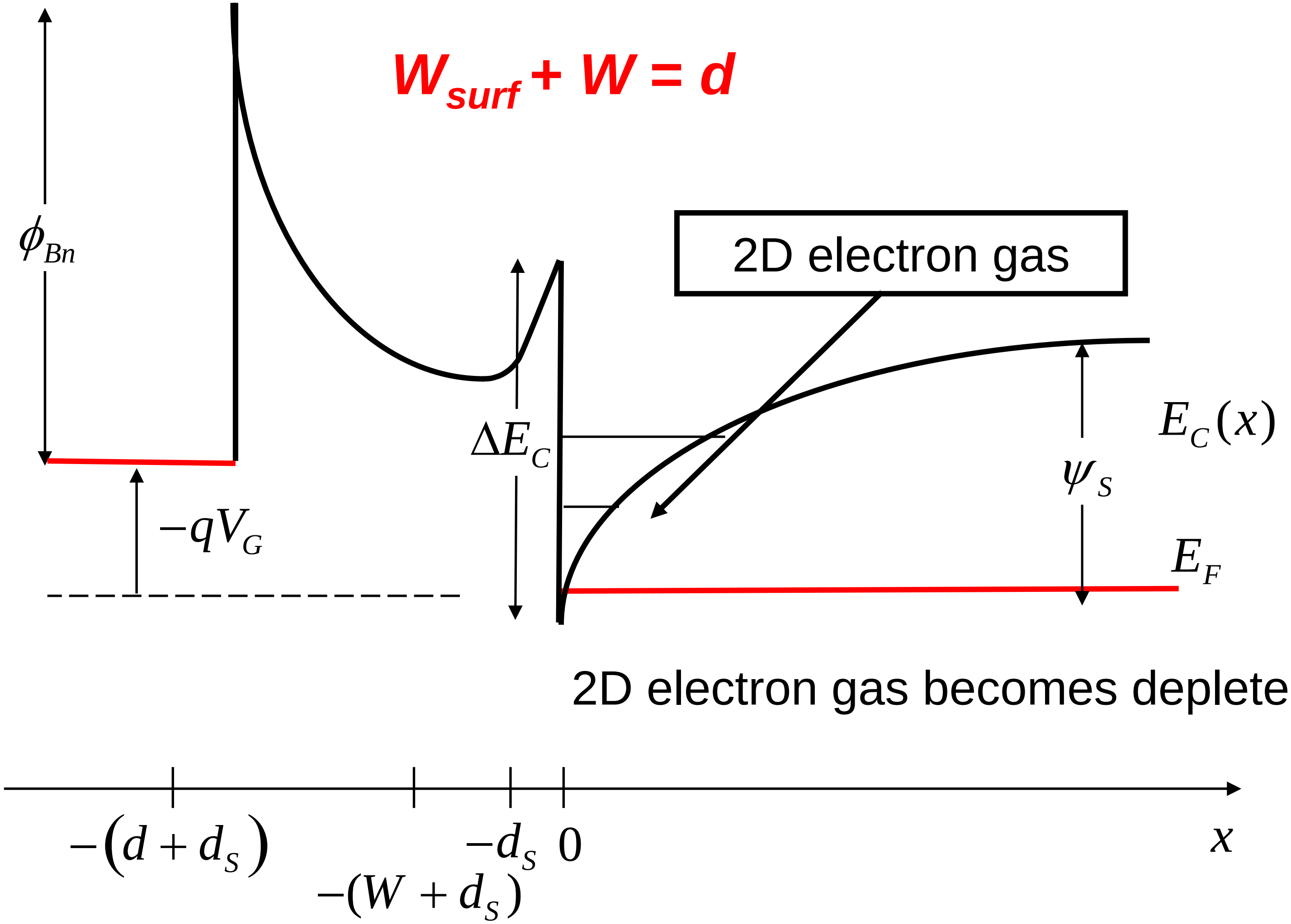
+ spacer thickness

V_G = 0 energy band diagram

$W_{surf} + W = d$

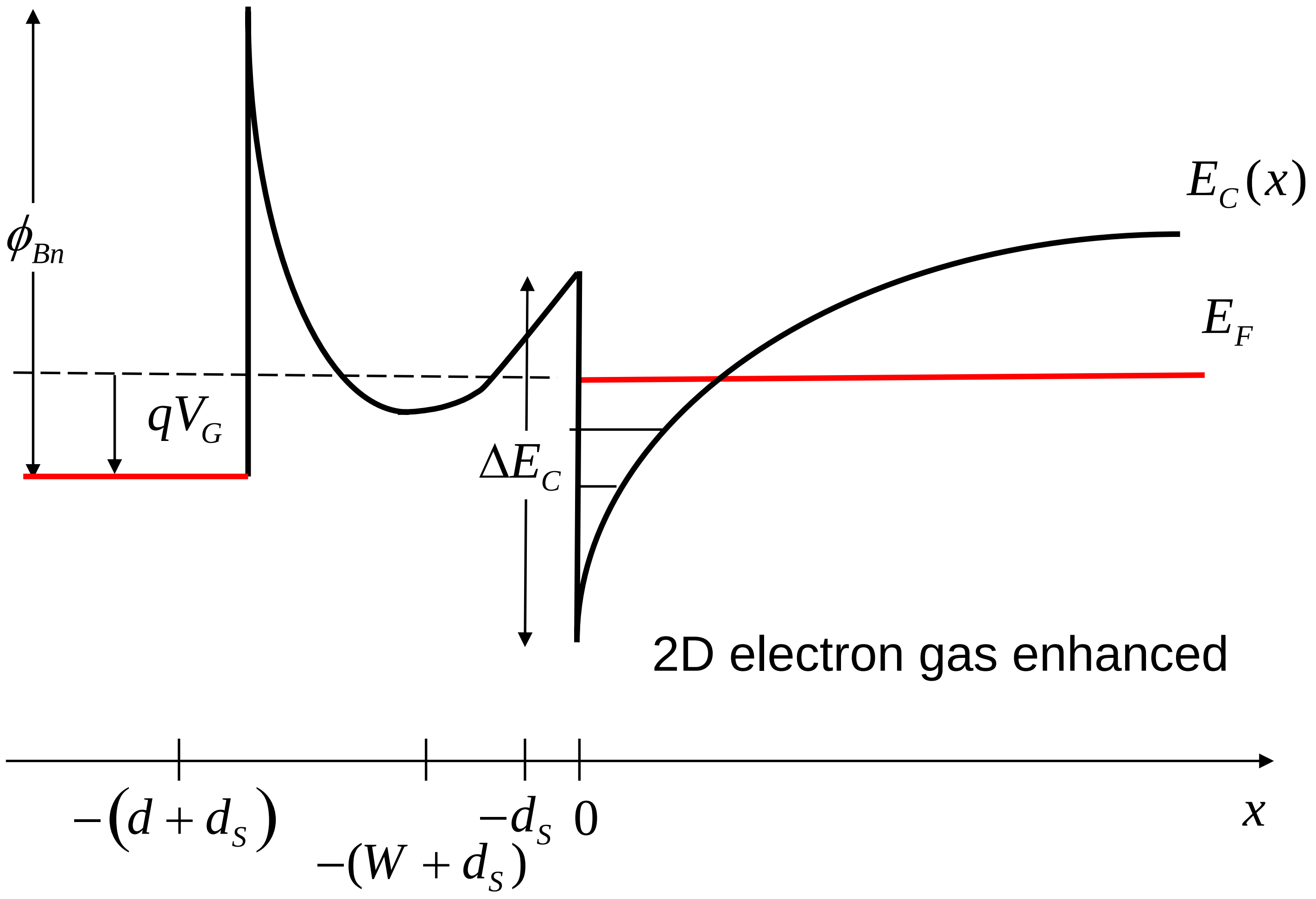


$V_G < 0$ energy band diagram



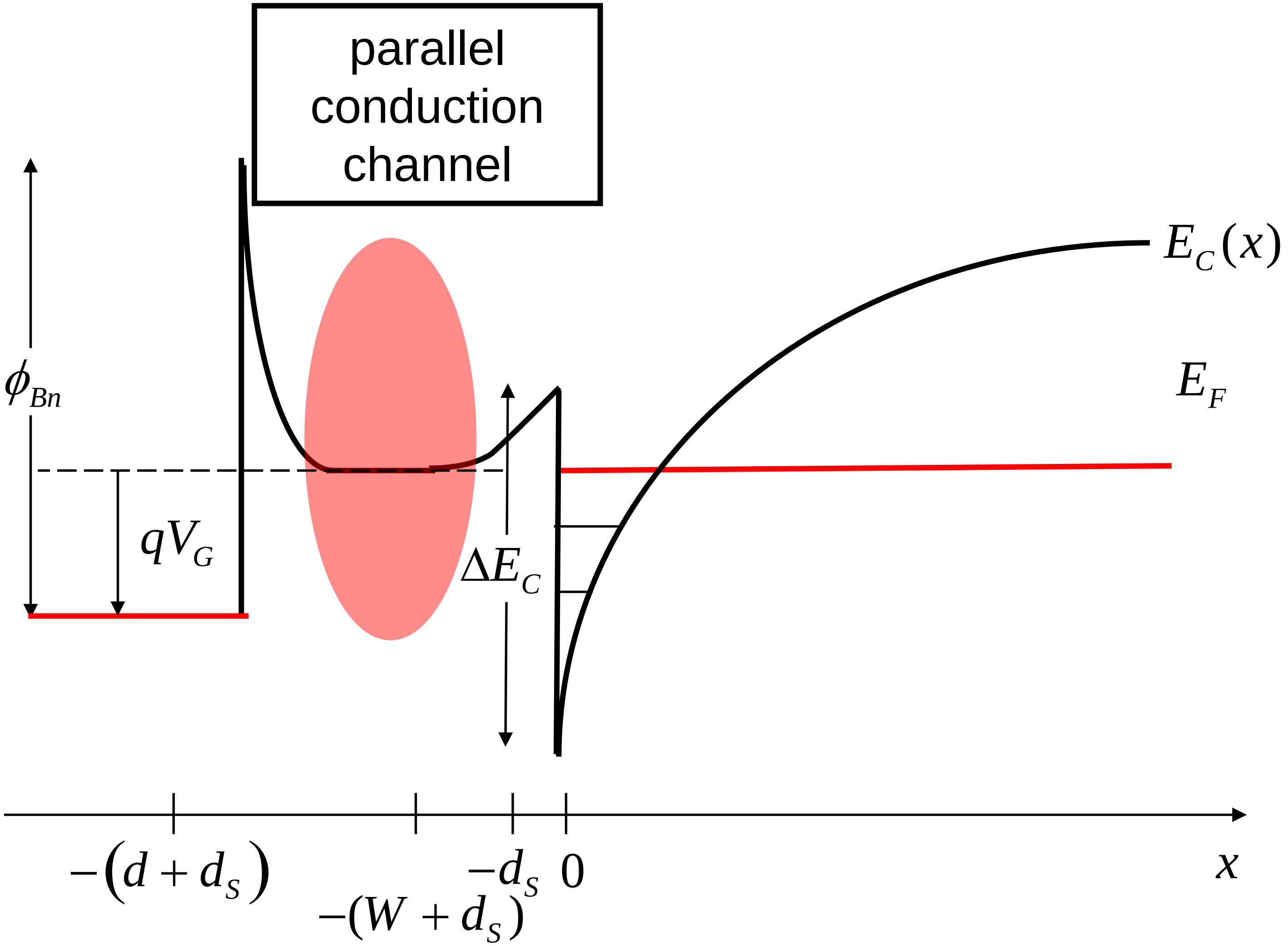
2D electron gas becomes depleted

$V_G > 0$ energy band diagram

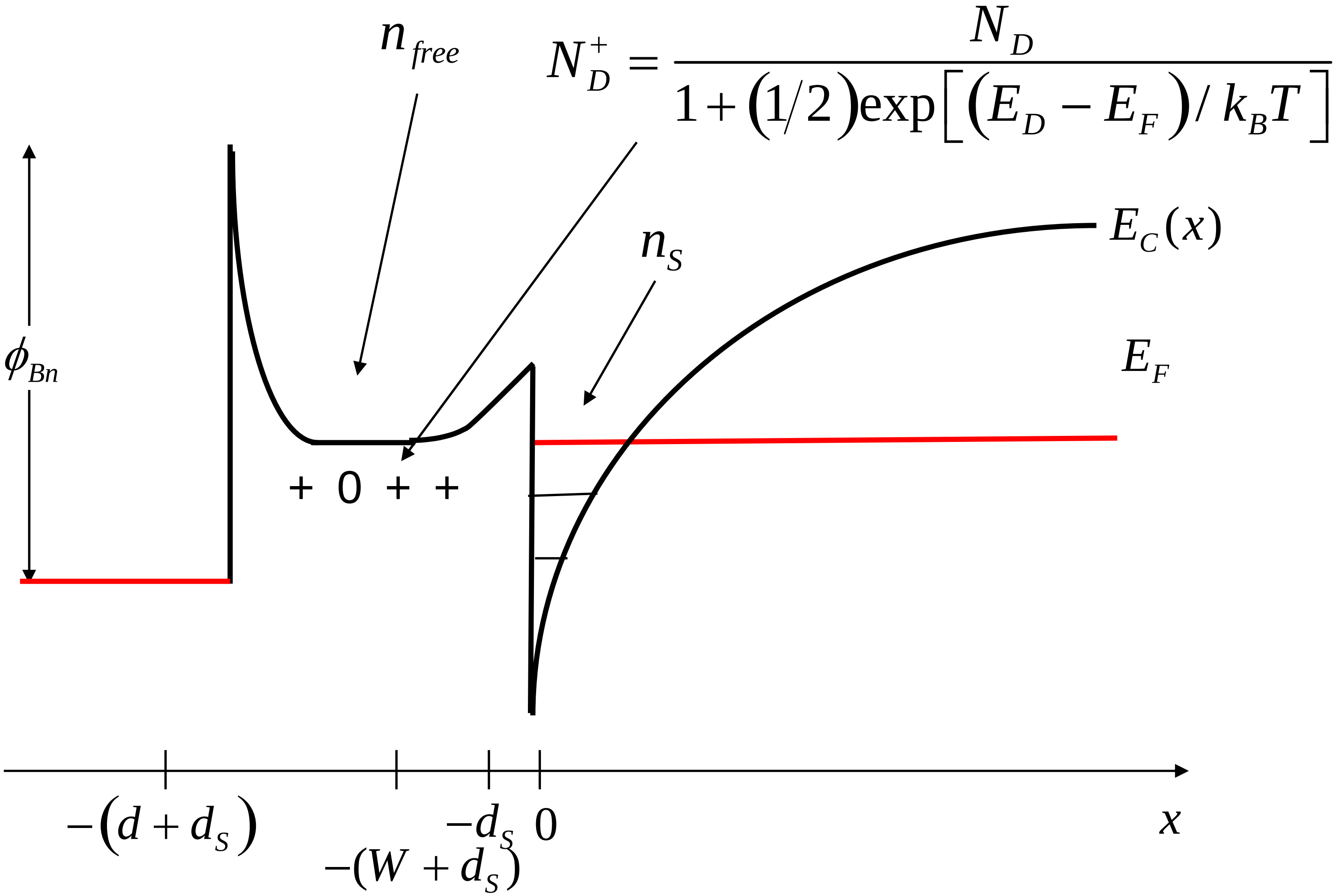


2D electron gas enhanced

$V_G >> 0$ energy band diagram

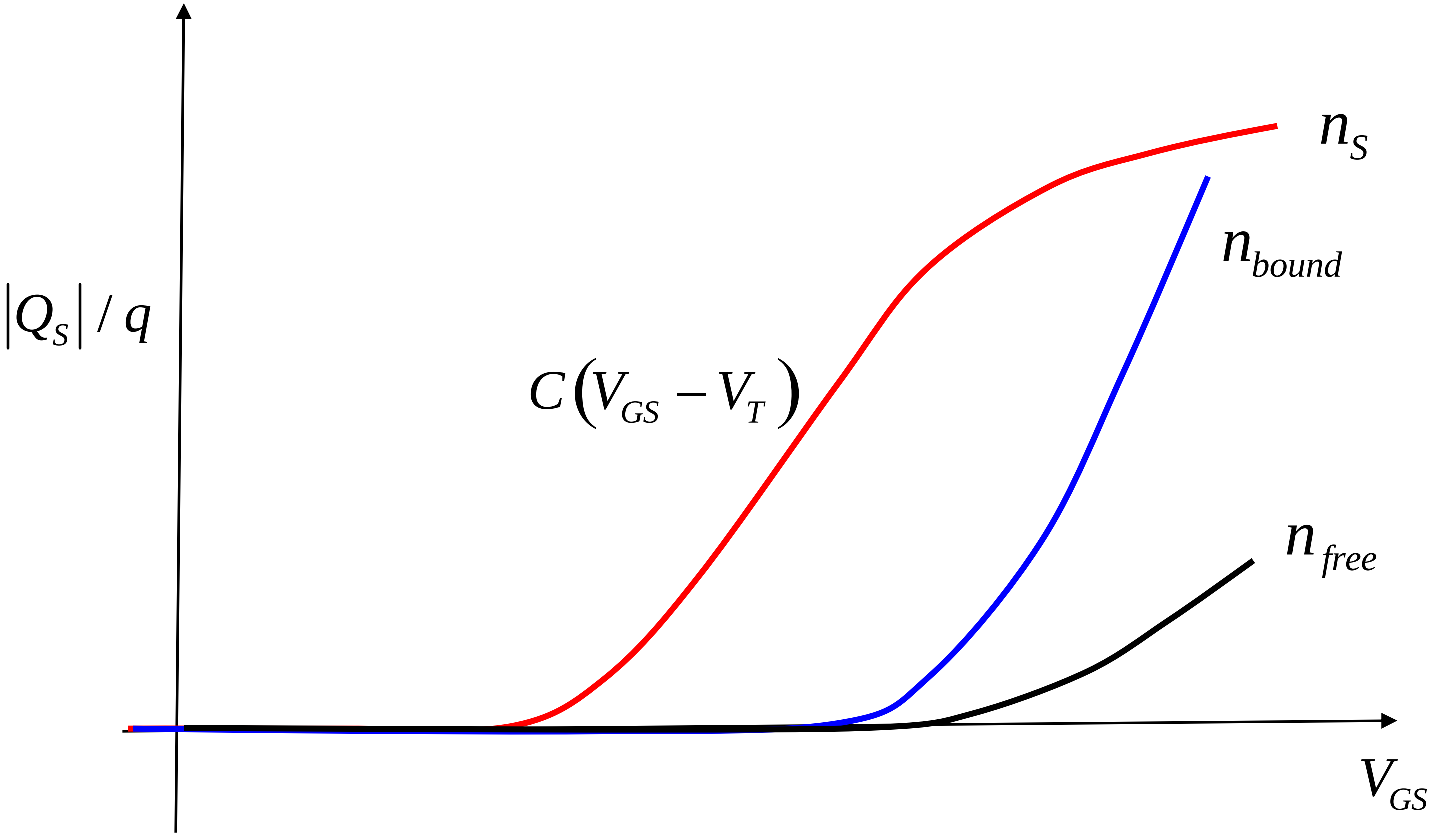


charges under forward bias

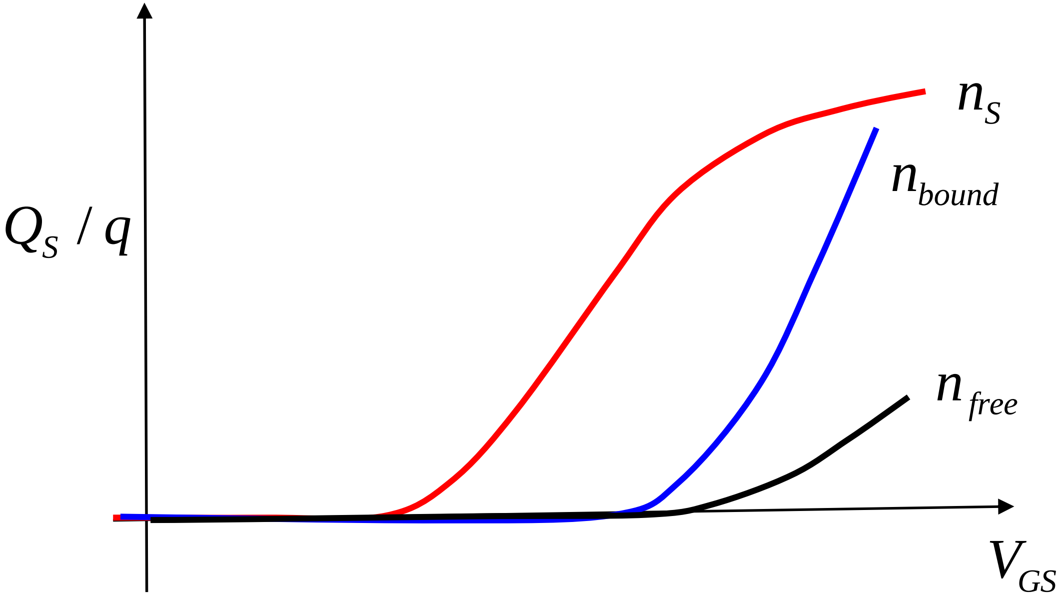


$$N_D^+ = \frac{N_D}{1 + \left(1/2\right)\exp\left[\left(E_D - E_F\right)/k_B T\right]}$$

charges under forward bias

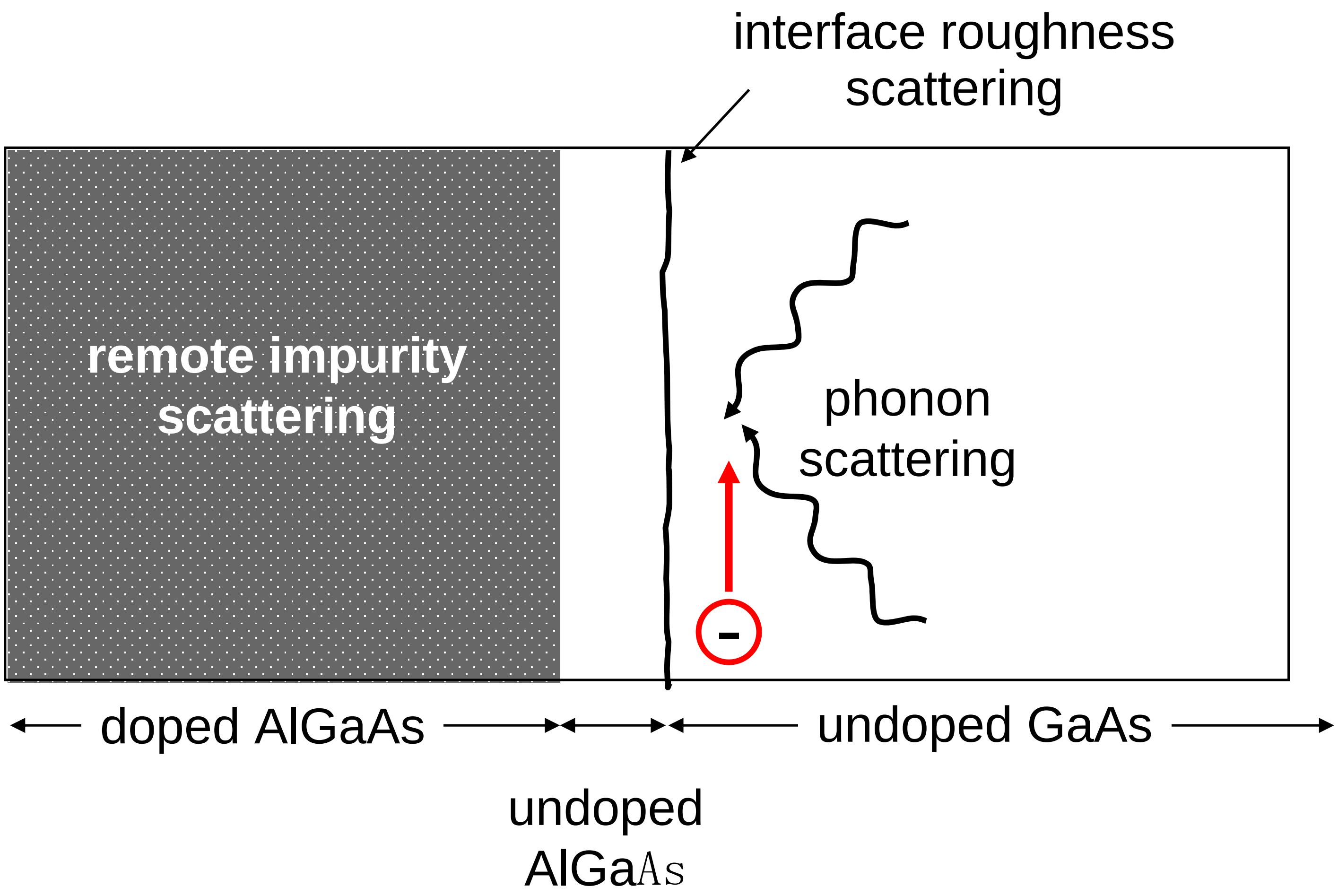


modulation efficiency



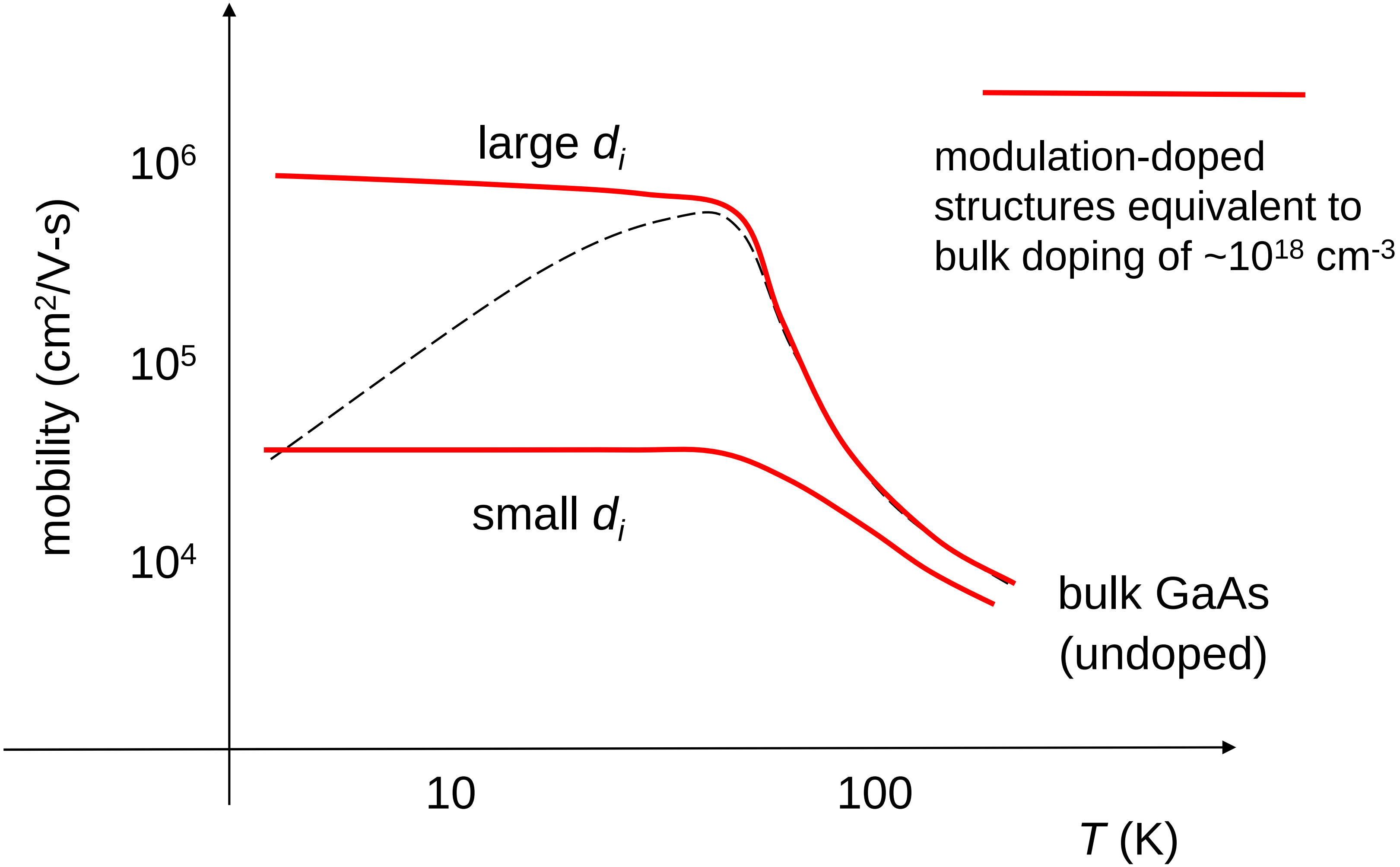
$$\eta = \frac{\partial n_S / \partial V_G}{\partial \left(n_S + n_{bound} + n_{free} \right) / \partial V_G} = \frac{C_S}{C_{TOT}}$$

scattering mechanisms



(after Solomon and Morkoc)

mobility vs. temperature



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I-V characteristics

First order model is much like a velocity saturated MOSFET

$$I_D = \mu_{2D} C_{INS} \frac{W}{L} \left[\left(V_{GS} - V_T \right) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \qquad \begin{array}{l} V_{GS} > V_T \\ V_{DS} < V_{DSAT} \end{array}$$

$$C_{INS} = \frac{\varepsilon_{AlGaAs}}{d}$$

$$I_D = W C_{INS} \upsilon_{SAT} \left(V_{GS} - V_T \right) \qquad \begin{array}{l} V_{GS} > V_T \\ V_{DS} > V_{DSAT} \end{array}$$

$$\upsilon_{SAT} \approx 2 - 3 \times 10^7 \text{ cm/s}$$

g_m compression

For large V_{GS}:

$$I_D \neq W C_{INS} \upsilon_{SAT} \left(V_{GS} - V_T\right) \qquad I_D = W \upsilon_{SAT} n_S$$

$$g_m = W \upsilon_{SAT} \frac{\partial n_S}{\partial V_{GS}}$$

$$f_T = \frac{g_m}{2\pi C_{GS}} = \frac{W \upsilon_{SAT}}{2\pi W L} \frac{\partial n_S / \partial V_{GS}}{C_{TOT}} = \frac{1}{2\pi t_t} \eta$$

$$g_m^{ext} = \frac{g_{mo}}{1 + g_{mo} R_S}$$

series resistance very important

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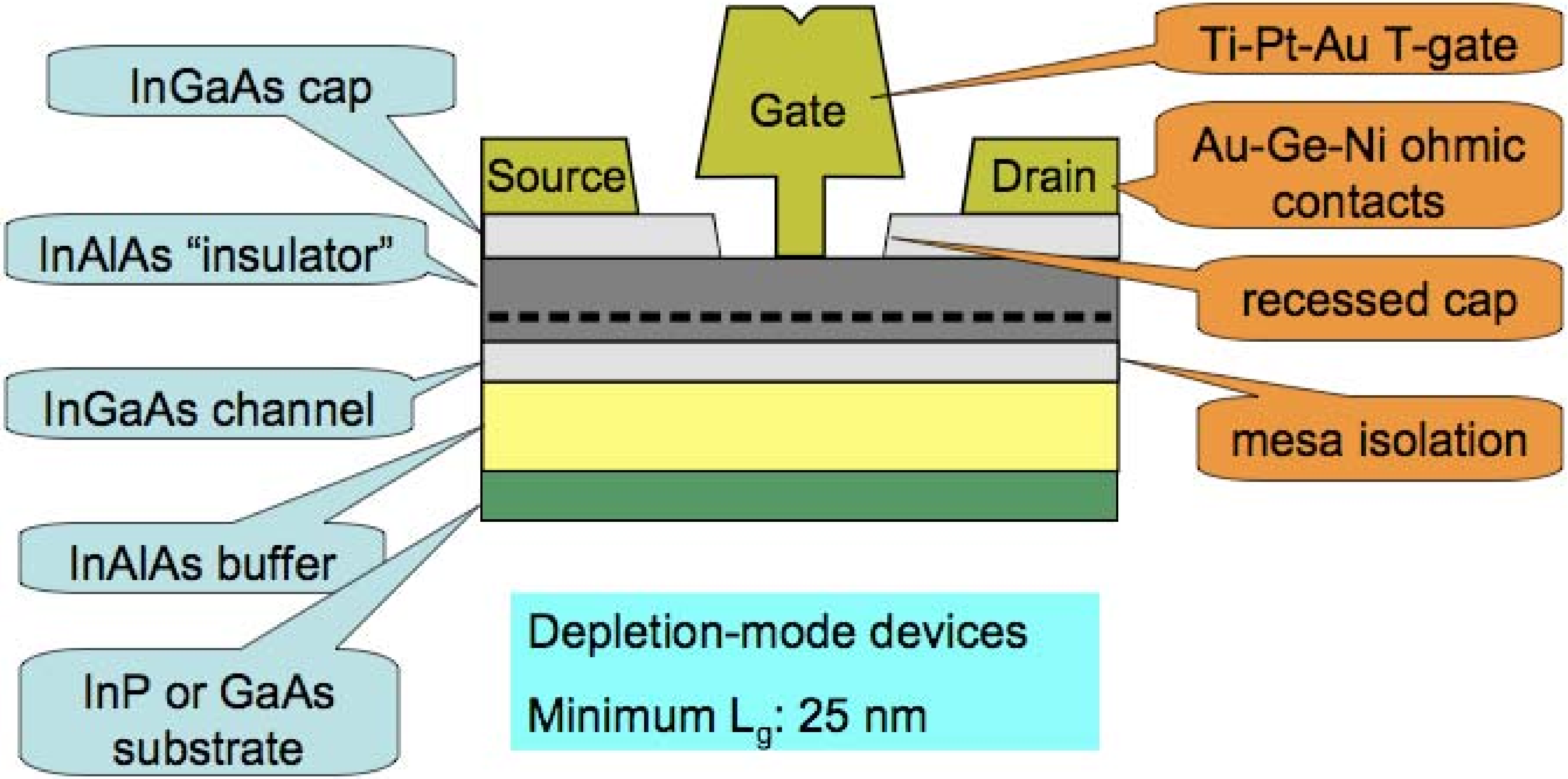
device performance

The following results were provided by J.A. del Alamo, D.-H. Kim, and N. Waldron, MIT

InGaAs HEMT



Depletion-mode devices

Minimum L_g: 25 nm

layer structure

Multilayer cap

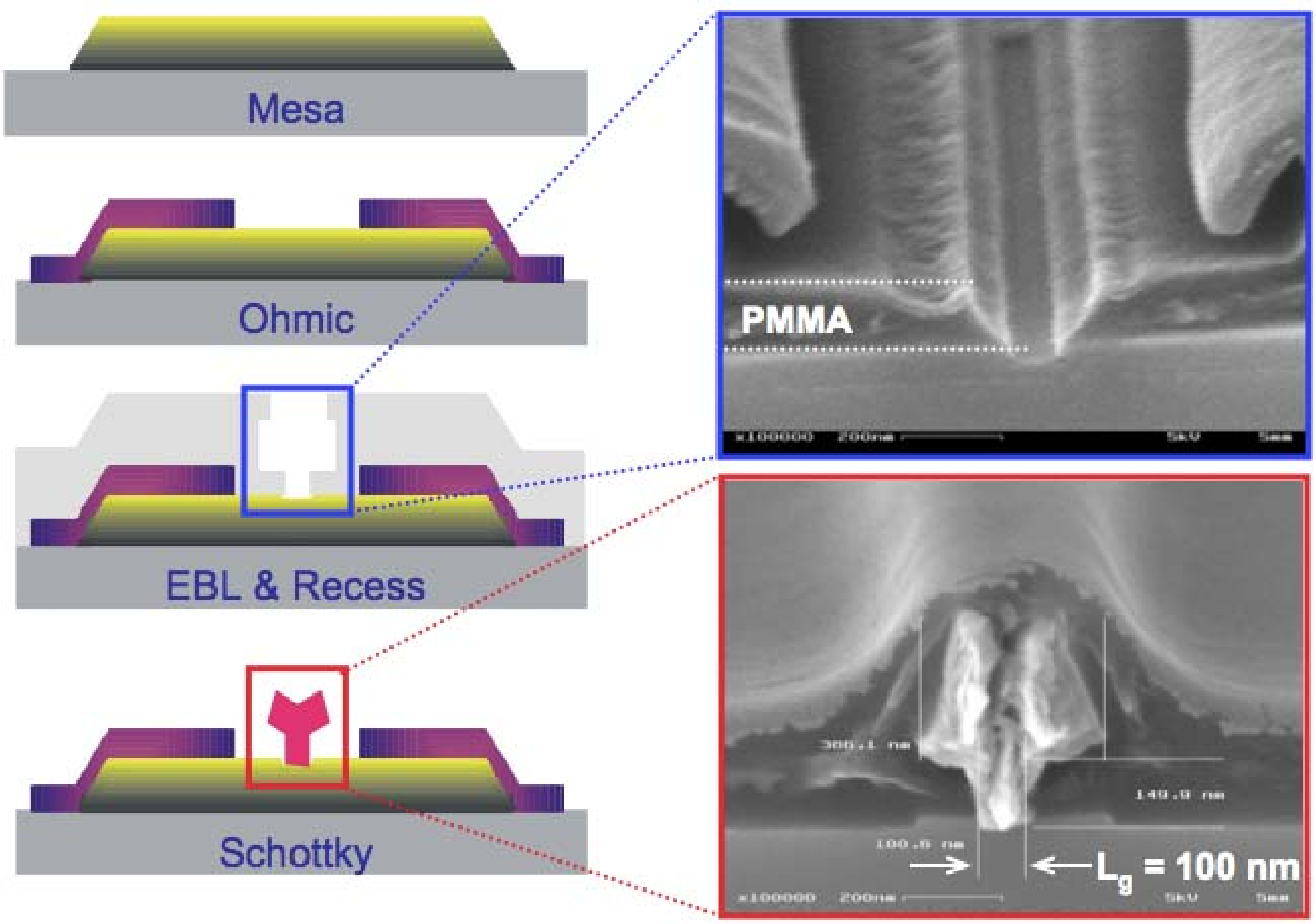
n+ Cap	**$In_{0.65}Ga_{0.35}As$**	**5 nm**
	$In_{0.53}Ga_{0.47}As$	15 nm
	$In_{0.52}Al_{0.48}As$	**15 nm**
Stopper	**InP**	**6 nm**
Barrier	$In_{0.52}Al_{0.48}As$	8 nm
δ-doping	Si	-
Spacer	$In_{0.52}Al_{0.48}As$	3 nm
Channel	$In_{0.53}Ga_{0.47}As$	2 nm
	$In_{0.7}Ga_{0.3}As$	**8 nm**
	$In_{0.53}Ga_{0.47}As$	3 nm
Buffer	$In_{0.52}Al_{0.48}As$	500 nm

Strained MQW

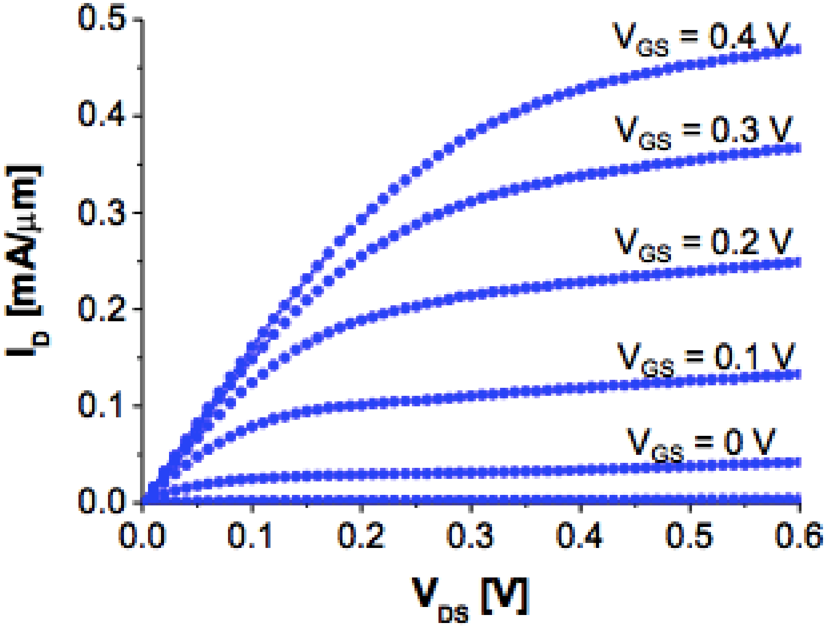
3 Inch S. I. InP Substrate

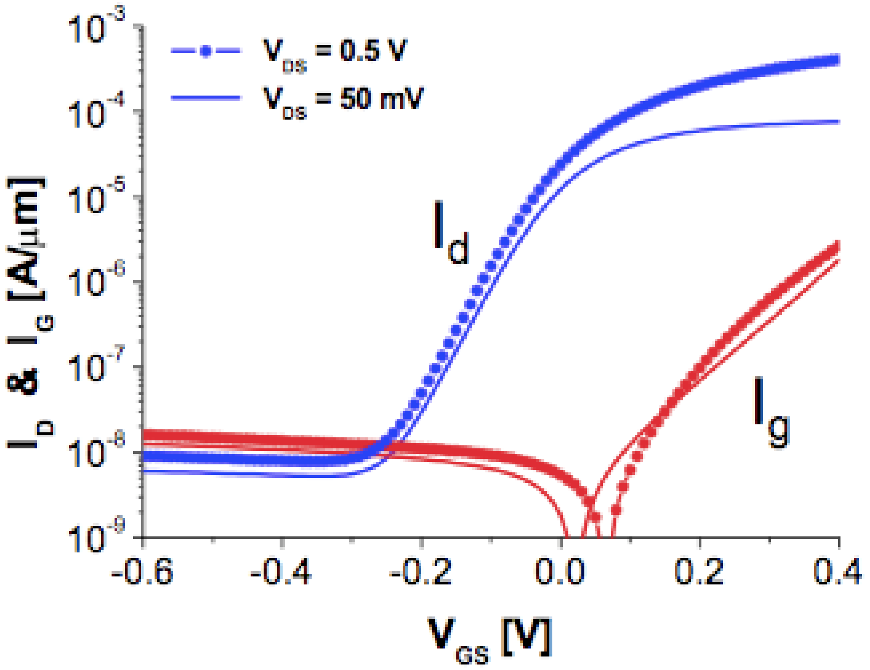
- ➔ N_{sh} = ~ 3×10^{12} /cm² @ 300 K
- ➔ $\mu_{n,Hall}$ = ~ 11,000 cm²/V-sec @ 300 K

device fabrication



IV characteristics of 60nm InGaAs HEMT

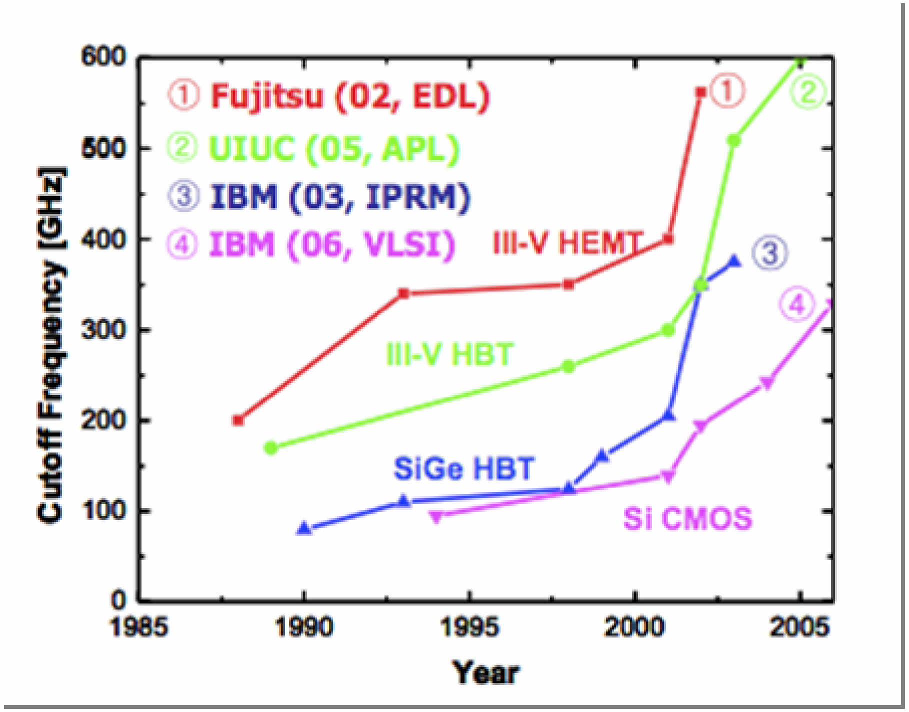




At 0.5 V:

V_T= -0.11 V, S= 70 mV/dec, DIBL= 44 mV/V, I_{on}/I_{off}= 2.7×10^4

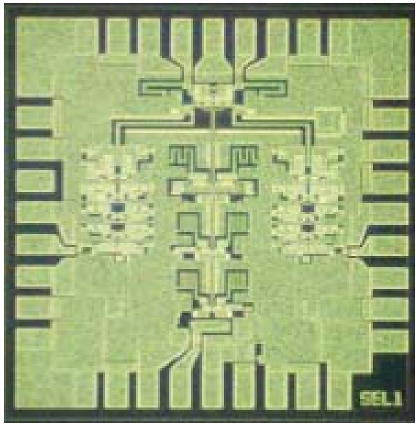
InGaAs HEMT technology



Fairly mature technology at SSI level:

- 120 Gb/s MUX (NEC, 2004)
- 110 Gb/s DEMUX (NEC, 2004)
- 140 Gb/s Selector (Fujitsu, 2004)
- 160-215 GHz Amp (TRW, 2002)
- Space qualified

100Gb/s selector IC
(NTT 2003)



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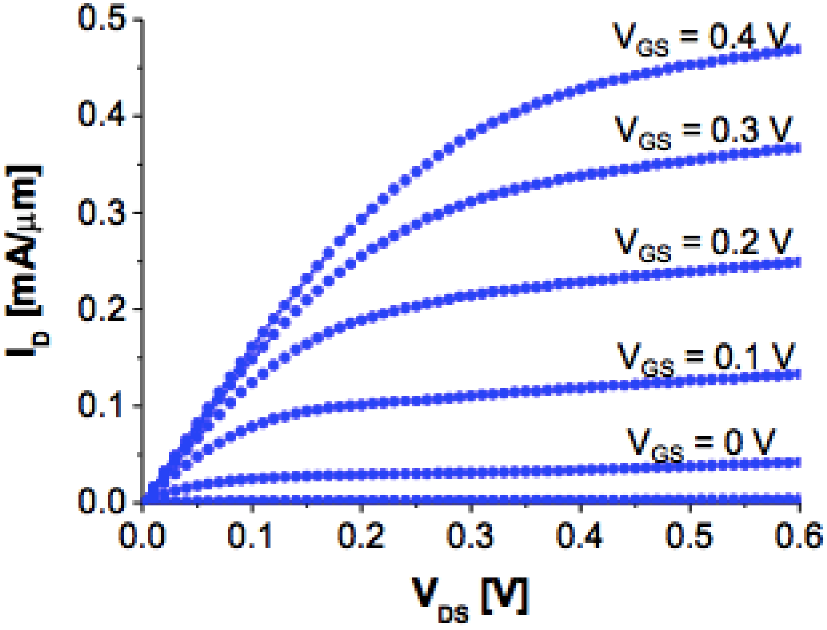
summary

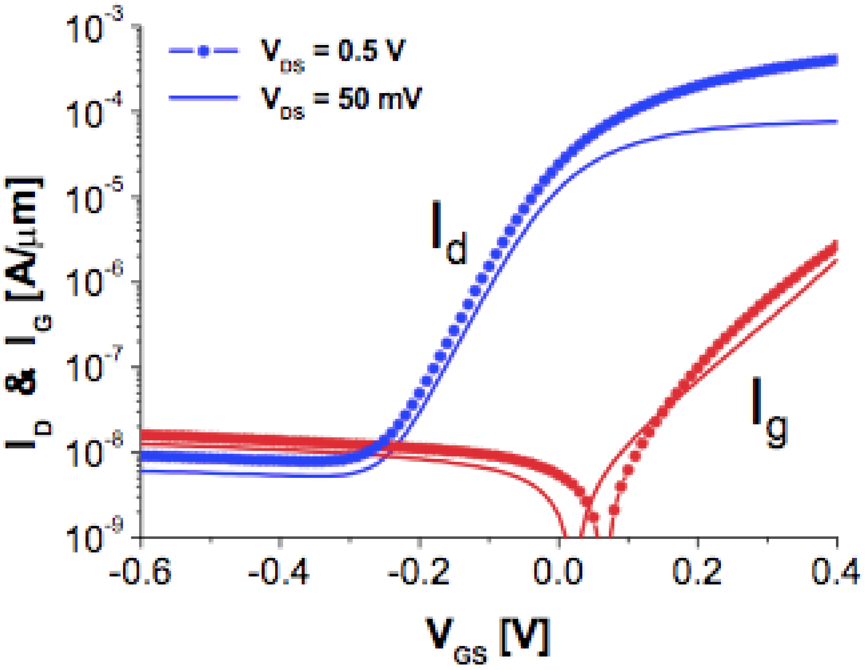
1) III-V FETs are an important technology for high-frequency rf applications
2) III-V FETs are currently being explored for possible applications in low-voltage, digital CMOS.

Thanks to Prof. J. del Alamo for providing the InGaAs HEMT results and to Prof. P. Ye for providing the InGaAs MOSFET results.

Questions & Answers

IV characteristics of 60nm InGaAs HEMT





At 0.5 V:

V_T= -0.11 V, S= 70 mV/dec, DIBL= 44 mV/V, I_{on}/I_{off}= 2.7x10^4