

EE-612: Lecture 26: Heterostructure FETs

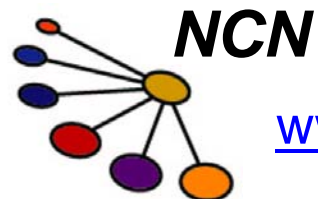
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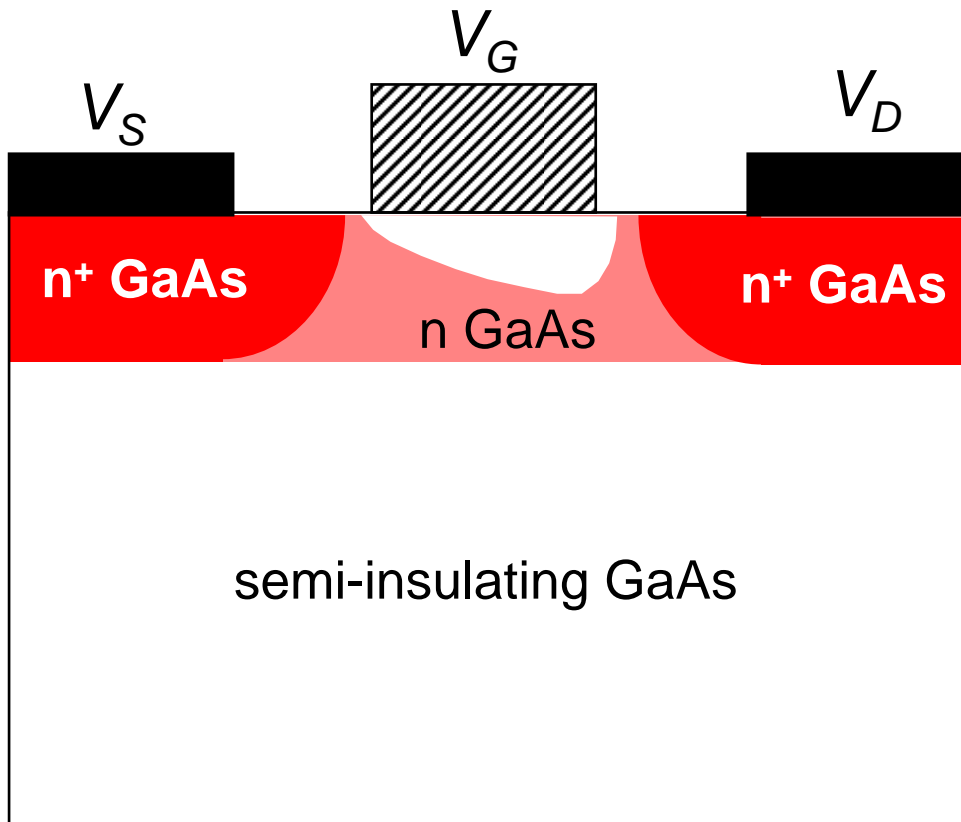


www.nanohub.org

outline

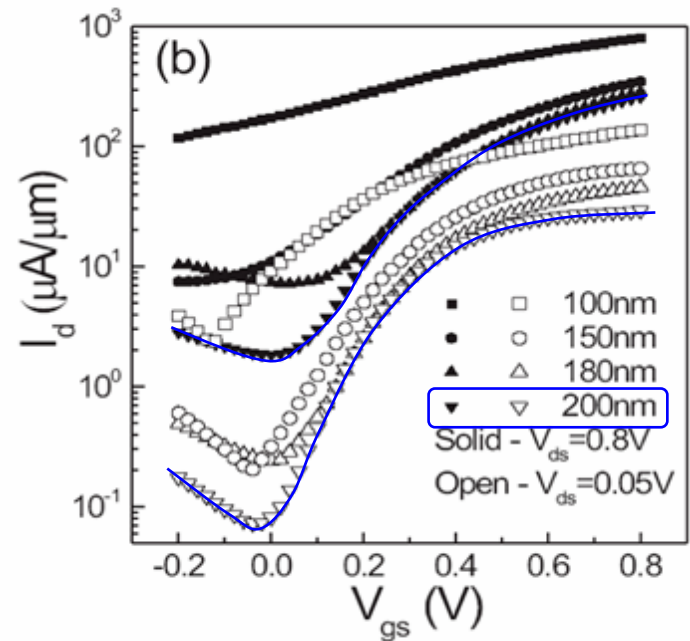
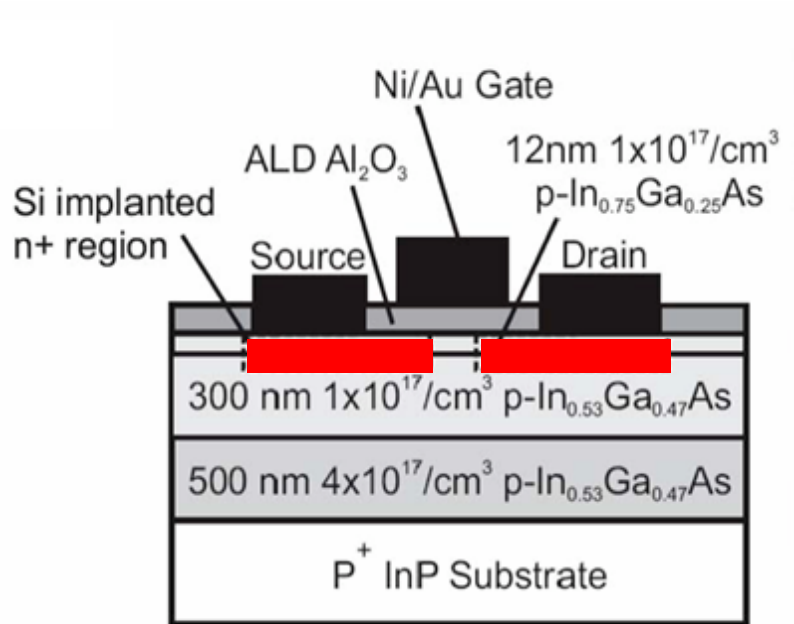
- I) **Introduction**
- II) Heterojunction review
- III) Modulation doping
- IV) I-V characteristics
- V) Device Structure / Materials
- VI) Summary

GaAs MESFET



- high mobility
 $\mu(10^{14}) \sim 8500 \text{ cm}^2/\text{V-s}$
- for high g_m , need both charge and velocity
- mobility and doping
 $\mu(10^{17}) \sim 4700 \text{ cm}^2/\text{V-s}$
 $\mu(10^{18}) \sim 2800 \text{ cm}^2/\text{V-s}$
- 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 In_{0.75}Ga_{0.25}As MOSFET," submitted for publication, 2008.

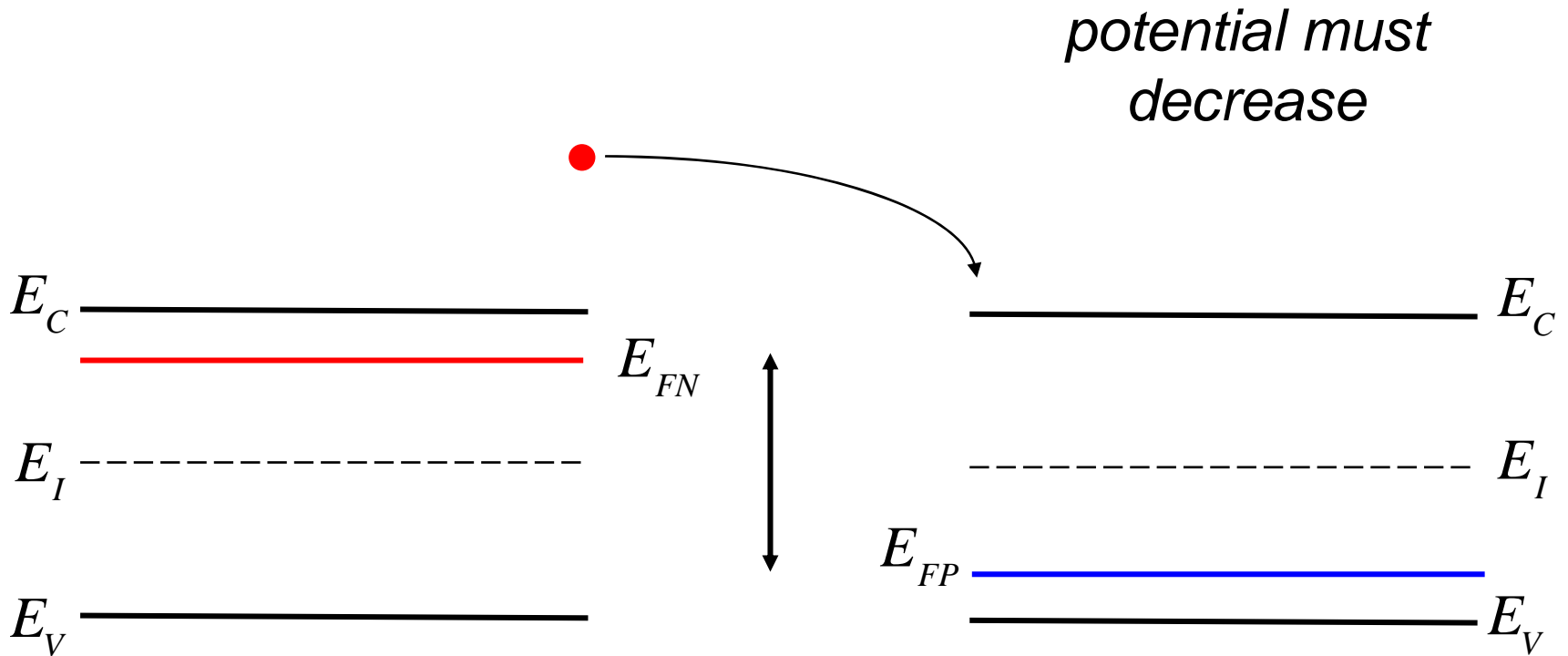
Heterostructure FETs

- 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.

outline

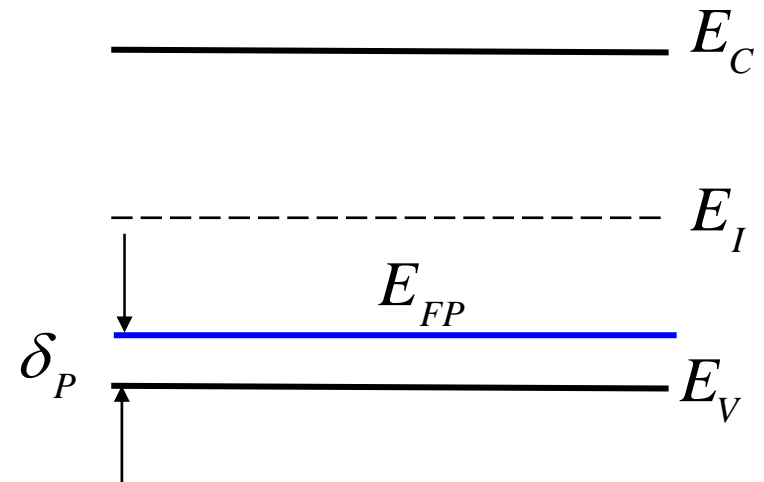
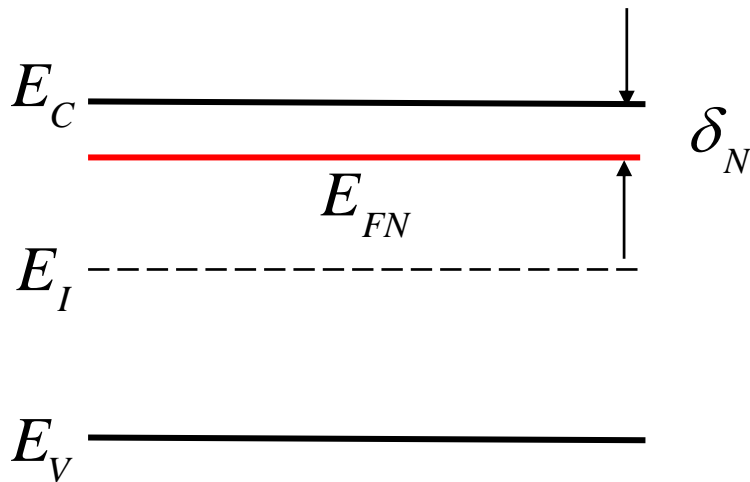
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review: pn homojunctions



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

built-in potential



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

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

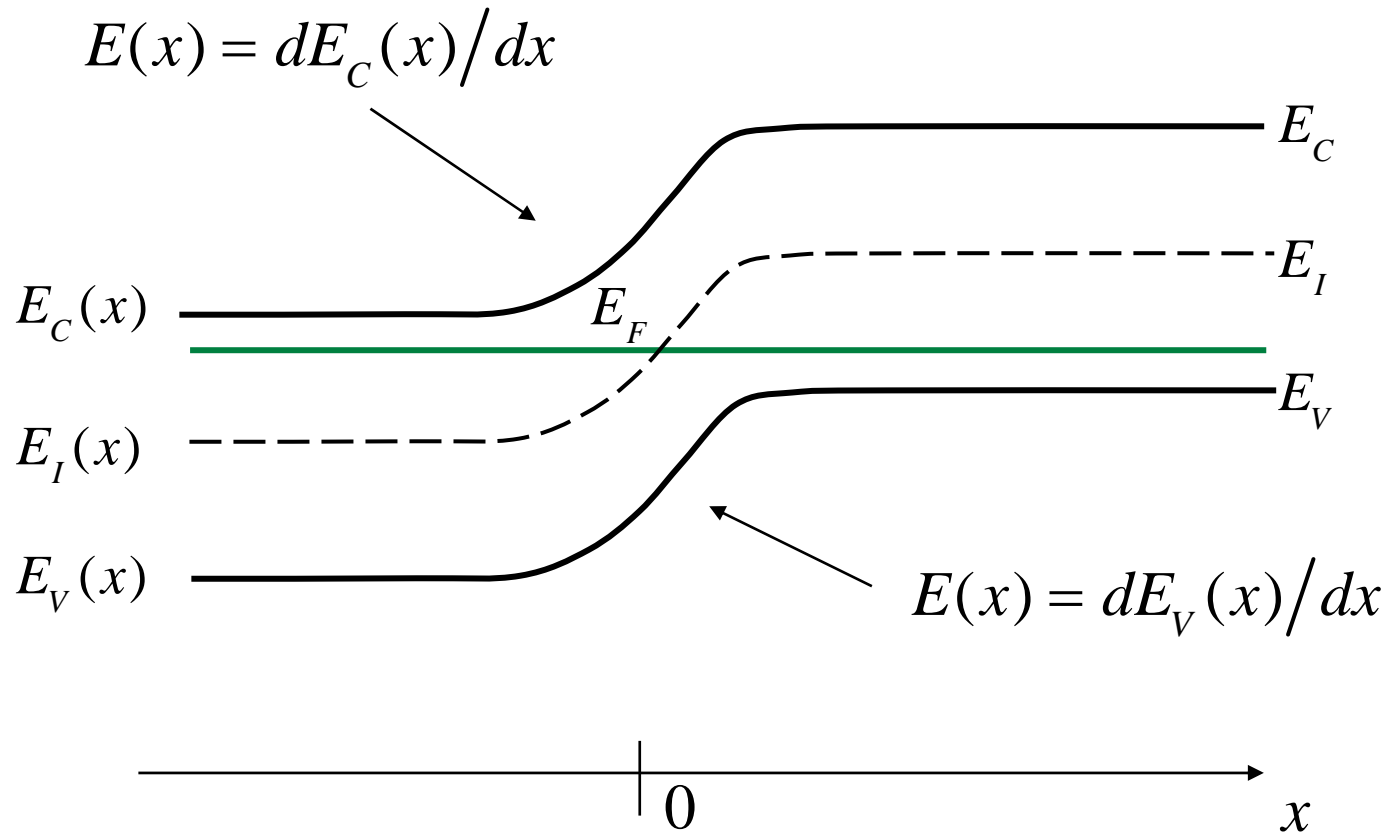
$$qV_{BI} = (E_C - E_V) - \delta_N - \delta_P$$

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

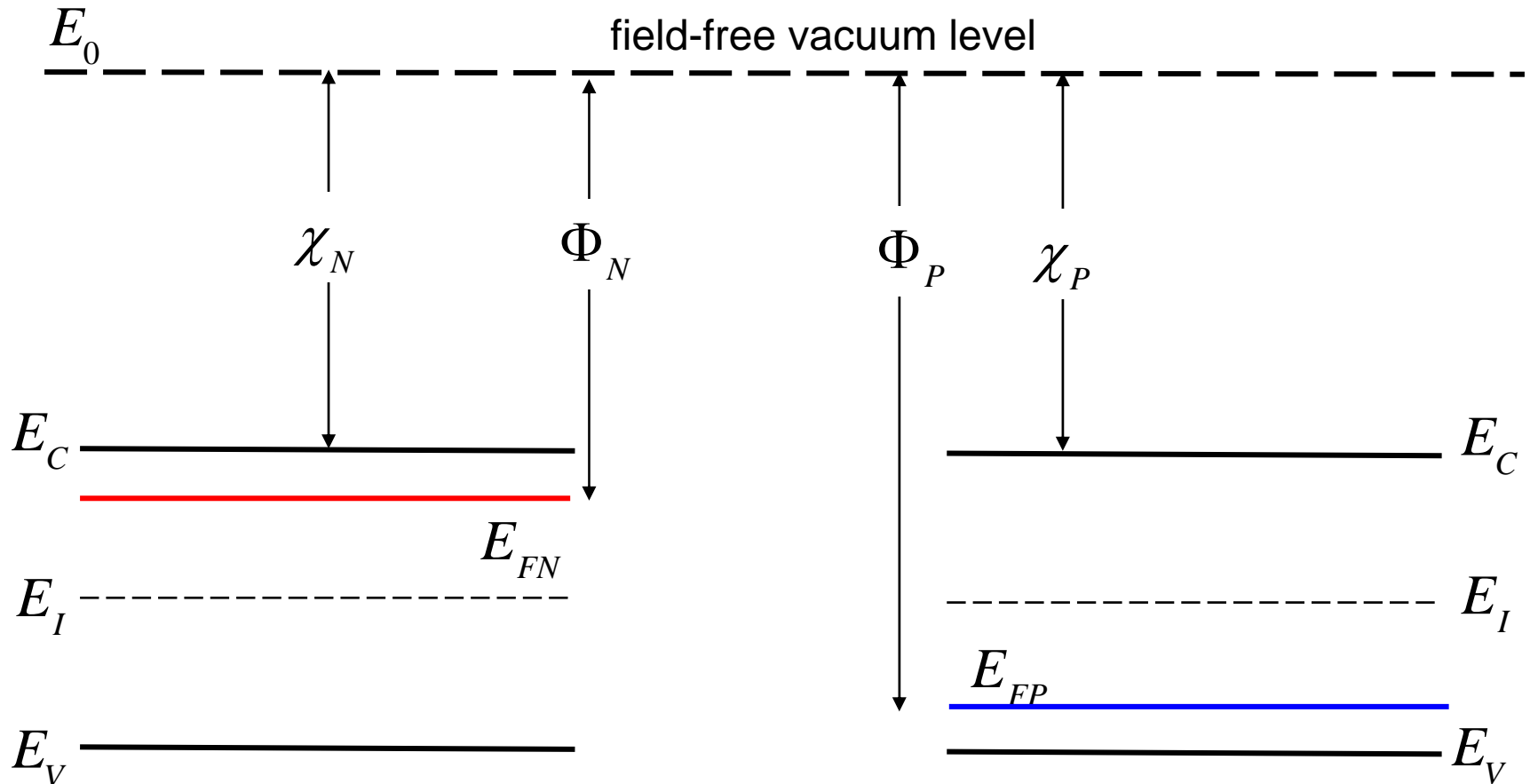
$$qV_{BI} = E_G - \delta_N - \delta_P$$

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

review: pn homojunctions



reference for the energy bands?

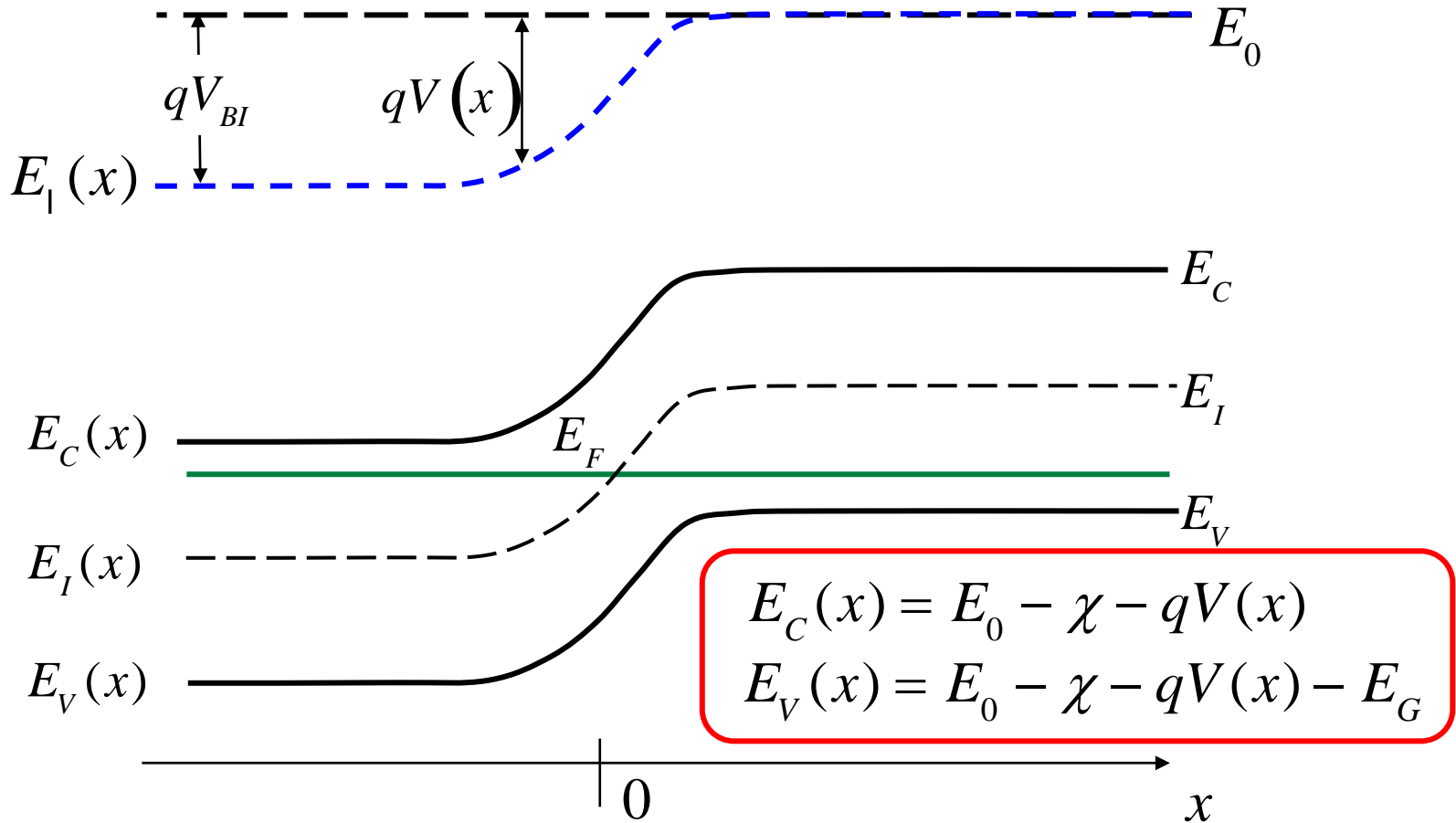


$$E_C = E_0 - \chi$$

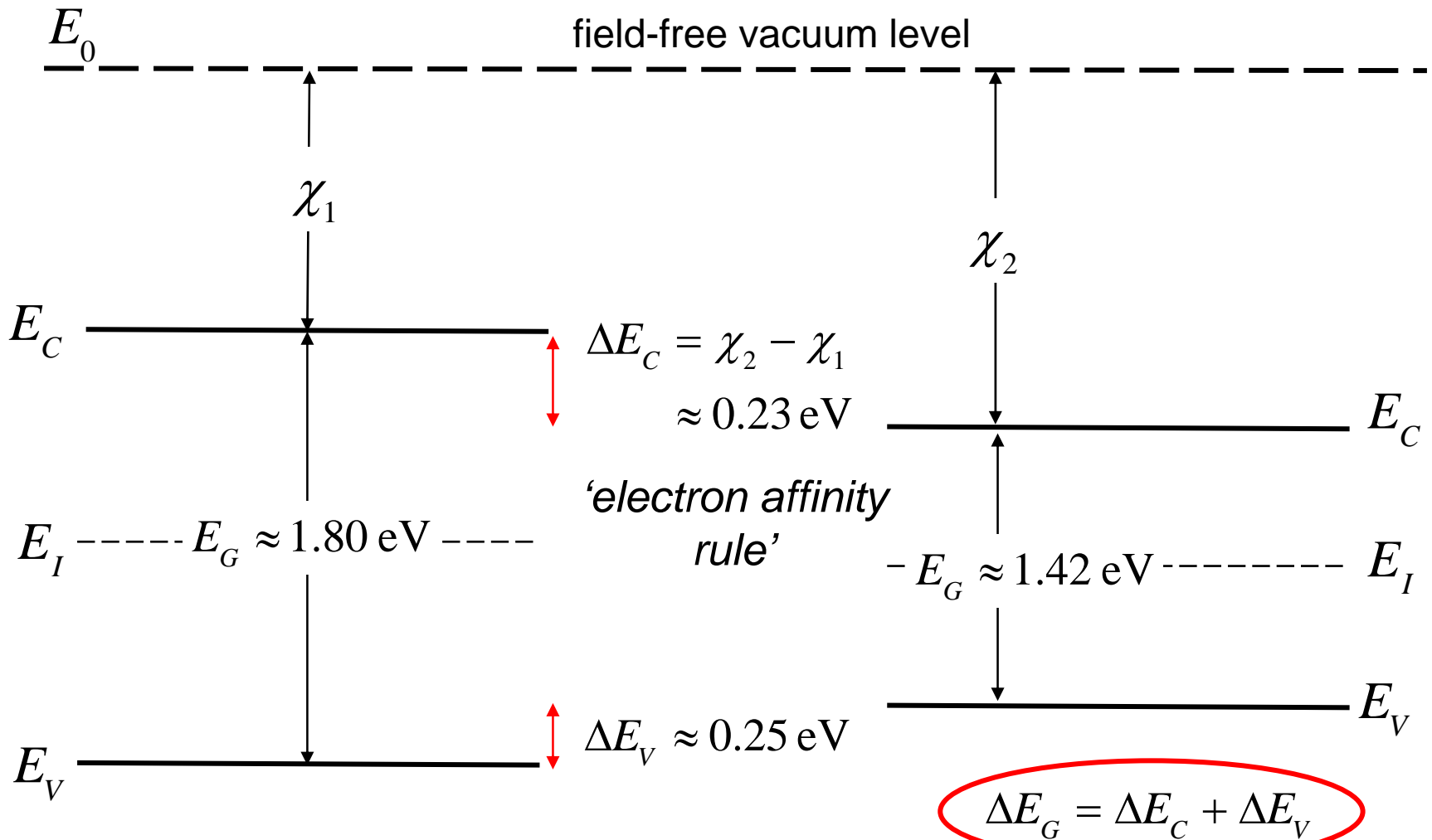
$$E_V = E_0 - \chi - E_G$$

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

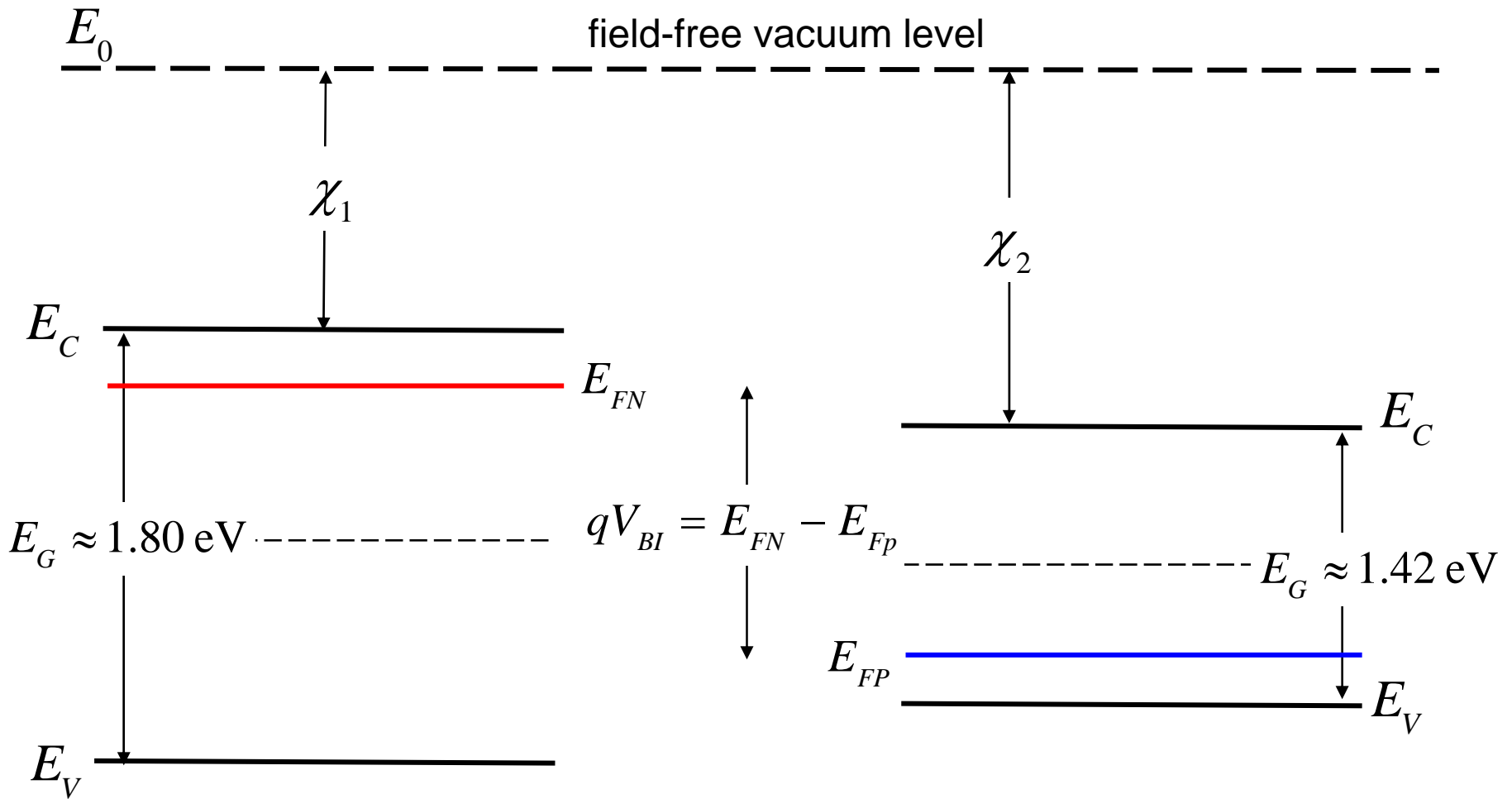
“local” vacuum level



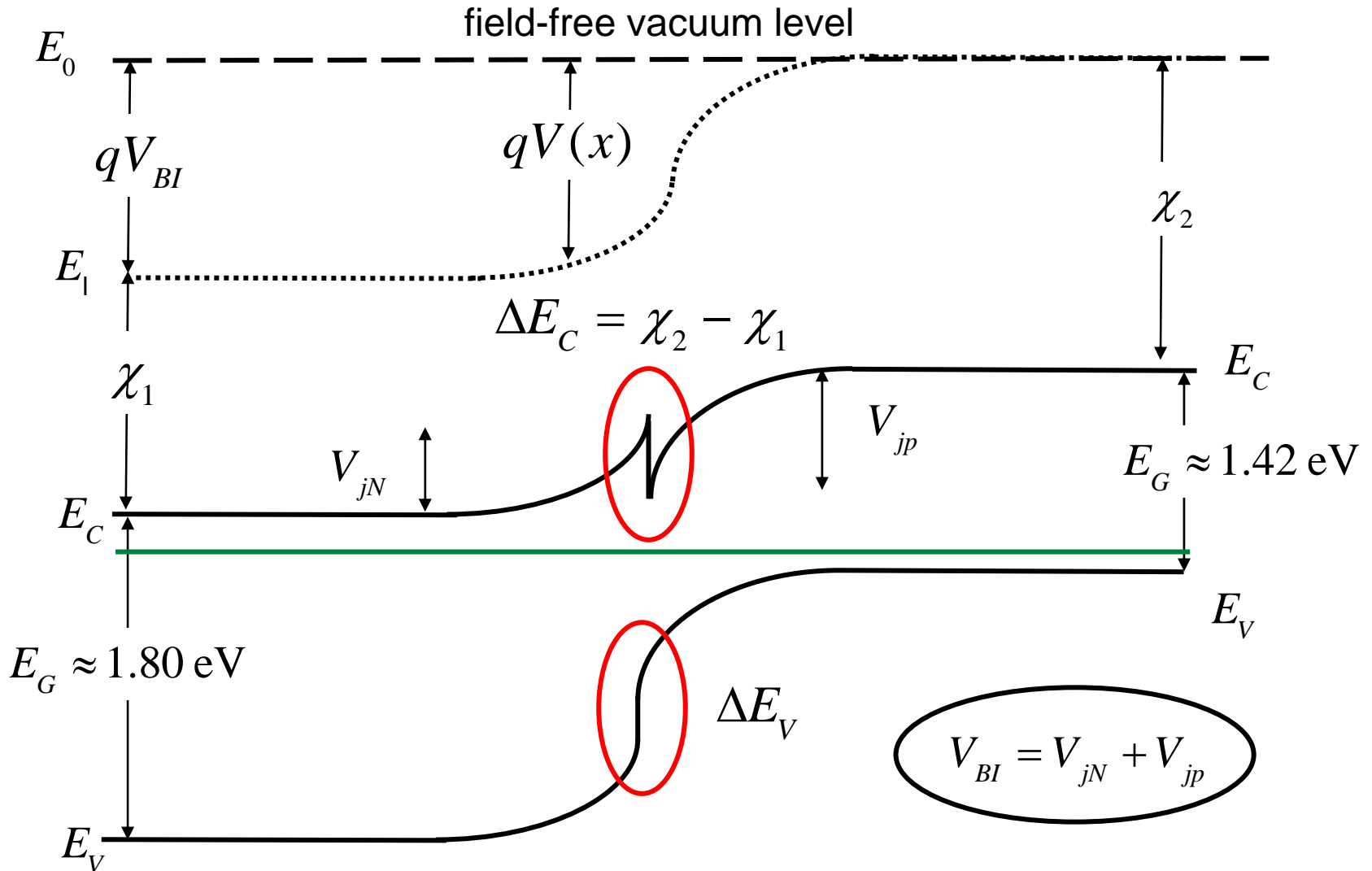
$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As} : \text{GaAs}$ (Type I HJ)



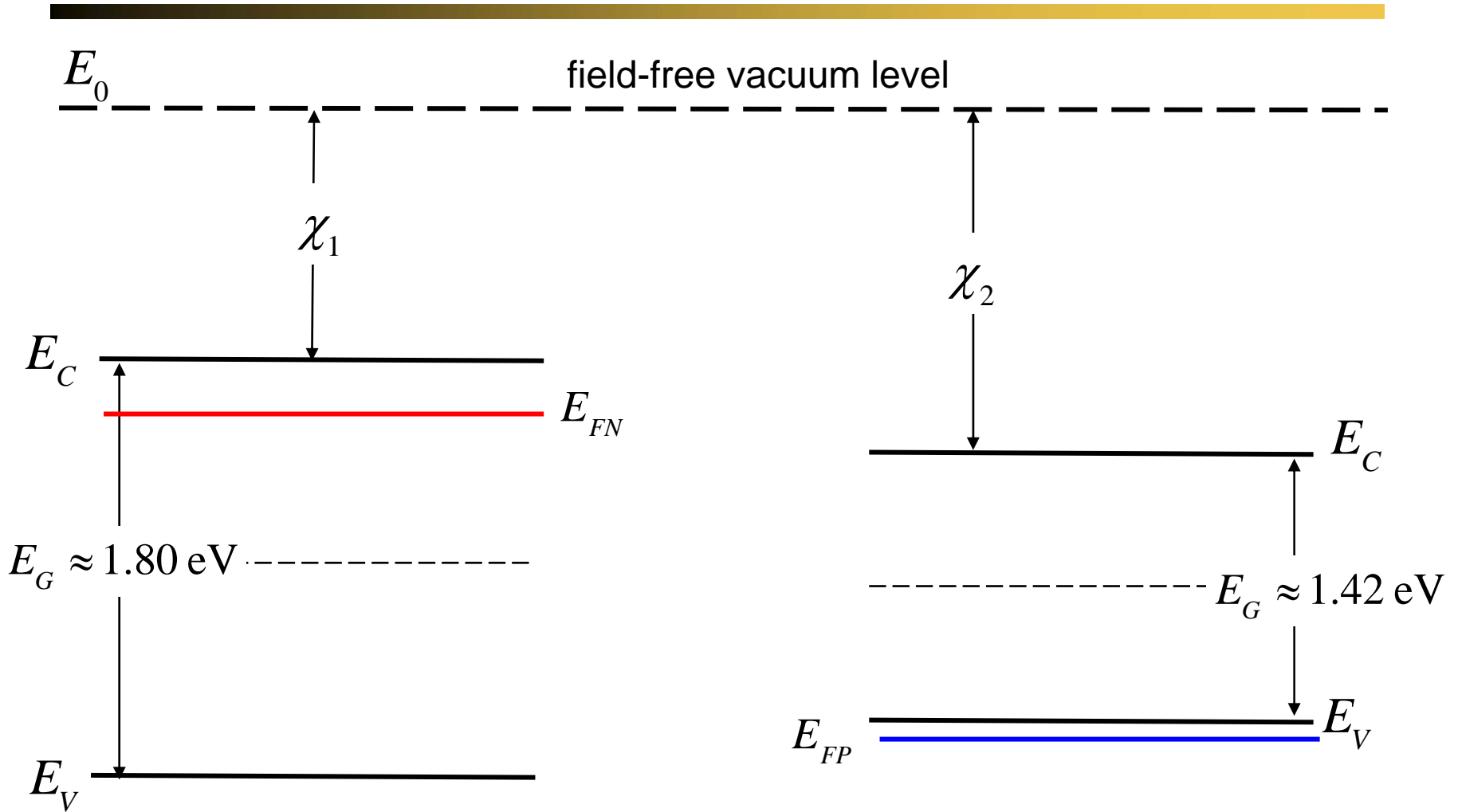
N-Al_{0.3}Ga_{0.7}As : p-GaAs (Type I HJ)



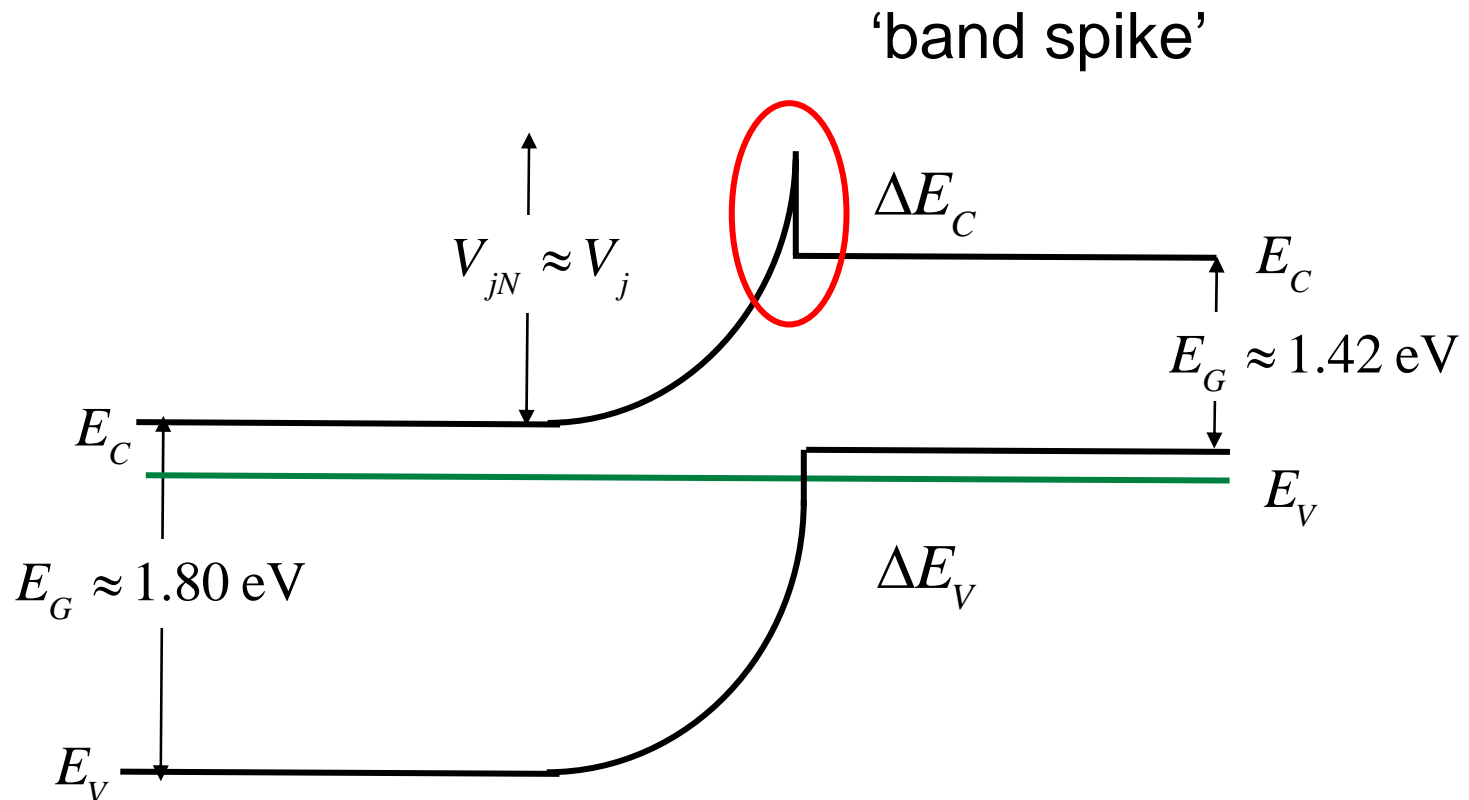
N-Al_{0.3}Ga_{0.7}As : p-GaAs (Type I HJ)



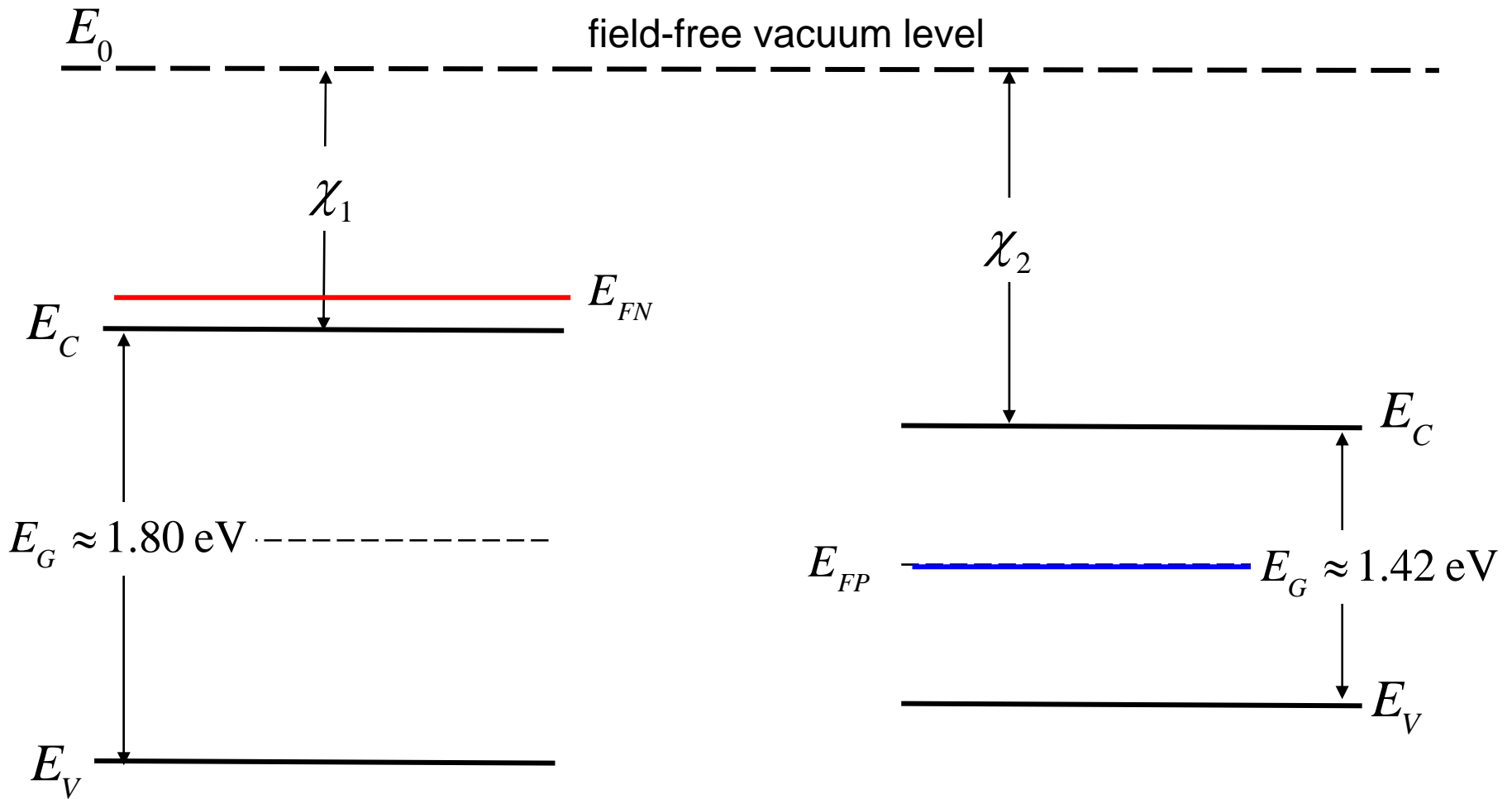
N-Al_{0.3}Ga_{0.7}As : p⁺-GaAs



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

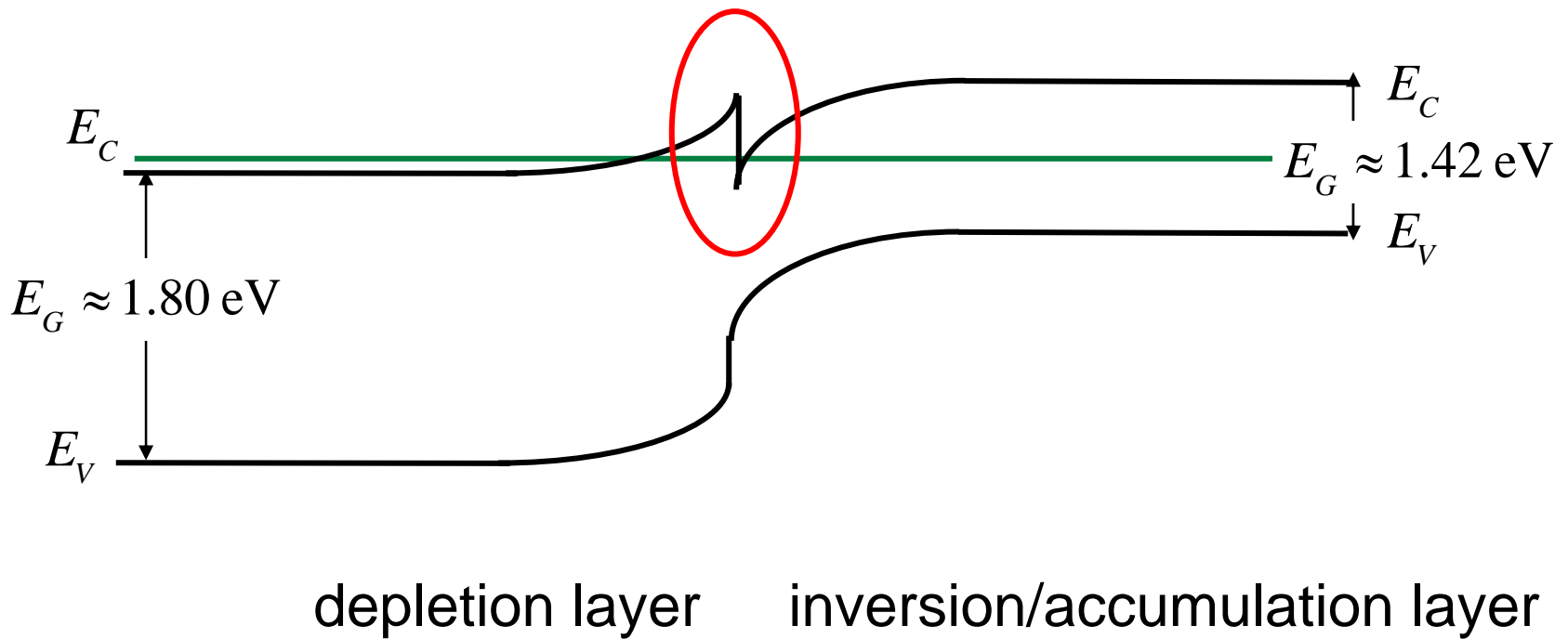


$N^+-Al_{0.3}Ga_{0.7}As$: i-GaAs



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

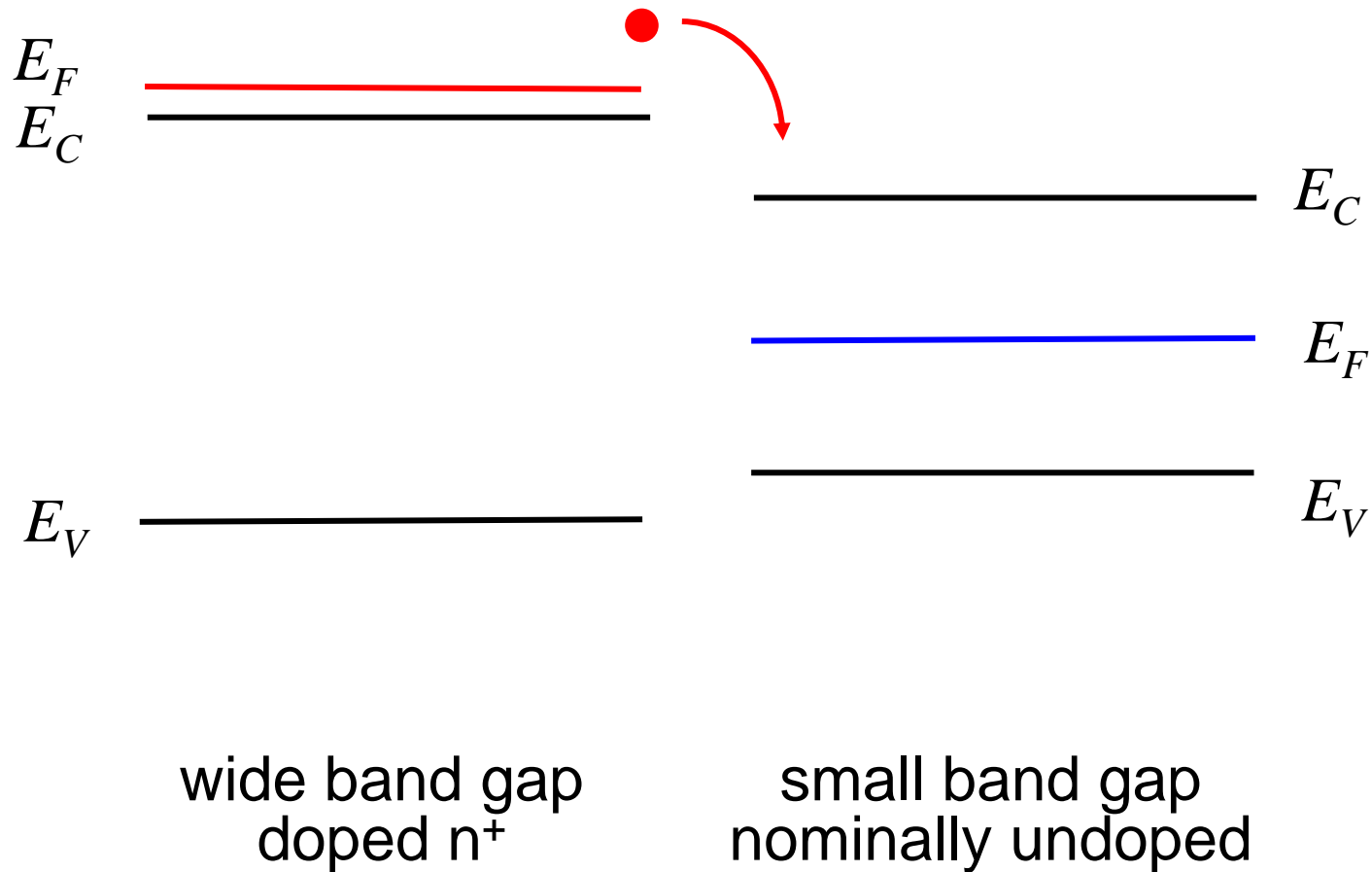
'modulation doping'
'2D electron gas'



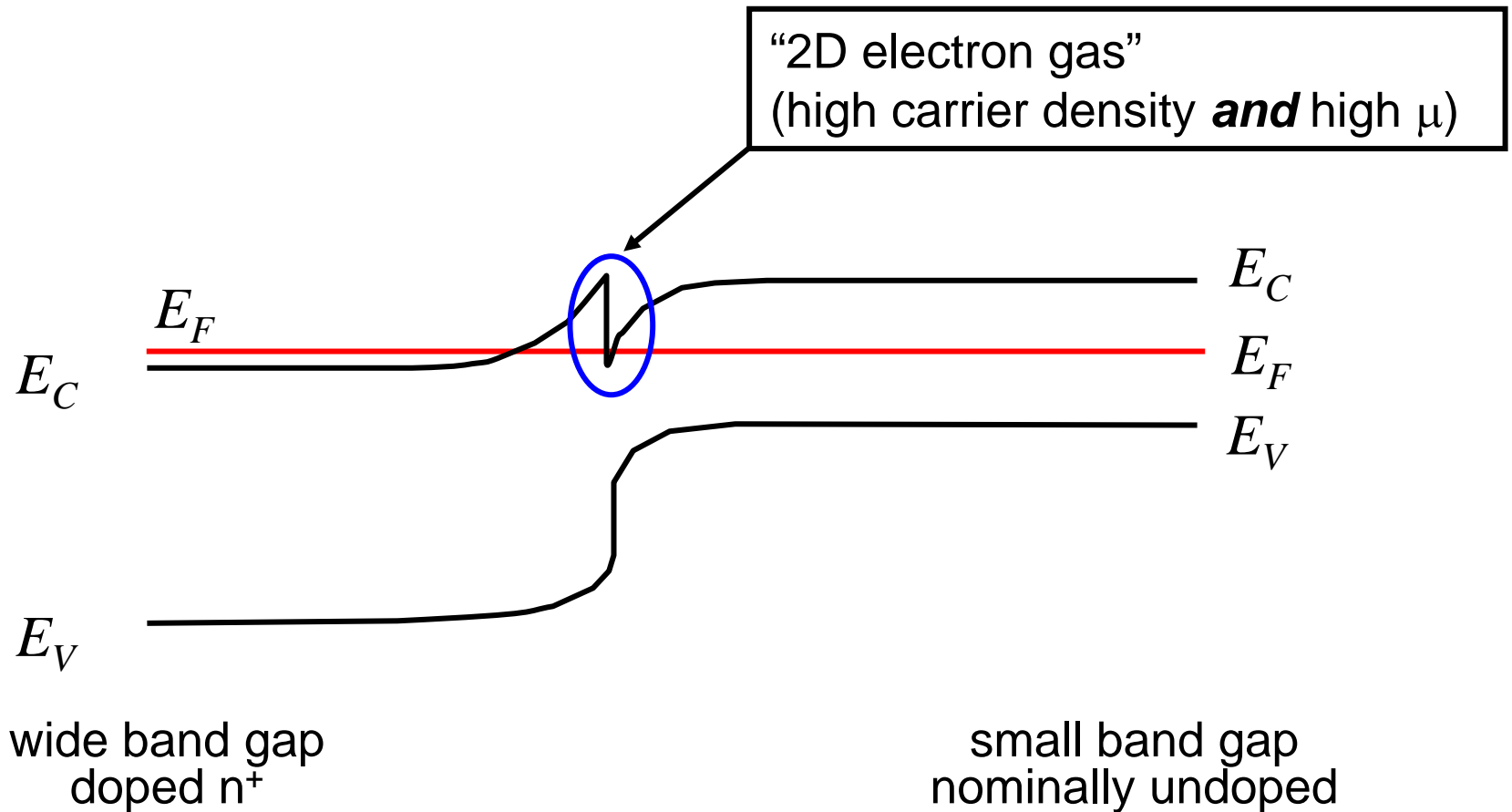
outline

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modulation doping

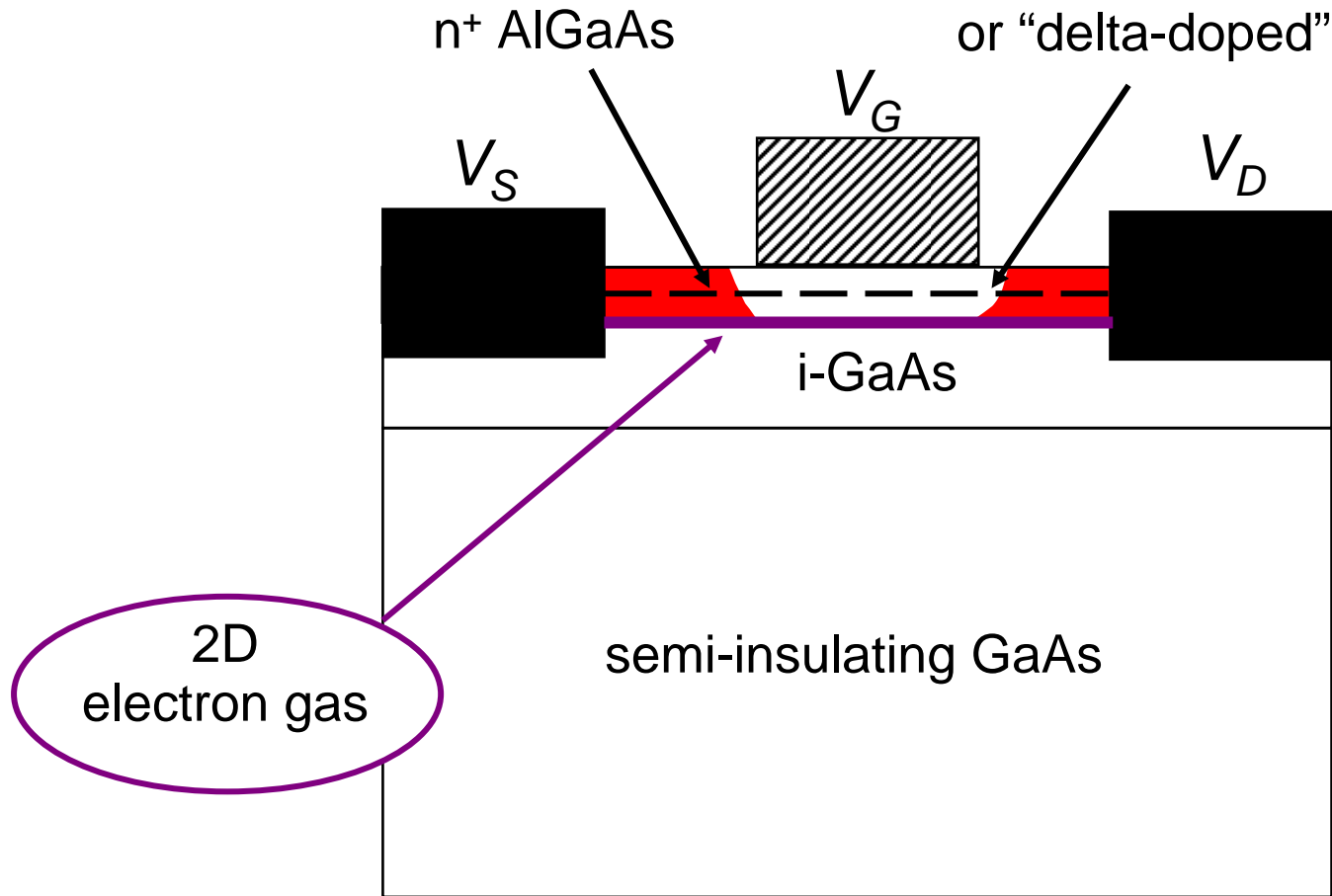


modulation doping



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:

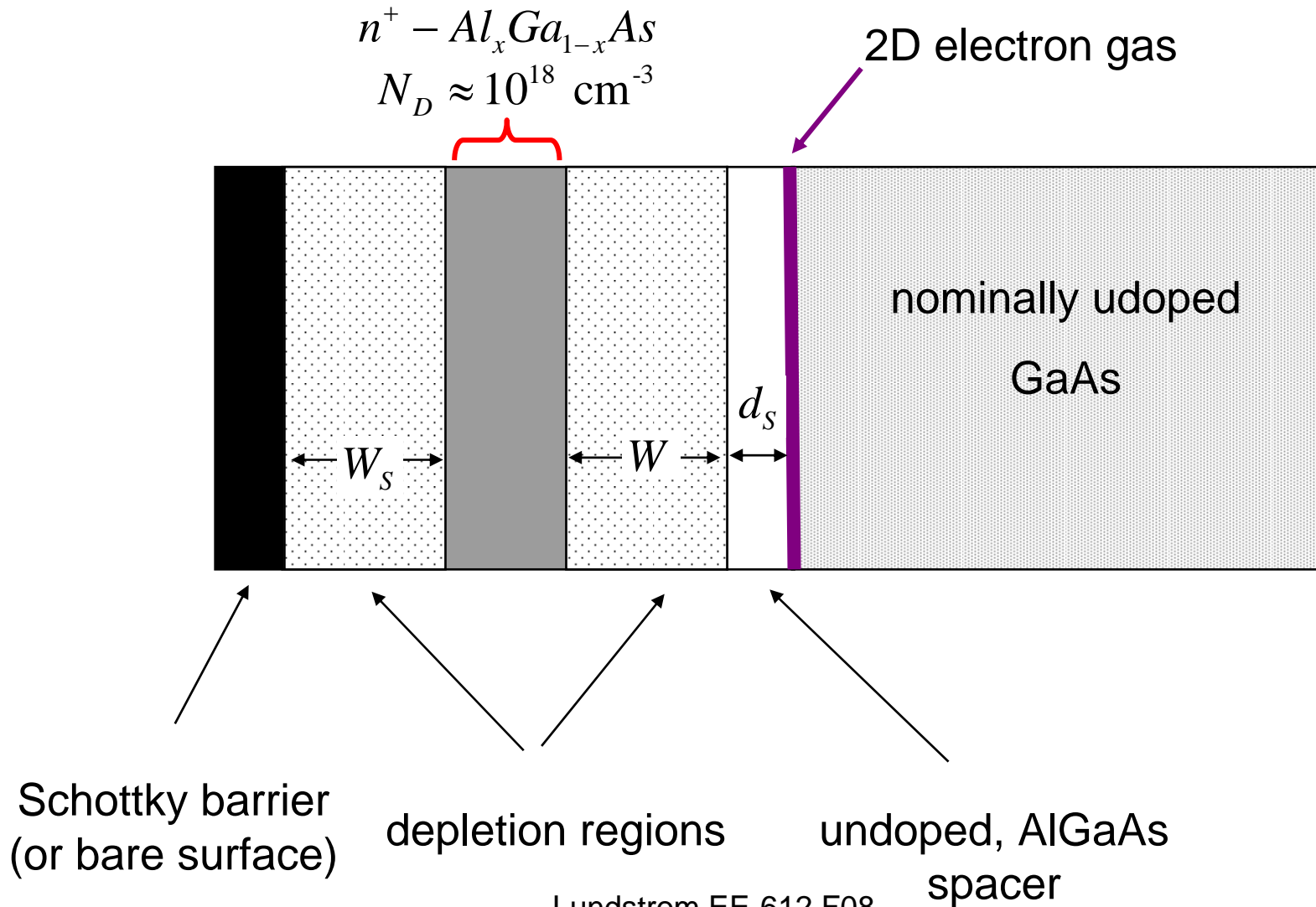
L. D. Nguyen, L.L. Larsen, and U.K. Mishra, “Ultra-high-speed modulation-doped field-effect transistors: A tutorial review,” *Proc. IEEE*, **80**, pp. 494-518, 1992.

references

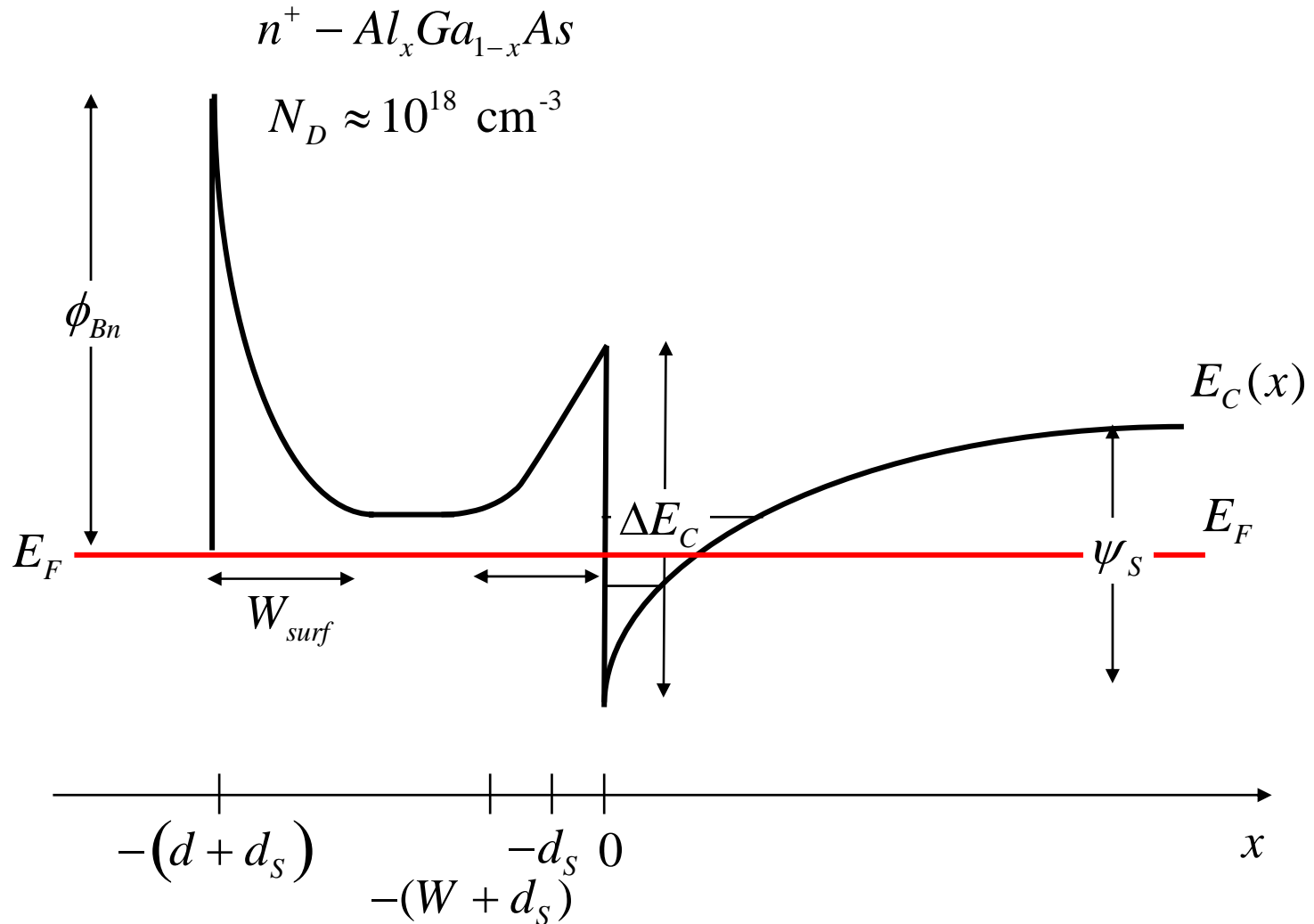
For a good textbook treatment of modulation doping and MODFETs, see:

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

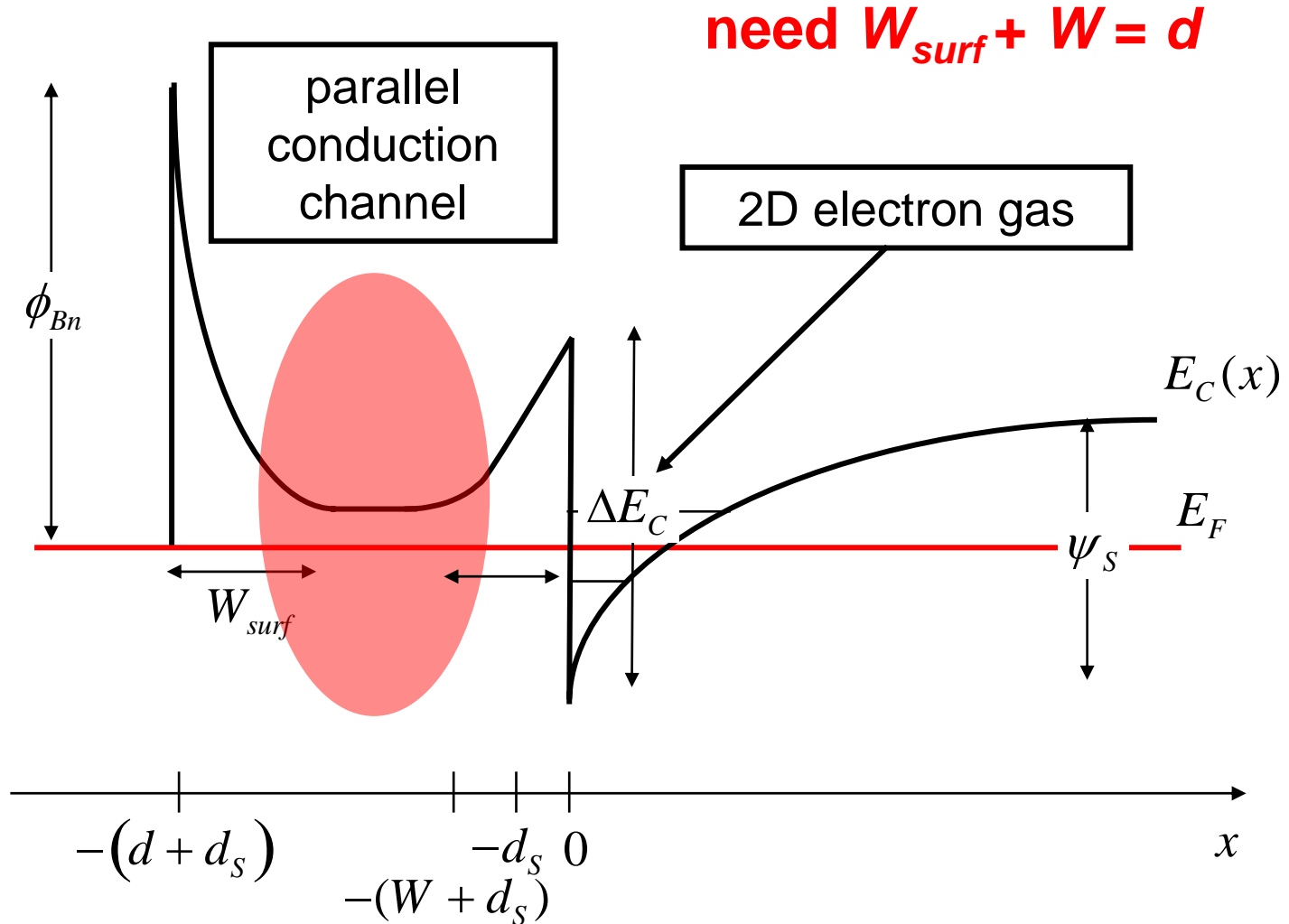
model structure



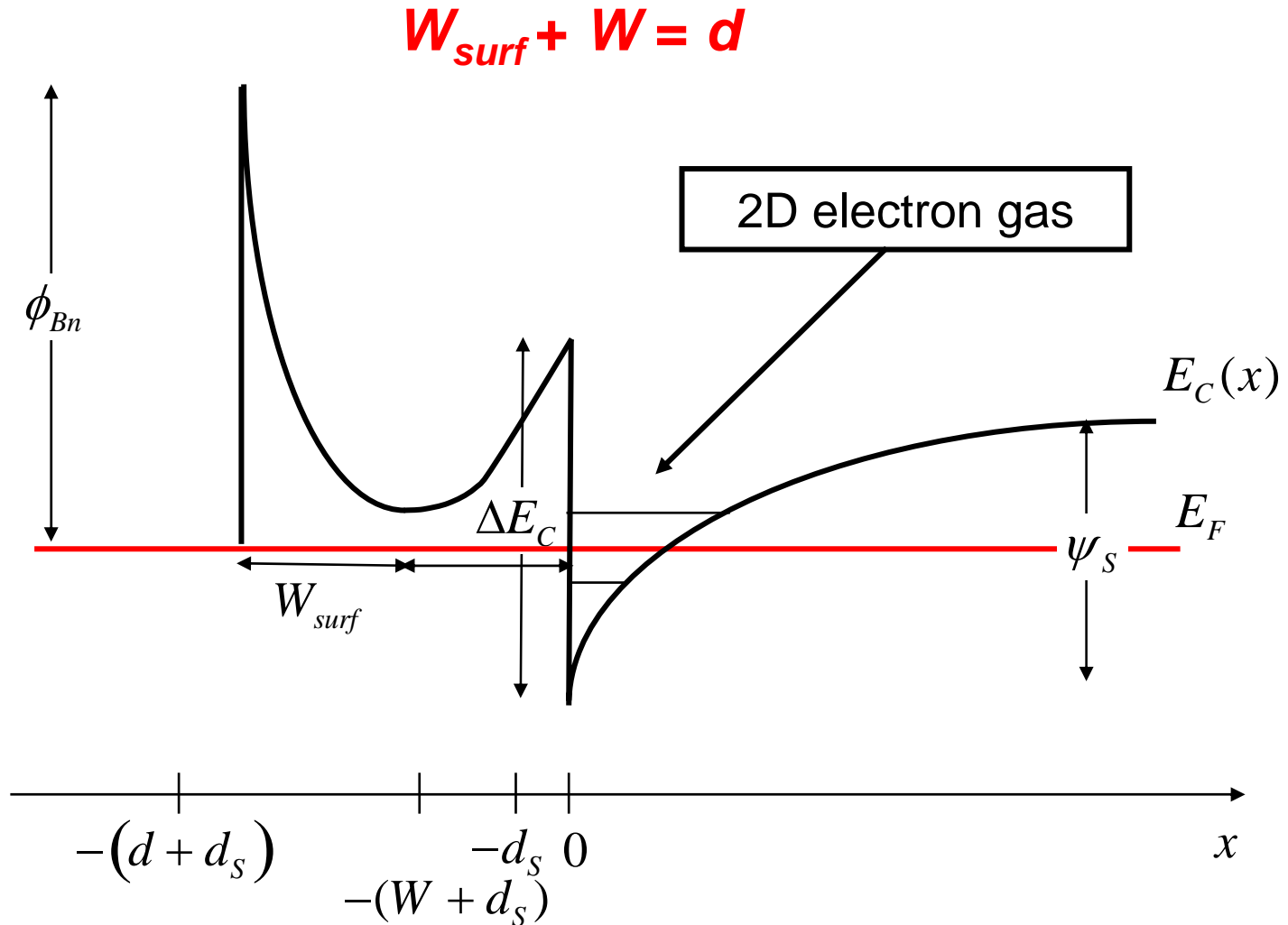
equilibrium energy band diagram



parallel conduction



equilibrium energy band diagram

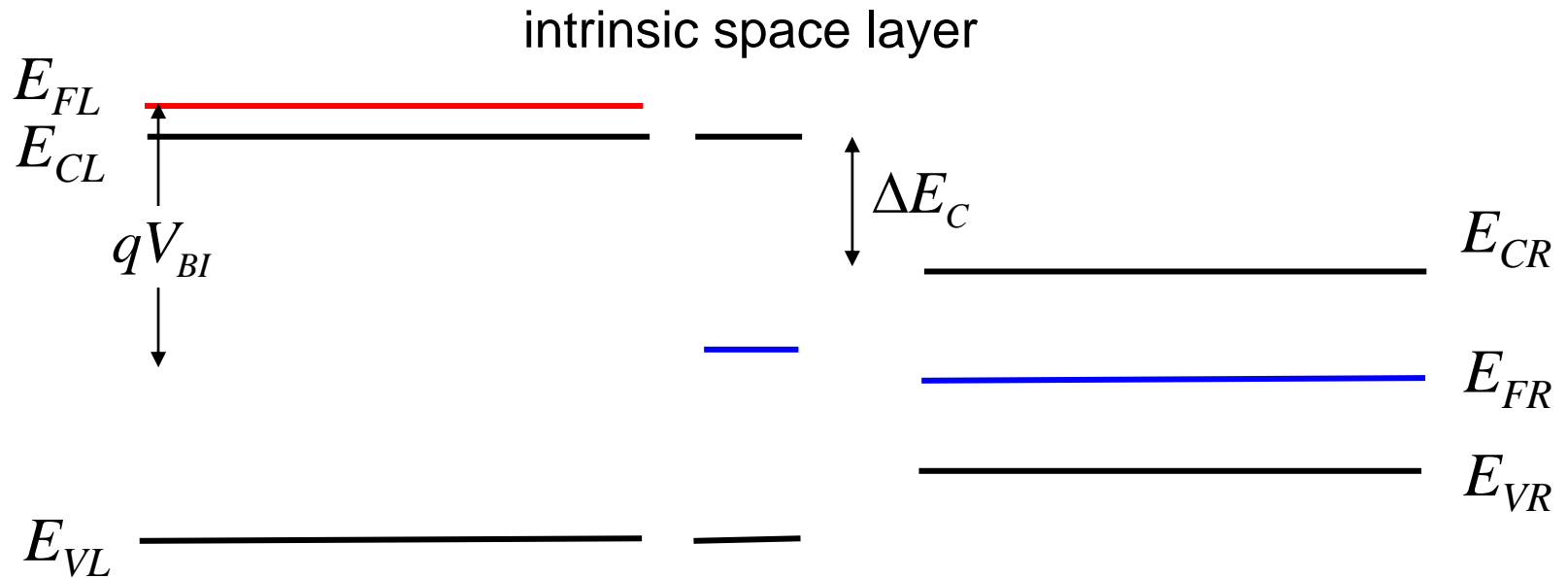


2D electron gas density

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



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

$$qV_{BI} = (E_{FL} - E_{CL}) + \Delta E_C + \Delta E_G/2$$

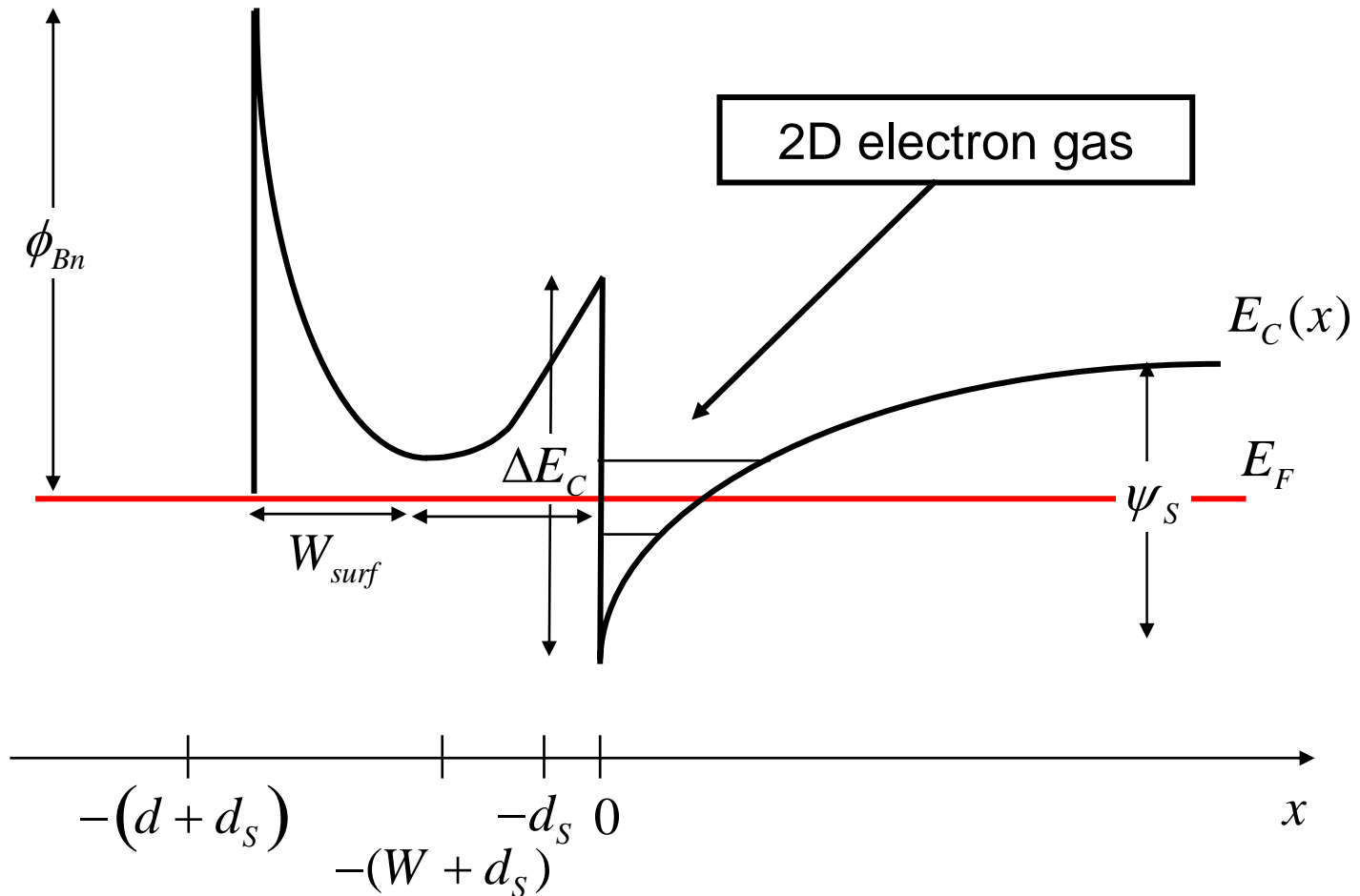
doping

band discontinuity

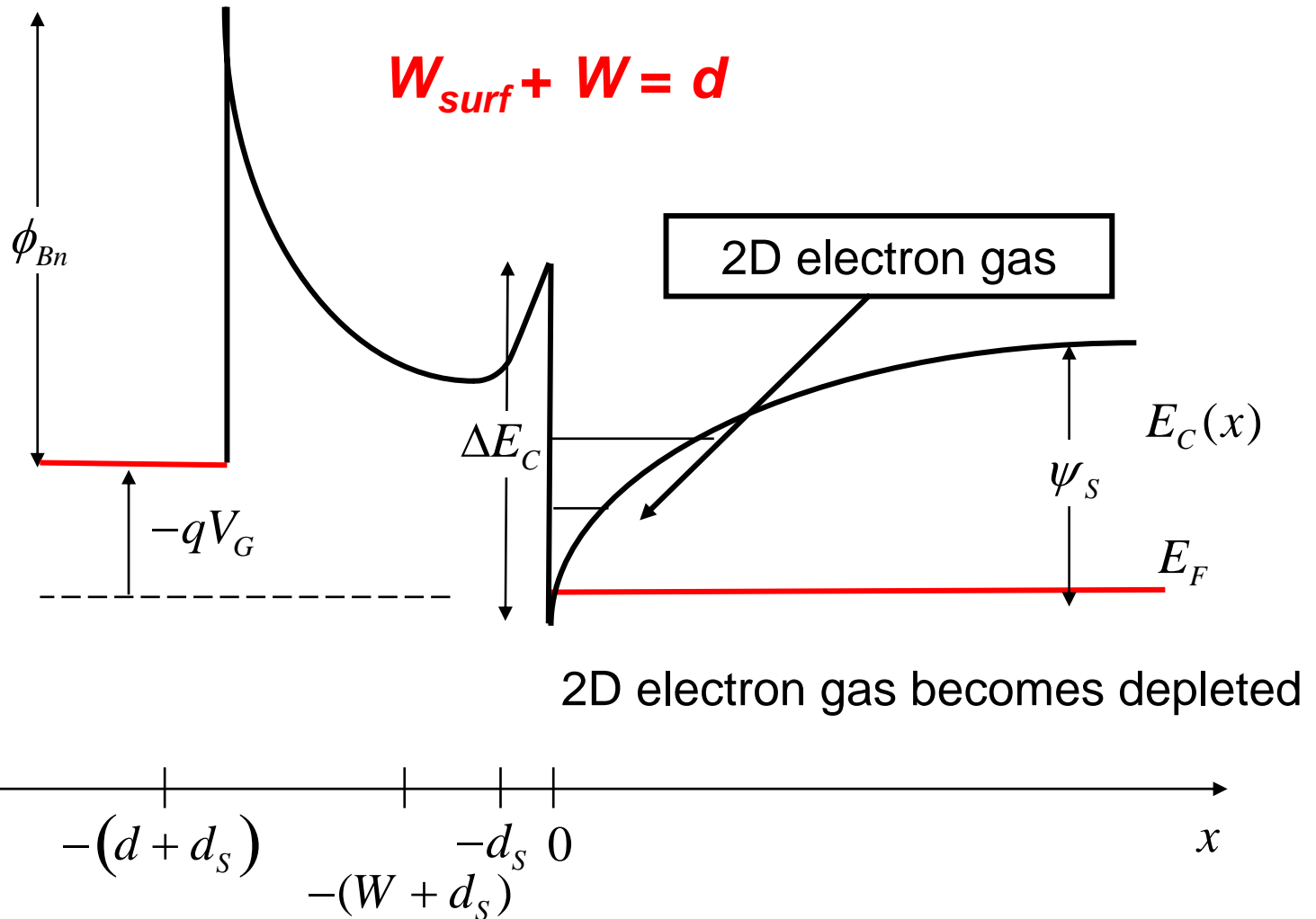
+ spacer thickness

$V_G = 0$ energy band diagram

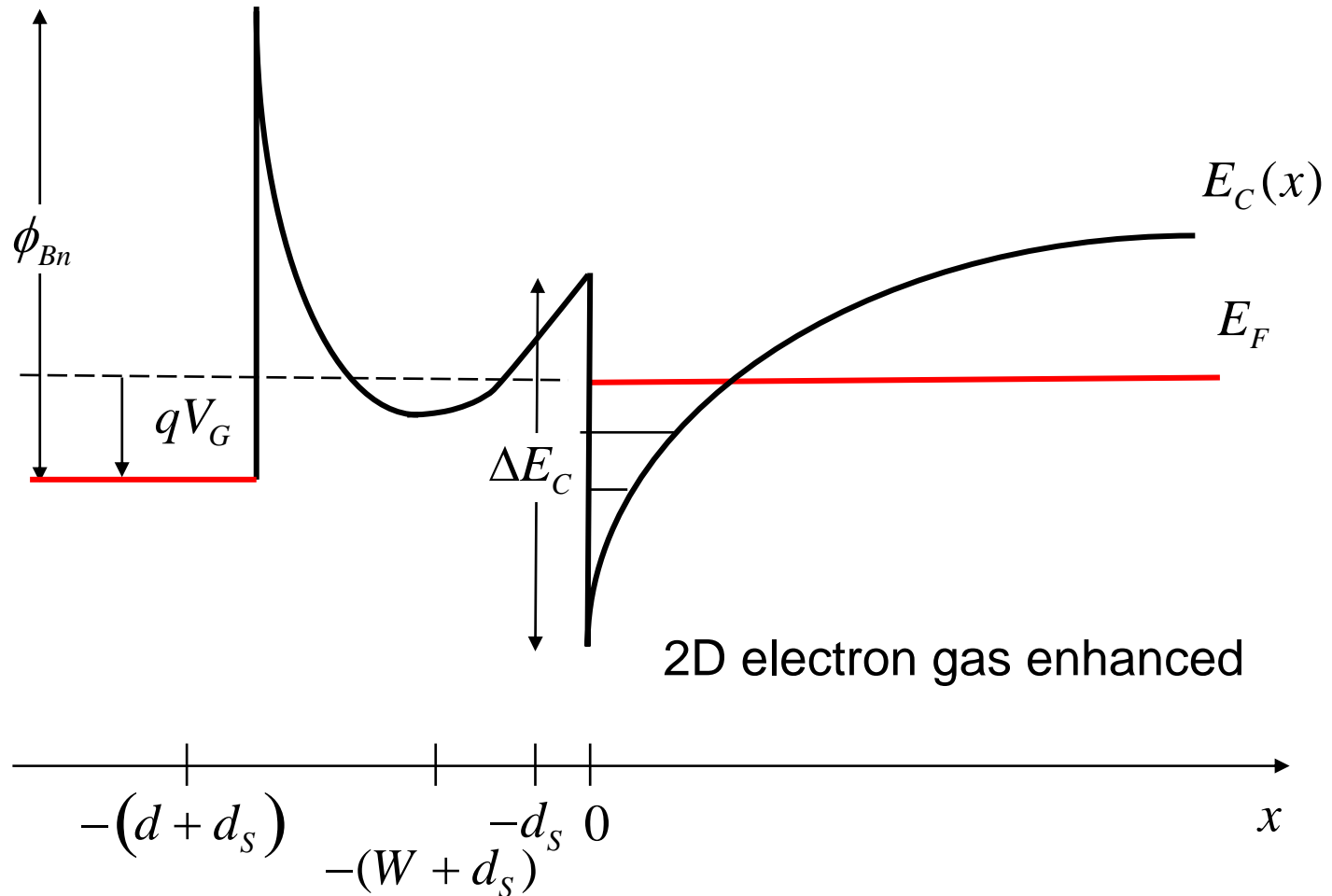
$$W_{surf} + W = d$$



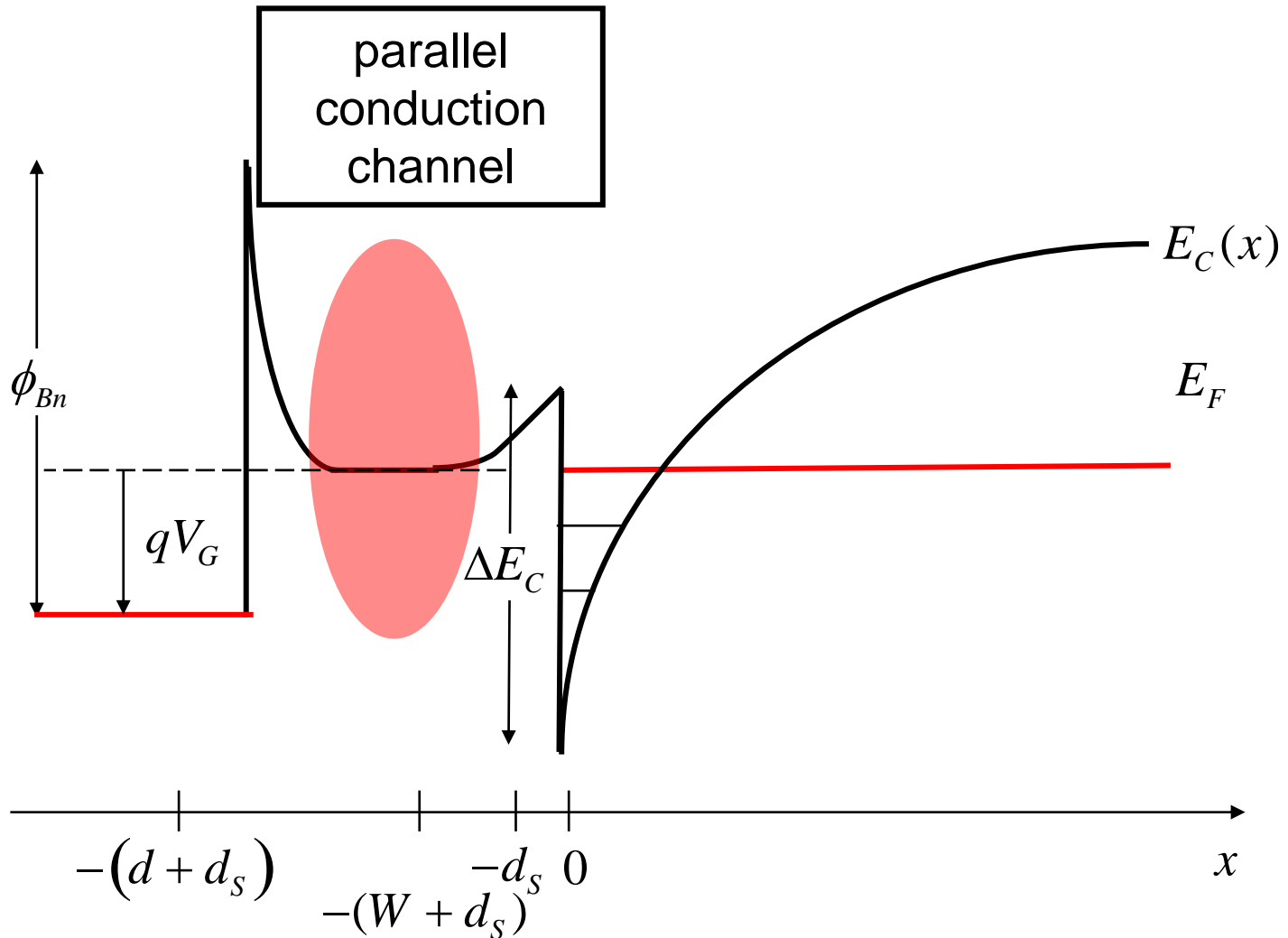
$V_G < 0$ energy band diagram



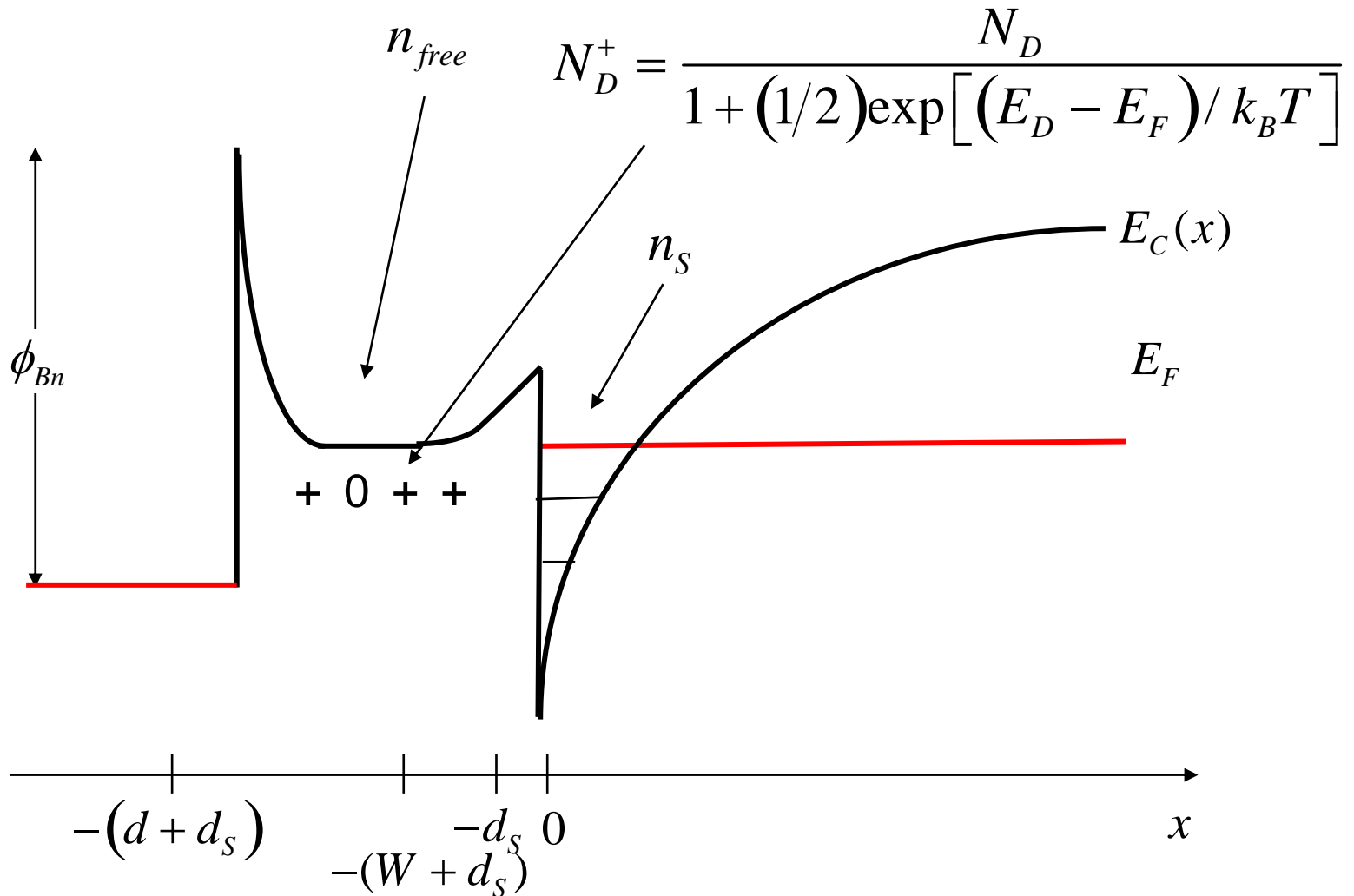
$V_G > 0$ energy band diagram



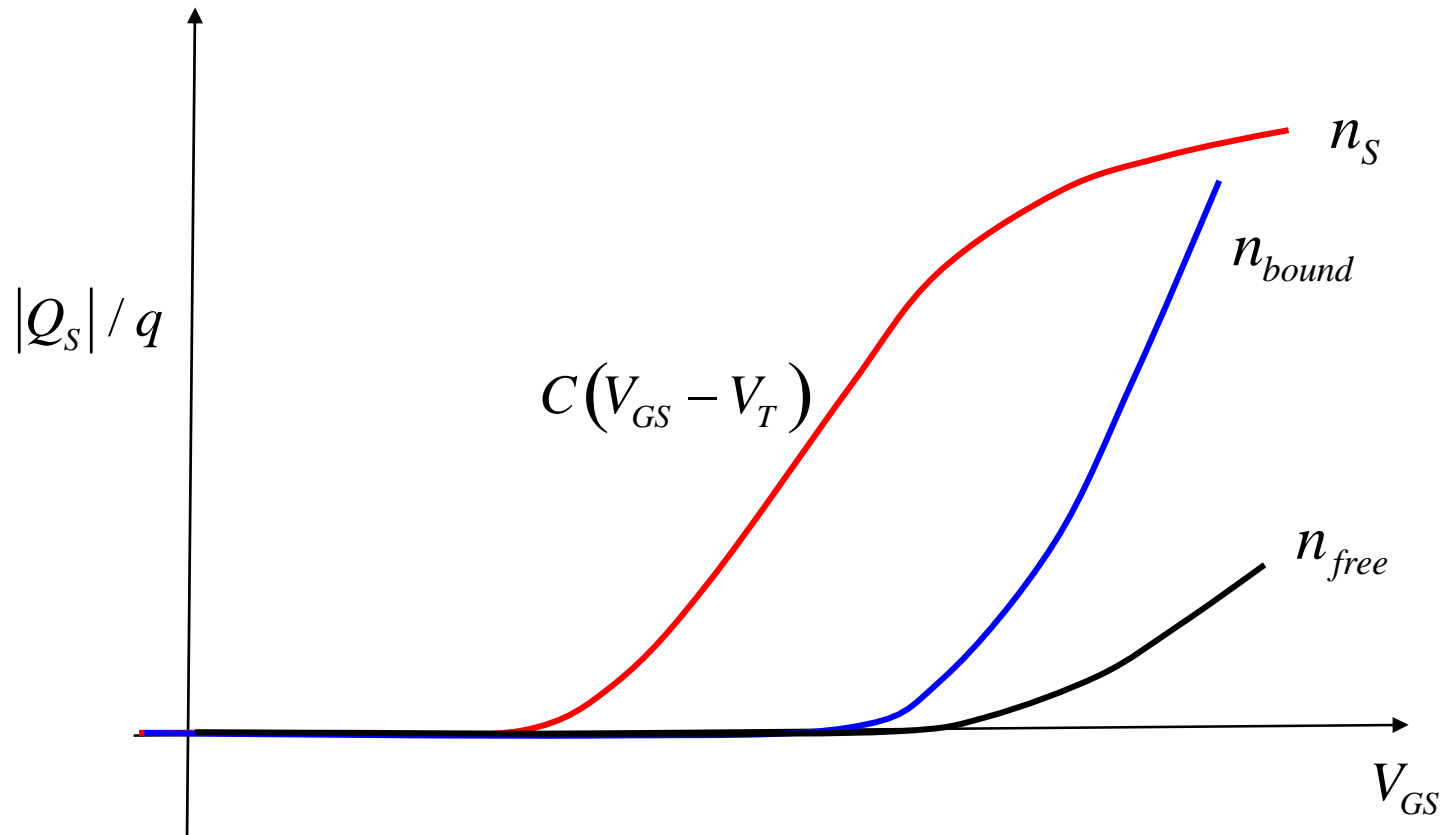
$V_G \gg 0$ energy band diagram



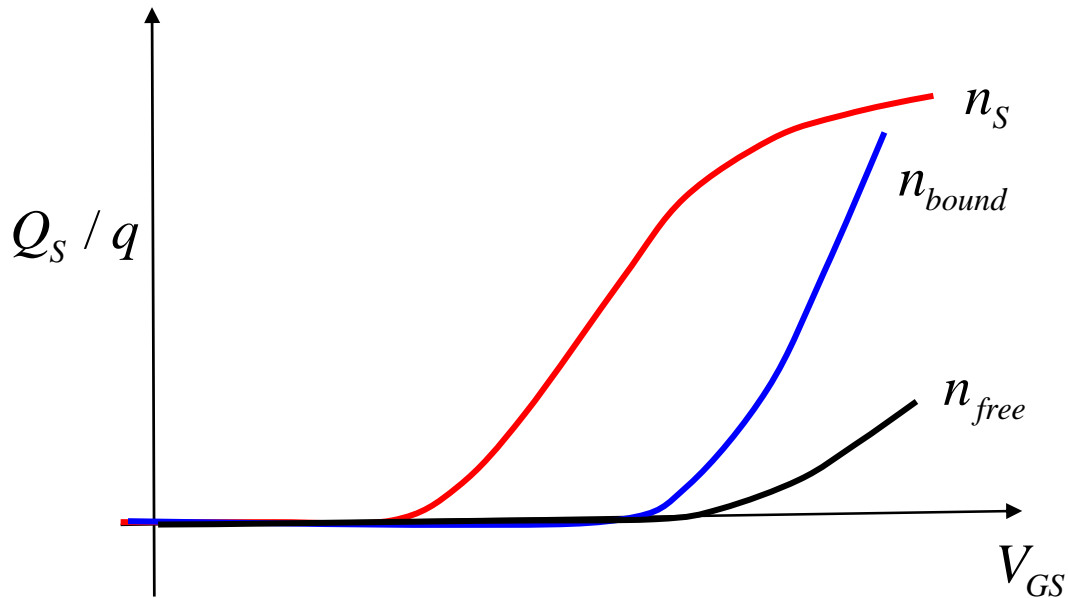
charges under forward bias



charges under forward bias

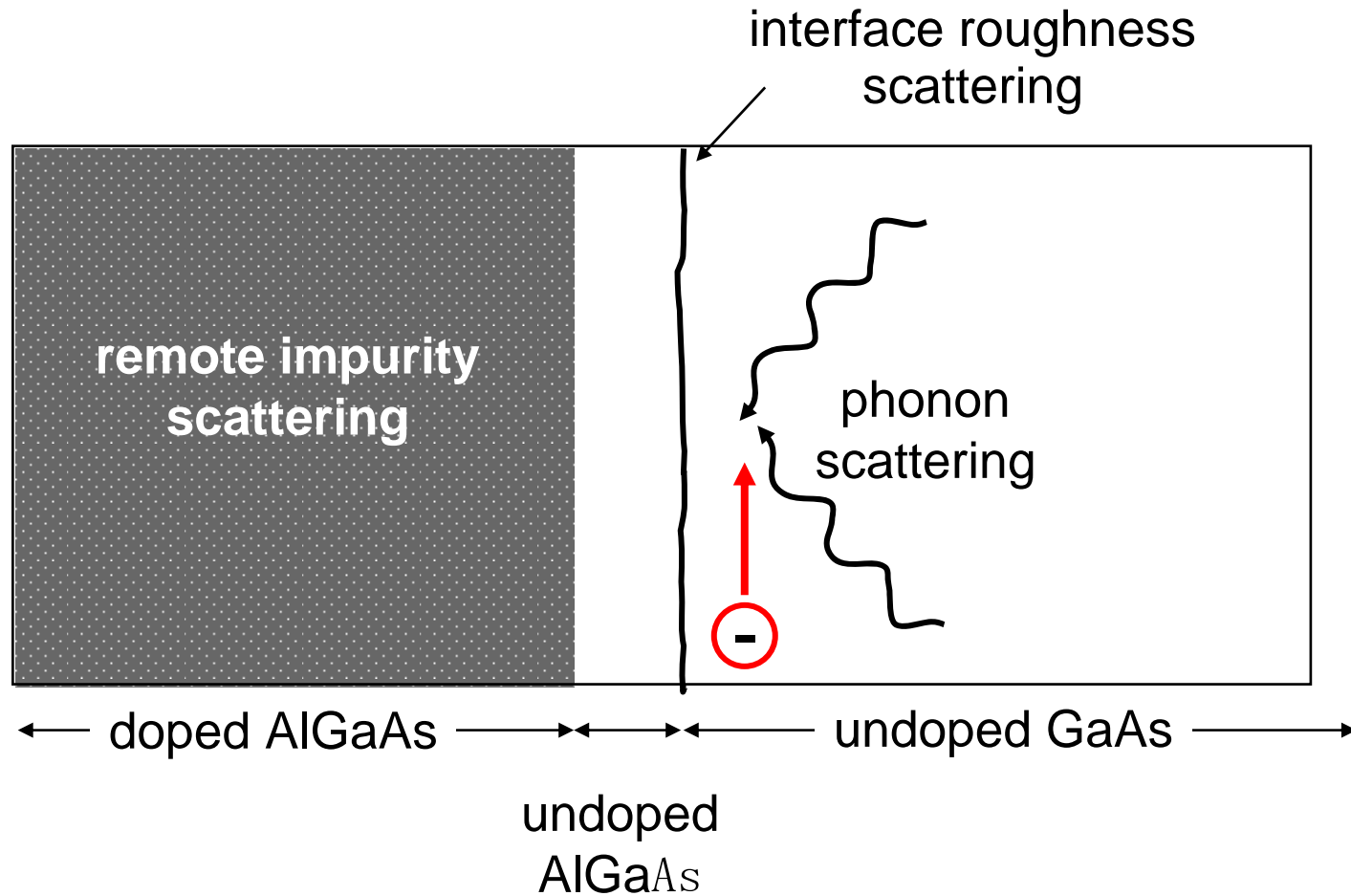


modulation efficiency



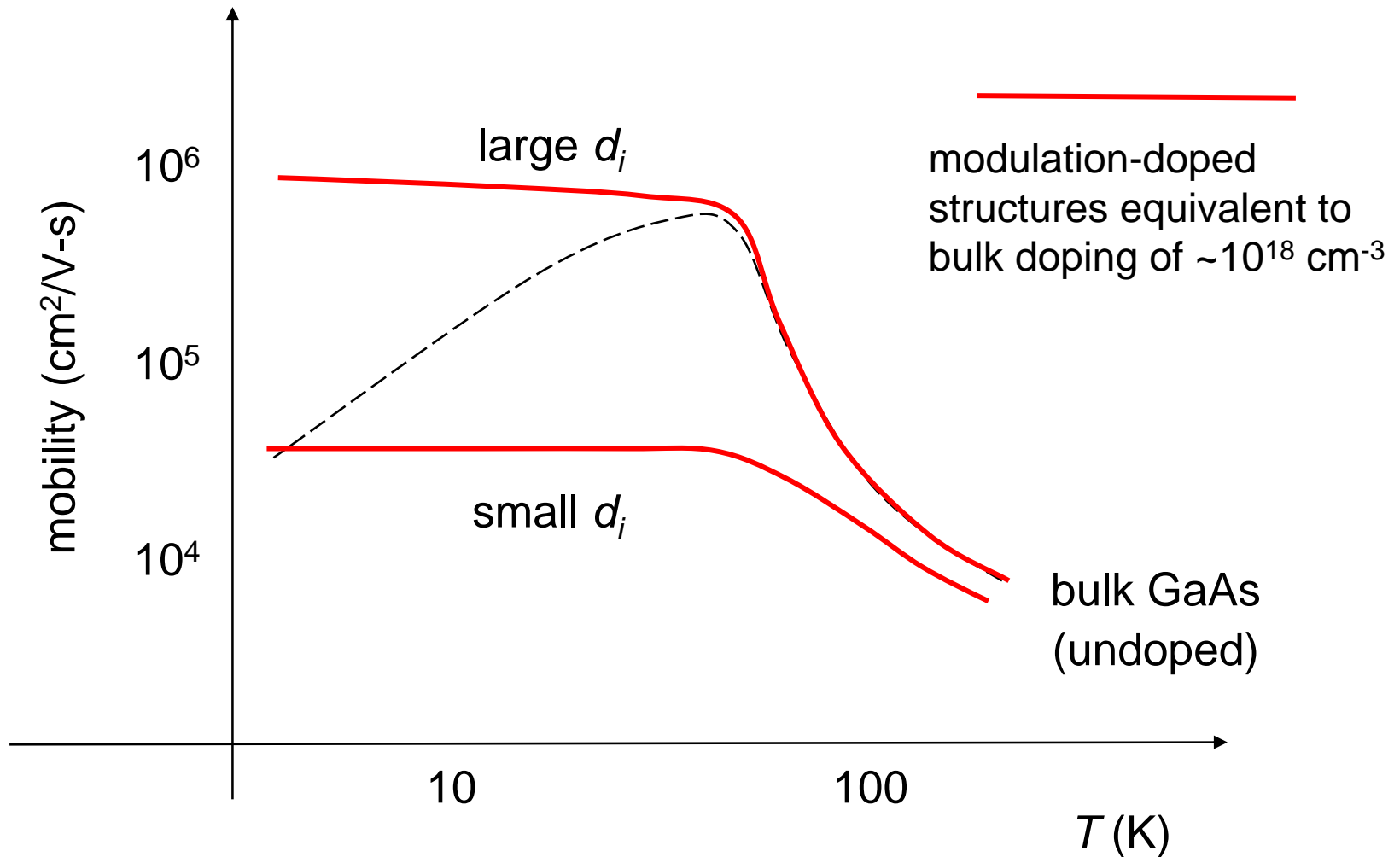
$$\eta = \frac{\partial n_S / \partial V_G}{\partial (n_S + n_{bound} + n_{free}) / \partial V_G} = \frac{C_S}{C_{TOT}}$$

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

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

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

$$I_D = WC_{INS} v_{SAT} (V_{GS} - V_T)$$

$$\begin{array}{l} V_{GS} > V_T \\ V_{DS} > V_{DSAT} \end{array}$$

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

g_m compression

For large V_{GS} :

$$I_D \neq WC_{INS} v_{SAT} (V_{GS} - V_T) \quad I_D = W v_{SAT} n_S$$

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

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

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

series resistance very important

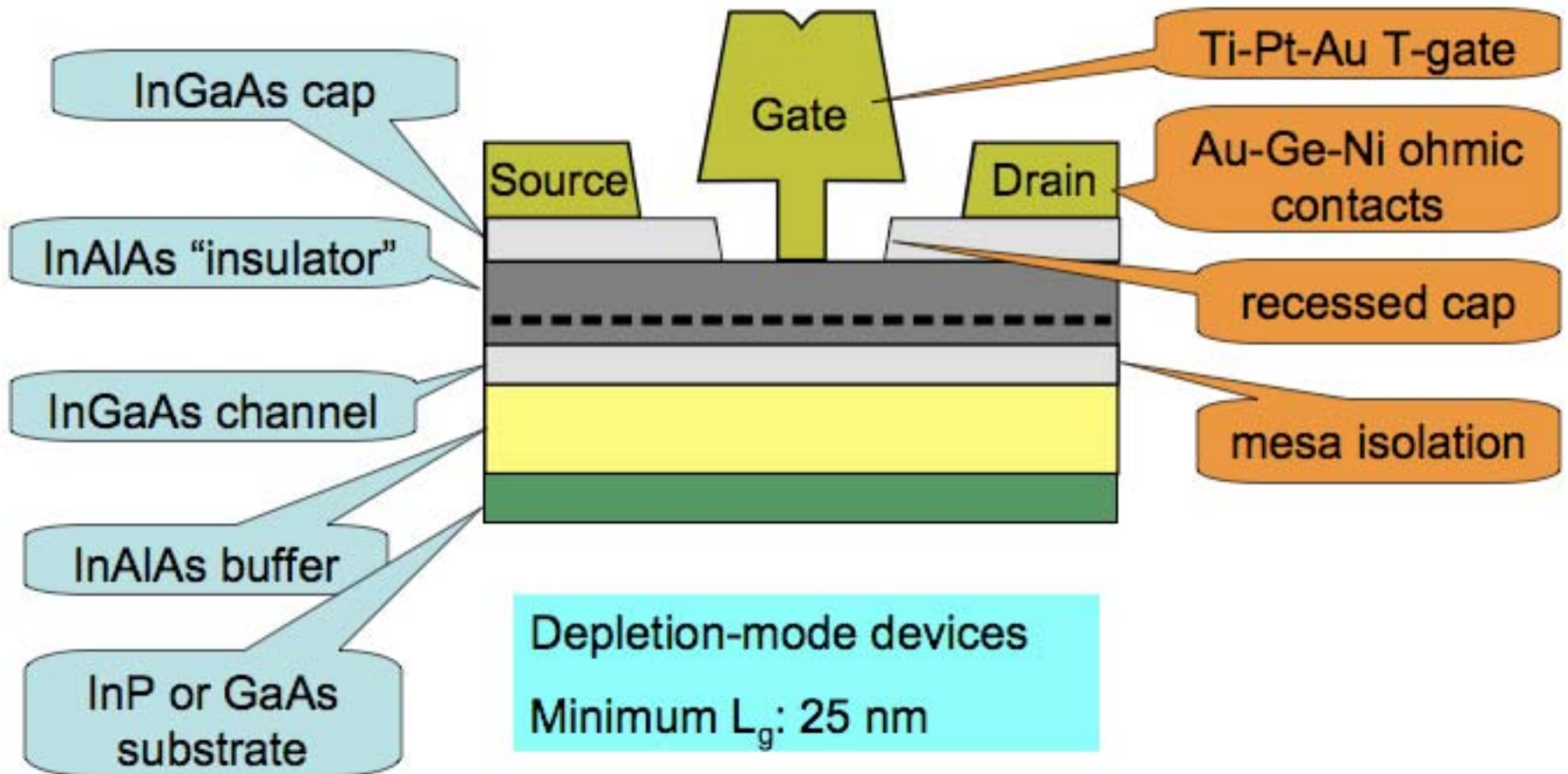
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device performance

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

InGaAs HEMT



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

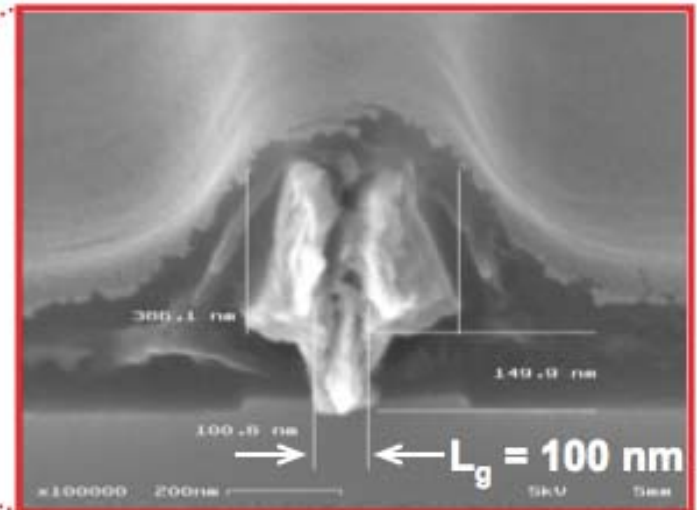
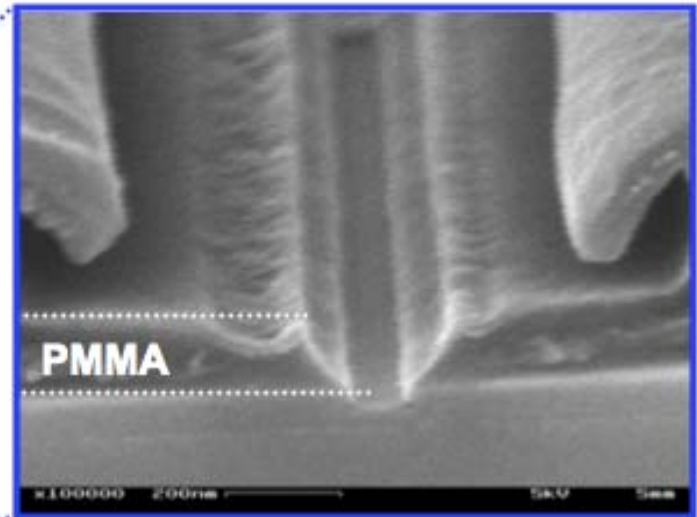
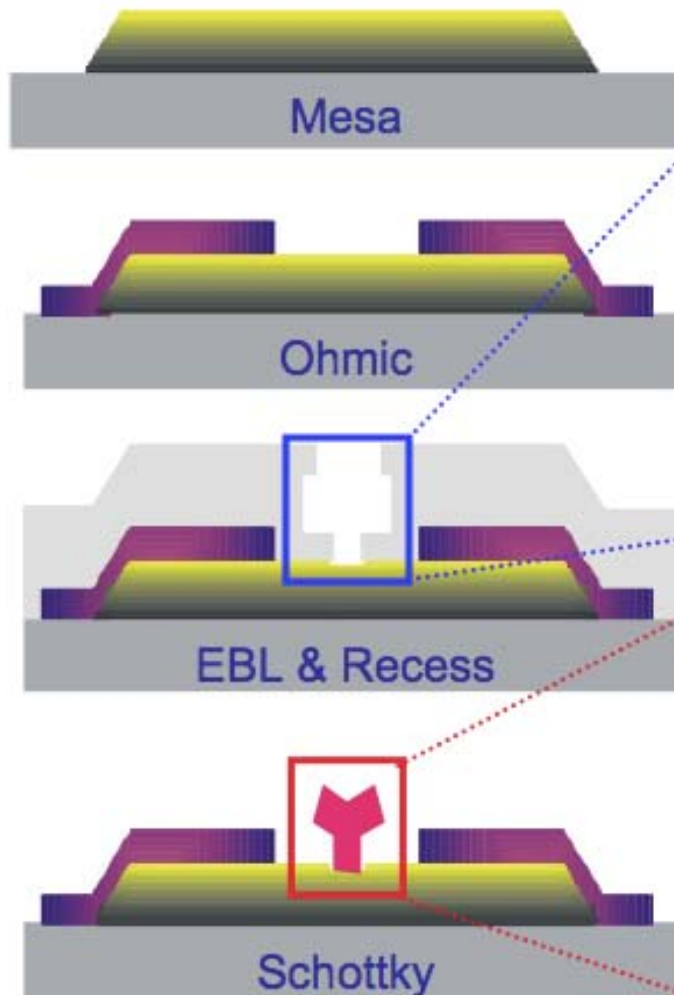
Strained MQW

3 Inch S. I. InP Substrate

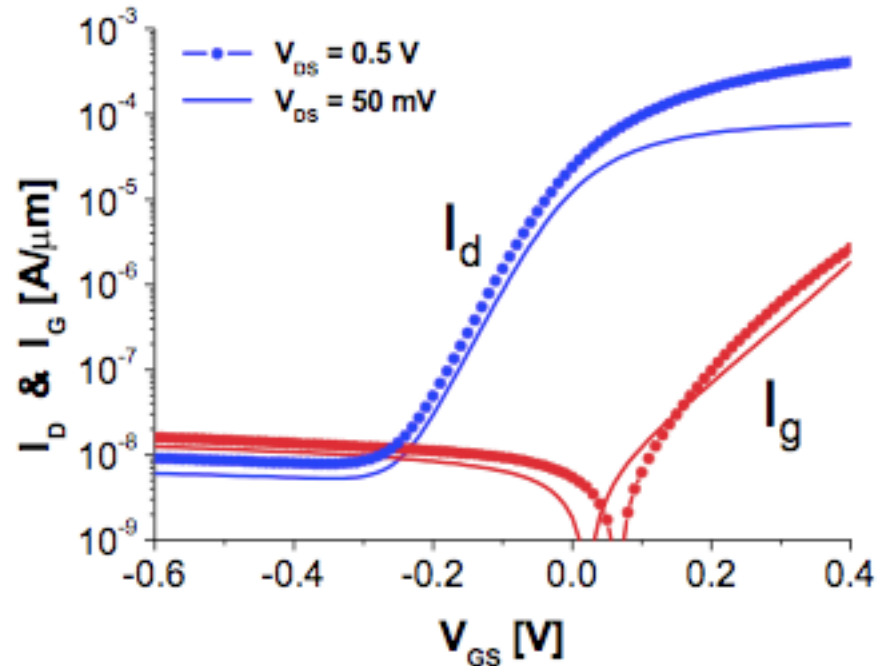
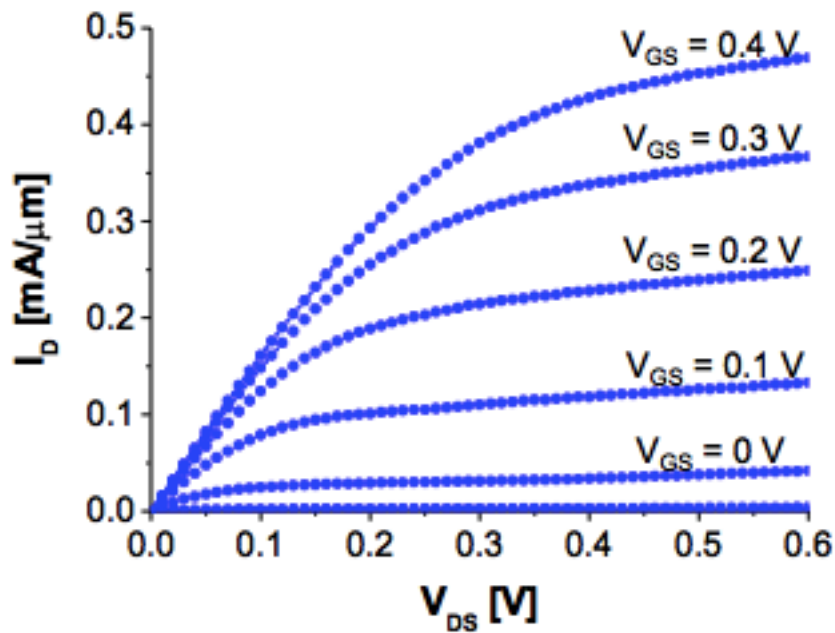
→ $N_{sh} = \sim 3 \times 10^{12} / \text{cm}^2 @ 300 \text{ K}$

→ $\mu_{n,Hall} = \sim 11,000 \text{ cm}^2/\text{V-sec} @ 300 \text{ K}$

device fabrication



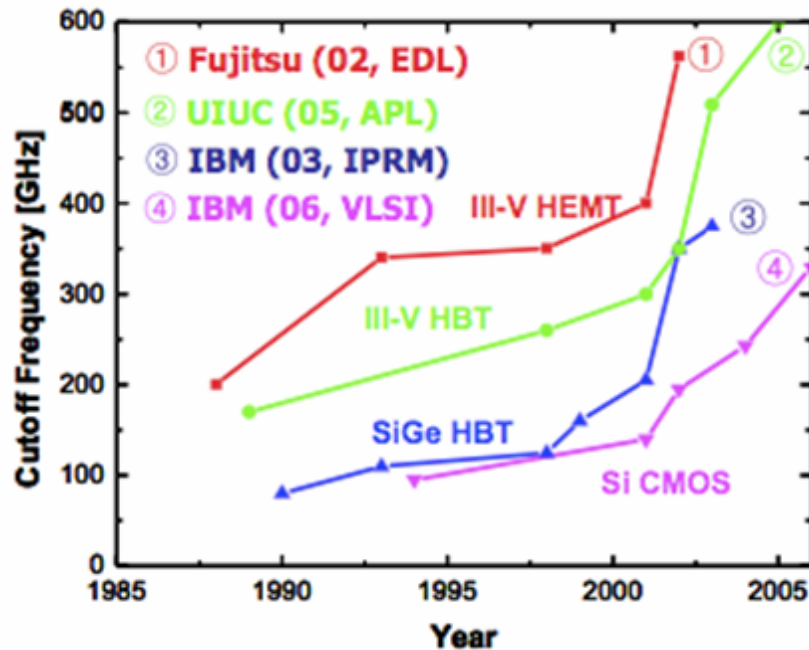
IV characteristics of 60nm InGaAs HEMT



At 0.5 V:

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

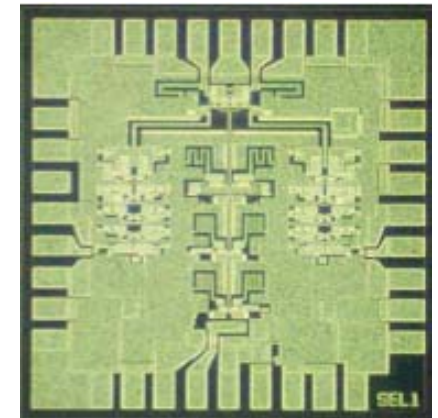
InGaAs HEMT technology



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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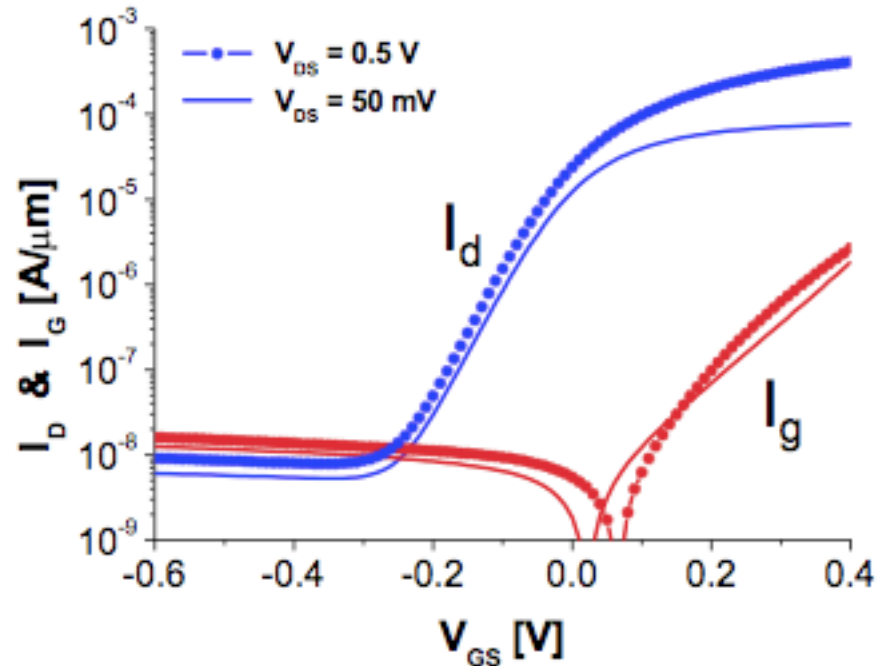
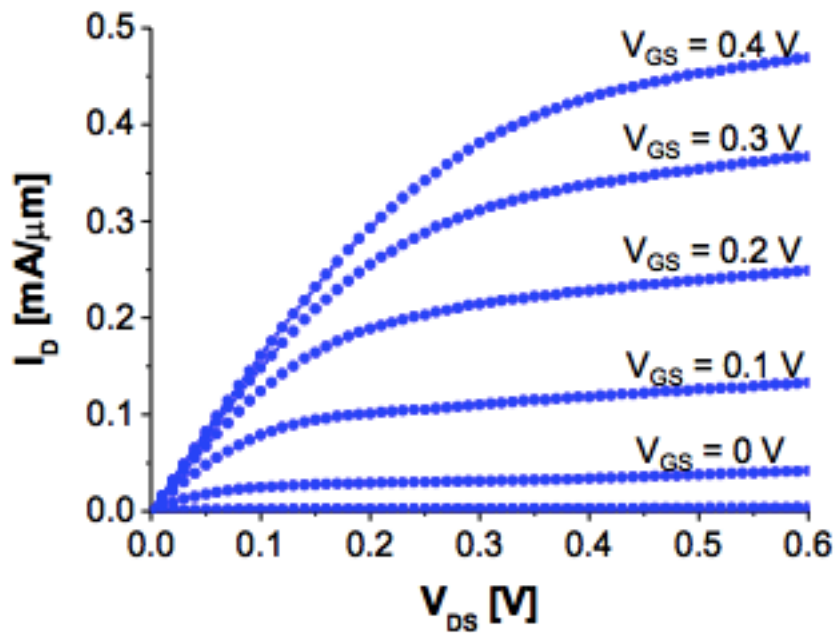
summary

- 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



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