EE-612:
Lecture 34:
Heterostructure FETs

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NCN

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outline

I) Introduction

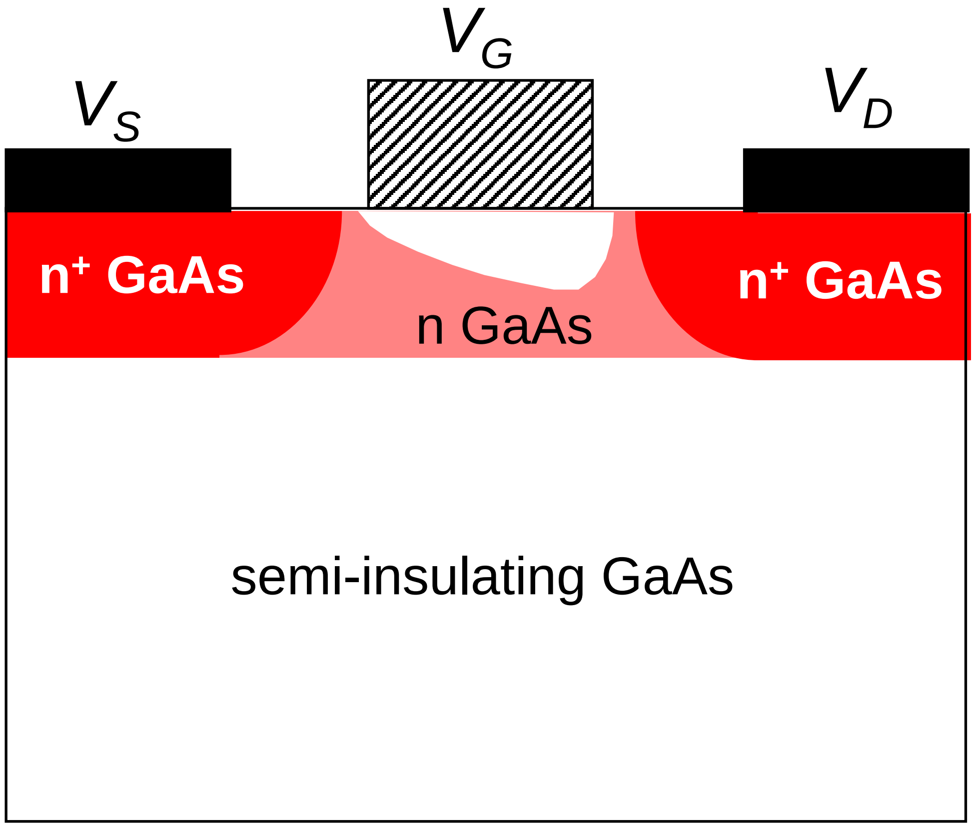
II) Modulation doping

III) I-V characteristics

IV) Device Structure / Materials

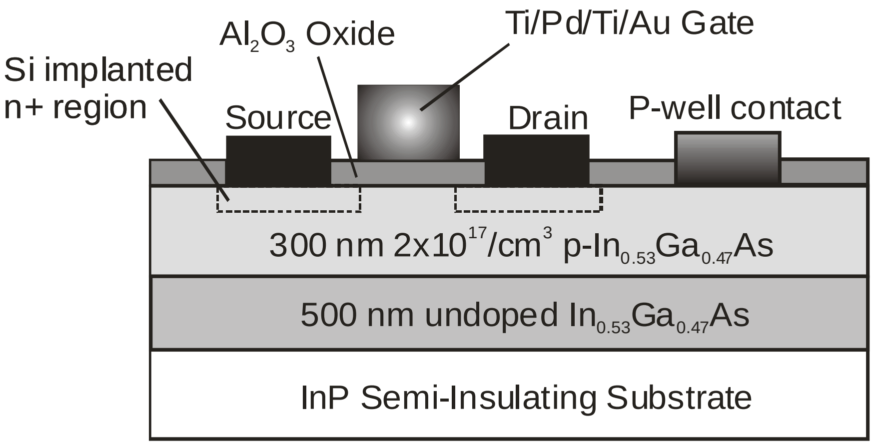
V) Summary

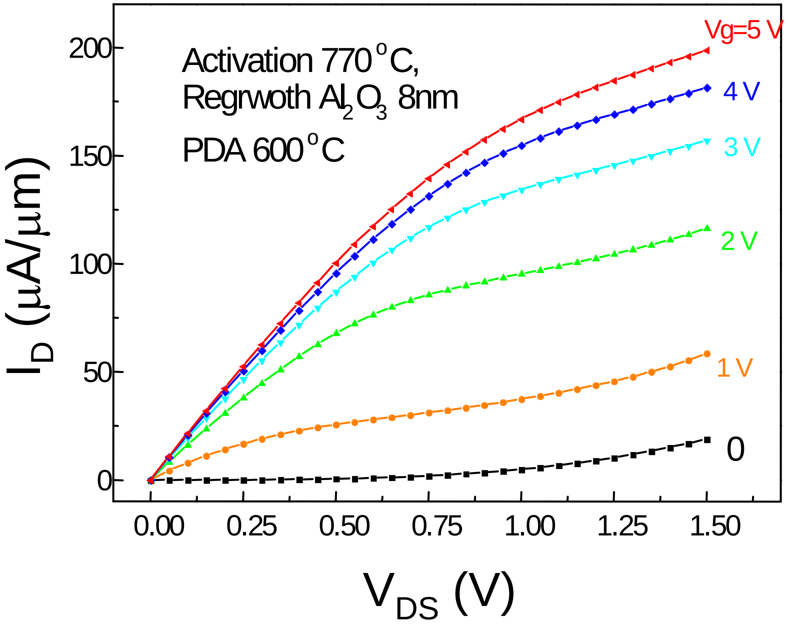
GaAs MESFET



- 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

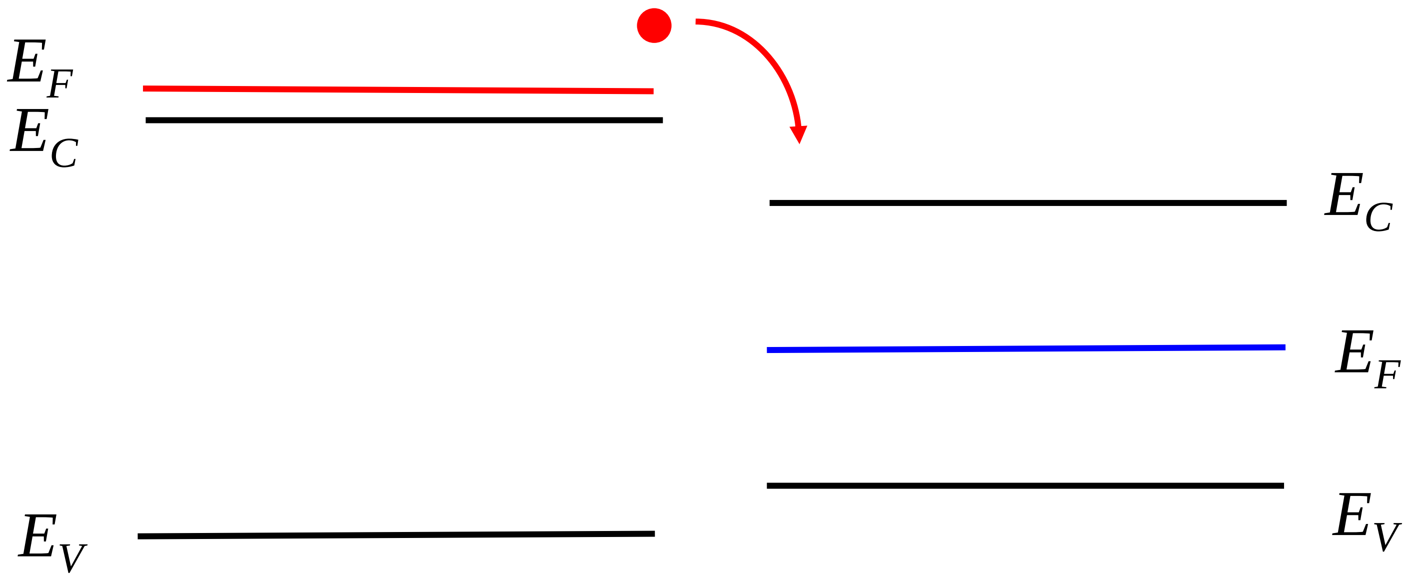
InGaAs MOSFETs?





P. Ye Group, Purdue University

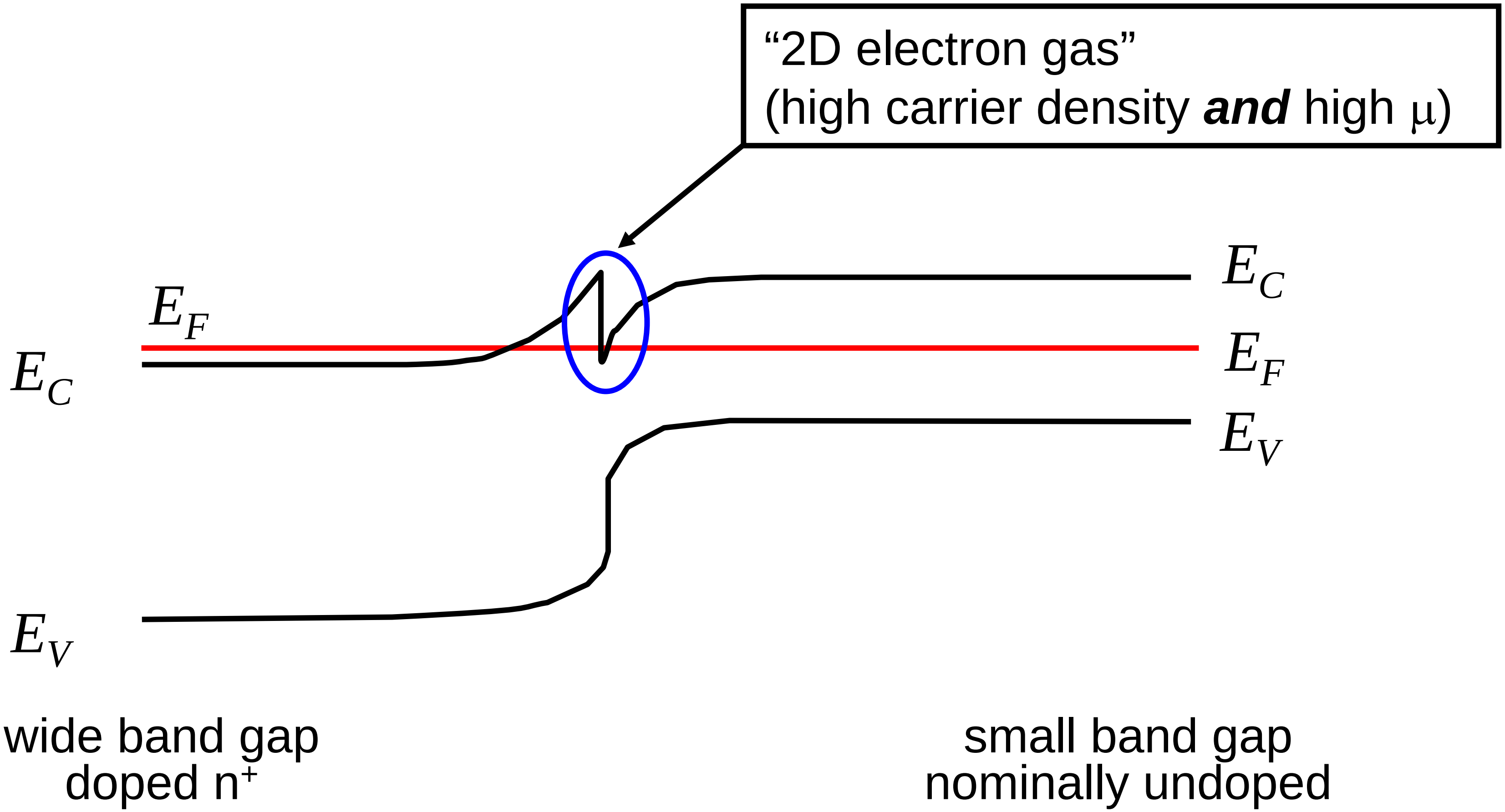
modulation doping



wide band gap
doped n^+

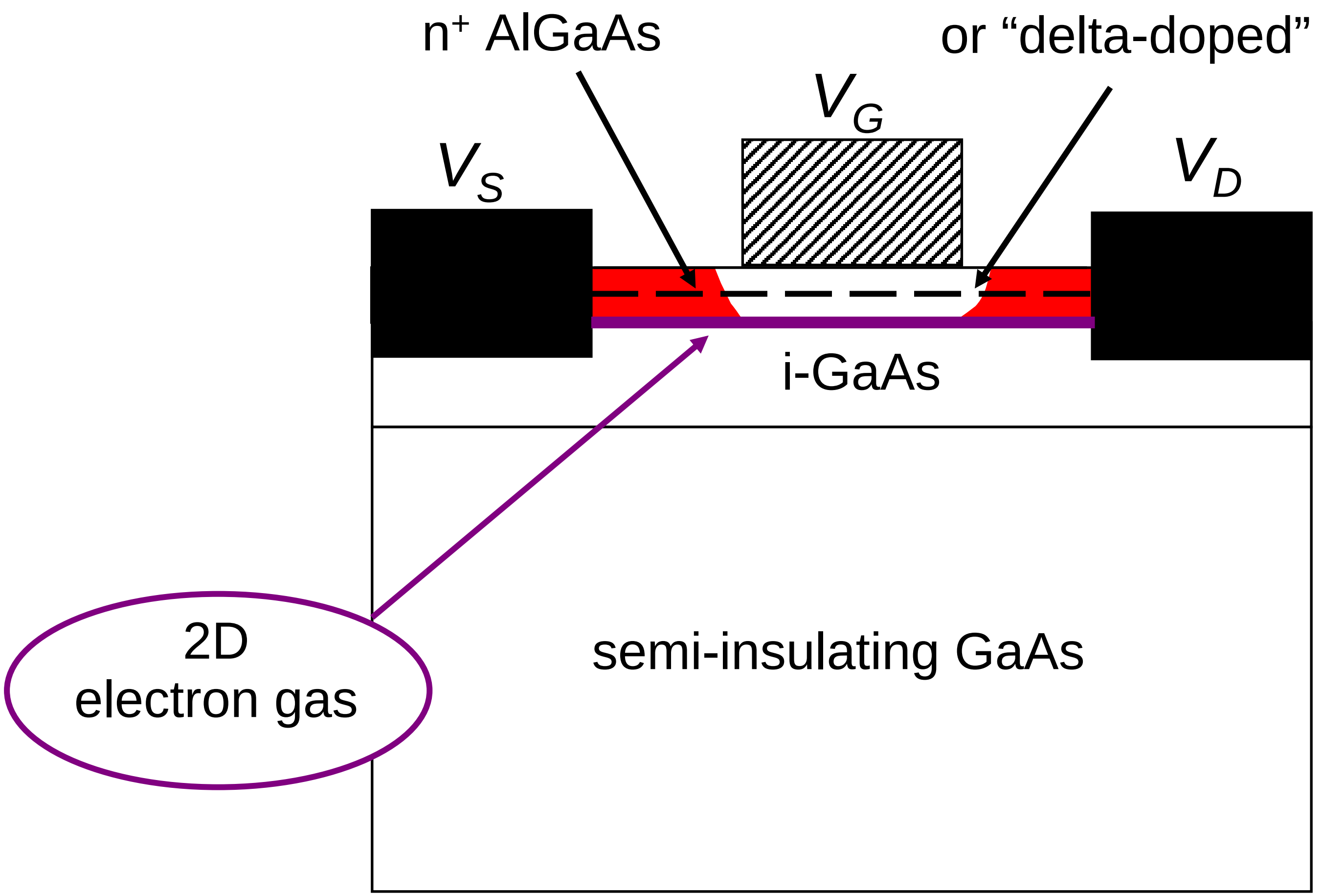
small band gap
nominally undoped

modulation doping



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

AlGaAs / GaAs MODFET



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**

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.*

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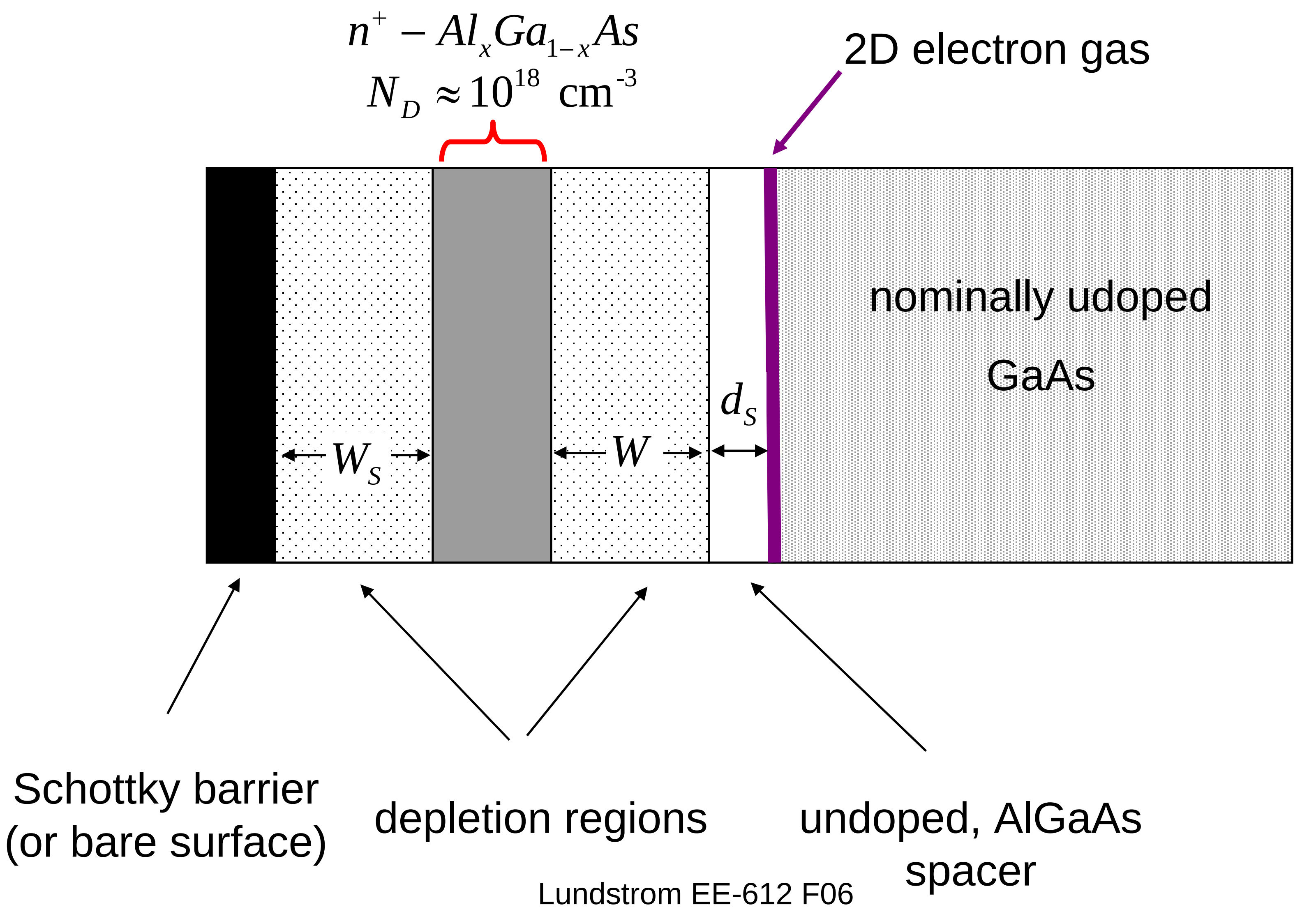
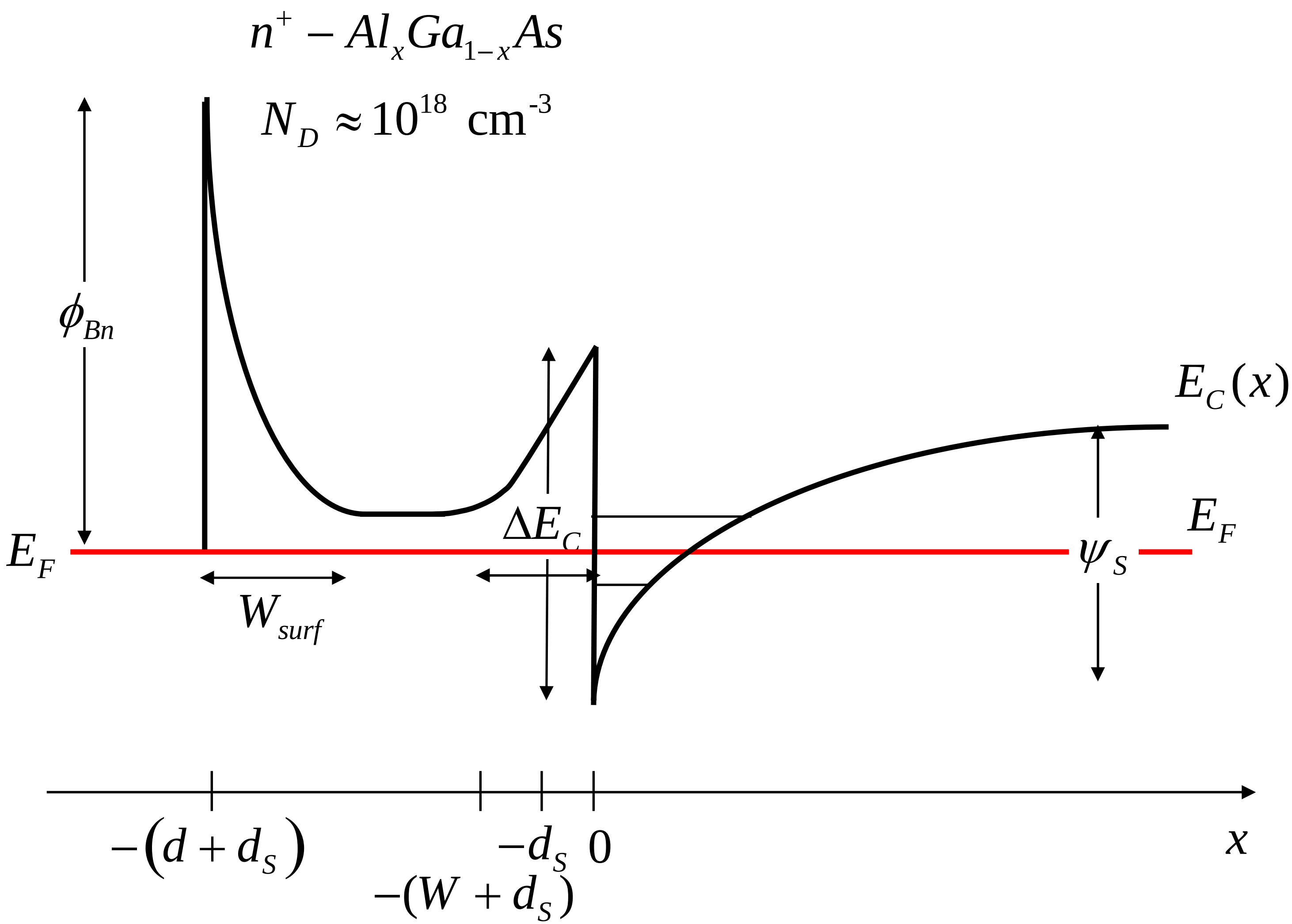
model structure

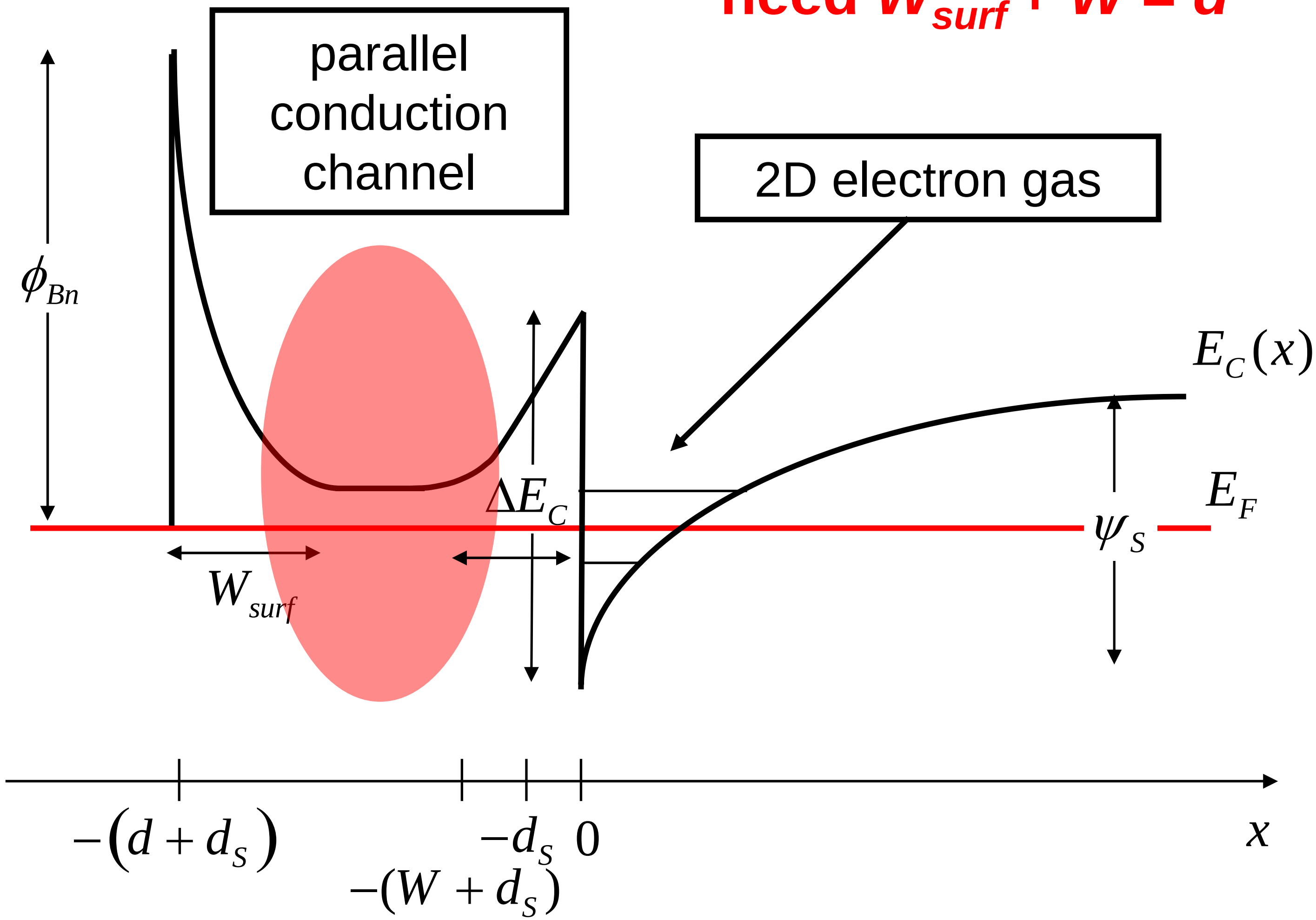


equilibrium energy band diagram



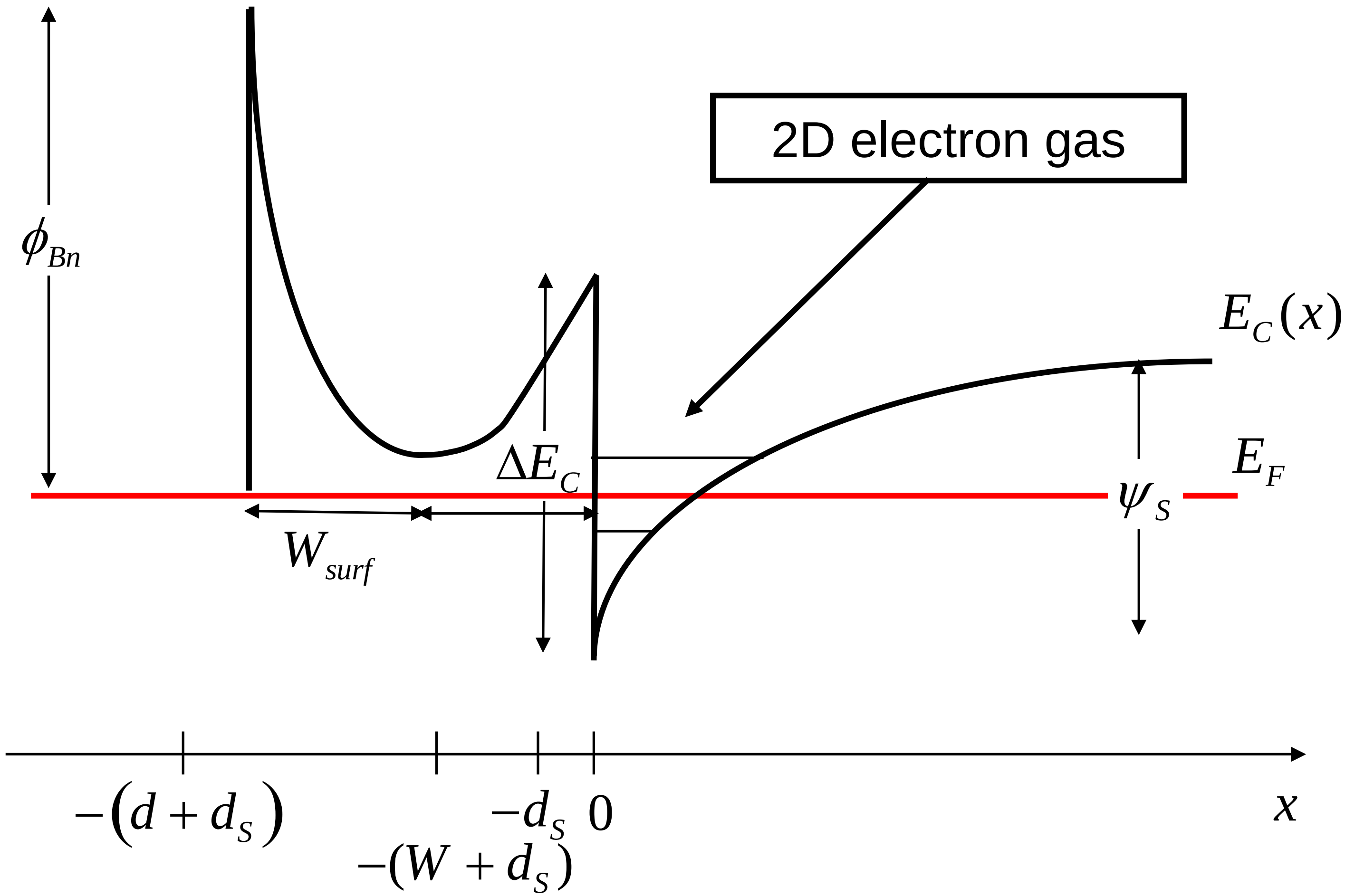
parallel conduction

need $W_{surf} + W = d$



equilibrium energy band diagram

$W_{surf} + W = d$



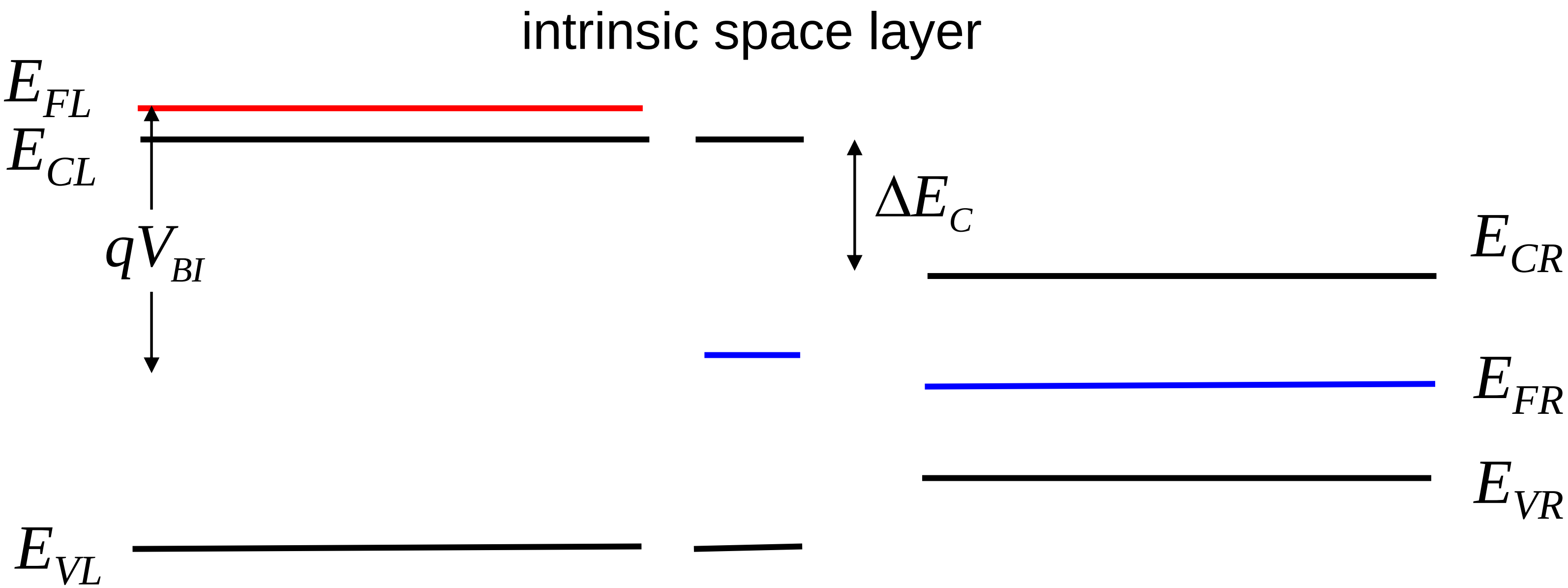
2D electron gas density

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



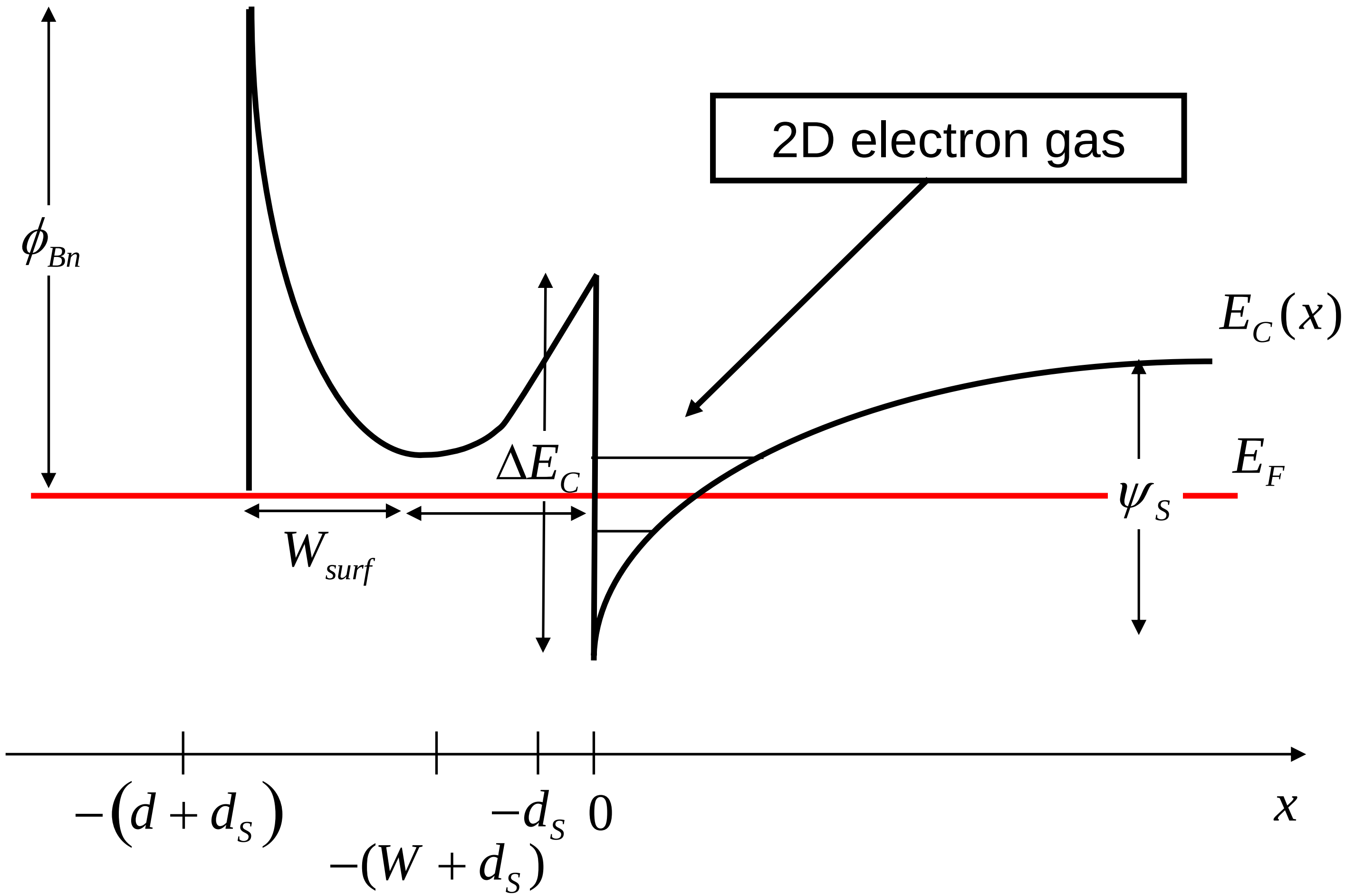
$$qV_{BI} = E_{FL} - E_{FR} \qquad E_{FR} = E_{CL} - \Delta E_C - E_G/2$$

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

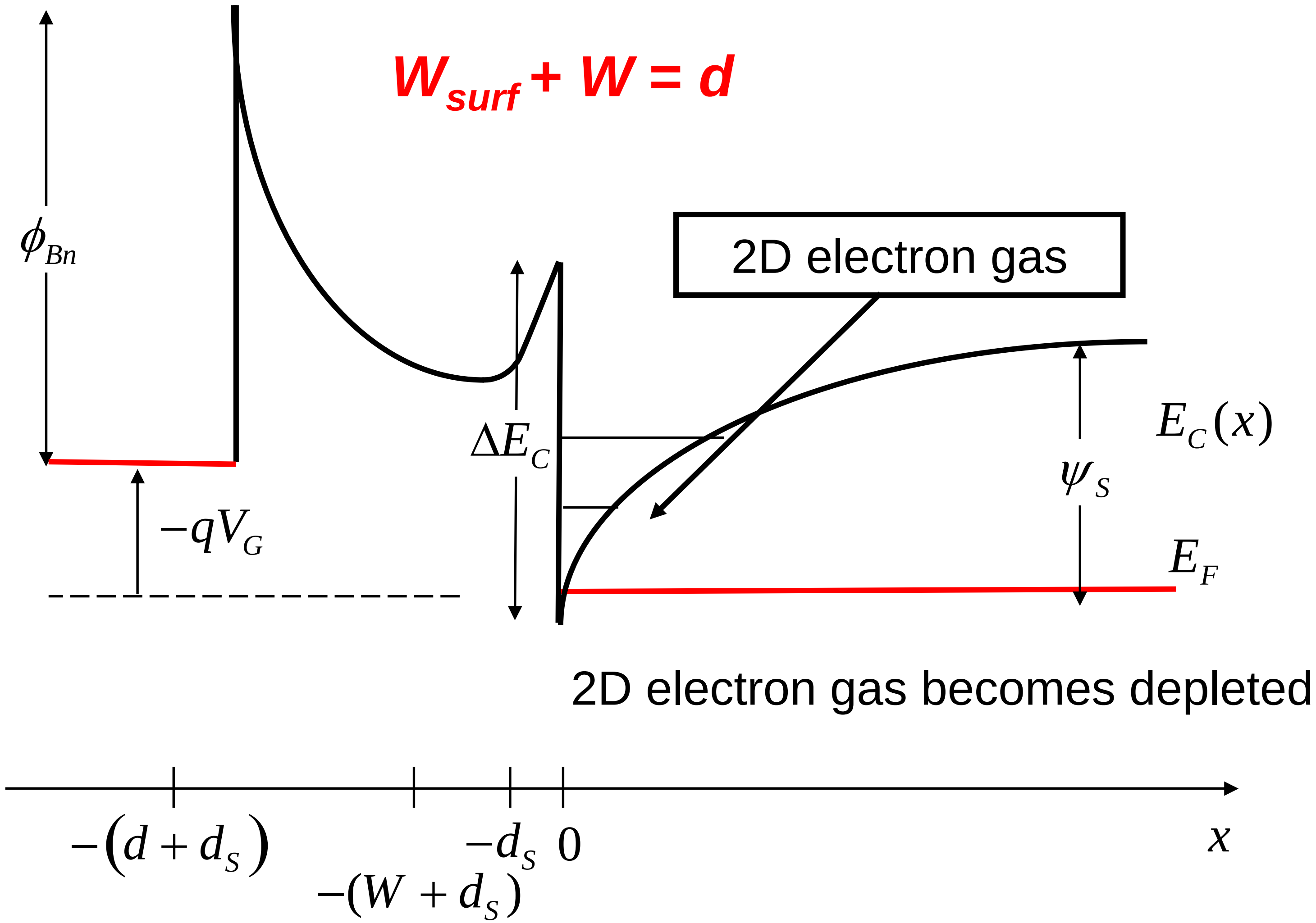
doping band discontinuity + spacer thickness

$V_G = 0$ energy band diagram

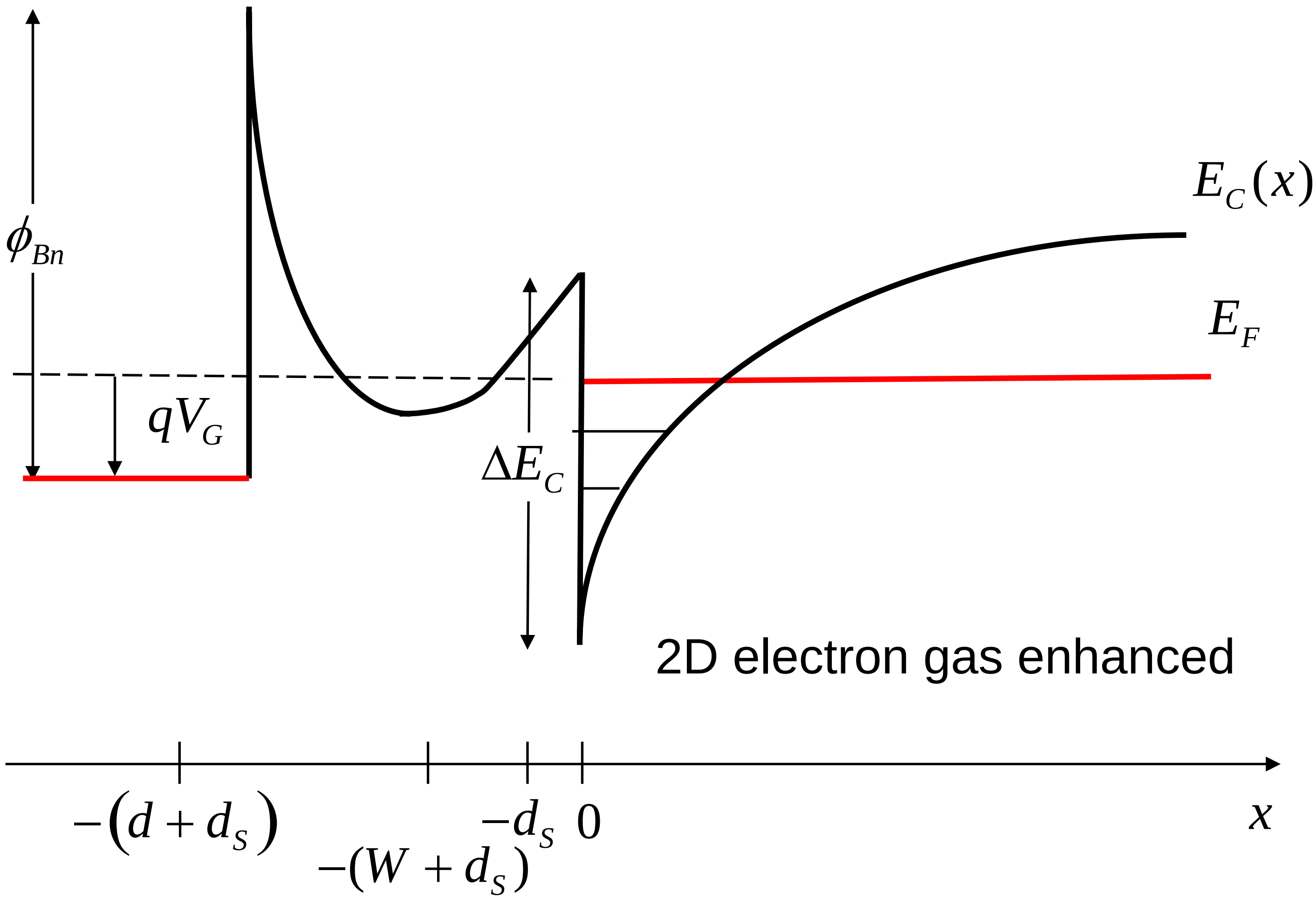
$W_{surf} + W = d$



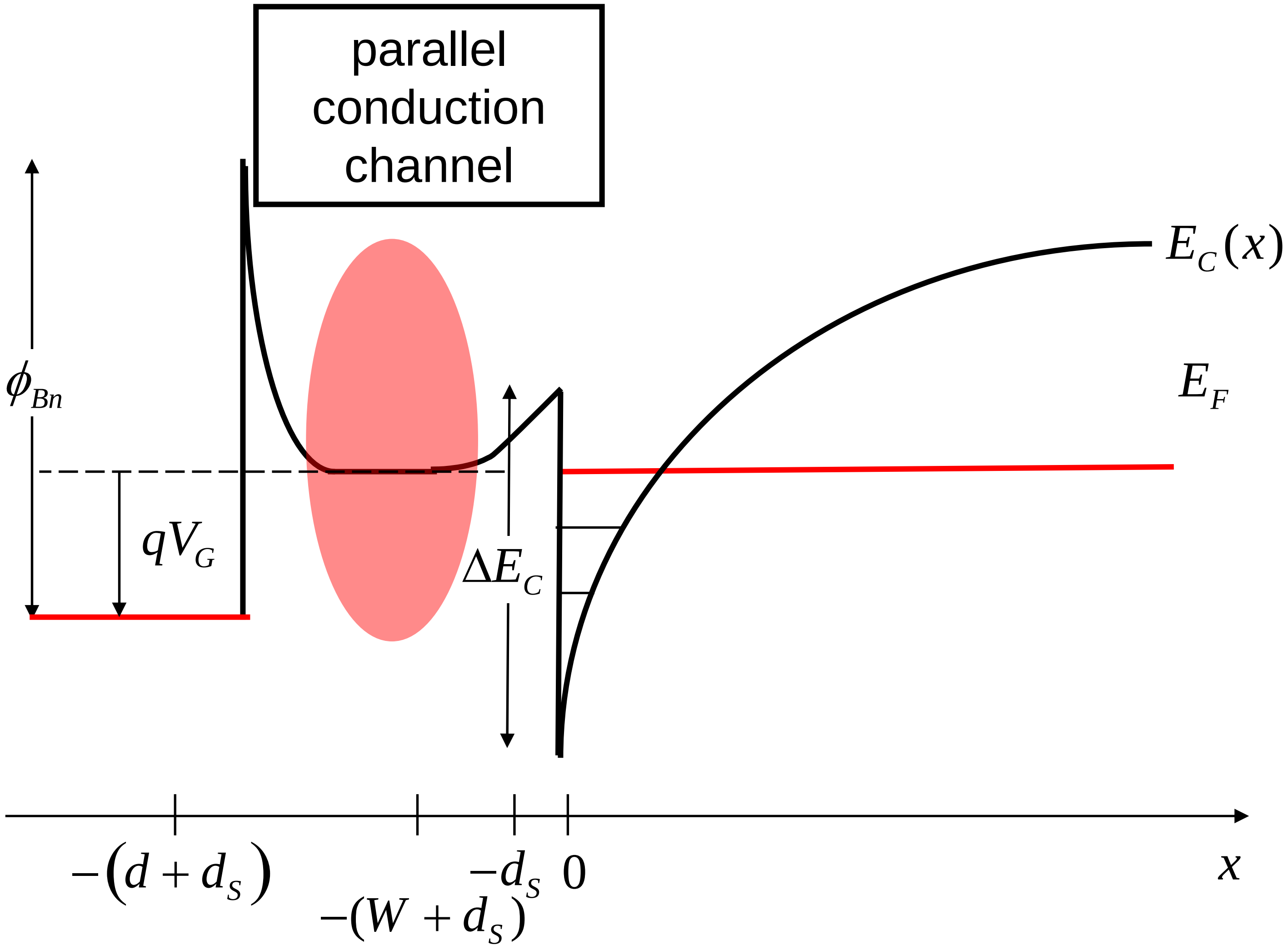
$V_G < 0$ energy band diagram



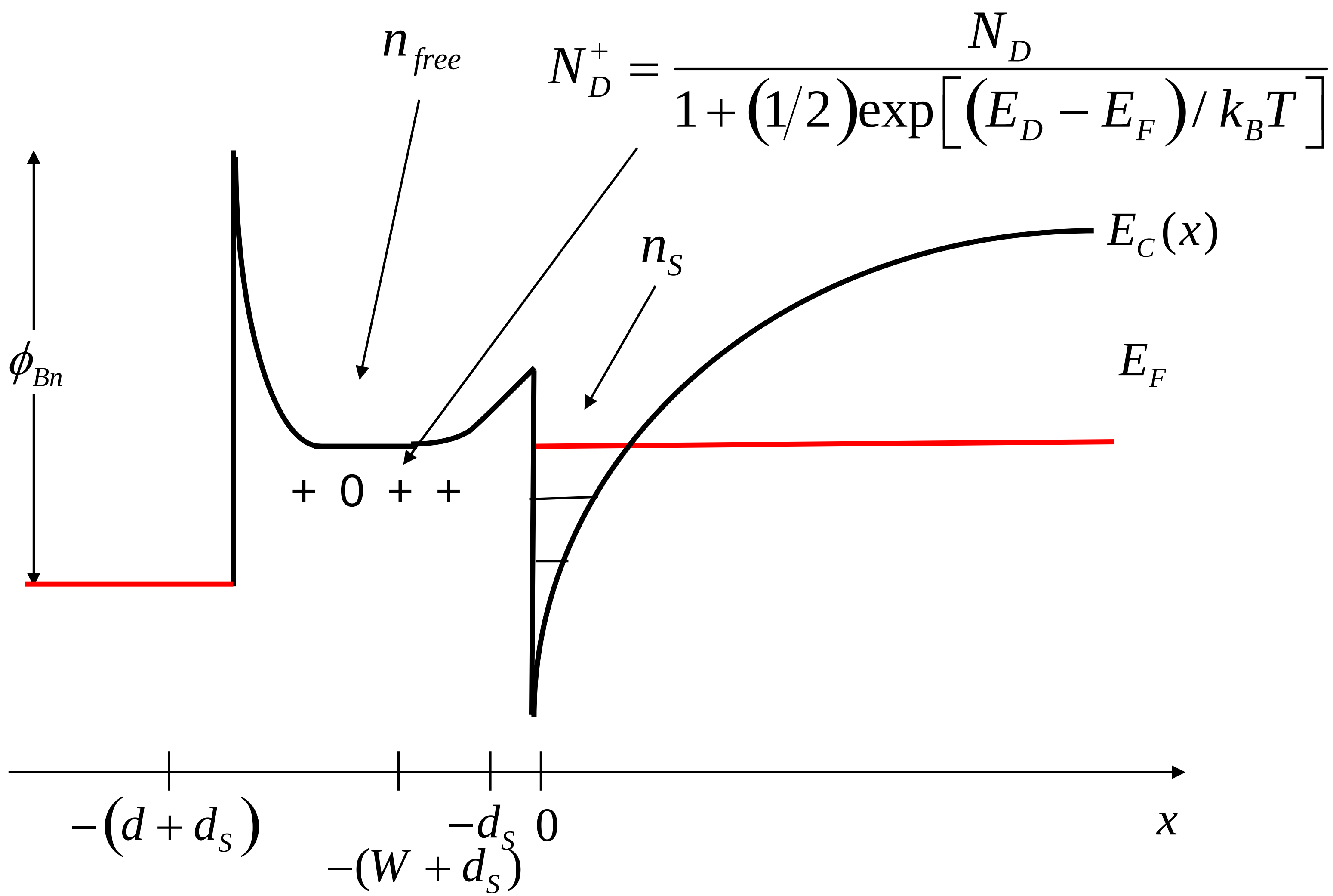
$V_G > 0$ energy band diagram



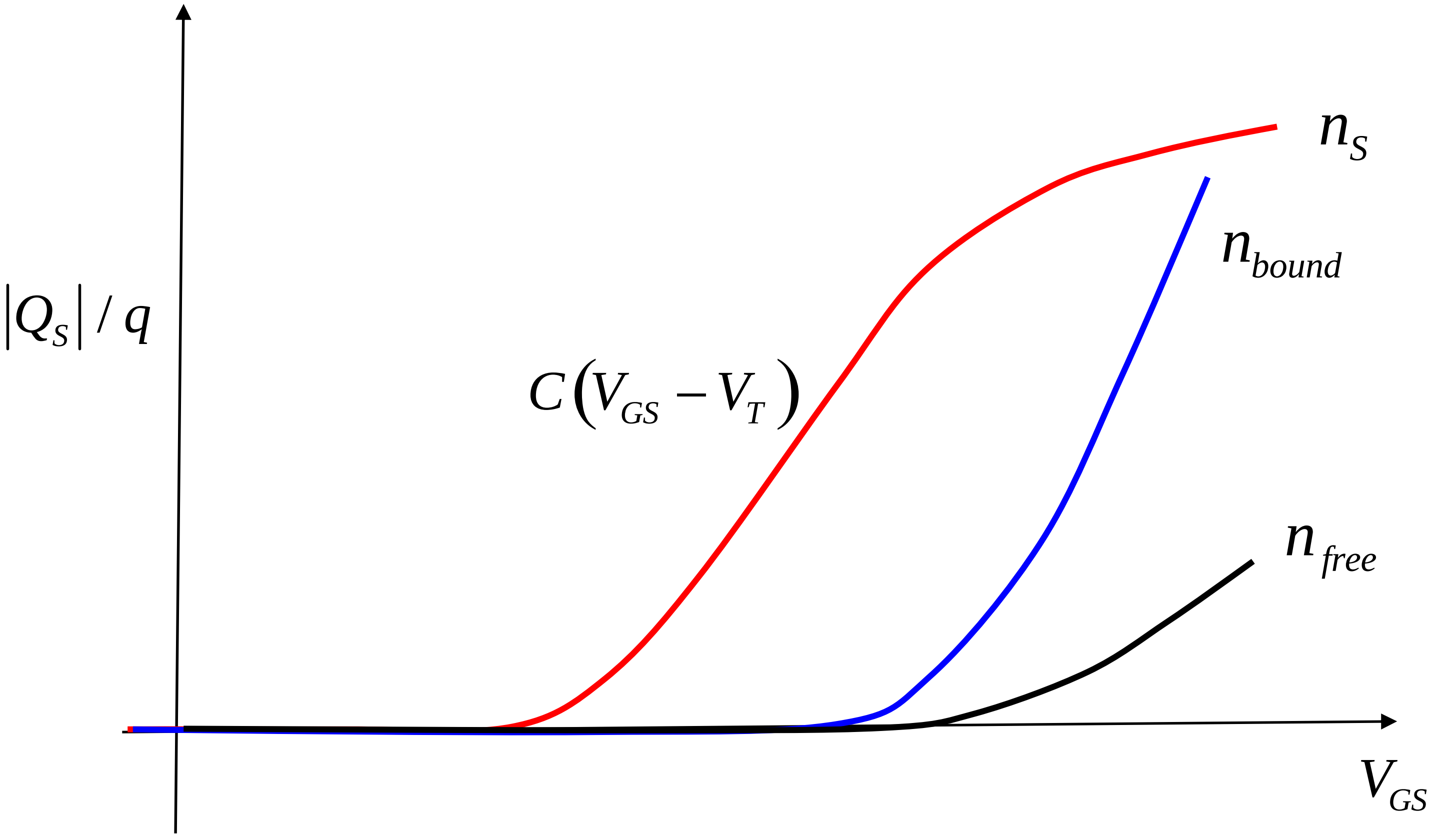
$V_G >> 0$ energy band diagram



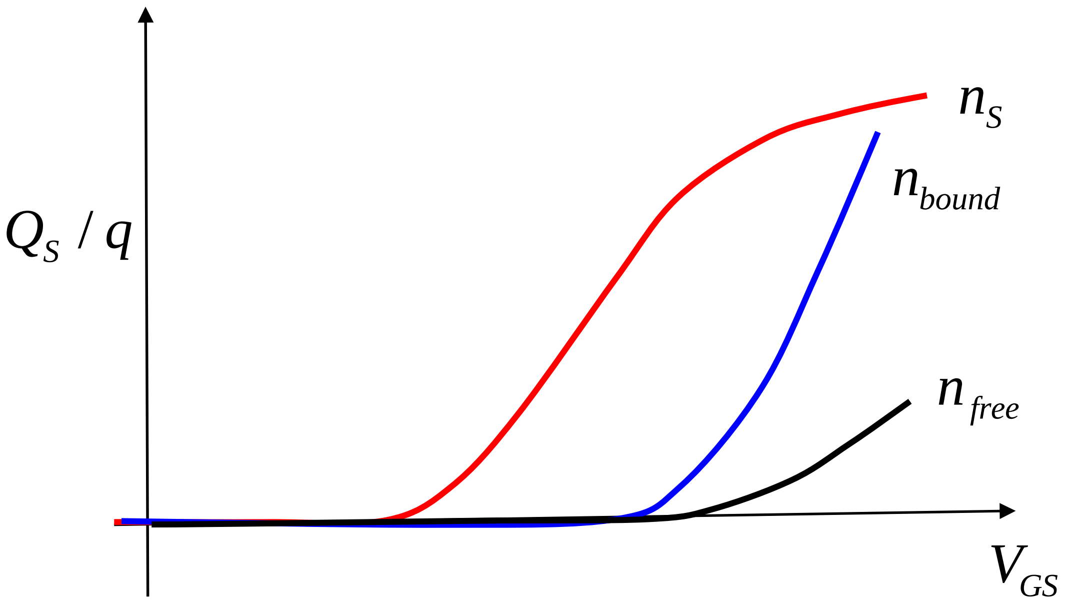
charges under forward bias



charges under forward bias

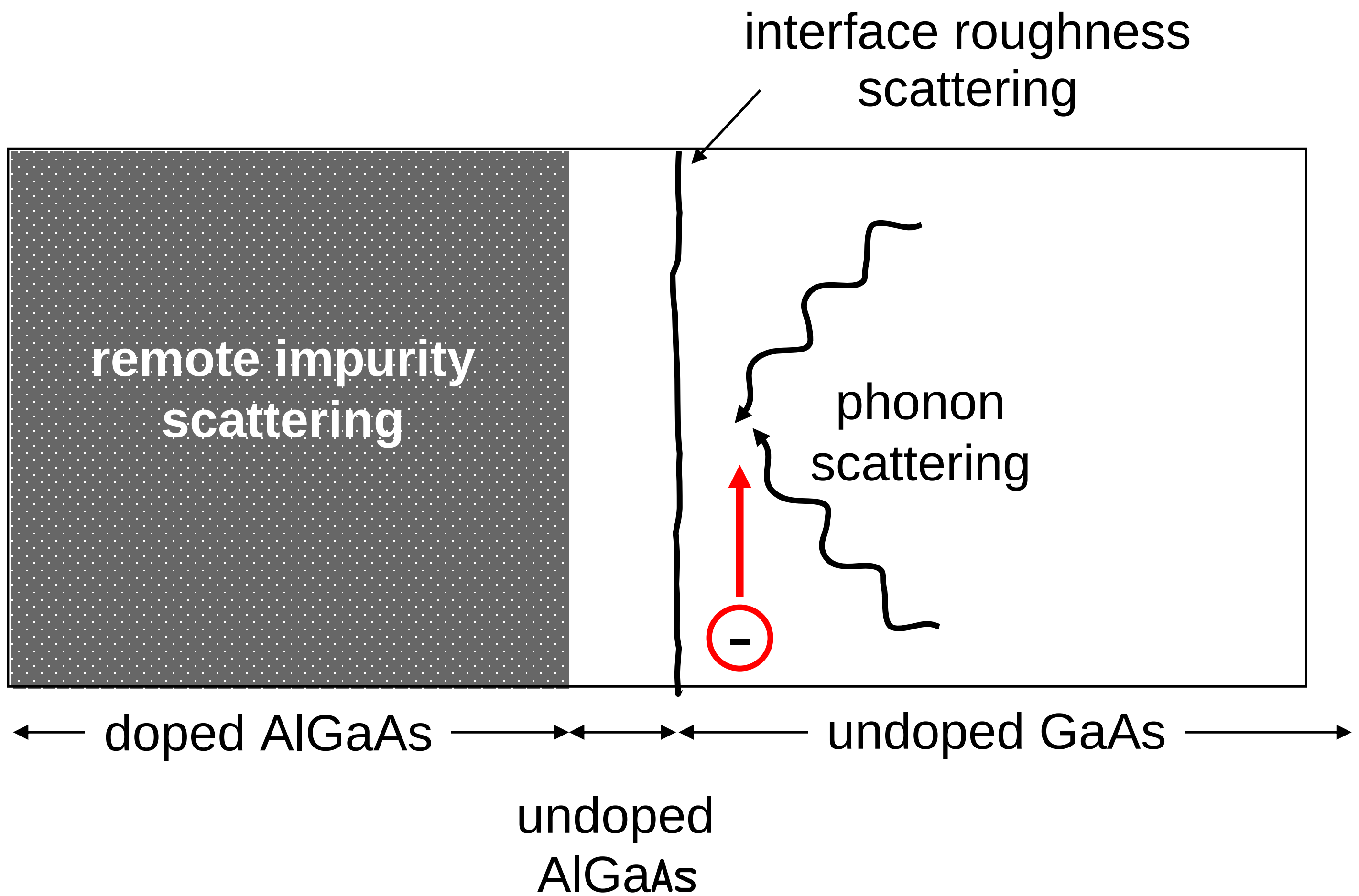


modulation efficiency



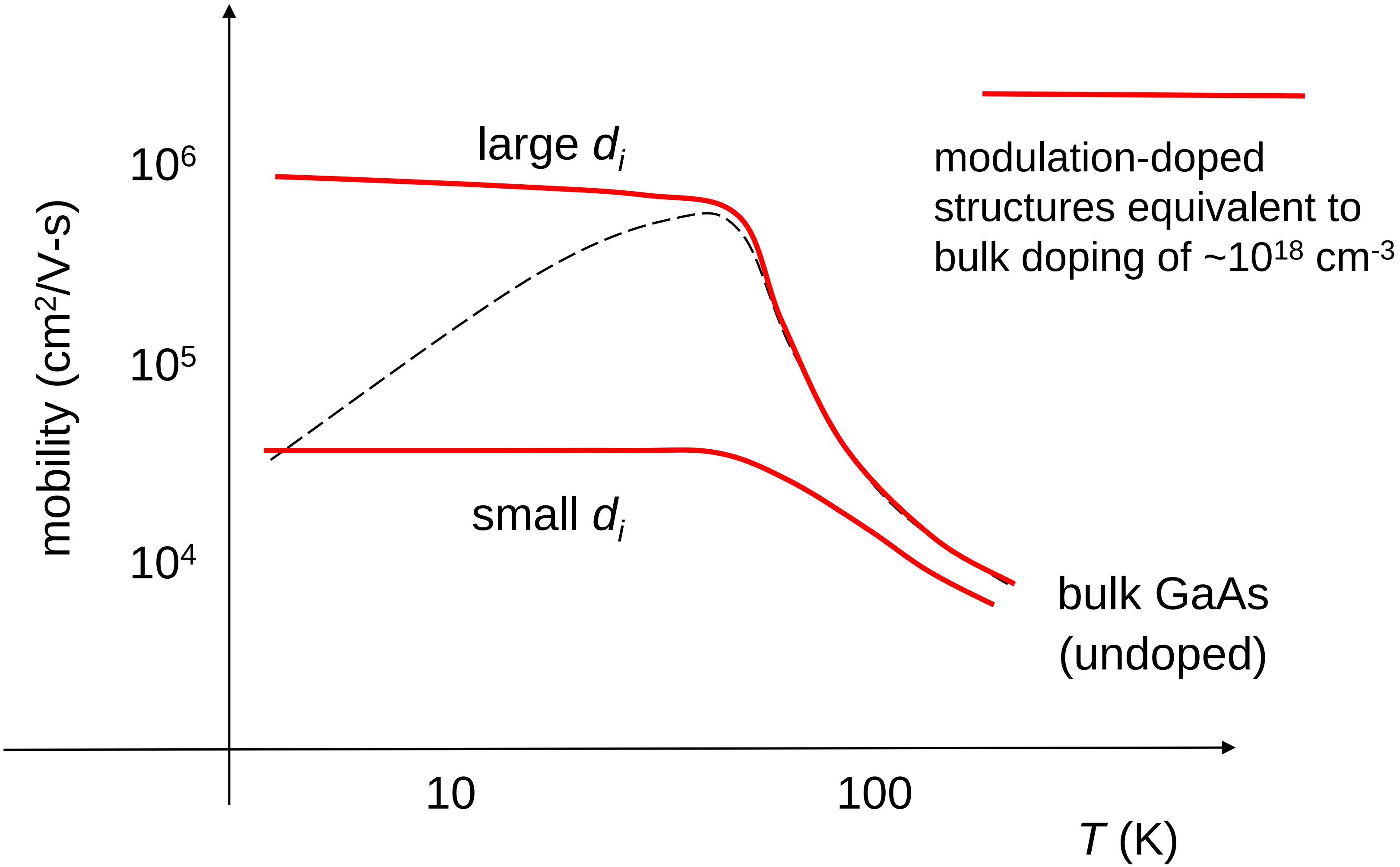
$$\eta = \frac{\partial n_S / \partial V_G}{\partial \left(n_S + n_{bound} + n_{free} \right) / \partial V_G} = \frac{C_S}{C_{TOT}}$$

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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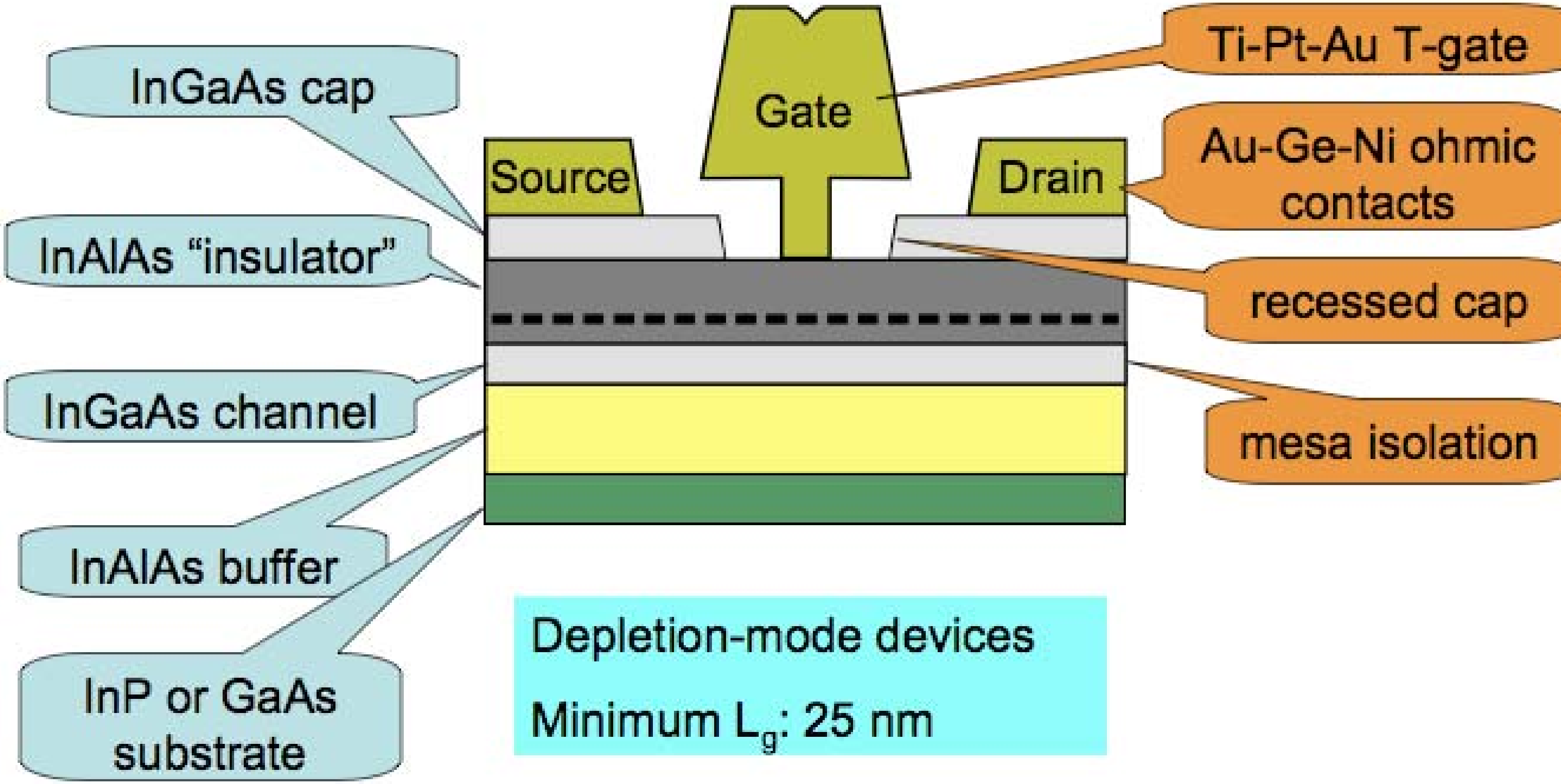
device performance

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

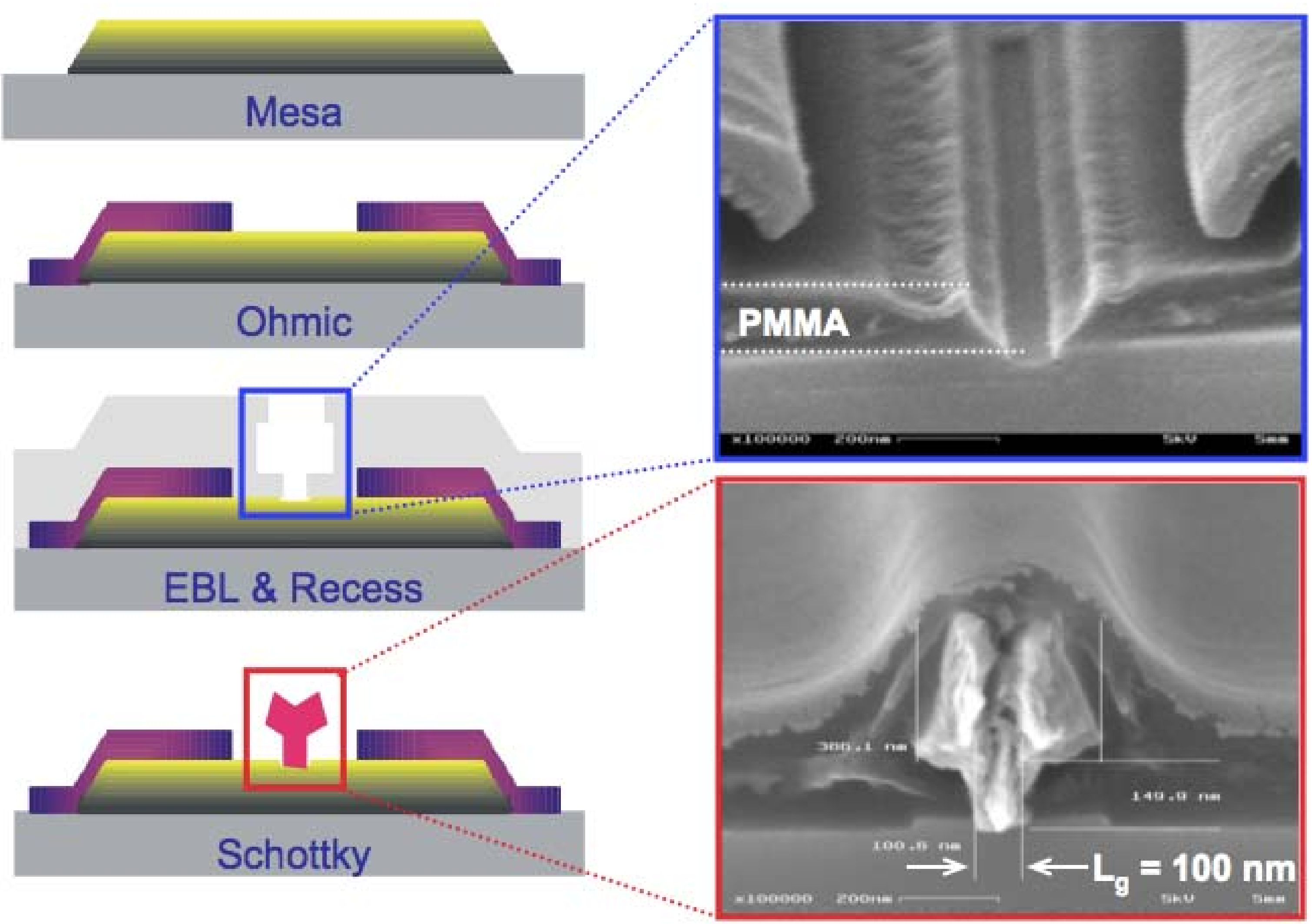
Strained MQW

3 Inch S. I. InP Substrate

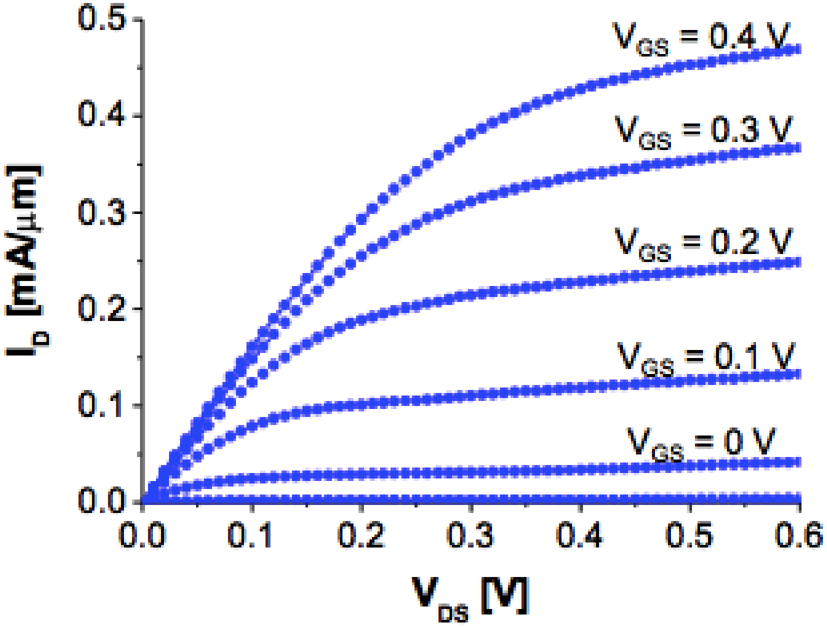
➔ N_{sh} = ~ 3 × 10^{12} /cm^2 @ 300 K

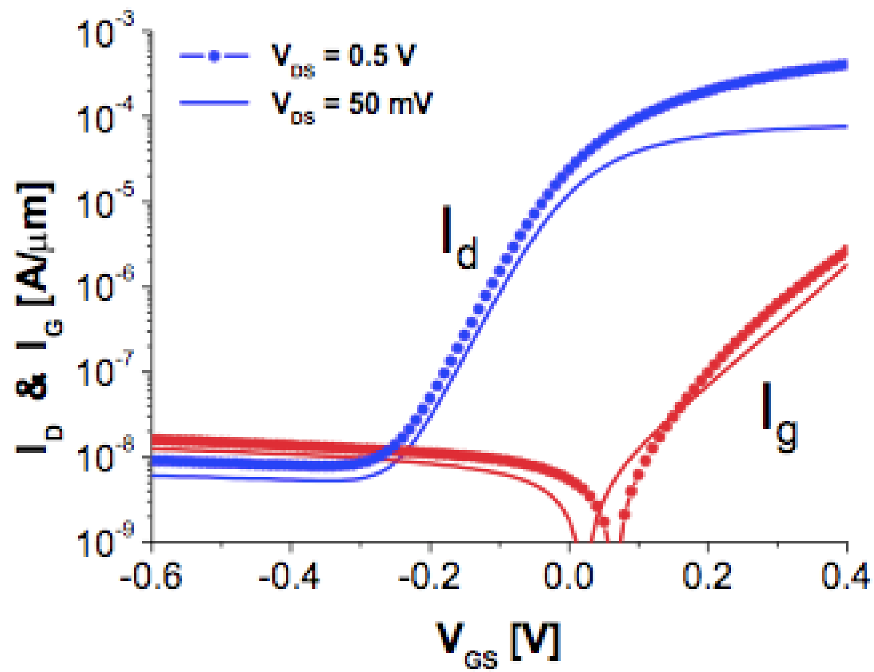
➔ $\mu_{n,Hall}$ = ~ 11,000 cm^2/V-sec @ 300 K

device fabrication



IV characteristics of 60nm InGaAs HEMT

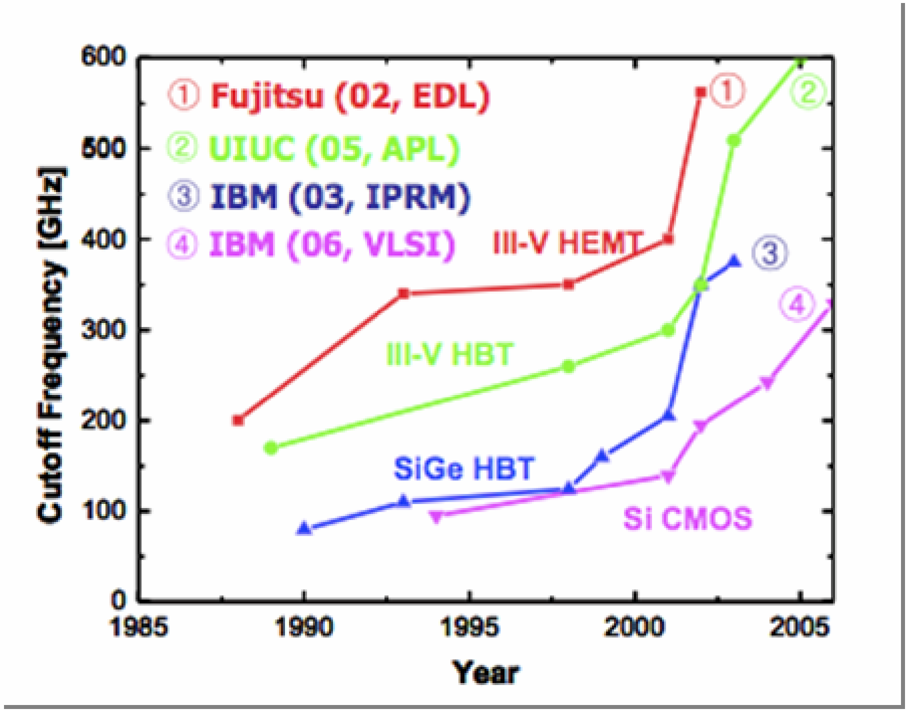




At 0.5 V:

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

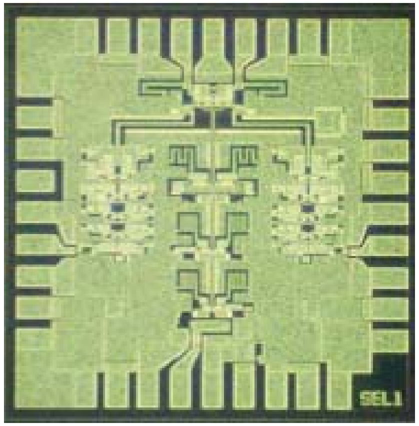
InGaAs HEMT technology



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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Thanks to Prof. J. del Alamo for providing the InGaAs HEMT results!