Unit 5: Additional Topics

Lecture 5.3: High Electron Mobility Transistors (HEMTs)

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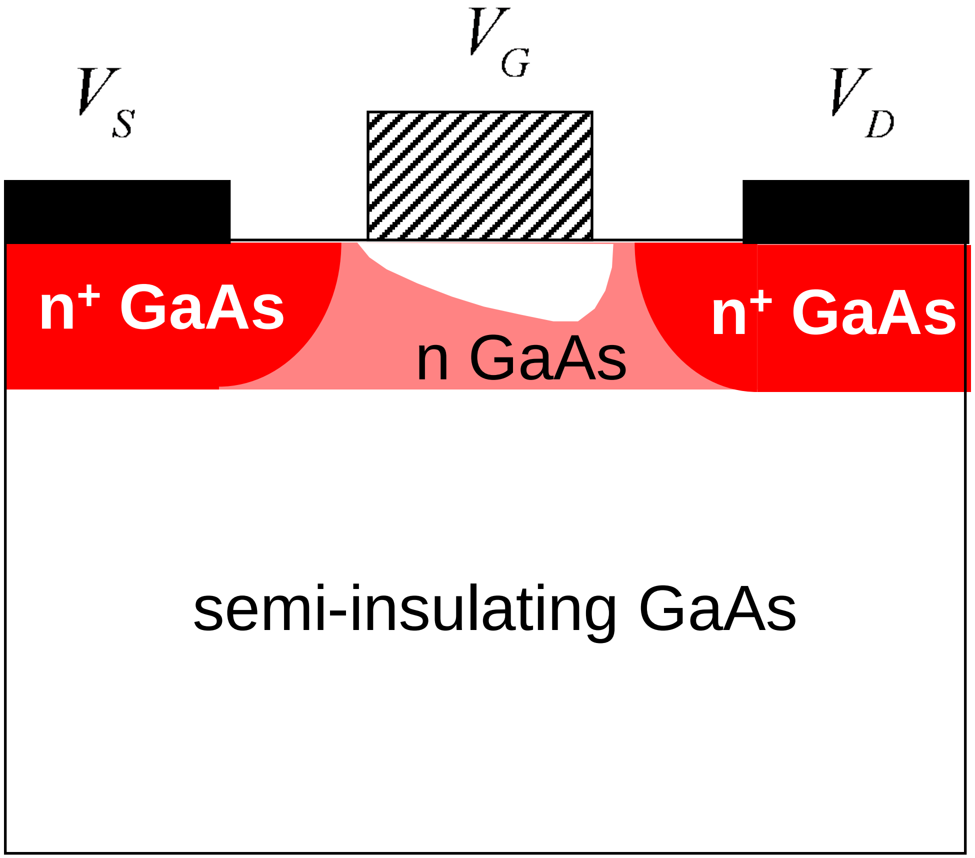
Transistors

MOSFET	HFET	RBT
MOST	DHFET	RHET
IGFET	HIGFET	QWBRTT
DMOS	SISFET	TETRAN
HEXFET	PBT	SIT
VMOS	LRTFET	NWFET
TFT	VMT	CNT FET
MISFET	BJT	SB FET
JFET	HBT	BTBT FET
VFET	DHBT	induced base transistor
MESFET	THETA	planar doped barrier transistor
MOSFET	RST	metal base transistor
HEMT	BICFET	Stark-effect transistor
TEGFET	RTBT	delta-doped channel heterojunction FET

Most of these are barrier-controlled transistors.

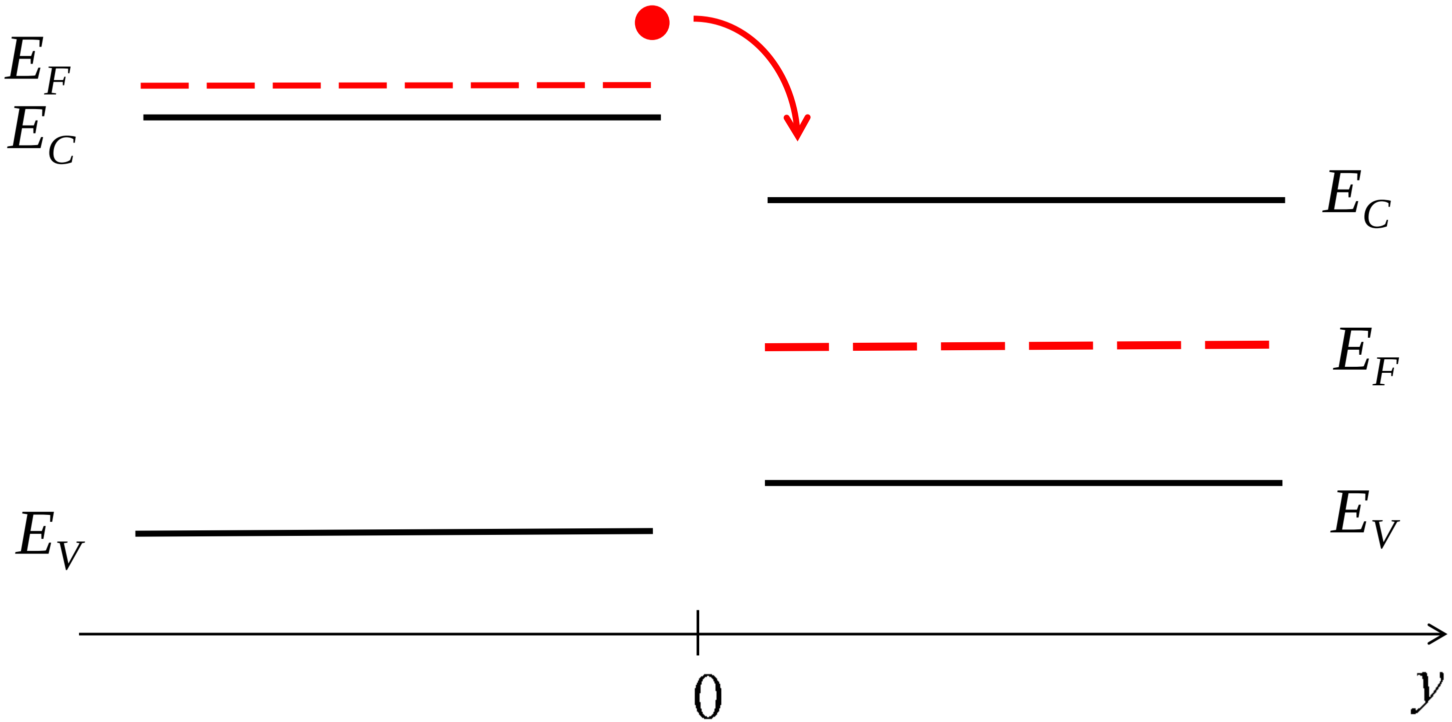
K.K. Ng, "A Survey of Semiconductor Devices, *IEEE Trans. Electron Dev*., **43**, 1760-1766, 1996.

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

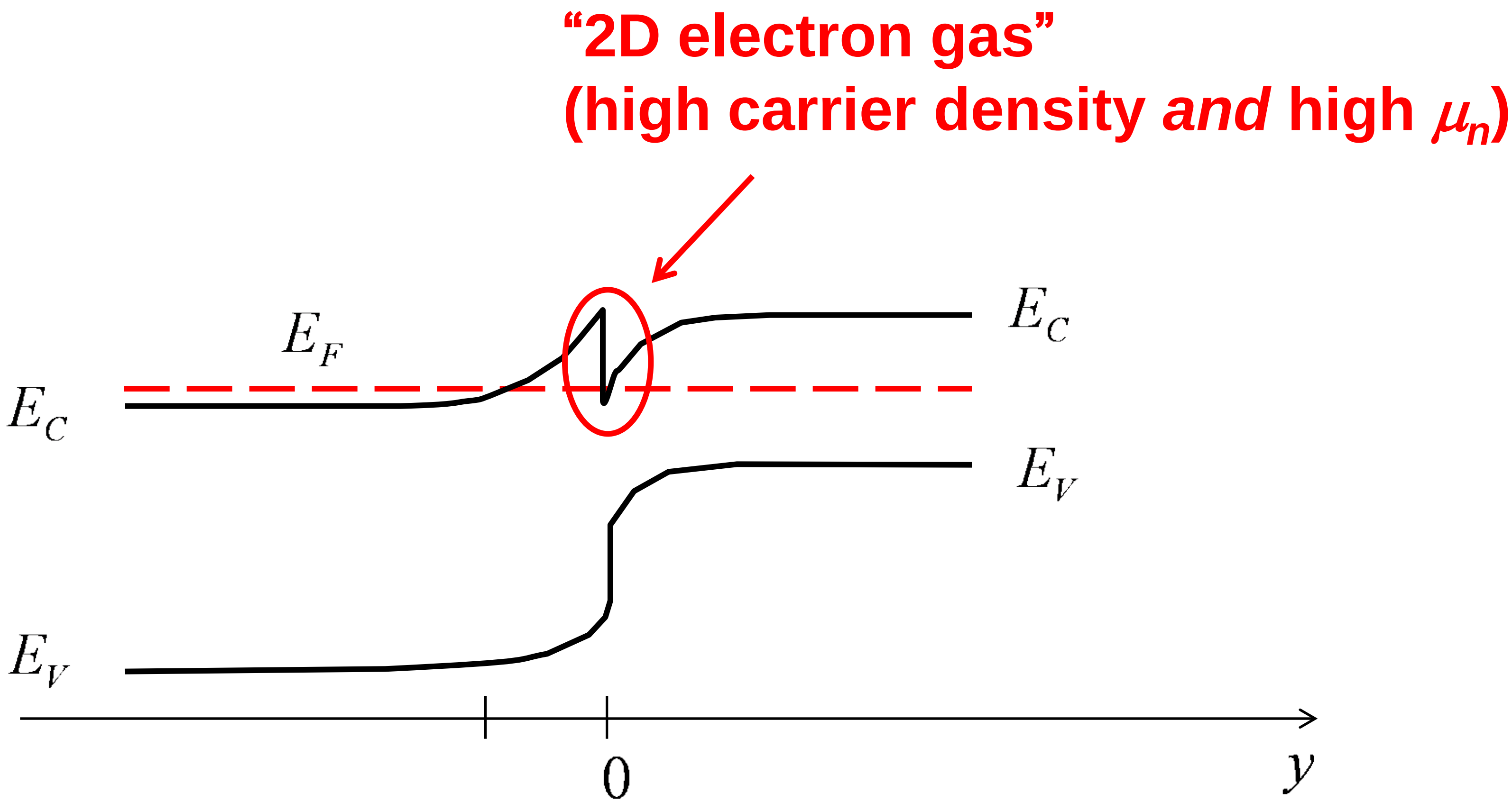
“Modulation doping”



wide bandgap
doped n$^+$

small bandgap
nominally undoped

Modulation doping

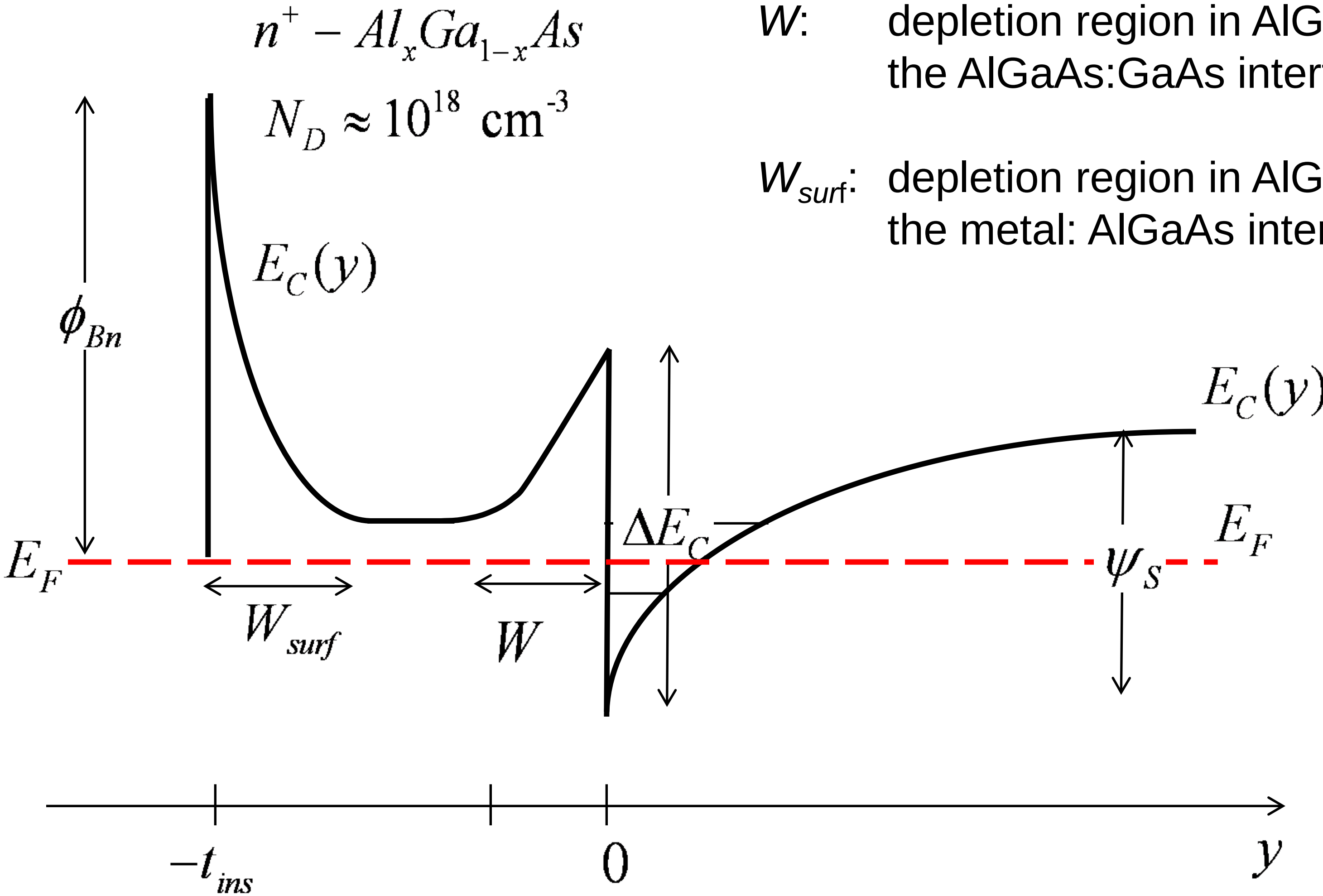


wide band gap doped n$^+$

small band gap
nominally undoped

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

Equilibrium energy band diagram

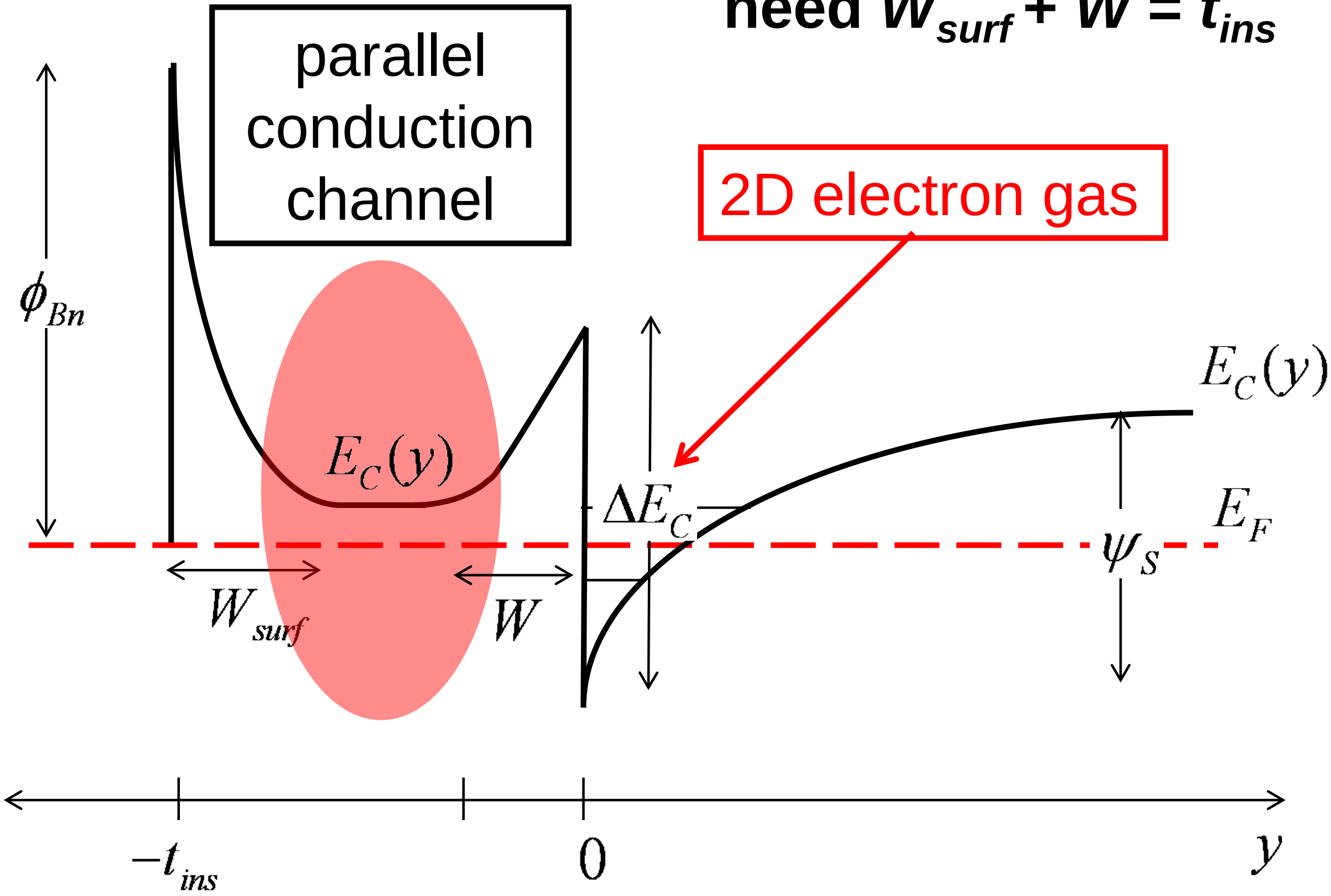


W: depletion region in AlGaAs at the AlGaAs:GaAs interface.

W_{surf}: depletion region in AlGaAs at the metal: AlGaAs interface

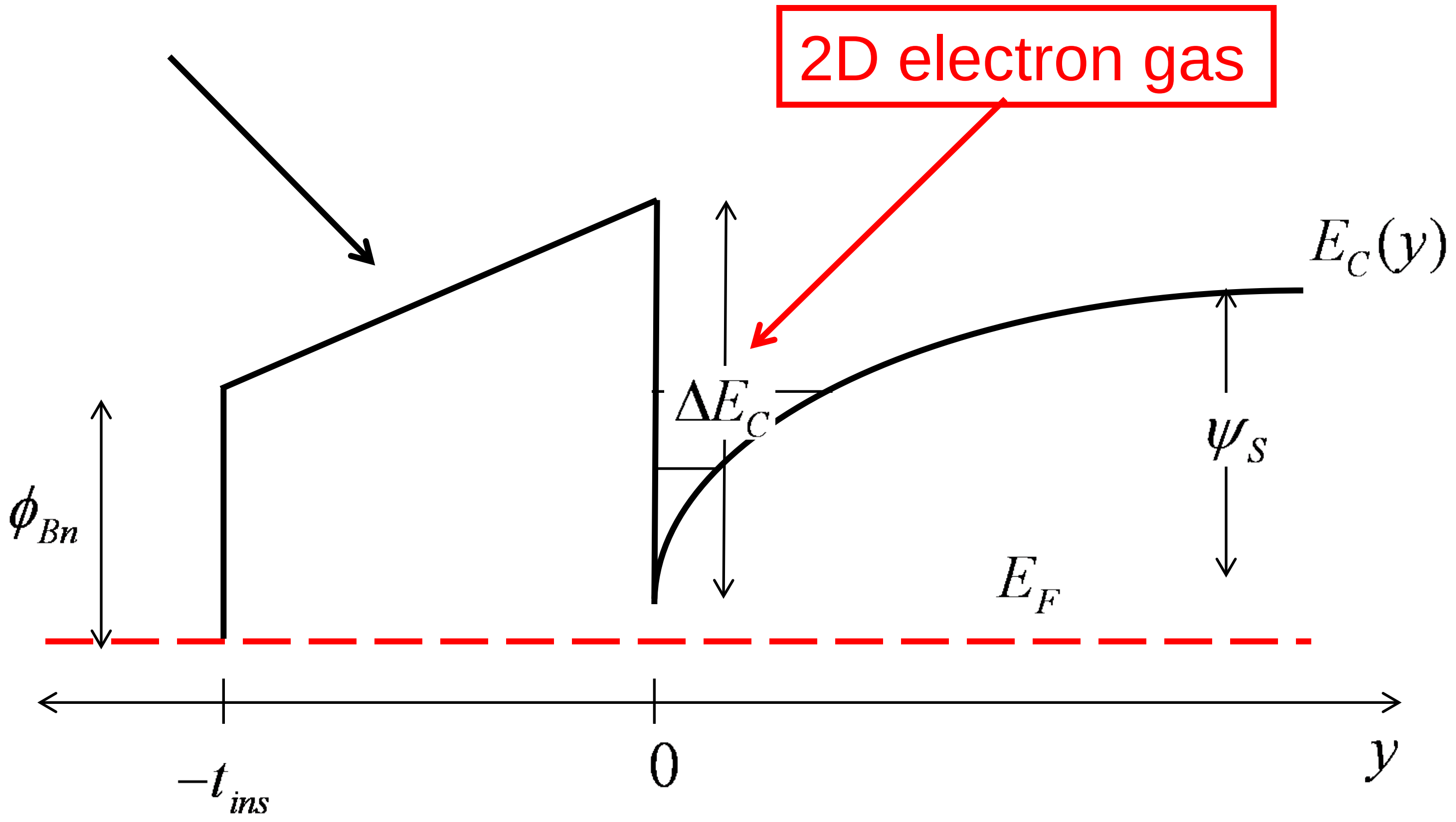
Parallel conduction should be avoided

need $W_{surf} + W = t_{ins}$

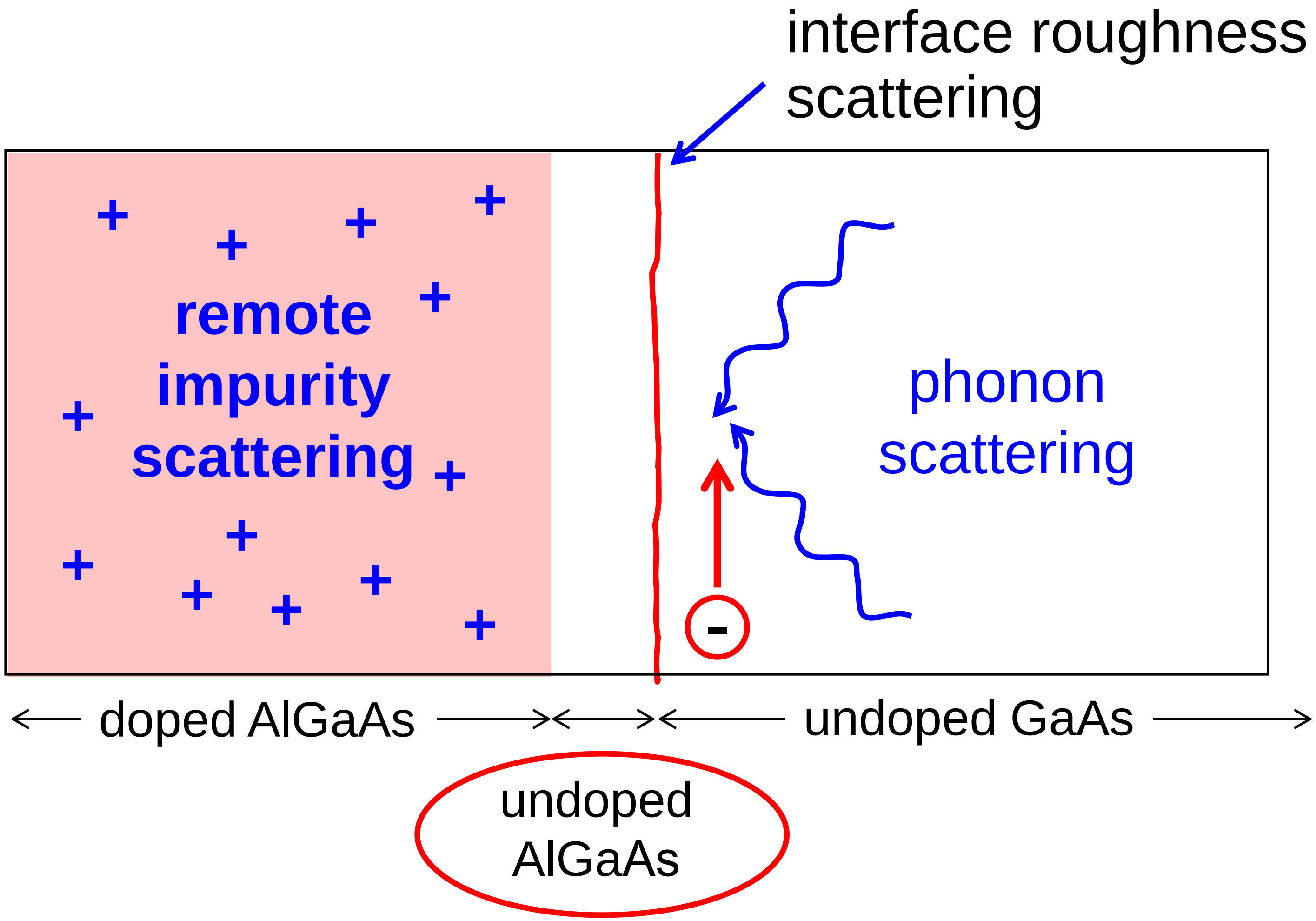


Why dope the wide bandgap layer?

"like a gate insulator"

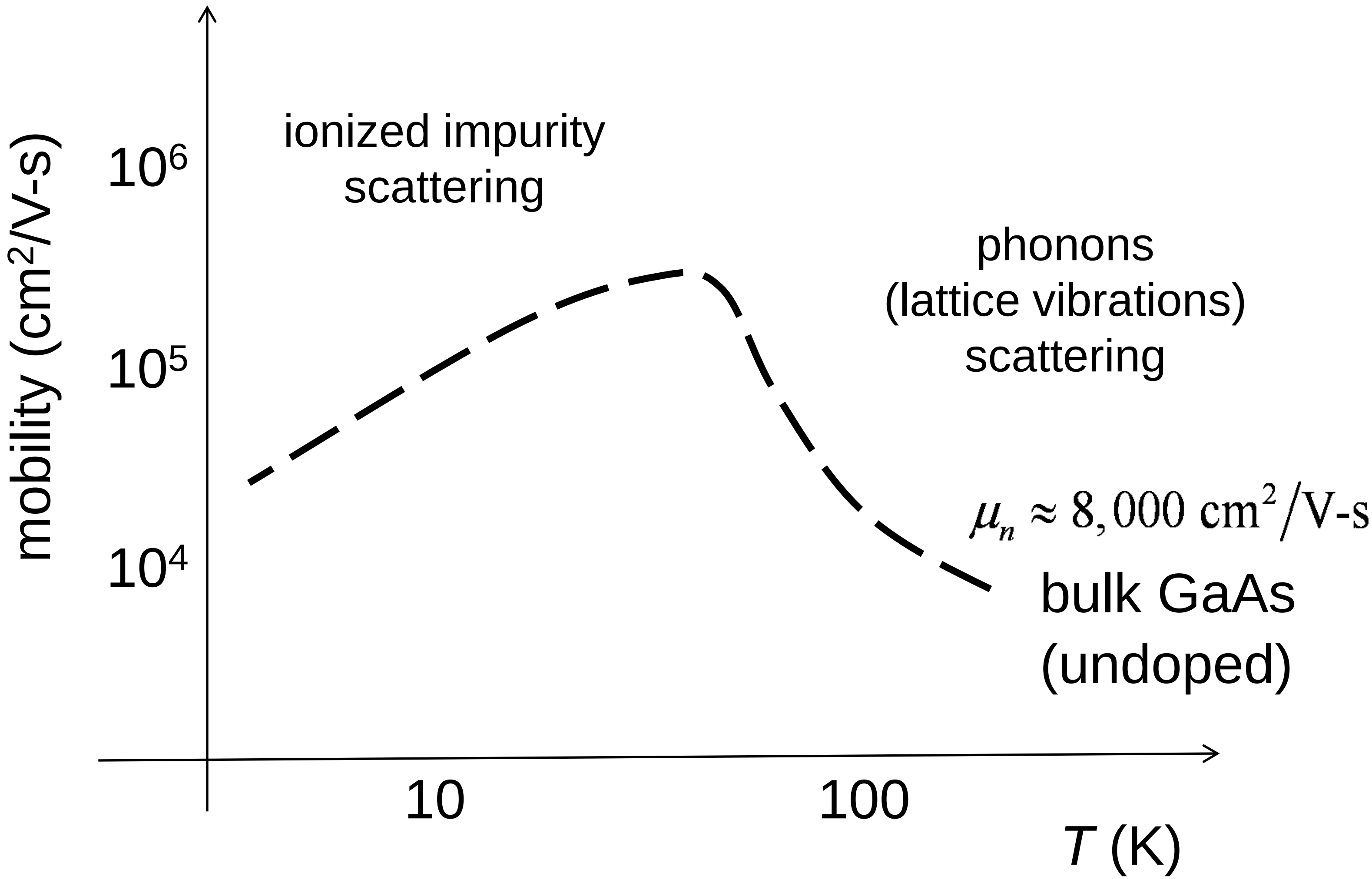


Scattering mechanisms (mobility)



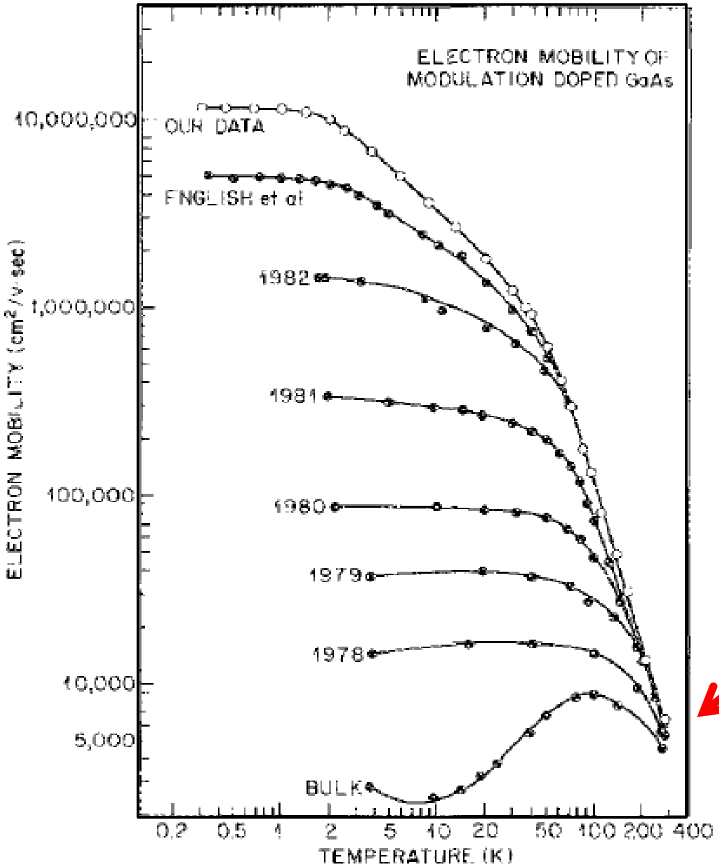
(after Solomon and Morkoc)

Mobility vs. temperature



Mobility vs. temperature (modulation doped)

$\mu_n > 10^7\ \text{cm}^2/\text{V-s}$!!

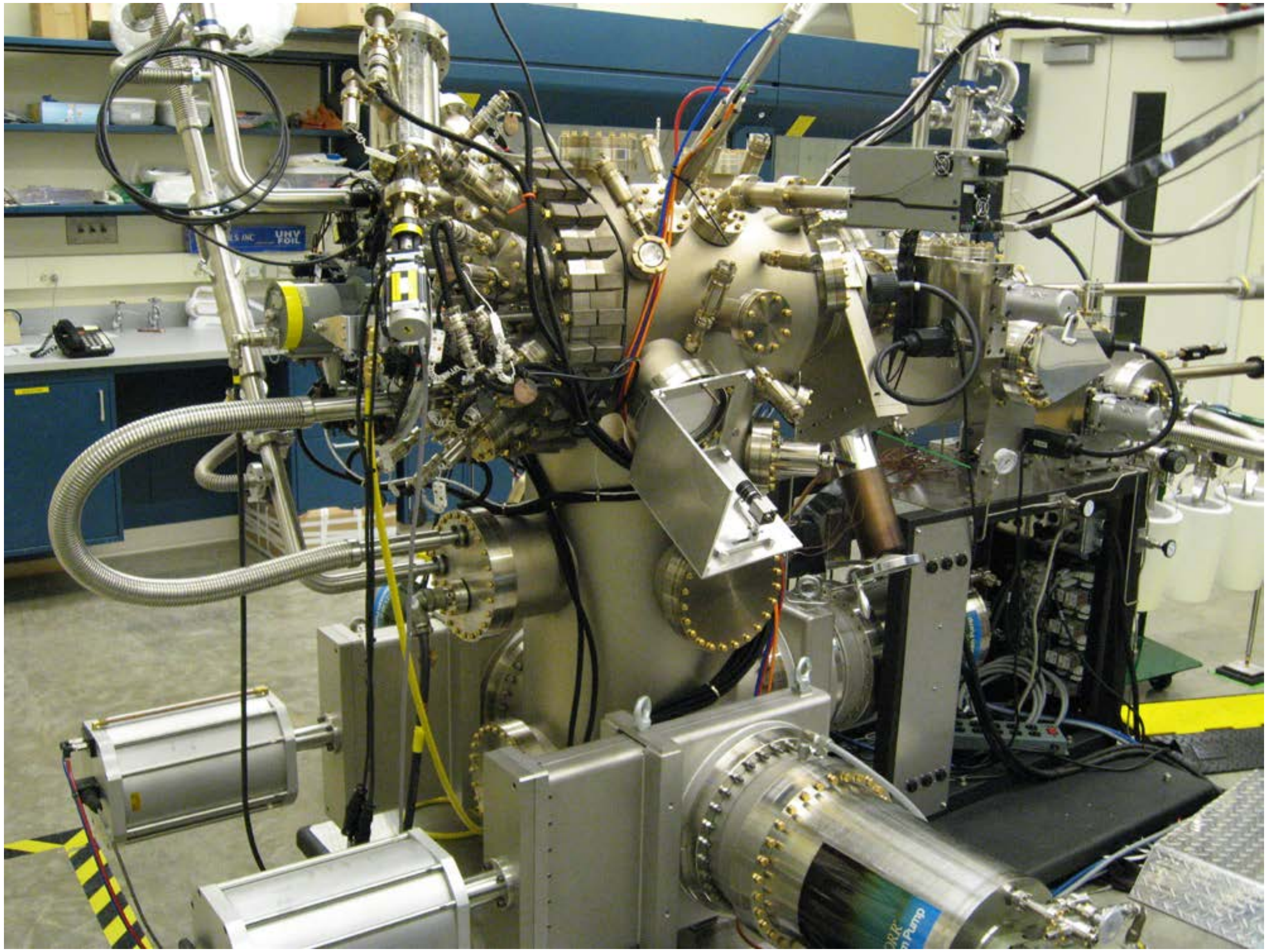


$\mu_n \approx 10^4\ \text{cm}^2/\text{V-s}$

300 K

L. Pfeiffer, K.W. West, H.L. Stormer, and K.W. Baldwin, "Electron mobilities exceeding 10^7 cm^2/V s in modulation-doped GaAs," *Appl. Phys. Lett.*, **55**, 1888, 1989.

Molecular beam epitaxy



Michael Manfra Lab, Birck Nanotechnology Center, Purdue University

From physics to technology

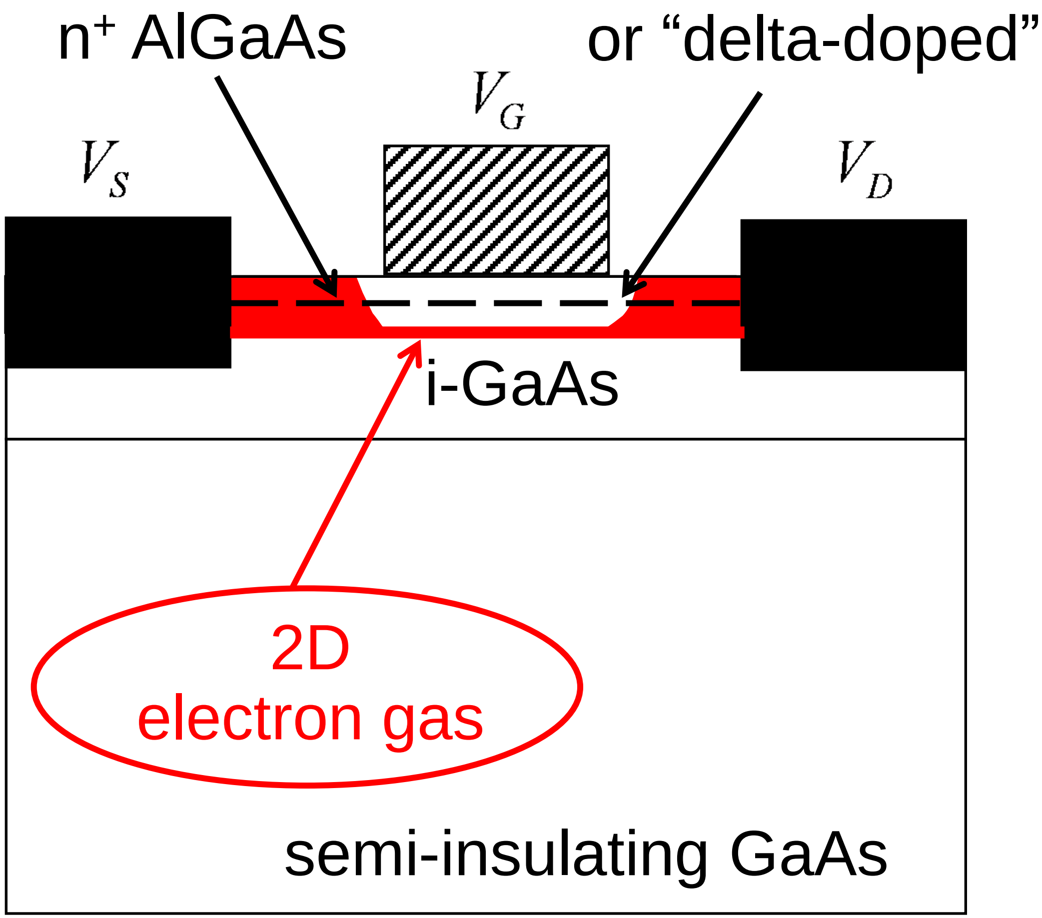
Modulation doping was discovered in 1978 by Dingle. Two years later, the High Electron Mobility Transistor (HEMT) was invented.

T. Mimura et al., ”A New Field-Effect Transistor with Selectively Doped GaAs/n-Al_xGa_{1-x}As Heterojunctions,” *Japn. J. Appl. Phys*. **19**, L225 (1980)

For an interesting perspective on this important device, see:

s A. del Alamo, “The High Electron Mobility Transistor at 30: Impressive Accomplishments and Exciting Prospects,” Proc. of the 2011 Int. Conf. on Compound Semiconductor Manufacturing Technology (2011) http://hdl.handle.net/1721.1/87102

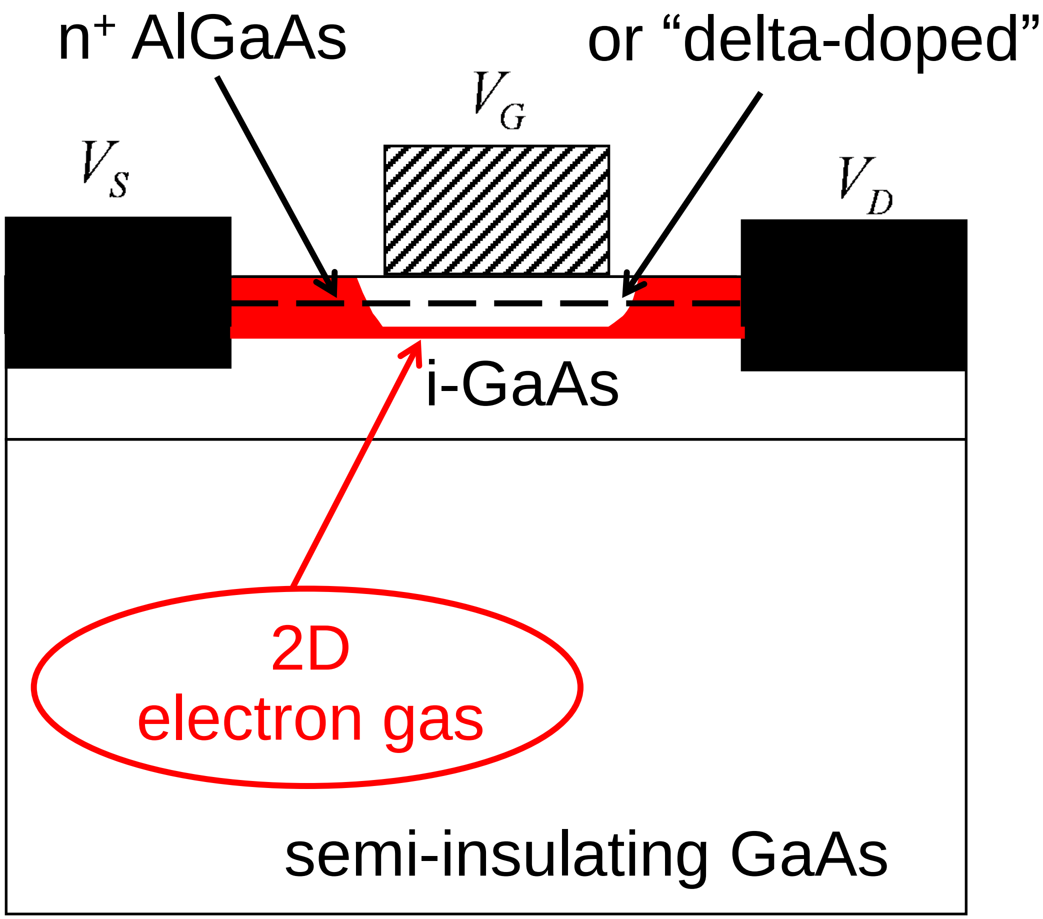
Heterostructure FET



Note:

InP / InAlAs more common now

Why delta doping?



1) Higher channel charge results

2) Higher gate breakdown voltage results

3) Gate electrode is closer to channel:
   - suppresses 2D effects
   - higher g_m

Names

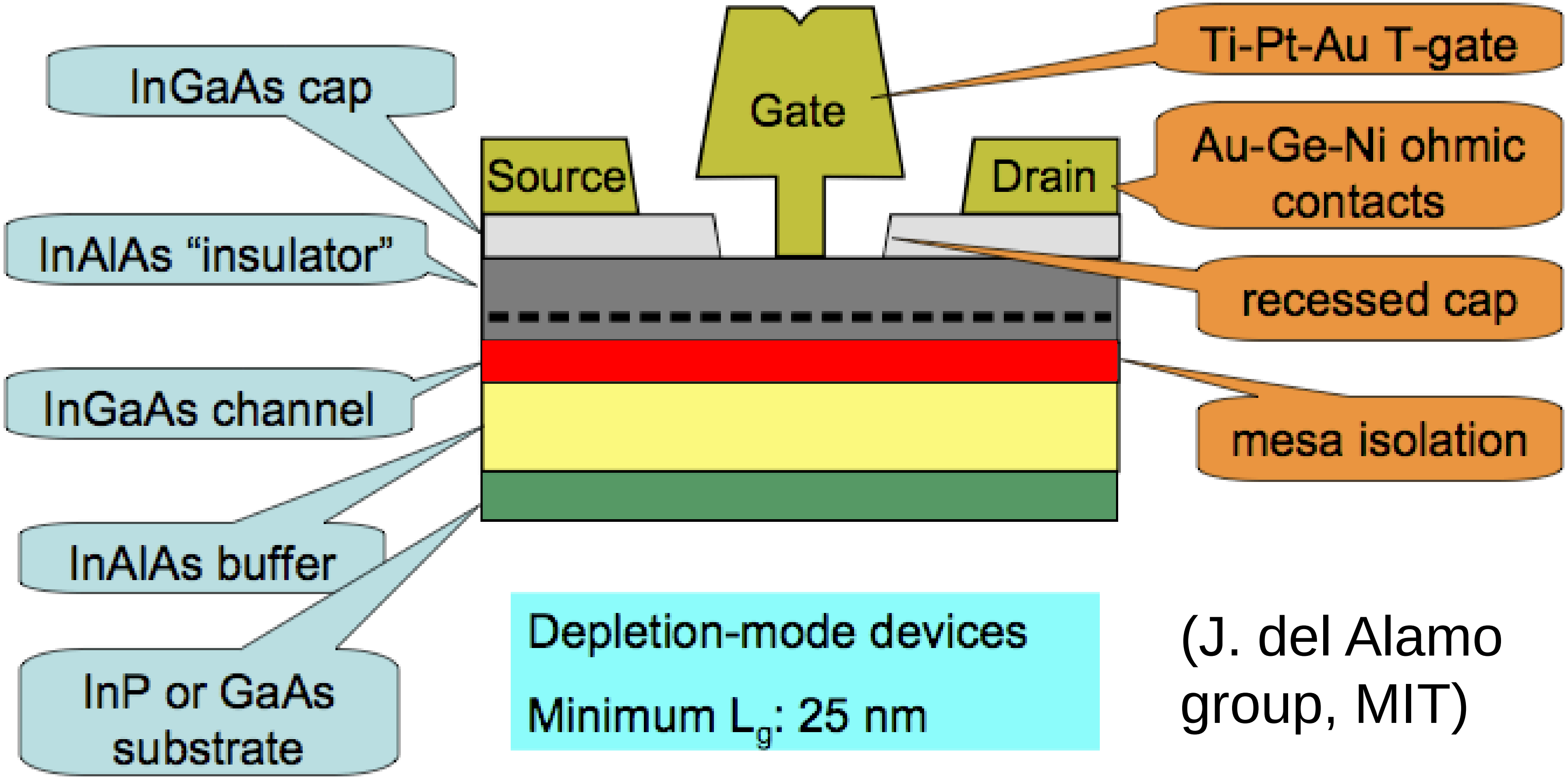
HEMT: “**H**igh **E**lectron **M**obility **T**ransistor”

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

InGaAs HEMT

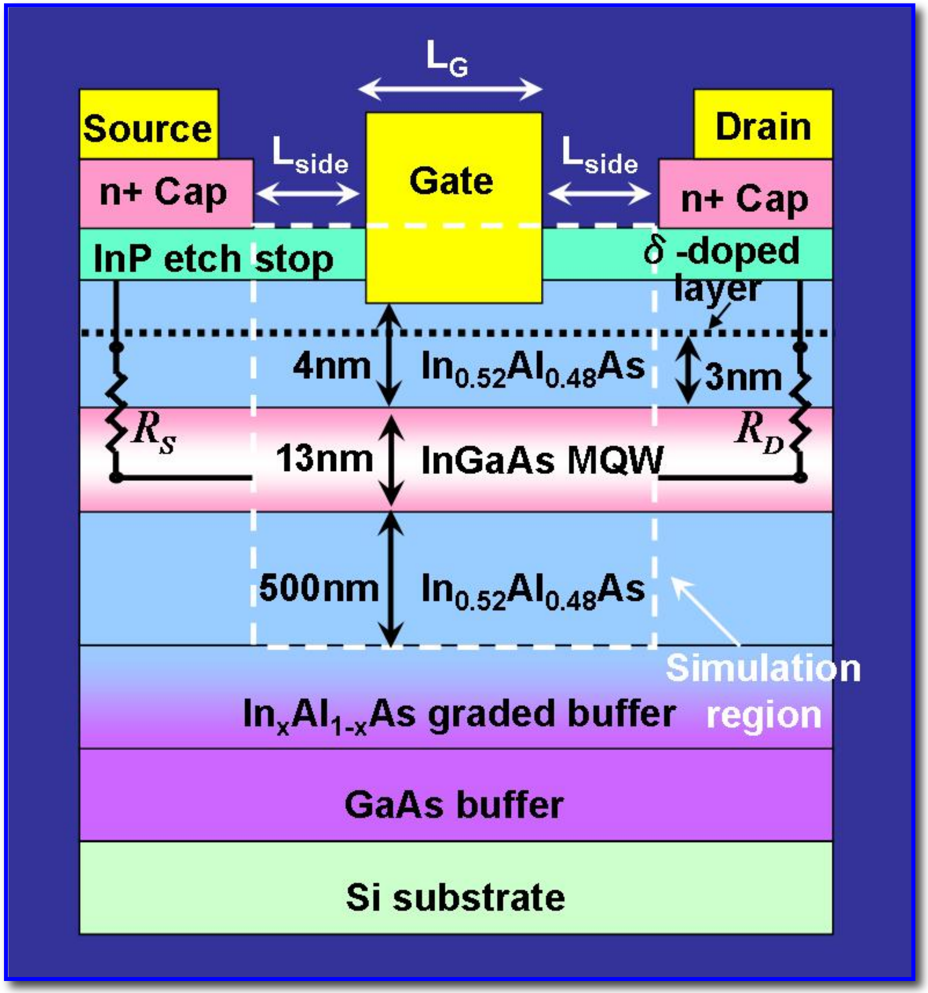


Depletion-mode devices

Minimum L_g: 25 nm

(J. del Alamo group, MIT)

Layer structure



Jesus del Alamo group (MIT)

Applications

1) Initially driven by high-speed logic

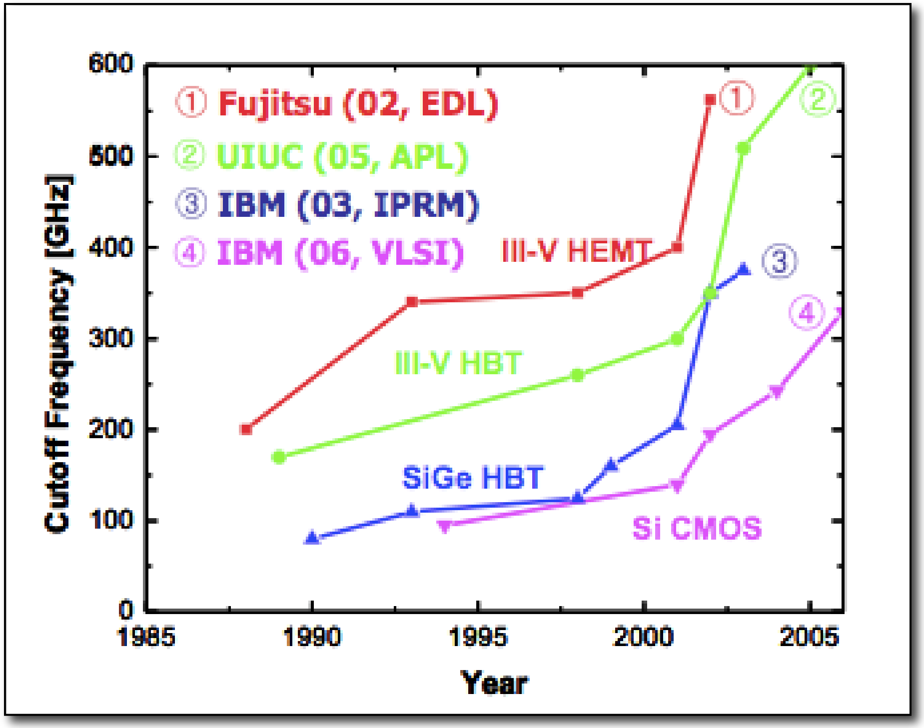
2) Low noise amplifiers (micro/millimeter waves)

-satellite communication, radio astronomy, electronic warfare

-cell phones

3) Millimeter-wave power amplifiers

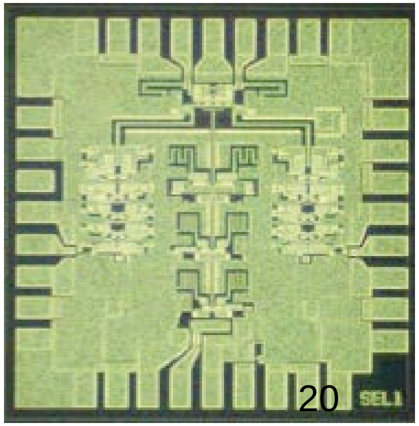
InGaAs HEMT technology



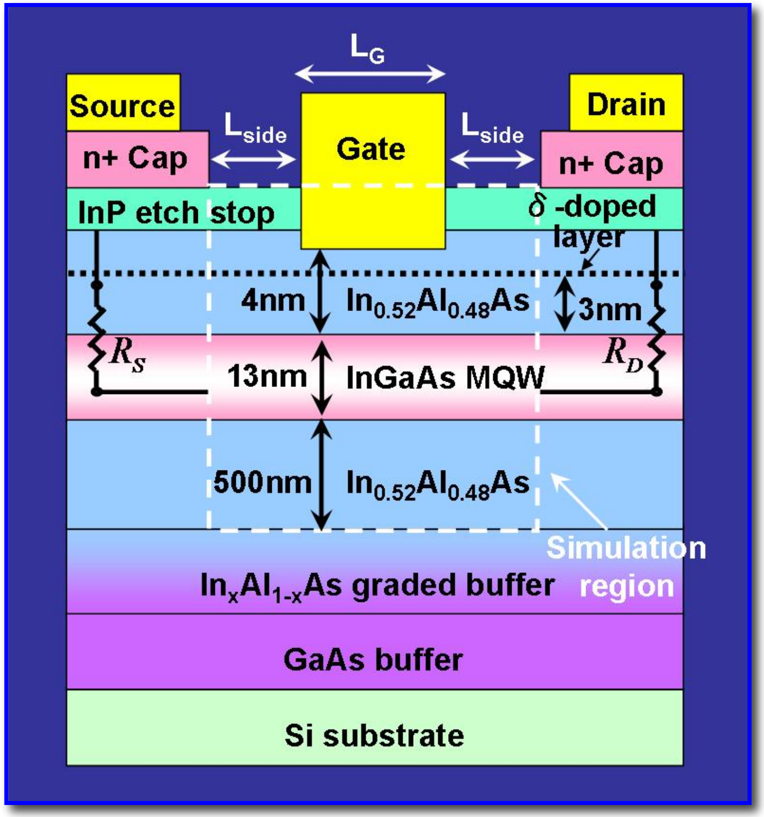
Fairly mature technology at SSI level:

- 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)



Comparison with experiment: InGaAs HEMTs



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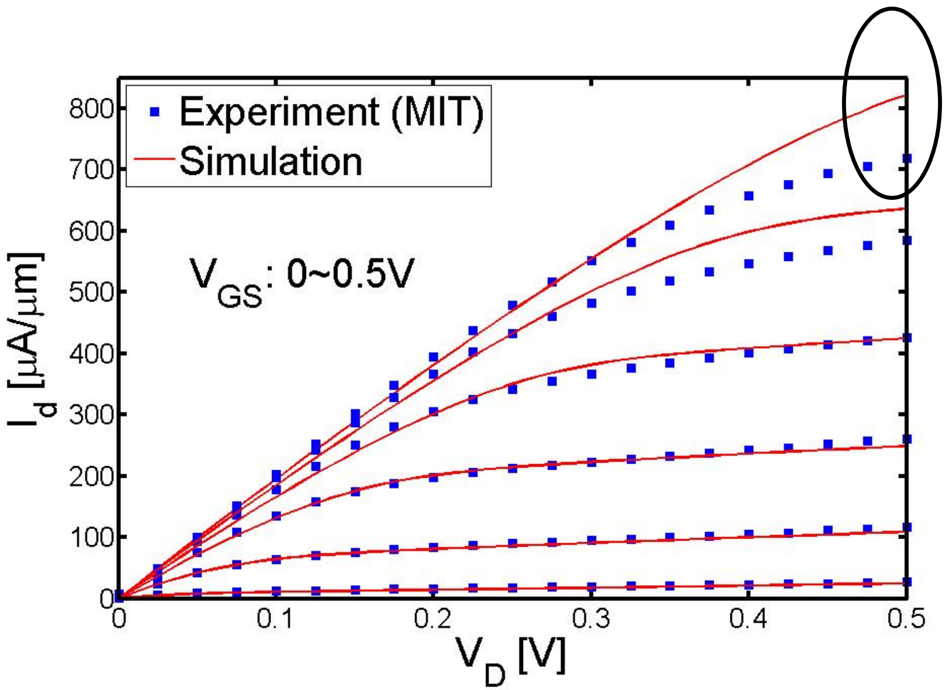

near-ballistic operation

III-V MOSFETs

There has recently been significant progress in III-V MOSFETs. For a review of the current state of the field, see:

J. A. del Alamo, D. A. Antoniadis, J. Lin, W. Lu,
A. Vardi, and X. Zhao, “Nanometer-Scale III-V MOSFETs,”
J. Electron Devices Society, vol. 4, pp. 205-214, 2016.

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.

Thanks to Profs. J. del Alamo (MIT), Mark Rodwell (UCSB), Peide Ye and Mike Manfra (Purdue) for their help in putting together this lecture.

Next topic

The very first transistors (Bell Labs, 1947), were bipolar transistors.

Bipolar transistors are also barrier controlled transistors.

Modern bipolar transistors (heterostructure bipolar transistors) also have important applications in RF.