EE669: VLSI Technology

Apurba Laha
Department of Electrical Engineering
IIT Bombay 400076

Email: laha@ee.iitb.ac.in, Tel: **022 25769408**

Office hour: Friday 10:00 – 11.00 AM, EE Annex, Room: 104

Types of semiconductor materials

- Group IV elemental semiconductors, (C, Si, Ge, Sn)
- Group IV compound semiconductors (SiC)
- Group VI elemental semiconductors, (S, Se, Te)
- III–V semiconductors: Crystallizing with high degree of stoichiometry) e,g. GaAs, GaP, GaN
- II–VI semiconductors: usually p-type, except ZnTe and ZnO which is n-type

Portion of periodic table relevant to semiconductor materials and doping

III-V

	5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00
	13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06
30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.92	34 **Se** 78.96
48 **Cd** 112.40	49 **In** 114.80	50 **Sn** 118.70	51 **Sb** 121.80	52 **Te** 127.60

II-VI

Semiconductors and their Band gaps

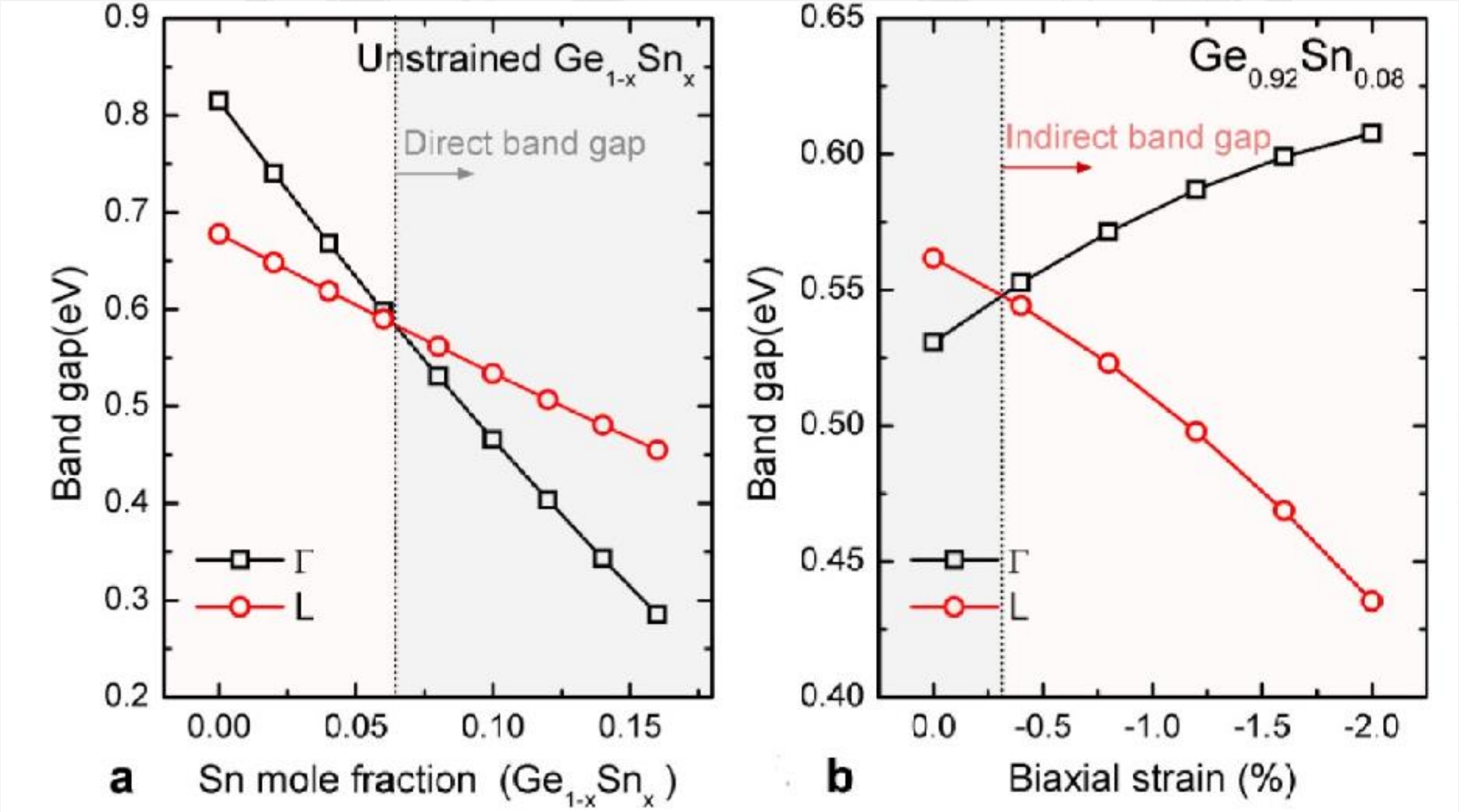
	No of element				
IV	1	Diamond	C	5.47	indirect
IV	1	Silicon	Si	1.12	indirect
IV	1	Germanium	Ge	0.67	indirect
IV	1	Gray tin, **α-Sn**	Sn	0.00, 0.08	indirect
IV	2	Silicon carbide, 3C-SiC	SiC	2.3	indirect
IV	2	Silicon carbide, 4H-SiC	SiC	3.3	indirect
IV	2	Silicon carbide, 6H-SiC	SiC	3.0	indirect
III-V	2	Boron nitride, **cubic**	BN	6.36[	indirect
III-V	2	Boron nitride, **hexagonal**	BN	5.96	quasi-direct
III-V	2	Aluminium nitride	AlN	6.28	direct
III-V	2	Aluminium arsenide	AlAs	2.16	indirect

Semiconductors and their Band gaps

	No of element				
III-V	2	**Gallium nitride**	GaN	3.44	direct
III-V	2	**Gallium phosphide**	GaP	2.26	indirect
III-V	2	**Gallium arsenide**	GaAs	1.43	direct
III-V	2	**Gallium antimonide**	GaSb	0.726	direct
III-V	2	**Indium nitride**	InN	0.7	direct
III-V	2	**Indium phosphide**	InP	1.35	direct
III-V	2	**Indium arsenide**	InAs	0.36	direct
III-V	2	**Indium antimonide**	InSb	0.17	direct
II-VI	2	**Cadmium selenide**	CdSe	1.74	direct
II-VI	2	**Cadmium sulfide**	CdS	2.42	direct
II-VI	2	**Cadmium telluride**	CdTe	1.49	direct
II-VI,	2	**Zinc oxide**	ZnO	3.37	direct
II-VI	2	**Zinc selenide**	ZnSe	2.7	direct

SnGe band structure

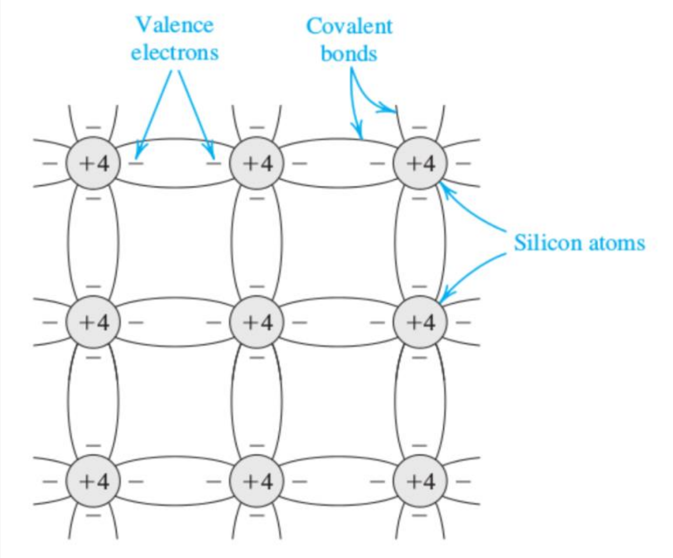
Achieving direct band gap in germanium through integration of Sn alloying and external strain

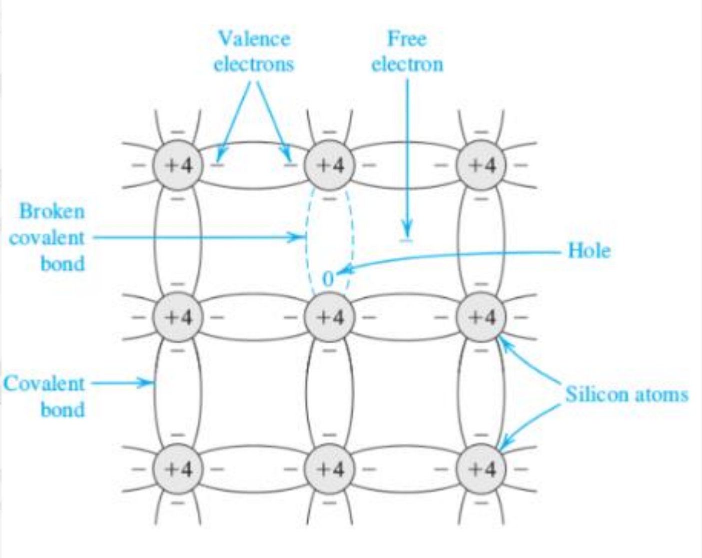


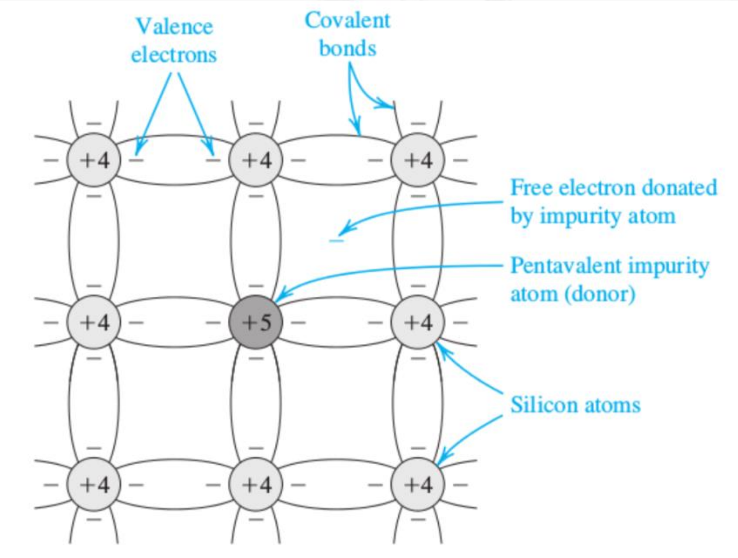
(a) Dependence of direct (Γ) and indirect (L) energy band gap in unstrained $Ge_{1-x}Sn_x$ on alloy Sn composition

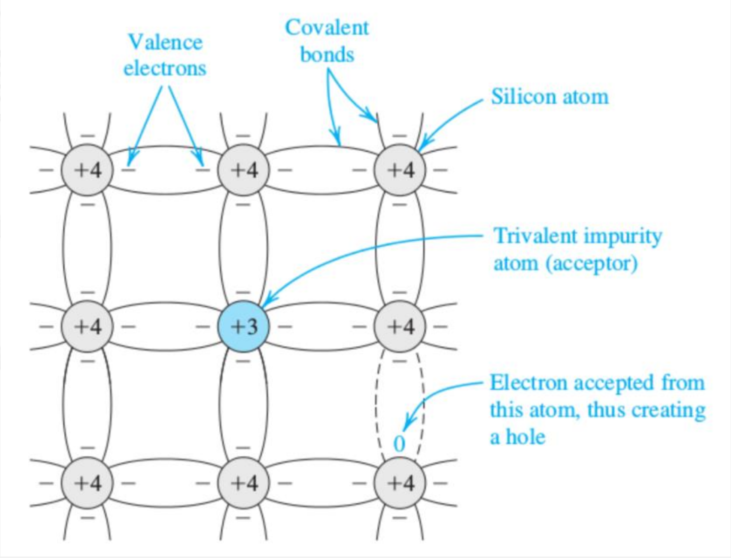
Source: S. Gupta et al. Nano Lett. **13,** (8) 3783-3790 (2013)

Carriers and doping in Si

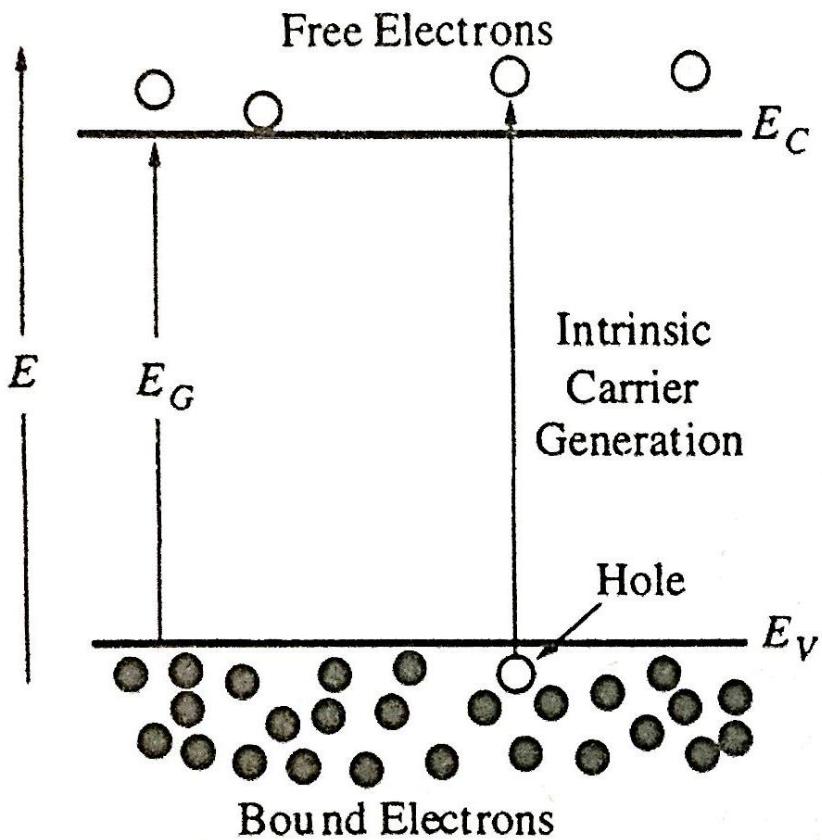




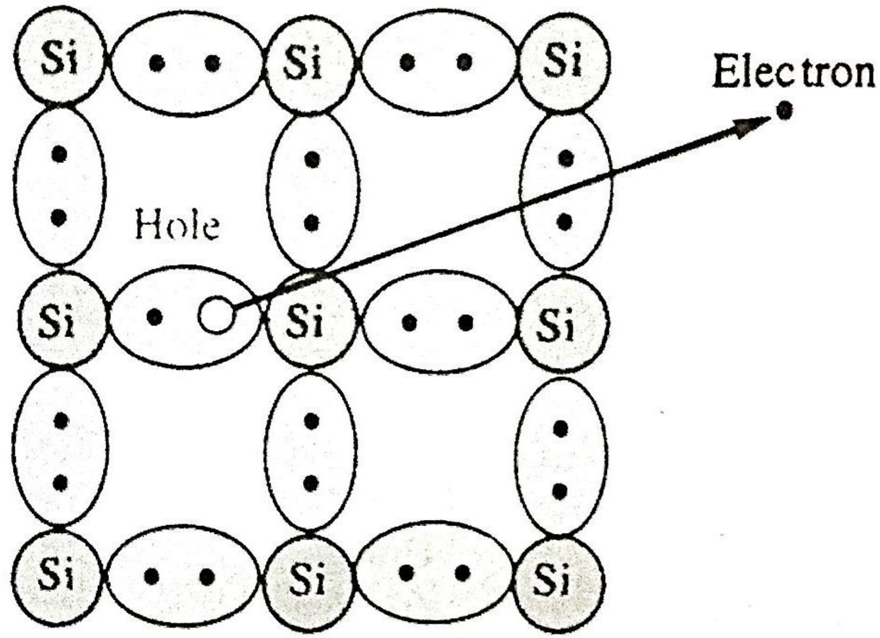




Free carrier generation



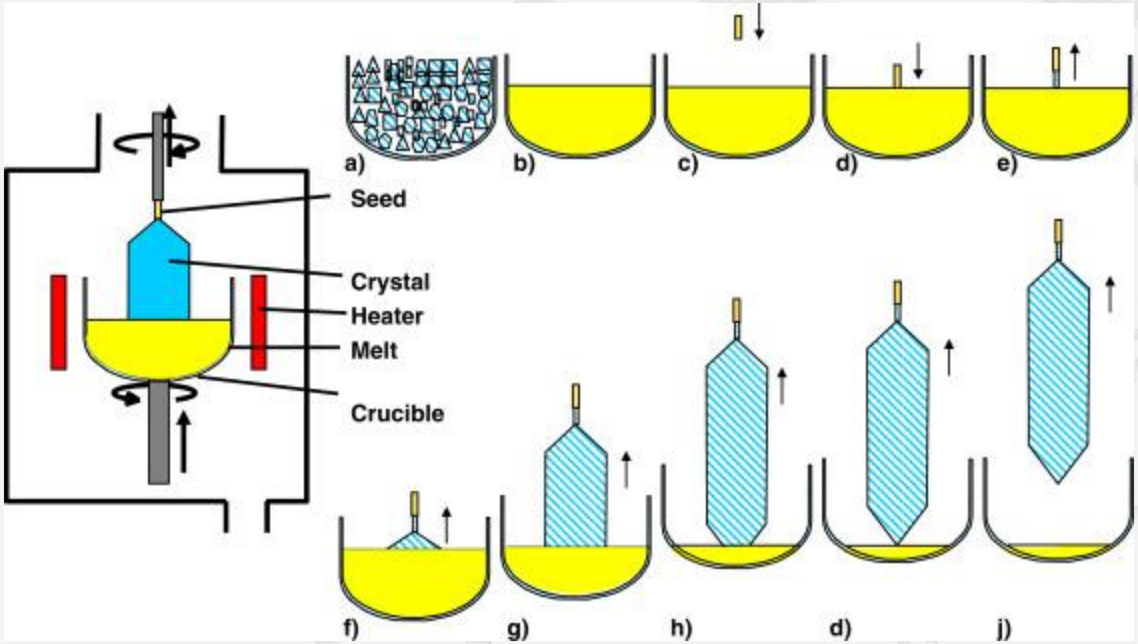
Band Model



Bond Model

Source: Plummer

Si Crystal growth : Czochralski method

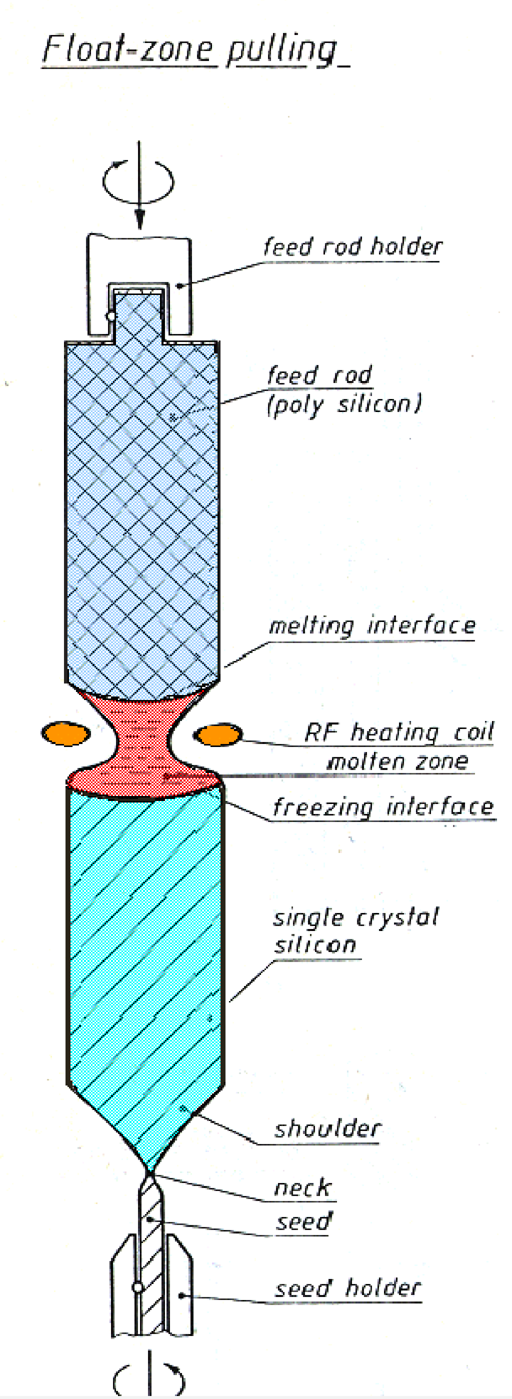


Schematic of the principle of the Czochralski method

The seed crystal is dipped into the melt, followed by Dash necking (e), shouldering (f), cylindrical growth (g), growth of end cone (h), lift off (i), cooling down and removing of the crystal (j).

Float Zone Crystal Growth

- The basic idea in float zone (**FZ**) crystal growth is to move a liquid zone through the material.
- A polycrystalline rod of ultra-pure electronic grade silicon is passed through an RF heating coil,
- Create a localized molten zone from which the crystal ingot grows.
- A seed crystal is used at one end in order to start the growth
- The whole process is carried out in an evacuated chamber or in an inert gas purge
- The molten zone carries the impurities away with it and hence reduces impurity concentration
- **Float-zone silicon is typically used for power devices and detector applications.**



Compound Semiconductor and Phase Diagrams

arise from minimizing free energies for each phase

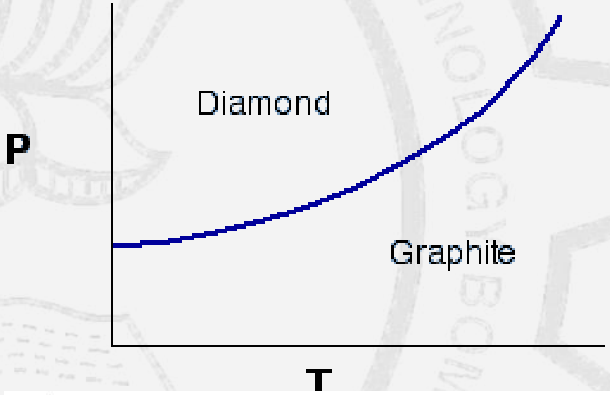
use for

- ✓ **gas - liquid - solid transitions**
- ✓ **structural changes (graphite <--> diamond)**
- ✓ **stable alloys**

ONE COMPONENT SYSTEM

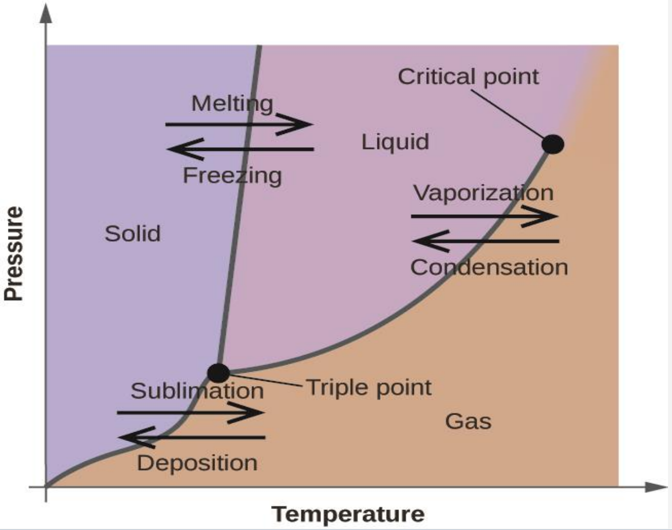
Example: Carbon (C)

the two phases (diamond and graphite) can coexist on the line that separates them



Water

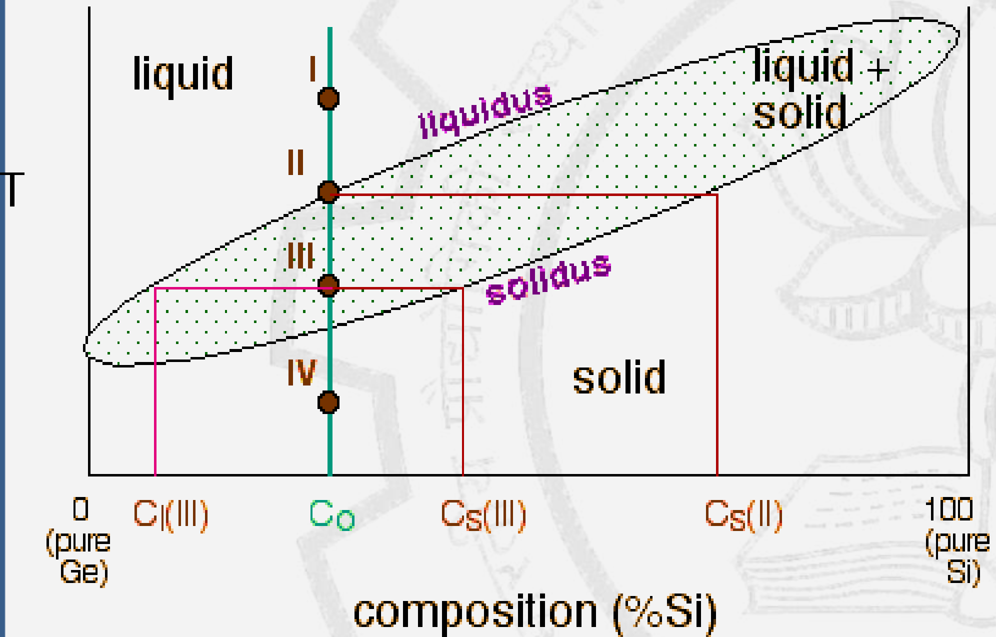
triple point has three phases coexisting (very well defined point)



Two components system: Example $Si_{(1-x)}Ge_x$

Binary Solid Solutions:

completely soluble in liquid and solid state at all compositions



phases and compositions:

at I: liquid with composition C_o (about 30% Si, 70% Ge)

at II: liquid with composition C_o and solid with composition $C_S(II)$

at III: liquid with composition $C_l(III)$ and solid with composition $C_S(III)$

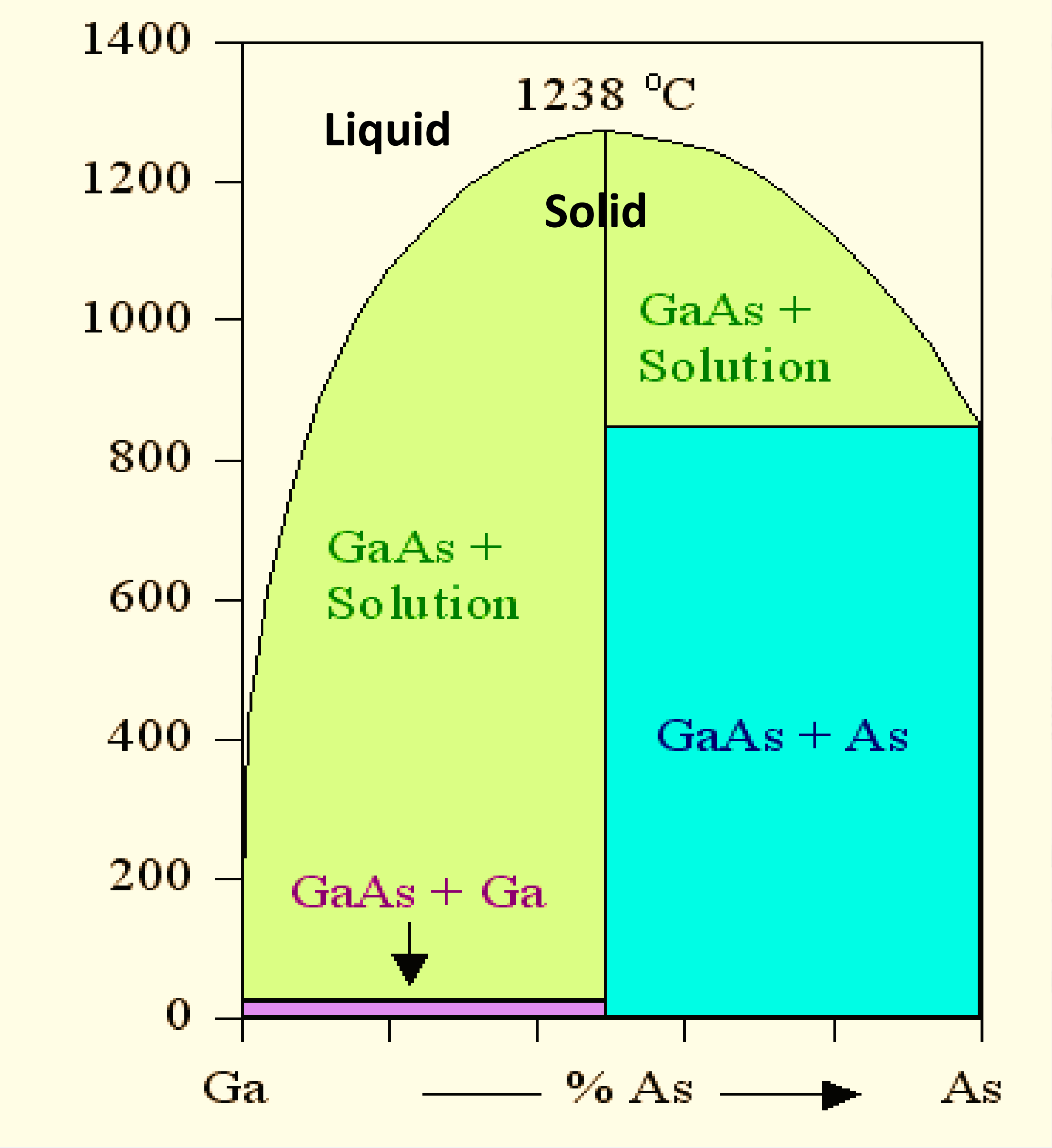
at IV: solid with composition C_o

How much (mole fraction) is in each phase ?

$$f_{solid} = \frac{C_o - C_l(III)}{C_s(III) - C_l(III)}$$

$$f_{liquid} = \frac{C_s(III) - C_o}{C_s(III) - C_l(III)}$$

Compound semiconductor and Phase diagram



T$_m$**(GaAs) = 1238 °C**

GaAs crystal growth

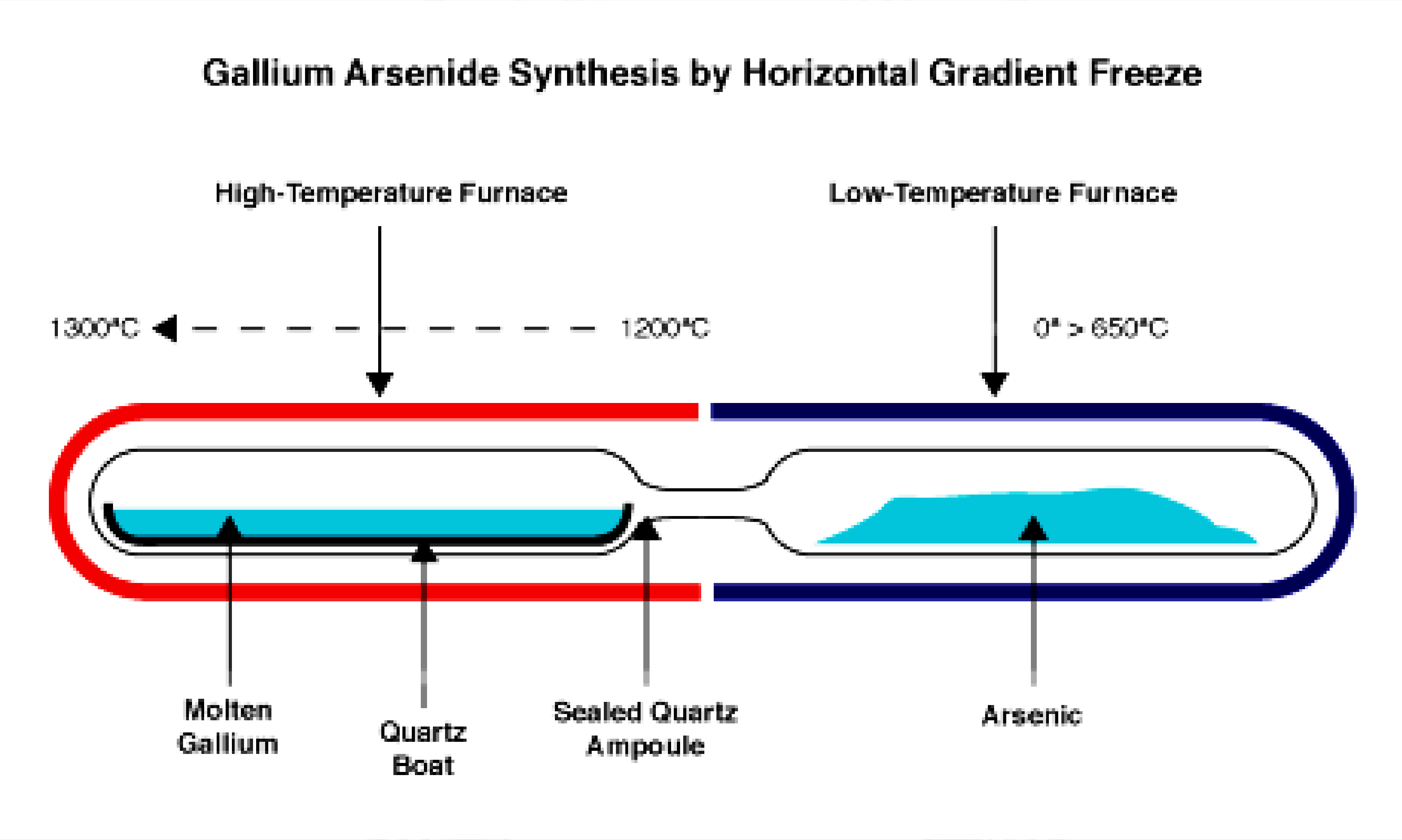
Mix Ga and As in a (molar) ratio of **50:50** and melt it in a crucible

T$_m$**: Ga: 30 °C; As: ? °C**

what happens if our mixture is not **50 : 50** but **49.999 : 50.001**?

little droplets of liquid in our growing crystal!

Compound semiconductor: High purity Poly GaAs

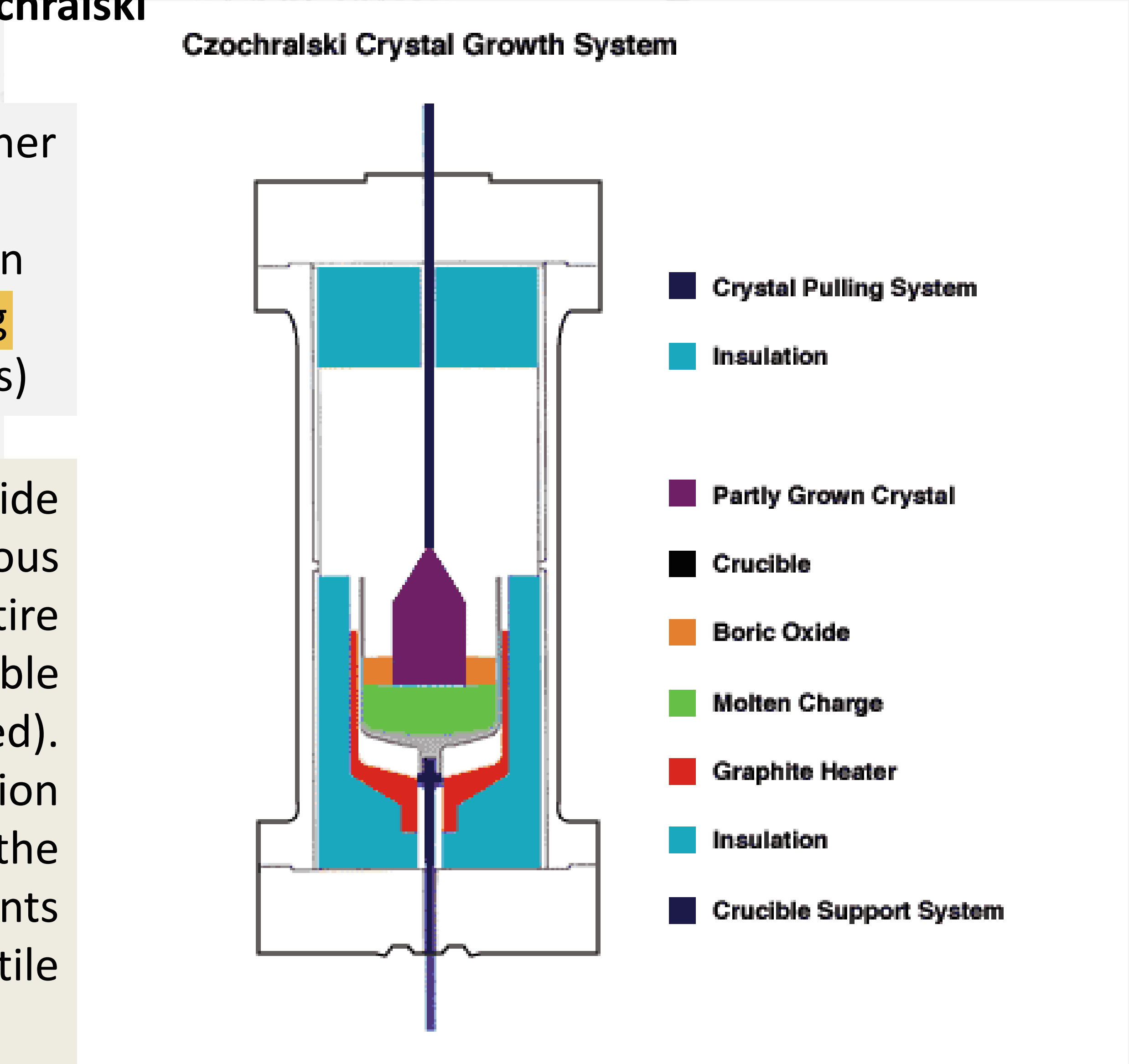


Compound semiconductor: Single crystal growth

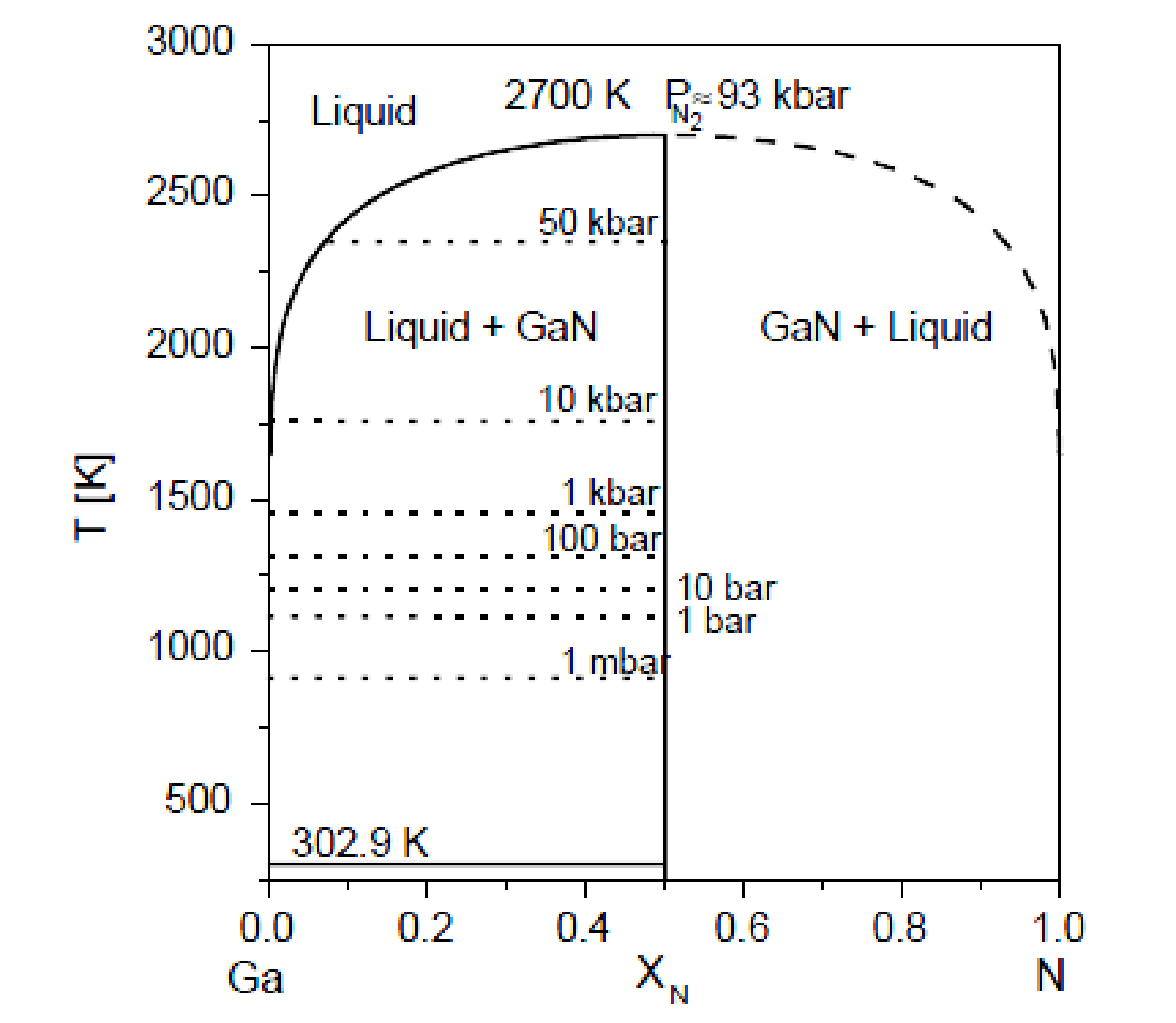
Liquid Encapsulated Czochralski

The starting materials (either pre-synthesised polycrystalline chunks or, in the case of semi-insulating GaAs, elemental Ga and As)

At 460°C the boron trioxide melts to form a thick, viscous liquid which coats the entire melt, including the crucible (hence, liquid encapsulated). This layer, in combination with the pressure in the crystal puller, prevents sublimation of the volatile group V element.



Gallium Nitride: The unconventional phase diagram



Growth must be carried out at a condition far away from thermodynamic equilibrium

Materials Properties Comparison

Material	μ	ε	Eg	BFOM Ratio	JFM Ratio	Tmax
Si	1300	11.4	1.1	1.0	1.0	300 C
GaAs	5000	13.1	1.4	9.6	3.5	300 C
SiC	260	9.7	2.9	3.1	60	600 C
GaN	1500	9.5	3.4	24.6	80	700 C

BFOM = Baliga's figure of merit for power transistor performance [$\varepsilon*\mu*E_g^3$]

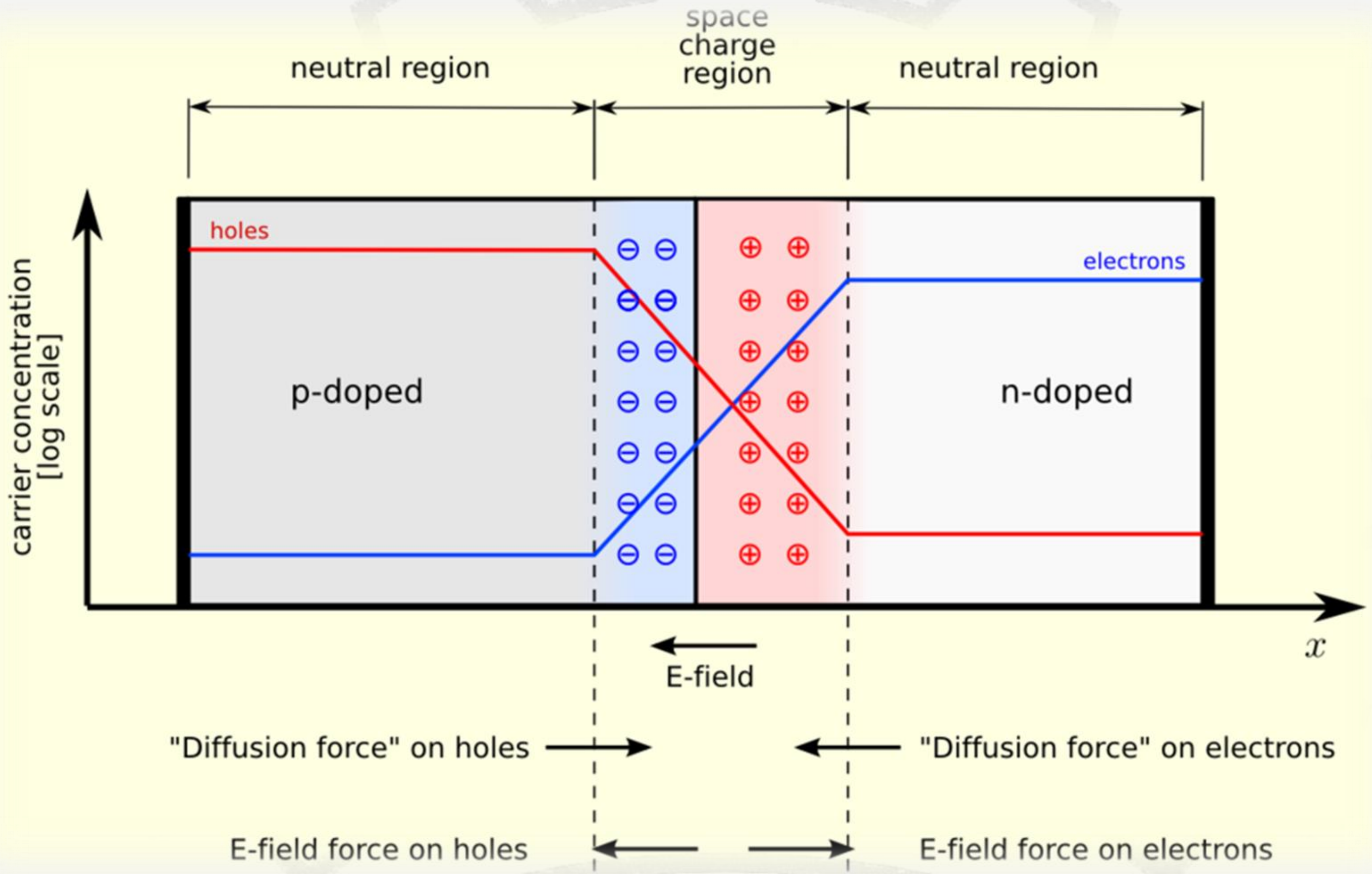
JFM = Johnson's figure of merit for power transistor performance

(Breakdown, saturation electron velocity product) [$E_{br}*V_{sat}/2\pi$]

GaN: A superman semiconductor

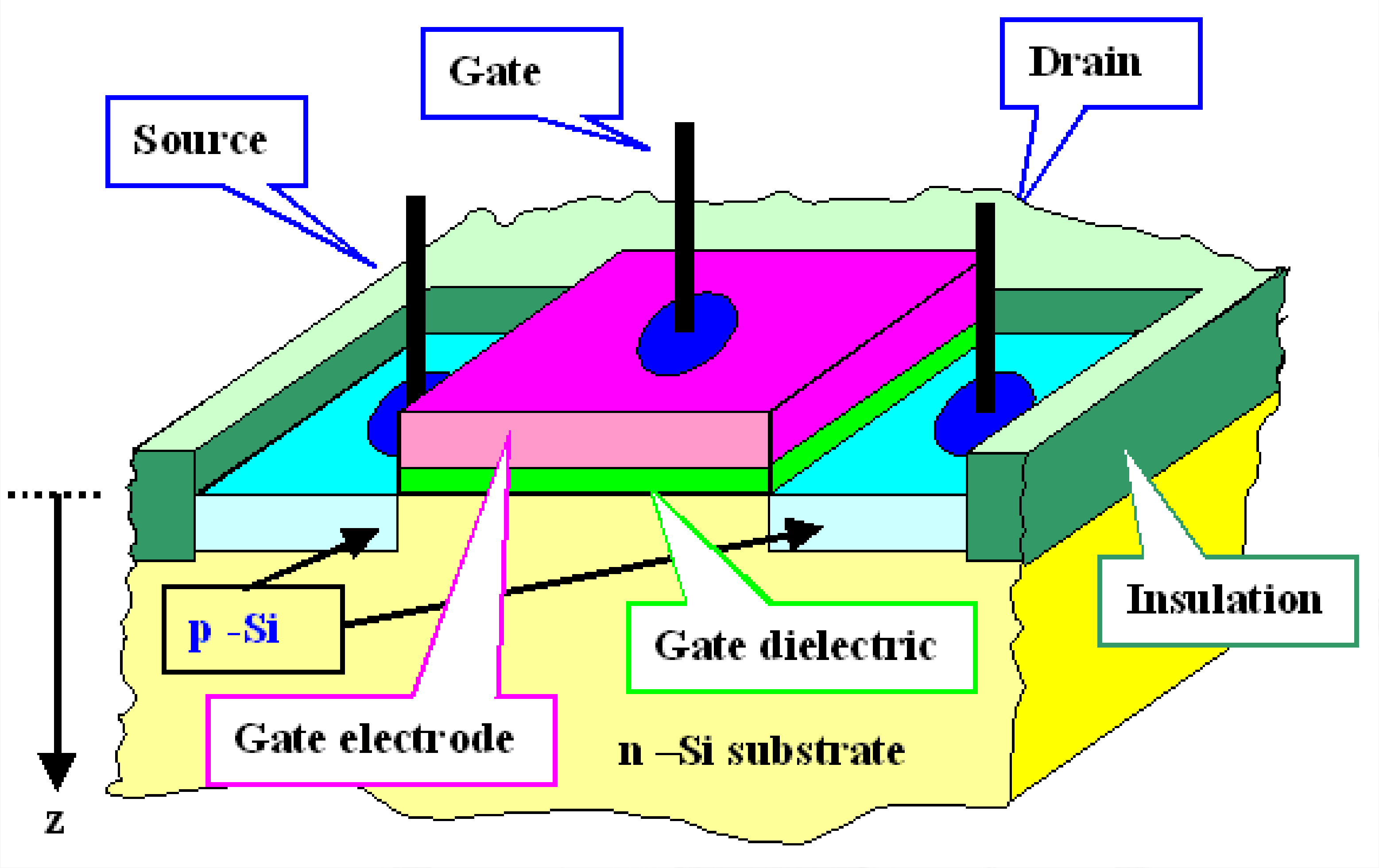
Source: Umesh Mishra, UCSB

Semiconductor Devices: PN Junction



- The p-n junction is created by doping, (ion implantation, diffusion of dopants)
- By epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant).

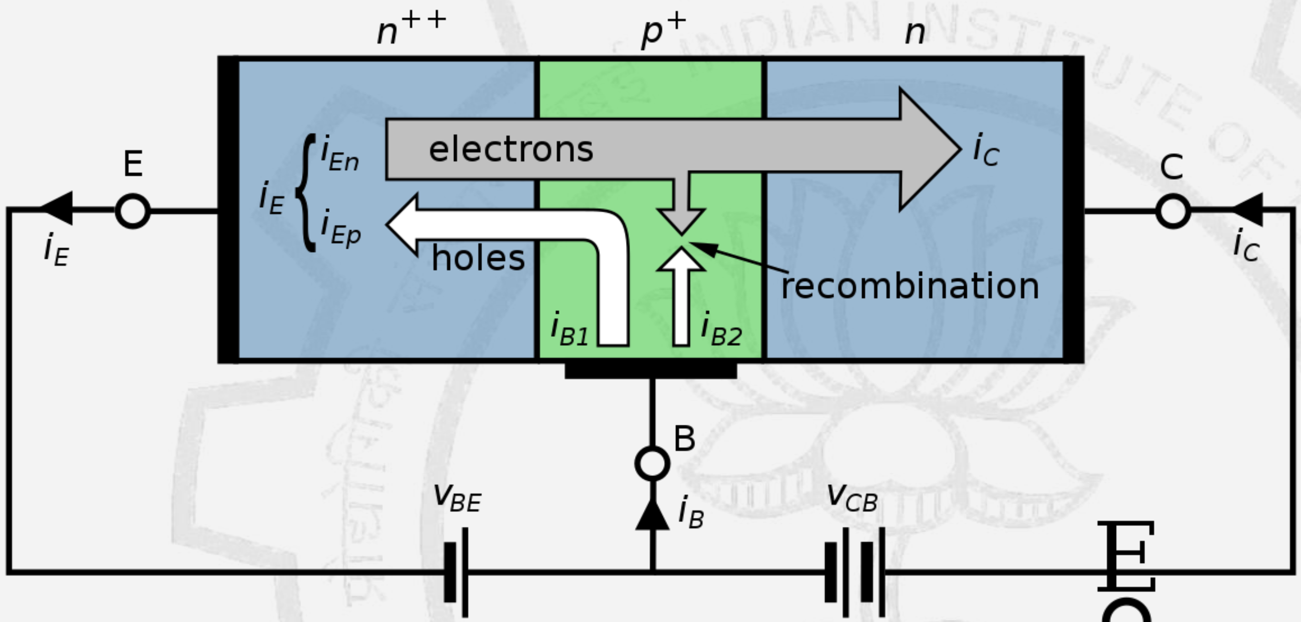
Semiconductor Devices: MOS transistor

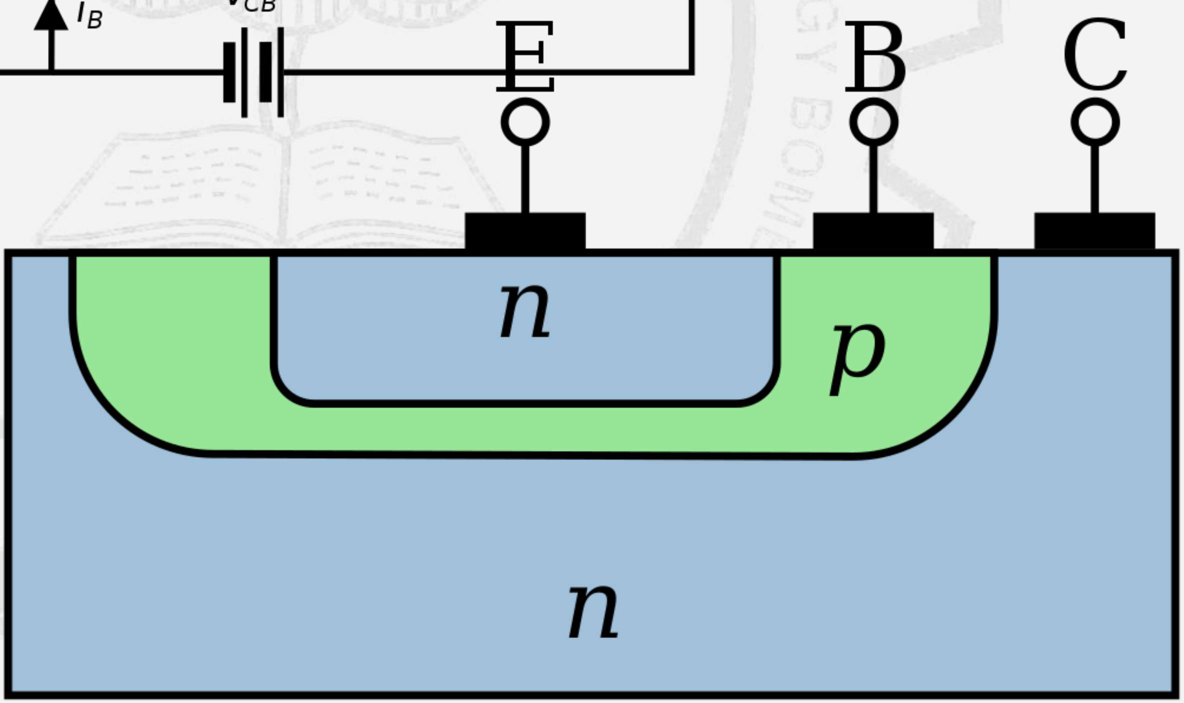


An integrated structure

Source: https://www.tf.uni-kiel.de

Bipolar Junction Transistor (BJT)



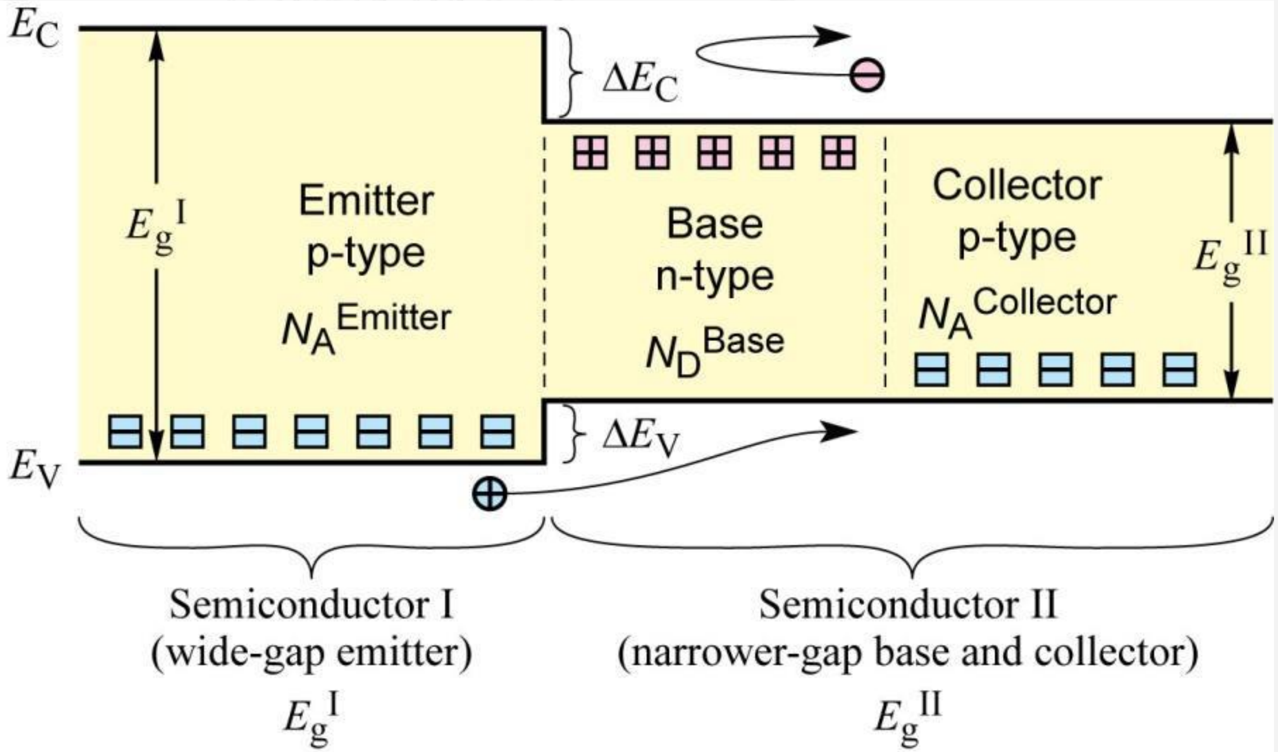


Heterojunction bipolar transistor (HBT)

Wide-gap emitter bipolar junction transistor (Band bending neglected)

$E_g^{I} > E_g^{II}$

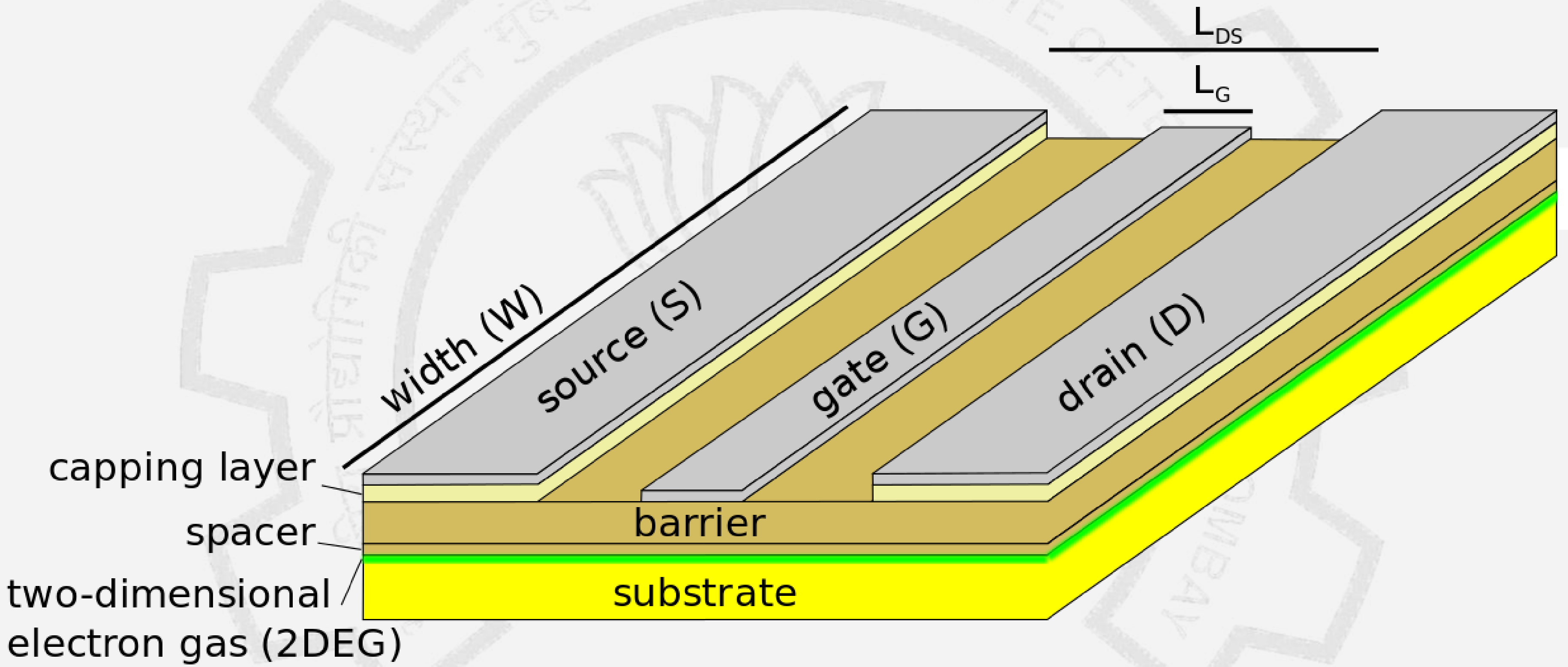
$E_g^{Emitter} > E_g^{Base}$



Example: Si and $Si_{(1-x)}Ge_x$ heterostructure

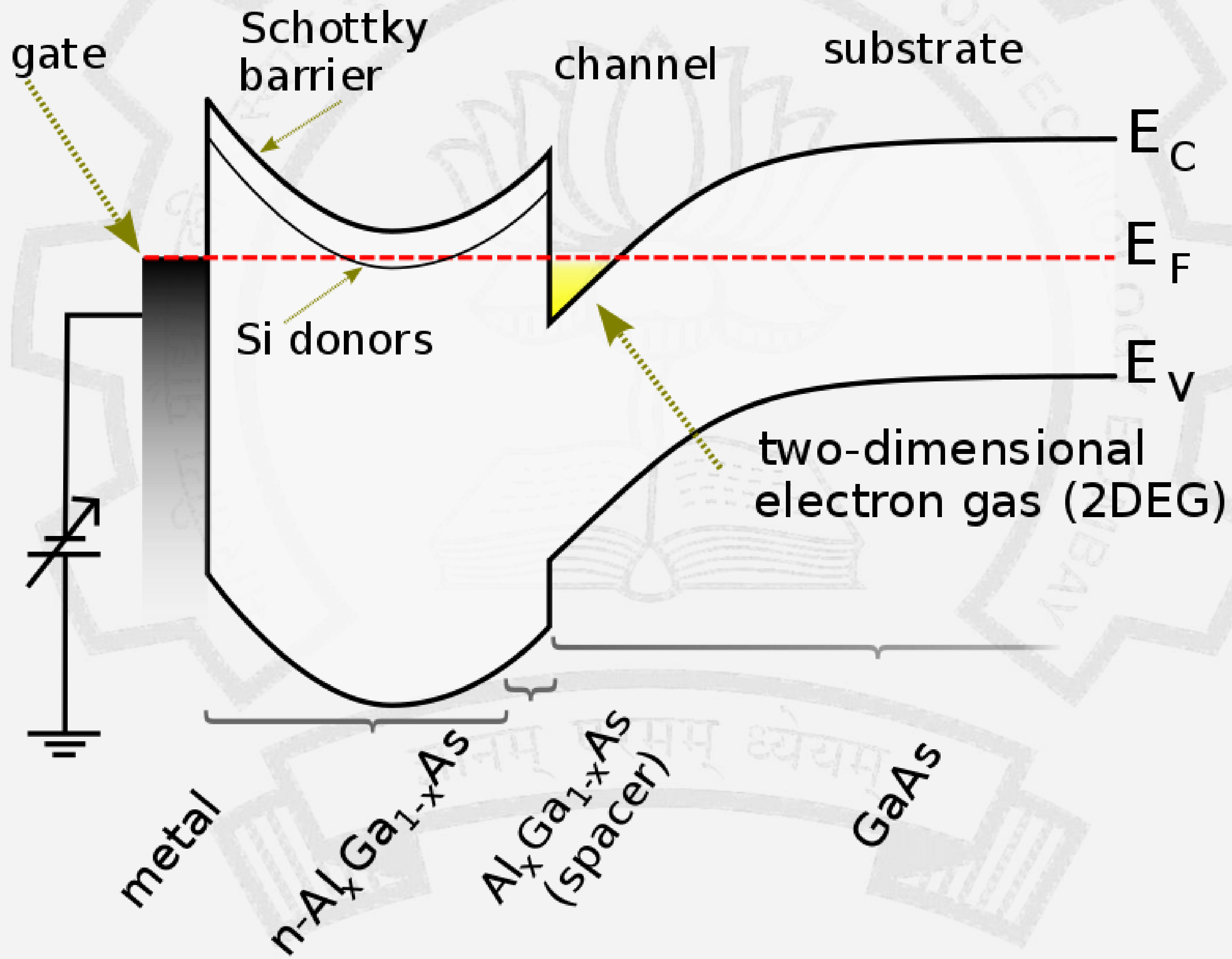
How do we grow such complicated structure??

High Electron Mobility Transistor (HEMT)

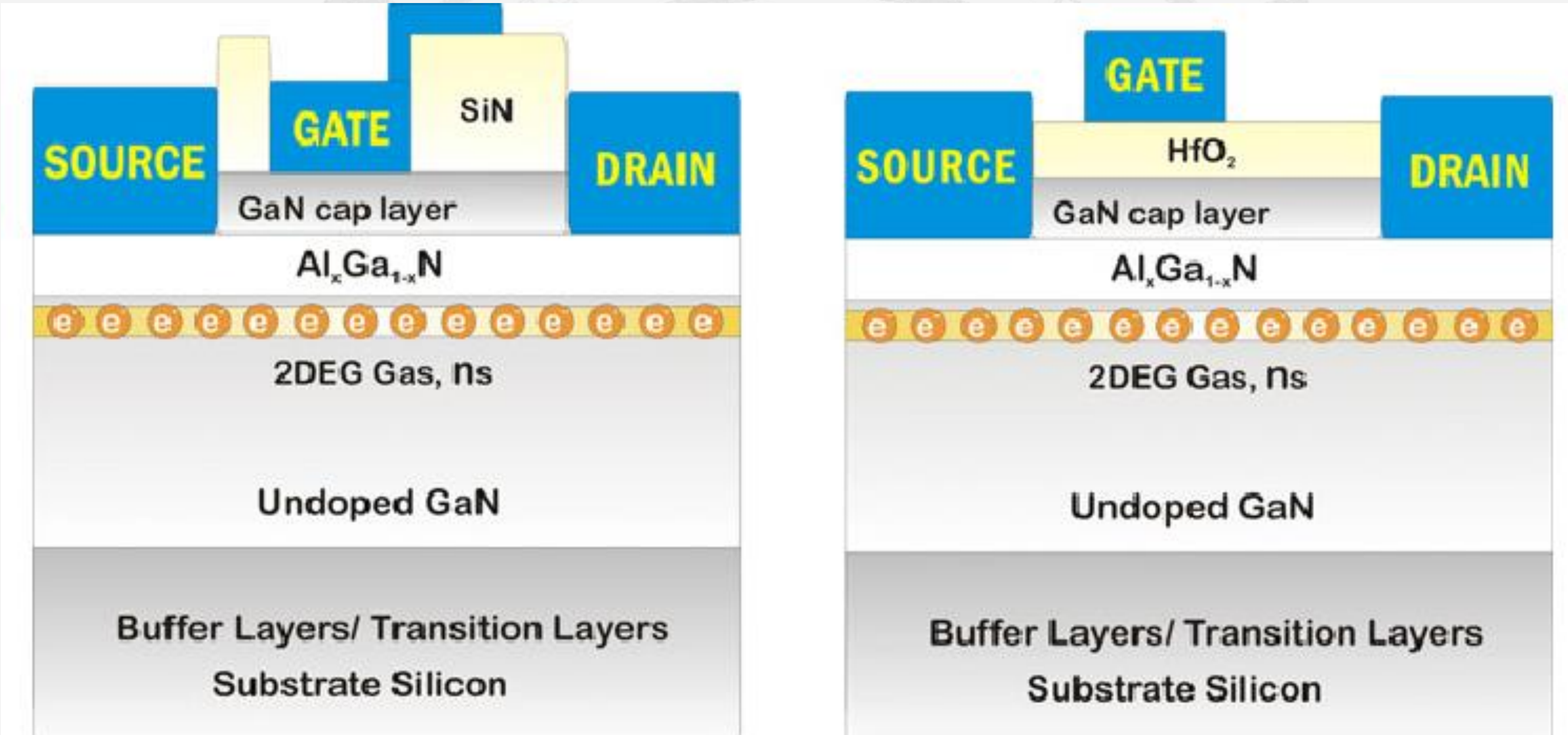


Cross section of a GaAs/AlGaAs/InGaAs pHEMT

Band diagram of GaAs/AlGaAs heterojunction-based HEMT, at equilibrium.

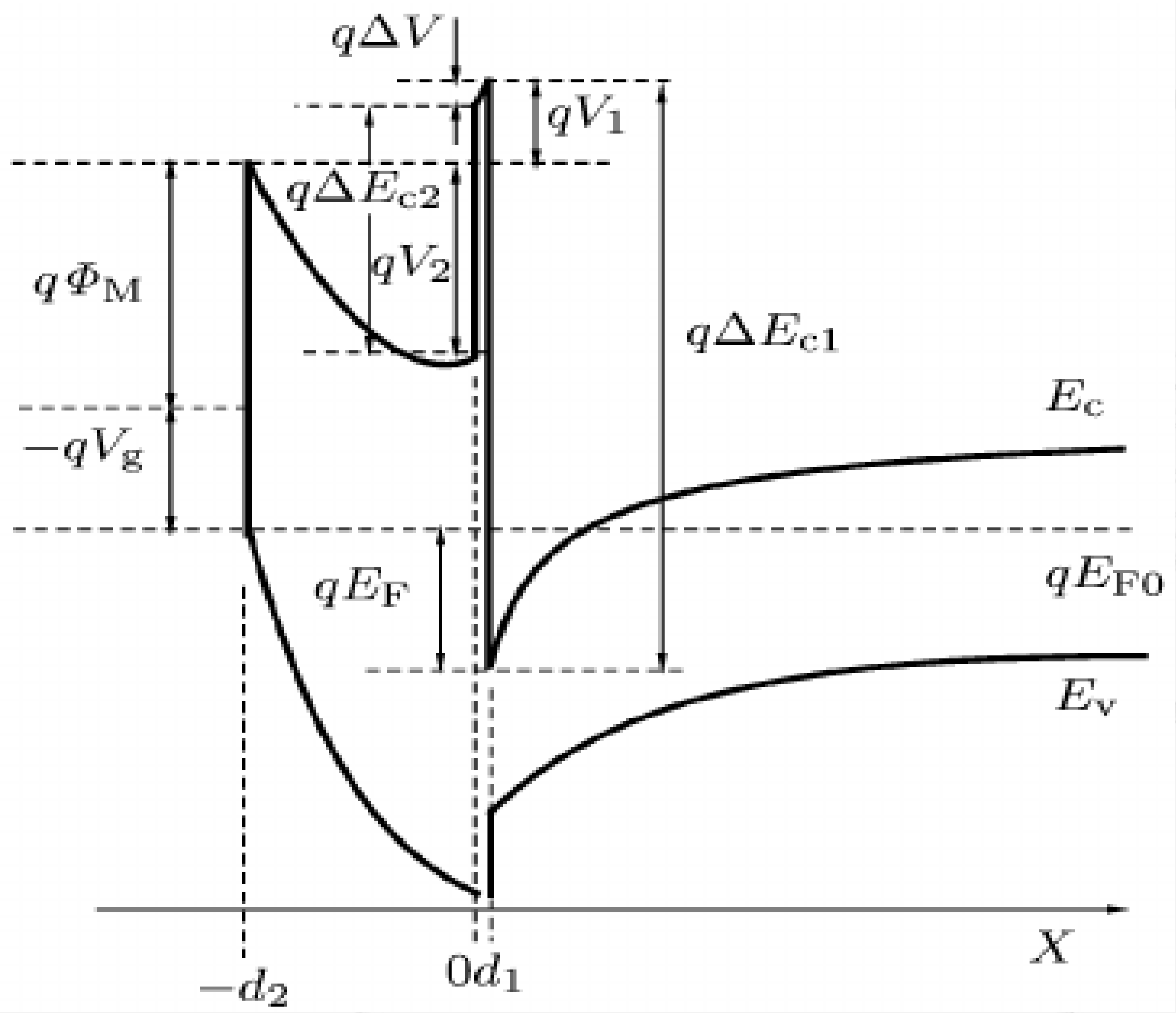


GaN HEMT



SOURCE
GATE
SiN
DRAIN
GaN cap layer
$Al_xGa_{1-x}N$
2DEG Gas, ns
Undoped GaN
Buffer Layers/ Transition Layers
Substrate Silicon
GATE
SOURCE
HfO_2
DRAIN
GaN cap layer
$Al_xGa_{1-x}N$
2DEG Gas, ns
Undoped GaN
Buffer Layers/ Transition Layers
Substrate Silicon

Energy band of AlGaN/AlN/GaN HEMT.



See you tomorrow