Course name:
Growth and Characterization of Nano-electronic Materials (EE728)

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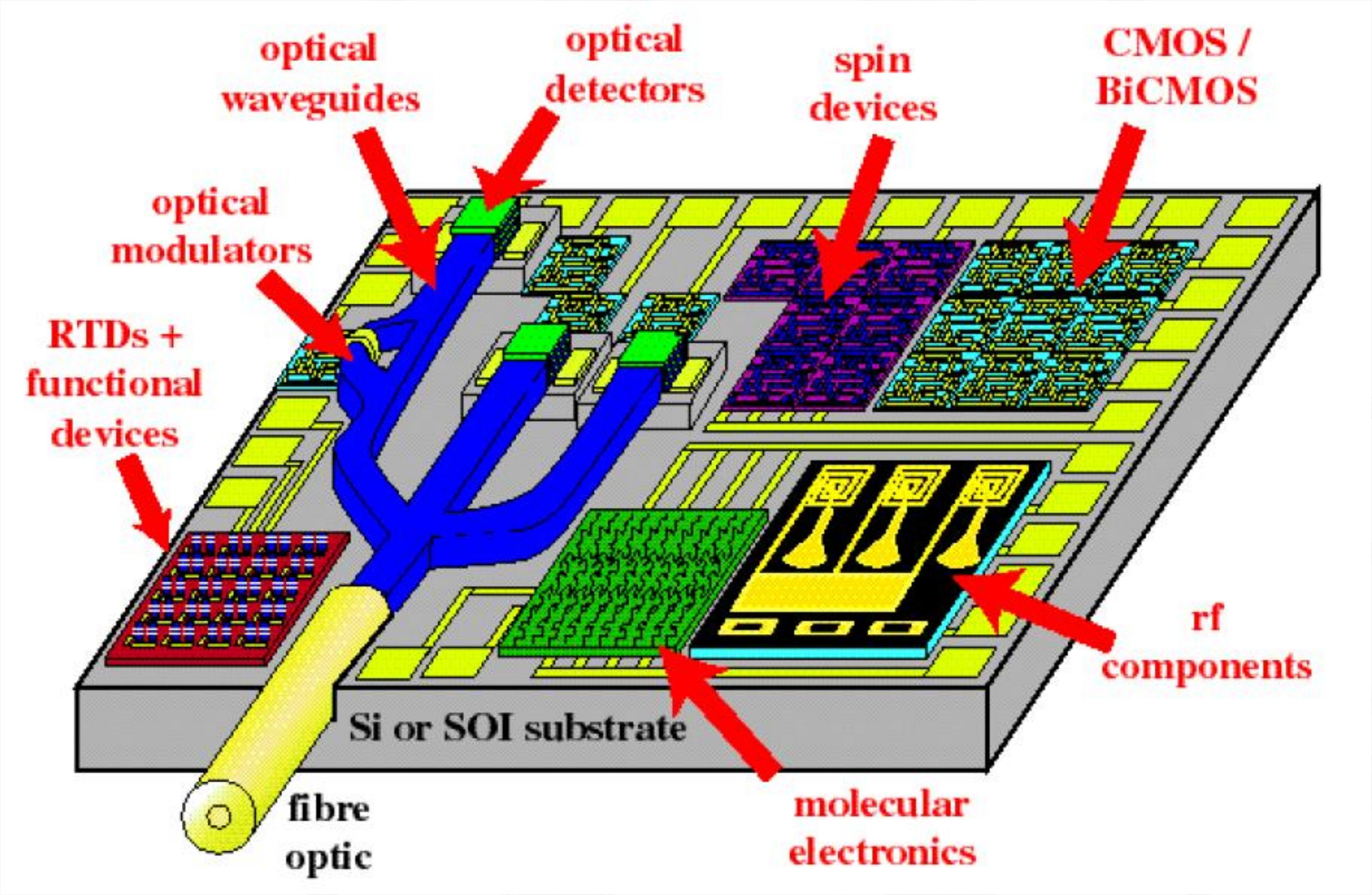
Epitaxy in Nanotechnology

Epitaxy and modern technology!



The system-on-a-chip of the future? *The ability to integrate new technologies with CMOS or BiCMOS is important*

Silicon integration platform

New challenges

- Growth of low dimensional structures of various complexity with high degree of control and reproducibility

- It demands materials engineering at the atomic level despite lattice mismatch, chemical incompatibility, structural dissimilarity and/or differences in thermal expansion

- We have to overcome also thermodynamical limitations by using sophisticated techniques and methods

Demands new epitaxial concepts, combination of different epitaxial growth methods and integration of other semiconductor technologies

Nanotechnology

- Semiconductor nanostructure science and technology develops very rapidly and many present-day devices directly based on quantum mechanics.

- Future quantum devices may play important roles in information technology and multi-disciplinary nanotechnology.

- Nanotechnology is already present, e.g. the „present-day Si transistor“, and will be much bigger in the future, that is at least after the „end-of-roadmap Si transistor“!

This development has strong impact on epitaxy!

Epitaxy

- επι (epi)– Position
- ταξις(taxis - ordered

- Orderly positioning of individual atoms
- Order is predetermined by a crystalline substrate (host lattice)
- Requires a certain consistency in crystal structure and symmetry (matching)
- Epitaxy is the growth of crystalline layers

Defining epitaxy

- **Substrate:**

  Homoepitaxy (= layer-substrate material)

  Heteroepitaxy (another layer of material)?

- **Phase equilibrium:**

  Solid phase epitaxy (SPE)

  Liquid phase epitaxy (LPE)

  Vapor phase epitaxy (MBE, VPE CVD)?

- **Nature of the source material:**

  Gas source MBE (GSMBE)

  Solid source MBE (SSMBE)

  Metal-organic chemical vapor deposition (MOCVD)

Epitaxy-Fundamental

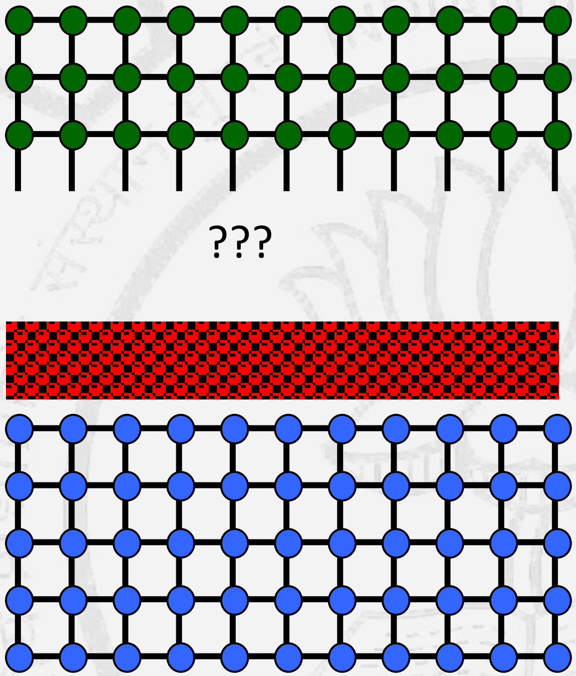
In equilibrium surface process such as condensation and re-evaporatio **decay and formation** of 2D cluster must obey ***detailed balance***. Therefore, in equilibrium, *there is no net growth of a film and so crystal growth must clearly be a* ***non-equilibrium kinetic process***

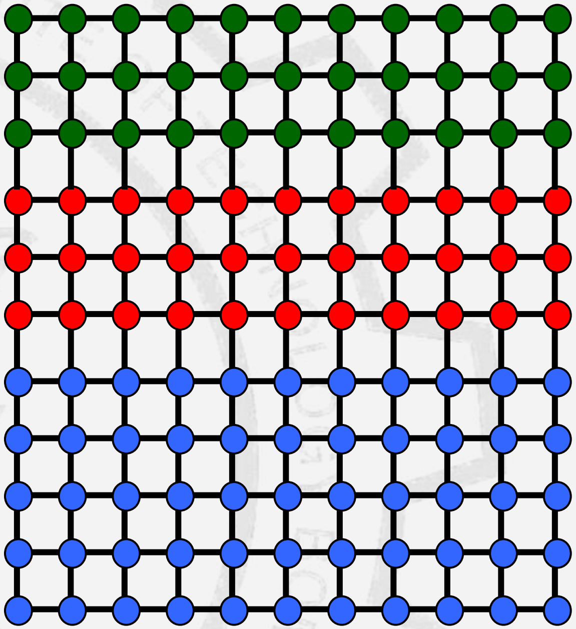
Three principle modes of growth:

1. ***Layer by layer grwoth (Frank-van der Merve, FM)***
2. ***Island growth (Vollmer-Weber, VW)***
3. ***Layer plus-island (Stransky-Krantanov, SK)***

1. **FM: The interaction between the substrate and layer atoms is stronger than that between neighboring layer atoms. Each layer starts to grow only when the last one has been complete.**
2. **VW: The interaction between the neighboring film atoms exceeds the overlayer substrate interaction. In this case an island deposit always means a multilayer multilayer conglomerate of adsorbed atoms.**
3. **SK: Layer followed by island formation. Many factors account for this mixed growth mode.**

Heterostructures: Epitaxy





Epitaxial growth: well defined interface:

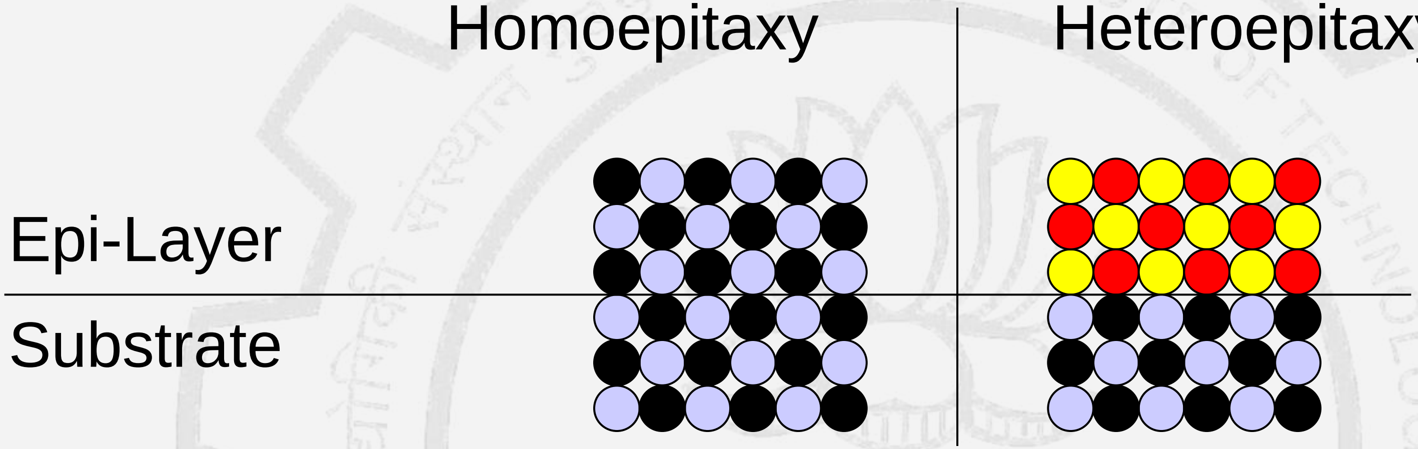
➔ interface engineering possible

Form a virtual crystalline substrate ➔ heterostructures

Milestone on Semiconductor Epitaxy

1957	First Epitaxy (CVD) of Ge and Si	N.N. Sheftal	Joffe, UdSSR
1960	Ge/GaAs Heteroepitaxy	J.C. Marinace	IBM, USA
1960	Si-Epi with controlled thickness and doping	H.C. Theuerer	Bell Labs, USA
1963	Heterojunction Laser	H. Kroemer Zh.I. Alferov, R.F. Kazarinov	RCA, USA Joffe, UdSSR
1967	First Heterojunction Laser	Zh.I. Alferov	Joffe, UdSSR
1969	MOCVD of GaAs	H.M. Manasevit, W.I. Simpson	USA
1969	Surface lattice theory	L. Esaki und R. Tsu	IBM, USA
1970	GaAs/GaAsP	A.E. Blakeslee, C.F. Aiotta	IBM, USA
1971	Molecular Beam Epitaxy	A.Y. Cho	Bell Labs, USA
1972	GaAs/AlGaAs	R. Tsu, L. Esaki	IBM, USA
1974	Resonant Tunnel diode	L.L. Chang, L. Esaki, R. Tsu	IBM, USA
1980	HEMT	T. Mimura	Fujitsu, Japan
1982	Fractional Hall Effect	D.C. Tsui, H.L. Störmer, A.C. Gossard	Lawr. Liverm. Nat. Lab., USA

Homo- und Heteroepitaxy



Similar Material as Substrate and overgrown layer

Different Material Overgrown layer is different from Substrate

Epitaxy: Necessary conditions

- Matching of Symmetry ✔
- Matching of lattice parameters ✔
- Surface free energy difference ???

Layer by layer growth (Mode) 2-Dimensional growth

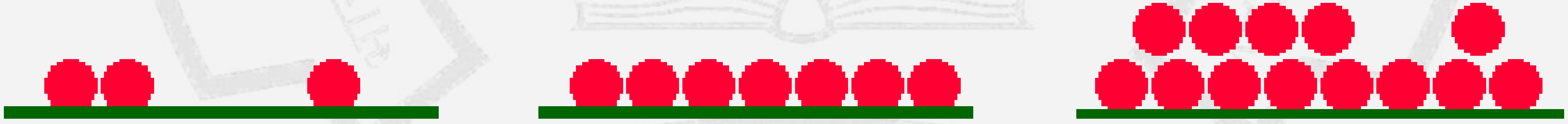
perfect wetting:

$$\gamma_s > \gamma_f + \gamma_{IF}$$

γ= Surface energy
s = Substrate
f = Film, IF= interface

→Flat layer

→called Frank-van-der Merwe (FM) or 2D-Grwoth mode



Layer growth (Mode) 3-Dimensional growth

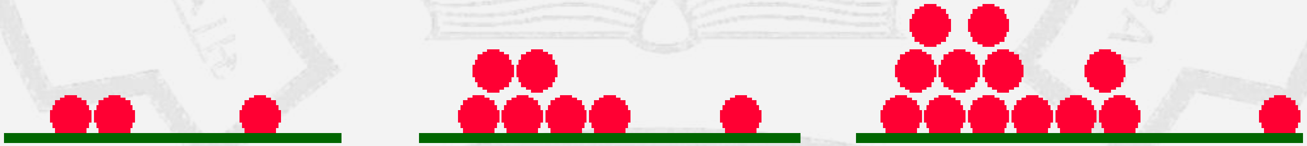
No wetting:

$$\gamma_s < \gamma_f + \gamma_{IF}$$

γ= Surface energy
s = Substrate
f = Film, IF= interface

→ Island formation

→ called Volmer-Weber (VW) or 3D-Grwoth mode



Layer growth (Mode) 2 - 3-Dimensional growth

Mixed growth:

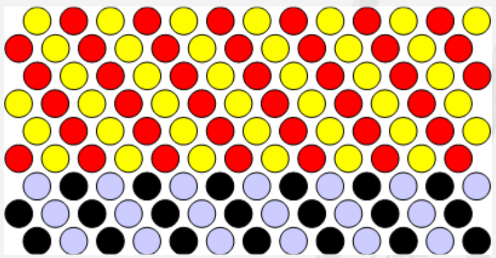
$$\gamma_s \sim \gamma_f + \gamma_{IF}$$

γ = Surface energy
s = Substrate
f = Film, IF= interface

➔ Flat starting layer
➔ Followed by Island formation
➔ called Stranski-Krastanov (SK)-growth mode

Different growth modes

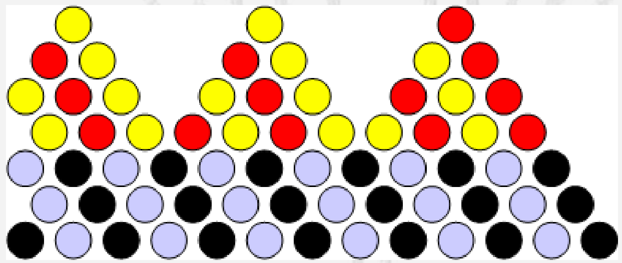
Van der Merwe layer growth (VM)



Flat layer

2D - Layer

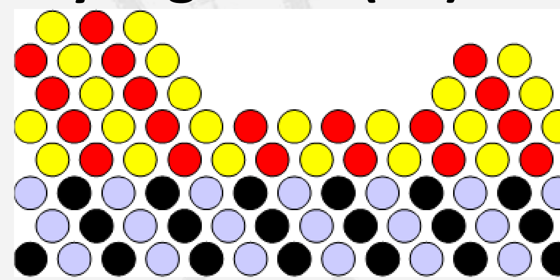
Volmer-Weber layer growth(VW)



3D –Island formation,

Quantum dots

Stranski-Krastanow layer growth(SK)



2D-3D Layer;

Island on 2D layer

Example: CVD of Si - Epitaxy

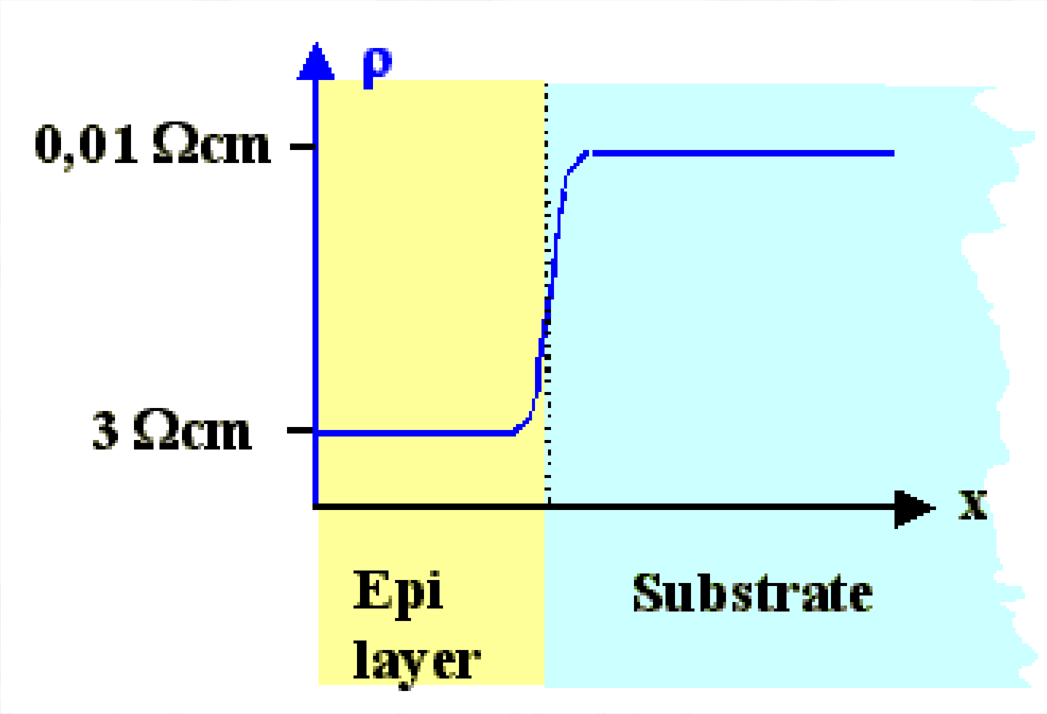
- When SiH_4 gas is used in a CVD reactor, a Si layer is deposited on the wafer surface. The size of the crystallites depends on the deposition temperature.

- At high enough temperature, the ad-atoms have enough kinetic energy to move on the surface and align themselves with the underlying Si.

- This is an epitaxial layer, and the process is called Epitaxy instead of CVD---Homoepitaxy

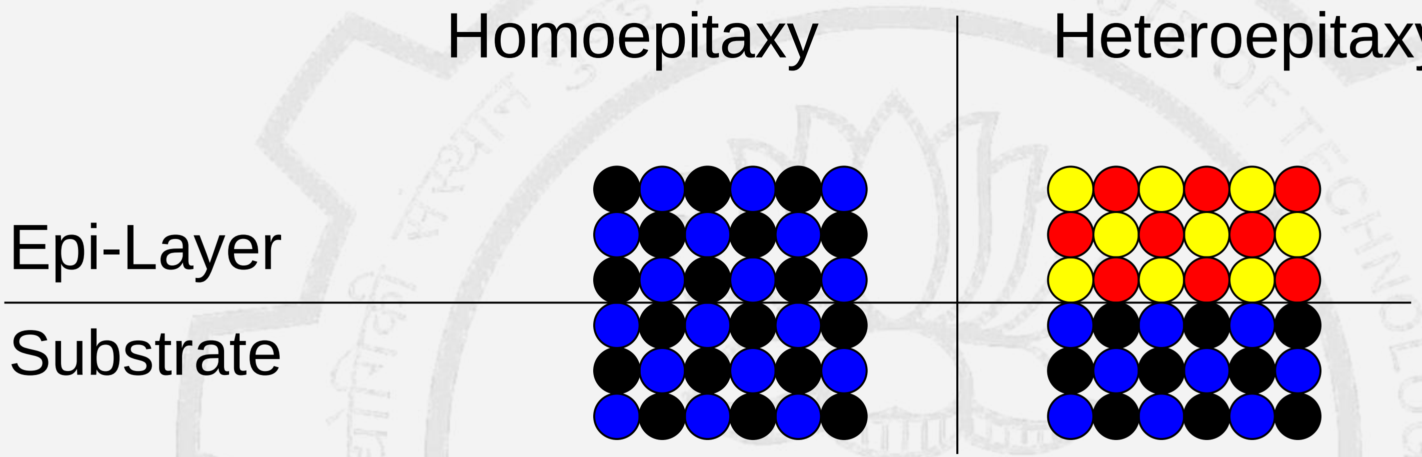
- At lower deposition temperatures, the layer is poly-crystalline Si (consisting of small crystallites)

Si epitaxy – controlling doping profiles



Epitaxy is definitely needed if a *doping profile* is required where the *resistivity in regions near the surface is larger than in the bulk.* By diffusion, you can always lower the resistivity and even change the doping type, but *increasing the resistivity by diffusion* is not realistically possible.

Homo- und Heteroepitaxy



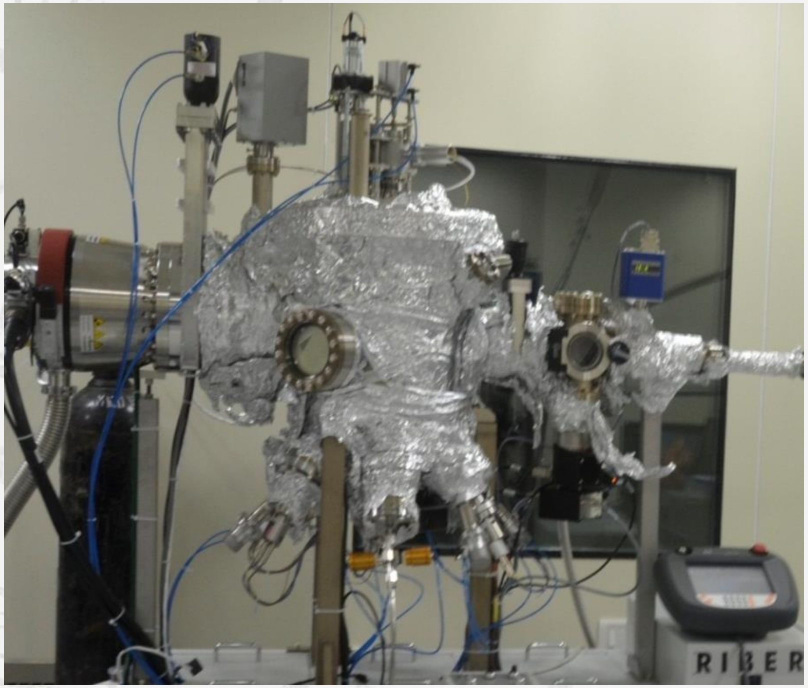
Same materials as substrate

Different Material from Substrat

Molecular Beam Epitaxy laboratory at IIT Bombay

3” Molecular Beam Epitaxy System for III-Nitride

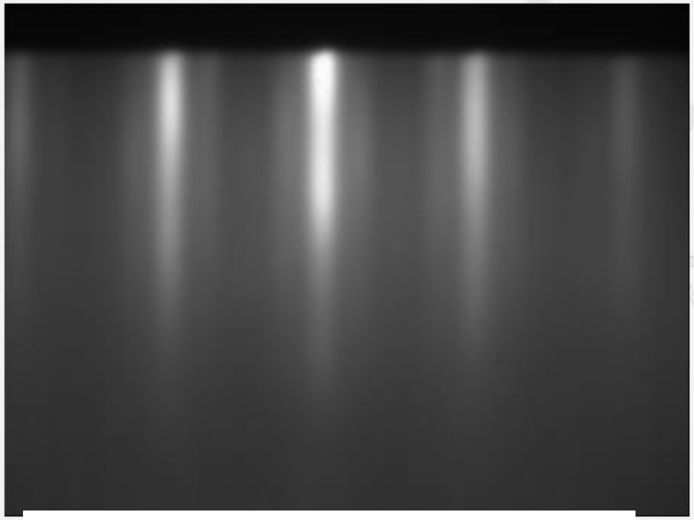
III-V semiconductors
GaN, $Al_xGa_{(1-x)}N$, AlN, $In_xGa_{(1-x)}N$, InN and InAlN

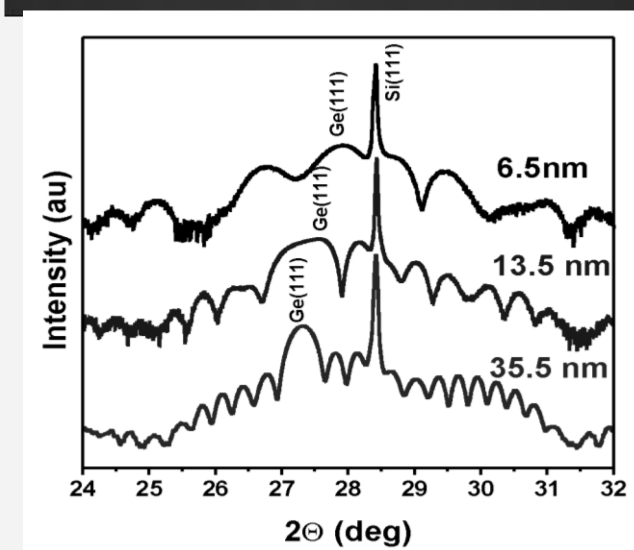


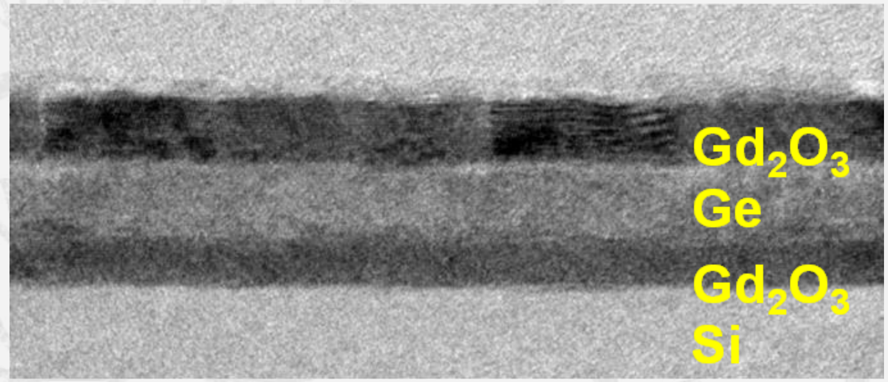
1” Molecular Beam Epitaxy System for group IV and oxide

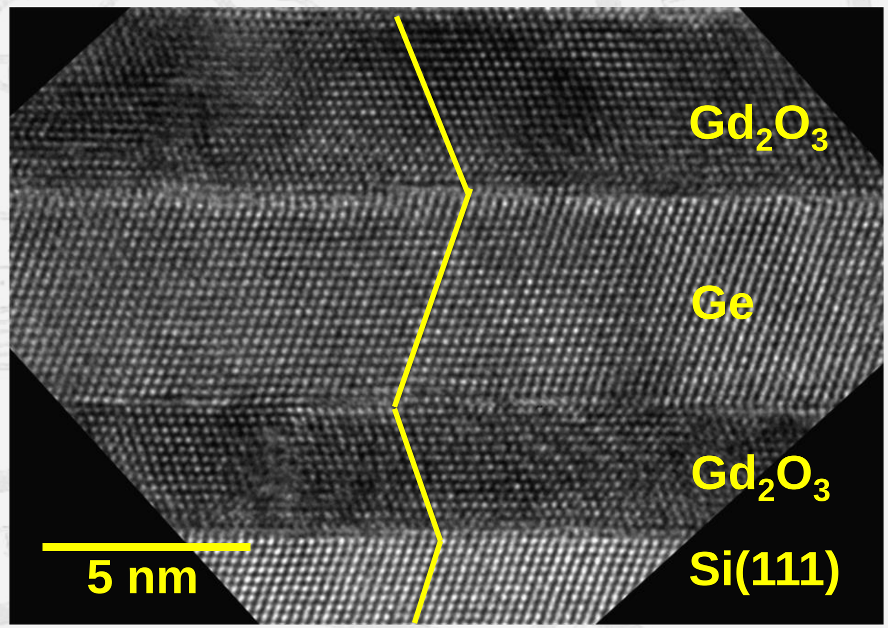
Group IV semiconductors
Si, Ge, Sn and oxides

Example: Epitaxial $Gd_2O_3/Ge/Gd_2O_3$-Si Heterostructure









A. Laha, MBE @ IITB

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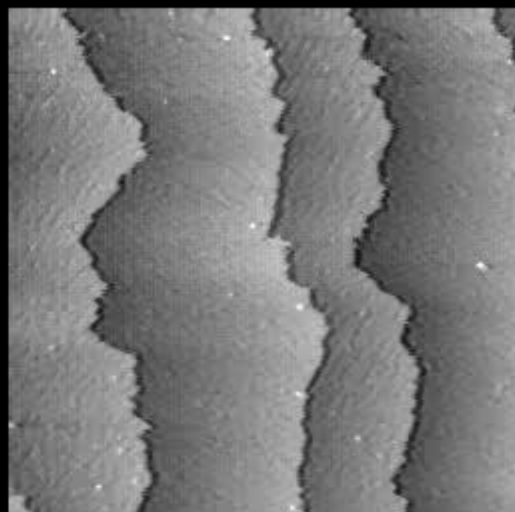
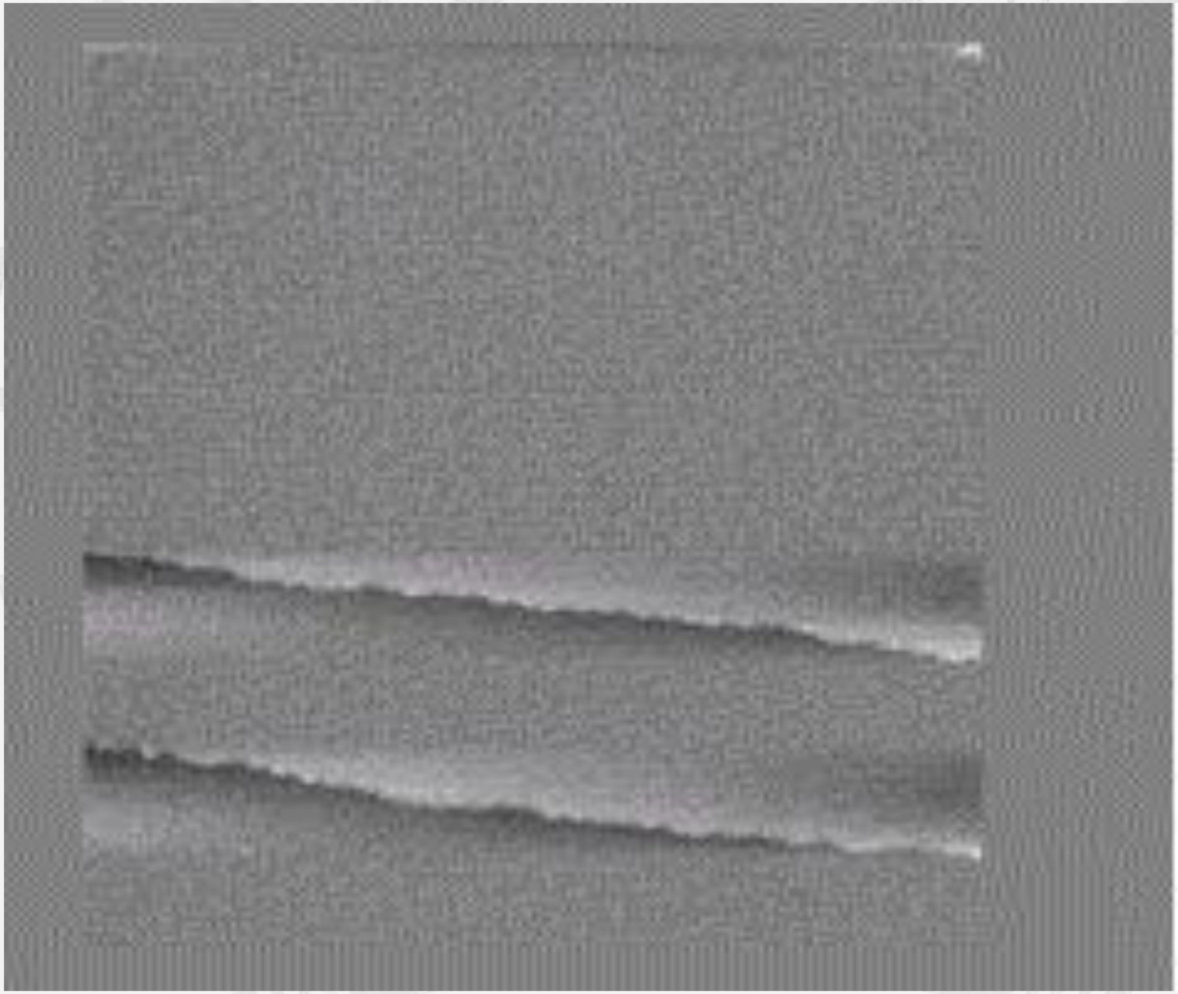
Step/Terraces on Si(001)



Arrangement of surfaces dimers

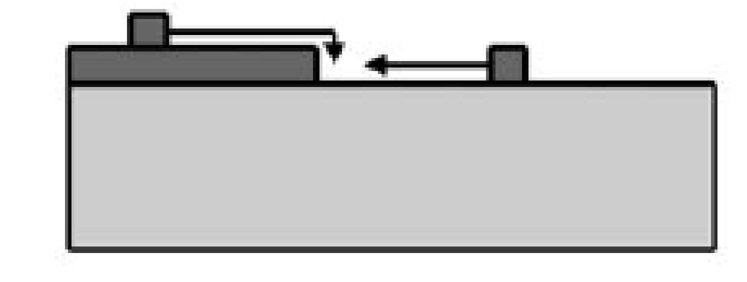
Homoepitaxy of Si on Si(111)

Transition from the Frank-van der Merwe growth to the step flow during the growth of Cu on W (111)



Van der Merwe layer growth

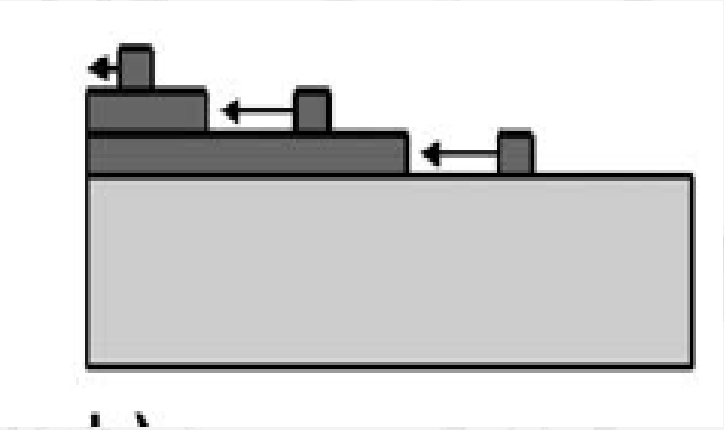
2D – Layer growth



Nucleation

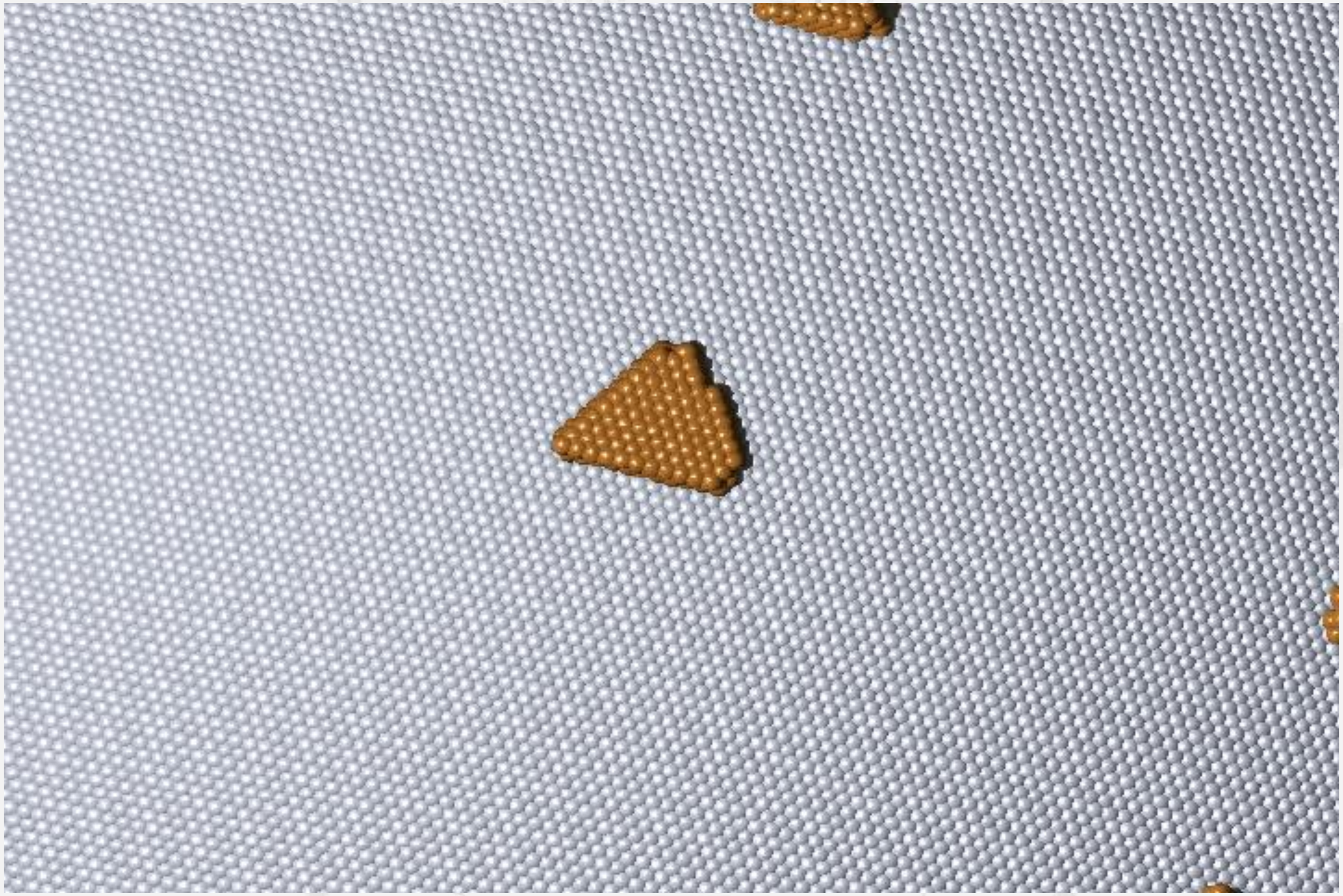
Transport from higher to lower levels

(Step-Flow)



Simultaneous growth

Heteroepitaxy



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