UNIVERSITÉ DE MONTPELLIER

Epitaxy of III-V semiconductors: some challenges and evolutions

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cnrs

institut universitaire de France

ies

A French idiom

A few months ago

Bonjour Eric

L'idée de la conf est d'essayer de réunir les communautés des epitaxieurs semiconducteurs et oxydes, et **l'idée des conf plénières est de présenter et de faire découvrir l'historique et les thématiques de recherche de chacune des communautés à l'autre**. Dans ce contexte, on avait pensé à toi en tant que pilier de la communauté des epitaxieurs iii-v. On s'était dit que tu pourrais dresser un historique de l'épi des iii-v (notamment mbe bien sûr) en France: évolution des matériaux étudiés, des applications, labos impliqués, thèmes de recherche actuels, avec bien sûr un focus sur les antimoniures et leur intégration sur Si puisque c'est votre spécialité.

Outline

- III-V semiconductors: properties and applications
- Epitaxy of III-V semiconductors: a (personal) historical view
- III-Sb based semiconductors
- III-Sb grown on (001) Si substrates
- Summary – Perspectives

Another French idiom

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III-V semiconductors: properties and applications
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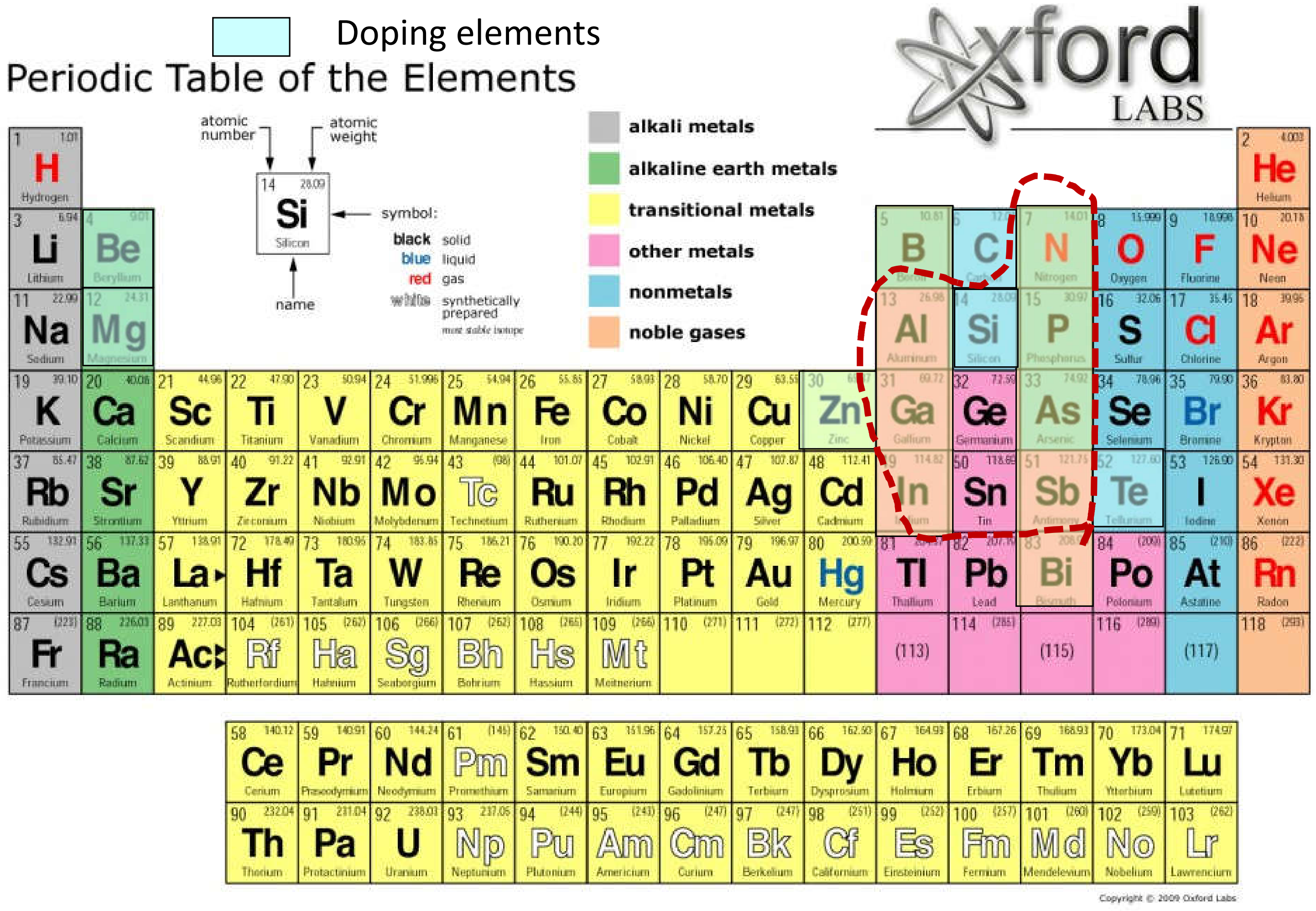
Summary – Perspectives

Back to the roots

🟨 III & V elements

🟦 Doping elements



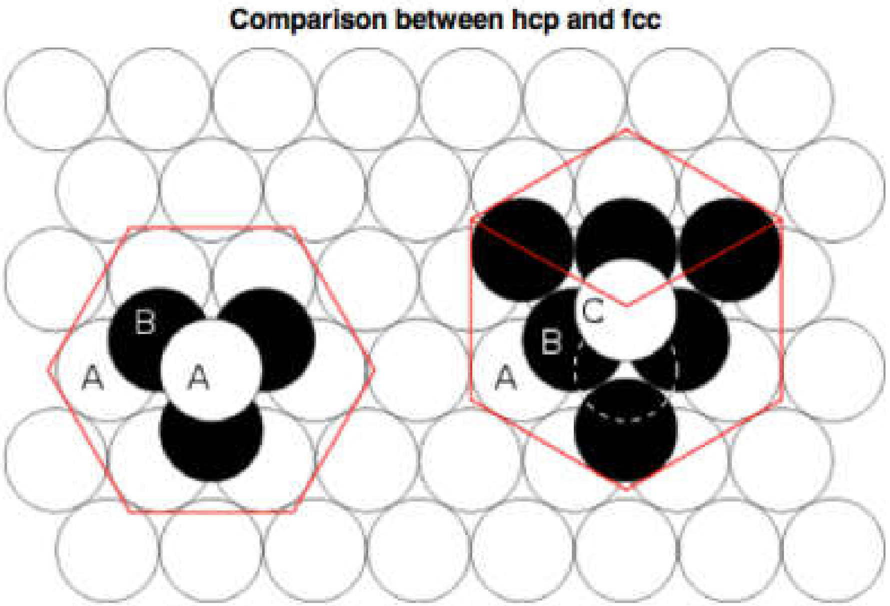
Periodic Table of the Elements

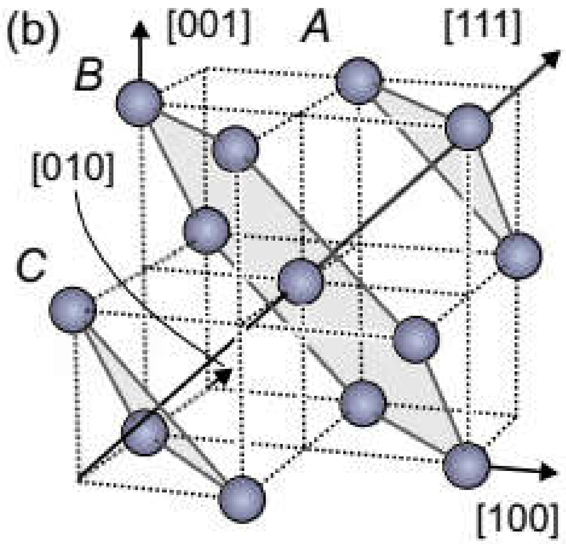
black solid
blue liquid
red gas
white synthetically prepared
most stable isotope

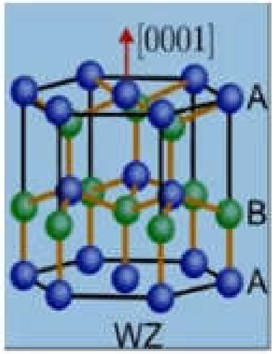
⬜ alkali metals
🟩 alkaline earth metals
🟨 transitional metals
🟪 other metals
🟦 nonmetals
🟧 noble gases

1 H Hydrogen 1.01																	2 He Helium 4.003
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon [illegible]	7 N Nitrogen 14.01	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.90	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.70	29 Cu Copper 63.55	30 Zn Zinc [illegible]	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.40	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.69	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.30
55 Cs Cesium 132.91	56 Ba Barium 137.33	57 La ▸ Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.20	77 Ir Iridium 192.22	78 Pt Platinum 195.09	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium [illegible]	82 Pb Lead [illegible]	83 Bi Bismuth [illegible]	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.03	89 Ac ▸ Actinium 227.03	104 Rf Rutherfordium (261)	105 Ha Hahnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (271)	111 (272)	112 (277)	(113)	114 (285)	(115)	116 (289)	(117)	118 (293)
			58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.40	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97	
			90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (260)	102 No Nobelium (259)	103 Lr Lawrencium (262)	

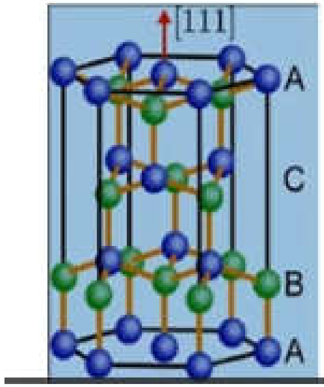
III-V Semiconductor structures







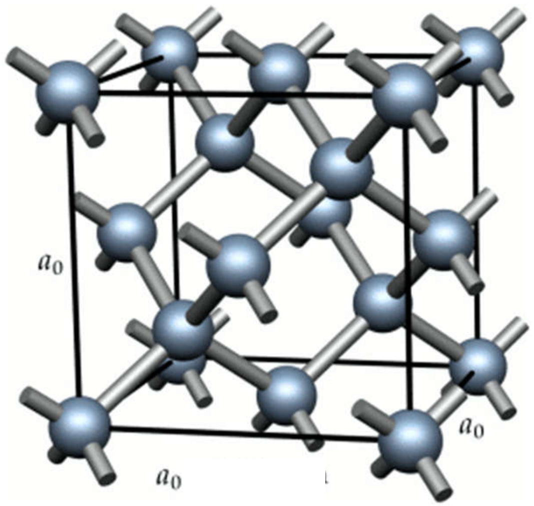
Hexagonal

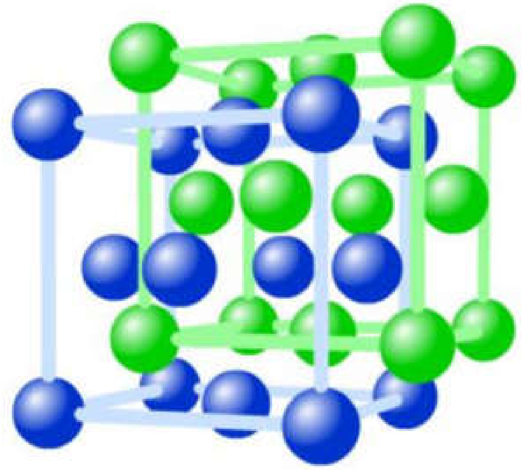


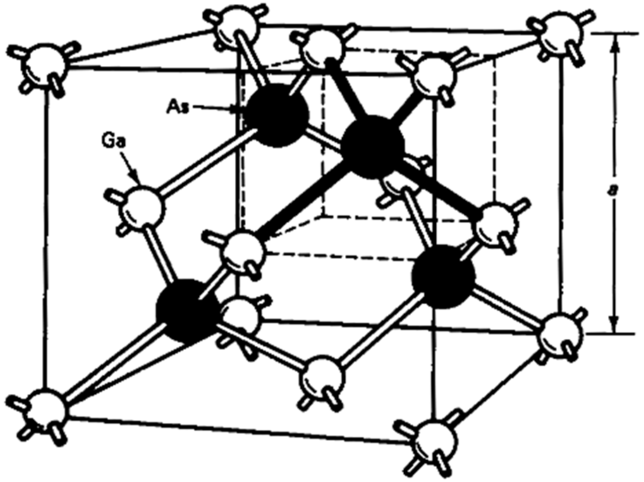
Cubic

Hexagonal and face-centered cubic lattices are the most compact way to stack spheres.

Diamond and zinc blende structures





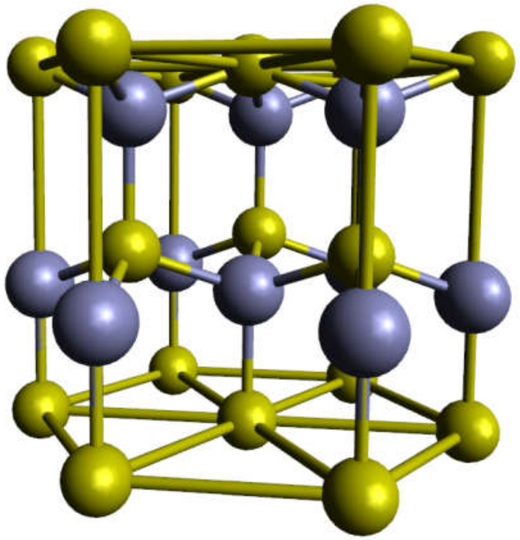


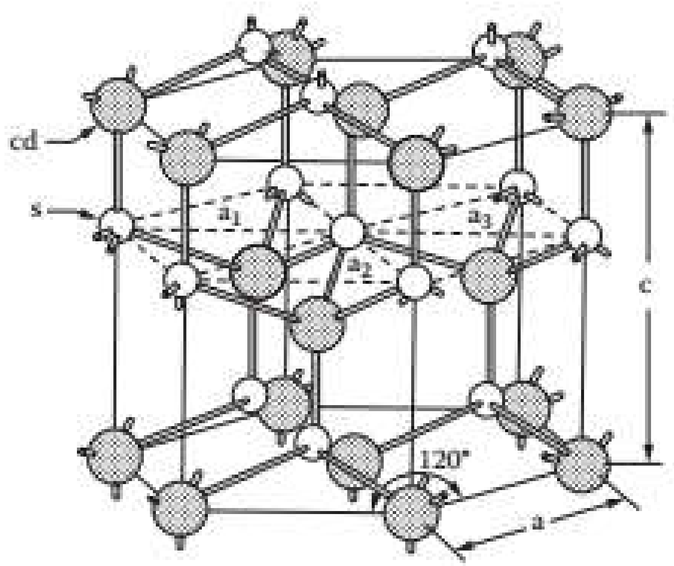
Diamond structure:
C, Si, Ge

Zinc blende structure:
ZnS, ZnSe
GaAs, InP, GaSb,…

Two fcc lattices shifted by a/4 along the cube diagonal.

Wurtzite structure





Wurtzite structure:

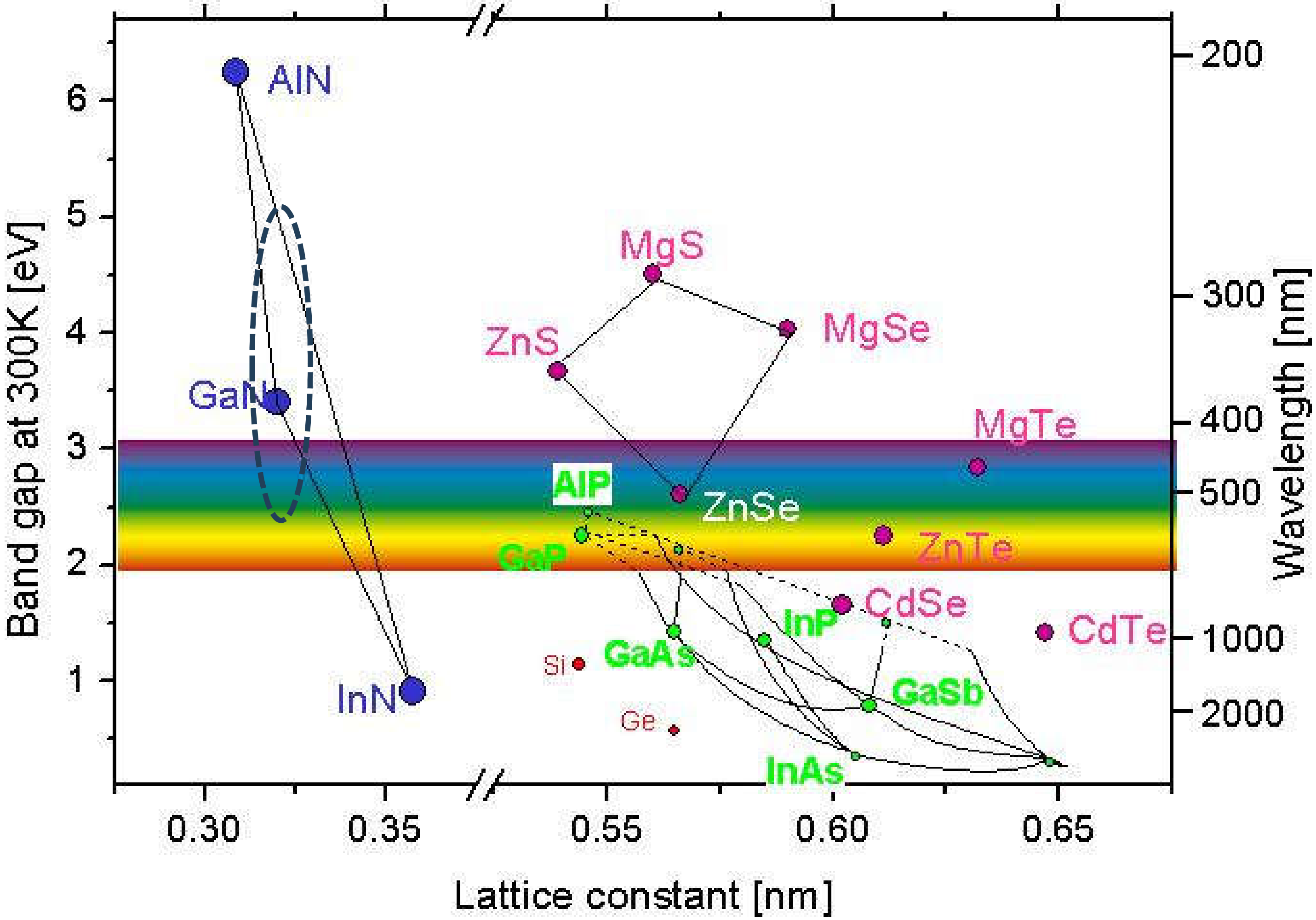
GaN,….

ZnS,….

Wurtzite structure:

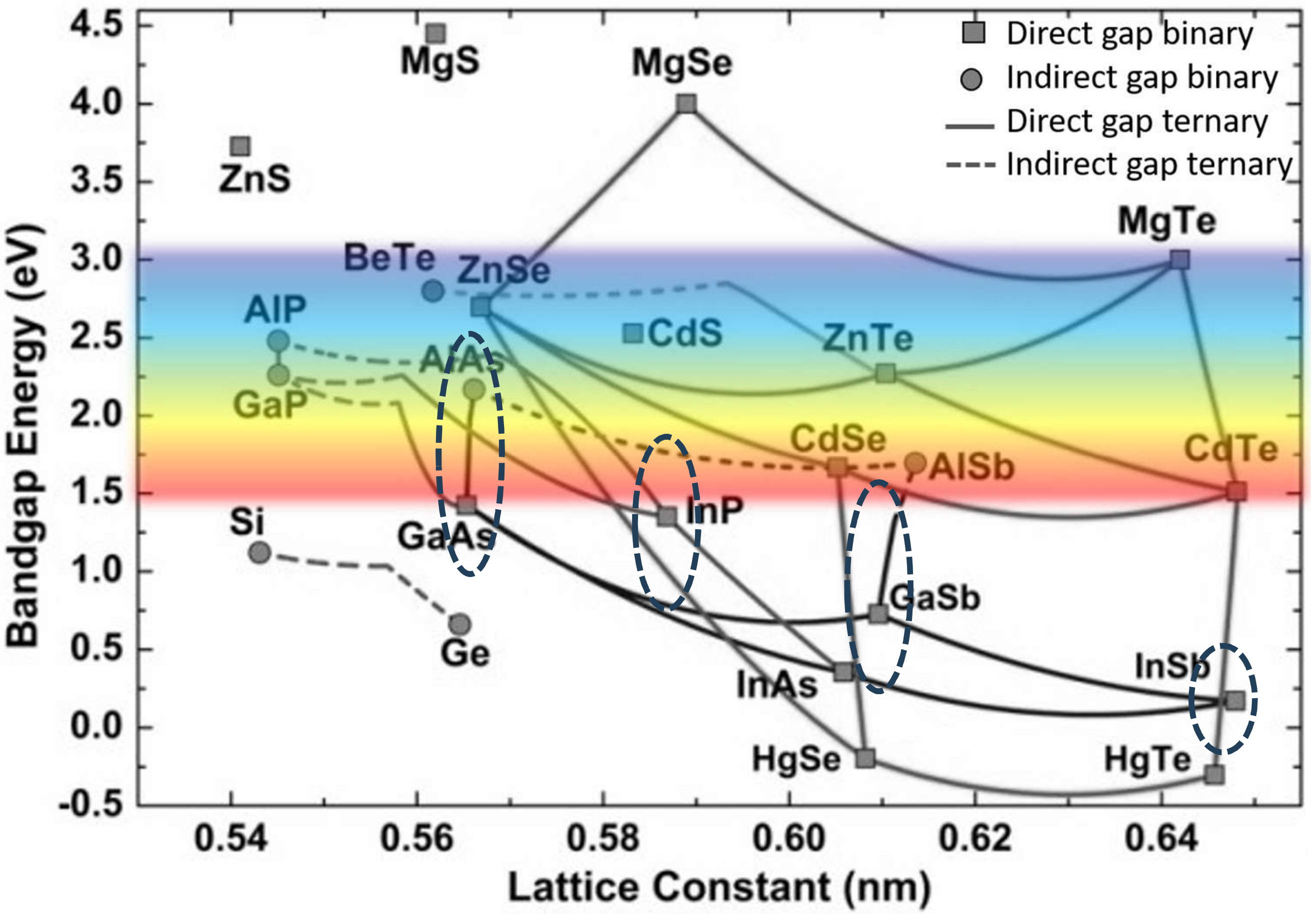
- Two lattice parameters (a, c)
- Two hcp lattices shifted by (5/8)c

The sky map: fundamental plot

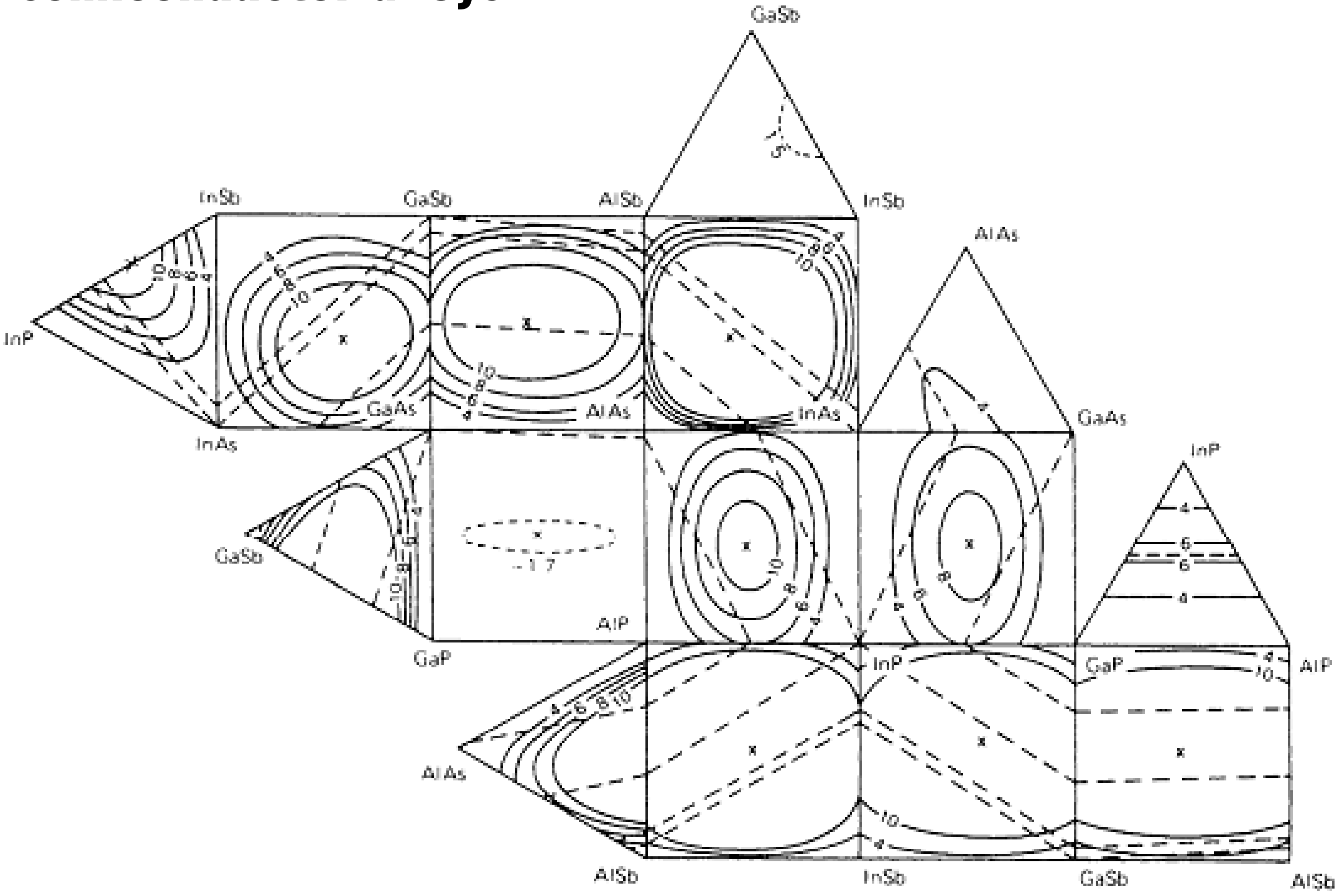


Voir Fabrice Semond, 14h45

The sky map


Bandgap Energy (eV)
Lattice Constant (nm)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
0.54
0.56
0.58
0.60
0.62
0.64
Direct gap binary
Indirect gap binary
Direct gap ternary
Indirect gap ternary
MgS
MgSe
ZnS
MgTe
BeTe
ZnSe
AlP
CdS
ZnTe
AlAs
GaP
CdSe
AlSb
CdTe
Si
GaAs
InP
GaSb
Ge
InSb
InAs
HgSe
HgTe

Stability of III-V semiconductor alloys



Large miscibility gaps for most III-V quaternary alloys:

Consequences on epitaxial growth

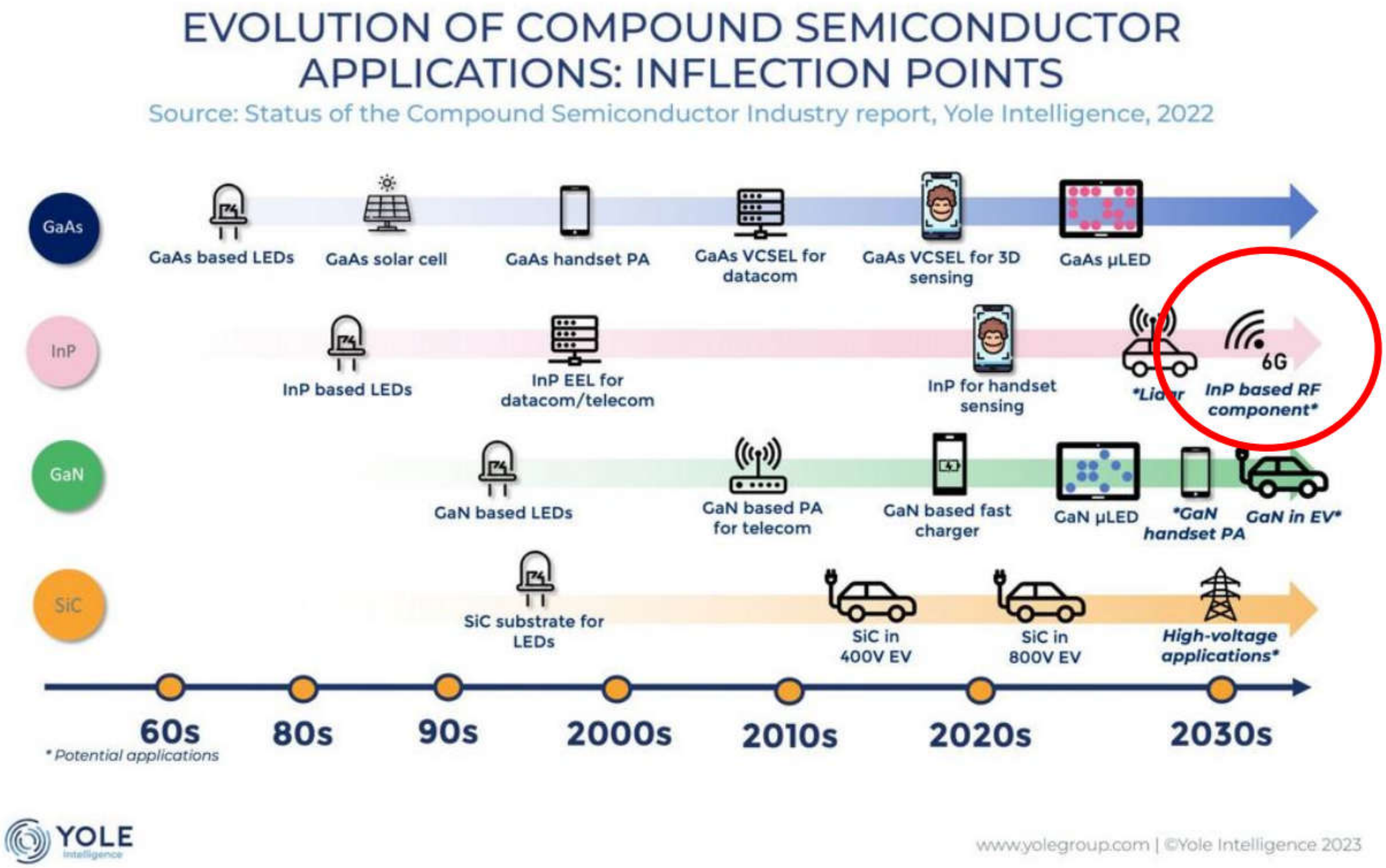
Onabe, Jpn. J. Appl. Phys. **21**, L323 (1982).

III-V semiconductors: effective masses, mobilities

	AlAs	**AlSb**	**GaN**	**GaAs**	**GaSb**	**InP**	**InAs**	**InSb**	**Si**	**Ge**
E_g(300 K) (eV)	2.2	1.6	3.4	1.4	0.7	1.3	0.3	0.2	1.1	0.7
m_e^* / m_0	0.083	0.102	0.2	0.066	0.042	0.073	0.023	0.014	0.15	0.044
m_{hh}^* / m_0	0.409	0.336	0.8	0.377	0.222	0.6	0.26	0.244	0.54	0.28
μ_e (300 K) ($cm^2. V^{-1}.s^{-1}$)			2 000	8 500	3 000	5 400	**40 000**	**77 000**	1 400	3 900
μ_h (300 K) ($cm^2. V^{-1}.s^{-1}$)			200	400	**1 000**	200	500	850	450	**1900**

Low masses, high carrier mobilities

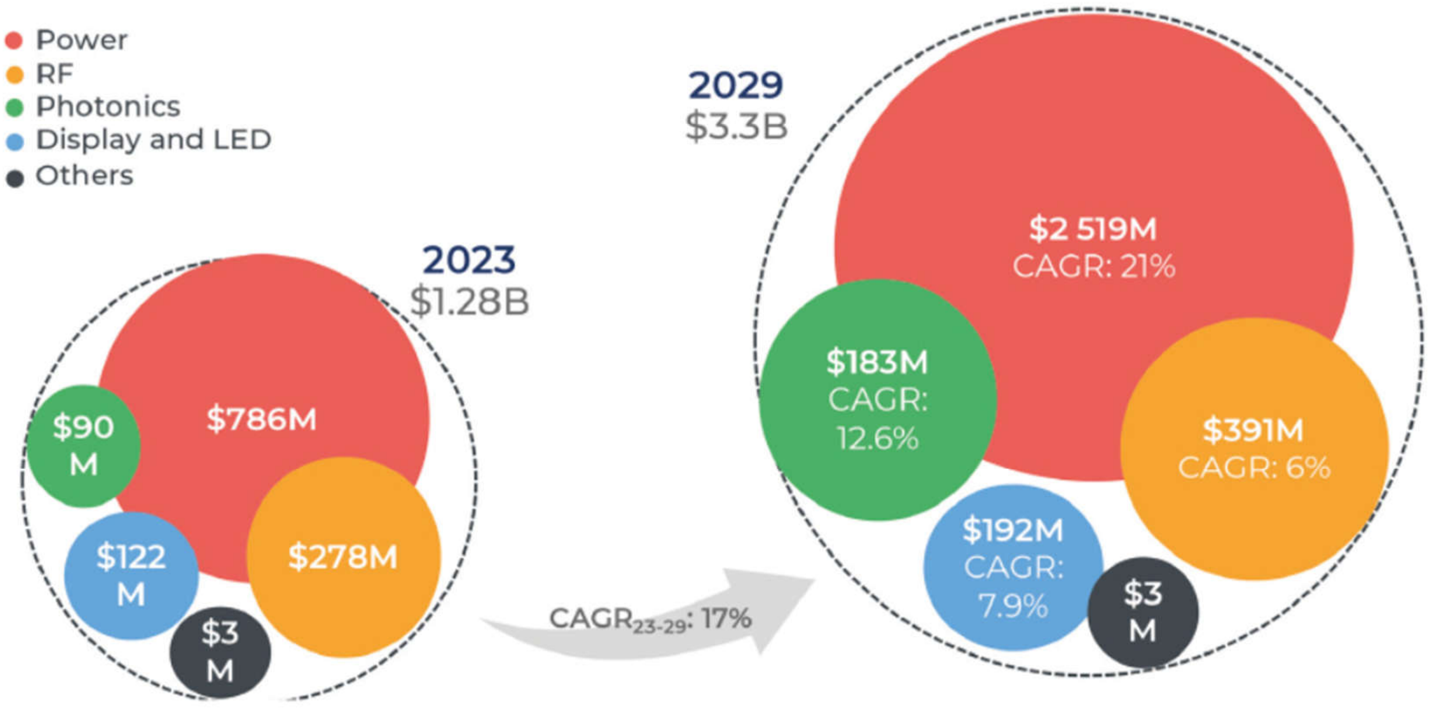
III-V semiconductors: applications



EVOLUTION OF COMPOUND SEMICONDUCTOR APPLICATIONS: INFLECTION POINTS

Source: Status of the Compound Semiconductor Industry report, Yole Intelligence, 2022

III-V semiconductors: markets



2023-2029 compound semiconductor substrate market by application ($M)

(Source: Status of the Compound Semiconductor Industry 2024, Yole Intelligence, January 2024)

© Yole Intelligence 2024

Outline

III-V semiconductors: properties and applications

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III-Sb grown on (001) Si substrates

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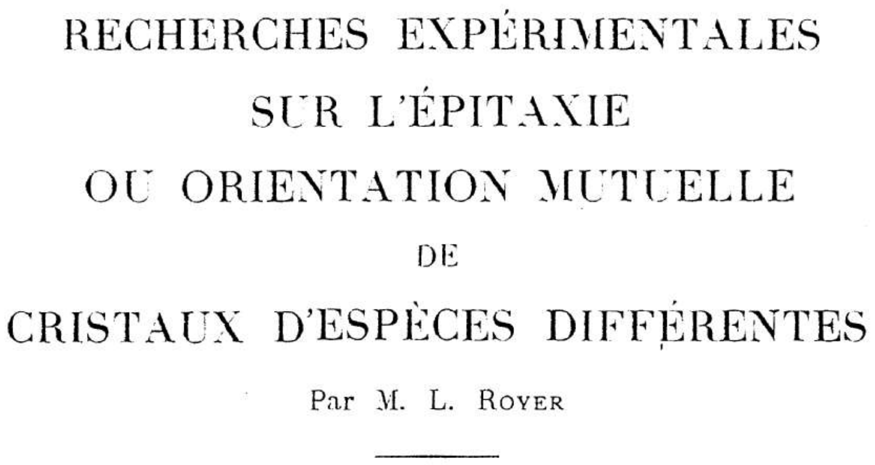
EPITAXY?



RECHERCHES EXPÉRIMENTALES
SUR L'ÉPITAXIE
OU ORIENTATION MUTUELLE
DE
CRISTAUX D'ESPÈCES DIFFÉRENTES

Par M. L. Royer

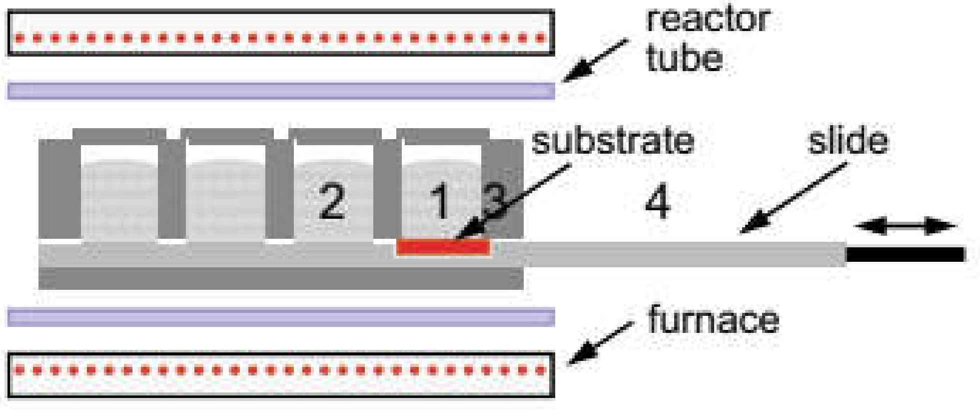
Bull. Soc. Fran. Min. 51 (1928) 7

First observation of mutual orientation
of natural crystals around 1878.

Epitaxy has been developed thanks to, and for the science and technology of III-V semiconductors.

The substrate is crucial.

Liquid-Phase Epitaxy (LPE)



Principle:

Superstaurated liquid solutions contain the constitutive elements of the epitaxial material.

The substrate is is brought in contact with the baths in sequence, which drives heterogeneous nucleation on the substrate, *i.e.* epitaxy.

Peculiarity:

- A near-equilibrium growth technique.
- Rather accurate description of the growth process by thermodynamics

Liquid-Phase Epitaxy (LPE)

Advantages of LPE:

- Simple experimental set-up, rather low cost.
- High material purity.
- High growth rate (~1 µm/min).

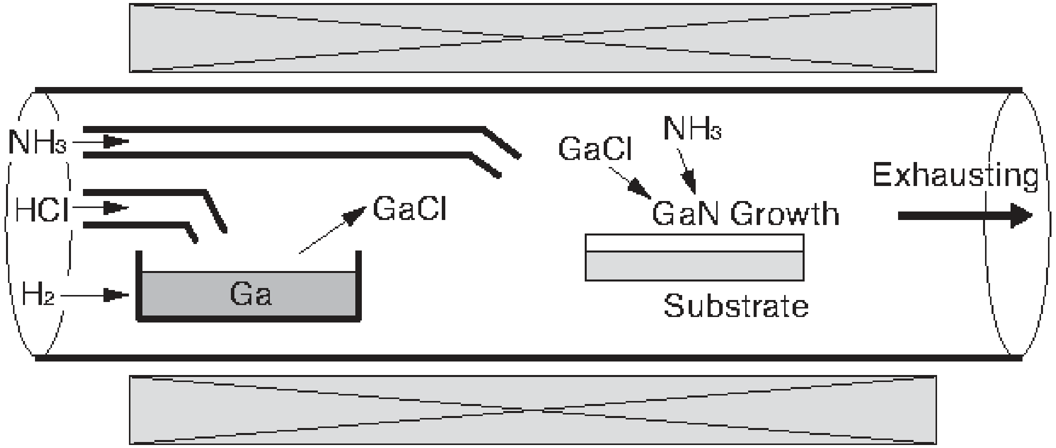
Disadvantages of LPE:

- Thermodynamics equilibrium: low flexibility (but results can be predicted).
- Reproducibility issues.
- High growth rate: difficult to control interfaces and thickness accurately, not adapted to the growth of nanostructures.

Applications:

- Very much used in the 80s for opto-devices, inc. in the industry.
- Still used for particular applications/materials:
  - CdHgTe infrared photodetectors
  - ………………

Vapor Phase Epitaxy (VPE)



Principle:

The elements are transported by carrier gases.

Reactions occur near the substrate zone to form the compound.

Ex:

- **Ga** (l) + HCl (g) → GaCl (g) + ½ H_2 (g)
- GaCl(g) + **NH_3** (g) → **GaN** (s) + HCl (g) + H_2 (g)

See Yamina André for more details

Vapor Phase Epitaxy (VPE)

Advantages of VPE:

- Simple, versatile: epitaxy or polycristal deposition, depending on the substrate.
- High material purity.
- High growth rate (>>1 µm/min).
- Possibility of *in situ* etching + re-growth.

Disadvantages of VPE:

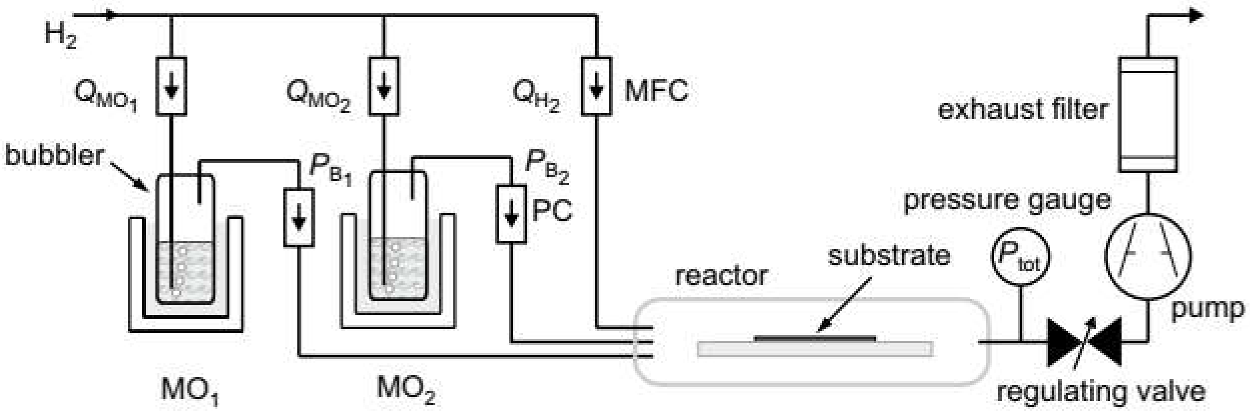
- Deposition everywhere in the reactor (parasitic reactions).
- Thermodynamics equilibrium: low flexibility (but results can be predicted).
- High growth rate: difficult to control interfaces and thickness accurately.

Applications:

- LEDs
- Very thick layers (quasi substrates, periodic polar orientation for non linear optics)
- Nanowires

See Yamina André for more details

Metal-Organic Vapor Phase Epitaxy (MOVPE)



Principle:

Sources are organo-metallic compounds or hydrides containing the elements of the layer.
They are transported to the substrate zone by a carrier gas.
The reaction occurs near the substrate which is the only zone at high temperature.

ex: $(CH_3)_3\mathbf{Ga}\ (g) + \mathbf{As}H_3(g) \rightarrow GaAs\ (s) + 3\ CH_4\ (g)$

Metal-organic vapor phase epitaxy (MOVPE)

US and German patents in the early 60s.

First papers in the UK in the late 60s from CVD users.

Also known as:

- **Metal-Organic Chemical Vapor Deposition (MOCVD)**
- Organo-Metallic Vapor Phase Epitaxy (OMVPE)
- Organo-Metallic Chemical Vapor Deposition (OMCVD)

MOVPE/OMVPE better reflects the real nature of the technique: **epitaxy**.

Metal-organic vapor phase epitaxy (MOVPE)

Advantages of MOVPE:

- Non-equilibrium technique: high flexibility.
- Adjustable growth rate: 0.05 – 0.5 µm/min.
- Accurate control of thicknesses, down to a fewMLs.
- Easy control of alloy composition by gas flux control.
- Easy maintenance.
- Well suited to the growth of materials containing volatile species (P, S,..).
- Chemistry: good selectivity.

Disadvantages of MOVPE:

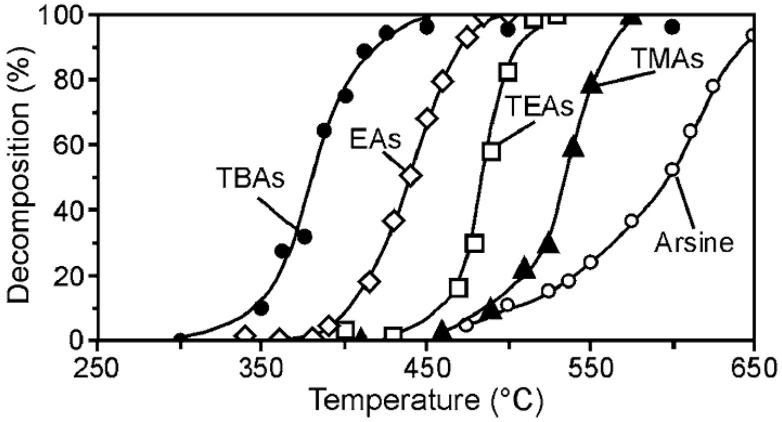
- Difficult *in situ* control
- Toxic gases (AsH_3, PH_3,..)
- Complex, expensive equipment.

⇒ New reactor geometries
⇒ New group-V molecules

Applications:

- GaN LEDs,
- Lasers (GaAs pump lasers, InP telecom lasers)

Group-V decomposition



- Pyrolysis within narrow T range (ΔT = 50 -100 K)
- Group-III OM helps the pyrolysis of group-Vs
- 2 paths of decomposition:
  - in gas phase (homogeneous reaction)
  - **at surface (heterogeneous reaction)**

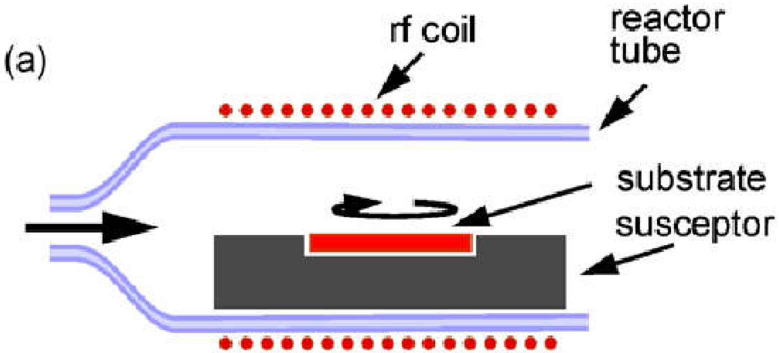
$$\mathrm{Ga(CH_3)_3 + AsH_3 \rightarrow GaAs + 3CH_4\uparrow}.$$

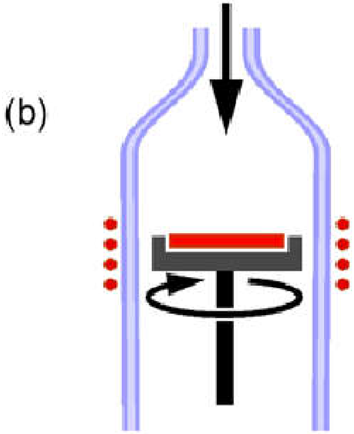
Note that the actual chemistry is not well known:

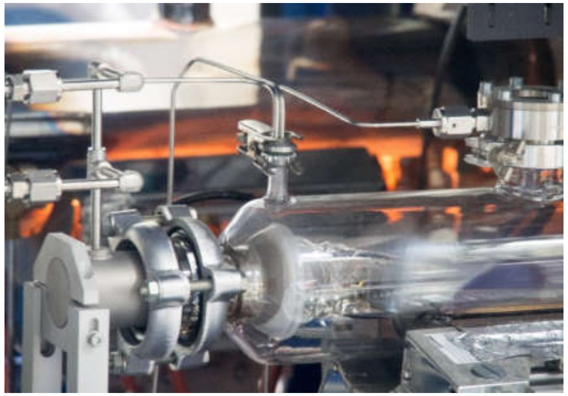
$$\mathrm{Ga(CH_3)_3 \rightarrow Ga(CH_3)_2 + CH_3 \rightarrow GaCH_3 + 2CH_3 \rightarrow Ga + 3CH_3}.$$

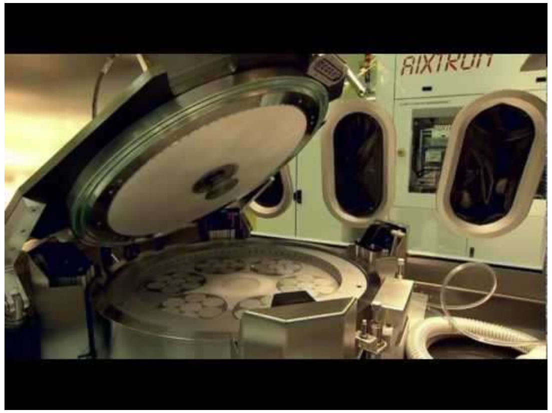
Pb: C incorporation is a serious problem in MOVPE

MOVPE









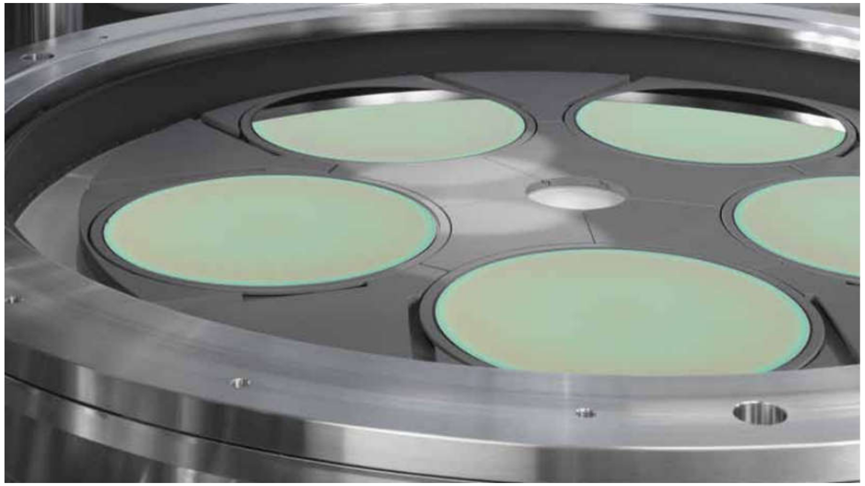
MOVPE reactor (Aixtron)

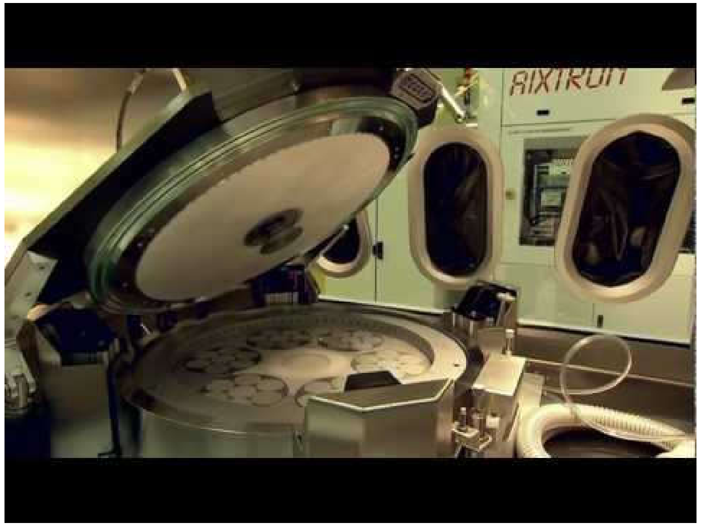
Depression pipes (security)

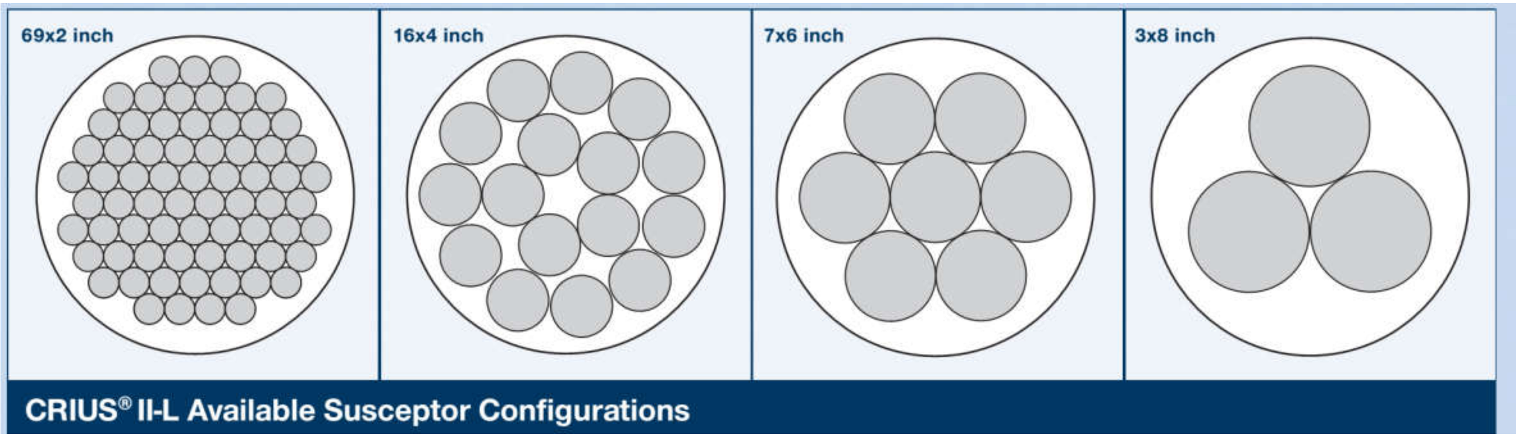
Load/lock chamber

In situ characterization tools available in new systems

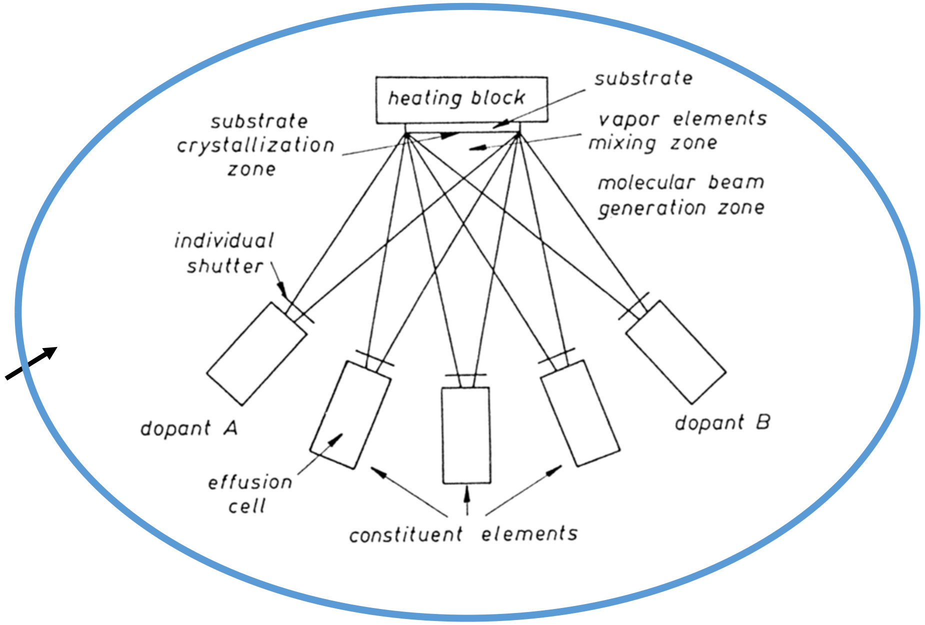
AIXTRON CCS or planetary reactors







Molecular Beam Epitaxy (MBE)



Ultra-High Vacuum:
$P_{lim} \sim 10^{-14}$ atm

Principle:

Evaporation of the elements constituting the epitaxial layer from ultra-pure source material.

UHV: mean free path larger than the cell-substrate distance: **reaction on the substrate surface.**

3-temperature principle: for III-Vs: $\mathbf{T_V < T_S < T_{III}}$: no group-V accumulation

Growth rates are governed by the group-III cell temperatures, that must be controlled to ± 0.5 °C.

Molecular beam epitaxy (MBE)

Advantages of MBE:

- Far-from-equilibrium technique: high flexibility.
- Low-temperature growth.
- Low growth rate: << 1 µm/h
- Accurate control of thicknesses, down to a fraction of ML.
- Easy control of group-III alloy composition by cell-temperature control.
- **UHV:** high material purity and *in situ* real-time characterization techniques.

Disadvantages of MBE:

- Difficult control of group-V alloy compositions (competition between group-V species)
- Not well suited to materials containing volatile elements (P, S,..)
- Temperatures have to be regulated to ± 0.5 °C
- Physical mechanisms: low/no selectivity
- **UHV**
- Complex, expensive equipment.

Applications:

- GaAs HEMTs
- III-Sb-based opto devices

Combined techniques (MBE + VPE)

Aim: Combining the main advantages of two techniques:

- MBE – UHV: *in situ* control, high purity, high interface control
- MOVPE: selective growth, volatile elements.

Principle: some of the individual elements are introduced as gases into an MBE-like reactor. Working pressure is then intermediate between MBE and MOVPE (~10^{-5} Torr).

Gas-source MBE (**GS-MBE**): group-V gas sources + elemental group III sources

Metal-organic molecular-beam epitaxy (**MOMBE**): metal-organic group III + group-V gas sources

Applications:

- InP telecom lasers

Molecular beam epitaxy (MBE)

Historical perspective

The principle has been demonstrated by Günther (Siemens) in the late 50s. He used an As crucible at a temperature T_V to impose a sufficient overpressure on the substrate, and a Ga crucible at temperature T_{III}. Fluxes were aiming toward a **polycristalline substrate** at temperature T_S. The system was in a reactor under **primary vacuum**.

Günther demonstrated that the growth of III-V layers is possible when $\mathbf{T_V<T_S<T_{III}}$ and T_S, the substrate temperature, is high enough to evaporate excess As.

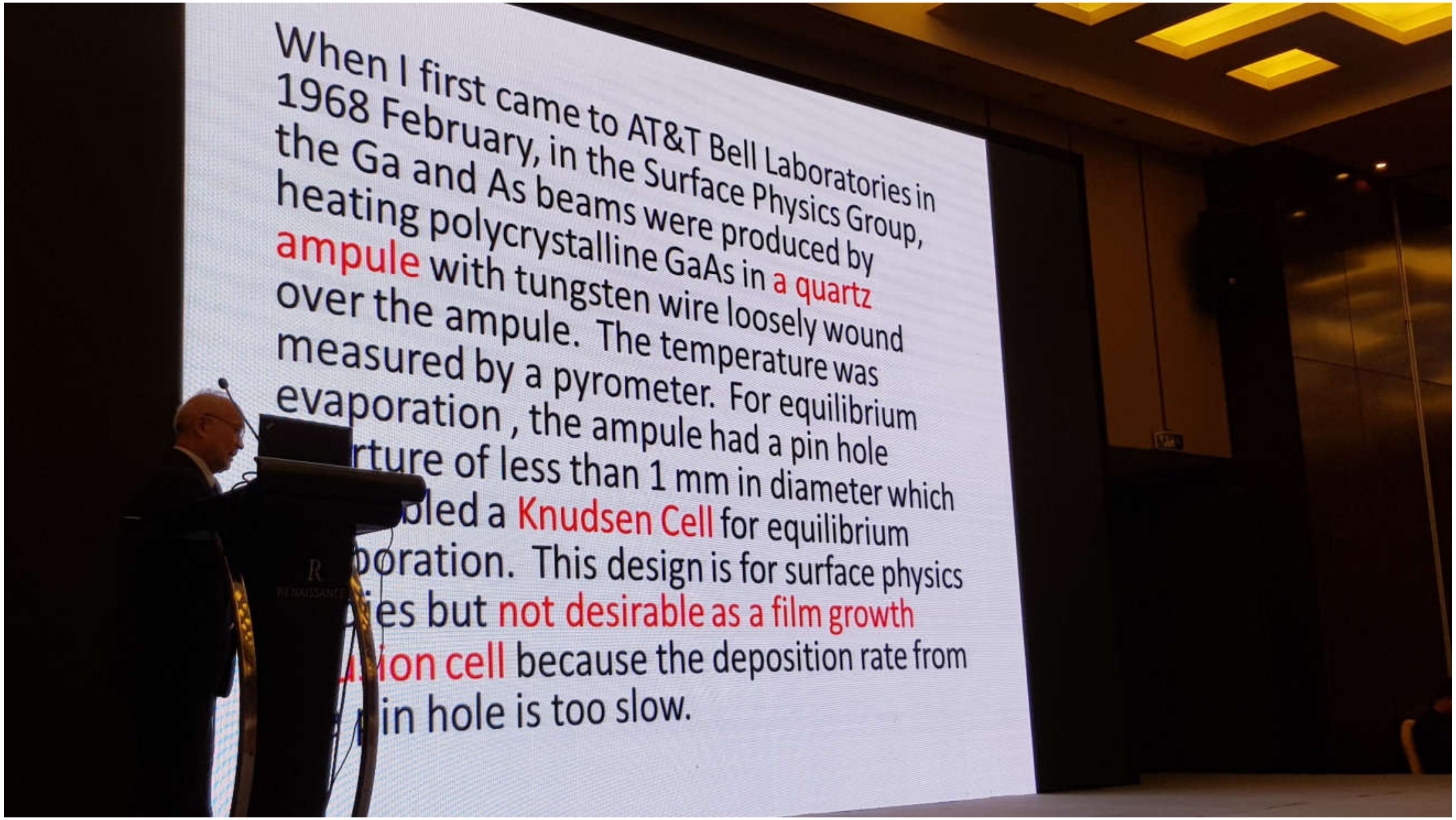
Still, Günther didn't get good results because he had polycristalline substrates and the vacuum was not good enough.

In the late 60s-70s, vacuum technology and cryogeny had made a lot of progress.

J. Arthur and A. Cho (Bell Labs) revisited the 3-temperatures technique. They achieved good crystal quality of epilayers grown on GaAs **single crystals** in a **ultra-high vacuum (UHV)** reactor (10^{-10} – 10^{-11} Torr). Ga and As fluxes were obtained by heating up liquid Ga and solid As in dedicated crucibles.

MBE was born

The invention of MBE by Al Cho

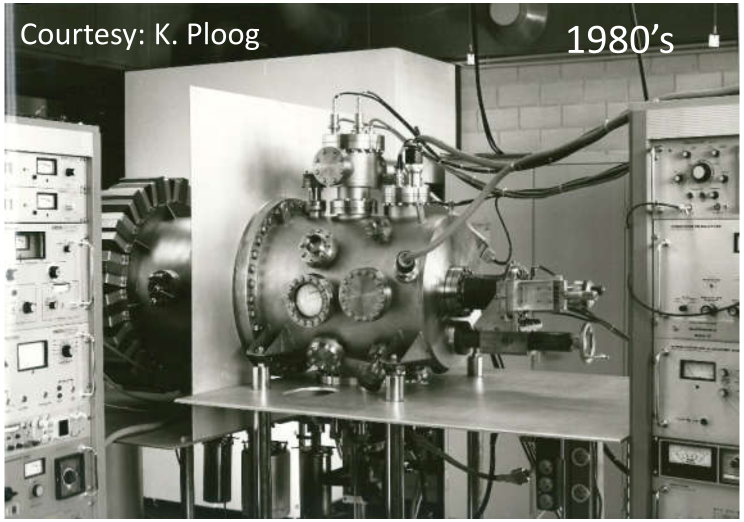


When I first came to AT&T Bell Laboratories in 1968 February, in the Surface Physics Group, the Ga and As beams were produced by heating polycrystalline GaAs in a quartz ampule with tungsten wire loosely wound over the ampule. The temperature was measured by a pyrometer. For equilibrium evaporation , the ampule had a pin hole
rture of less than 1 mm in diameter which
bled a Knudsen Cell for equilibrium
poration. This design is for surface physics
ies but not desirable as a film growth
ion cell because the deposition rate from
in hole is too slow.

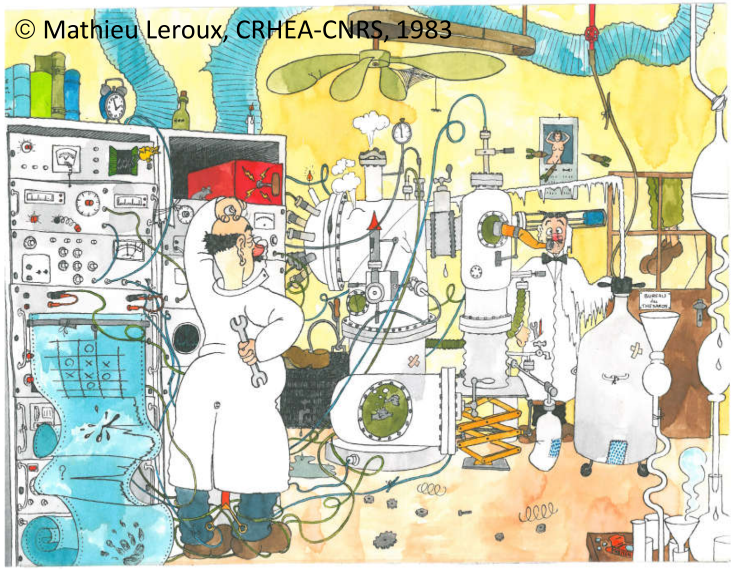
Al Cho, IC-MBE 2018, Shanghai


M.B.E. 78
FIRST INTERNATIONAL SYMPOSIUM ON MOLECULAR BEAM EPITAXY AND ASSOCIATED SURFACE TECHNIQUES
PROGRAM
John Arthur
Al Cho
Pierre Auger
Bouchaib
Jalenques
HOTEL MERIDIEN
RENAISSANCE

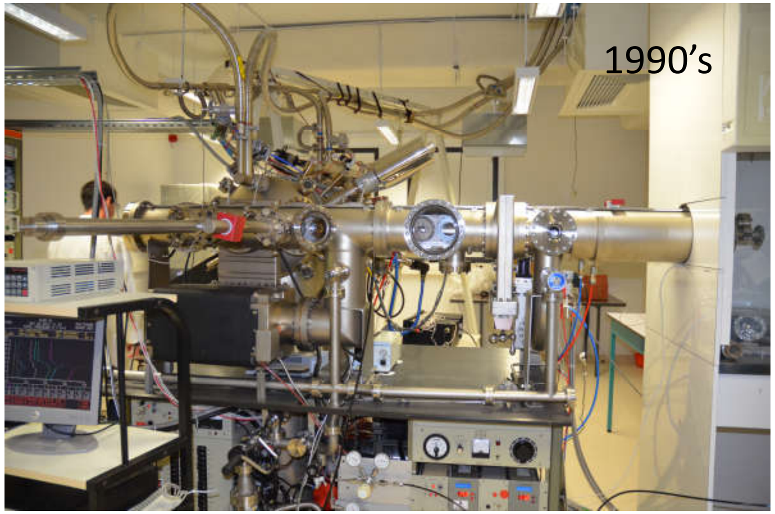
The equipment

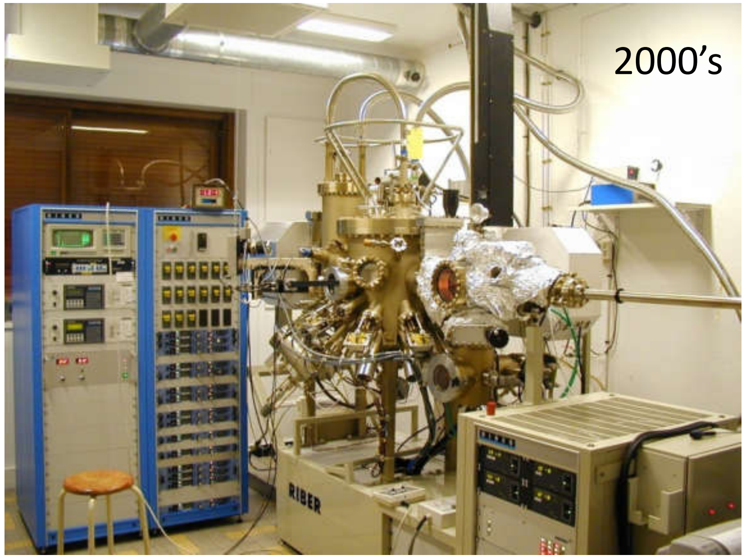

Courtesy: K. Ploog

1980’s

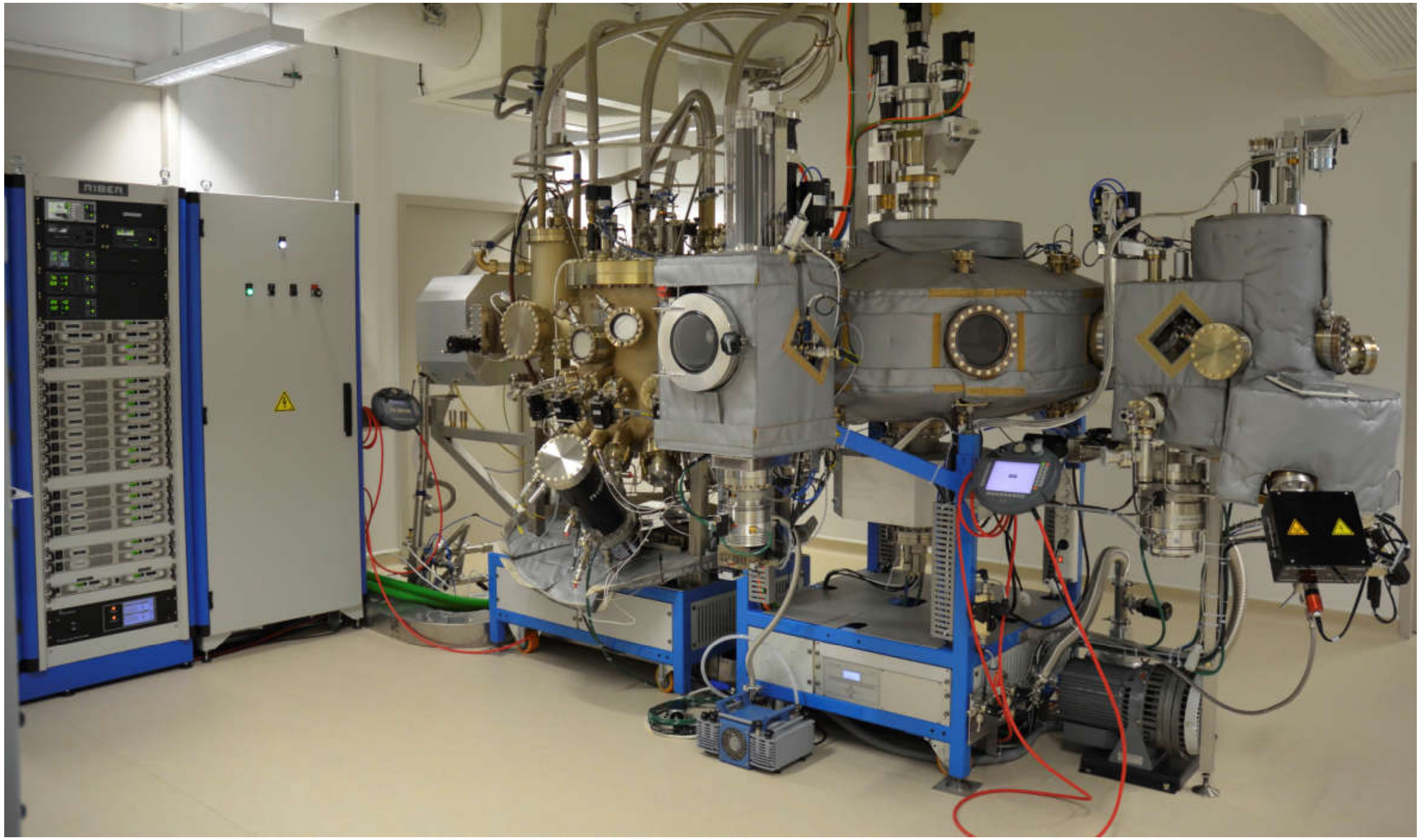

© Mathieu Leroux, CRHEA-CNRS, 1983

Early MBE systems


1990’s

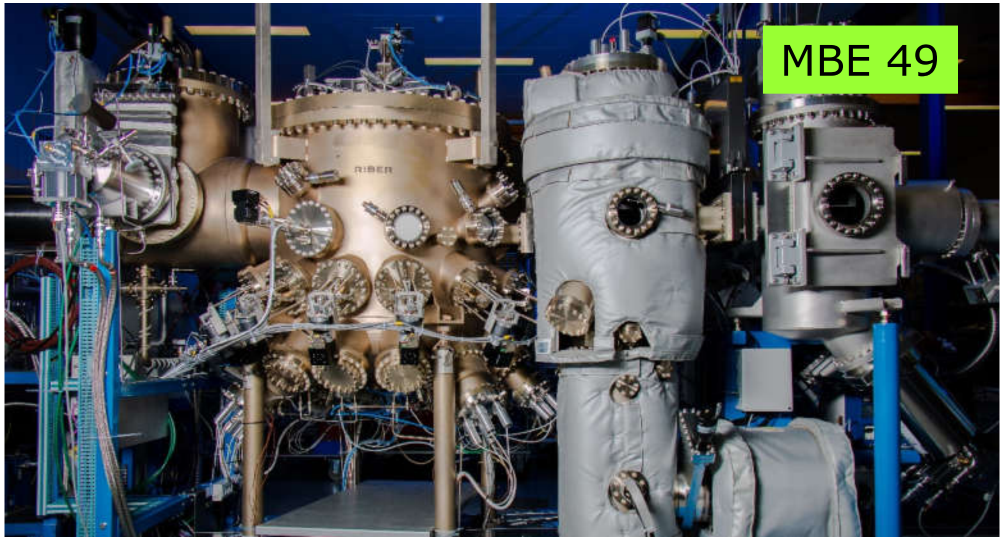

2000’s

Recent MBE lab



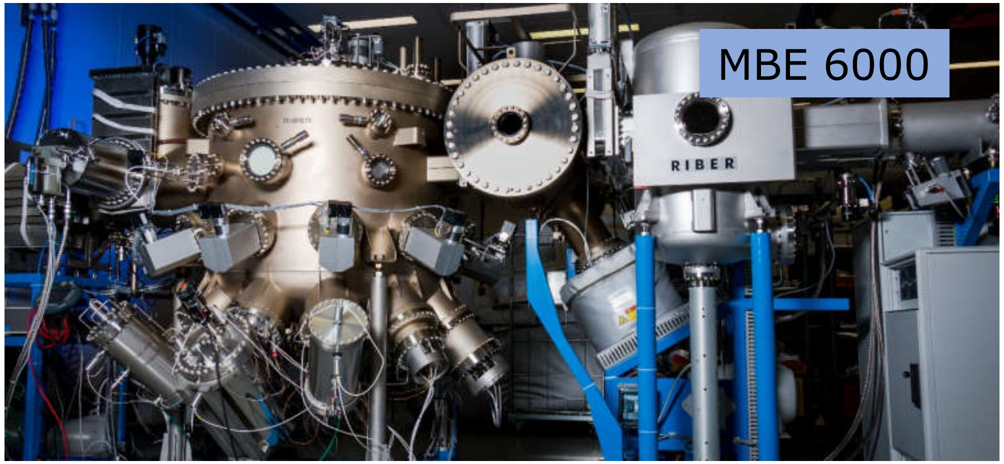
Batches of samples can be grown, which allows systematic investigations

Riber MBE production systems

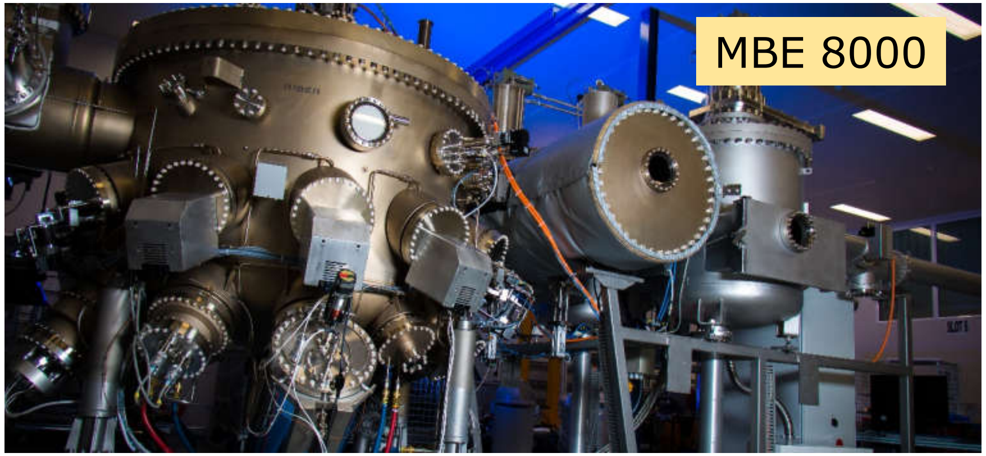


1x200mm
1x150mm
3x4’’

1x200mm
4x150mm
9x4’’



4x200mm
9x150mm
14x4’’



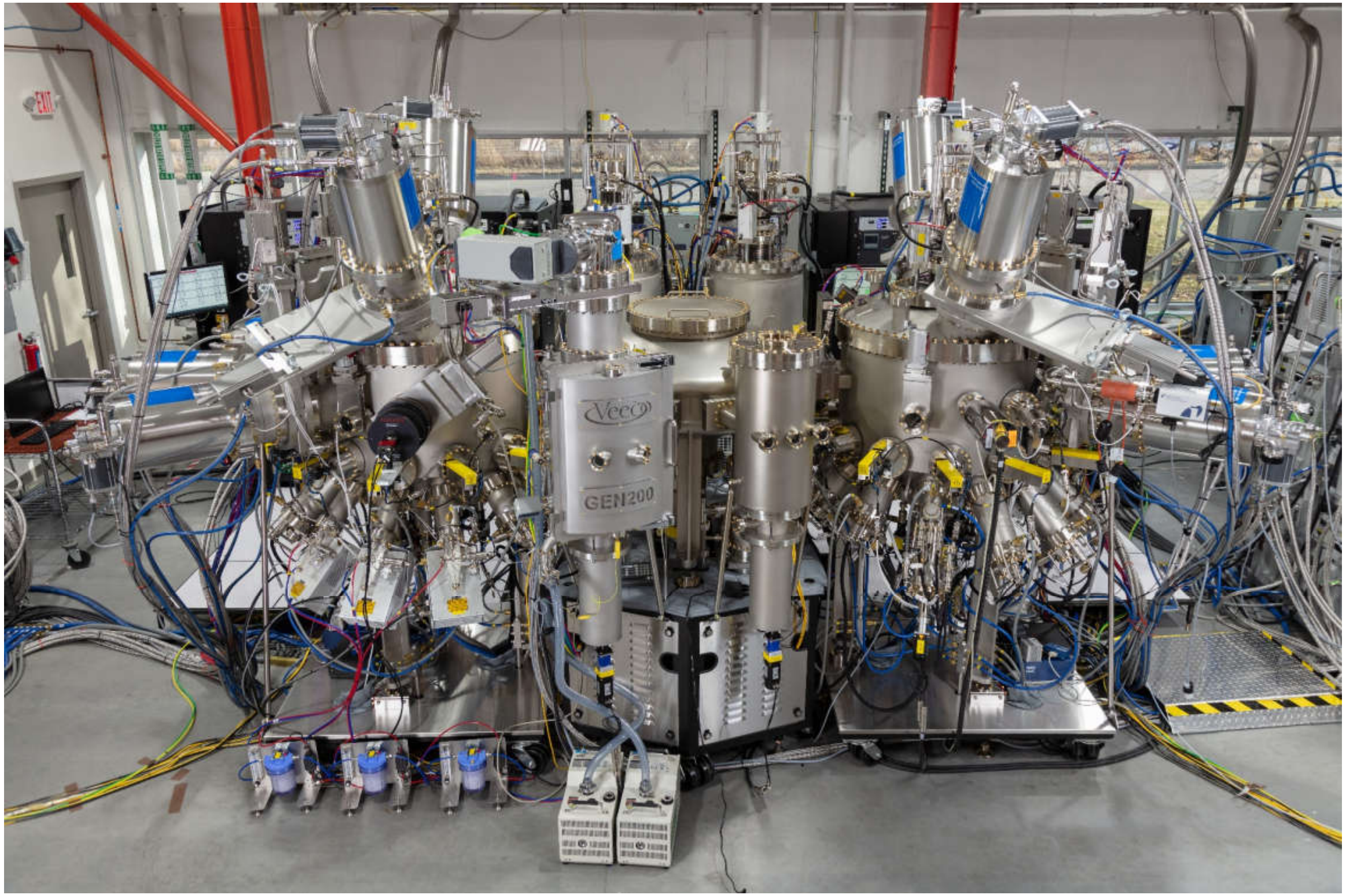
Riber MBE production systems


C21


8000

Veeco MBE production systems

Dual GEN200 system



7 x 3inch,
4 x100mm,
1x6inch,
1x200mm

Riber MBE production systems

IntelliEPI

USA MBE pure player – 100% RIBER

2x MBE 49 - 9x MBE 6000 – 1x MBE 8000

GaAs-, InP-, GaSb-based products
III-V –on-Si
Opto. Devices (APD, EEL, VCSEL, QWIP, QCL)

Chineese company

China MBE player

9x MBE 6000

HEMT, PHEMT, MHEMT, HBT

IQE

USA both MOCVD and MBE player

1x MBE 6000

7x V100 – 4x V150

NORTHROP GRUMMAN

USA MBE player

2x MBE 6000

Nitrides for microelectronics applications

rfmd
POWERED TO CONNECT

USA MBE player

1x MBE 6000

3x V100 – 3x V150

Singapore company

Singapore MBE player – 100% RIBER

6x MBE 6000

II-VI LASER ENTERPRISE

TOSHIBA
Leading Innovation

PHILIPS
Photonics

imec
embracing a better life

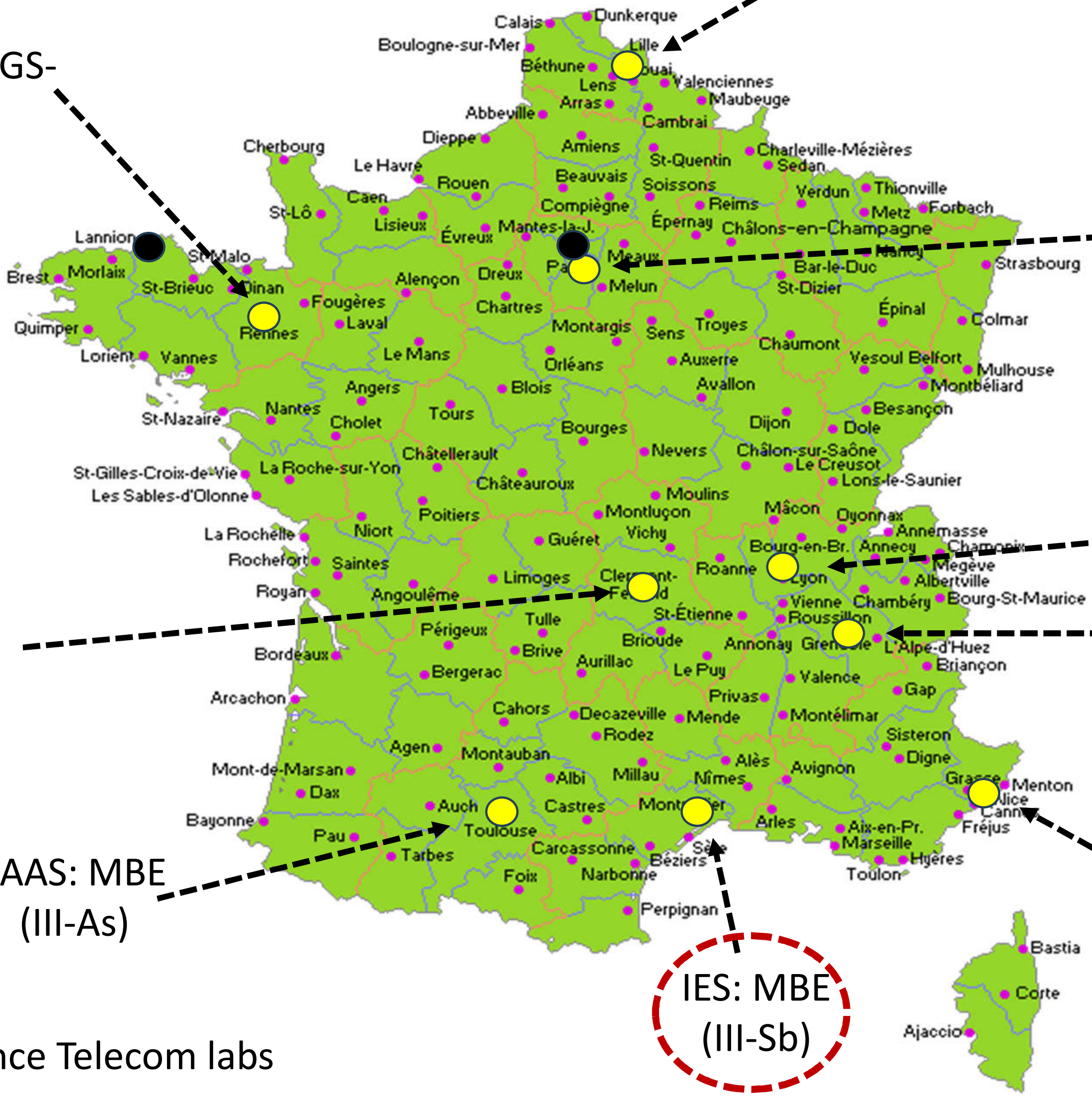
ACKEN

Raytheon

TRUMPF

And many more

III-V epitaxy in France



IEMN: MBE (III-P, III-As)

FOTON: MBE & GS-MBE (III-P)

INL: MBE (III-P)

I. Pascal: VPE (III-As, III-N)

I. Néel, CEA: MBE and MOVPE (III-N)

LAAS: MBE (III-As)

IES: MBE (III-Sb)

CRHEA: MBE and MOVPE (III-N)

● Former France Telecom labs

MBE (and MOVPE?) of III-As started at Thomson-CSF, now Thales R&T, in the mid 70's.

- Thales: VPE, MBE and MOVPE
- Alcatel, now Nokia: MOVPE and GS-MBE of III-P.
- OMMIC: MOVPE (III-As).
- ALMAE : GS-MBE (III-P).
- C2N, MBE and MOVPE : III-As, III-P, III-N.

Outline

III-V semiconductors: properties and applications

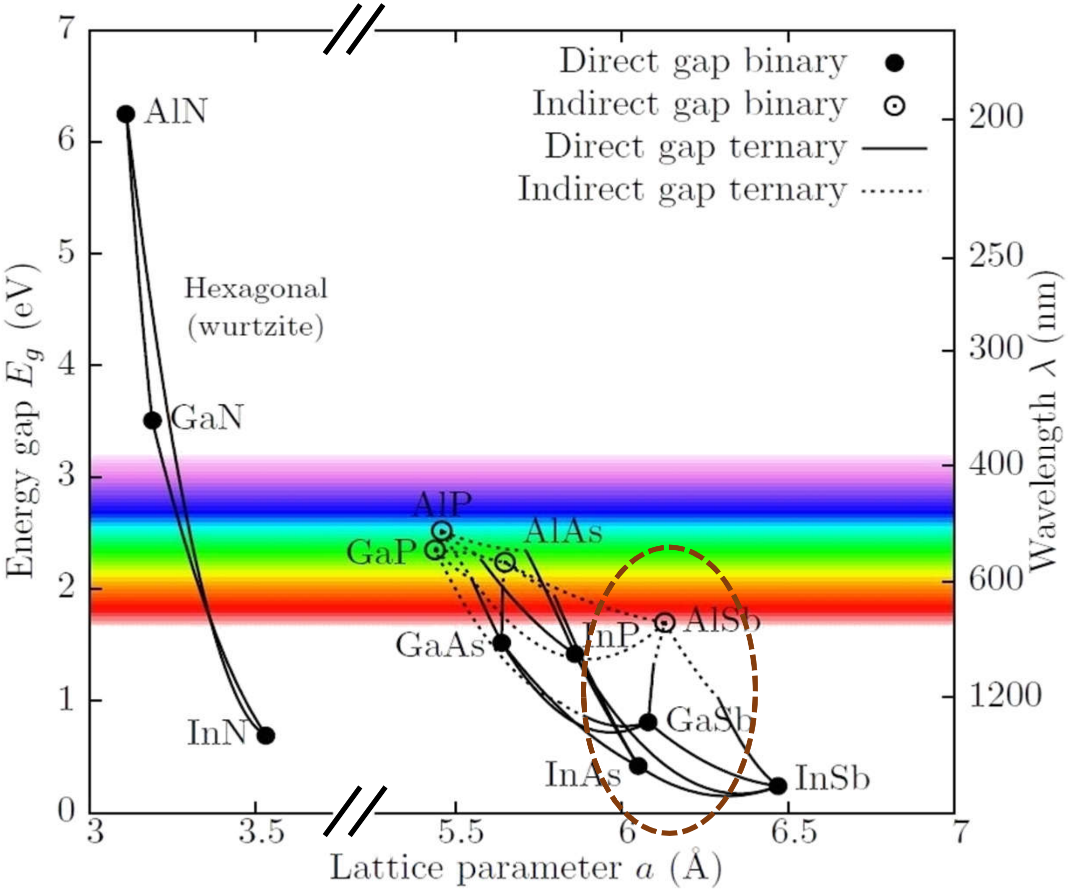
Epitaxy of III-V semiconductors: a (personal) historical view

III-Sb based semiconductors

III-Sb grown on (001) Si substrates

Summary – Perspectives

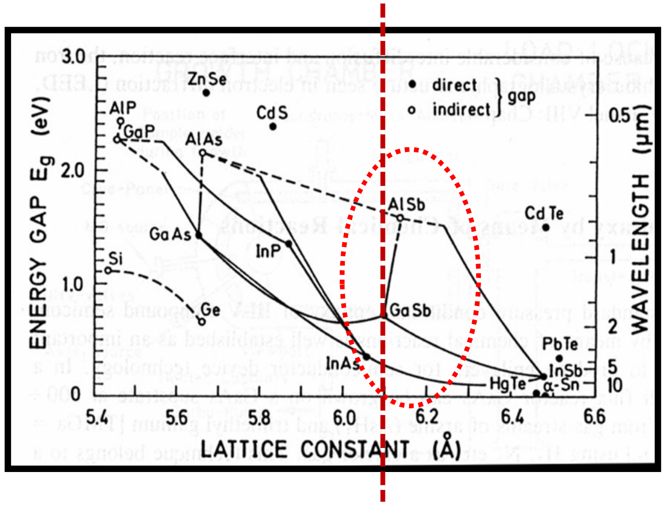
The antimonides

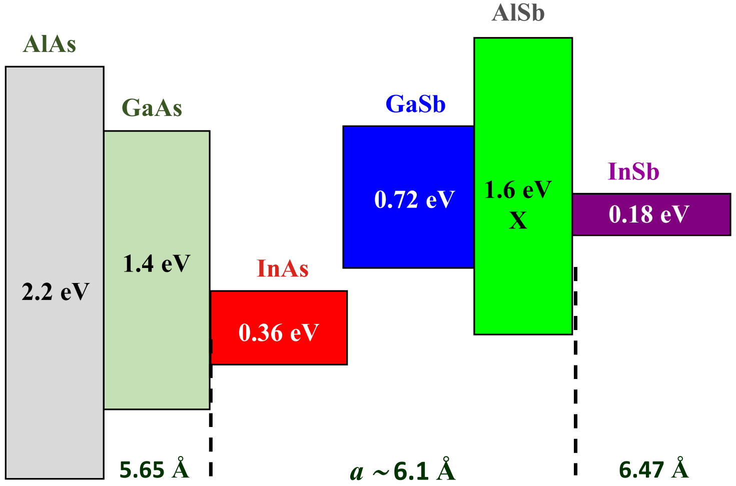


The semiconductors based on GaSb, InAs, AlSb, InSb and their alloys:
AlGaAsSb, GaInAsSb, AlGaInAsSb…
Generally grown on GaSb or InAs substrates

Sb-based materials: narrow bandgap semiconductors

The antimonides





- **Large bandgap range :**

0.1 – 1.6 eV

☞ ***Band gap engineering***

- **Various band alignments:**

Type I, Type II, Type III

- **Large band offsets:**

ΔE_c = 0 – 1.5 eV
ΔE_v = 0 – 0.5 eV

☞ ***Band offset engineering***

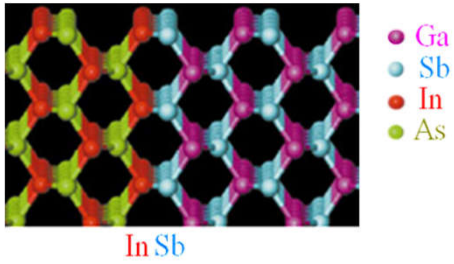
- **Large lattice parameter range:**

☞ ***Lattice matching is an issue***

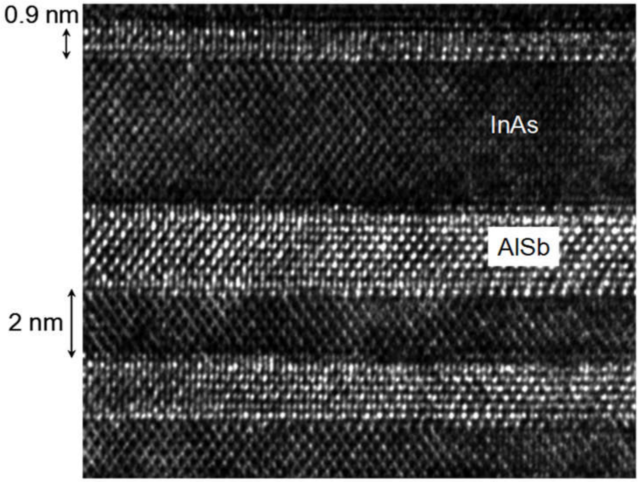
The antimonides: interfaces

Some material combinations exhibit no-common atom interfaces:

- GaSb / InAs
- AlSb / InAs

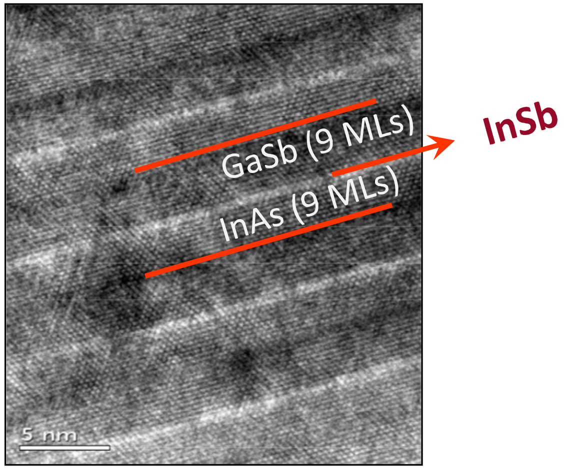


⇒ Interface engineering



TEM image : Anne Ponchet, CEMES, Toulouse

InAs/AlSb



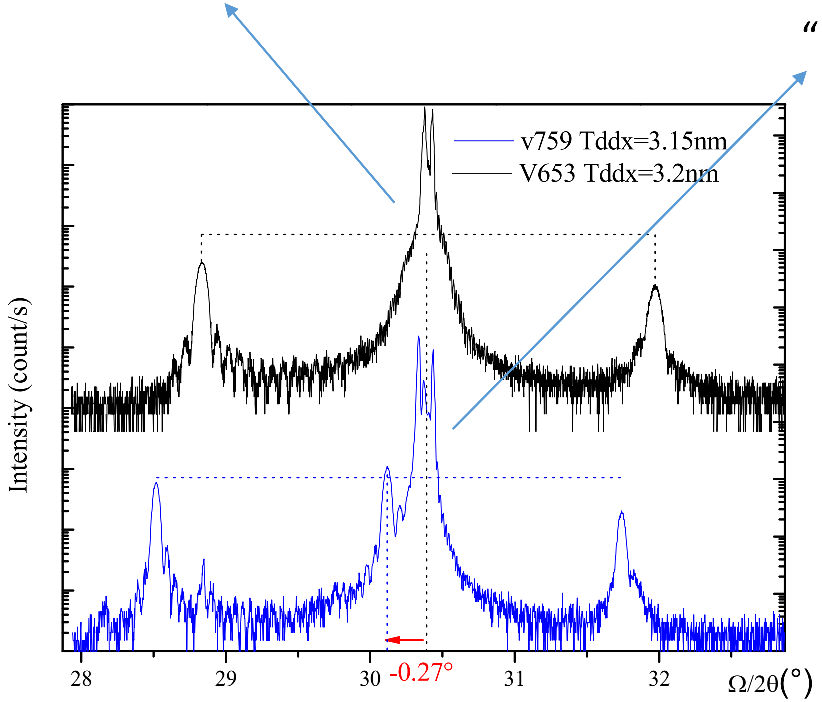
TEM: E. Luna, PDI-Berlin

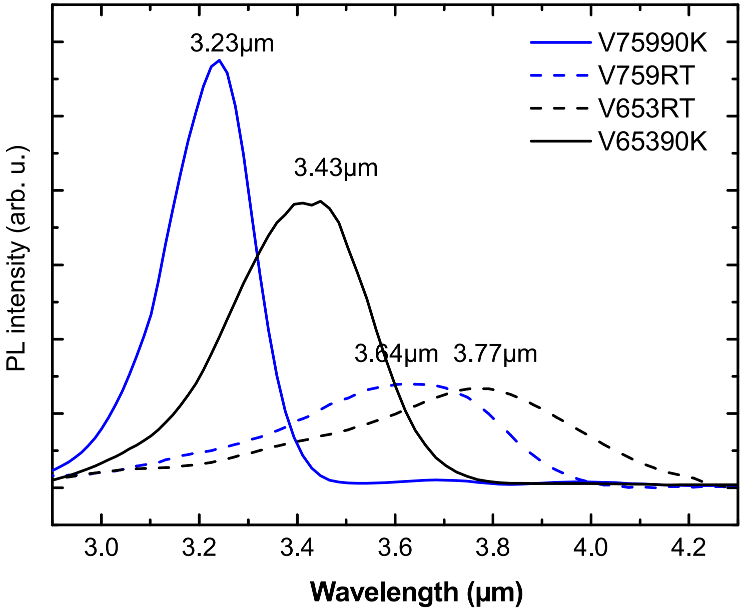
InAs/GaSb

No common atom InAs/GaSb SLs

“natural” interfaces

“InSb-like” interfaces





Interfaces matter!

- **To be taken into account when designing heterostructures**
- **A tool to adjust the lattice parameter and the electronic properties**

The antimondes: epitaxy

- III-Sb compounds and heterostructures:
    - “Low temperature” materials: T_m(InSb) = 515 °C, T_m(GaSb) = 712 °C (GaAs: 1238 °C)
        - low growth temperature : 400 °C < T_g < 520 °C
    - Unstable/metastable compounds,
    - High-Al content in many devices.

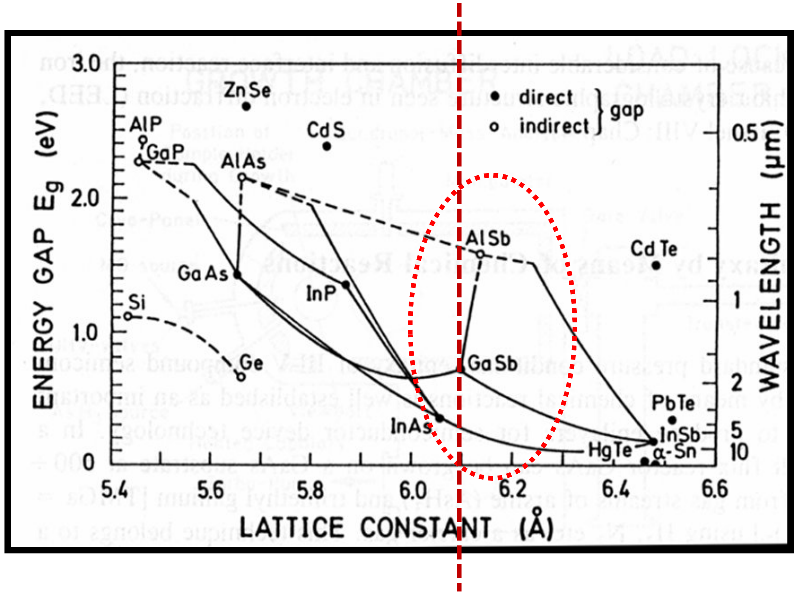
- **Molecular-beam epitaxy (MBE) is the preferred (only?) growth technique for optoelectronic devices.**
    - Lack of MOVPE developments: catching up?

- GaSb and InAs substrates:
    - **Always** conductive,
    - 2 to 4 inch, 5 inch under development,
    - Few producers of high-quality substrates: high price! (~400 €/2 inch wafer)

- Doping properties:
    - Residual GaSb always *p*-type in the 10^{16} cm^{-3} range: native defects,
    - Si = *p*-type dopant in III-Sb compounds,
    - Te = preferred *n*-type dopant,
    - Be = typical *p*-type dopant.

The antimonides

- Unrivaled band gap range ☺
- Large band offsets ☺
- Type I to type III alignments ☺
- Low effective masses ☺
- Two group-V elements ☺ 😐 ☹
- No common atom interfaces ☺ 😐 ☹
- Complex (quat-/pent-anary) alloys ☹
- Large mismatch range (-8% / +7 %) ☹
- Conductive substrates ☹



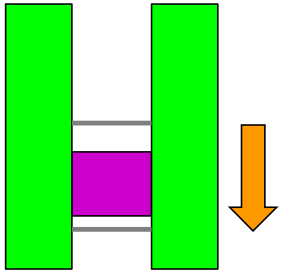
III-Sbs are well adapted to:

- high frequency, low power devices
- **opto devices operating the IR, particularly mid- and far- IR**

III-Sb-based IR devices

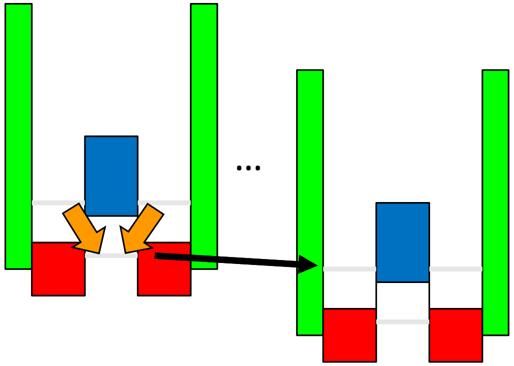
QW Lasers

GaInAsSb/AlGaAsSb



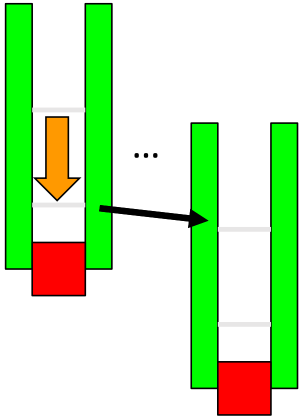
Interband Cascade Lasers

InAs/GaSb/AlSb



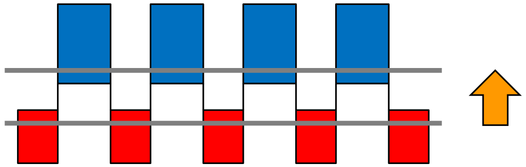
Quantum Cascade Lasers

InAs/AlSb



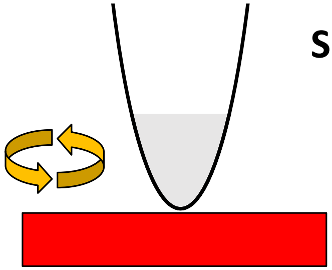
Type II SL Detectors

InAs/GaSb (or InAs/InAsSb)

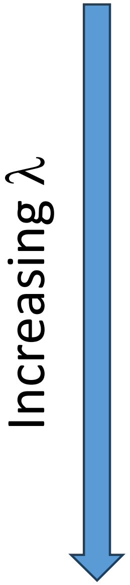


SC Plasmonics

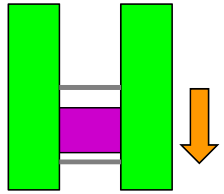
InAs(Sb)



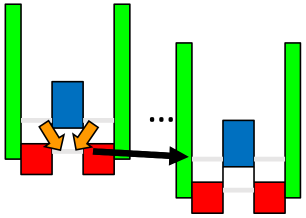
III-Sb mid-IR lasers



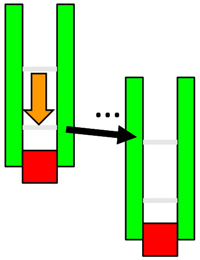
QW Laser diodes
GaInAsSb/AlGaAsSb

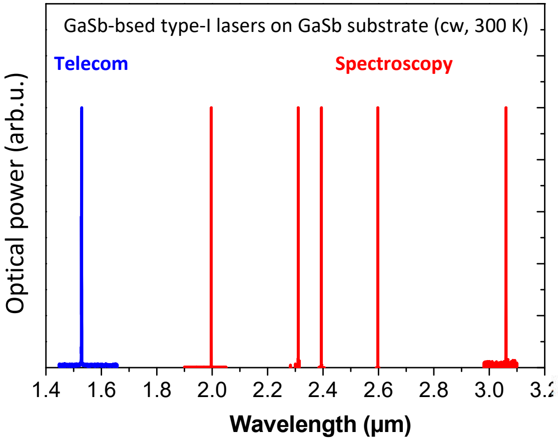


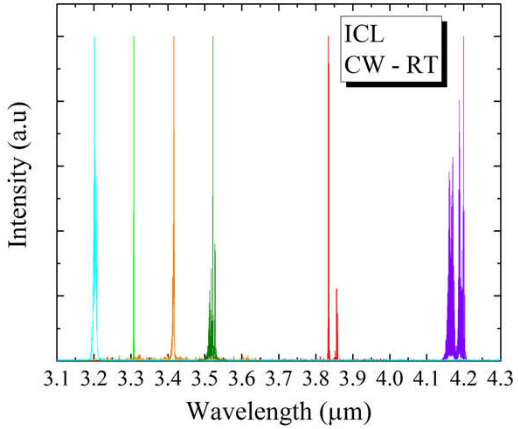
Interband Cascade Lasers
InAs/GaInSb/AlSb

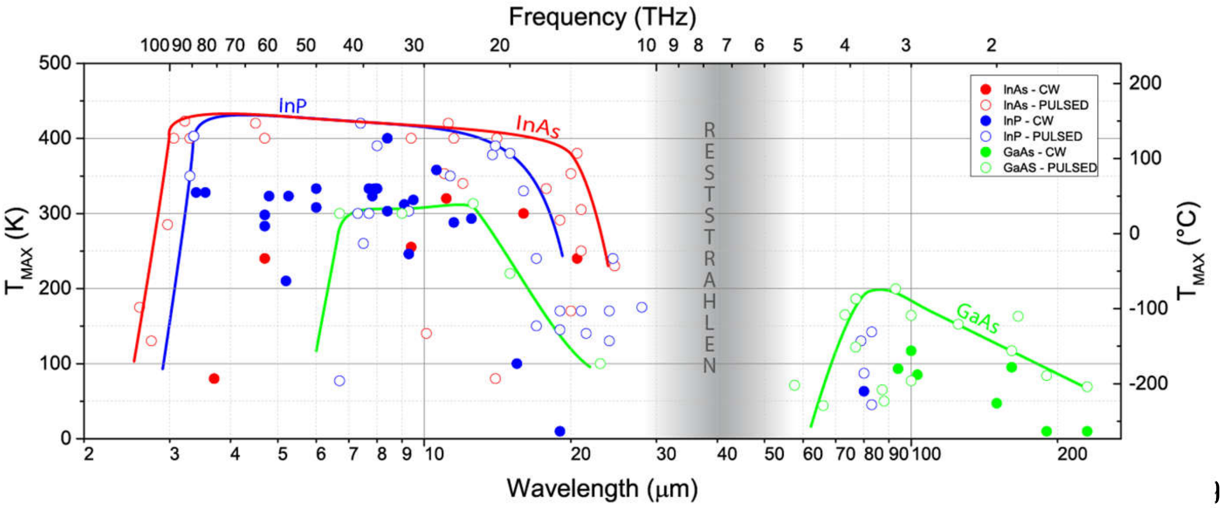


Quantum Cascade Lasers
InAs/AlSb









Outline

III-V semiconductors: properties and applications

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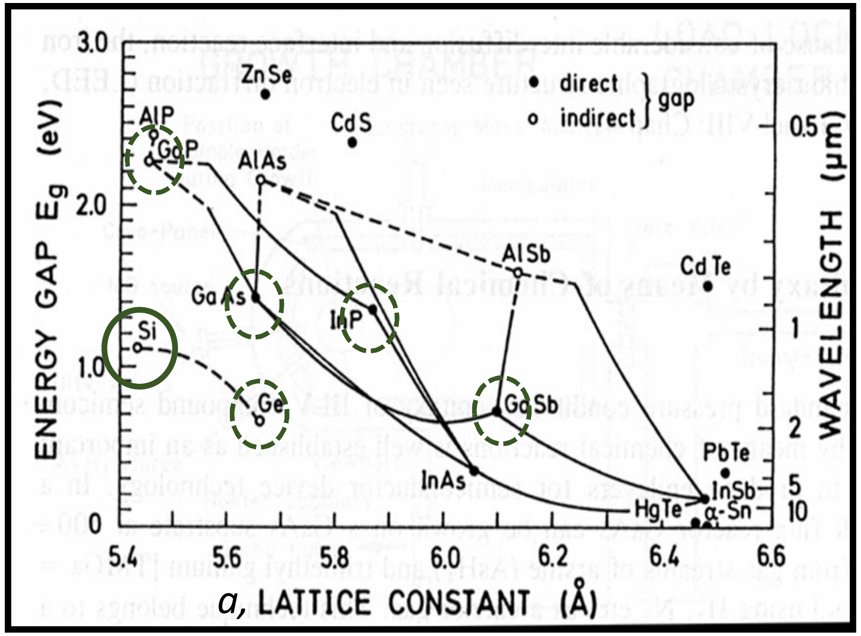
III-Sb grown on (001) Si substrates

Summary – Perspectives

III-V epitaxy on Si: issues



$$\frac{\Delta a}{a} = \frac{a_{layer} - a_{Si}}{a_{Si}}$$

$$\frac{\Delta a}{a} \sim$$

- GaP: 0.3 %
- **Ge: 4 %**
- **GaAs: 4 %**
- **InP: 7 %**
- **GaSb: 12 %**

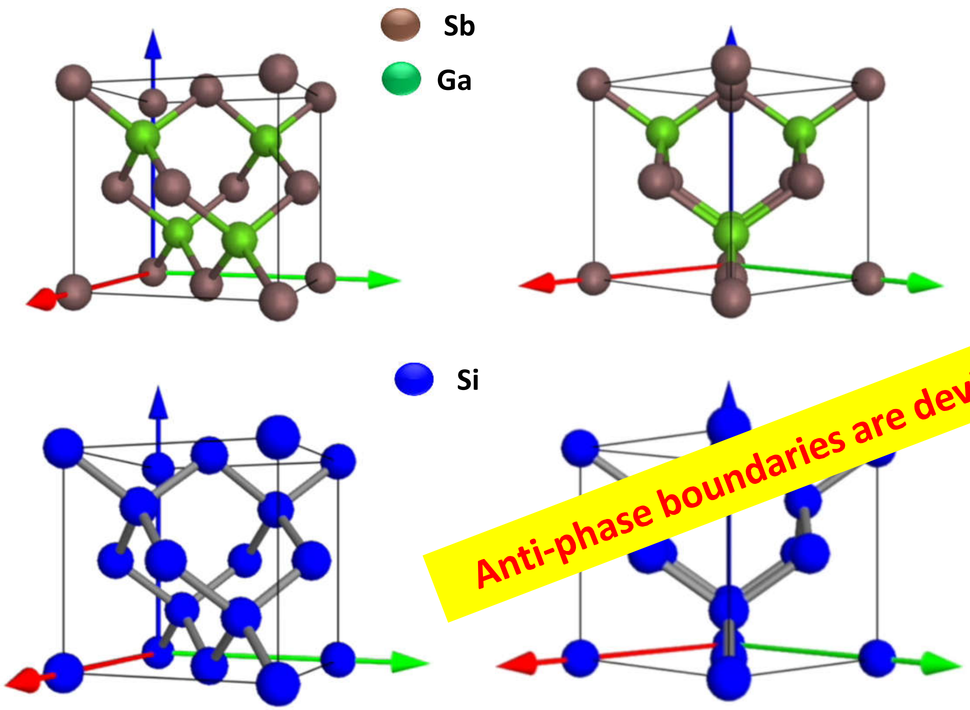
A number of mismatches:

- **Surface energies: Volmer-Weber (3D) growth mode of III-Vs on Si**
- **Lattice parameter: dislocations (cannot be avoided!)**
- **Thermal expansion coefficient: cracks (when the III-V thickness > 7 – 10 µm)**
- **Crystal structure: polar *vs* non polar: anti-phase domains and boundaries**

Epitaxy generally results in high threading-defect density

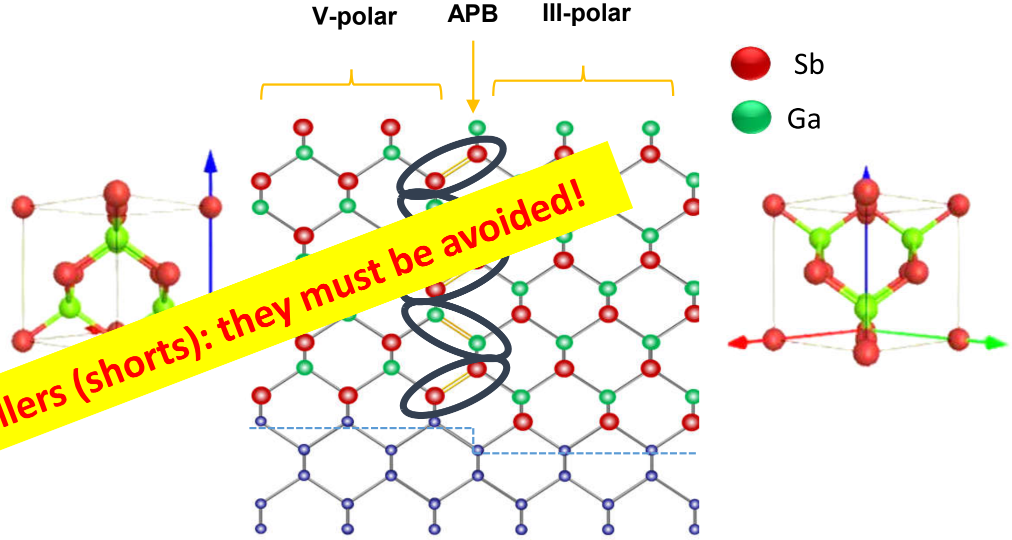
Antiphase domains and antiphase boundaries

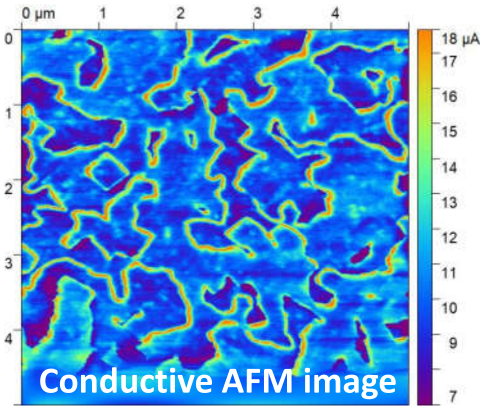
Zinc blende = polar



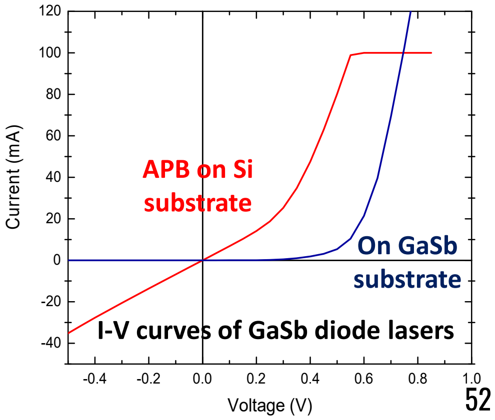
Diamond = centrosymmetric

Anti-phase boundaries are device killers (shorts): they must be avoided!





Conductive AFM image



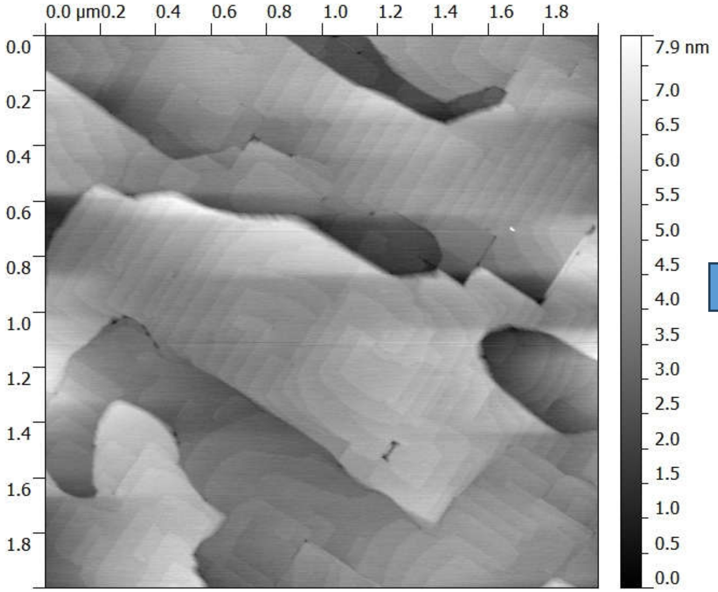
I-V curves of GaSb diode lasers

GaSb on Si

Key to eliminate APBs in III-Vs grown on on-axis group-IV substrates:
Substrate surface organization with parallel steps

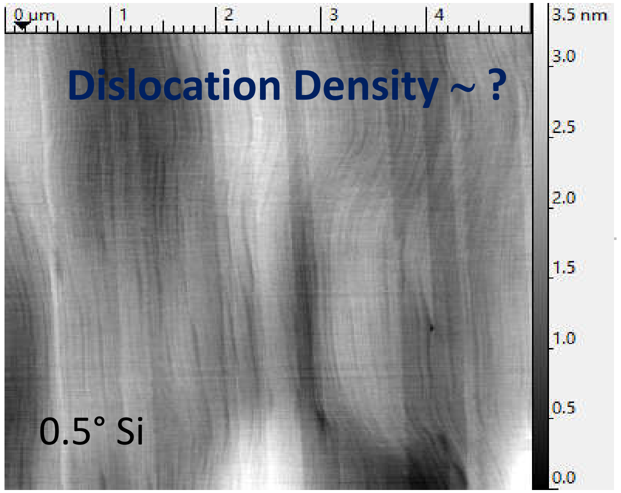
III-V growth anisotropy: the antiphase domain is buried by the main domain

See Charles Cornet, tomorrow, 10h45



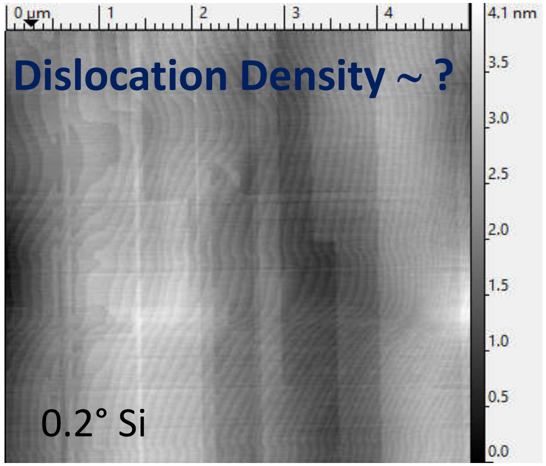
Early GaSb on Si layer

10 years



Dislocation Density ~ ?

0.5° Si



Dislocation Density ~ ?

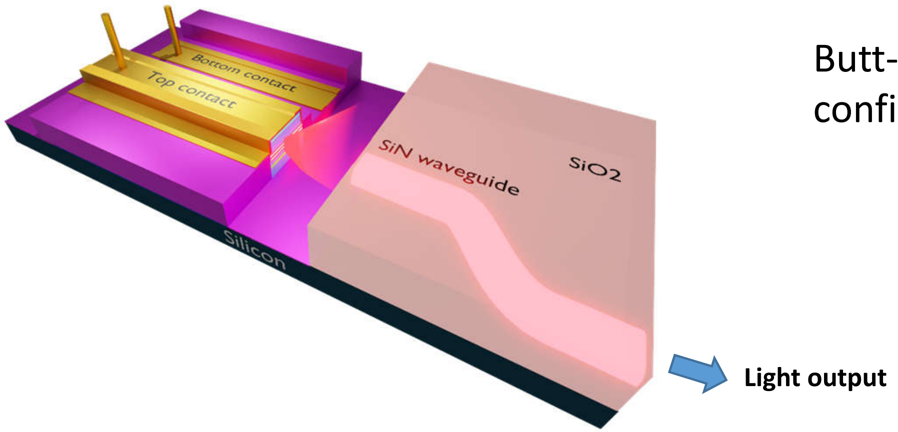
0.2° Si

Dislocations **cannot be avoided**, but their threading density can be reduced

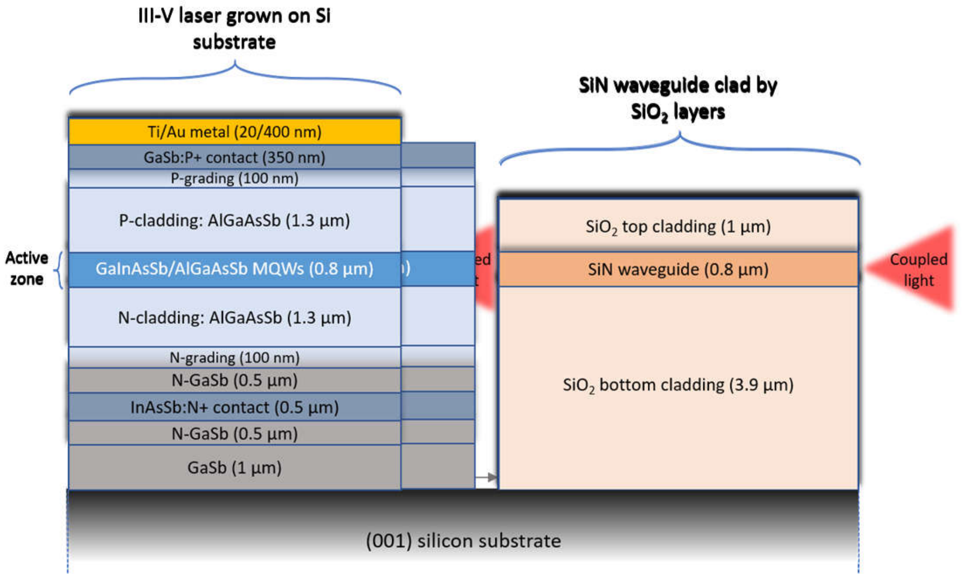
See J.-B. Rodriguez, today, 11h50 ; A. Gilbert, tomorrow, 11h30

On going collaboration with:

Integration on a Si photonic circuit



Butt-coupling configuration

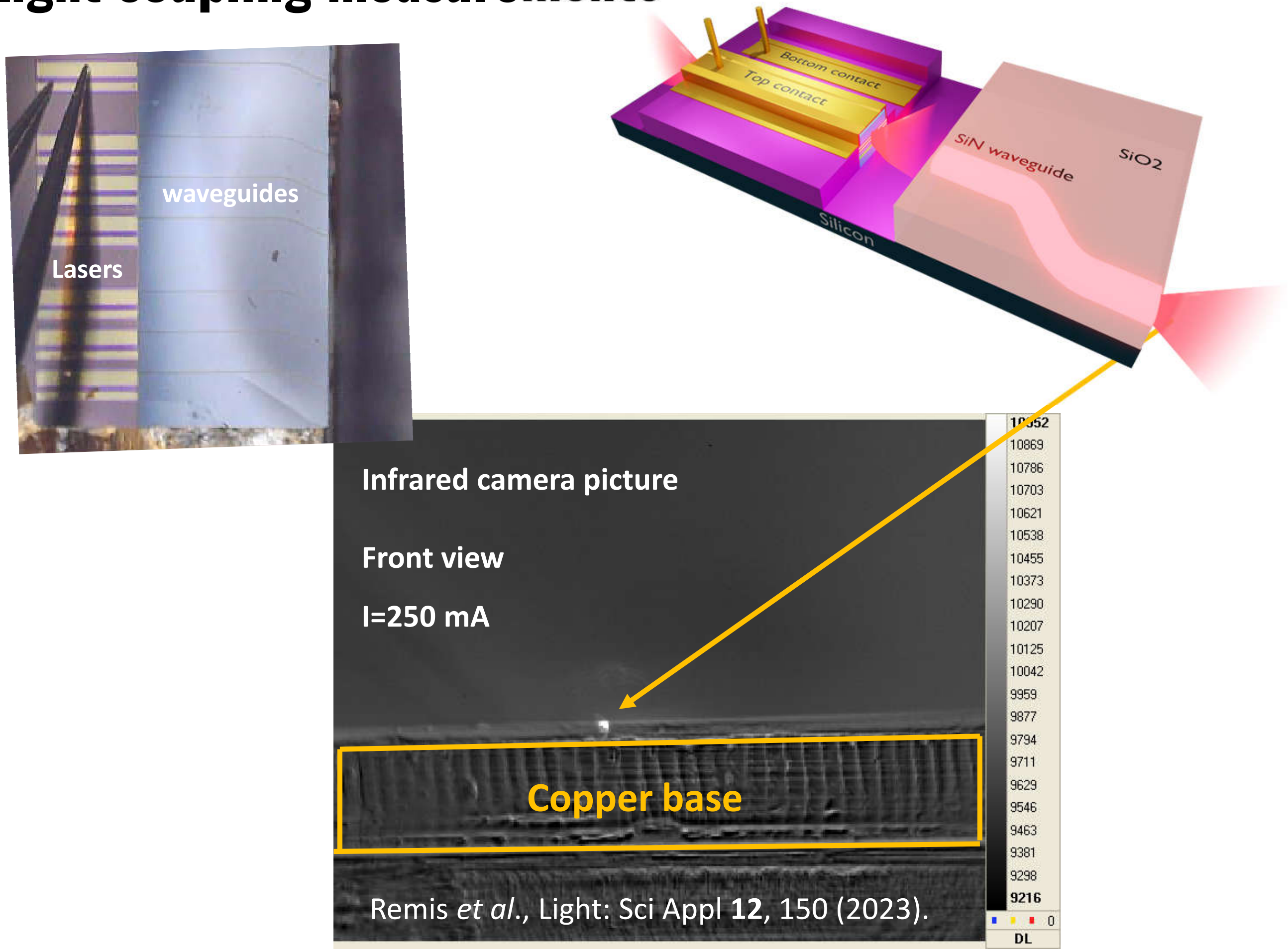


Integrated sensors need photonic integrated circuits: preliminary step = laser on patterned Si wafers + passive waveguides

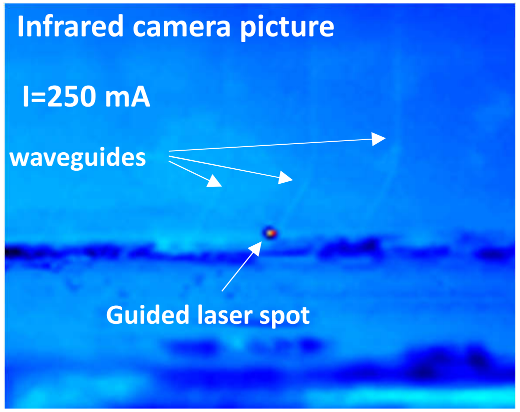
CHALLENGES:

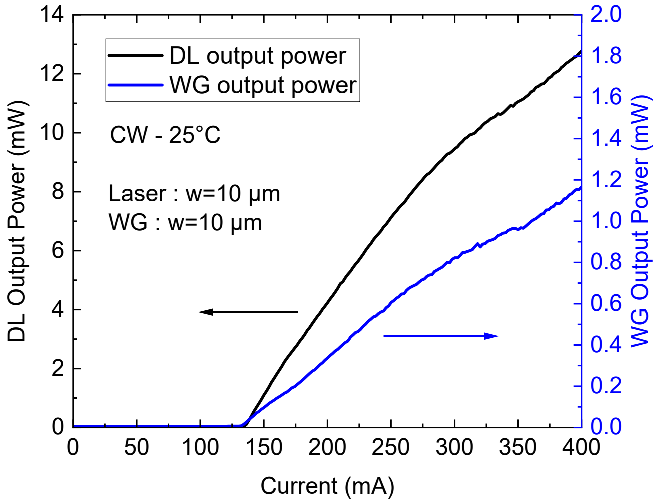
- Processing Si photonic platform without damaging the Si substrate
- Epitaxial growth on a patterned Si platform
- Etched-facet mirrors of the laser: smooth (to preserve laser performance) and vertical (to promote light coupling)
- Complex laser integration process : air gap between laser and waveguide unavoidable + WGs should be carefully protected
- Divergence of the laser emission 60°

Light coupling measurements



Remis *et al.*, Light: Sci Appl **12**, 150 (2023).





- ➢ Coupling efficiency of ~10%
- ➢ Insertion losses of 10 dB

Light transmitted through the waveguide!

ICLs and QCLs perform similarly to their native counterpart: tolerant to dislocations (see Maëva Fagot, Friday, 9h15)

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Epitaxy of III-V semiconductors

- ~50 years of development.
- MOVPE and MBE mature for production (for some materials).
- Large activity in France, inc. in the industry.

- New research activity toward the hybridation of different technologies :
  - III-V and Si(Ge)
  - III-V and II-VI
  - III-V and metals?
  - III-V and oxydes?

III-Sb MBE at U. Montpellier

Jean-Baptiste RODRIGUEZ
CNRS

Laurent CERUTTI
U. Montpellier

+ many PhD students!!
Currently:
- **Audrey Gilbert**
- **Maëva Fagot**
- **Milan Silvestre**

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Thank you!!