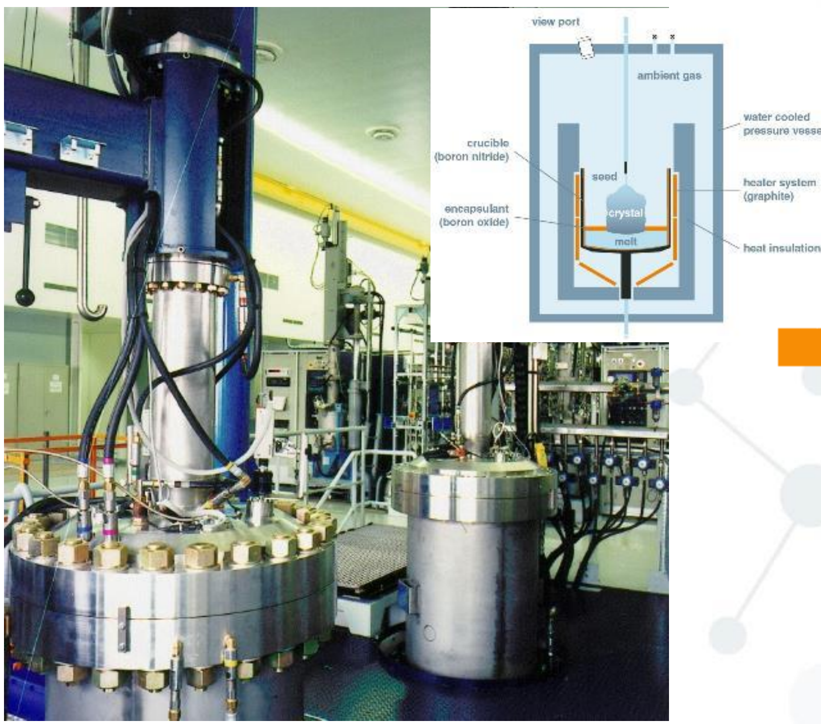
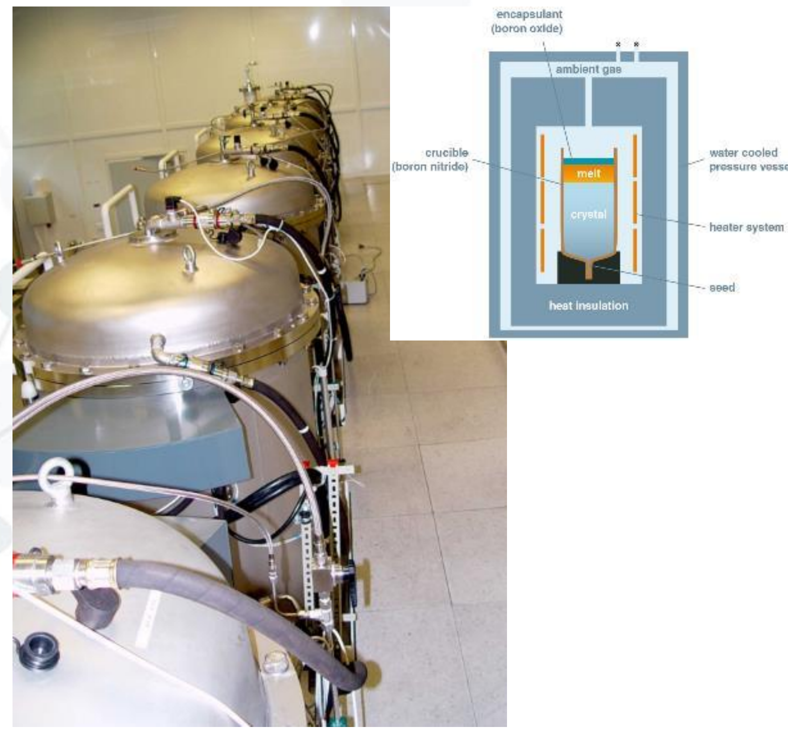
History of Freiberger Compound Material GmbH
Transformation of Technologies



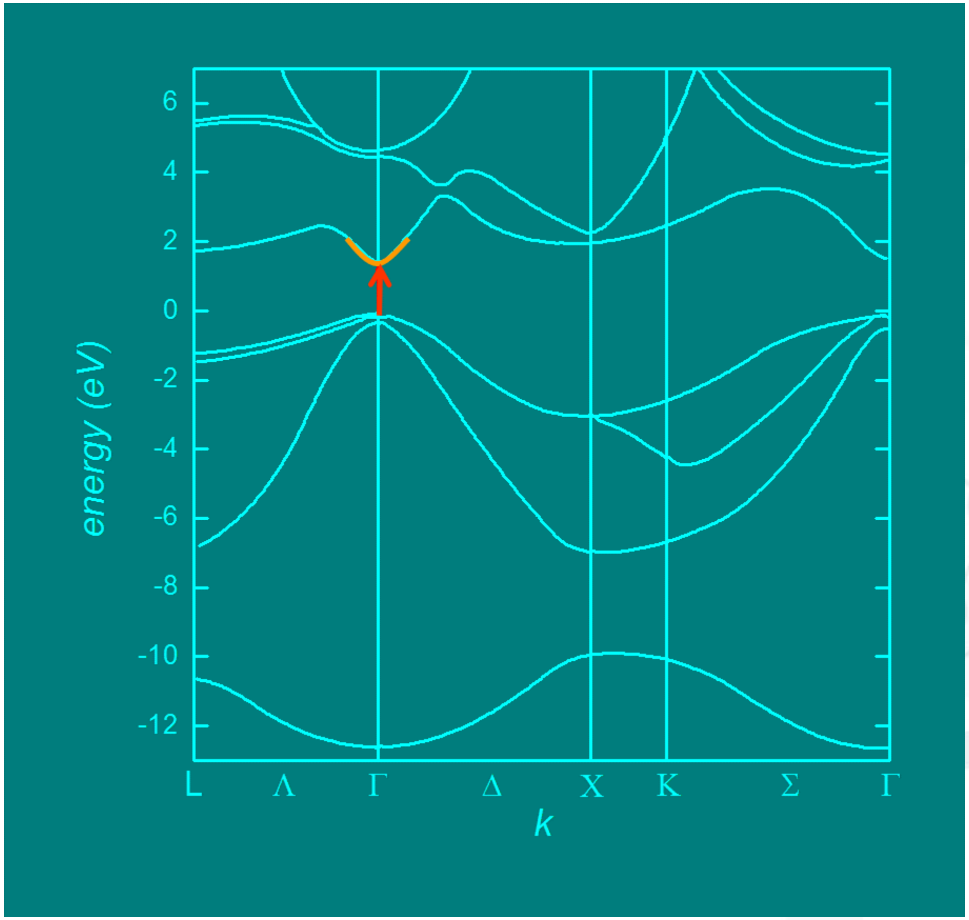


FCM Product Portfolio GaAs

LEC Liquid Encapsulated Czochralski		VGF Vertical Gradient Freeze		
				
Semi-insulating	Semi-conducting	Semi-insulating	Semi-conducting	
C	Te	C	Si	Zn
3" 4" 6"	3" 4"	3" 4" 6" 8"	3" 4" 6" 8"	4" 6"

FCM Core Products

Properties of GaAs



direct gap at Γ-point

gap energy 1.424 eV

high bending of conduction band

small effective electron mass

($m_{e\Gamma}$ = 0.063 m_0)

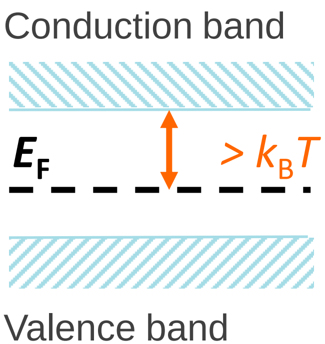
high electron mobility

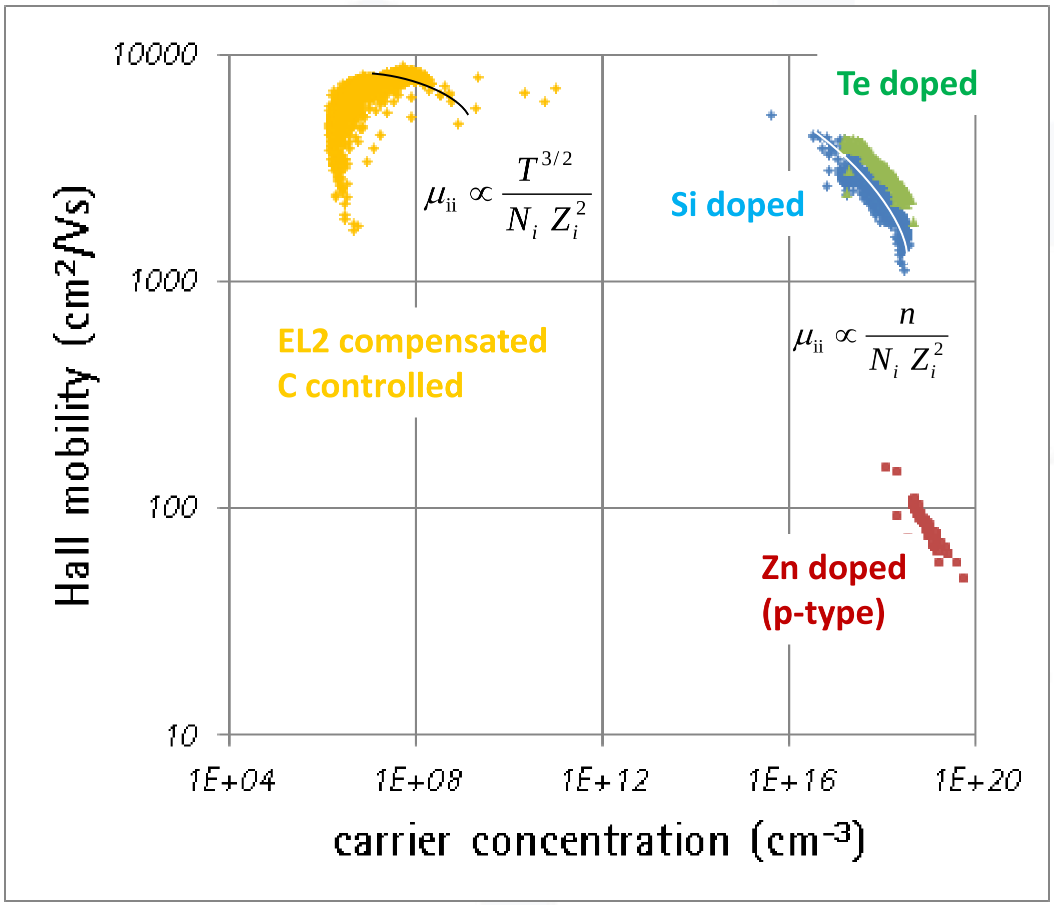
Intrinsic Semi-insulating due to EL2

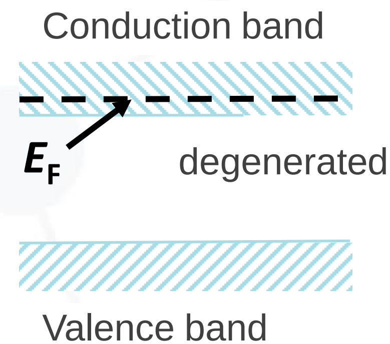
Using for:

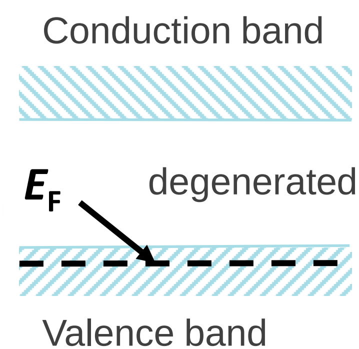
Microelectronic (SI)
Optoelectronic (SC)

Doping of GaAs





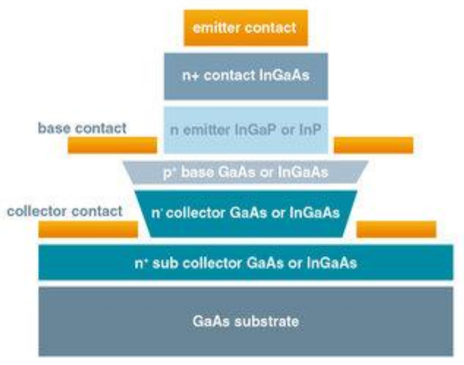




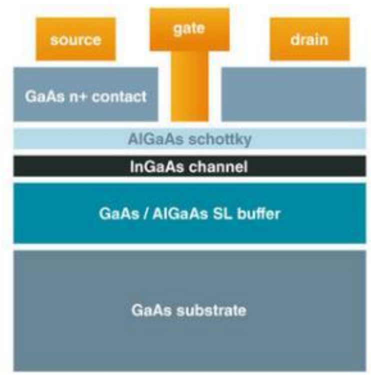
Products of our Customers (GaAs)

Wireless Devices

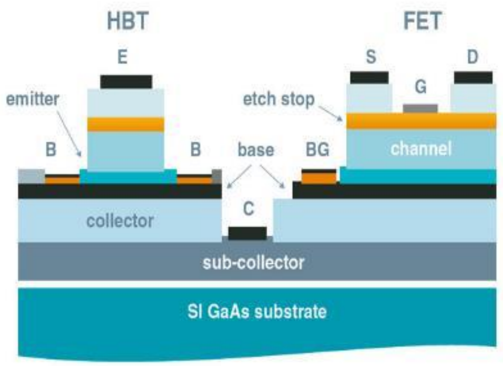
HB-Transistors



pHEM-Transistors

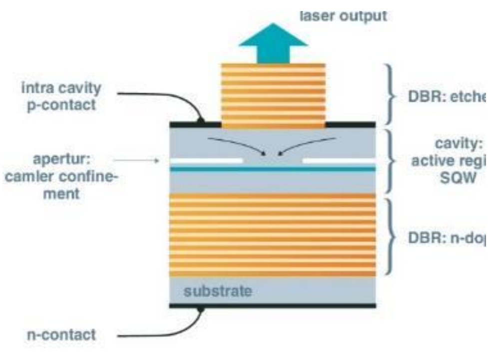


BIFE-Transistors

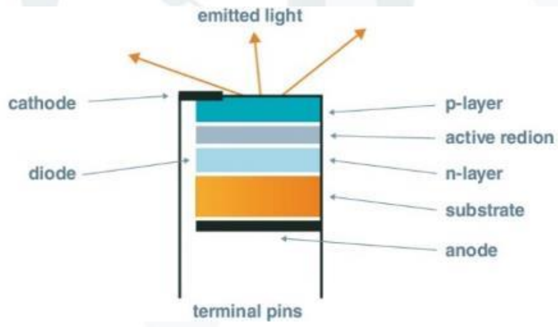


Opto-Electronics

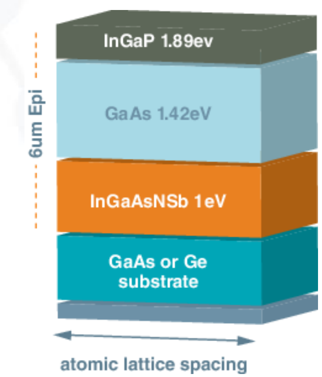
LASER



LED



PV



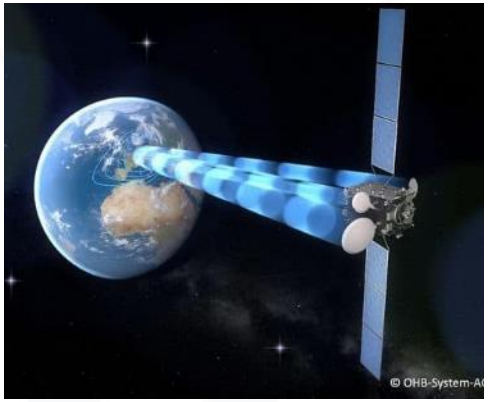
GaAs Enables Future Technologies

Wireless Devices

Handy-Verstärker

WiFi

Defense and Space



Opto-Electronics

LASER



µLED Displays

LED

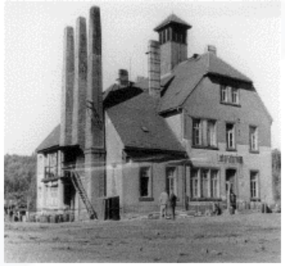

Organization Structure

Freiberger Compound Materials GmbH

- **CEO Dr. Michael Harz**
  - Controlling & Finance
  - Human Resources
  - Manufacturing
  - Production Logistics
  - Sales & Application
  - Supply Chain
- **CTO Dr. Stefan Eichler**
  - Technology GaAs
  - Technical Service
  - Project Mngmt & IP
  - GaN Development
  - InP Crystal Growth
  - Quality Management
  - Information Technology
  - Product Management

Brief History of Freiberger Compound Materials

1957 Founded as a state-owned enterprise for the development of high-purity and semi-conducting materials
1981 Start of GaAs wafer production
1992 Technology merger Wacker Chemitronic-FEW
1995 Acquisition by Federmann Enterprises, Ltd.
1996 Start of GaAs wafer production Fab I
2001 Capacity expansion and opening of Fab II
2005 Start of VGF production
2011 Construction of power cogeneration plant
2015 15 million Euros investment into Fab II extension
2018 Acquisition of FAB III (Expansion GaAs Crystallization)
2020 Acquisition of FAB IV (Production Floor InP)
2021 Acquisition of FAB V (GaAs Expansion)



III-V Production Area 1970 - 1990

Production Area 1991 – 1997

Grundsteinlegung, Bau und Einweihung 1995 -1997

Freiberger
Compound Materials

Production Area of FCM since 1997

FCM today

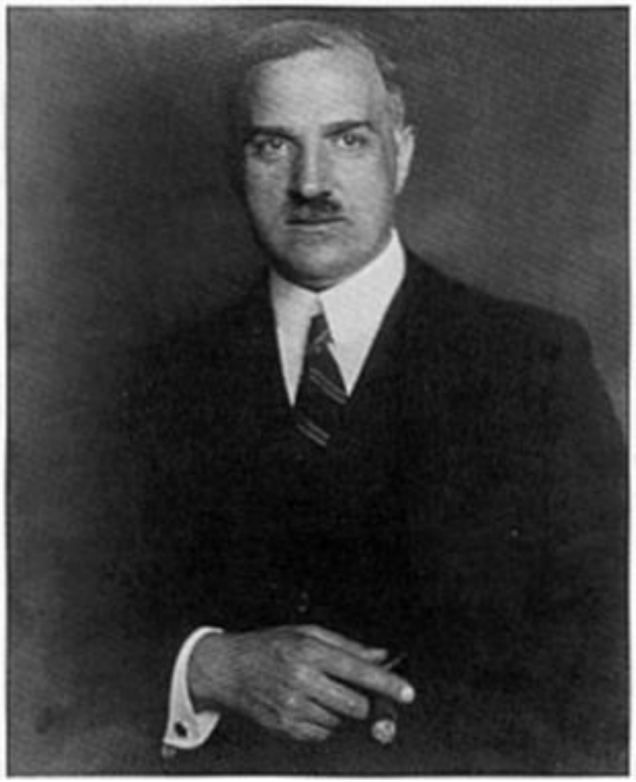
Freiberger Compound Materials GmbH with its 4 fabs is located in the south industrial park in Freiberg.

Technological Flow

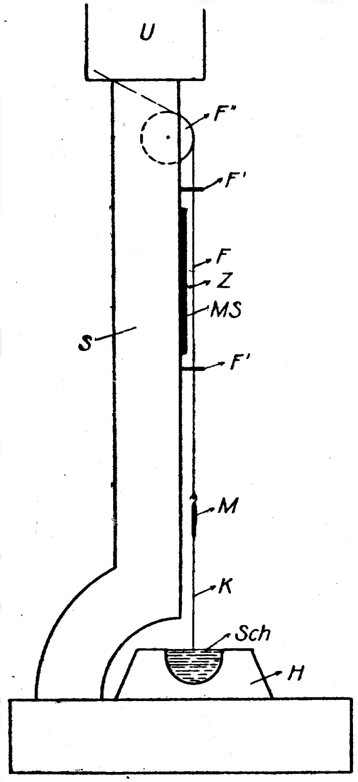
Data tracking and logistics is supported by modern MES according ISO 9001.

Make perfect wafers

Czochralski Growth (1917)



Prof. Jan Czochralski (1929)



Z. Phys. Chem 92 (1918) 219

Idea (1951) and proof (1953): Welker

Über neue halbleitende Verbindungen II

Von H. Welker

Aus dem Forschungs-Laboratorium der Siemens-Schuckertwerke, Erlangen

(Z. Naturforschg. 8a, 248—251 [1953]; eingegangen am 28. Februar 1953)

Die vorliegende Arbeit bringt Leitfähigkeitsmessungen an verschiedenen Proben der kristallinen Verbindungen InSb, GaSb und AlSb als Funktion der Temperatur. Es werden die Breiten der verbotenen Zonen ermittelt. Ferner werden Gleichrichterkennlinien von AlSb, GaSb, GaAs, InP und Transistorkennlinien von InP mitgeteilt.

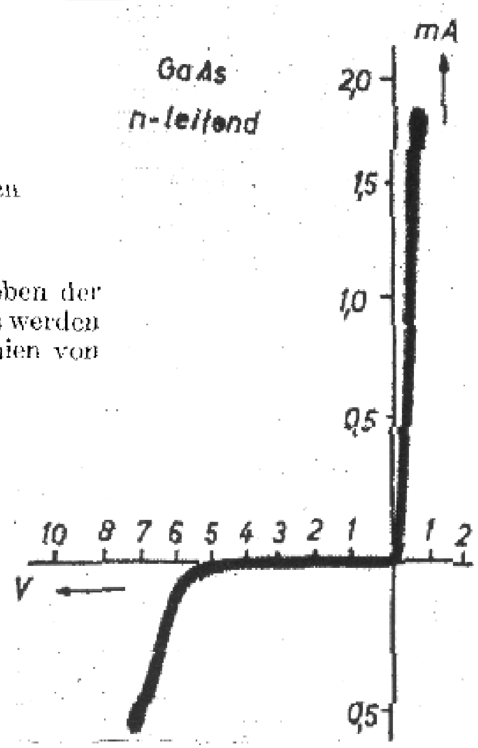


Abb. 6. Gleichrichterkennlinie eines n-leitenden GaAs Kristalls mit Spitzenkontakt.

Pretzfeld!

First GaAs single crystals: Gremmelmaier (1956)

Herstellung von InAs- und GaAs-Einkristallen

Von R. Gremmelmaier

Forschungslaboratorium der Siemens-Schuckertwerke AG., Erlangen

(Z. Naturforschg. 11 a, 511—513 [1956]; eingeg. am 27. Dezember 1955)

Herrn Professor Trendelenburg *zum 60. Geburtstag gewidmet*

Die Eigenschaften der Halbleiter hängen sehr stark von Störungen des Kristallgitters ab. Man strebt daher danach, die Halbleiter in der Form möglichst ungestörter Einkristalle herzustellen. Für diesen Zweck hat sich das Verfahren von Czochralski [1] sehr bewährt. Der

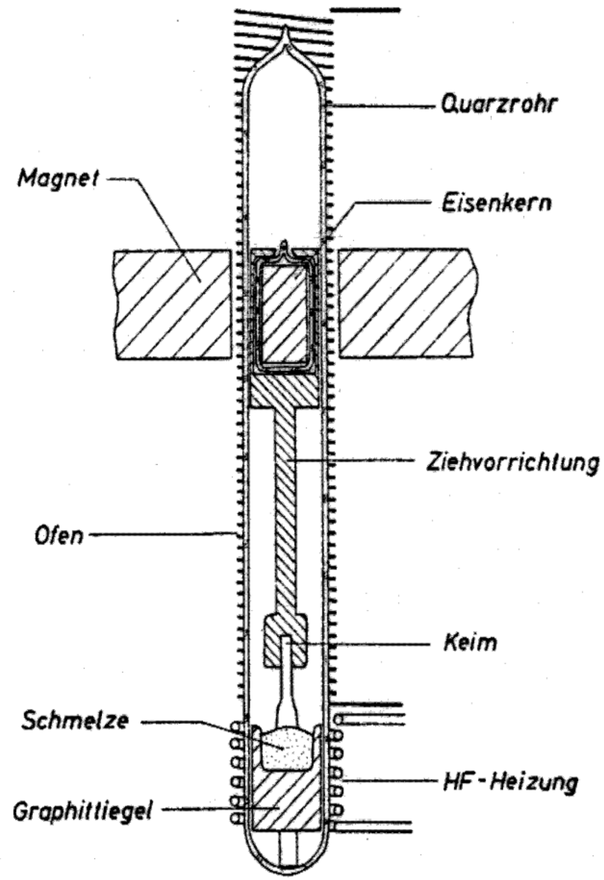


Abb. 1. Apparatur in schematischer Darstellung.

Liquid Encapsulated Czochralski (LEC):
Mullin, Straughan, Brickell (1964)

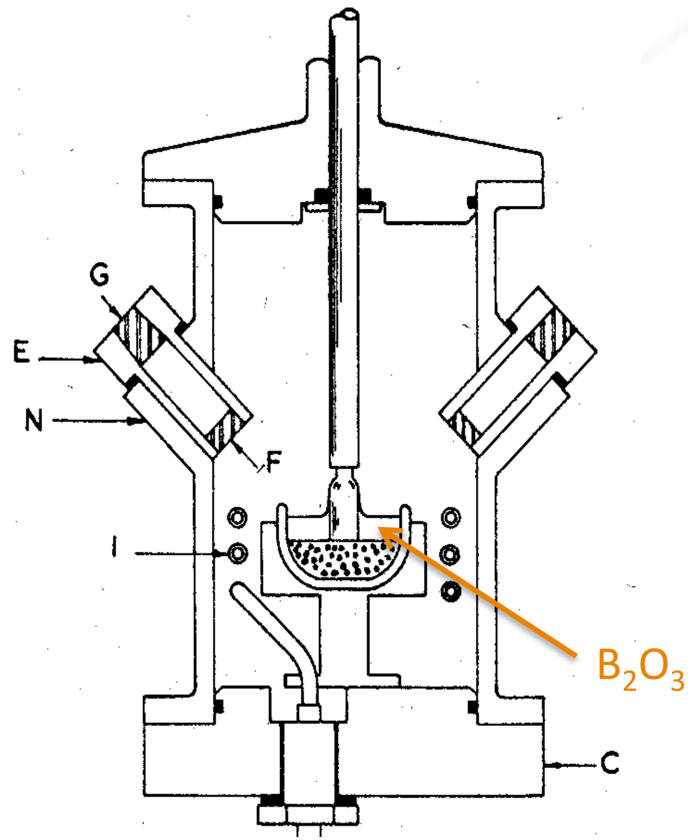
Freiberger
Compound Materials

J. Phys. Chem. Solids Vol. 26, pp. 782–784

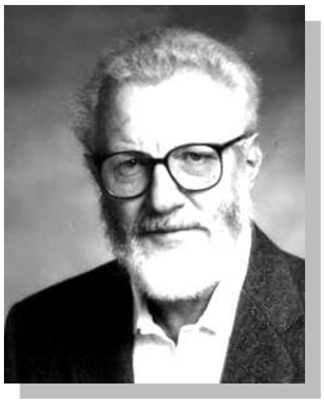
Liquid Encapsulation Techniques: The use of an inert liquid in suppressing dissociation during the melt-growth of InAs and GaAs crystals

(*Received* 23 *November* 1964)

WE REPORT here the results of the application of a technique, which we call a Liquid Encapsulation Technique, to the melt-growth of high purity InAs and GaAs crystals. Further, we consider briefly some of the implications and novel potential advantages of Liquid Encapsulation Techniques in the growth of high purity materials generally. The principle involved in Liquid En-



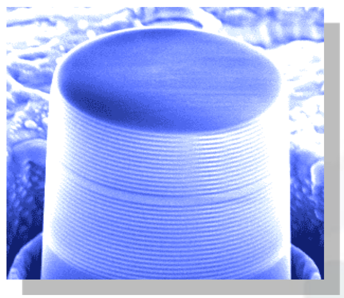
III-V Heterostructures (1957-1966)



Herbert Kroemer

Zhores I. Alferov

Nobel Prize
in Physics
2000

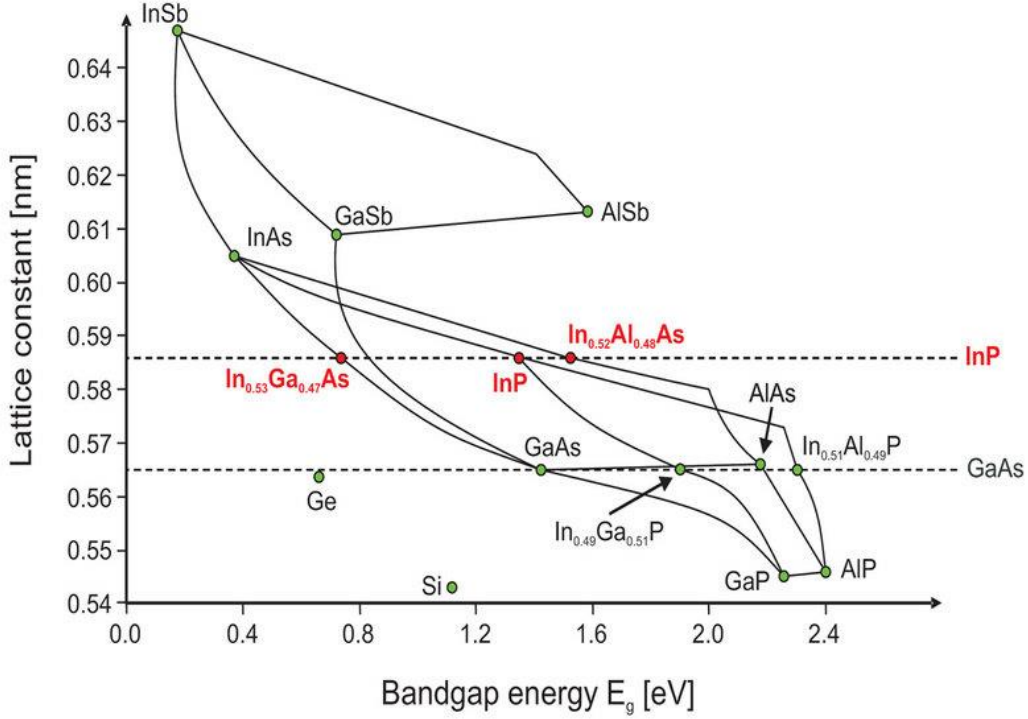


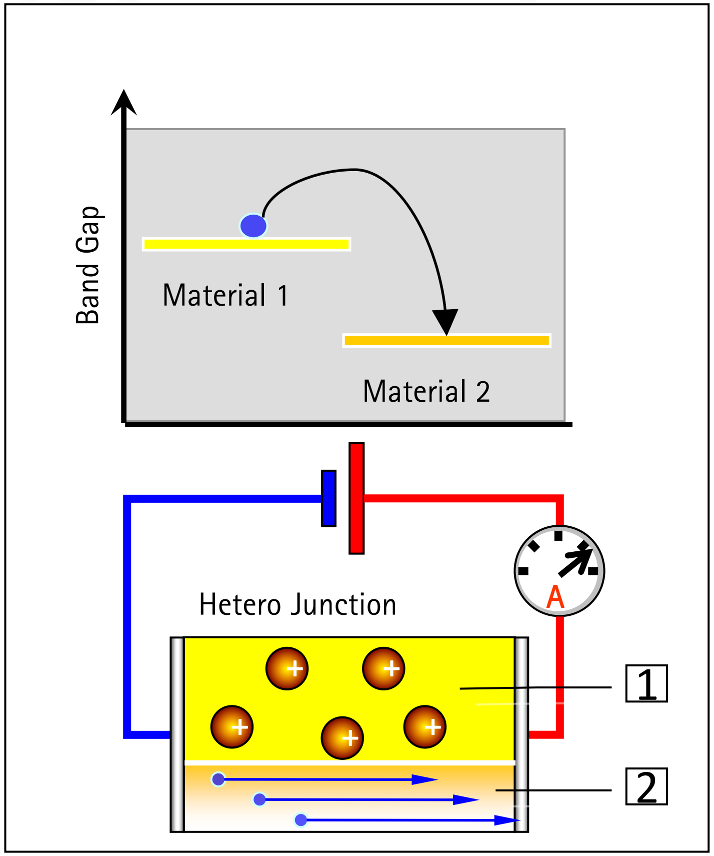
"For developing semiconductor heterostructures used in ***high-speed- and opto-electronics*** *…"*

III-V Compounds

	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg	Tl	Pb	Bi	Po

III-V Heterostructures





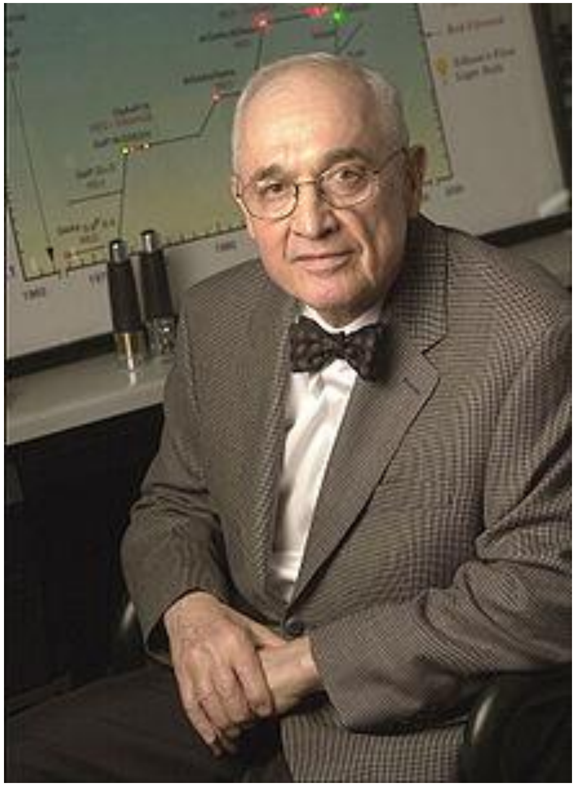
Concepts for opto-electronics (1962)

Volume 1, Number 4 APPLIED PHYSICS LETTERS 1 December 1962

COHERENT (VISIBLE) LIGHT EMISSION FROM $Ga(As_{1-x}P_x)$ JUNCTIONS*

Nick Holonyak, Jr. and S. F. Bevacqua
Advanced Semiconductor Laboratory
Semiconductor Products Department
General Electric Company, Syracuse, N. Y.

(Received October 17, 1962)



Nick Holonyak

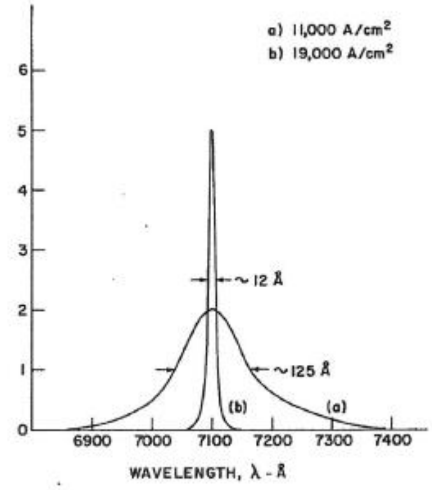
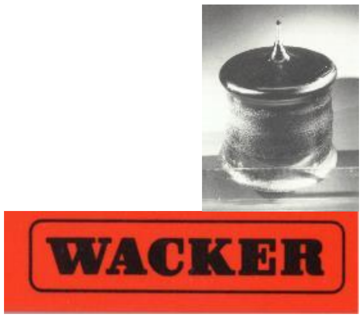
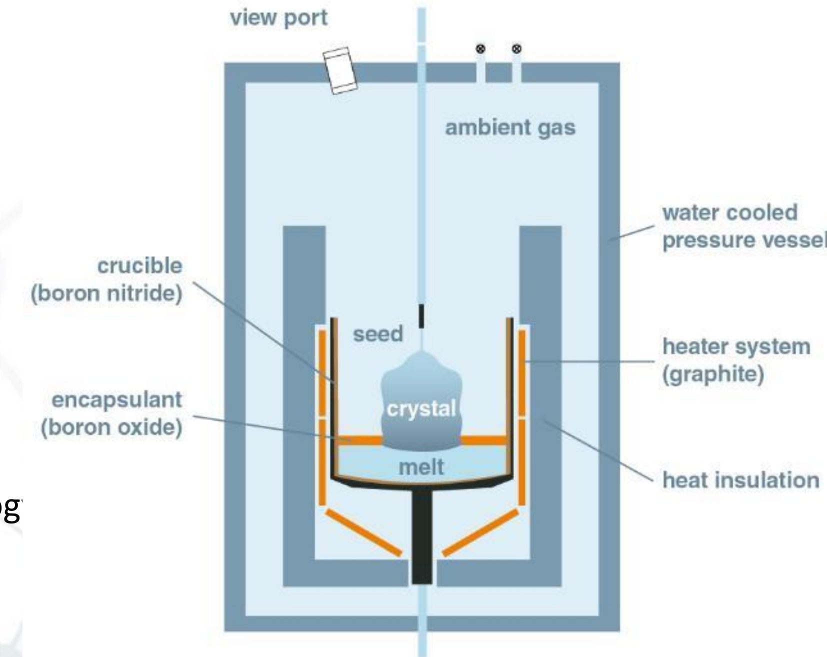


Fig. 1. Spectral distribution of $Ga(As_{1-x}P_x)$ diode 28A at 77°K. (a) Below threshold (11,000 A/cm^2) and (b) above threshold (19,000 A/cm^2). Different vertical scales.

LEC-Growth at Freiberger

Freiberger
Compound Materials

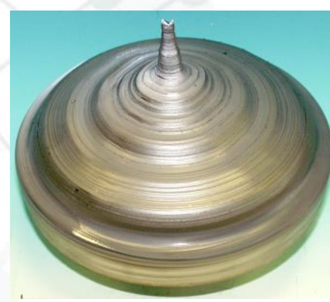




LEC: Liquid Encapsulated Czochralski
Temperature gradient controlled

- automated crystal pullers, computer aided design, technolog
- three heater system, T-gradient control
- crucibles up to 16 inch, charges up to 50 kg
- crystals up to 6 inch (8 inch demonstrated)

✓ diameter control (3 - 8 inch)
✓ growth rate O(7 mm/h)
✓ carbon control (10^{13} - 10^{16} cm^{-3})
✓ pressure control (0.2 - 2 MPa)
✓ temperature gradient control (50 - 100 K/cm)



200mm LEC

150 mm LEC

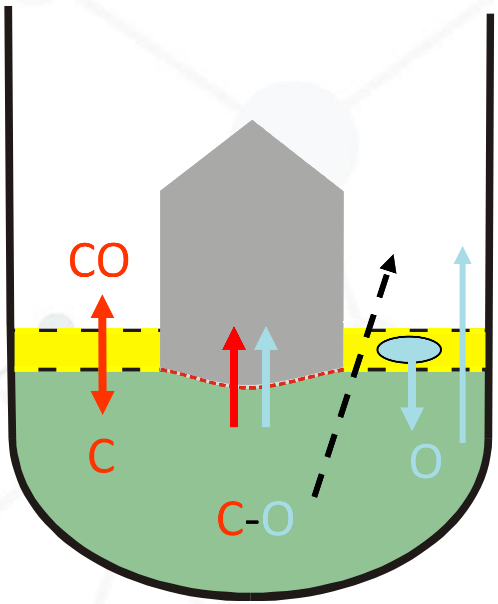
Carbon doping:
Carbon + oxygen segregation model

ox. reservoir: $$\frac{dN_{res}^{O}}{dt} \sim N_{res}^{O}$$

ox. transport: $$\frac{dN_{B_2O_3}^{O}}{dt} \sim C_m^{O}$$

C-O reaction: $$\frac{dN_R^{C,O}}{dt} \sim C_m^{O} C_m^{C}$$

carbon + oxygen transport for LEC (schematic)



$$\frac{dN_m^C}{dt} = -\frac{dN_s^C}{dt} + \frac{dN_{B_2O_3}^C}{dt} - \frac{dN_R^C}{dt},$$

$$\frac{dN_m^O}{dt} = -\frac{dN_s^O}{dt} + \frac{dN_{res}^O}{dt} - \frac{dN_{B_2O_3}^O}{dt} - \frac{dN_R^O}{dt}$$

→ Numerical solution

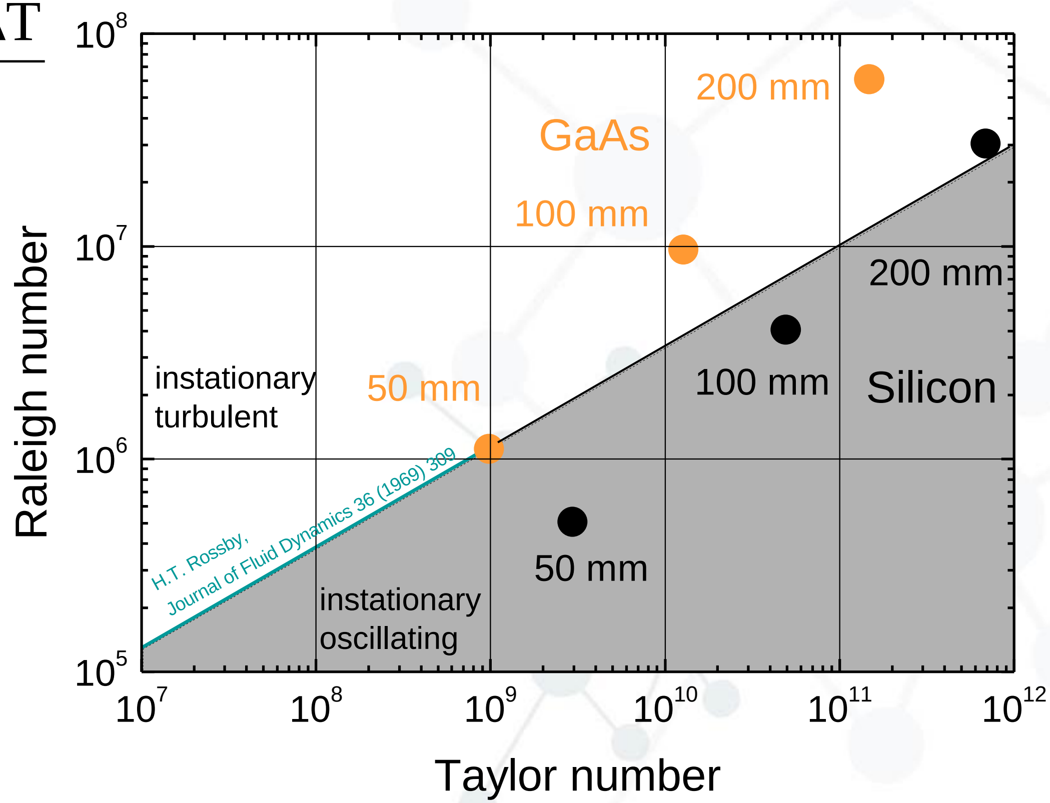
(S. Eichler et al., JCG 247 (2003) 69-76)

Limits for LEC-Growth

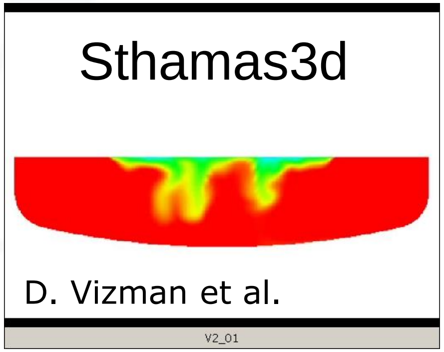
Melt turbulence (A. Seidl et al.)

Freiberger Compound Materials

$$Ra = \frac{g \beta h^3 \Delta T}{\nu \kappa}$$



IISB
Institut Integrierte Systeme und Bauelementetechnologie

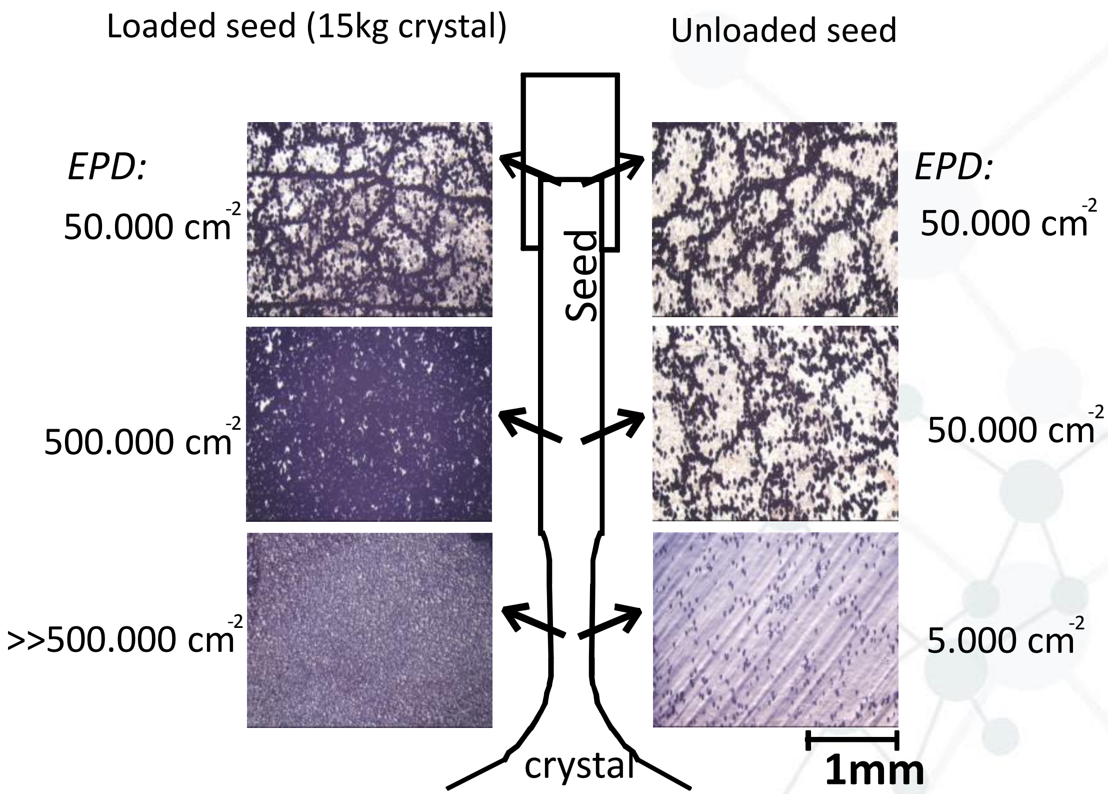


$$Ta = \frac{4 \omega^2 h^4}{\nu^4}$$

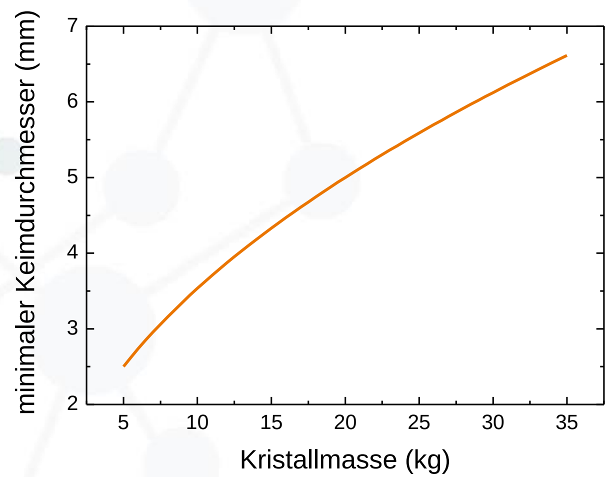
➡ Increasing turbulence limits possible melt height

Limits for LEC-Growth

Seed stability (A. Seidl et al.)



V. Swaminathan, S. M. Copley; Journal of The American Ceramic Society 58 (1975) 482 :Fracture strength about 10 MPa

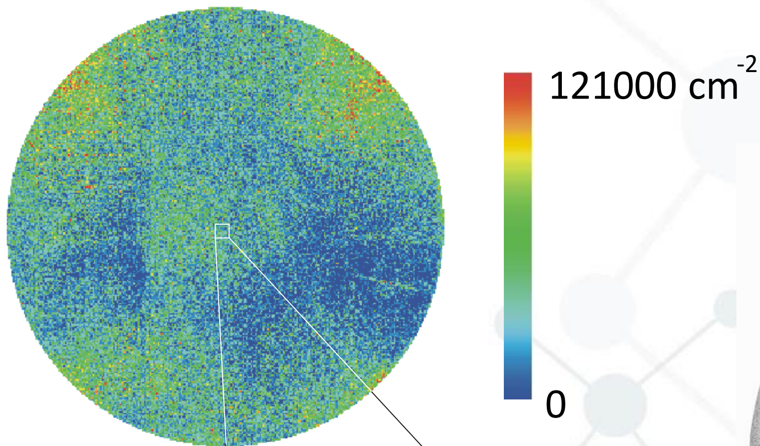


Charge mass is limited to 50kg!

Crystal quality: Dislocations in SI-GaAs

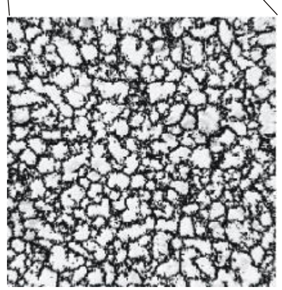
6” wafer

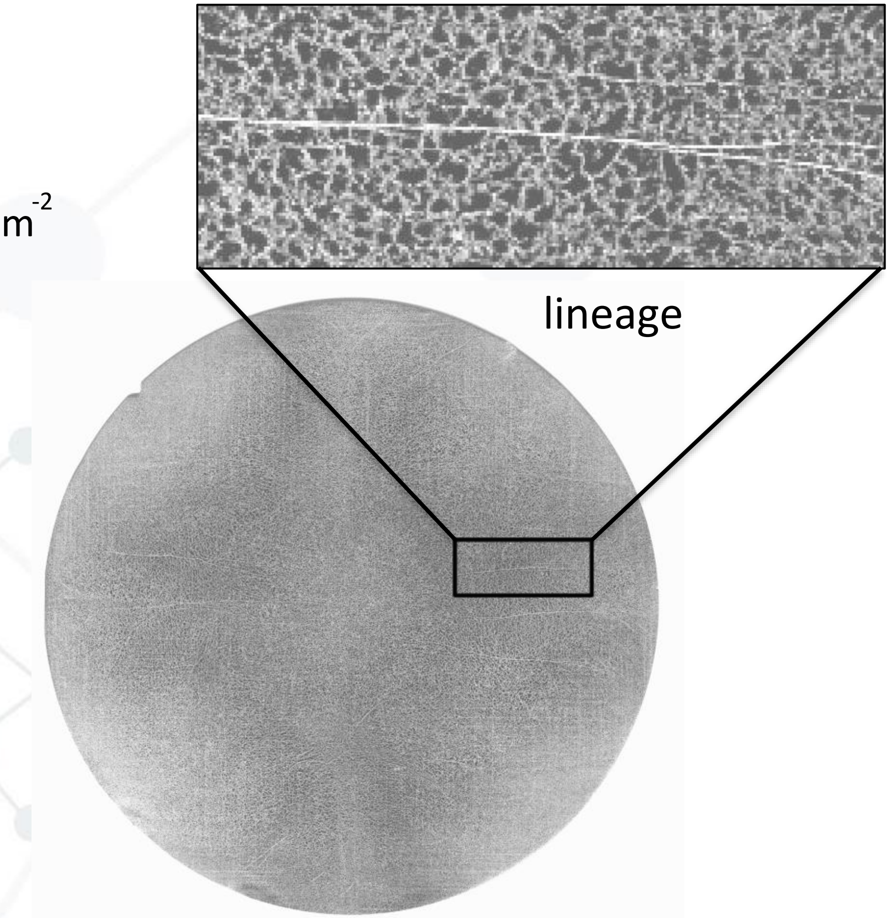
Etch Pit Density (EPD)



Ca. 80K/cm
EPD = 84000cm^{-2}

4×4mm²





Freiberger Product Portfolio until year 2000

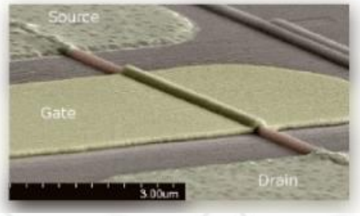
Freiberger Compound Materials

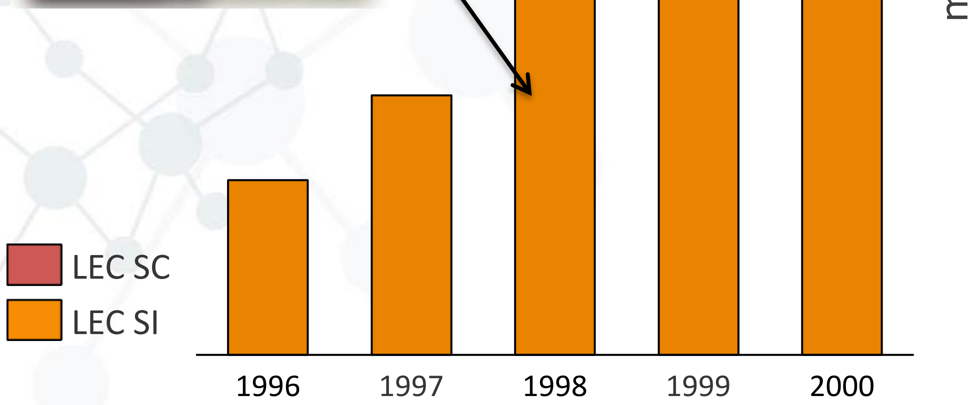
LEC
Liquid Encapsulated Czochralski

Semi-insulating			Semi-conducting	
C			Te	
3“	4“	6“	3“	4“

LED
by LPE/MOCVD

MESFET
by Ion Implantation



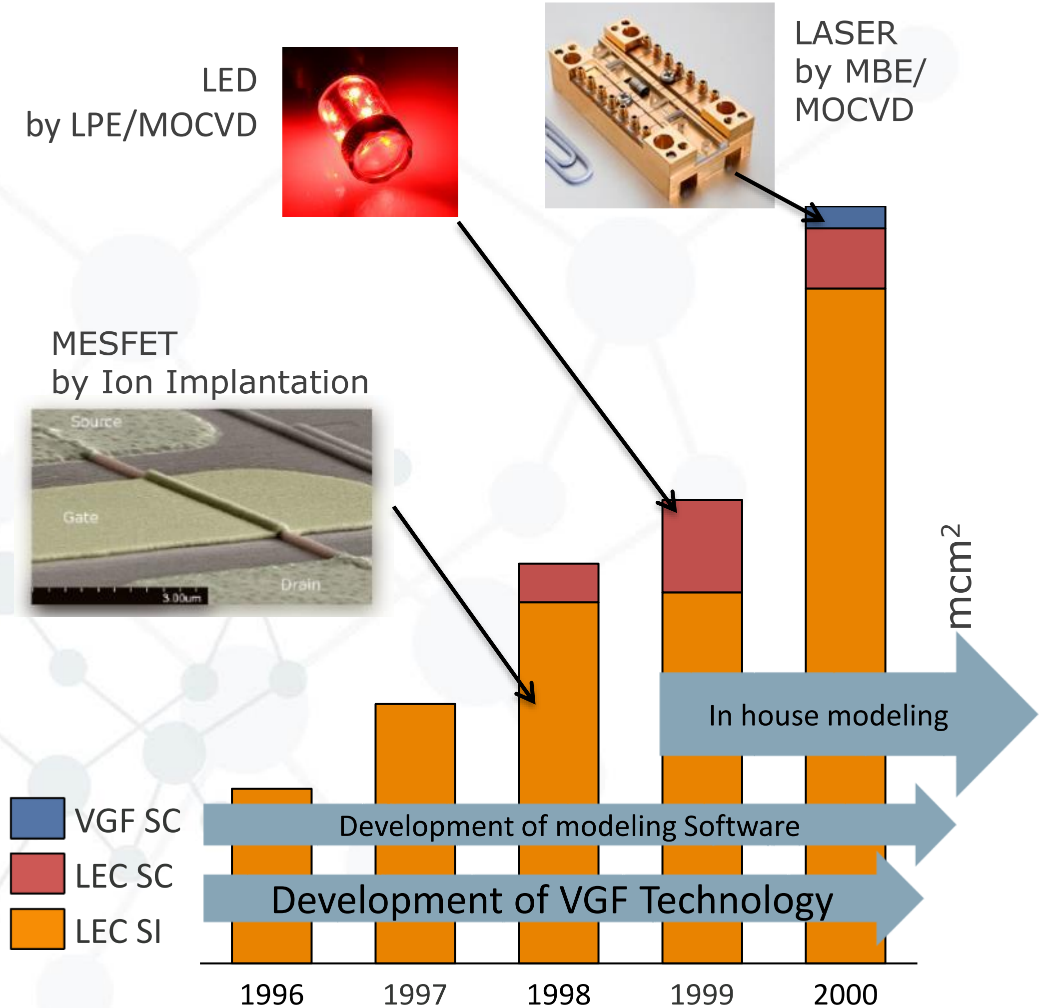


Freiberger Product Portfolio until year 2000

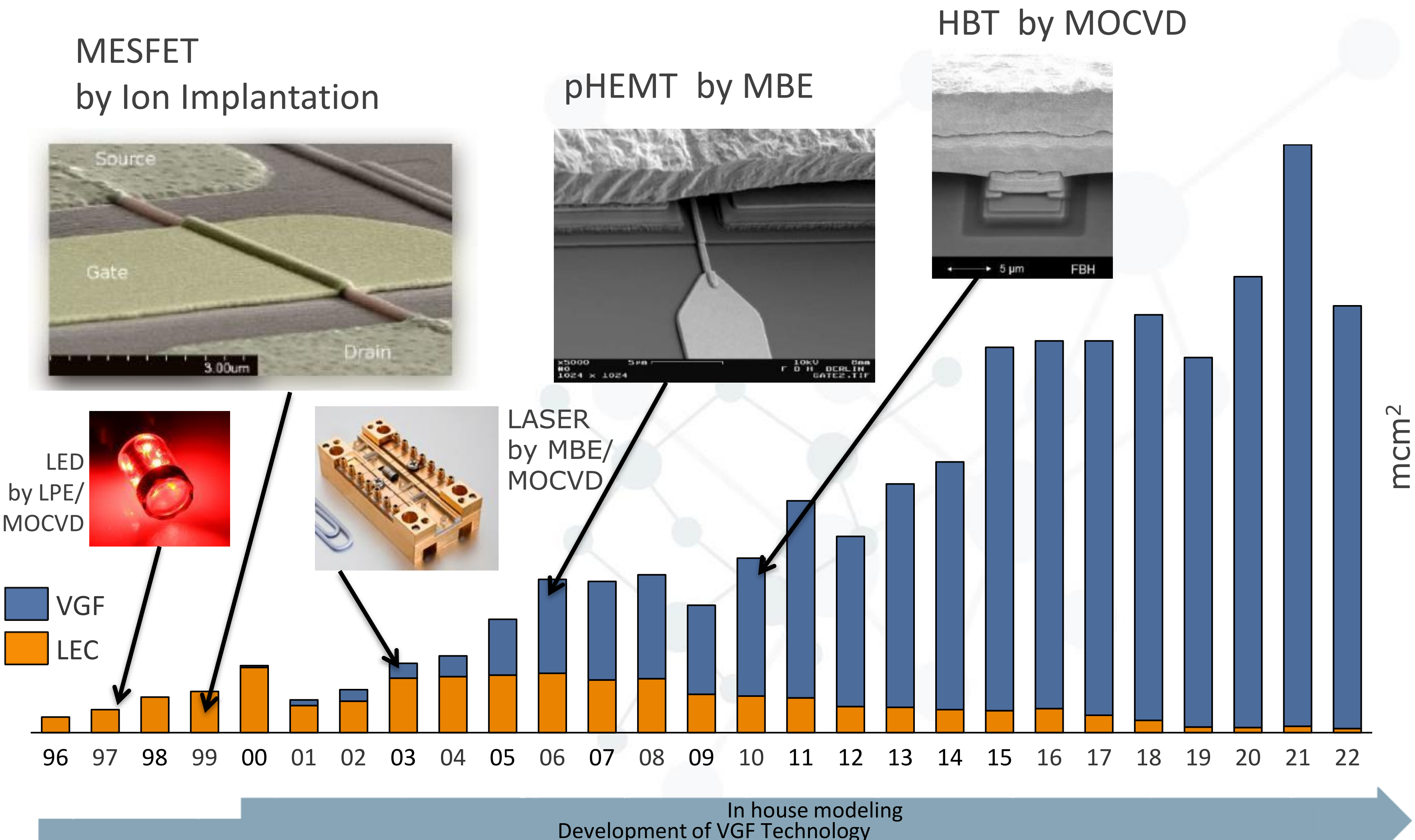
Freiberger
Compound Materials

LEC
Liquid Encapsulated Czochralski

Semi-insulating			Semi-conducting	
C			Te	
3“	4“	6“	3“	4“



Technology change by application



Freiberger Product Portfolio Today

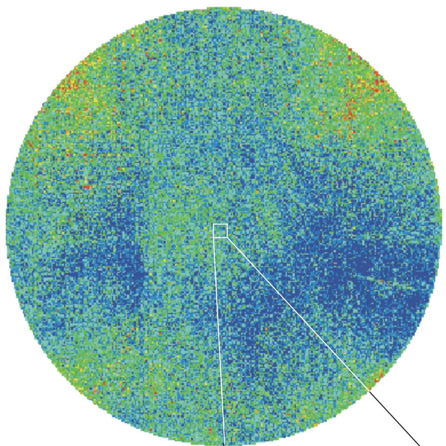
LEC Liquid Encapsulated Czochralski		VGF Vertical Gradient Freeze		
				
Semi-insulating	Semi-conducting	Semi-insulating	Semi-conducting	
C	Te	C	Si	Zn
3“, 4“, 6“	3“, 4“	3“, 4“, 6“, 8“	3“, 4“, 6“, 8“	4“, 6“, 8“

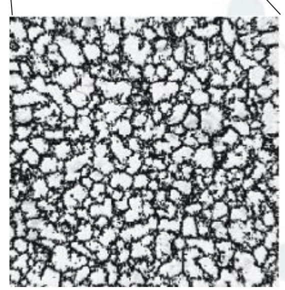
Dislocations in SI-GaAs (LEC vs. VGF)

6″ wafer

Etch Pit Density (EPD)

LEC





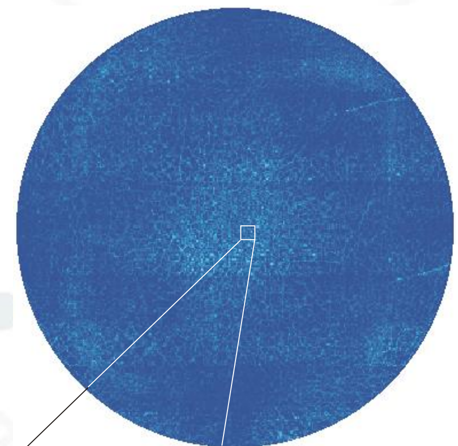
Ca. 80K/cm
EPD = 84000cm^{-2}

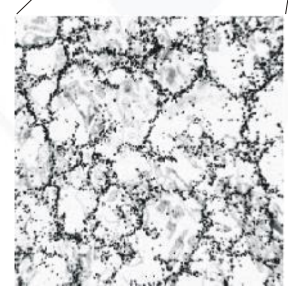
121000 cm^{-2}

0

4×4mm²

VGF





<5K/cm
EPD = 8600cm^{-2}

Most suitable for ion implantation

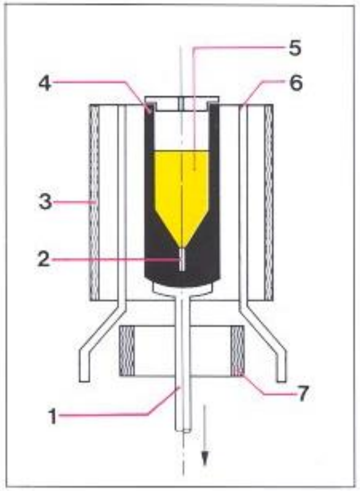
Most suitable for epitaxy

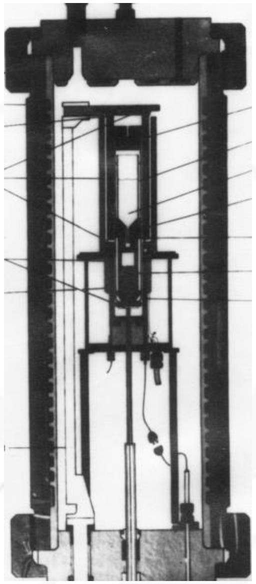
Bridgman-Growth – directional crystallization (1923)

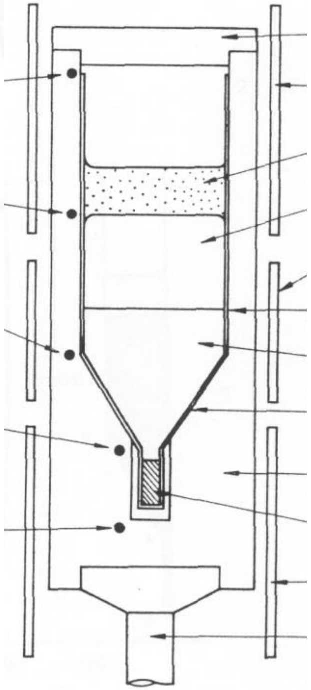
Peter Rudolph

P. W. Bridgman (1882-1961)

Nobel price in Physics 1945







W.A. Gault, E.M. Monberg, J.E. Clemans, A novel application of the Vertical Gradient Freeze method to the growth of high quality III-V crystals.

Journal of Crystal Growth 74 (1986) 491-506

K. Hoshikawa, H. Nakanishi, H. Kohda, M. Sasaura, Liquid encapsulated, Vertical Bridgman growth of large diameter, low dislocation density, semi-insulating GaAs.

Journal of Crystal Growth 94 (1989) 643-650

VGF-Growth at Freiberger

LEC experience:

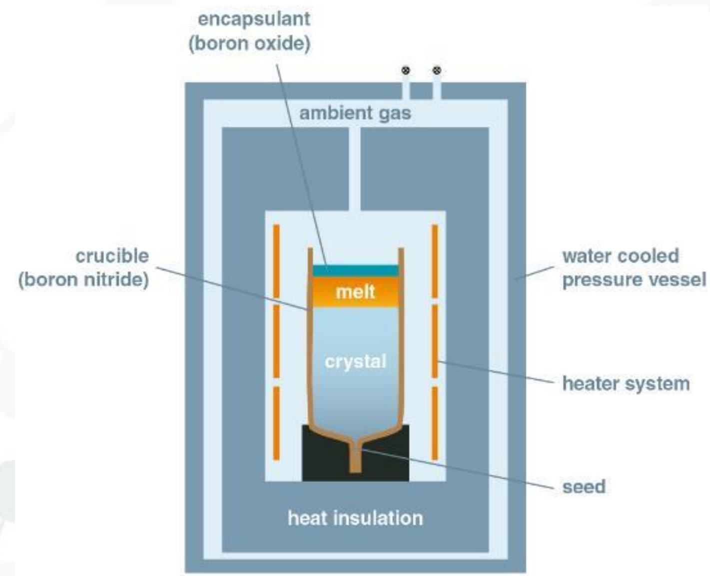
- Cold wall pressure vessel
- Carbon doping control by CO-gas
- pBN Crucible
- B_2O_3 (LE-VGF)
- Graphite setup

VGF: Vertical Gradient Freeze, Vertical Boat
lowest possible temperature gradients

- new, fully automated crystal growth furnaces (open system, cold wall furnace, graphite environment)
- crucibles up to 8 inch diameter, 400 mm in length
- charges presently up to 20 kg
- crystals up to 6 inch (8 inch demonstrated)

✓ perfect diameter control due to crucible (3 - 8 inch)
✓ carbon control
✓ growth rate **O(3 mm/h)**
✓ temperature gradient control (**below 5 K/cm**)

Tammann / Stöber-type



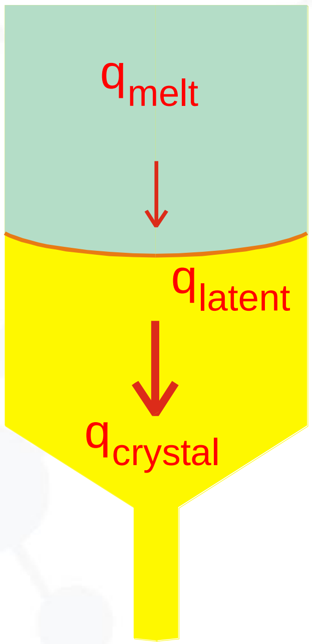
FCM VGF crystal 100 mm

Limits for VGF-Growth

Growth velocity

$$q_{\text{crystal}} = q_{\text{melt}} + \Delta h_{\text{latent}}\, j$$

q_i	…	Density of Heat flux
Δh	…	Specific Latent heat
j	…	Density of Mass flux
v	…	Growth velocity



$$\frac{v}{\text{grad}\, T} \leq \text{const.}$$

Si	5.4×10^{-5} cm^2 / K s
InP	4.5×10^{-5} cm^2 / K s
GaAs	**2.0×10^{-5} cm^2 / K s**

➡ **Growth velocity as well as crystal length is limited!**

Throughput (LEC vs. VGF)

LEC 6"

Charge up to 30kg

Growth rate about 7mm/h

VGF 6" (explicit parallel)

Charge up to 5x20kg

Growth rate about 5x3mm/h

Throughput about 1.5 x LEC

CAPEX 0.3 x LEC

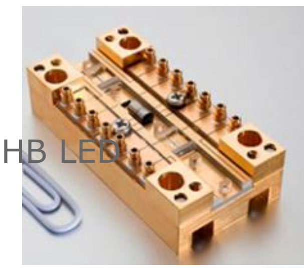
Foot print 0.3 x LEC

What else?

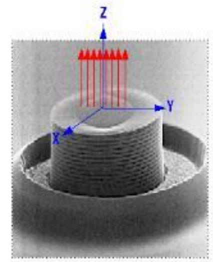
What else?

Optoelectronic niche – but growth potential!

HB LED

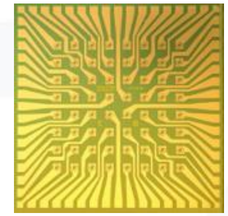


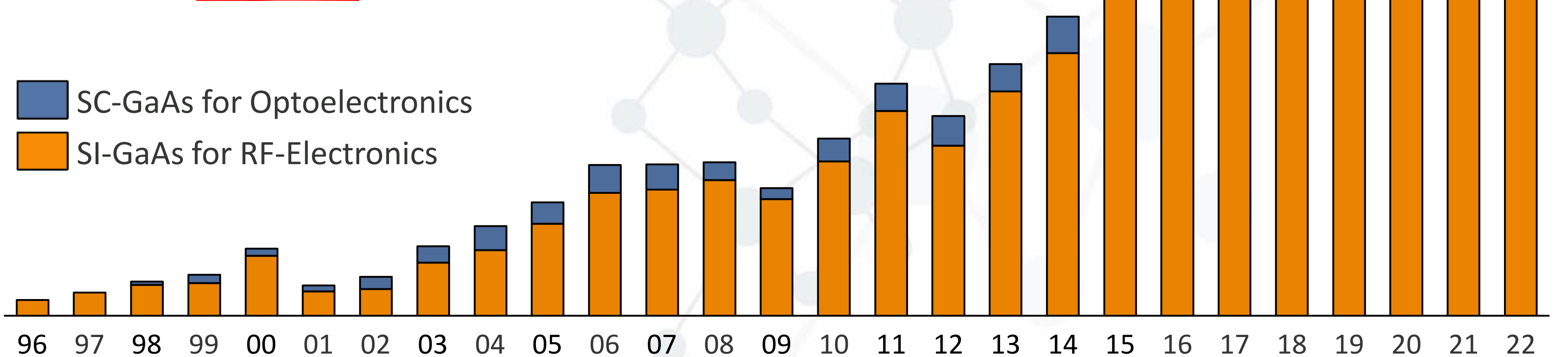
Edge emitting LASER



vertical-cavity surface-emitting laser (VCSEL)

VCSEL-Array

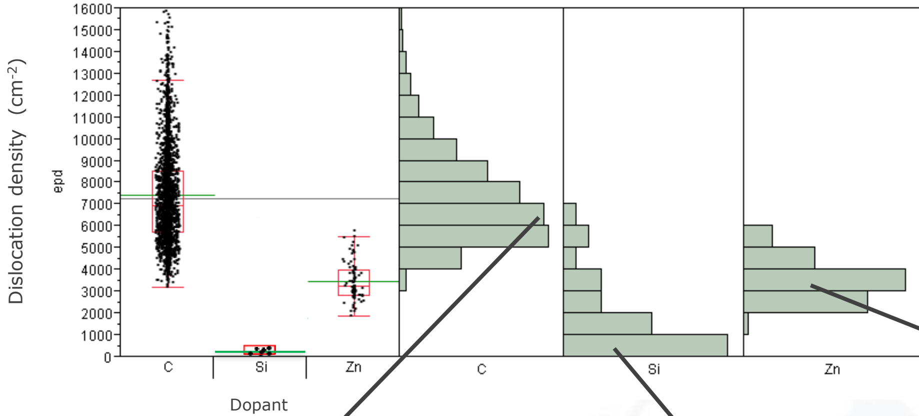




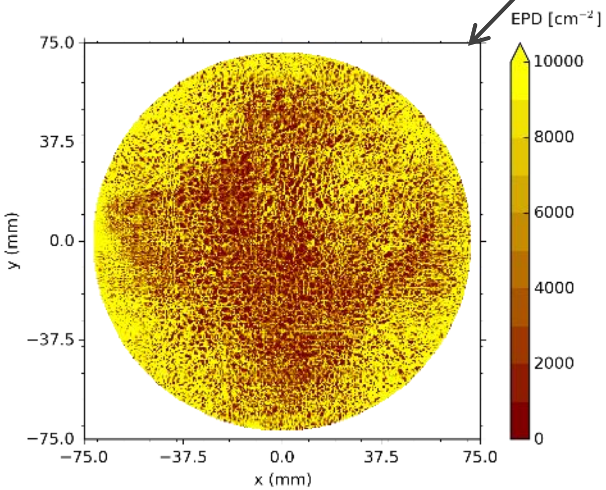
In house modeling
Development of VGF Technology

Dislocation density vs. doping of GaAs 150 mm VGF (epd mappings)

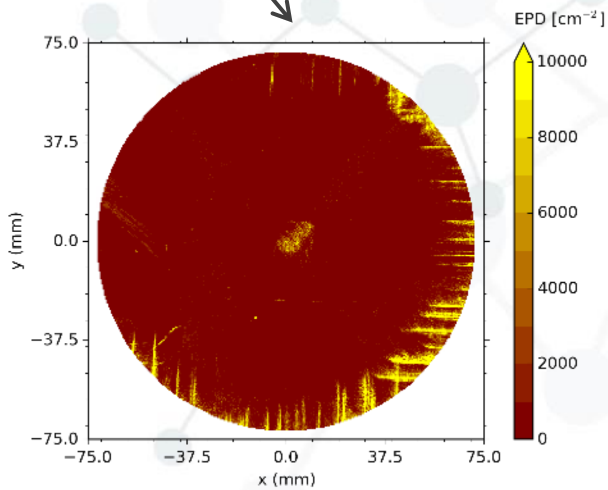
Freiberger Compound Materials



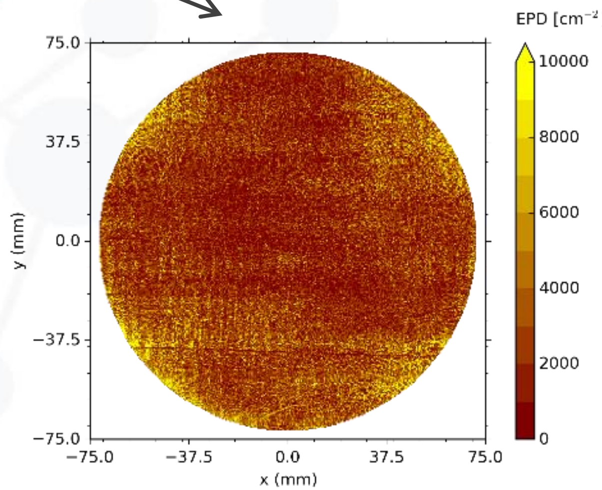
The structural perfection of GaAs (dislocation density) is influenced by doping species and dopant concentration because of lattice hardening.



$\overline{epd}$=8700 cm^{-2}

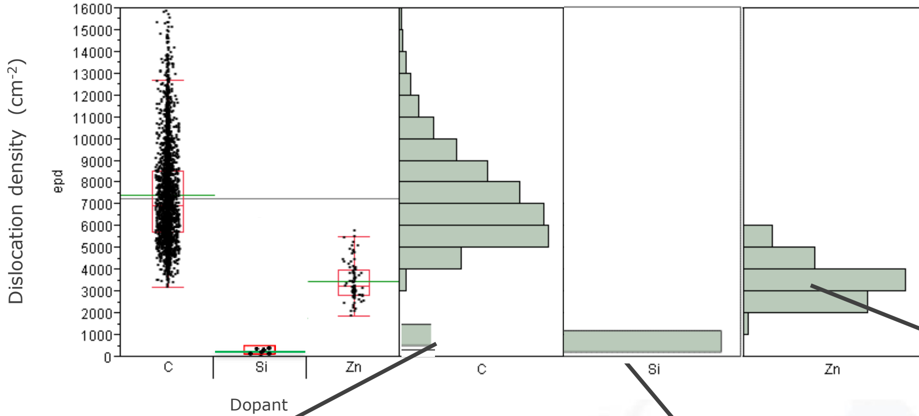


$\overline{epd}$=350 cm^{-2}

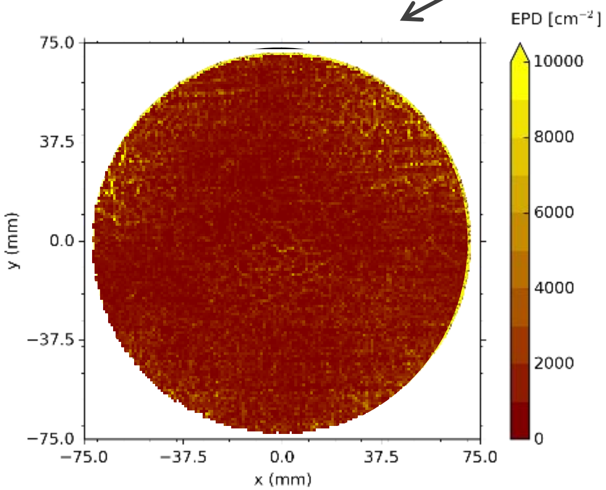


$\overline{epd}$=2700 cm^{-2}

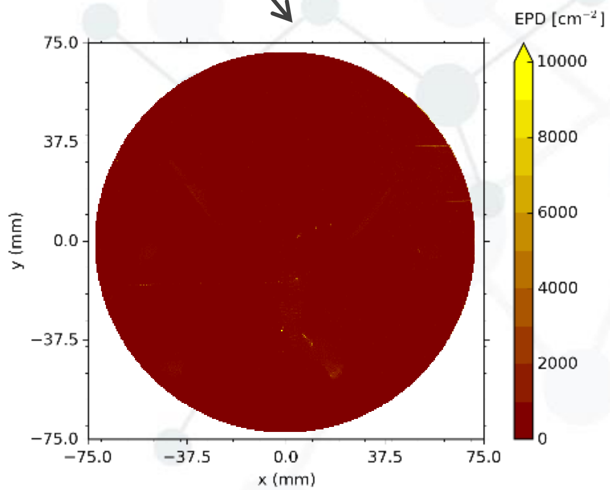
Dislocation density vs. doping of GaAs 150 mm VGF (epd mappings) for VCSEL



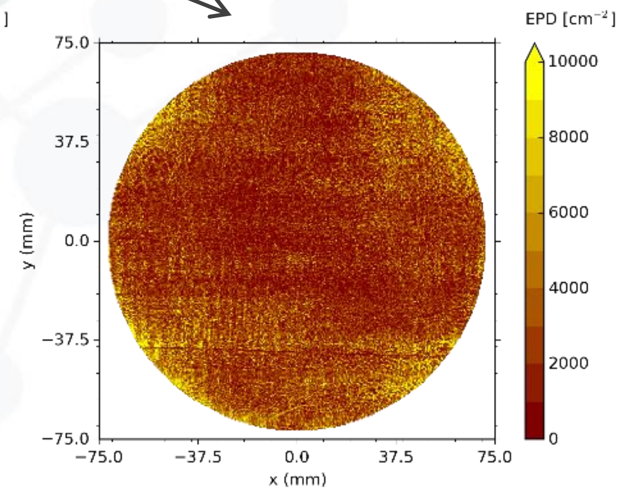
The structural perfection of GaAs (dislocation density) is influenced by doping species and dopant concentration because of lattice hardening.



$\overline{\text{epd}}$=790 cm^{-2}

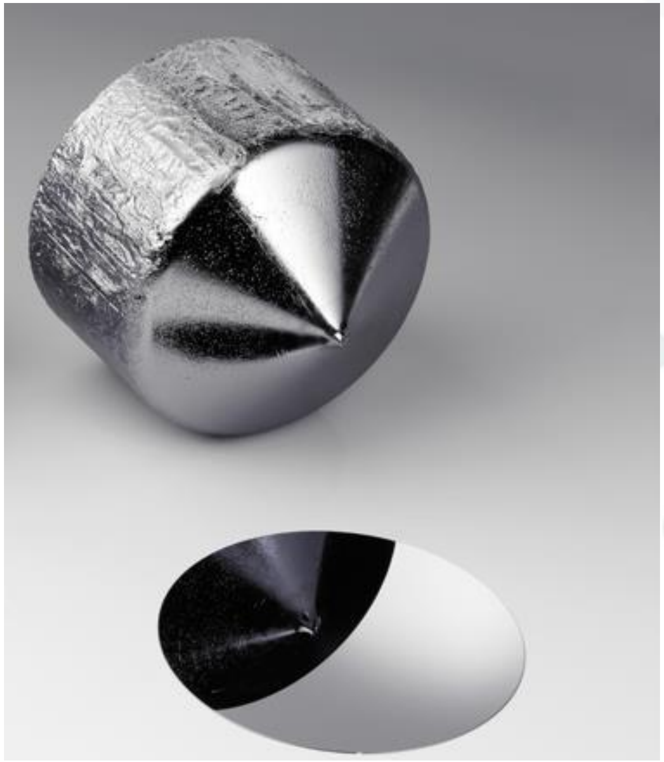


$\overline{\text{epd}}$=15 cm^{-2}



$\overline{\text{epd}}$=2700 cm^{-2}

Freiberger 200mm GaAs substrates



Quality and consistency
with industry leading low defect density and superior flatness

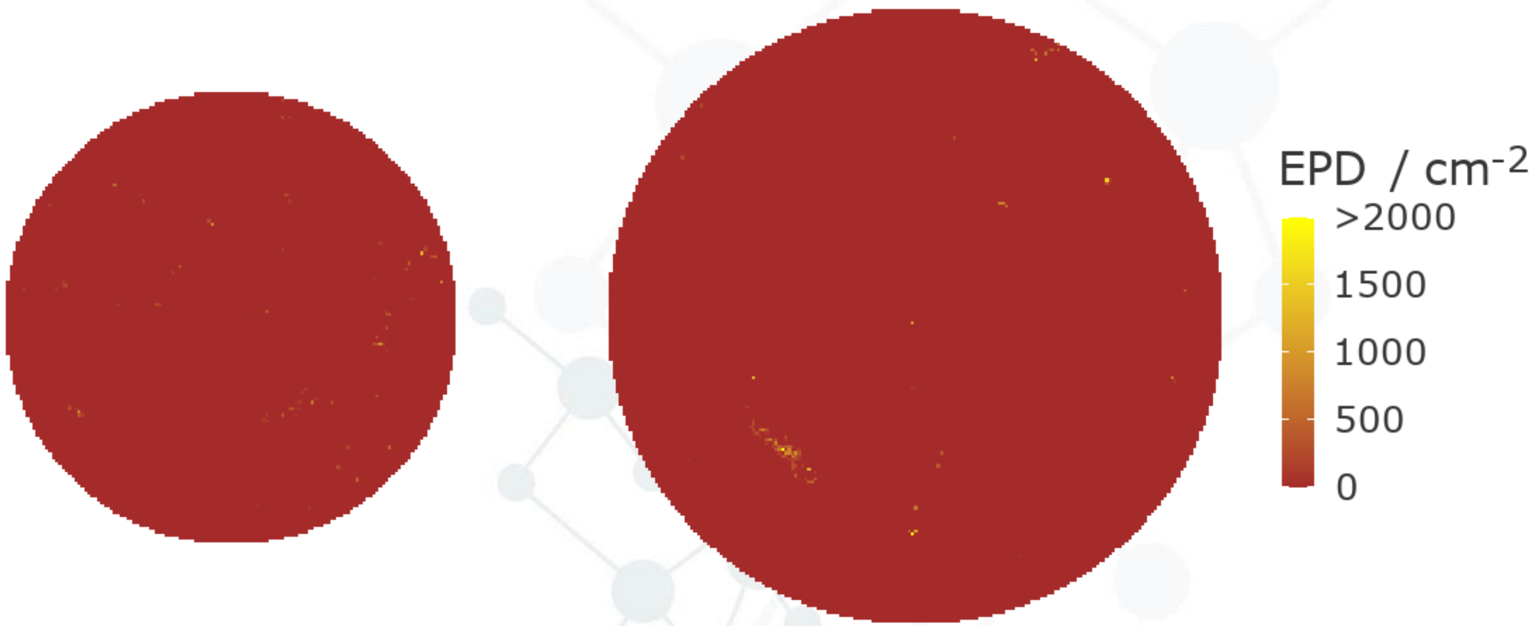
Manufacturing scalability
ready for mass production to supply into high volume applications

Compatibility and compliance
with 200mm manufacturing (SEMI) of Opto- and RF devices

Sustainability
by reducing consumption of energy, water and raw material

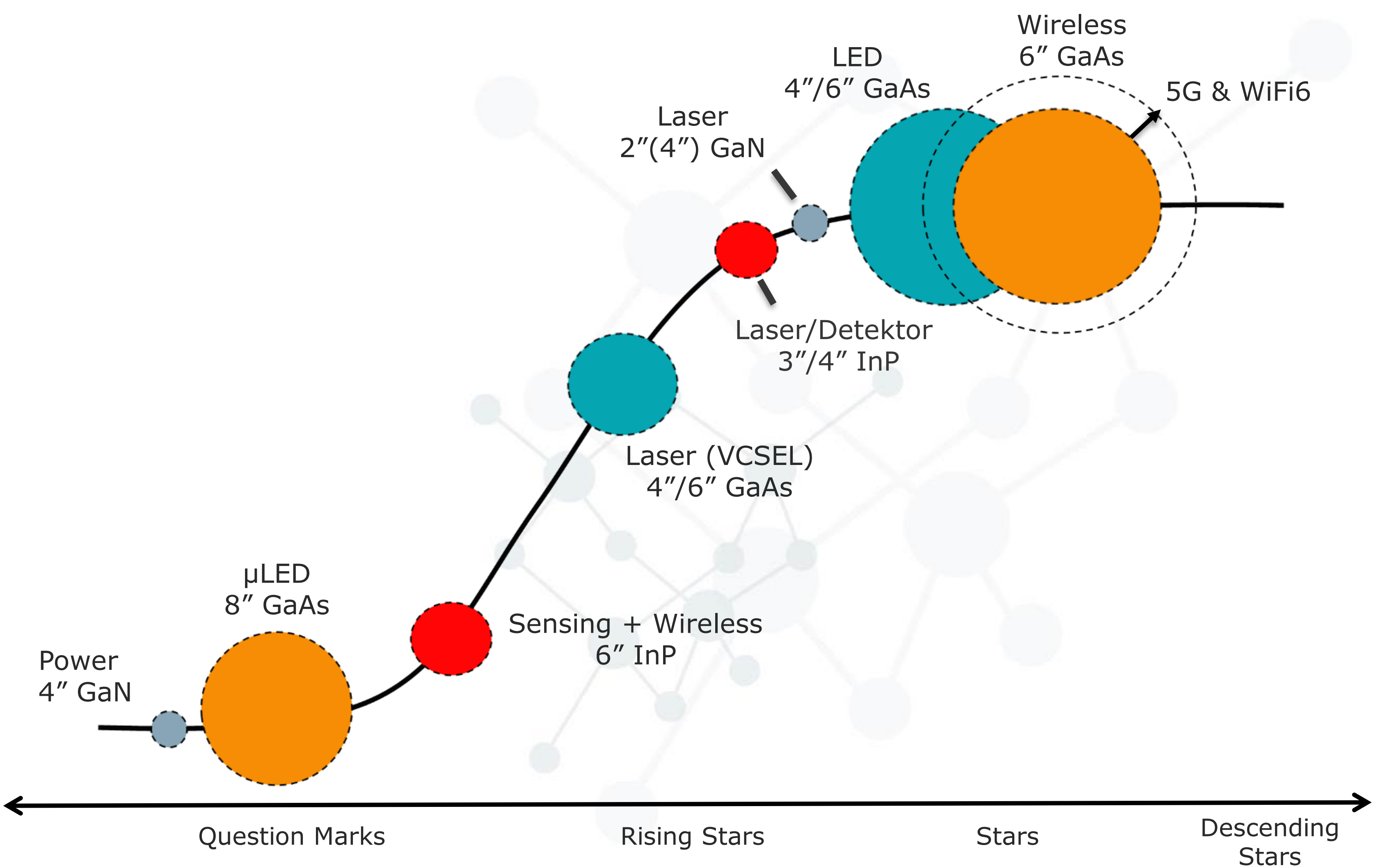
Quality ready – crystal perfection

150mm LASER grade	**Our 200mm capability**
EPD < 20 cm^{-2}	EPD < 20 cm^{-2}



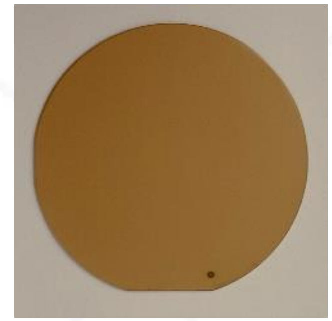
Ultra low dislocation
at best-in-class 150mm level available

Product cycles



FCM Product Portfolio InP & GaN

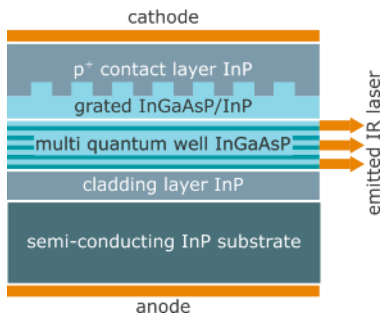
InP						GaN					
VGF Vertical Gradient Freeze						HVPE Halide Vapor Phase Epitaxy					
Semi-conducting			Semi-insulating			Semi-conducting				Semi-insulating	
S			Fe			Si		Ge		Mn	
3"	4"	6"	3"	4"	6"	2"	4"	2"	4"	2"	4"



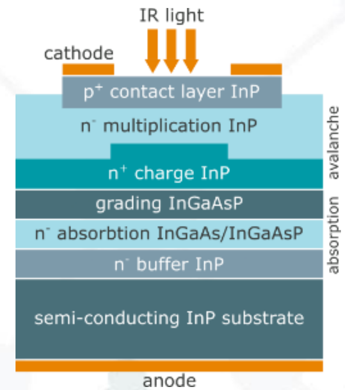
Products of our Customers (InP)

Device Examples

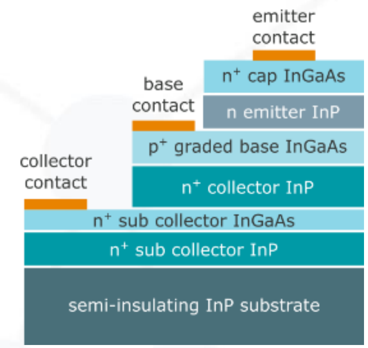
Distributed Feedback Edge Emitting Laser



Avalanche Photodiode

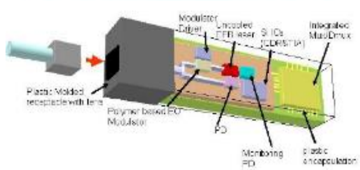


Double HB-Transistor

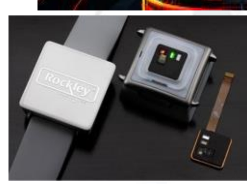


Applications

Data Communication



IR Sensing & Detection

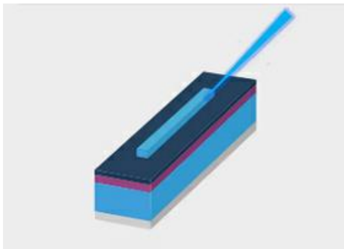


mmWave & THz

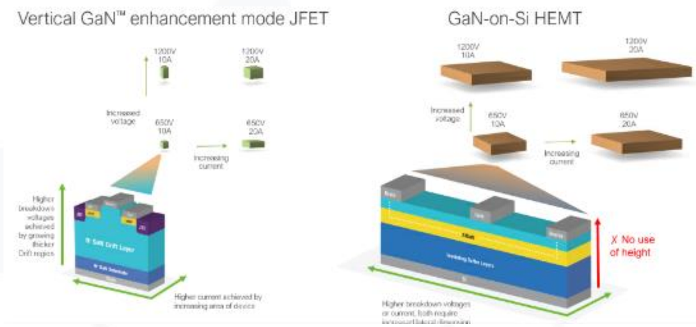
Products for GaN

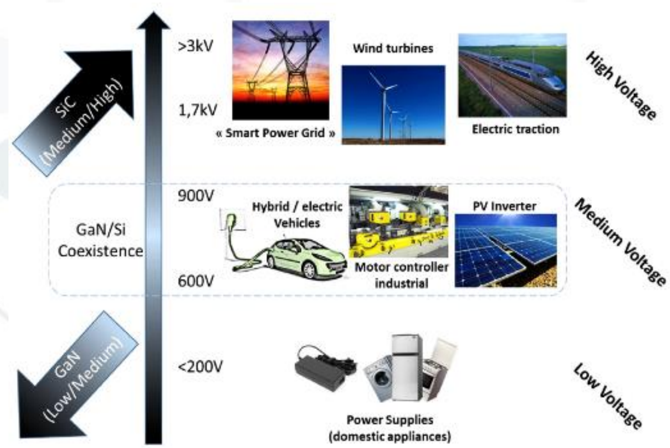
Freiberger
Compound Materials

Current application



Potential applications





Vertical power transistors (GaN-On-GaN)

Lateral power transistors (GaN-On-Si)

Graph from
Meneghini et al. J. Appl. Phys. **130**, 181101 (2021)

More information

www.freiberger.com