Electronic Materials Lab

ADDRESS

이원재 교수

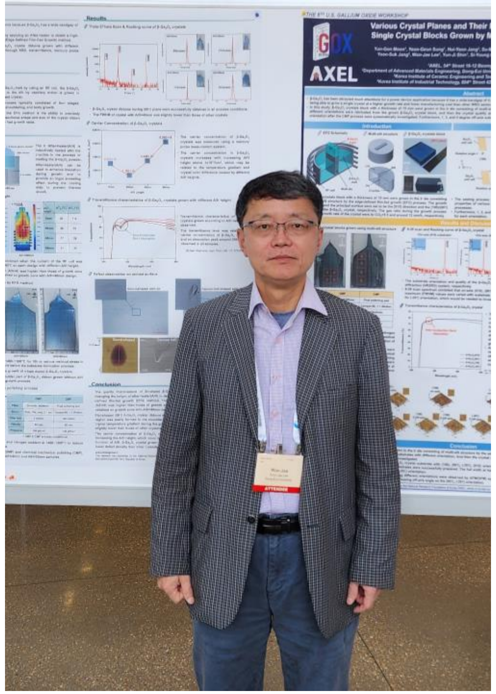
부산광역시 부산진구 엄광로 176,
동의대학교 정보공학관 308호
(우 : 47340)

CONTACT

E-mail : leewj@deu.ac.kr

Hotline : 051-890-2524

Member



Prof. Won-Jae Lee
leewj@deu.ac.kr

EDUCATION

- 1990– 1995, M.S. and Ph.D in Electroceramic Thin Films,
  Korea Advanced Institute of Science & Technology (KAIST), Korea
- 1986– 1990, B.S. in Materials Science & Engineering
  Korea Advanced Institute of Science & Technology (KAIST), Korea

RESEARCH EXPERIENCE

- 2002 – Present, Dong-Eui University, Busan, Korea
  Professor, Department of Mat. Components Eng. & Electronic Research Center (ECC)
- 2009 – 2010, University of Maryland at College Park, MD, USA
  Visiting Scholar, AZO films by Atomic Layer Deposition (ALD) and characterization of their electrical properties for TCO application.
- 1997 – 2002, Electronics and Telecommunications Research Institute (ETRI), Daejon, Korea
  Senior Research Engineer, ETRI-Micro-Electronics Technology Lab.
- 1996 – 1997, North Carolina State University, Raleigh, NC, USA
  Post-doctor, Department of Materials Science and Engineering
  Process development of BST films using a liquid delivery source MOCVD process

MAIN RESEARCH AREAS

- SiC Single Crystal & epitaxial growth by PVT method and their characterization as a wafer.
- Ga_2O_3 Single Crystal by EFG method
- GaN wafer fabrication by HVPE technique.
- ZnO thin films deposited by pulsed laser deposition (PLD) technique
- Dielectric layers grown by plasma enhanced atomic layer deposition (PEALD) process.
- International Journals; 160, Patents; 50

Member

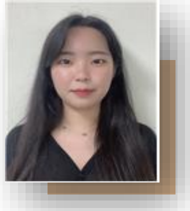
Researcher

Yeon-Suk Jang
Single crystal growth
d91052@nate.com

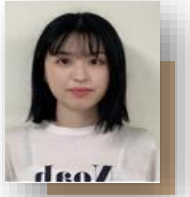
Mi-Seon Park
Single crystal analysis
mi_seon7@naver.com

Master's Candidate

Jun-Hyuk Na (2st year)
SiC single crystal growth
mjna21v@gmail.com



Su-Min Choi (2st year)
Ga_2O_3 single crystal growth
subin6696@naver.com

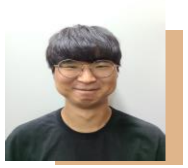


Ha-Lin Lee (2st year)
SiC single crystal growth
su103305@naver.com

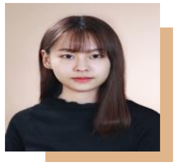
Hui-Yeon Jang (2st year)
Ga_2O_3 single crystal growth
wkddmsgk7848@naver.com

Hae-Jin Jeon (2st year)
CaF_2 single crystal growth
jjjhj0813@gmail.com

Gi-Uk Lee (1st year)
SiC single crystal growth
dlrldnr7774@naver.com



Min-Gyu Kang (1st year)
SiC single crystal growth
kminq980@gmail.com



Ye-Jin Choi (1st year)
SiC single crystal growth
dpwls9080@naver.com

Min-Ji Chae (1st year)
Ga_2O_3 single crystal growth
alswlz643@gmail.com

Sun-Young Seo (1st year)
Ga_2O_3 single crystal growth
tjtjsdud1119@naver.com

Undergraduate Student

Gyeoung-Jun Song (Senior)
ssjt1147@gmail.com

Dae-Uk Kim (Senior)
kdy32327@naver.com

Yun-Jin Kim (Senior)
dbswls330@naver.com

So-Min Shin (Senior)
tlsthals9931@naver.com

Na-Kyoung Kim (Senior)
anne0518@naver.com

Overview

Electronic Material Lab

Main Research Area

- Single Crystal Growth of Compound Semiconductor
- Electronic Ceramics
- Ceramic Thin Film / Component
- Wafer Processing and Analysis
- Numerical Simulation

Overview

Crystal Growth

- Single crystal growth of various materials used in semi-conductor or display by Sublimation Growth or Solution Growth
  - SiC, AlN, Semi-insulator SiC

- Epitaxial growth on substrate using PVD or CVD
  - GaN, ZnO, TiO_2, SiC, Ga_2O_3

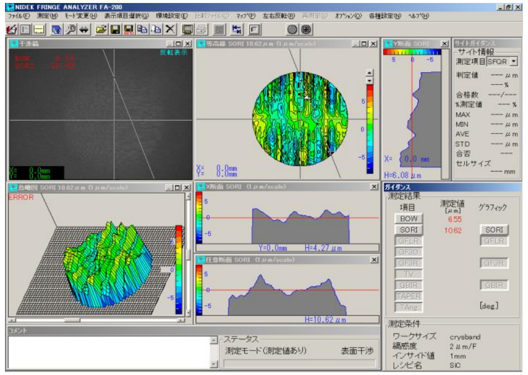
Processing (Wafering)

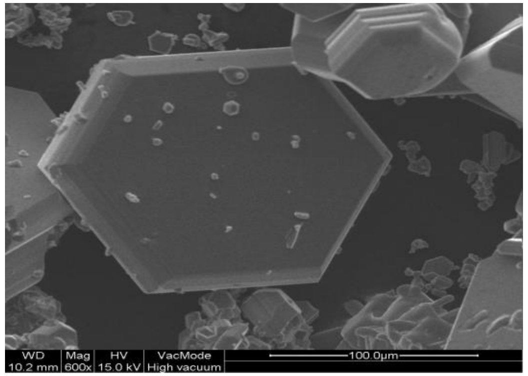
- Equipped to process grown ingot into wafers (Wafering)
- Cutting : Multi-Wire Saw, Single-Wire Saw, Blade Cutter
- Surface : Grinder, Lapping, DMP, CMP
- Others : Lateral Grinder, Edge Grinder, Seeding Equipment, Plasma Etcher

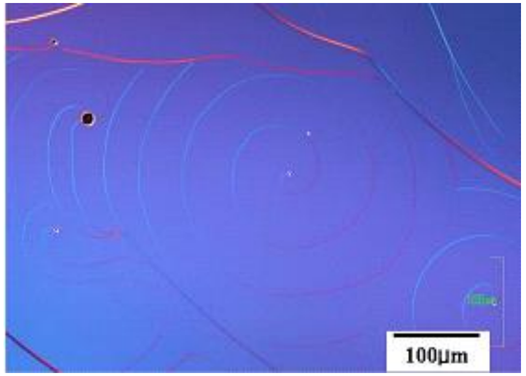
Overview

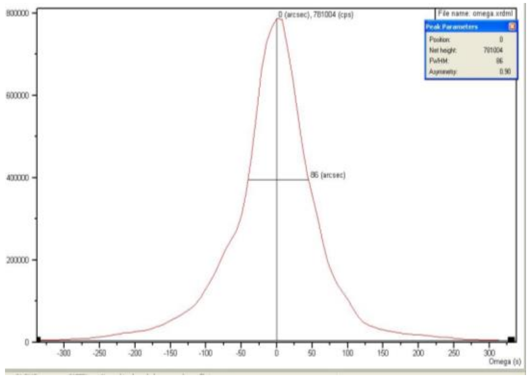
Analysis

- Analyzing crystallographic quality and defect of single crystal
  - XRD, HR-XRD, Goniometer
- Surface quality analysis
  - OM, AFM, Wetting Angle, SEM /EDS
- Electrical properties analysis
  - Hall measurement, UVF









Simulation

- Optimization of experiment condition by simulating a single crystal growth to predict temperature distribution, growth rate and fluid flow
  - CGSim, Virtual Reactor

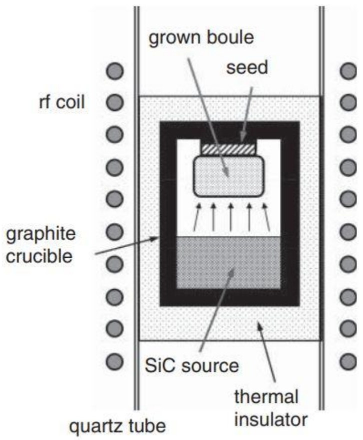
[Ref.] STR Group, www.str-soft.com

SiC Single Crystal

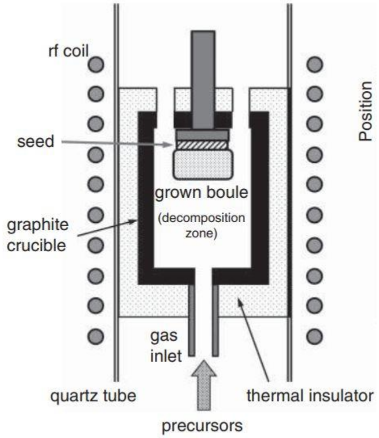
SiC

- SiC (Silicon Carbide) is a promising substrate applicable to power device working at high power, high frequency and high temperature.

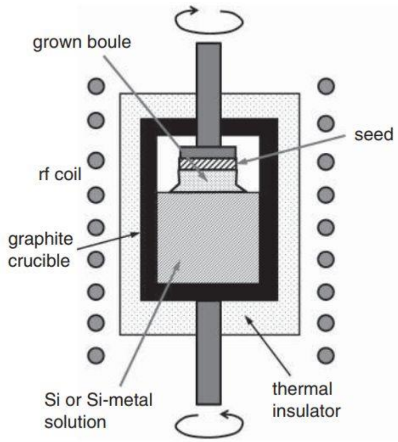
PVT



CVD

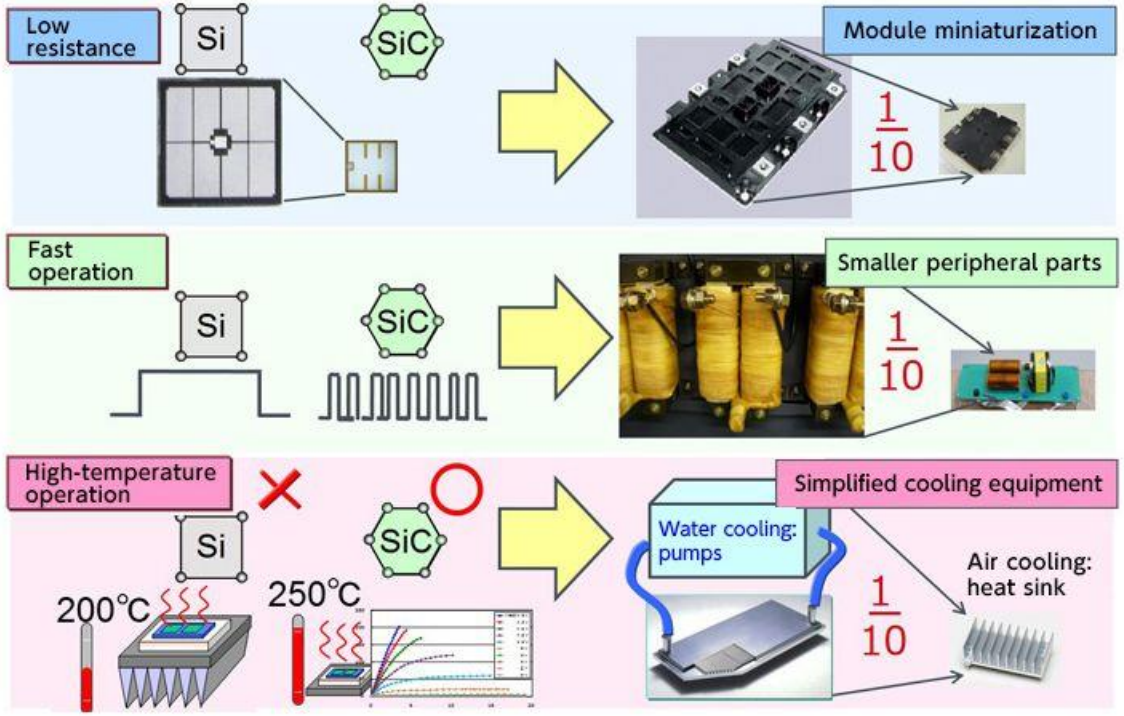


TSSG



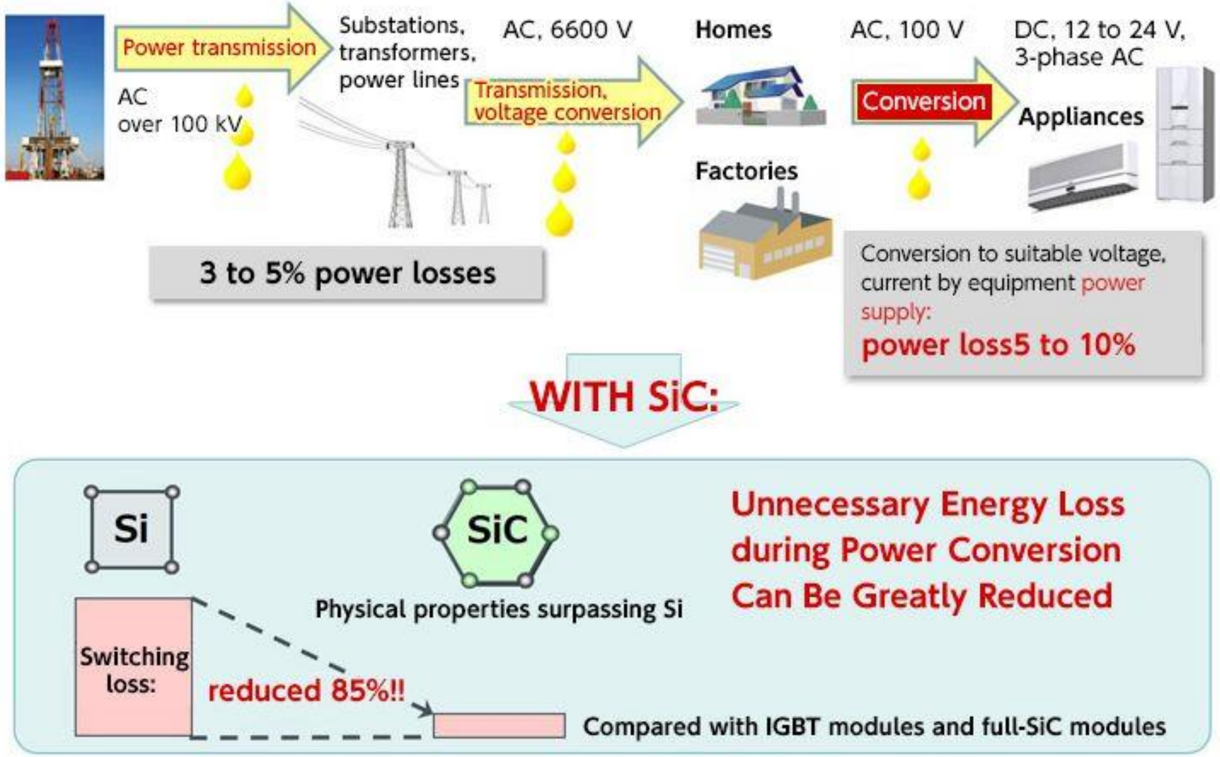
[Ref.] Fundamentals of Silicon Carbide Technology_ Growth, Characterization, Devices and Applications-Wiley-IEEE Press (2014)

Advantage



[Ref.] Tech web, https://micro.rohm.com/en/techweb/knowledge/sic/s-sic/02-s-sic/4161

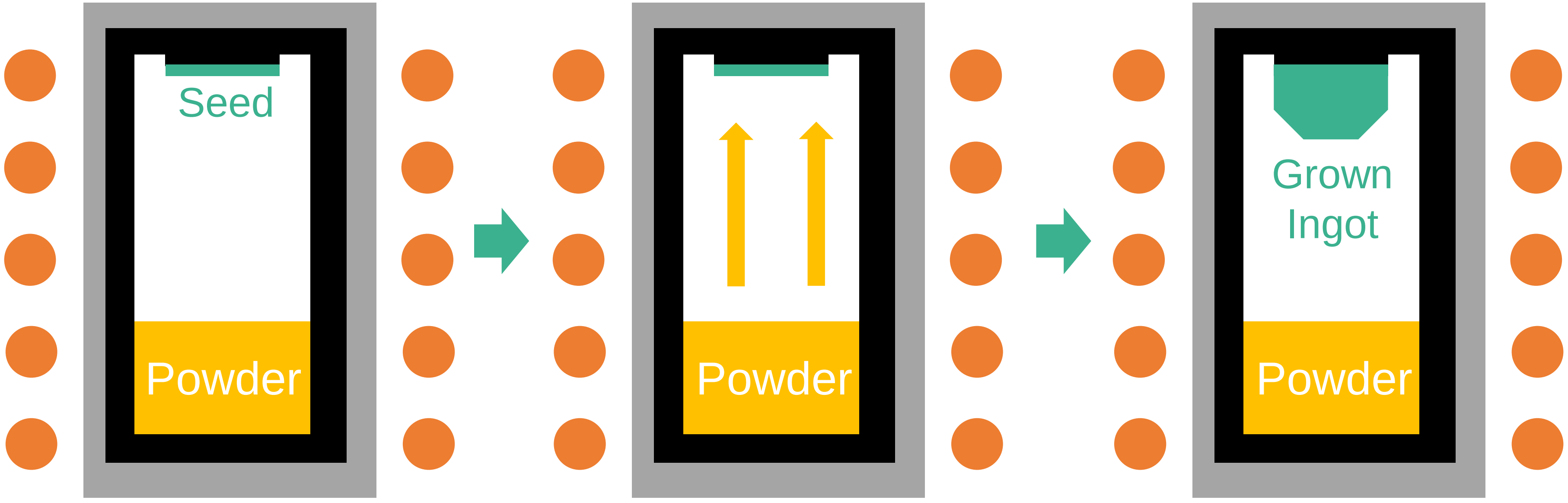
Application



PVT

PVT

- PVT (Physical Vapor Transport) is sublimation growth with seed and standard method for growing single crystal SiC



Heating Sublimation Growth

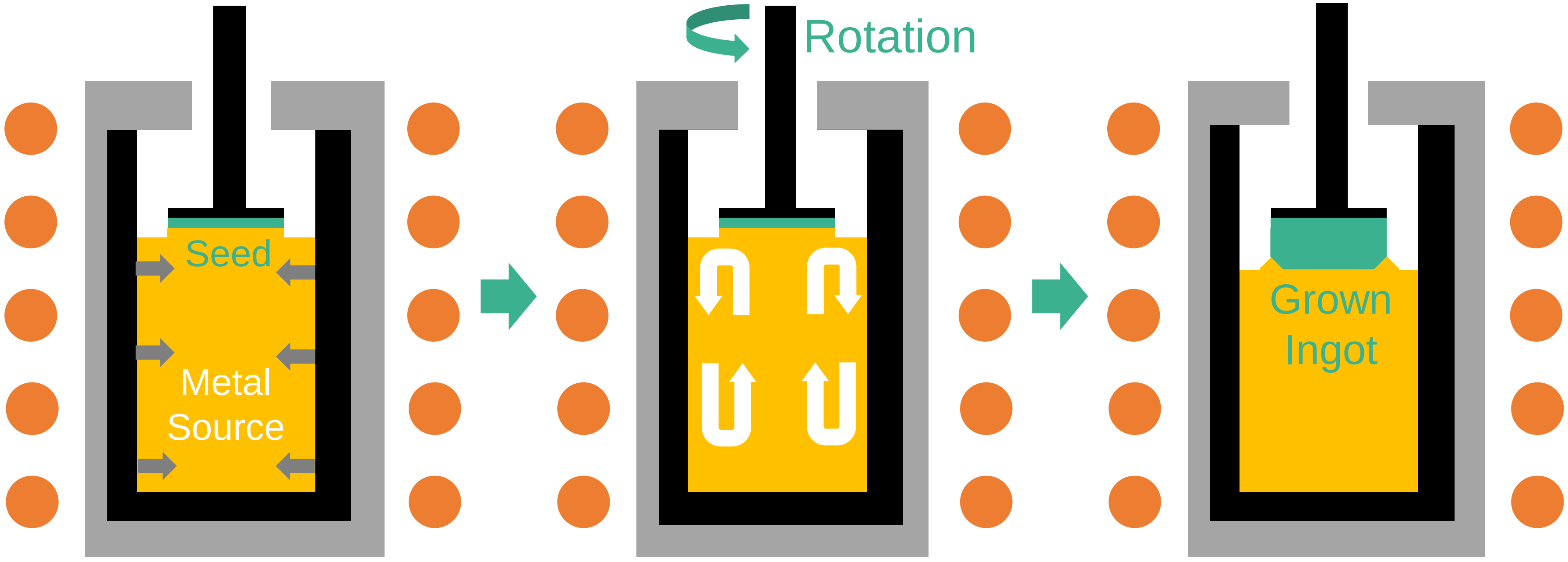
PVT grower

SiC Ingot

TSSG

TSSG

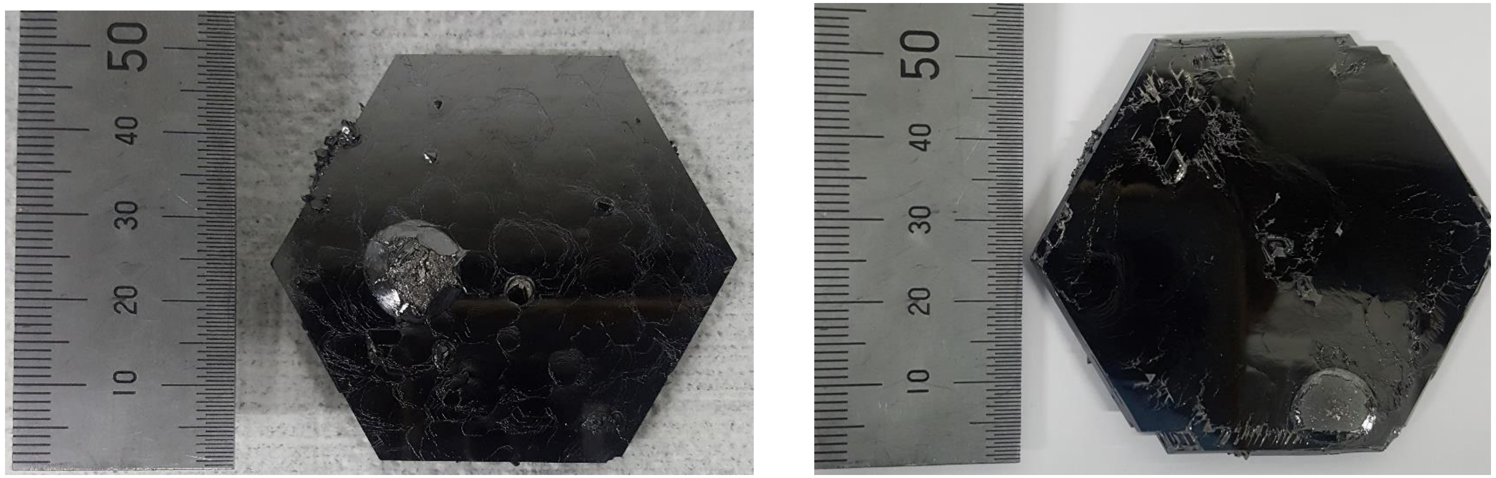
- TSSG (Top-Seeded Solution Growth) is alternative method growing high quality SiC crystal under a close condition to thermodynamic equilibrium state



Heating / Carbon dissolution

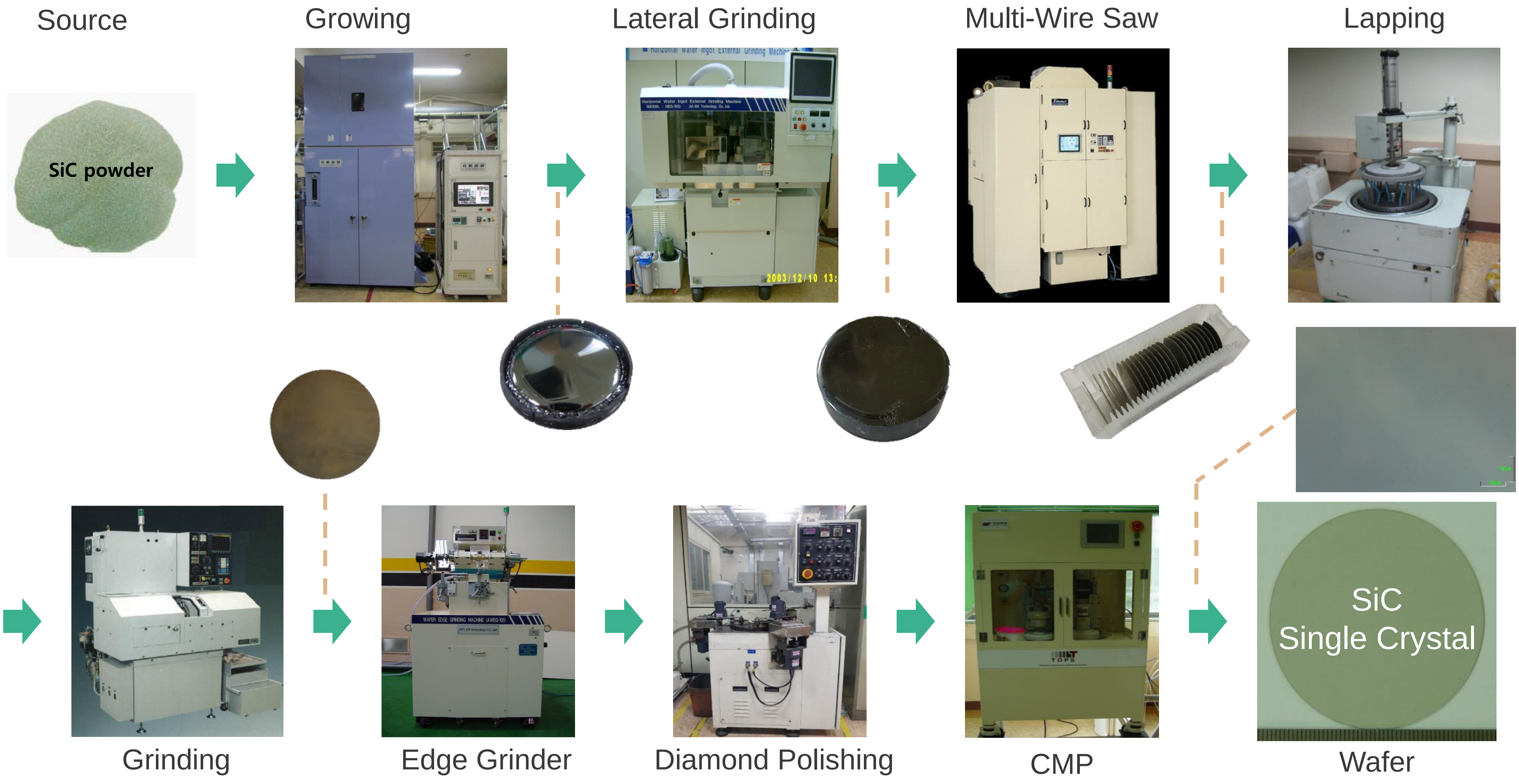
Convection / Diffusion

Supersaturation / Growth



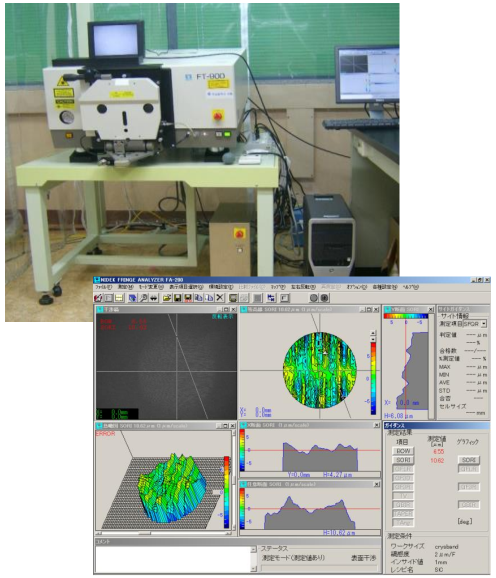
SiC Ingot

Manufacturing Process

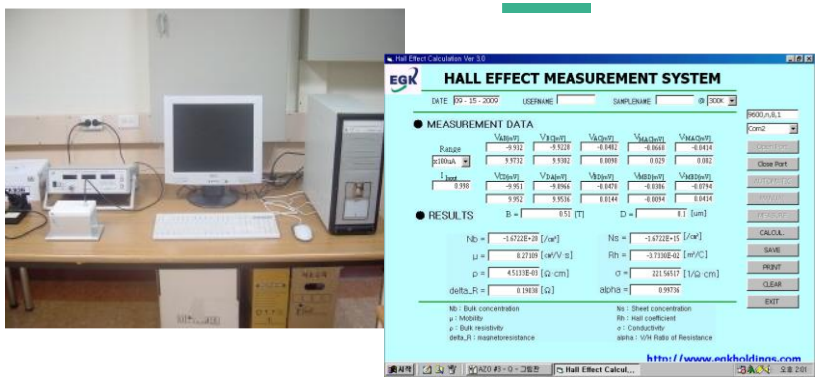


Analysis system for Single Crystal

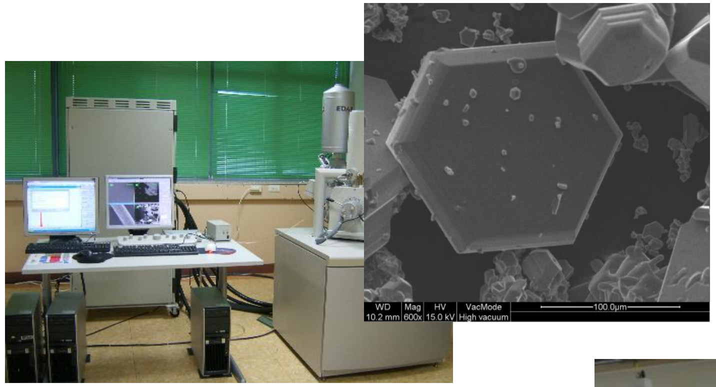
Flatness Tester



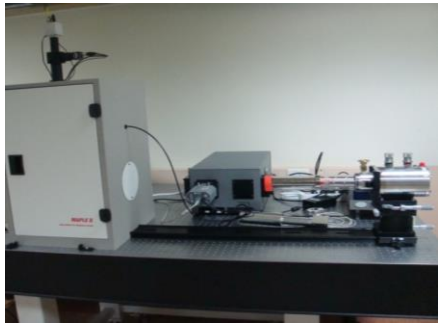
Hall Measure System

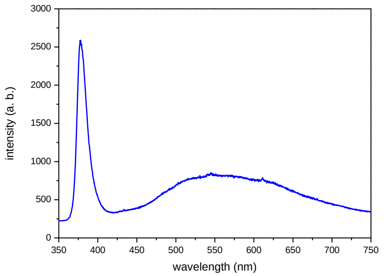


FE-SEM / EDS



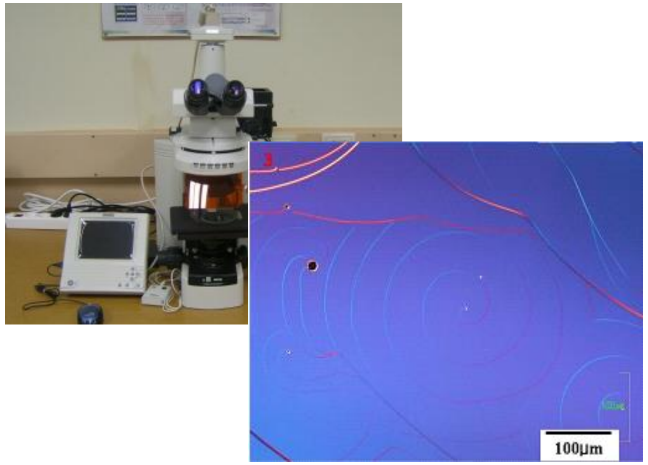
CL / PL



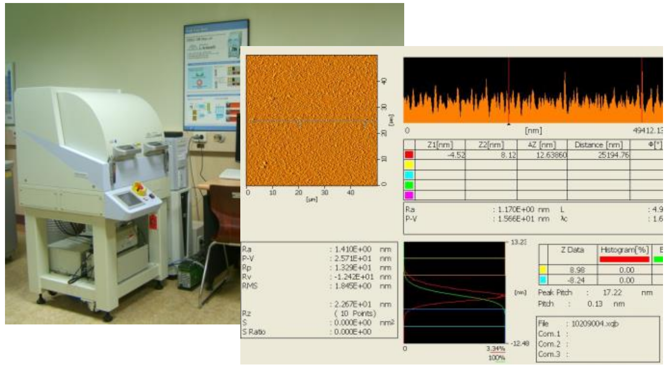


- Flatness tester: wafer Bow/Sori
- HR-XRD: Rocking curve data
- FE-SEM/EDS: Microstructure, composition
- OM/Polarizer: Stress, Defect
- CL/PL: Defect
- Large Area AFM: Roughness
- Hall Measure System: Electrical data

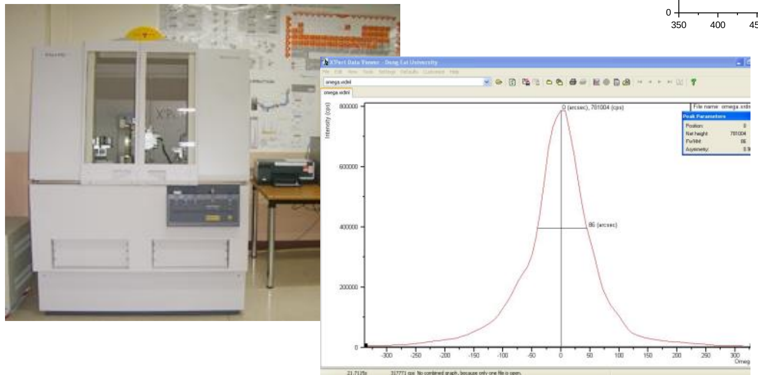
OM / Polarizer



AFM



HR-XRD



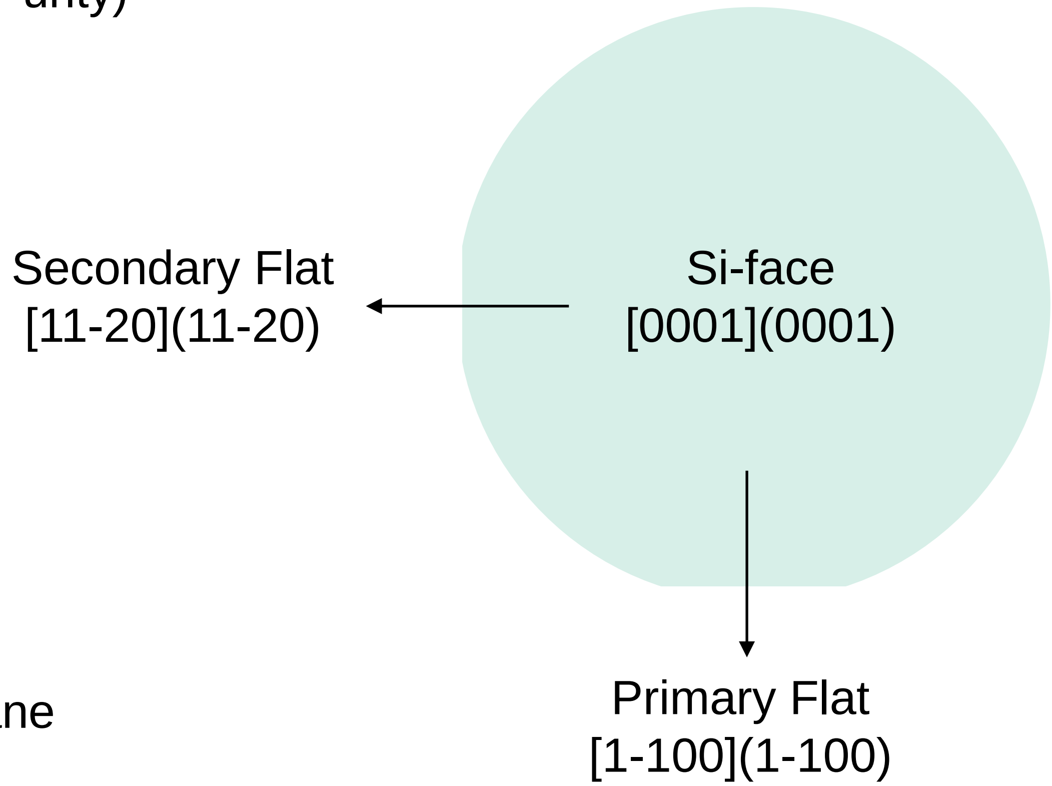
SiC Substrate

Surface

- Si-face, C-face
- Optical polish: single, double-side polish ($R_a \leq 3$nm)
- Standard polish: Epi ready ($R_a \leq 2$nm)
- CMP, Epi ready ($R_a \leq 1$nm)

Doping

- N-type(N)
- P-type(Al, B)
- Semi-Insulating (V, High Purity)



Plane

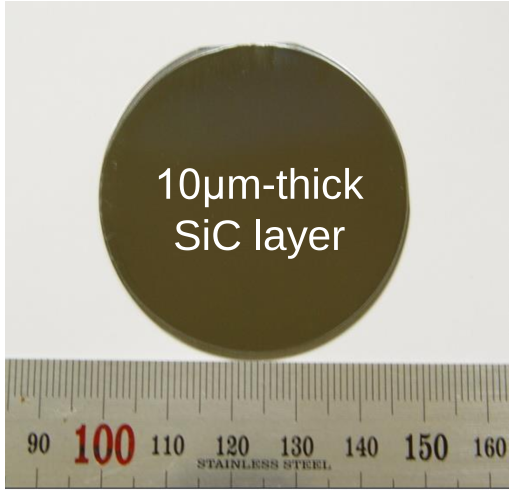
- on-axis (c-axis)
- off-axis(4.0^{o}-off, 8.0^{o}-off)
- Positive Polarity : Si-face
- Negative Polarity : C-face
- Non-polar : a-plane, m-plane
- Semi-polar : r-plane

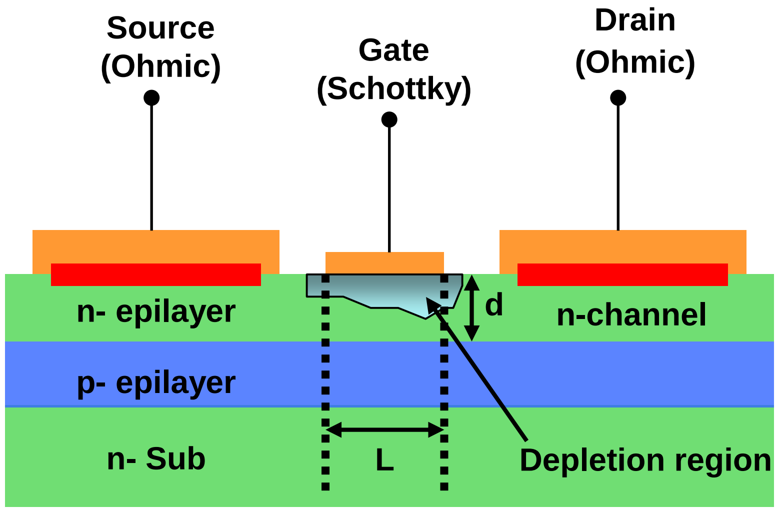
Defect

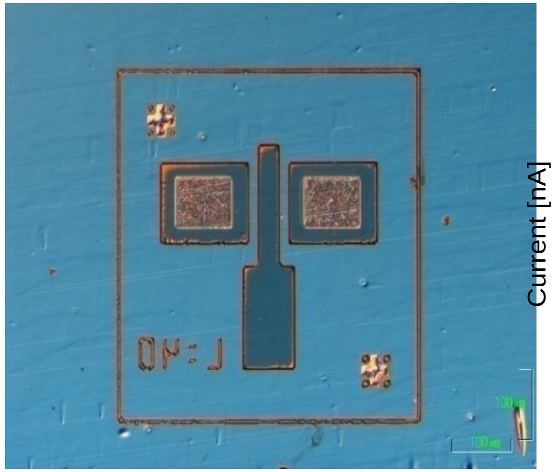
- Micropipe (MP)
- Foreign Polytype
- Edge exclusion
- Dislocation
- Stacking Fault
- Bow
- Scratch

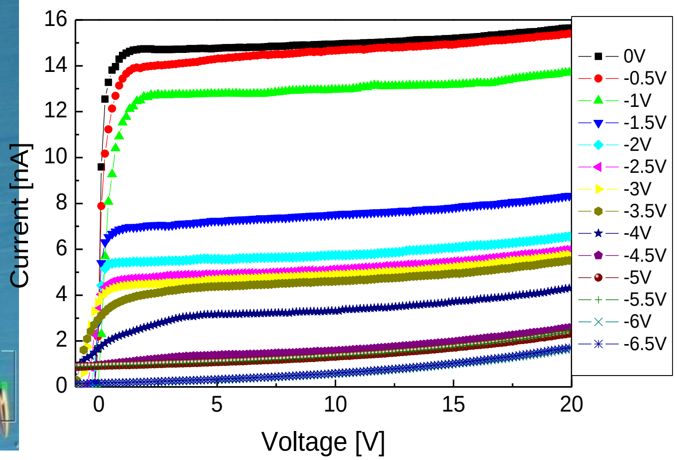
SiC Epitaxial Layer and MOSFET Device

2"-SiC epitaxial layer





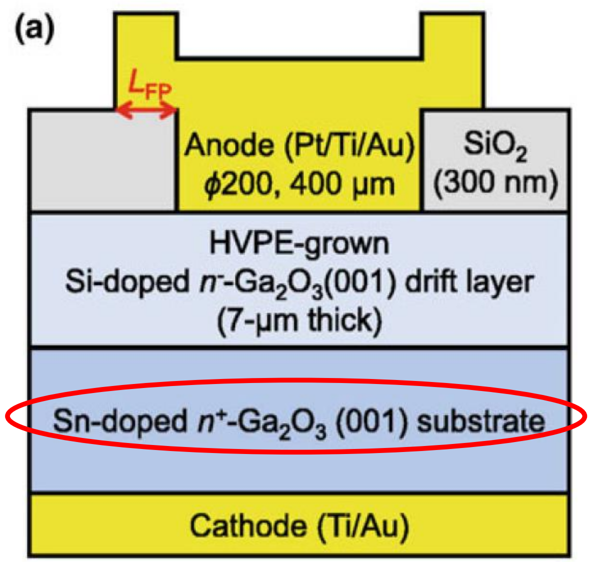




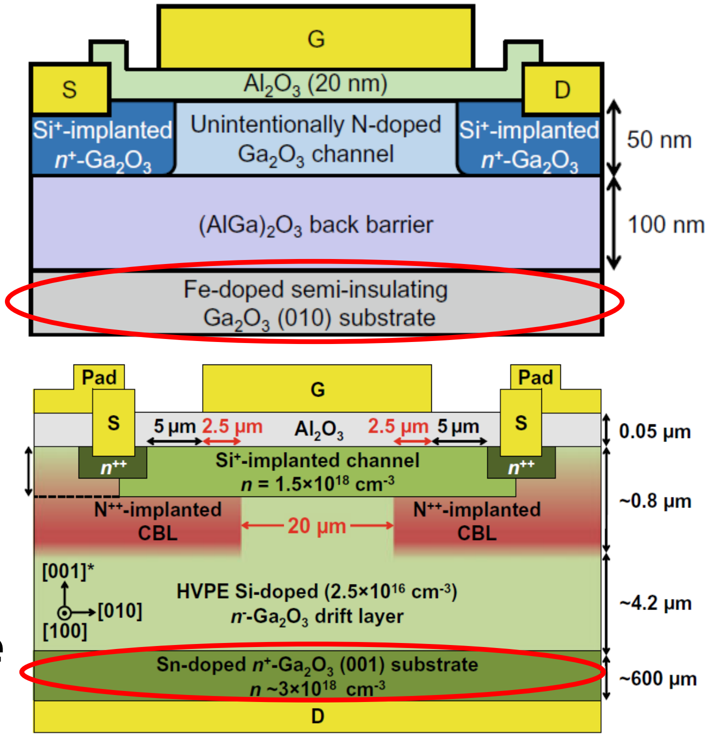
Publications

- High Quality SiC Crystal with New Crucible Design, ***Mater. Sci. Forum.*** Vol. 527-529 (2006) 83-86.
- Epitaxial Growth of 4H-SiC (0001), ***Mater. Sci. Forum.*** Vol. 527-529 (2006) 267-270.
- Inserted Epitaxial Layer for High Quality SiC Single Crystal, ***Mater. Sci. Forum***. Vol.556-557 (2007) 9-12
- Hydrogen Effect on SiC Single Crystal, ***Mater. Sci. Forum.*** Vol.556-557 (2007) 25-28
- p-type Epitaxial Layers using Various Si/Al ratios, ***Mater. Sci. Forum***. Vol. 556-557 (2007) 153-156
- CMP Process Parameters of 6H-SiC(0001), ***Mater. Sci. Forum***. Vol .600-603 (2009) 831-834
- Initial Stage Modification for 6H-SiC Crystal, ***Mater. Sci. Forum***. Vol. 615-617 (2009) 7-10
- Seed Polarity Dependence of SiC Crystal Growth ***J. Kor. Phys. Soc.*** Vol.54, No.5 (2009) 1834-1839
- Non-polar SiC substrate, ***Mater. Sci. Forum***. Vols. 645-648 (2010) pp 37-40
- a-plane (11-20) 6H-SiC Crystal Grown, ***J. Korean Physical Society***, Vol. 58, No. 5 (2011) pp1541-1544
- Comparative study on dry etching of α- and β-SiC nano-pillars, ***Materials Letters*** 87 (2012) 9–12
- Modified Crucible Design and Seed Attachment , ***Mater. Sci. Forum***, Vols. 740-742 (2013) pp 77-80

Ga_2O_3-based Power Devices

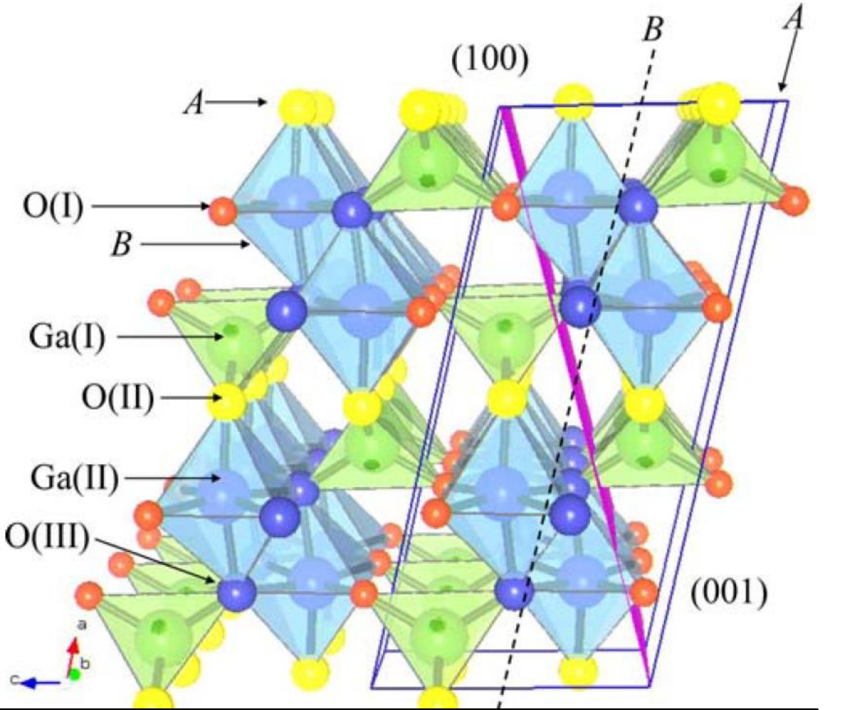


Ga_2O_3 field-plated SBD structure



Ga_2O_3 MOSFET Device

Structural Anisotropy of β-Ga_2O_3



Surface energies (σ, J m^{-2}) for the ideally-terminated and the relaxed or reconstructed surfaces

	Area	Ideal σ	Relaxed σ
(1 0 0)-A	0.1760	1.68	1.13[a]
(1 0 0)-B		0.96	0.68[a]
(0 1 0)	0.6874	2.78	2.03[a]
(0 0 1)-A	0.1852	3.35	
(0 0 1)-B		2.65	1.40[b]
$(1\ 0\ \bar{1})$	0.3705	3.99	1.57[a]

The area (nm^2) is that of the primitive (1 × 1) surface unit cell. The labels "A" and "B" refer to different lattice terminations.

[a] Relaxed (1 × 1) unit cell. 1 eV nm^{-2} = 0.160219 J m^{-2}.

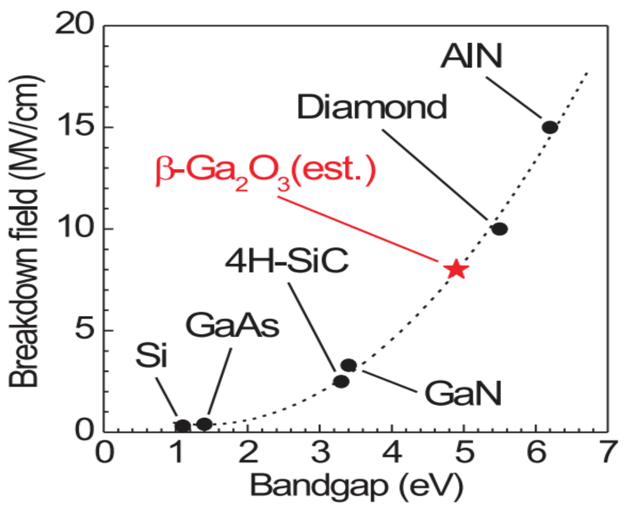
[b] Reconstructed (2 × 2) unit cell. A minimum-energy configuration could not be located by relaxing a (1 × 1) unit cell (see text).

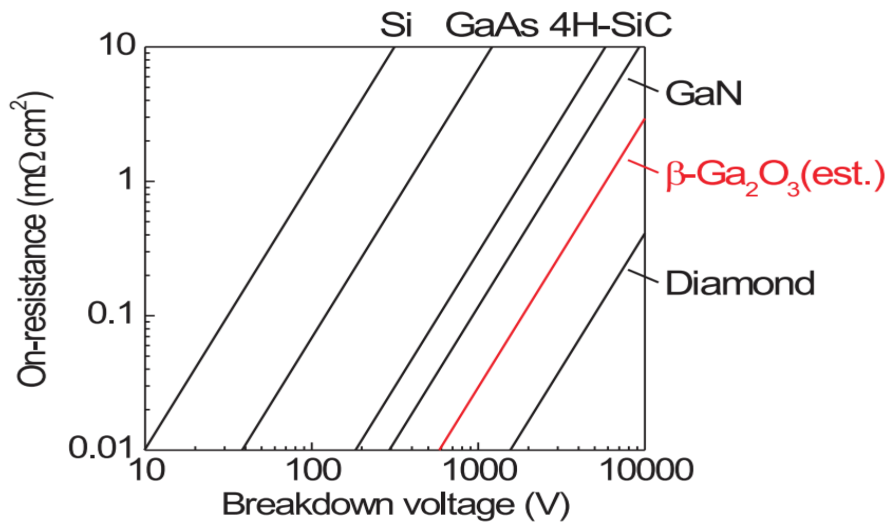
Unit cell of β-Ga_2O_3.

Gallium atoms Ga(I) and Ga(II) are coordinated tetrahedrally and octahedrally, respectively. Inequivalent O atoms have threefold (O(I) and O(II)) and fourfold (O(III)) coordination. Unit cell of monoclinic β-Ga2O3 with indicated cleavage planes {100} and {001}.

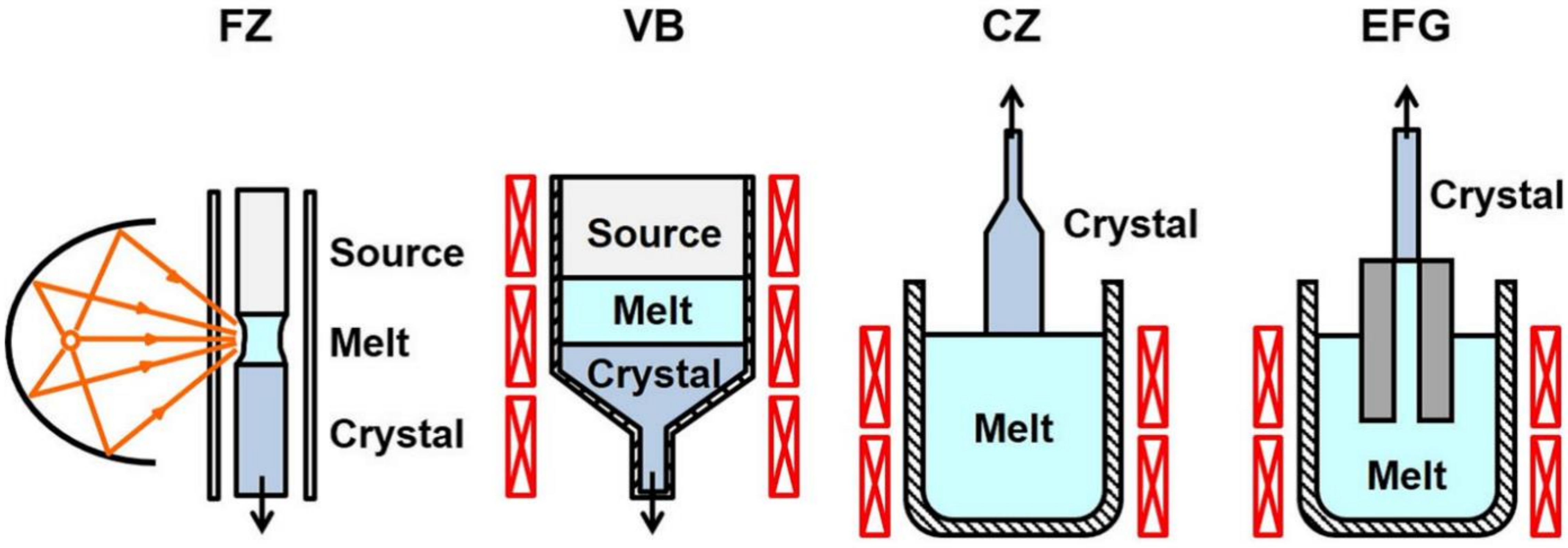
Properties of β-Ga_2O_3

Properties	Si	4H-SiC	GaN	β-Ga_2O_3
Bandgap (eV)	1.1	3.3	3.4	**~4.8**
Breakdown Field (MV/cm)	0.3	2.5	3.3	**8**
Electron Mobility ($cm^2/V \cdot s$)	1450	1000	1200 (Bulk) 2000 (2DEG)	200-300 (Bulk)
Saturation velocity ($\times 10^7$ cms^{-1})	1	2	2.5	~2
BFOM / BFOM $_{Si}$ ($\varepsilon_s \mu E^3_{Cr}$)		317	846	3214
JFOM / JFOM $_{Si}$ ($(V_{sat} E_{Cr})^2$)		278	1089	2844
Substrate cost		High	High	**Low**
Heterojunction		No	Yes	Yes



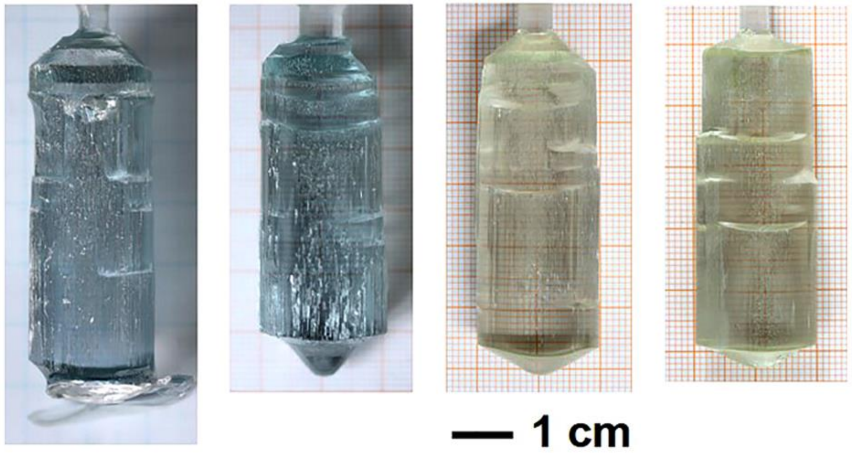


Various growth methods of Ga_2O_3

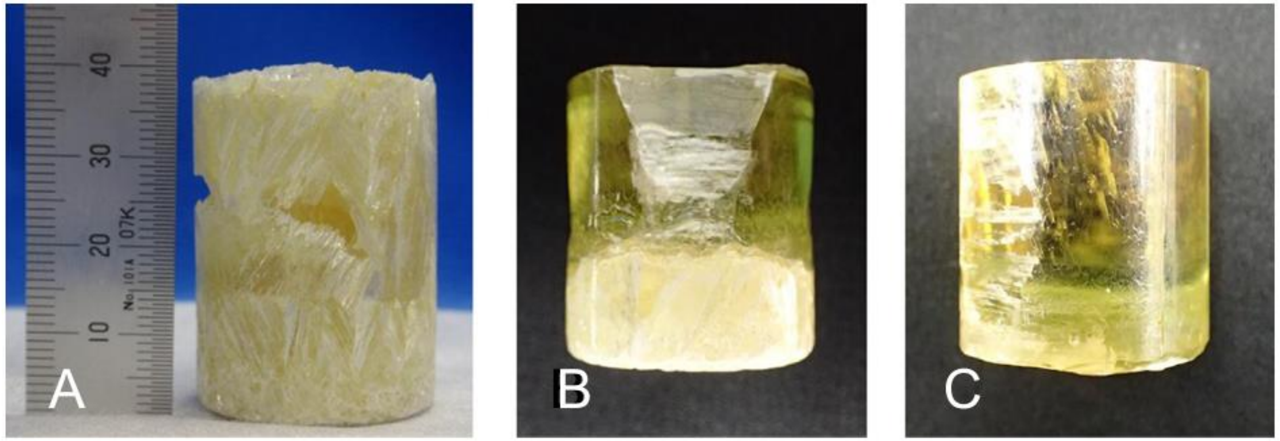


- Ga_2O_3 single crystals can be obtained through various solution growth methods such as FZ(Floating-Zone), VB(Vertical Bridgman), CZ(Czochralski), and EFG(Edge-defined Film-fed Growth) methods.

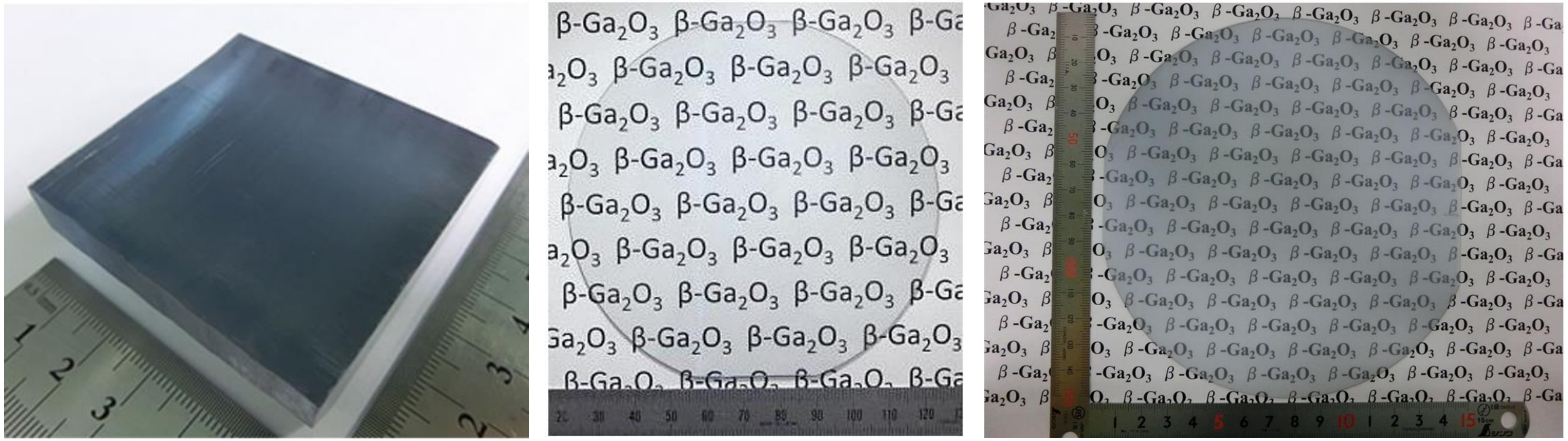
Various growth methods of Ga_2O_3



CZ (Germany, IKZ _ dia 2cm)



VB (Japan, Shinshu Univ _ dia 2.5cm)

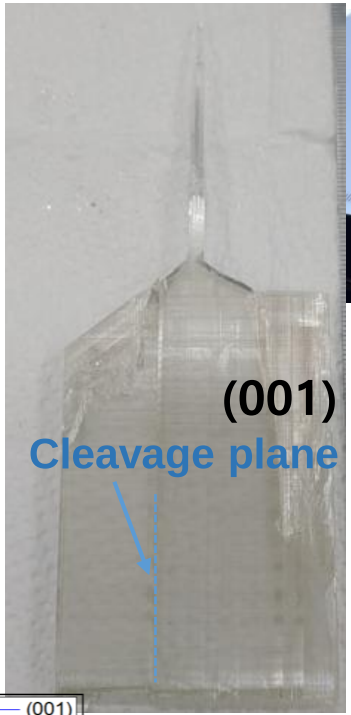


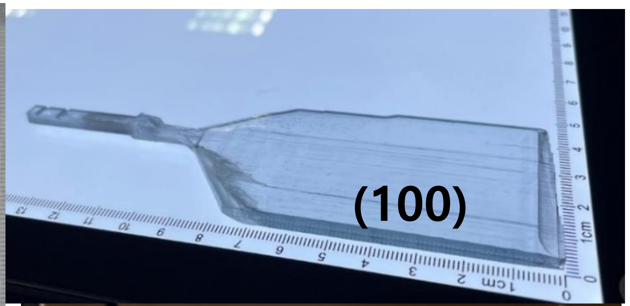
Ref. Novel Crystal Technology, Inc.

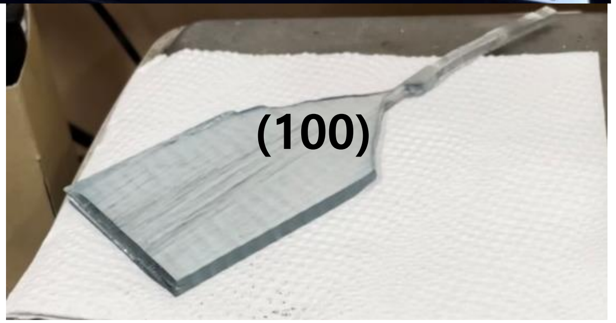
EFG (Japan, NCT _ dia 2, 4, 6inch)

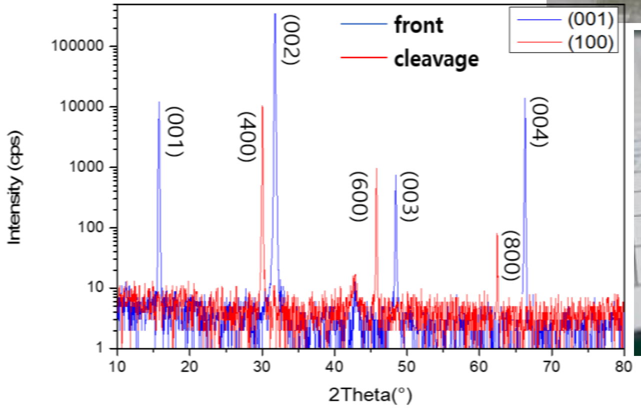
- **A key feature of the EFG method is the ability to precisely control the cross-sectional shape and size of the crystal ribbon using a die at very fast growth rates.**

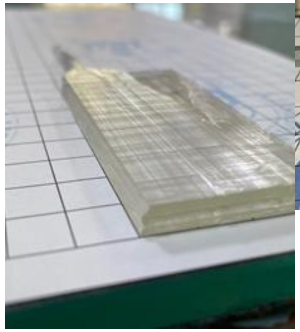
Ga_2O_3 Single Crystals

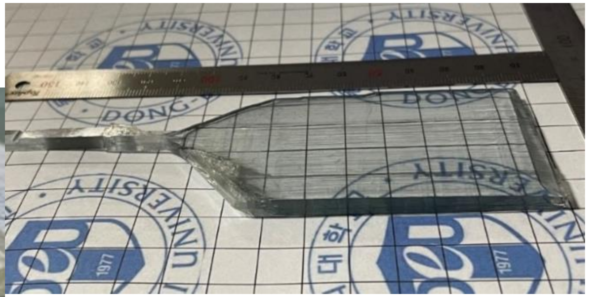




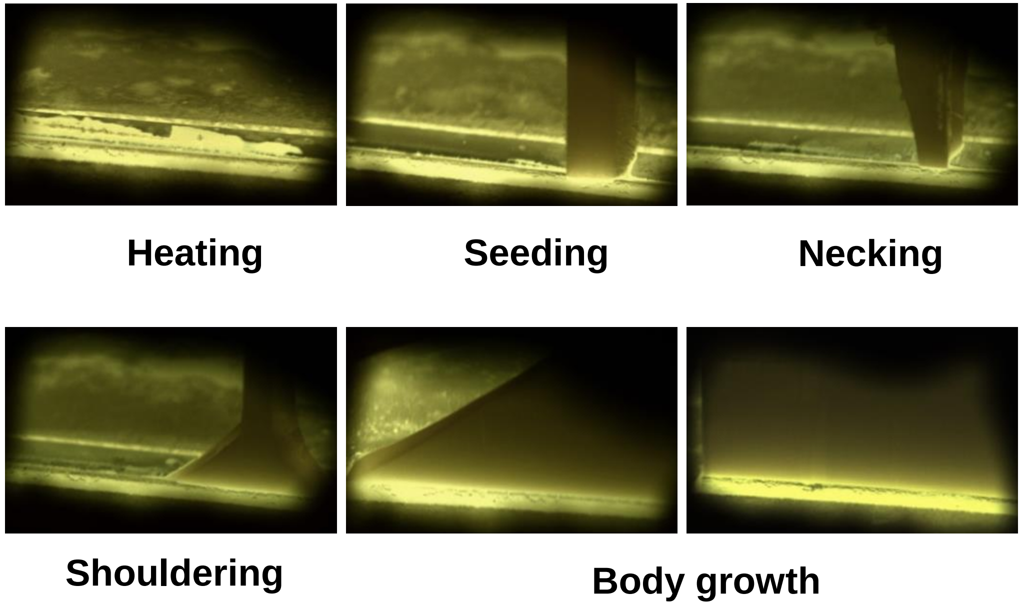






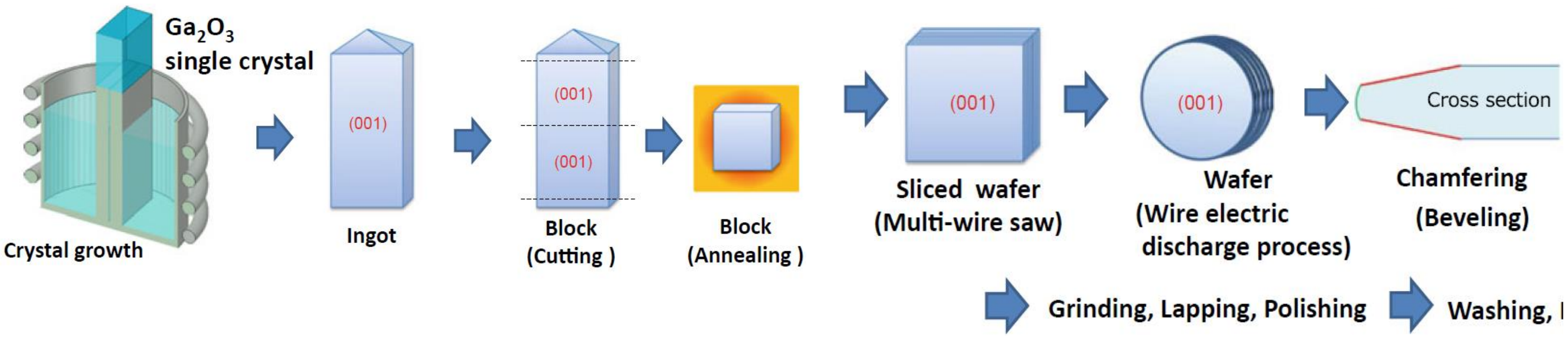


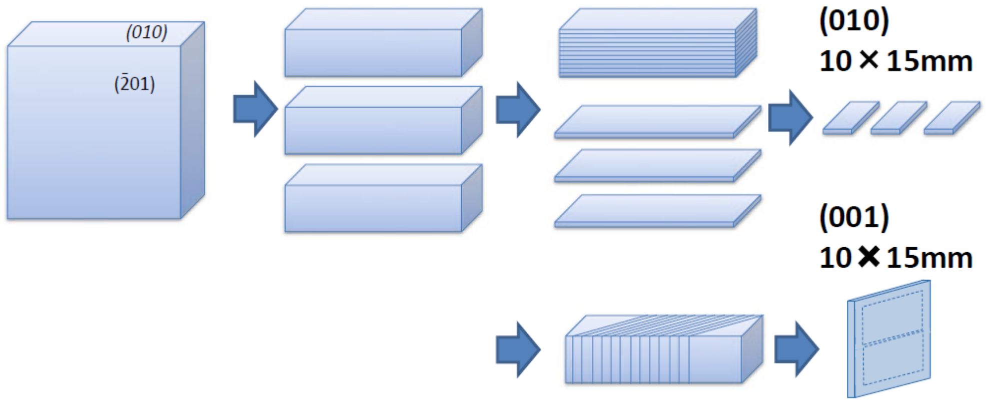
Edge-defined Film-fed Growth Method



▲ UID β-Ga_2O_3 single crystal

Ga_2O_3 Wafer Manufacturing





- **Schematic drawing of process for manufacturing wafers with a surface orientation different from that of the principal plane of the bulk crystal**
- **Process optimization should be done in different ways appropriate for each plane.**
- **Optimization of this process may have significant impact on the future of *β*-Ga2O3 manufacturing cost.**

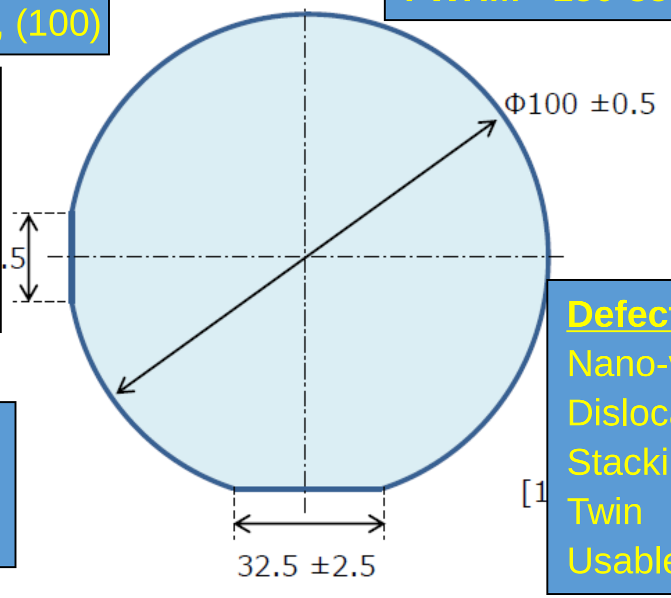
Ga_2O_3 Commercial Substrate

Orientation
(001) ($\bar{2}$01) (010), (100)

Thickness= 650µm
FWHM <150-350arcsec

Doping
N-type (Si, Ge, Sn)
Insulating (Fe, Mg)
Unintentionally-doped
P-type (?)

Surface
Front; CMP
Back; Grinding/CMP

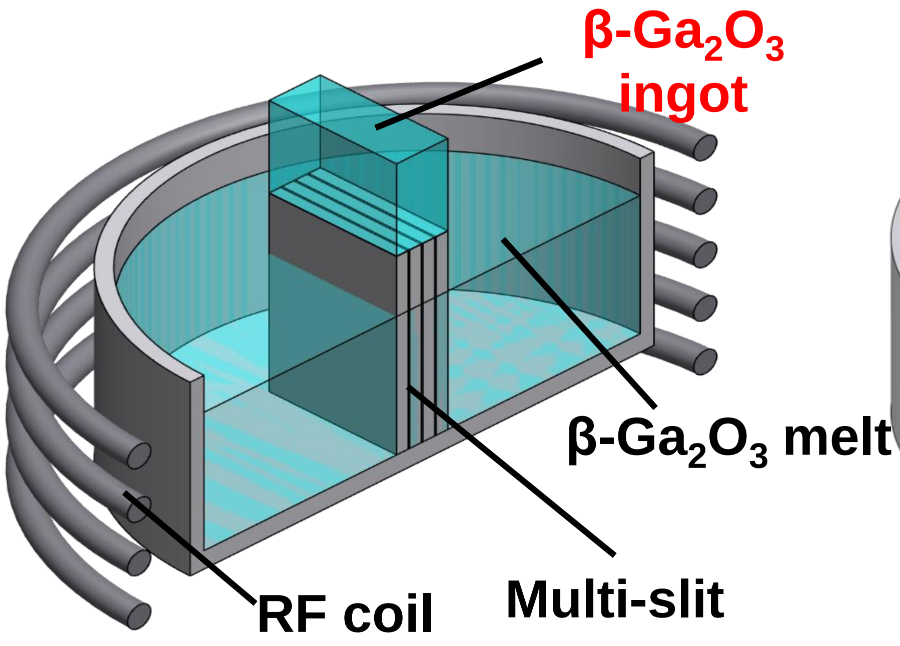


Defect
Nano-void
Dislocation
Stacking Fault
Twin
Usable area

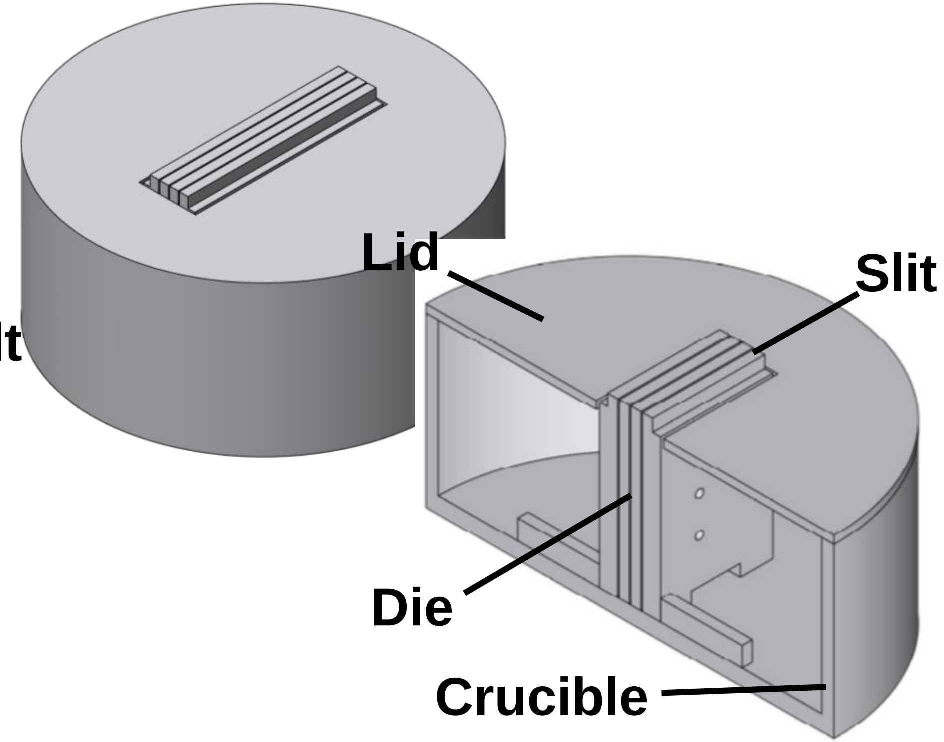
Novel Crystal Technology, Inc.

SYNOPTICS
CETC46

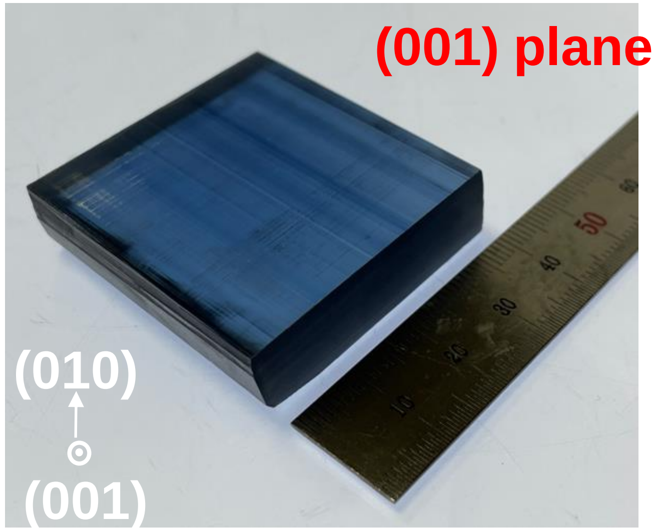
Growth Zone for β-Ga_2O_3 Crystals Block

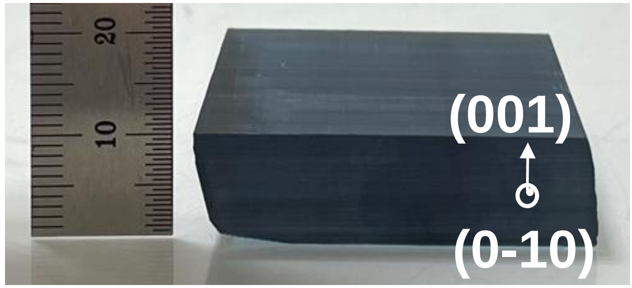


EFG Schematic



Multi-slit structure





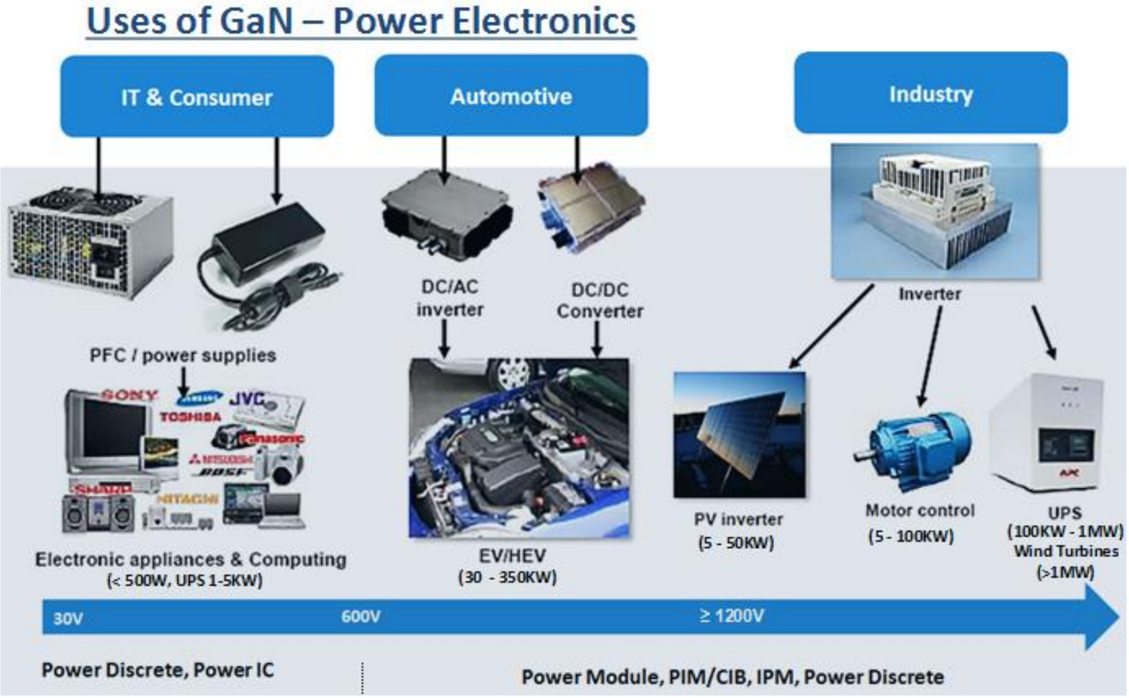
β-Ga_2O_3 crystals block were grown in the Ir die consisting of multi-slit structure by the edge-defined film-fed growth (EFG) process.

GaN Epitaxial Wafer

GaN

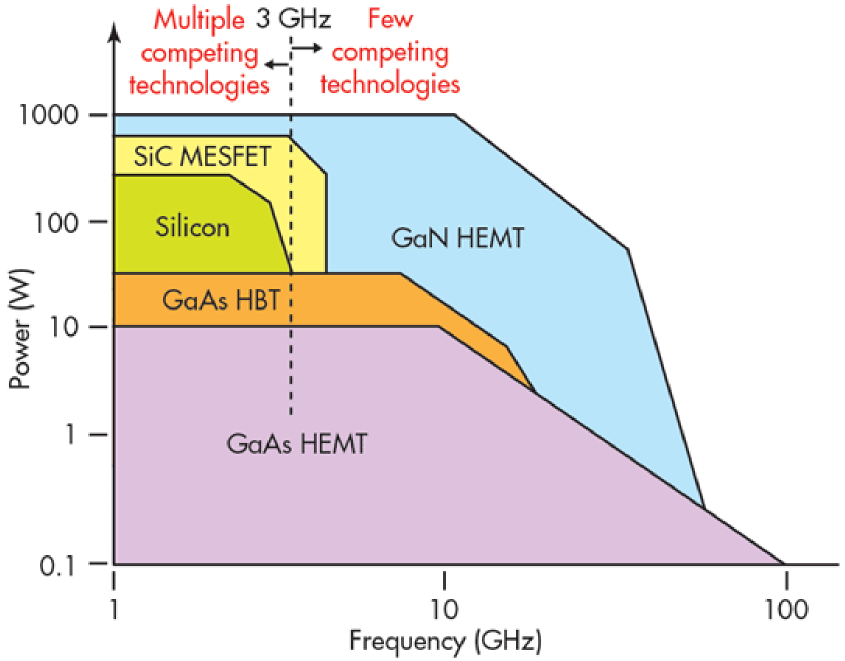
- GaN (Gallium Nitride), which is used in semiconductor power device as well as RF components and LEDs, enables high-speed, increase efficiency and higher power density

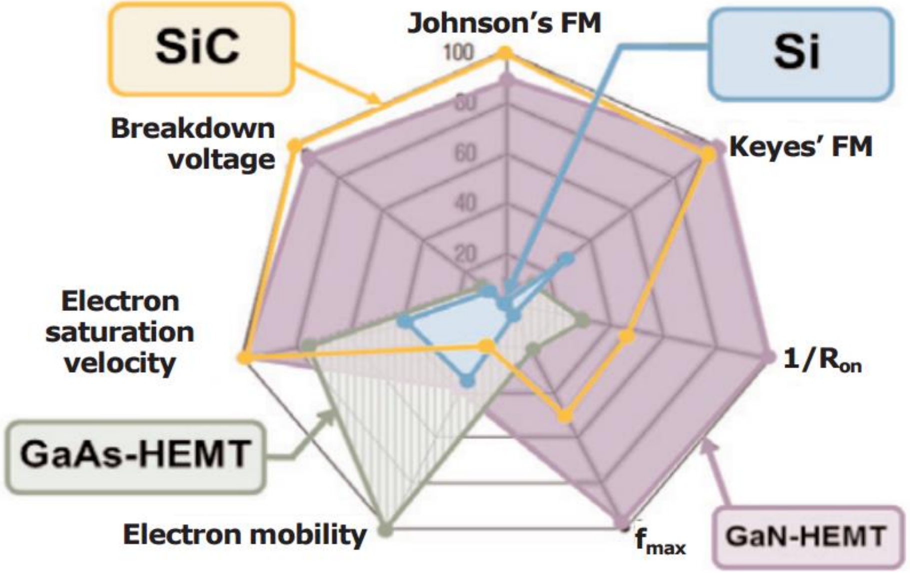
Application



[Ref.] http://uef.fei.stuba.sk/moodle/mod/book/print.php?id=7920

Advantage



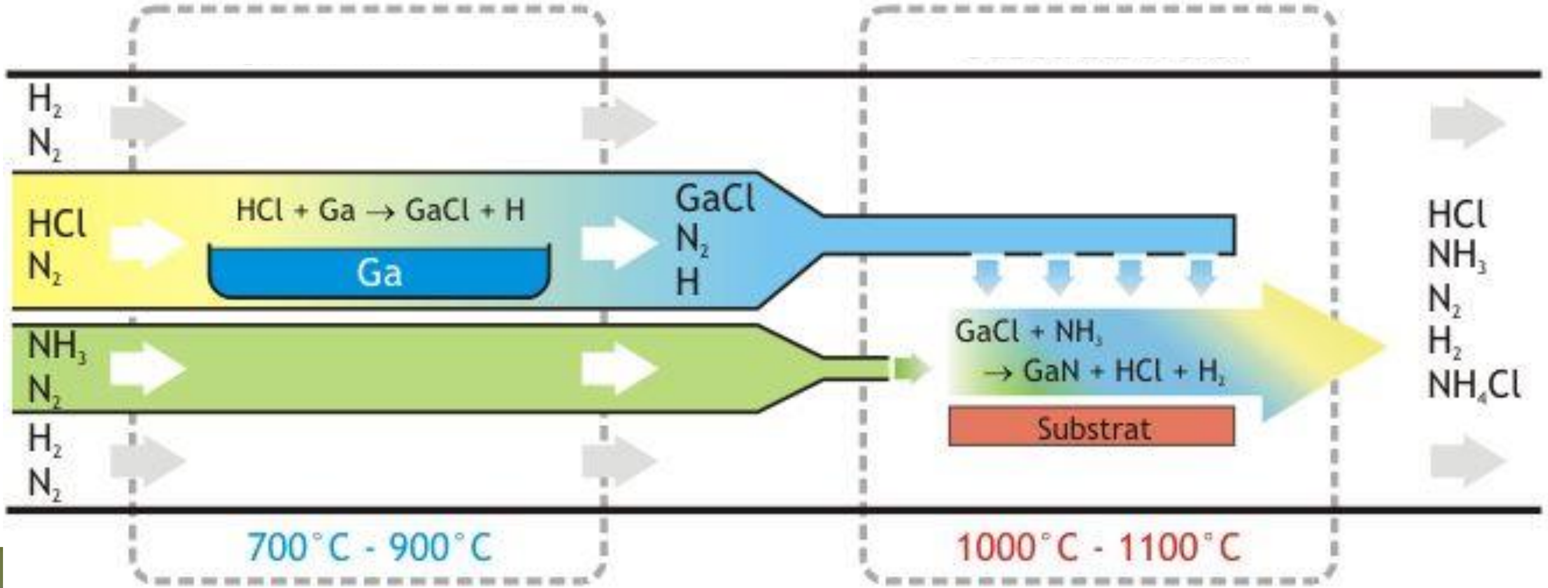


[Ref.] http://uef.fei.stuba.sk/moodle/mod/book/print.php?id=7920

HVPE system for GaN crystal growth

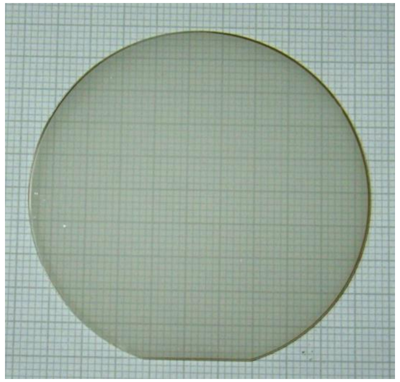
HVPE

- HVPE (Hydride Vapor Phase Epitaxy), which is which gaseous metal chlorides react with ammonia to produce the group-III nitrides, is an epitaxial growth method such as GaN, GaAs and InP.

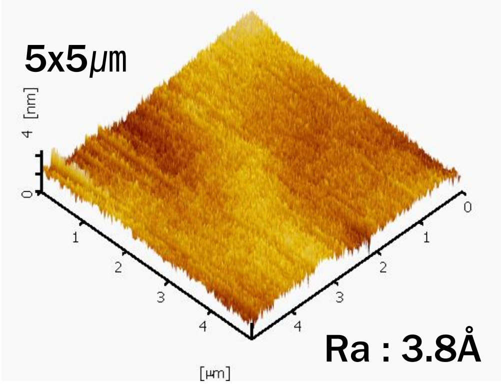


[Ref.] WIKIMEDIA COMMONS, https://commons.wikimedia.org/wiki/File:Schema_HVPE-Reaktor_de.png

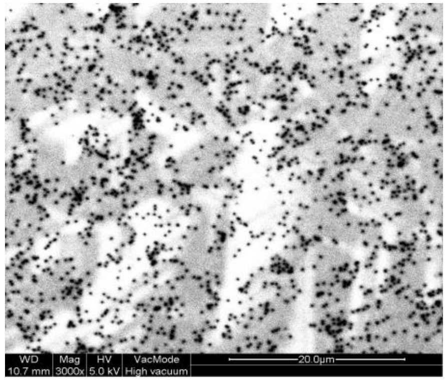
GaN on Sapphire (2 inch)



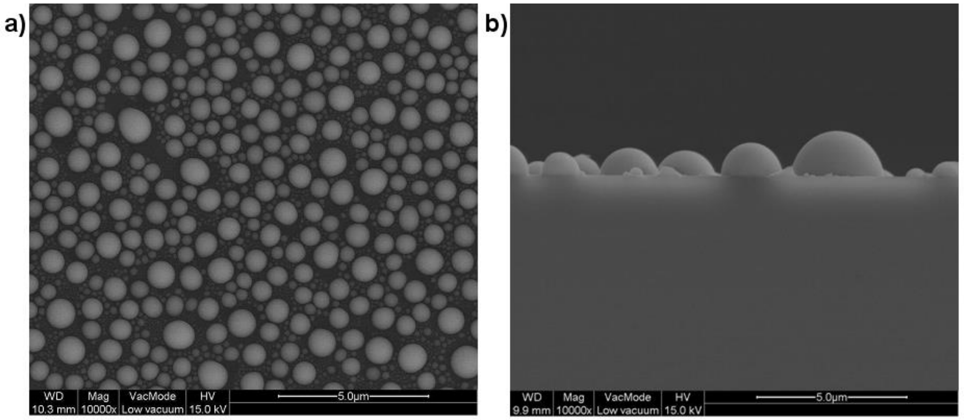
AFM data

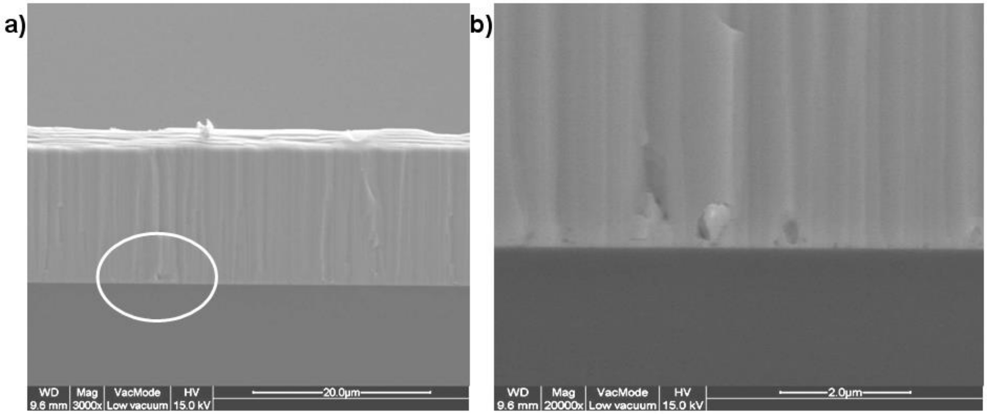


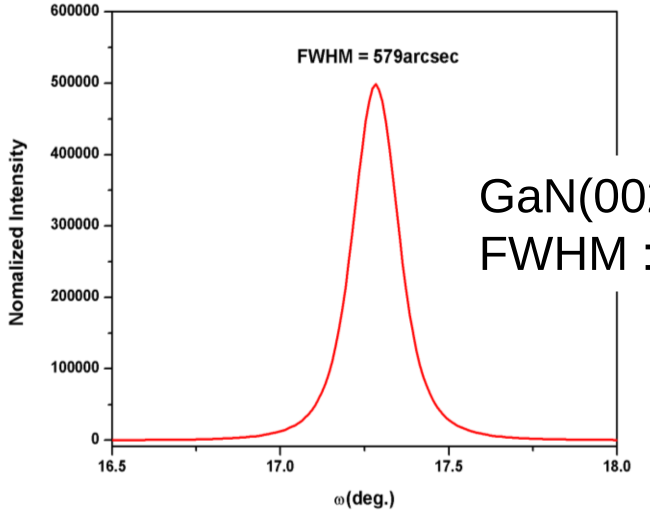
Defect of GaN



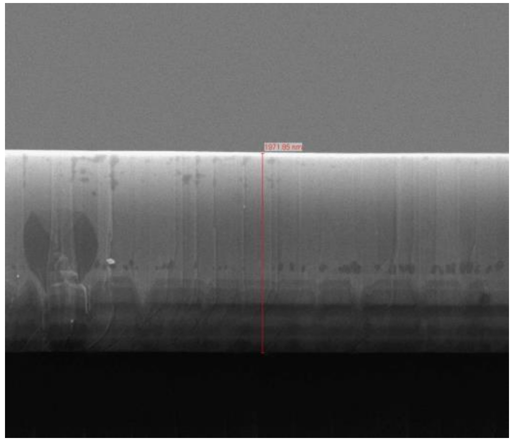
GaN growth by HVPE method

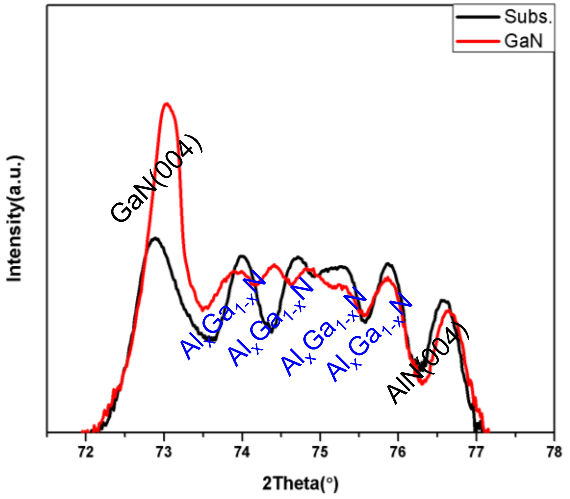






GaN(002)
FWHM : 579arcsec



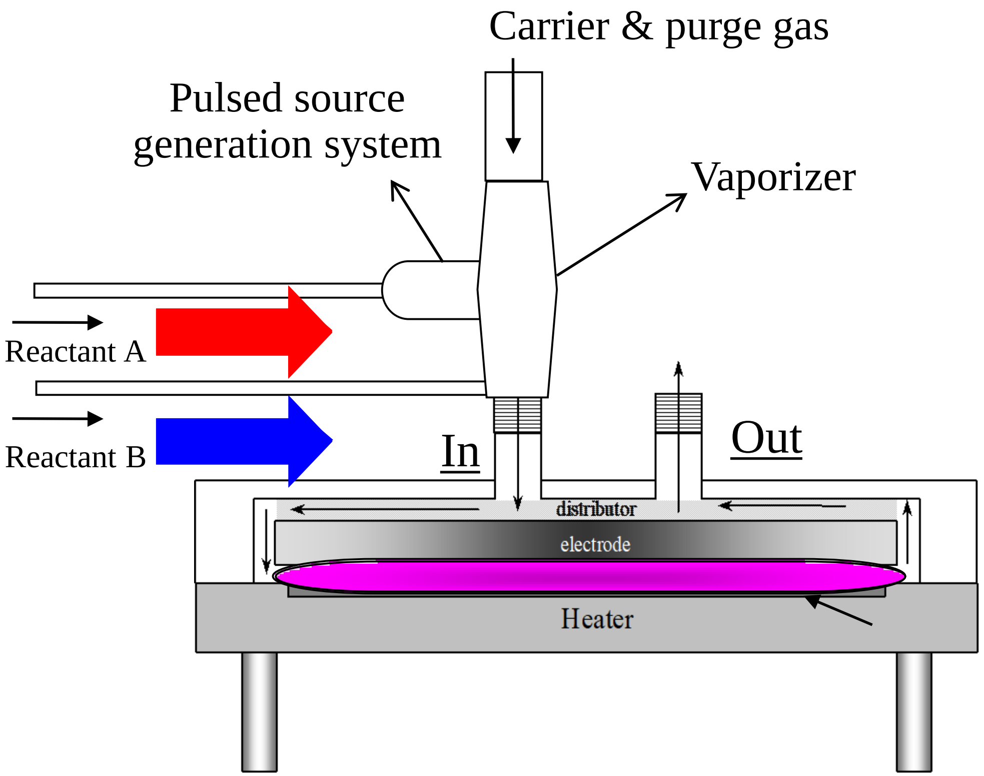


GaN/AlGaN buffer/Si Structure

Recent Publications

- GaN by HVPE technique, ***Phys. Status. Solidi C*** Vol. 7 (2010) 1770-1774
- GaN by HVPE and MOCVD methods, ***Phys. Status. Solidi C*** Vol. 7 (2010) 1794-1797
- Epitaxy of GaN on Si(111) substrate, ***Journal of Crystal Growth***, (2013)

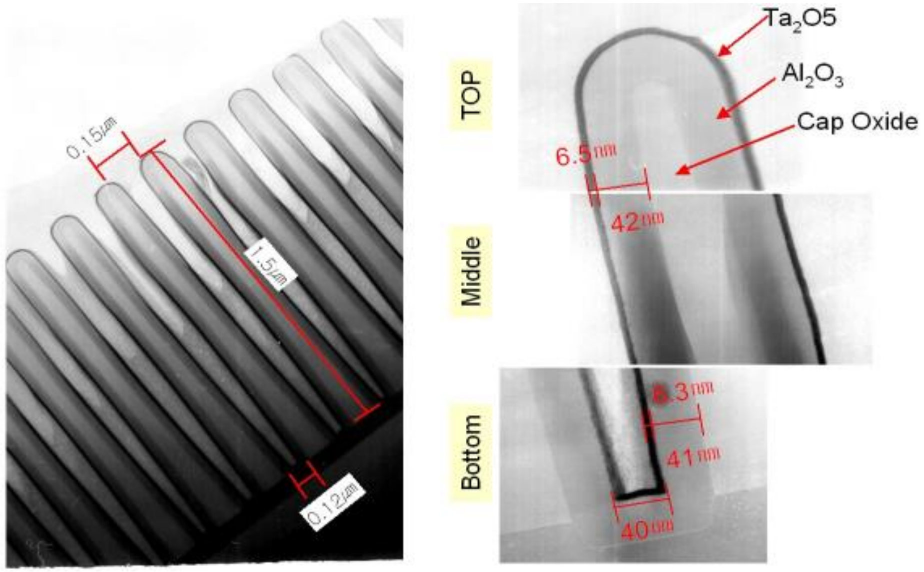
PEALD system for oxide films

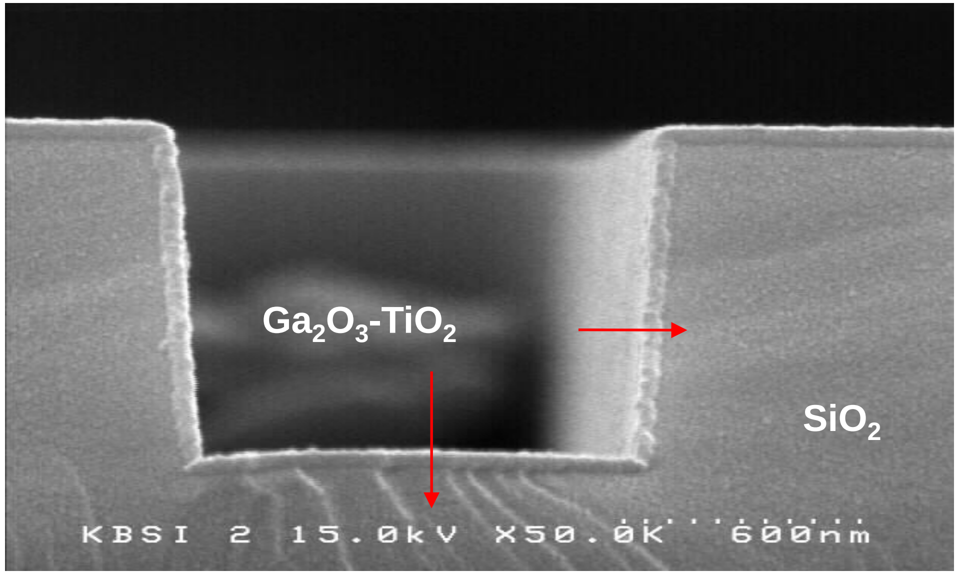


Main specification

- 5-inch wafer loading
- RF generator for plasma enhancement
- Injector(Vaporizer) for liquid source

Dielectric thin films by PEALD / PLD

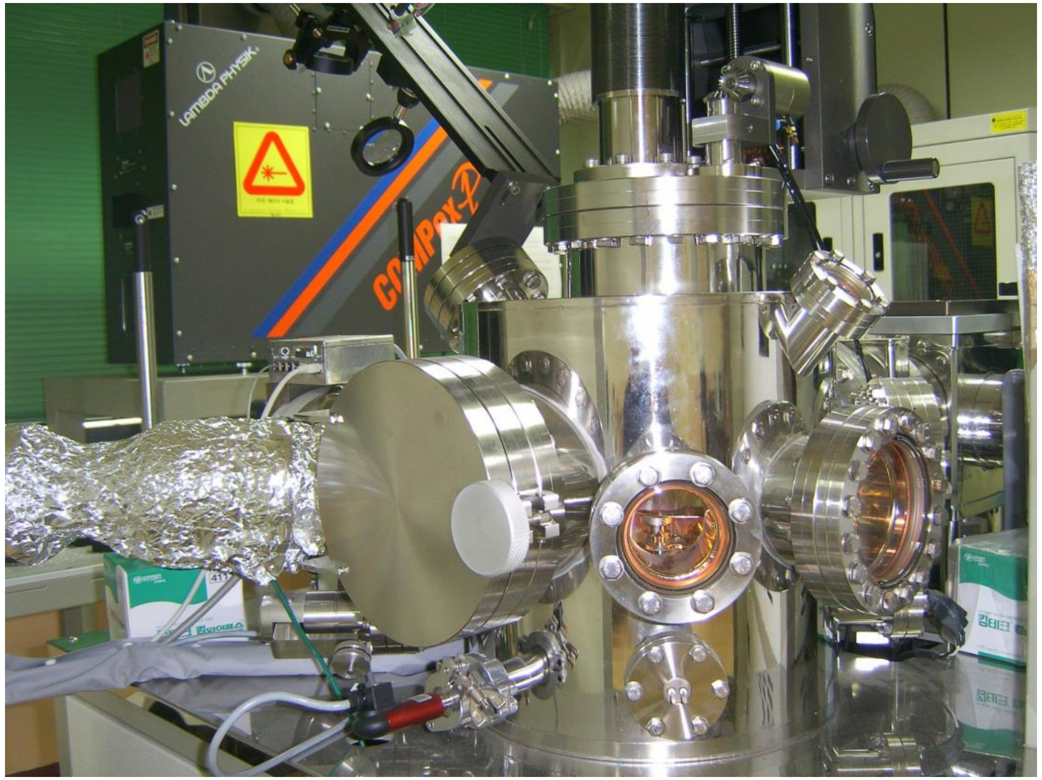


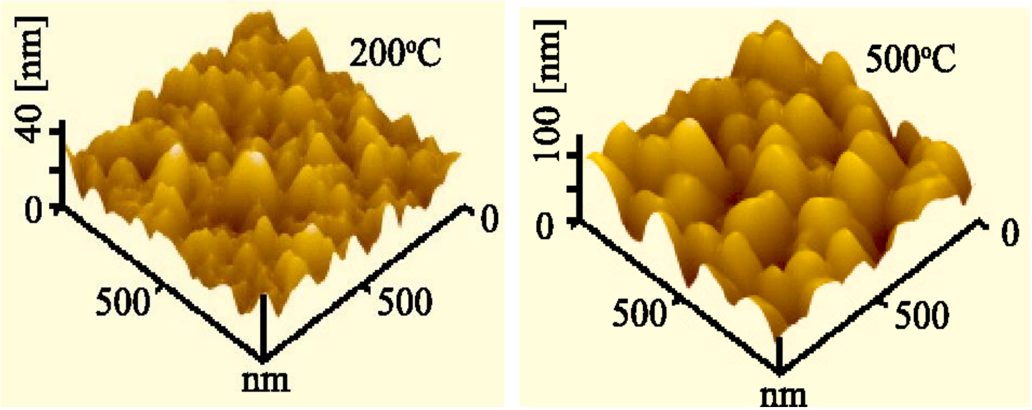


Recent Publications

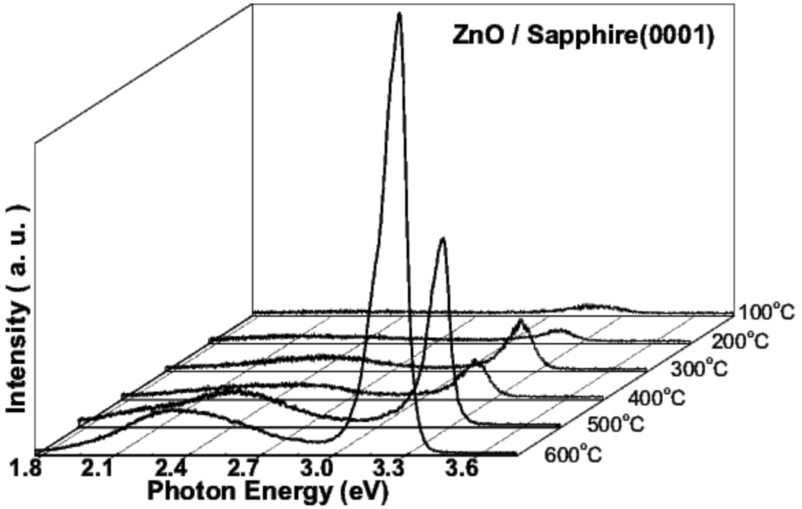
- Gallium Oxide thin film, ***J. Appl. Phys.*** Vol. 98 (2005) 023504
- Ga_2O_3-TiO_2 nanomixed films, ***Appl. Phys. Lett.*** Vol.87 (2005) 082909
- Ga_2O_3-based thin films, ***J. Electroceramics*,** 17 (2-4) (2006) 145-149.
- Growth Temperature Dependence of TiO2. ***J. Korean Phys. Soc***. Vol. 50 (6) (2007) 1827-1832
- Al0.016In0.003Zn0.981O by PLD, ***J. Electrochemical Soc.***,Vol. 155, 10 (2008) H786-H790
- Bi3NbO7 Films by Nanocluster Deposition, ***Electrochemical Solid-State letter***, 12 (5) (2009) G23-G26
- ITO by NCD technique, ***J. Electrochemical Soc.***, Vol. 157, 10 (2010) H937-H941
- Atomic layer deposition Al-doped ZnO films, ***J. Appl. Phys.*** 108, (2010) 043504
- 0.65Pb($Mg_{1/3}Nb_{2/3}$)O_3–0.35PbTiO_3 epitaxial films, ***Sensors and Actuators B*** 155 (2011) 854–858
- Structural and Optical Properties of TiO2 Films on Glass Substrate, ***Jpn J Appl Phys*** 51 (2012) 09MF12
- Selective growth of pure magnetite thin films, nanowires, ***J. Mater. Chem. C.*,** (2013) 1, pp.1977–1982

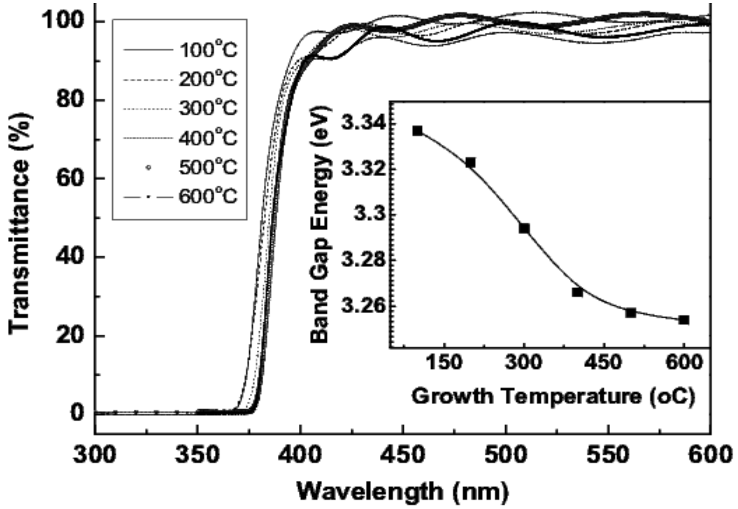
PLD system for ZnO / doped-ZnO





ZnO / doped-ZnO Thin Films





Recent Publications

- Mg doped ZnO thin films and aging, ***J. Appl. Phys.*** Vol. 95(9) (2004) 4772-4776
- ZnO thin films on sapphire (0001) substrates ***J. Electroceramics*. ** 13 (2004) 189-194
- Deep-level emission in ZnO thin films ***Appl. Phys. Lett.*** 86 (2005) 221910
- Transparent Conductive ZnO thin films on glass substrates ***J. Crystal Growth*.** 277 (2005) 284-292
- Stokes shift, blue shift and red shift of ZnO ***J. Crystal Growth*.** 291 (2006) 328-333.
- Ga:ZnO thin films on sapphire substrates ***J. Electroceramics*,** 17 (2-4) (2006) 287-292.
- In_2O_3-Doped ZnO Thin Films ***J. Korean Phys. Soc*,** Vol. 50 (3) (2007) 626-631.
- The role of oxygen vacancies in epitaxial-deposited ZnO thin films. ***J. Appl. Phys.*** Vol. 101 (2007) 053106
- Na-Doped ZnO Thin Films***, J. Nanoscience and Nanotechnology,*** Vol. 8, (2008) 5203-5207
- Boron and nitrogen co-doped ZnO Thin Films, ***Ceramics International,*** Vol. 34 (2008) 1011-1015
- Codoping in ZnO by AlN, ***Vacuum*** Vol. 83 (2009) 1081-1085
- Zn1-xCrxO thin films, ***J. Alloys Compd.*** Vol.478 (2009) 45-48
- In-doped ZnO nanorods, ***Appl. Phys. Lett.*** Vol. 94, (2009) 041906
- ZnO/SiC, ***J. Crystal Growth*** Vol.312 (2010) 2393-2397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Thank you
Questions & Comments !