Intelligent Epitaxy Technology, Inc.

IntelliEPI

CS International 2023

Capability Advancement of Production MBE for Next Generation Compound Semiconductors

By
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BSI
ISO 9001:2015
FM511967

Outline

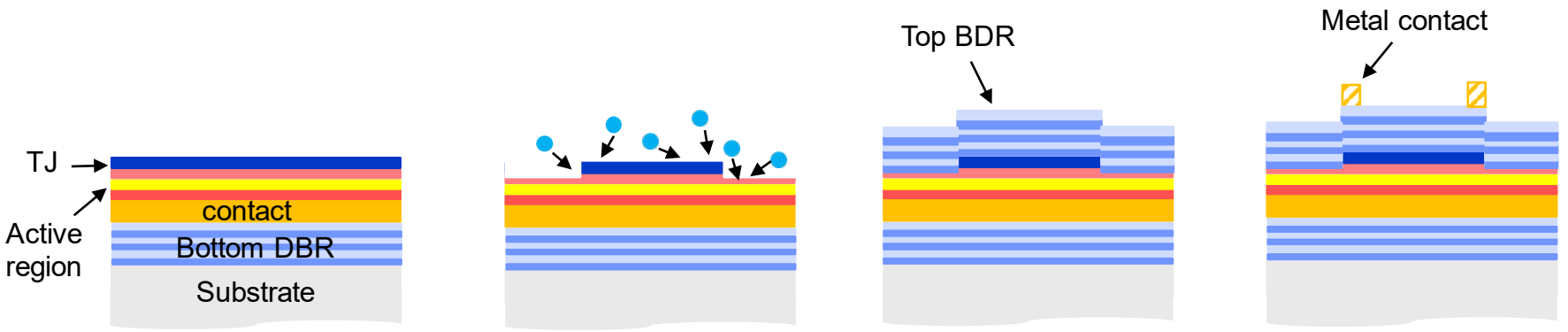
- Motivation
- Riber 8000: Status of qualification
  - *Uniformity*
- In-situ sensor capabilities
- MBE compatible process integration
  - *Hydrogen-cleaning*
  - *In-situ metallization*
  - *Multi-chamber MBE integration*
  - *Cluster tool for integration with 300mm process*
- Summary

Motivation for Advancement of MBE and Process Integration

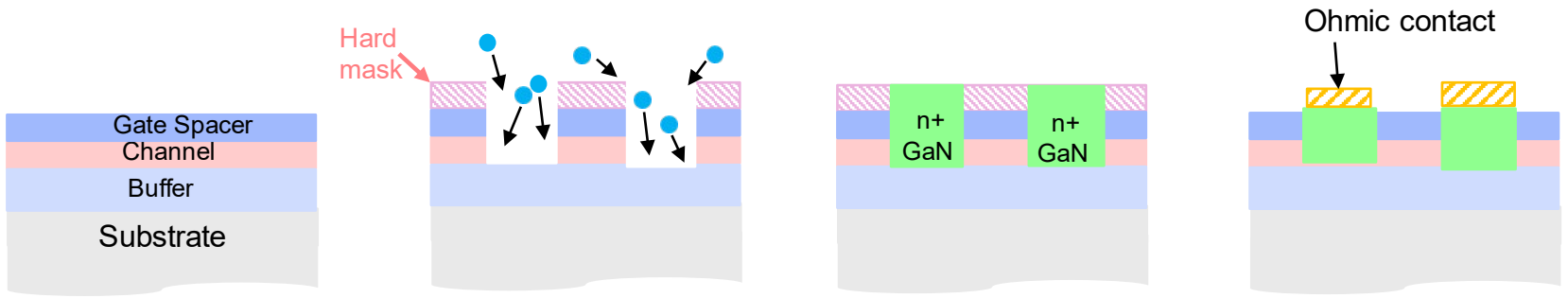
Challenge for compound semiconductor manufacturing: More manufacturing capacity with more performance

- Advantages for MBE growth technology
  - *More abrupt interface control*
  - *Lower intrinsic background especially for C & H*
- Challenge for scaling up of production MBE: Increase throughput with improved performance
- In-situ sensor capabilities available for production MBE → improve/maintain process control
- Integration of more complex processes with other process technologies (MOCVD, CVD, ….)
  - *Multiple growth chambers & re-growth processes to address integration of incompatible epi growth materials*
    - CPV with multi-junction solar cell or long wavelength GaAs VCSEL with dilute nitride
    - InP growth compatibility with thick Sb-based growth such as GaAsSb-base HBT
  - *Pre- & post-growth in-situ process capabilities: cleaning, etching, metallization, passivation, ….*

Multiple Epi Growth & Processing Steps for More Advance Devices



VCSEL with DBR re-growth



GaN HEMT with S/D n+ contact re-growth

Initial Starting Epi:
MBE, MOCVD, CVD, ….

Pre-epi in-situ Process:
Clean, Etch, ALD, ALE, ….

Re-growth:
re-growth (additional structure or ohmic contact), passivation, ….

Post-epi In-situ process:
Metal (W, Mo, Ti/Au, Passivation (SiNx, SiOx), ….

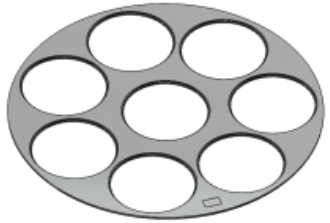
- **Increase in device performance → more complex integration of epi & process steps**

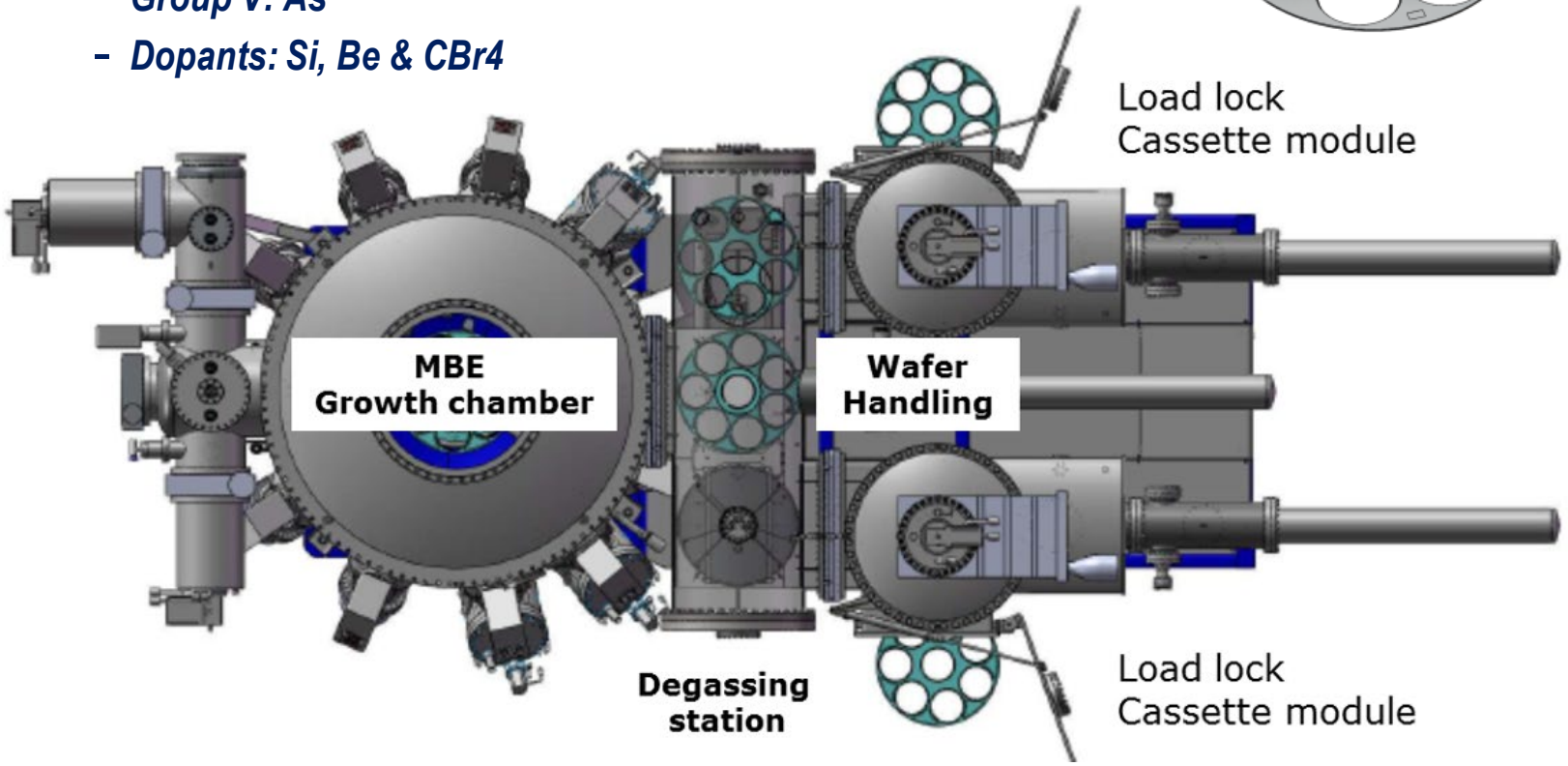
Riber MBE 8000 Status Update

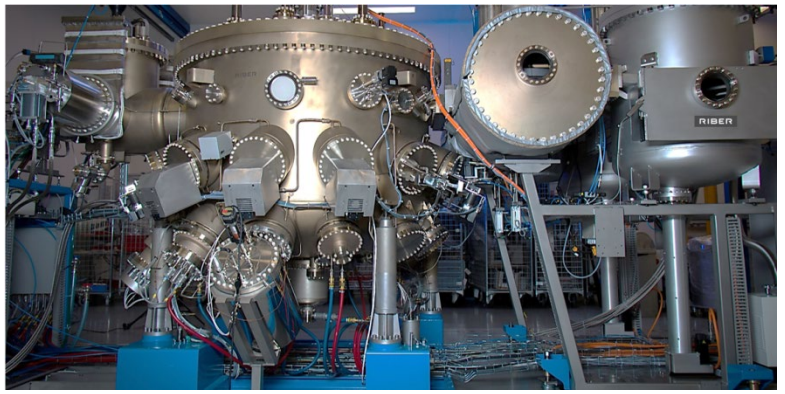
8x6” Riber MBE 8000 Development

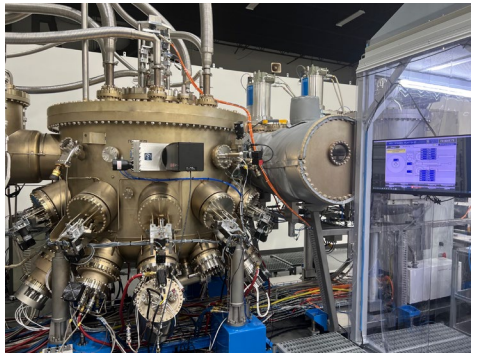
MBE 8000 joint development effort between Riber and IntelliEPI

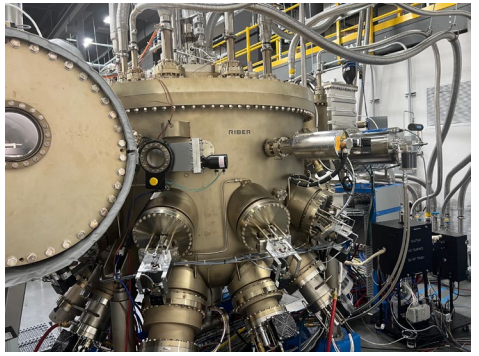
- Optimized for high uniformity for demanding application such as VCSEL
- Large capacity epi reactor: Support 4x8” & 8x6” platen
- 12 main source ports
  - *Group III: Al, Ga & In*
  - *Group V: As*
  - *Dopants: Si, Be & CBr4*





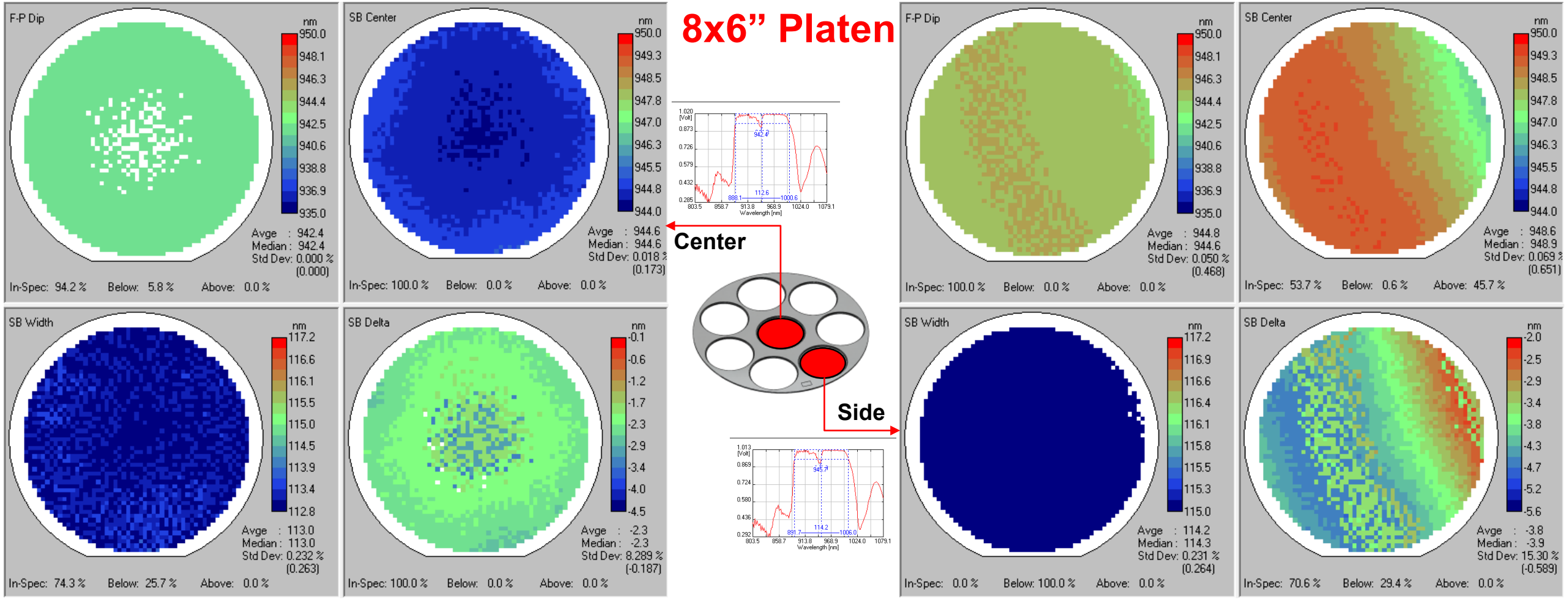






RIBER VCSEL Map from Epi Wafers Grown with Riber 8000

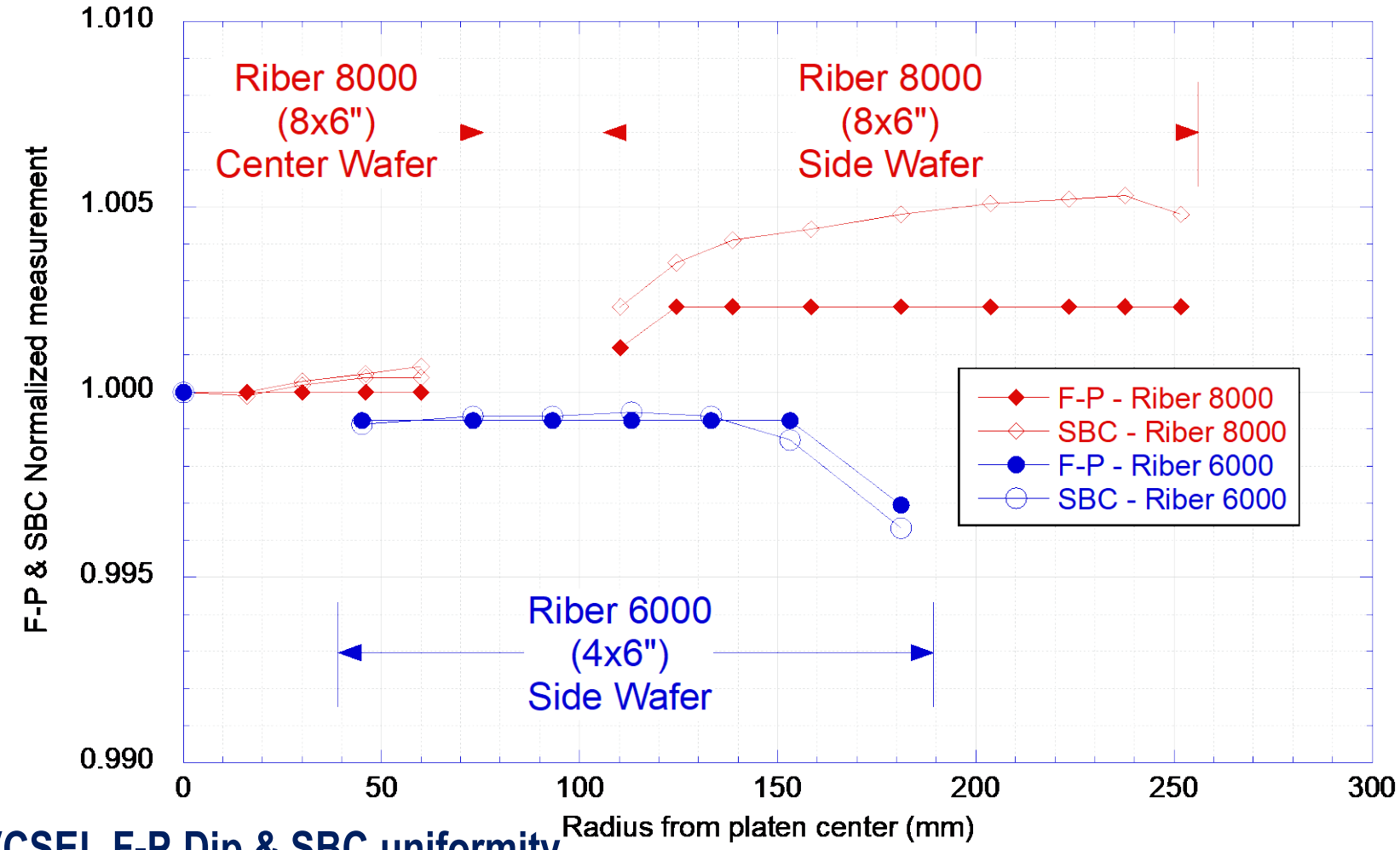
IntelliEPI

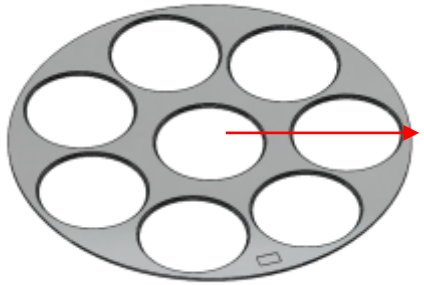


Wavelength variation for 940 VCSEL grown on 8x6” platen

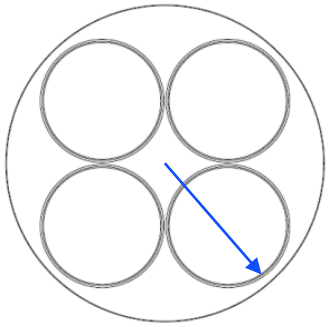
- F-P dip: < 1 nm across center wafer; & within 2 nm across side wafer
- SBC: < 1 nm across center wafer; & within 3 nm across side wafer

MBE 8000: VCSEL Optical Cavity Uniformity Map





Riber 8000:
8x6” Platen
Dia.: 550 mm



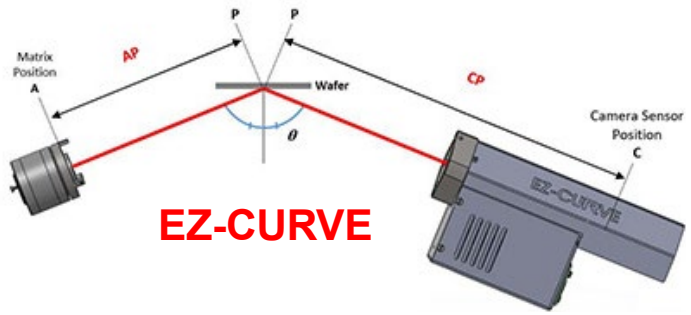
Riber 6000:
4x6” Platen
Dia.: 400 mm

VCSEL F-P Dip & SBC uniformity

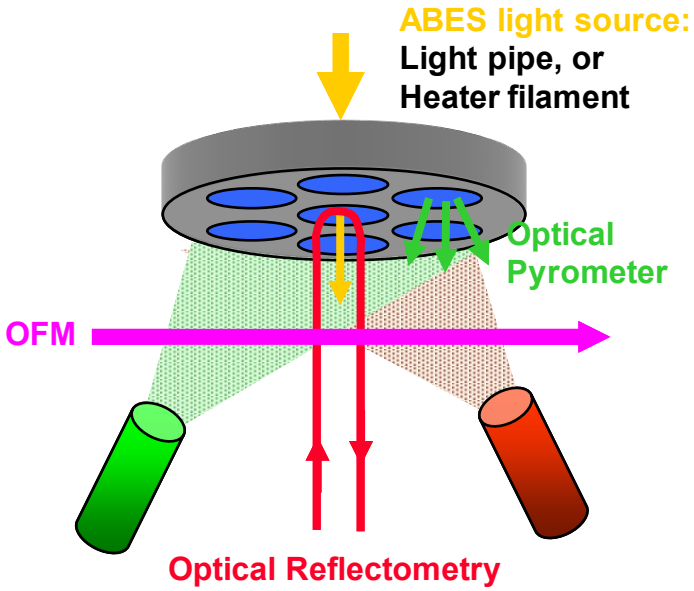
- **< 0.5% across entire Riber 8000 8x6” platen → Equivalent to ~ 850 ± 3 nm or better**
- **Uniformity across 6” wafer < 0.3% → Equivalent to ~850 ± 1.5 nm or better**

Overview of in-situ Sensor Technologies for MBE

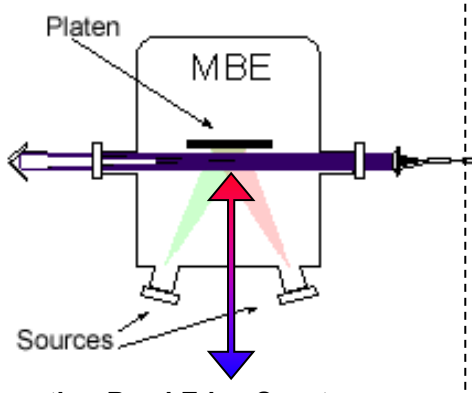
- **Substrate temperature**
  - *Pyrometry*
  - *Absorption Band-Edge Spectroscopy (ABES): band-gap dependence on temp*
- **Materials composition**
  - *Optical-based Flux Monitor (OFM): atomic absorption of group III fluxes*
- **Growth rate**
  - *RHEED*
  - *Optical Reflectometry*
  - *Pyrometric Interferometry*
- **Wafer flatness (lattice matching control)**
  - *Optical reflection imaging (EZ-CURVE)*



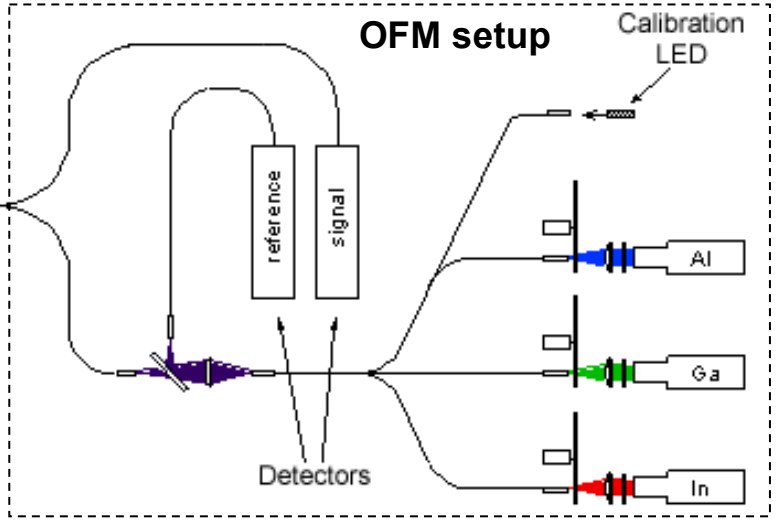
EZ-CURVE



Optical Reflectometry



Absorption Band-Edge Spectroscopy, Pyrometer, and Optical Reflection.

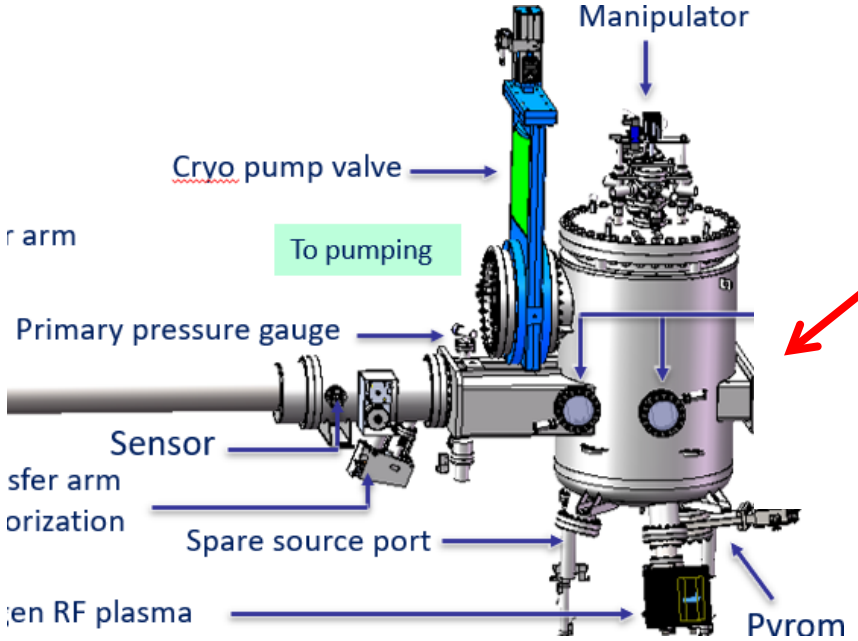


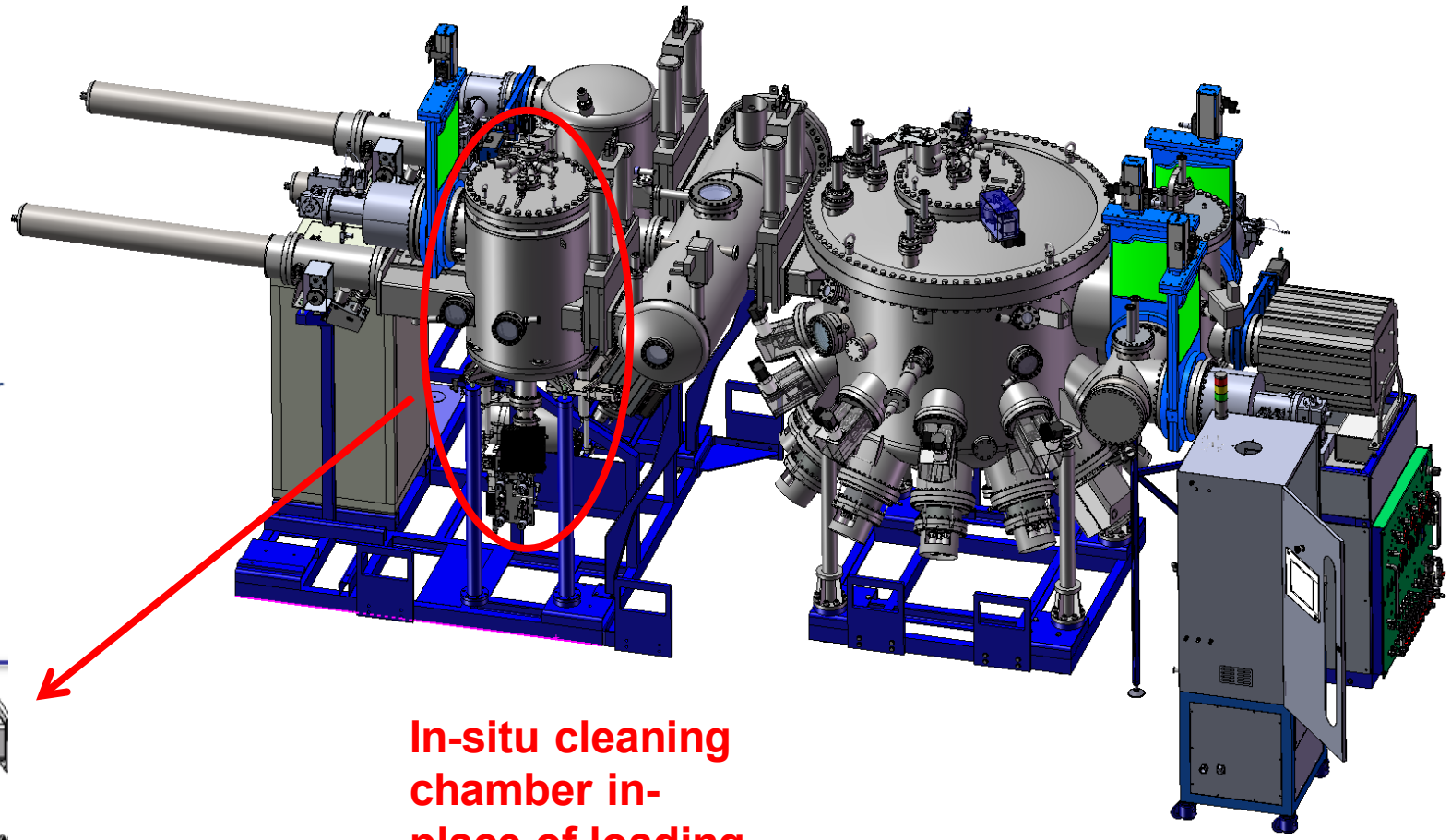
MBE Compatible Process Integration

Pre-growth *in-situ* Hydrogen-Cleaning Chamber

Hydrogen-cleaning chamber added as additional process chamber to Riber 6000

- In-situ cleaning process chamber
- Sources such RF plasma & additional source



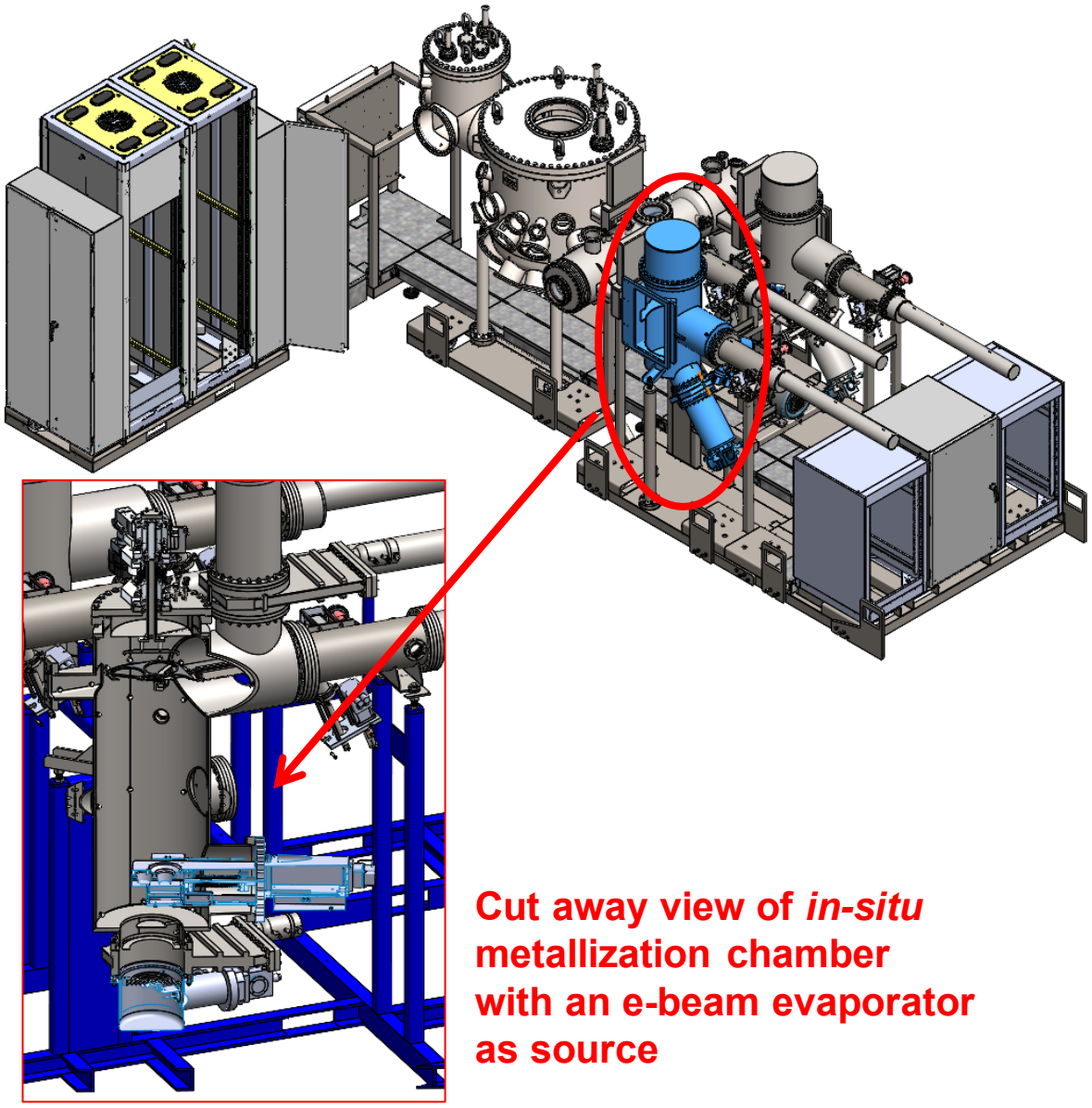


In-situ cleaning chamber in-place of loading chamber

Post-Growth *in-situ* Metal Deposition Chamber

Metallization chamber added as additional process chamber to Riber 49

- In-situ e-beam evaporator setup is used to deposit metal (Mo, W, ….) on epi wafer
- UCSB demonstrated significant improvement of ohmic contact for InGaAs/InP without exposure of epi surface to air—especially oxygen*
- Example applications: InGaAs emitter ohmic contact for InP HBT

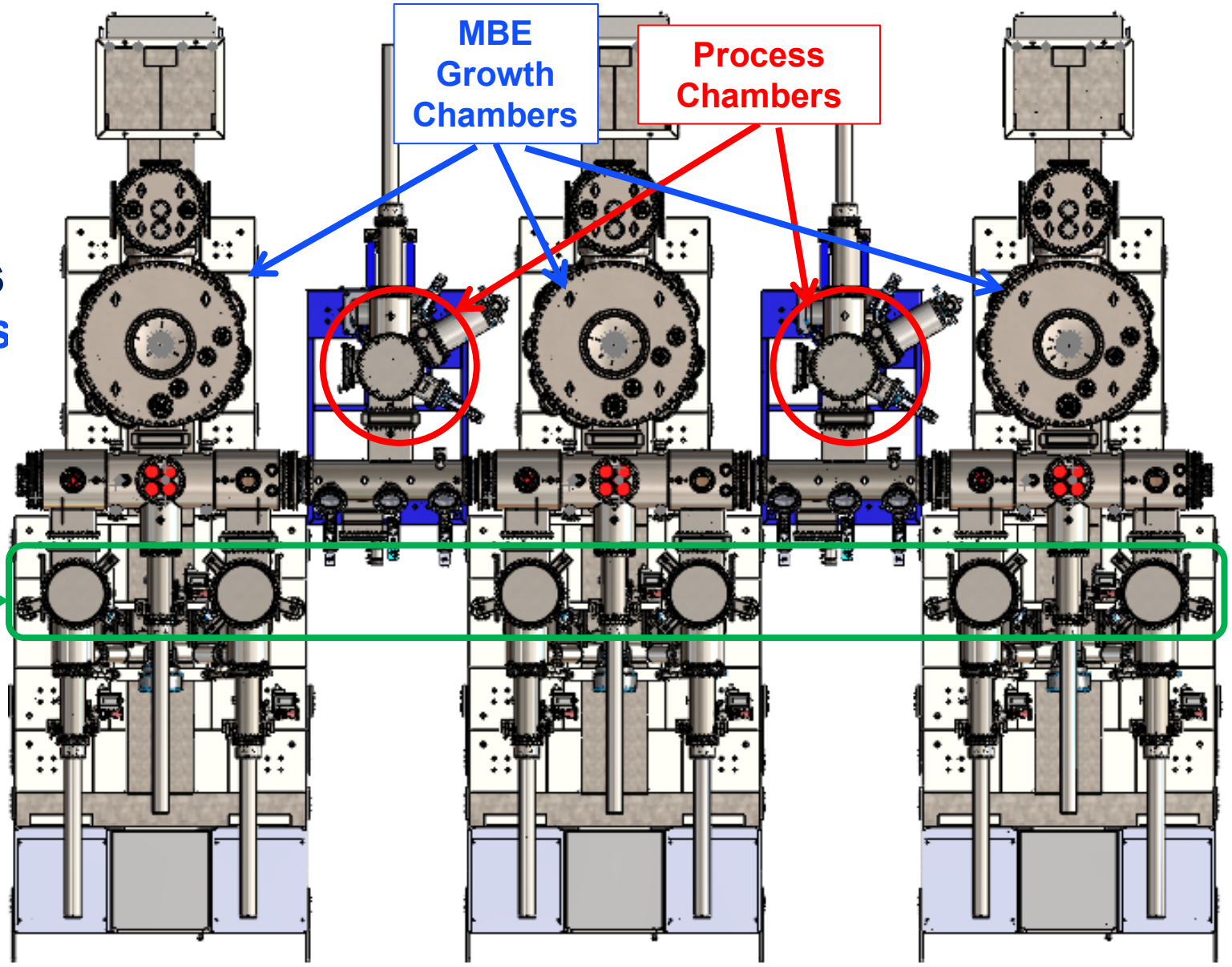


*Singisetti, Uttam; Wistey, Mark A.; Zimmerman, Jeramy D.; Thibeault, Brian J.; Rodwell, Mark J. W.; Gossard, Arthur C.; Bank, Seth R., “Ultralow resistance in situ Ohmic contacts to InGaAs/InP”, App. Phys. Lett., 93, 183502 2008.

Cut away view of *in-situ* metallization chamber with an e-beam evaporator as source

Linear Connection for Multiple Production MBE & Process Chambers

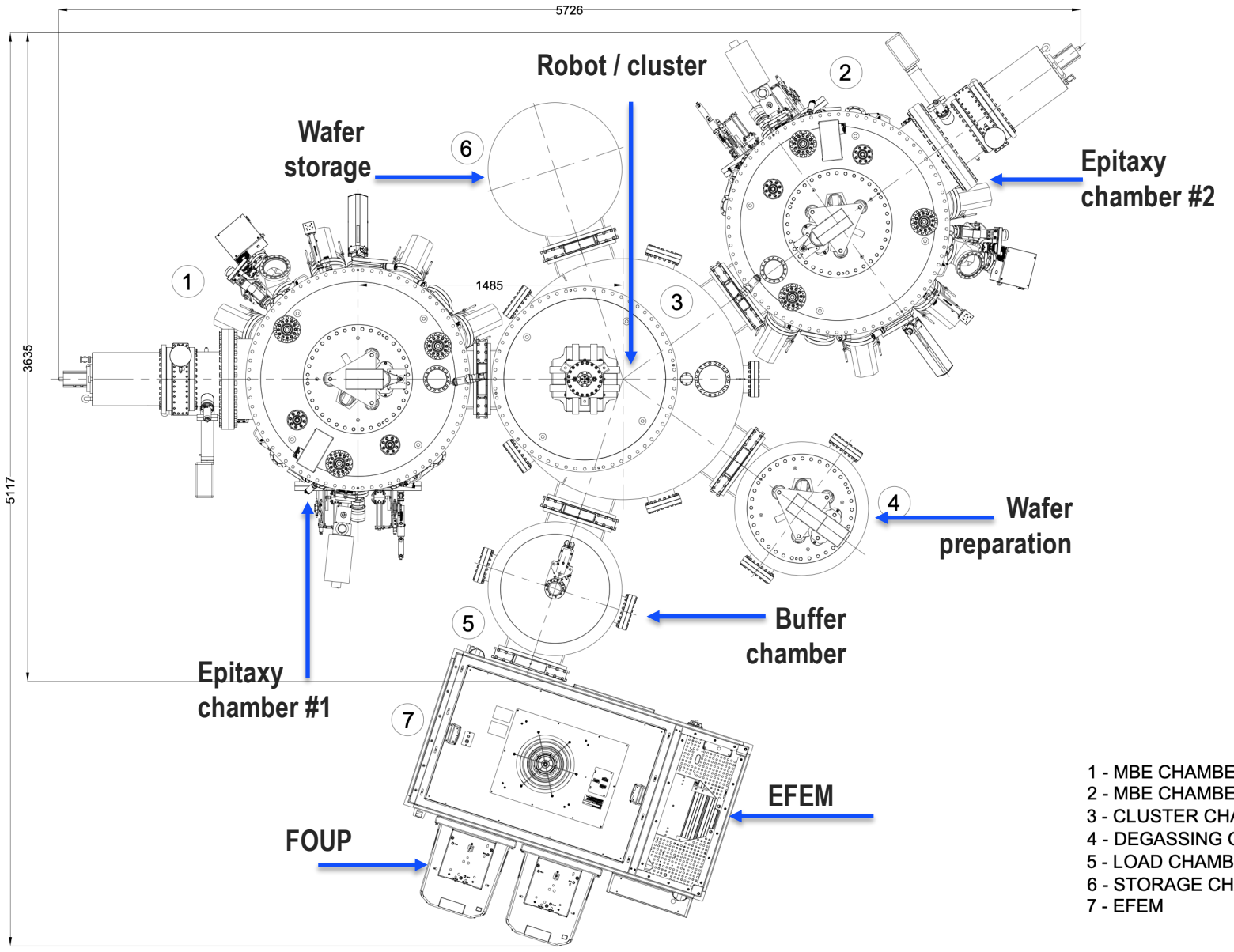
- Linear UHV connection allows for integration of multiple Process Chambers—including MOCVD or CVD—with MBE Growth Chambers
- Linear connection approach allows for multiple MBE Growth Chambers to address epi growth and re-growth of incompatible materials and throughput optimization
  - *InP & Sb-based materials (HBT or IR detectors)*
  - *Dilute nitride VCSELs*
- Platen Load/Unload Chambers can be converted to additional Process Chambers as well



300mm UHV Cluster Tool Compatible with MBE for Process Integration

Riber ROSIE + CLUSTER 300mm concept

- UHV compatible cluster tool for process integration of MBE environment with 300mm silicon manufacturing line
- EFEM module : FOUP to FOUP
- Parallelized wafer processing
- Fully automated solution with software compatible with SEMI standard



Summary

- **New Riber8000 8x6in multi-chamber MBE**
  - ***High throughput*** *with 8x6in wafer loading capability*
  - ***Uniformity*** *to state-of-the-art < 0.5% across platen non-uniformity*
  - *Hetero-structure* ***composition and thickness accuracy*** *control with* ***in situ sensors***
  - *Enable pre-growth* ***in situ cleaning*** *and post-growth* ***in situ metallization*** *capabilities → multiple epitaxy, re-growth*
- **Integration of complex processes with different process technologies**
  - *Pre- and post-growth processing chambers (cleaning & metallization) integrated to current gen MBEs*
  - *Multiple MBEs integration has been demonstrated for more complex hetero-structure growth*
  - *Advanced cluster tools integration with attached MBE chambers under development*
  - *MOCVD and other gas-based epitaxy tools will be integrated in the near future*

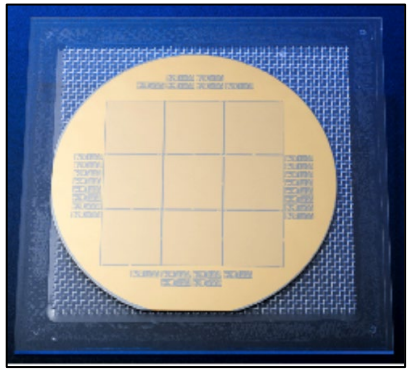
End

IntelliEPI: Company Overview

- Texas semiconductor manufacturing company founded in Jan. 1999
  - *Manufacturing facilities: Richard & Allen, Texas, USA*
- Leading merchant MBE-epi provider of III-V epitaxy materials and substrates to electronic and optoelectronic industries
- Manufacturer of GaAs, InP, GaSb & GaN epitaxial wafers based on production MBE technology
- Manufacturer of epi-ready GaSb substrates
  - *2 – 5 inch commercially available; 6 inch demonstrated*
- ISO 9001: 2015 certified
- Publicly listed on TPEX (Taiwan Taiepi Exchange) since 2013 (#4971, IET-KY)

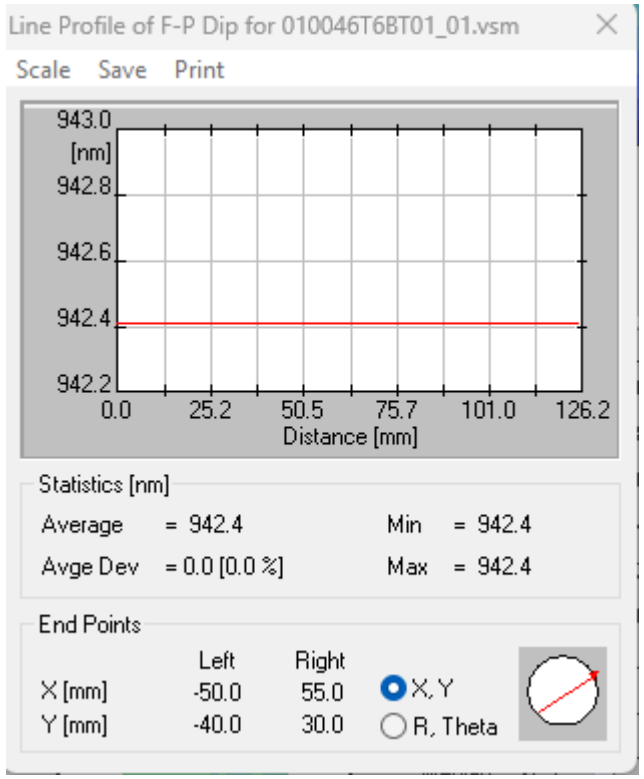
Production Molecular Beam Epitaxy (MBE) Reactor

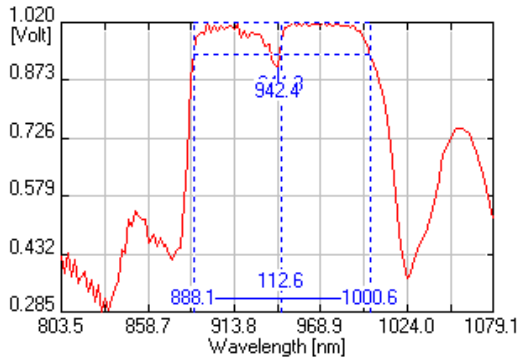
LEC GaSb Crystal Ingot Pulling

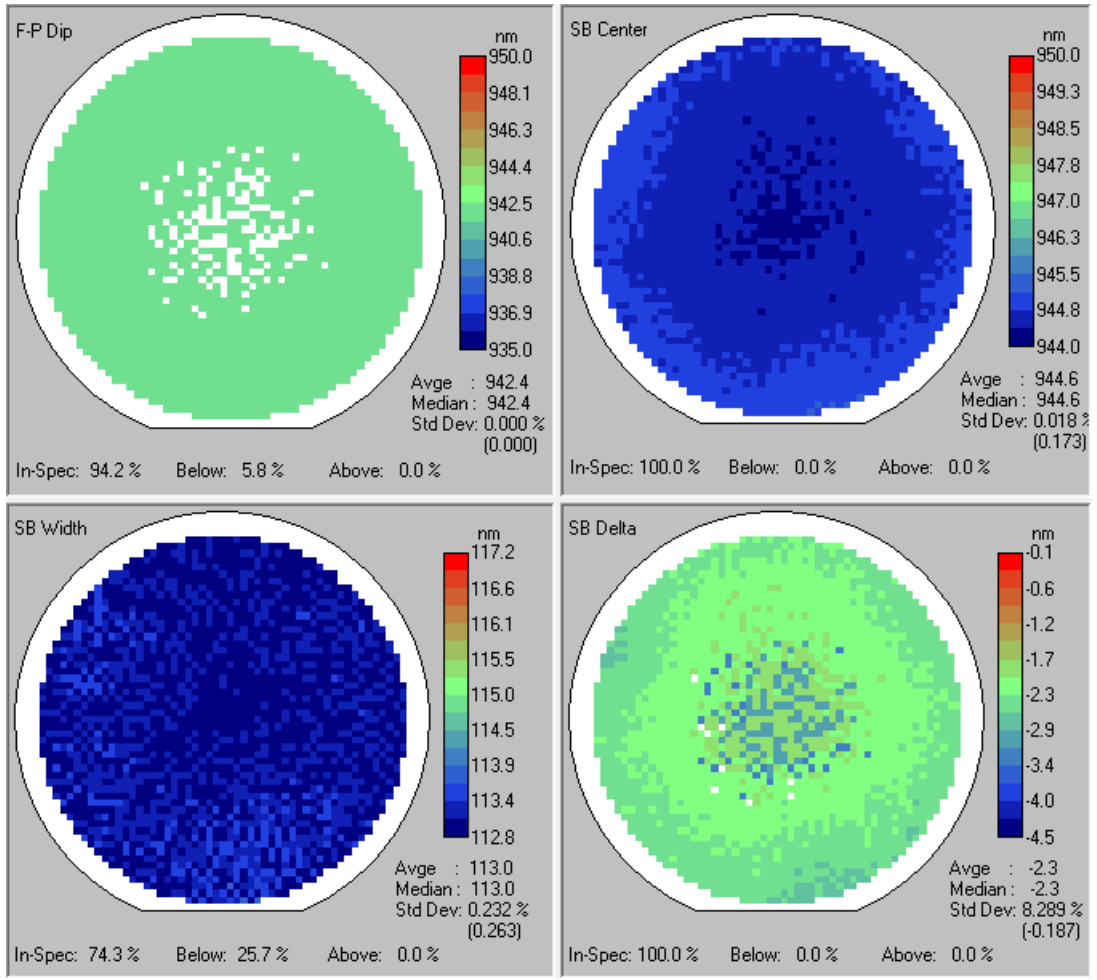


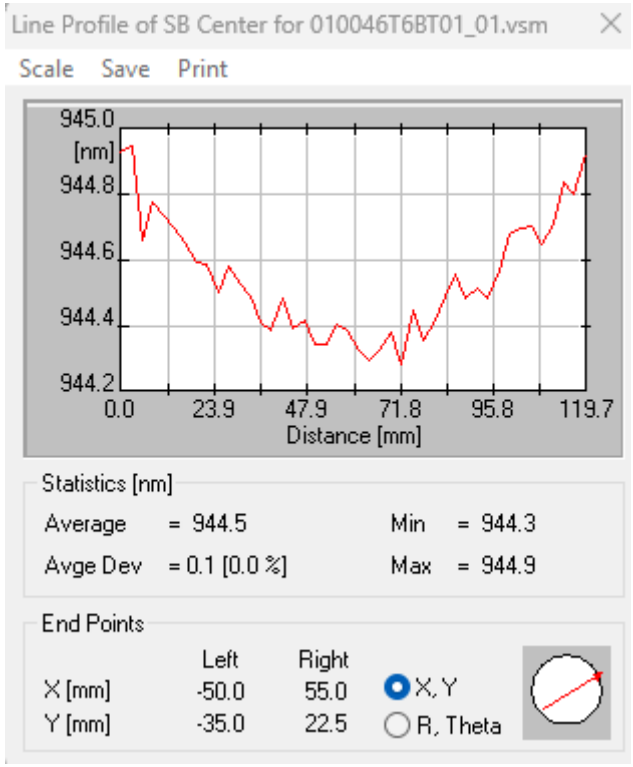
Focal Plane Arrays(FPAs) fabricated on IntelliEPI 4inch GaSb wafer by NASA/JPL

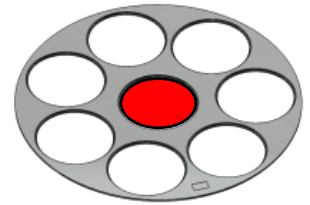
Riber 8000 940 VCSEL Map from 8x6” Platen – Center Wafer





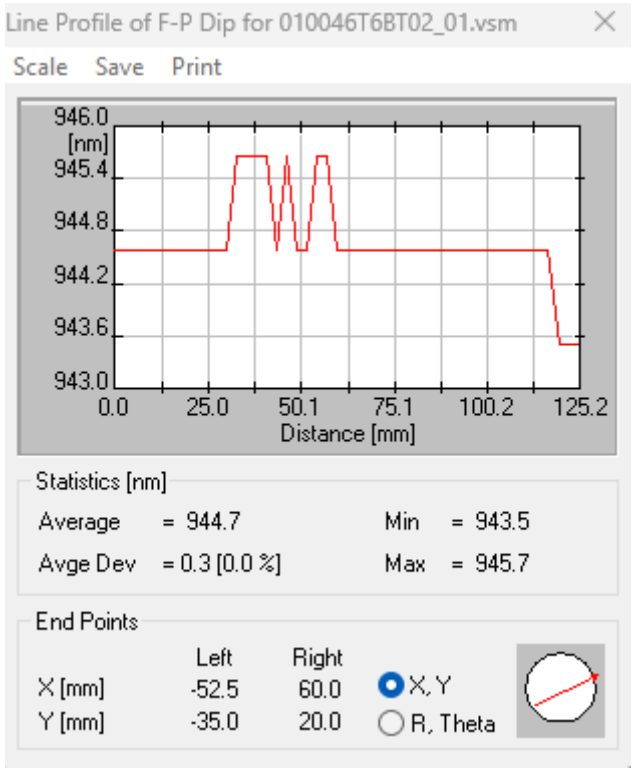


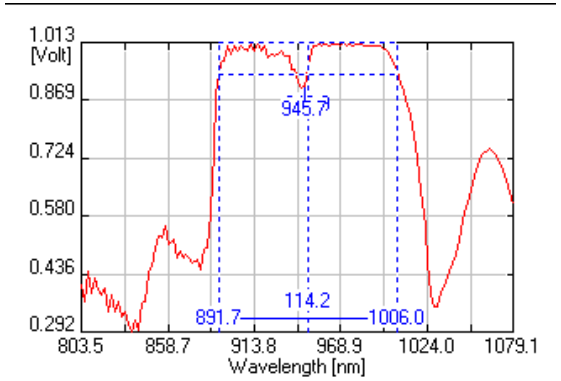


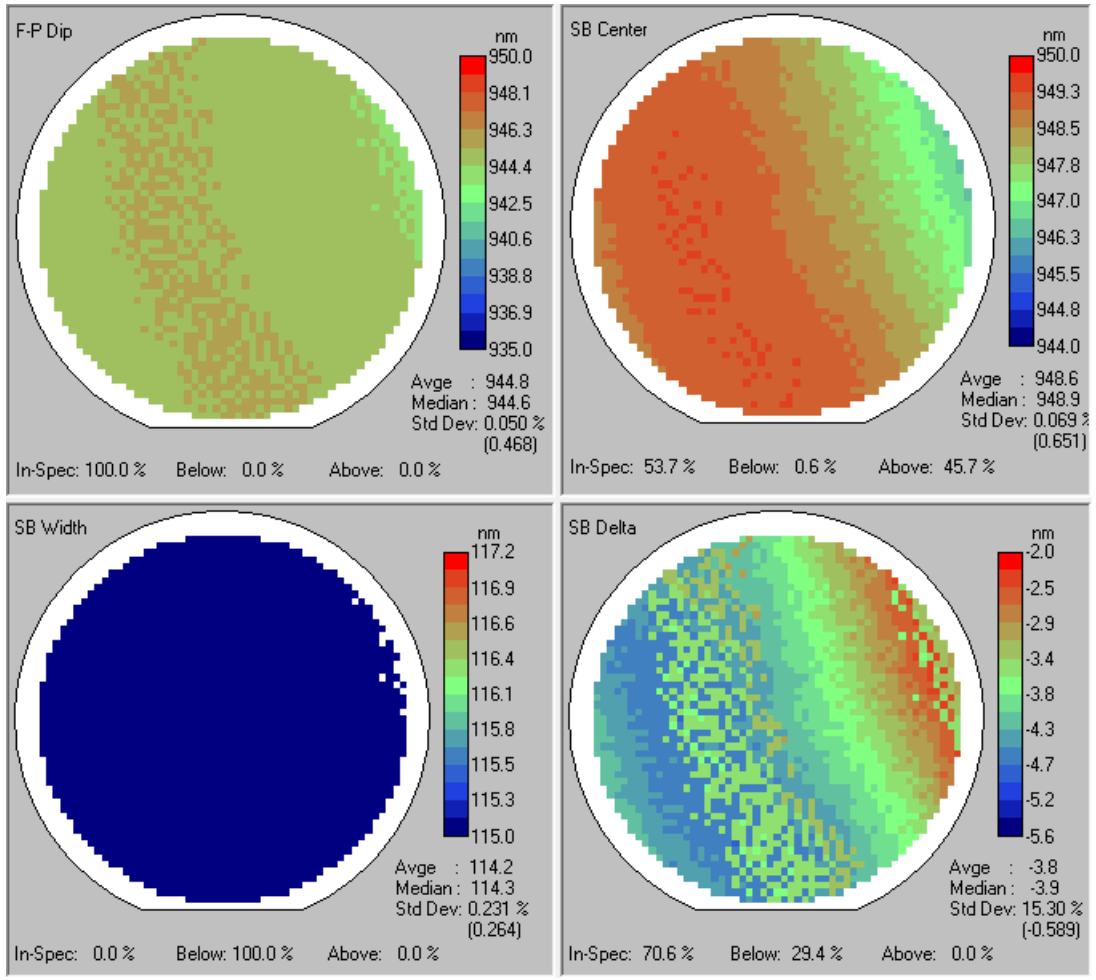


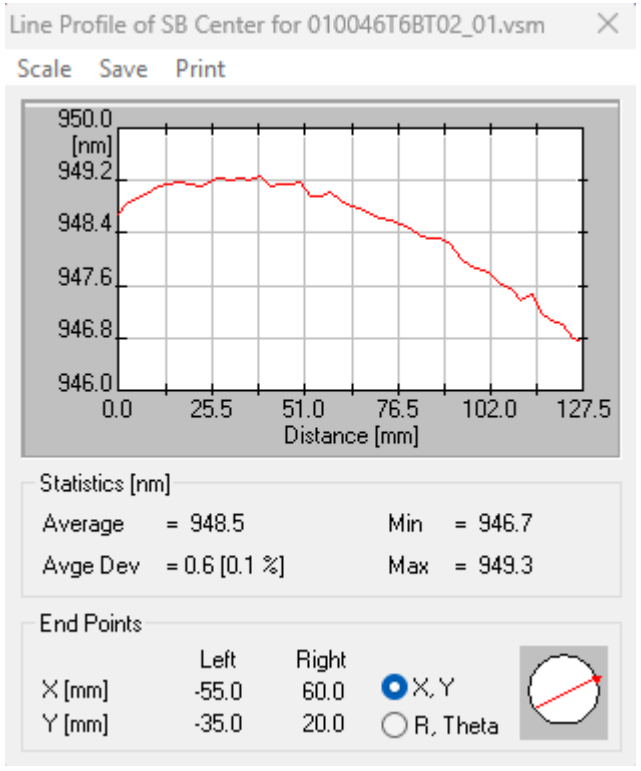
- **Variation of center wafer: F-P dip < 1 nm; & SBC < 1 nm**

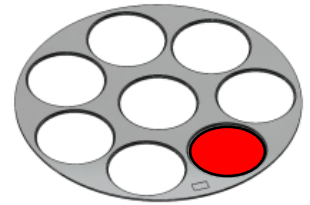
Riber 8000 940 VCSEL Map from 8x6” Platen – Side Wafer











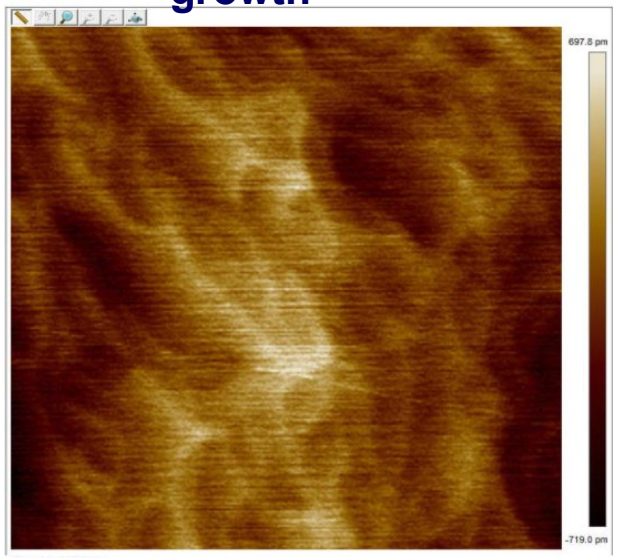
- **Variation of center wafer: F-P dip < 2 nm; & SBC < 3 nm**

N+GaN on 4” MO-GaN Template

- Typical N+GaN thickness ~60nm
- Growing customers of 4”/6” GaN/SiC
- Non-selective growth with N2 plasma

Center

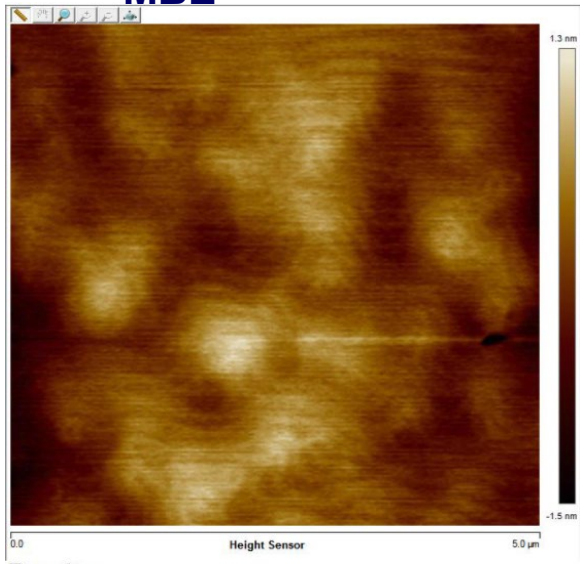
Before growth



Results

Image Rq	0.204 nm
Image Ra	0.160 nm

After N+GaN MBE



Results

Image Rq	0.394 nm
Image Ra	0.312 nm

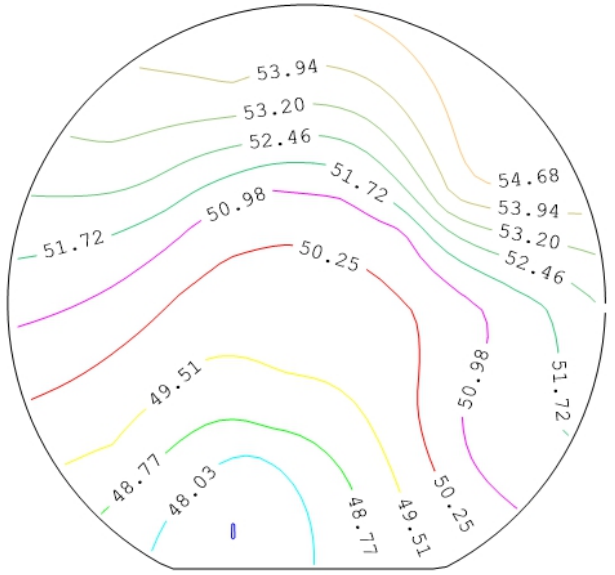
SemiLab LEI

Test File: 060138K4AK01.tst

Test Date:1/25/2022 Test Time:5:05:52 PM

Statistical Summary

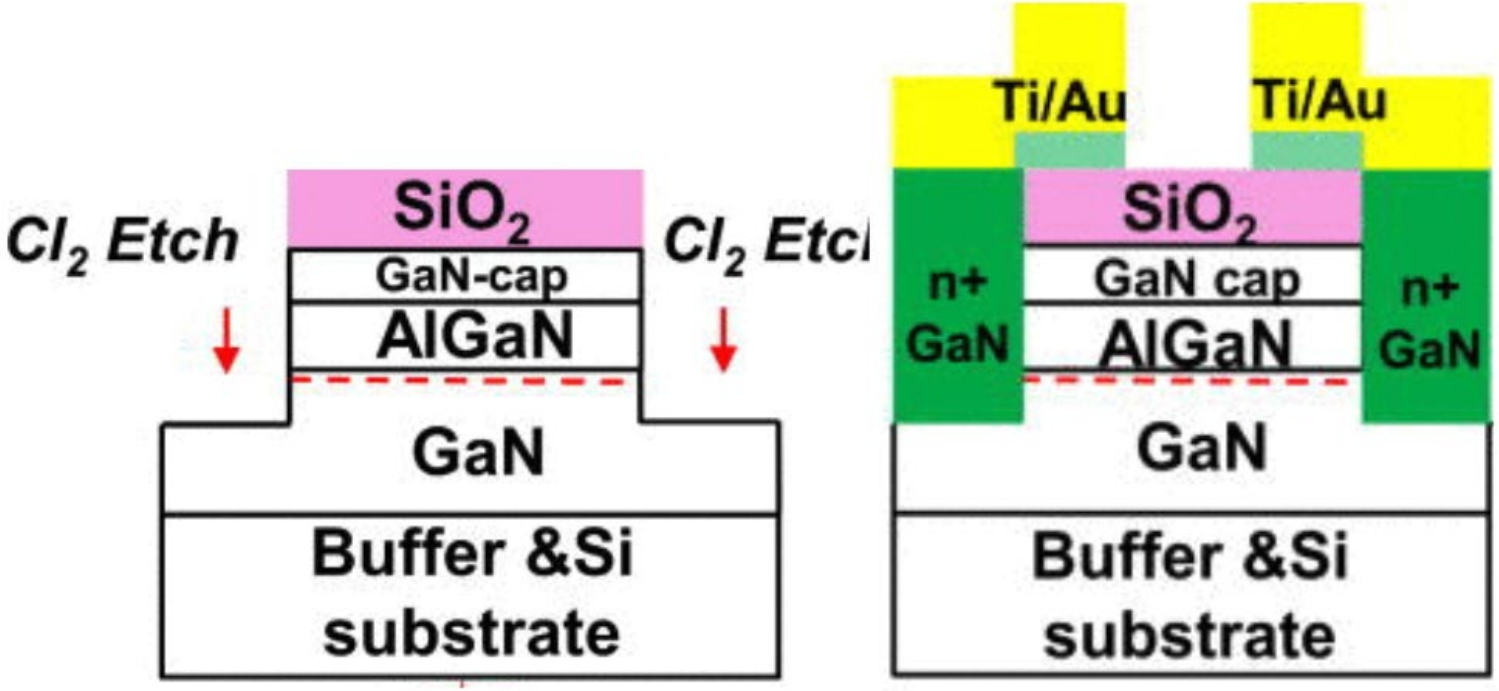
Number of Test Points	36
Average Value	50.79
Maximum Value	55.34
Minimum Value	47.24
Sample Spread(%)	15.94
Std Dev Value	1.81
Wafer Uniformity Value(%)	3.56
Contour Interval Value	0.739



Rs=50.79 ohm/sq., Uniformity=3.56%

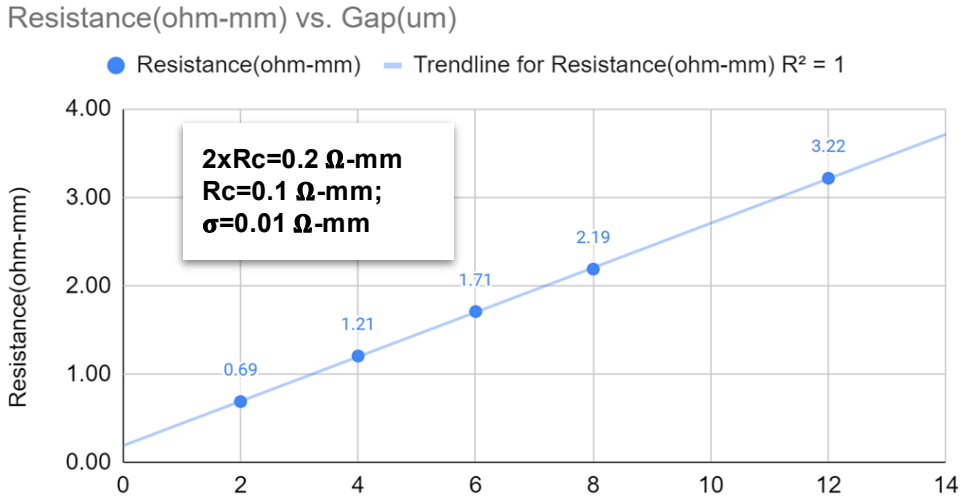
N+GaN Ohmic Regrowth

- N+GaN contacts to the source and drain openings
  - Early in the process, before ohmic metal and gate
- Schematic from published result, unaffiliated
  - Appl. Phys. Lett. 109, 041602 (2016); S. Joglekar, M. Azize, M. Beeler, E. Monroy, and T. Palacios; Microsystems Tech. Labs, MIT; U. Grenoble-Alpes, 3CEA Grenoble, INAC-PHELIQS



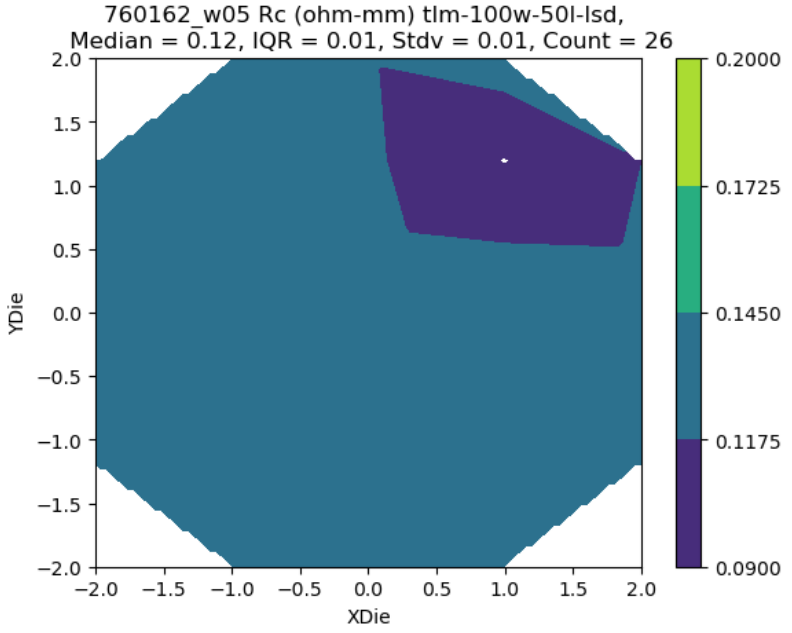
Low Contact Resistance Using N+GaN Ohmic Regrowth

- **TLM results from various customers**
  - **Very low Rc:**
    - ***~5x improvement***
  - **Good uniformity on 8” Si**
    - ***Same area as 3x4”***
    - ***4x4” may be achievable by modifying the plasma pattern***



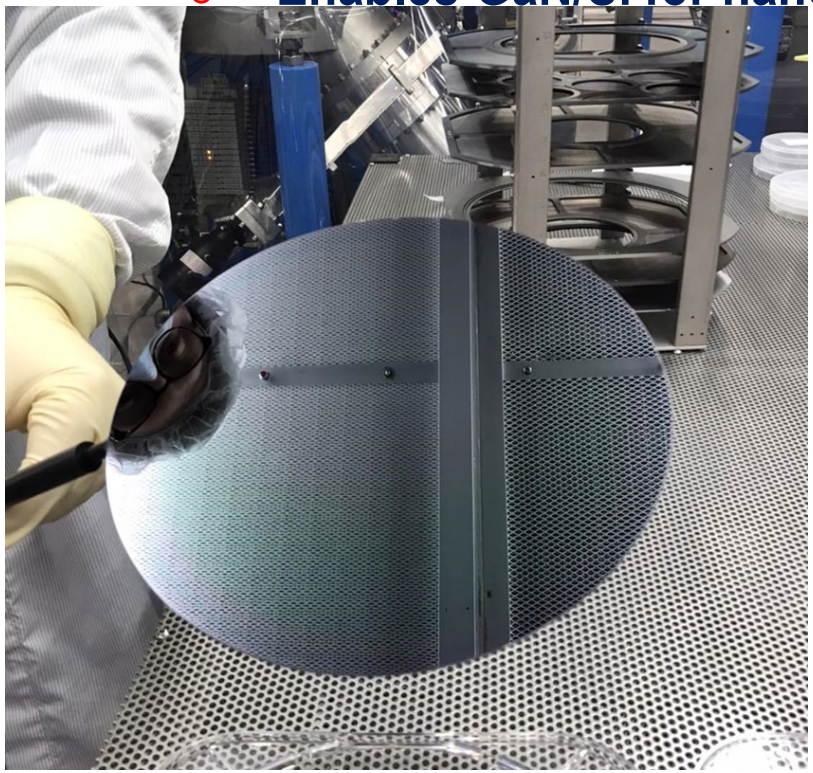
* Table 1. Summary of the Rc values, metal to n+GaN and metal to n+GaN/2DEG, on patterned substrate from various collaborators

Collaborator	Wafer type	Rc, metal to n+GaN (ohm-mm)	Rc, metal to n+GaN/2DEG (ohm-mm)
A	4-inch SiC	N/A	0.10
B	4-inch SiC	0.05	0.08
C	6-inch SiC	N/A	0.12
D	6-inch SiC	0.03	N/A
E	200-mm Si	0.07	0.13

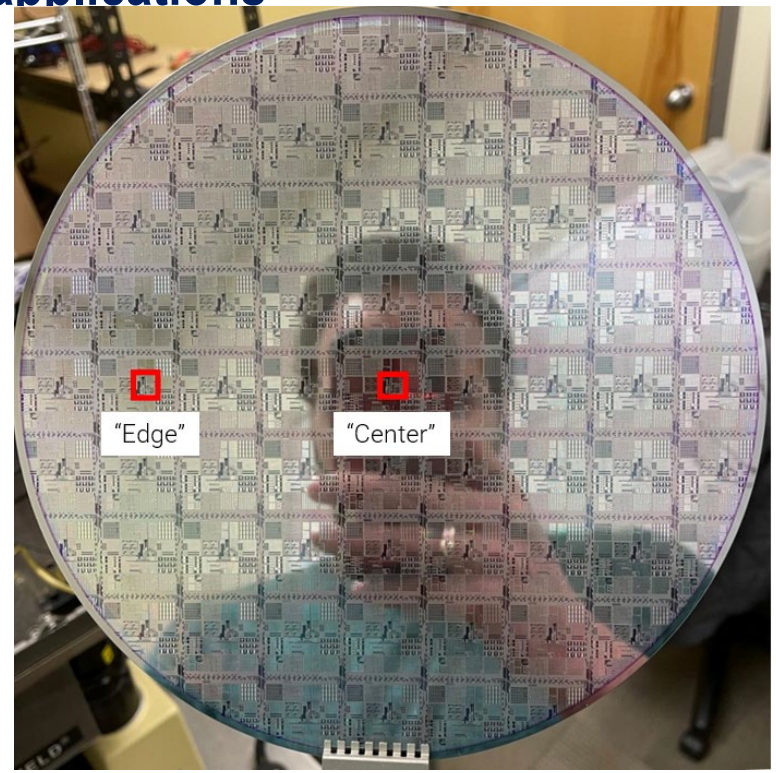


N+GaN on 200mm GaN/Si Template

- 1x8” platen, N2 plasma source
- Calibrating Rs of N+GaN on 8” MO-GaN/Si
- Reduced knee voltage and Ron
  - Enables GaN/Si for handset applications



N+GaN on 200mm GaN/Si template GaN/Si



200mm patterned

Lehighton Electronics Inc.

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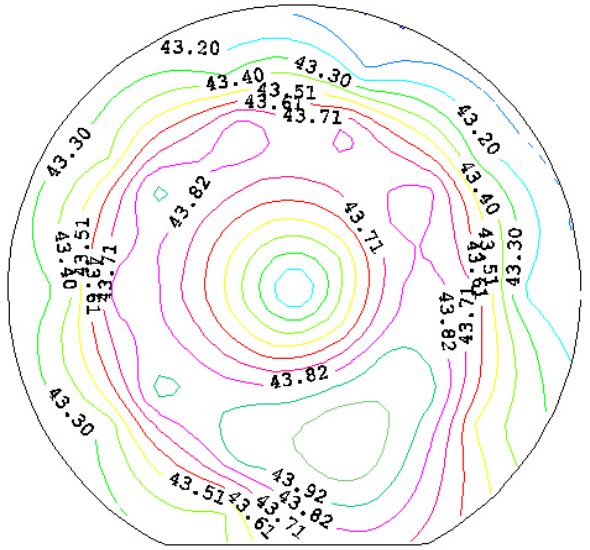
Statistical Summary

Number of Test Points	36
Average Value	43.65
Maximum Value	44.14
Minimum Value	43.05
Sample Spread(%)	2.5
Std Dev Value	0.30
Wafer Uniformity Value(%)	0.68
Contour Interval Value	0.104



Rs=43.65 ohm/sq.,
Uniformity=0.68%

Abstract

Recent advancements in production scale Molecular Beam Epitaxy (MBE) capabilities are being driven by the needs for increasing both the capacity and the level of integration for the manufacturing of the next generation compound semiconductor devices. Riber (MBE equipment manufacturer) and IntelliEPI (epi foundry) is jointly developing a high volume (8x6”/4x200mm) MBE reactor to address manufacturing scalability while maintaining the precision interface control advantage offered by MBE. Integration for multiple process steps onto a single UHV platform to increase the final device performance is another major industry trend. Value added processing capabilities include in-situ metallization, hybrid growth/re-growth and in-situ cleaning. Select device applications such as InP-HBTs, p-HEMTs, VCSELs, dilute nitride QW & GaN ohmic contact re-growth will be discussed.