RHOMBO-TRIGONAL EPITAXY OF SiGe ON *c*-SAPPHIRE

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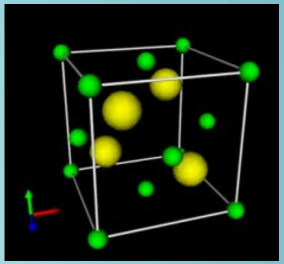
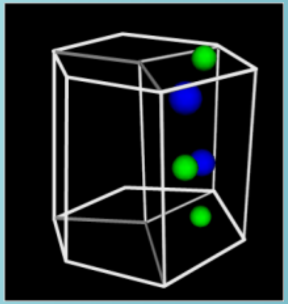
Today's Semiconductor Bandgap Engineering

- Currently, worldwide major semiconductor alloy epitaxial growth is divided into two material groups.

  - Cubic:
    - Diamond structures: group IV semiconductors (Si, Ge, C),
    - Cubic zinc-blende structures: group III-V semiconductors (GaAs, InP), group II-VI semiconductors (ZnSe, CdTe)

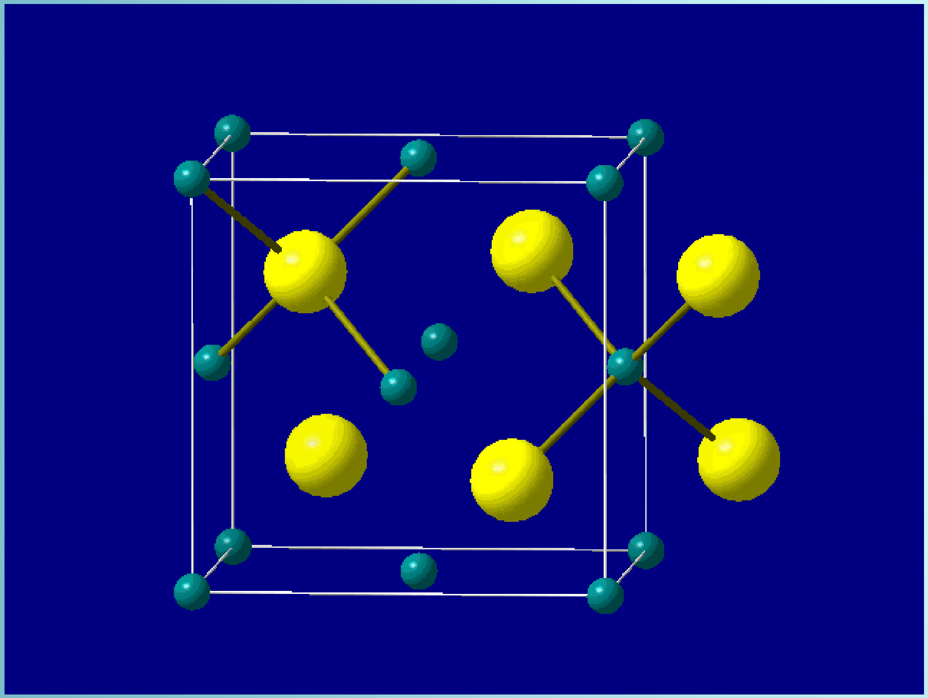


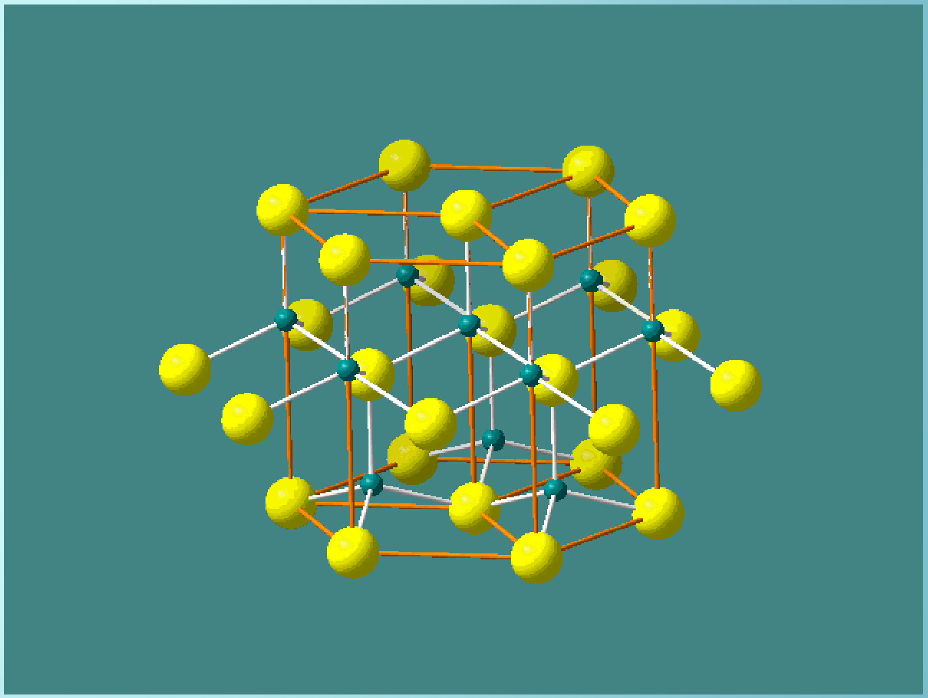
  - Hexagonal:
    - Wurtzite structures: III-Nitride semiconductors (GaN,AlN,InN)
    - II-VI semiconductor: Zinc-Oxide
    - Hexagonal SiC (2H, 4H)



- The mixture of different crystal structures was thought to be very difficult so far. We propose a new growth technology of "Super Hetero Epitaxy" with SiGeC alloy in which each layer can have different materials and different crystal lattice structures.

Comparison of Atomic Structures

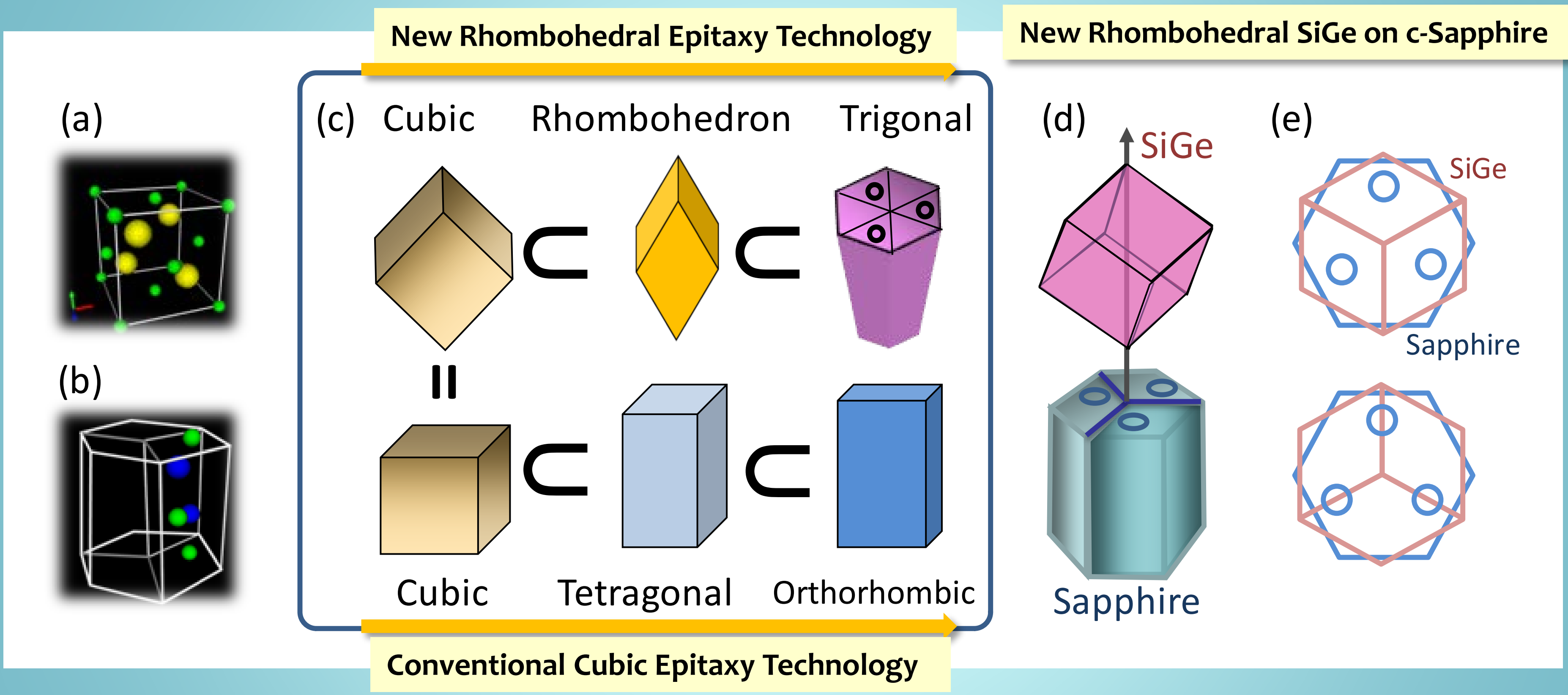




Cubic Zinc Blende structure:
GaAs, ZnS, InP, CdTe

Hexagonal Wurtzite structure:
GaN, ZnO

Crystal Symmetry Relations

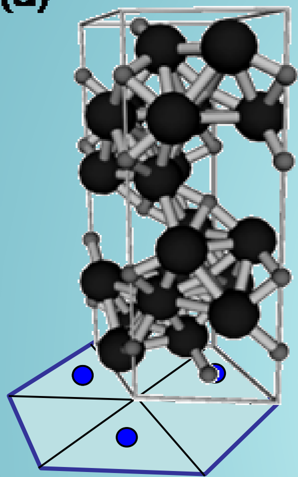


*** Cubic crystal also belongs to the Trigonal crystal group by the symmetry. A fundamental cross-structural epitaxy can be established beyond an accidental coincidence lattice matching!**

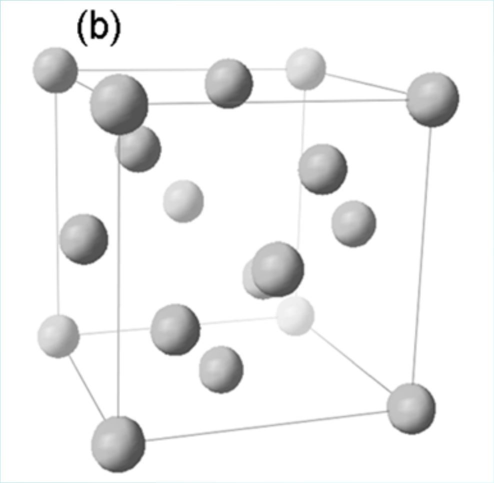
New Super Hetero Epitaxial Technology for Hybrid Crystal Growth

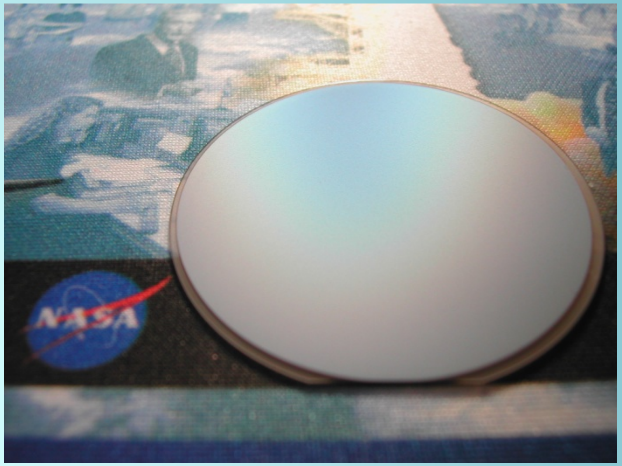
Trigonal Substrate

(a)



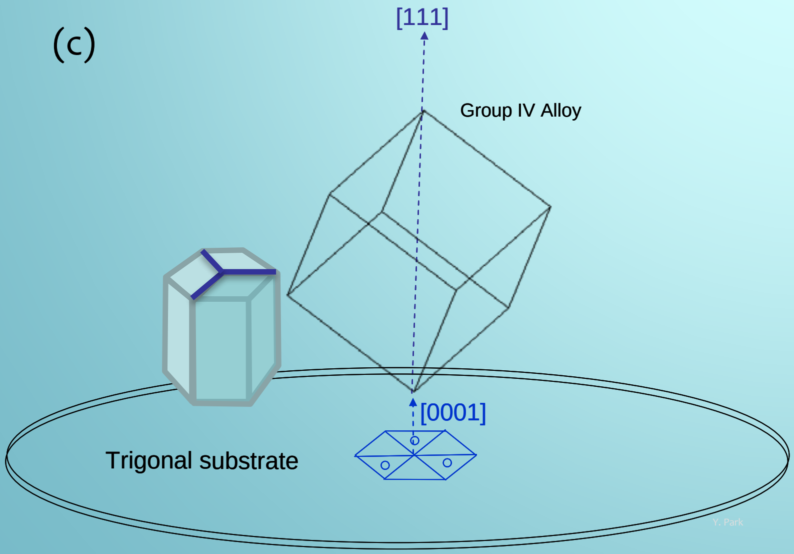
SiGe (Diamond Structure)



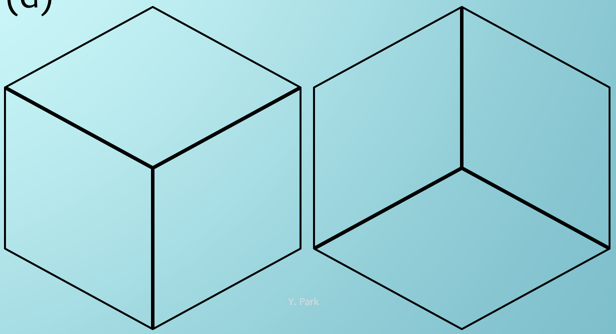


2” SiGe on trigonal substrate

(c)



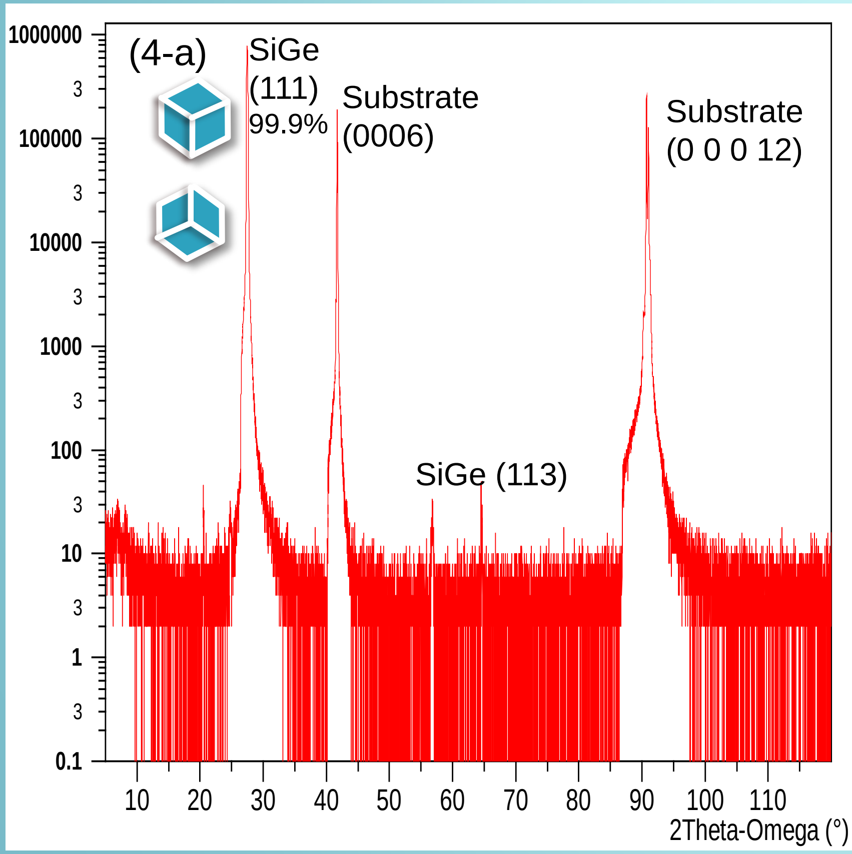
(d)

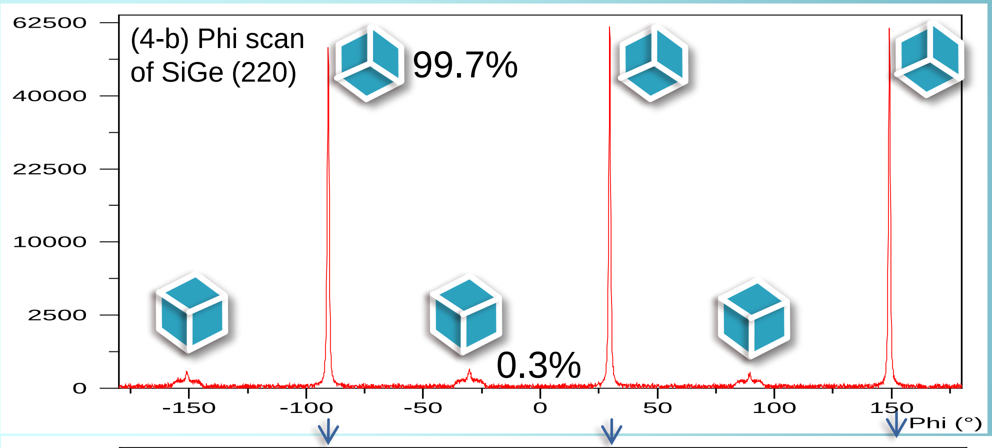


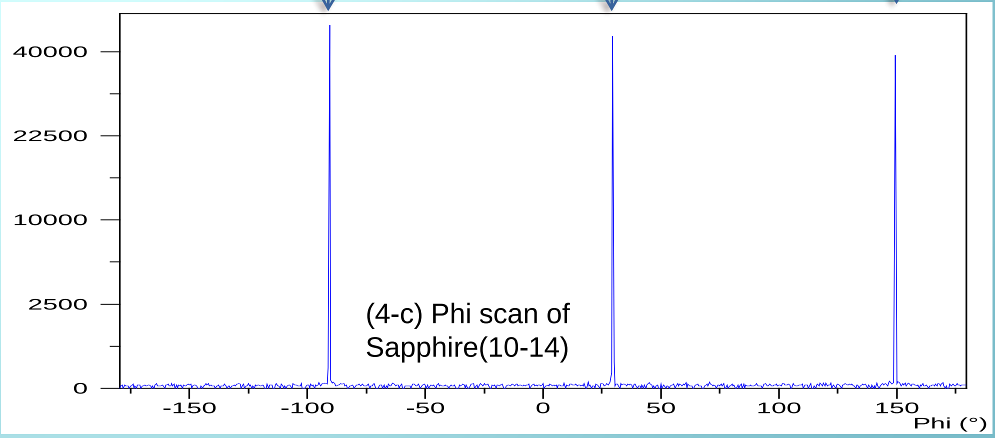
Twin crystal to each other

1st Key:

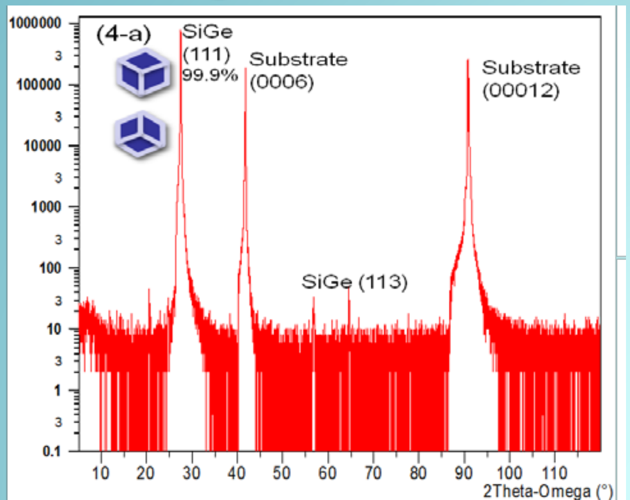
XRD Integral Twin Density Measurement

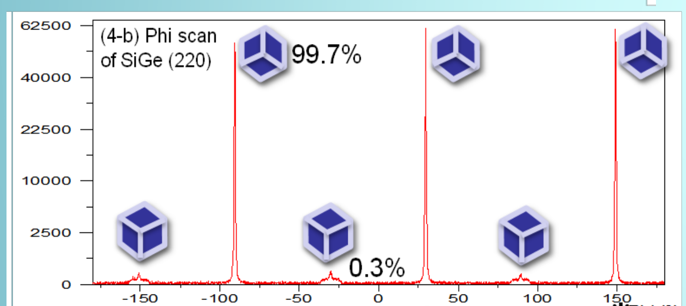


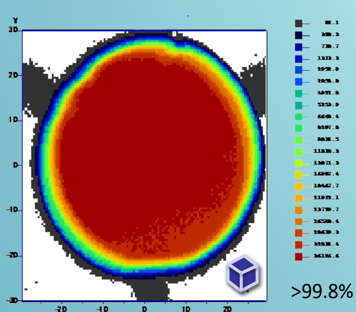


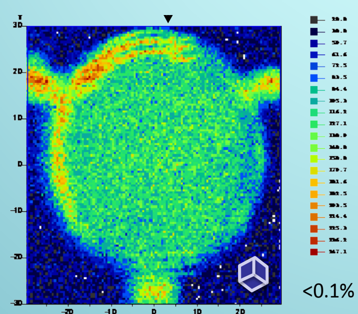


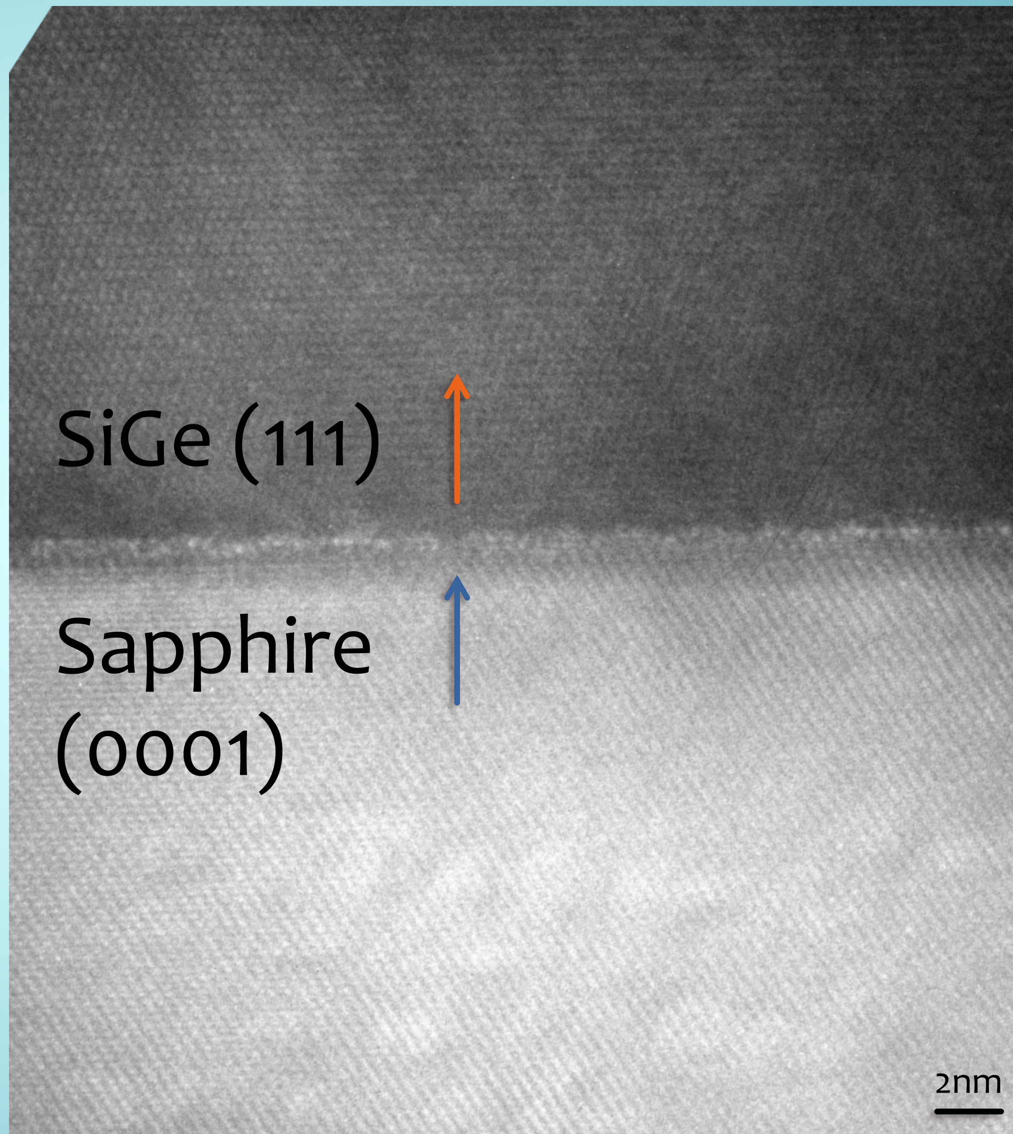
Single Crystalline SiGe Atomic Layers on Sapphire











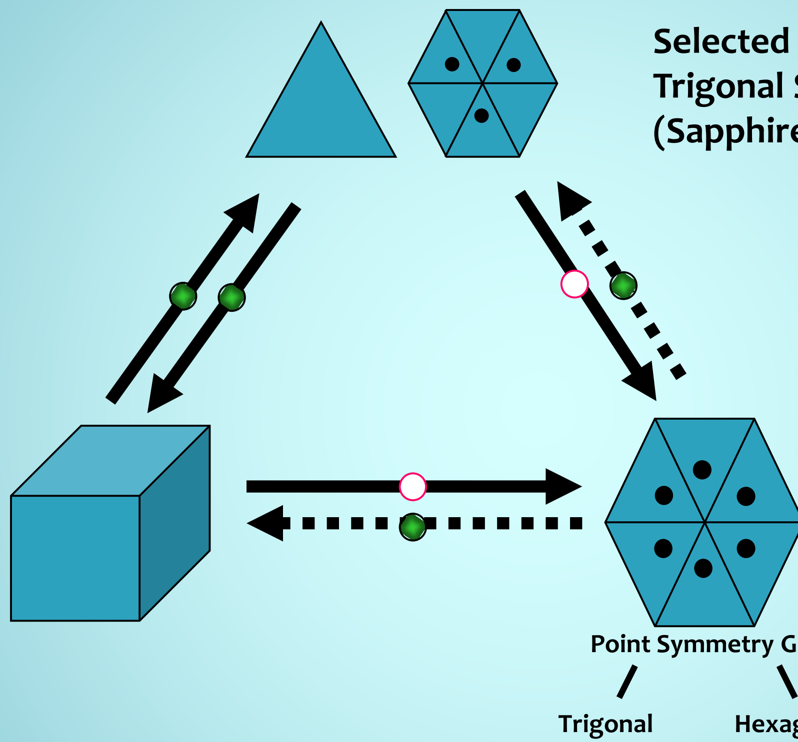
NASA patented XRD methods, materials, and fabrication processes.
(US Patent # 7341883, 7558371, 7769135, 7906358, 8226767 and more.)

Epitaxial Relationship with Three Space Symmetry Groups

Inter-Crystal-Lattice Epitaxial Relation

Three different crystals can be integrated into one continuous epitaxial structure.

Selected Crystals with Trigonal Space Symmetry (Sapphire and so on)



Crystals with Hexagonal Space Symmetry (GaN, AlN, Wurtzites)

*** Wurtzites are trigonal in point symmetry group but they belong to hexagonal space symmetry group due to its alternating stacking sequence.**

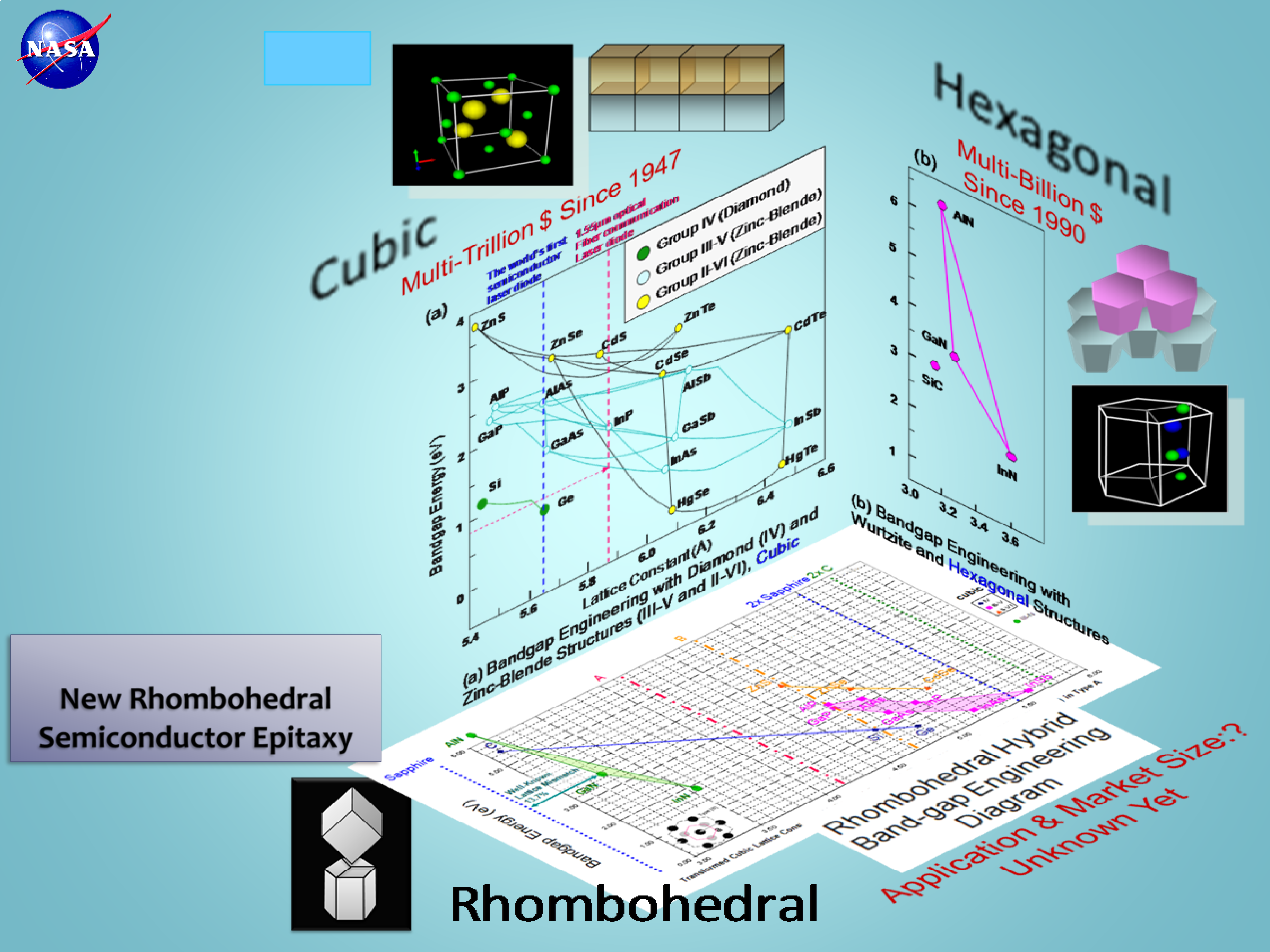
Cubic Crystals
With [111] direction
(Si, Ge, Diamond, GaAs, ZnTe, InP, Zinc-blendes)

Substrate ——→ Epitaxial Layer : No Double Position Defect

Substrate ▪▪▪▪▪▪▪▪→ Epitaxial Layer : Double Position Defect at Stepped Interface

● Twin detection XRD works

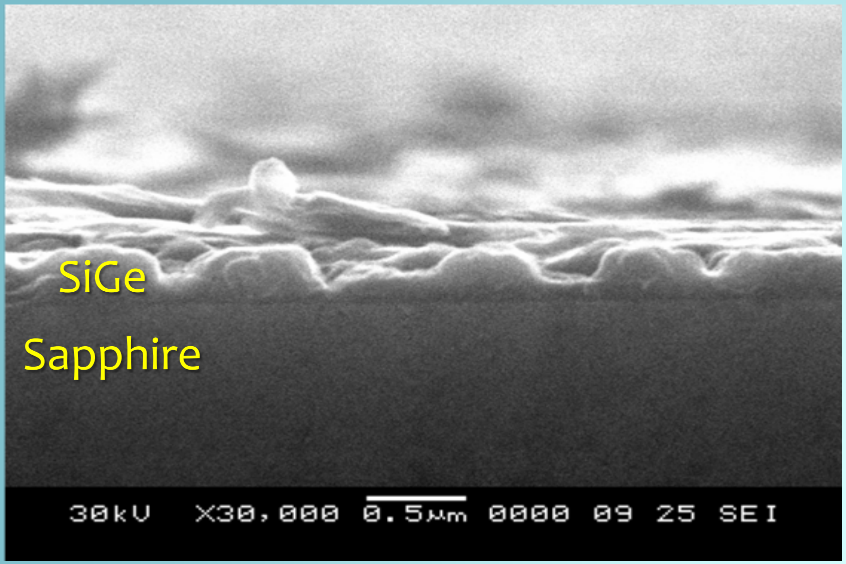
○ Twin detection XRD does not work



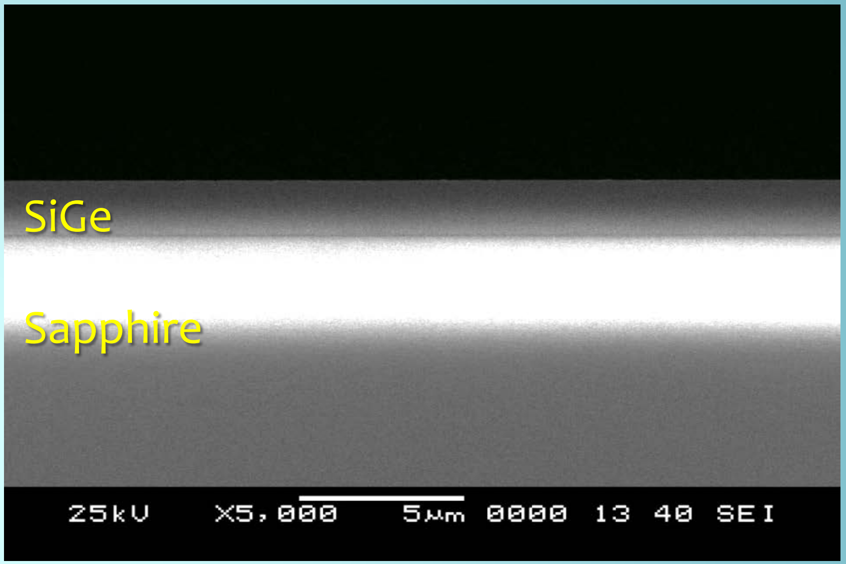
NASA
Cubic
Multi-Trillion $ Since 1947
The world's first semiconductor laser diode
1.55μm optical Fiber communication Laser diode
Group IV (Diamond)
Group III-V (Zinc-Blende)
Group II-VI (Zinc-Blende)
(a)
Bandgap Energy (eV)
Lattice Constant (Å)
ZnS
ZnSe
CdS
ZnTe
CdTe
CdSe
AlSb
AlP
AlAs
InP
GaSb
InSb
GaP
GaAs
InAs
HgTe
Si
Ge
HgSe
(a) Bandgap Engineering with Diamond (IV) and Zinc-Blende Structures (III-V and II-VI), Cubic
Hexagonal
Multi-Billion $ Since 1990
(b)
AlN
GaN
SiC
InN
(b) Bandgap Engineering with Wurtzite and Hexagonal Structures
Sapphire
2x Sapphire
2x C
Bandgap Energy (eV)
Transformed Cubic Lattice Const
Rhombohedral Hybrid Band-gap Engineering Diagram
Application & Market Size:? Unknown Yet
New Rhombohedral Semiconductor Epitaxy
Rhombohedral

Epitaxial Layer Growth Optimization

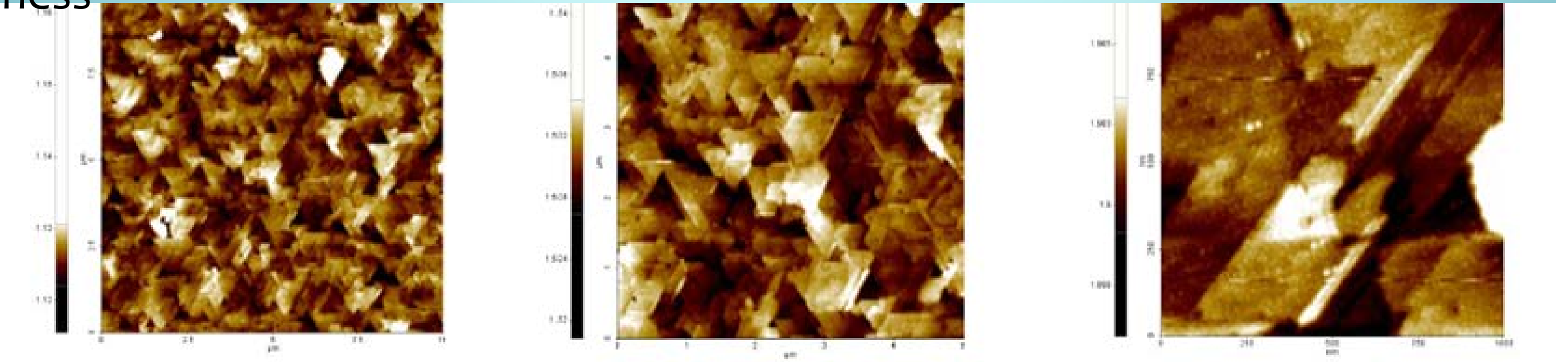
SEM: Unstable island growth



Stable layer-by-layer growth



AFM: Triangular Crystal Planes of SiGe (Atomic Steps), Smooth Surface with 2.2nm Roughness

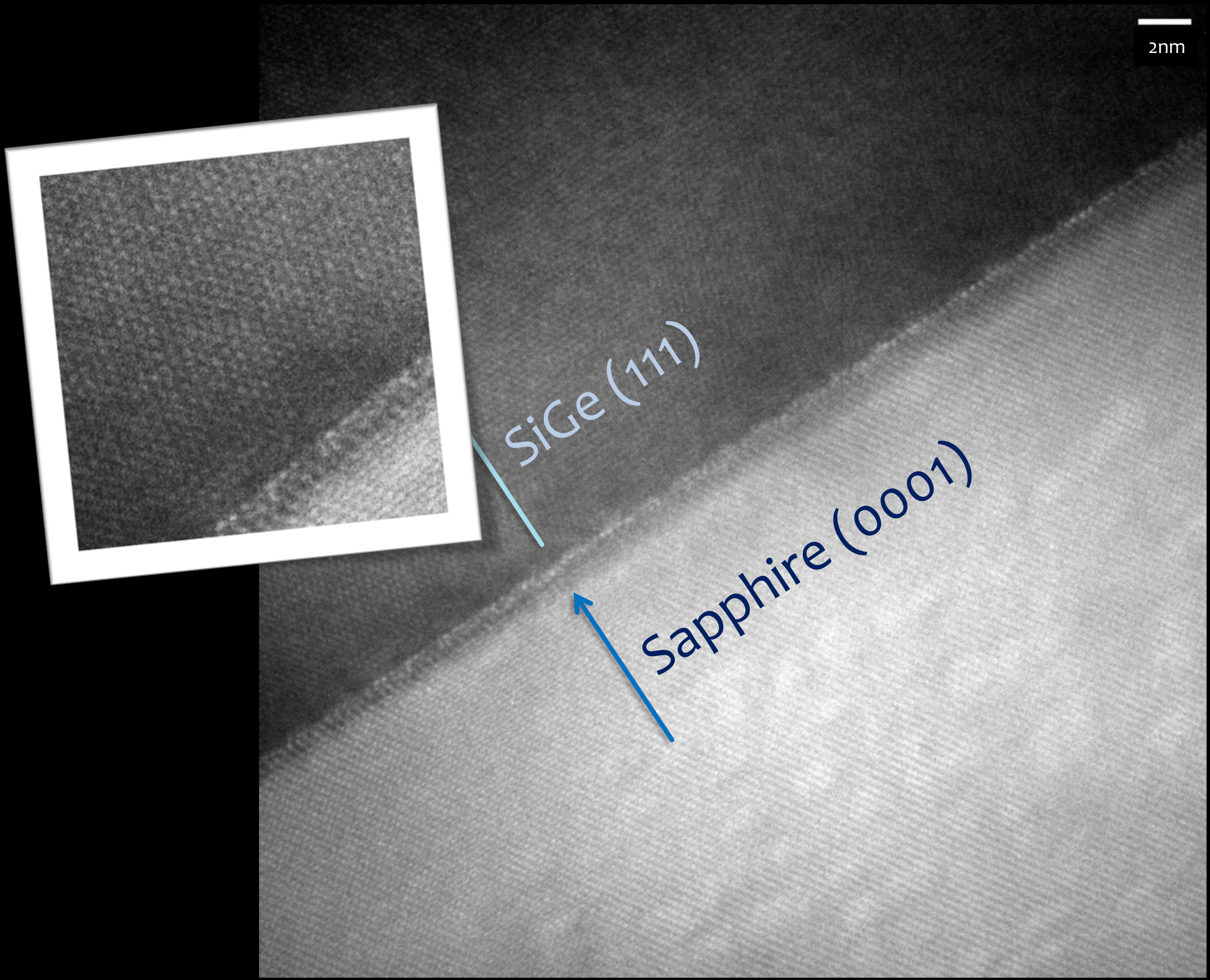


10µm x 10µm Image
RMS Roughness = 2.24nm

5µm x 5µm Image
RMS Roughness = 1.87nm

1µm x 1µm Image
RMS Roughness = 1.06nm

Atomic Resolution TEM Image of Rhombohedral-Trigonal Super Structure



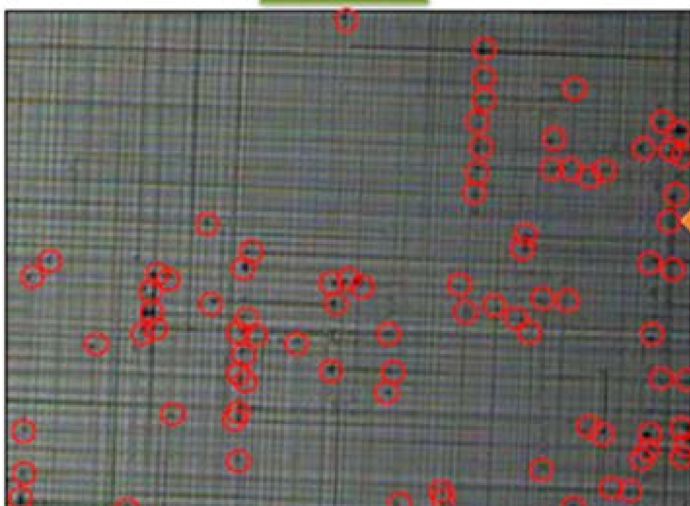
Comparison of Etch-Pit Densities

Threading Dislocation Pit Density after Secco Etching

IBM's SiGe

SiGe on Si substrate Si(100)

35 % Ge

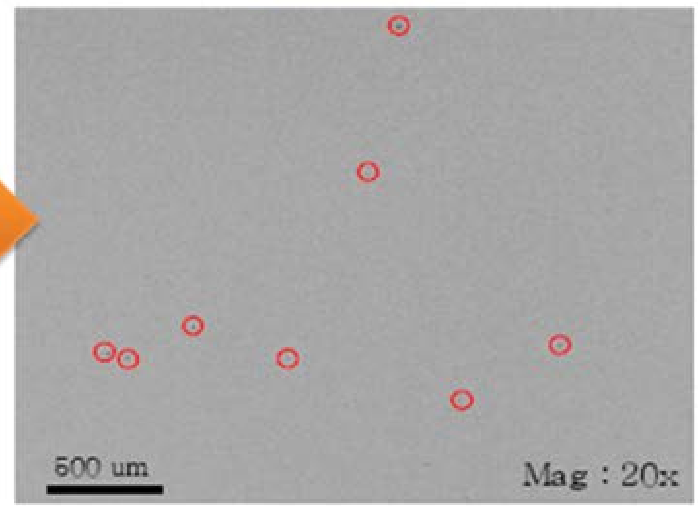


- TDP density : $3.90 \times 10^4/cm^2$
- LD density : $1.73 \times 10^4/cm$
- Cross-hatch pattern

NASA Langley's SiGe

SiGe on sapphire substrate Sapphire(0001)

78 % Ge



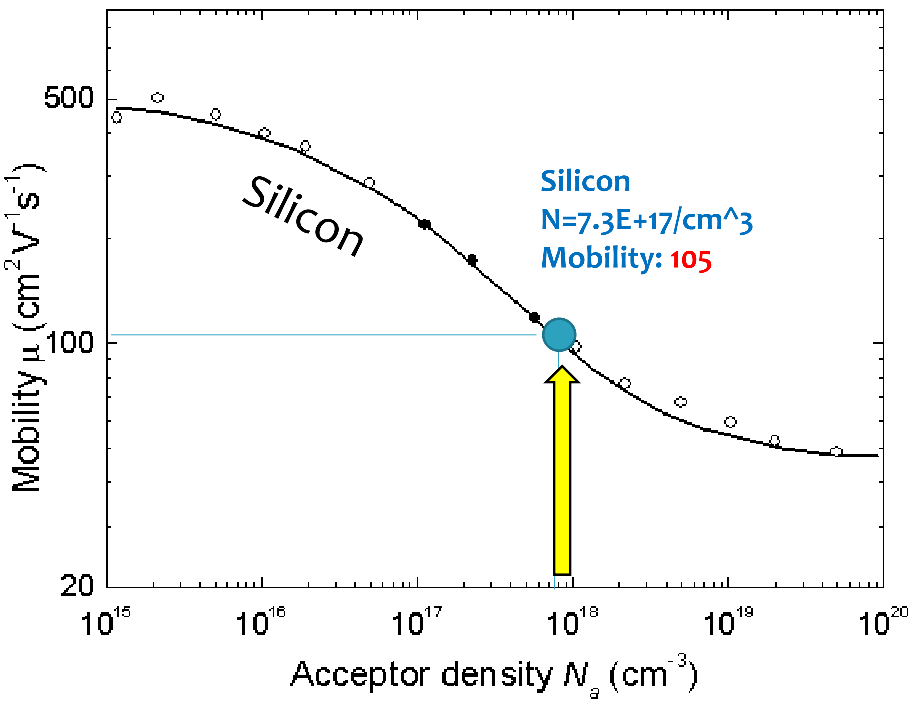
- TDP density : $1.9 \times 10^2/cm^2$
- LD density : 0/cm
- No Cross-hatch pattern

The surface was etched by using Secco Etchant for 3 seconds.

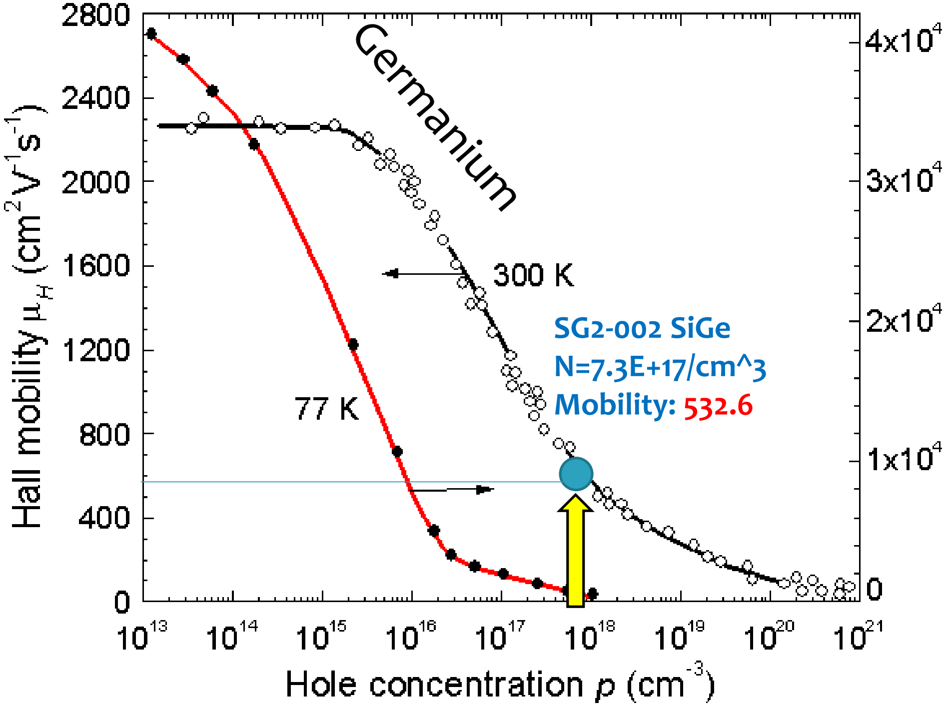
(Etch rate: 25nm/sec)

Hole (p-type) Mobility of SiGe

500% Faster Than Silicon (Si=105 vs. SiGe=532)



P-type Silicon's Mobility vs. Doping

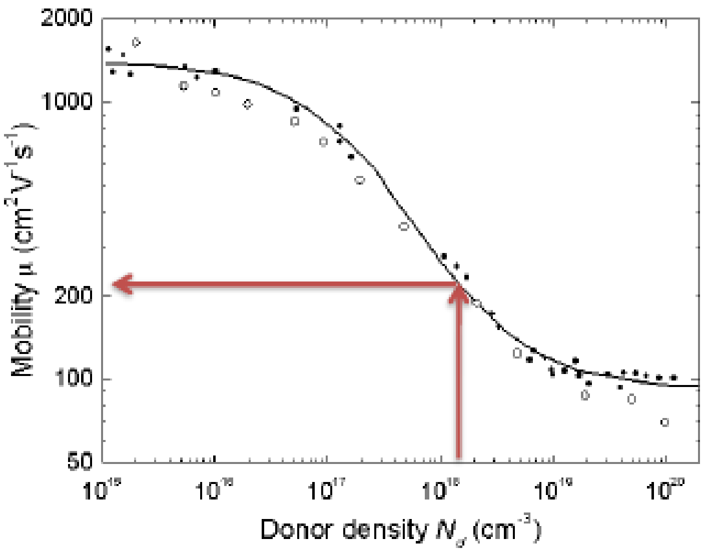


P-type Germanium's Mobility vs. Doping

Electron (n-type) Mobility of SiGe

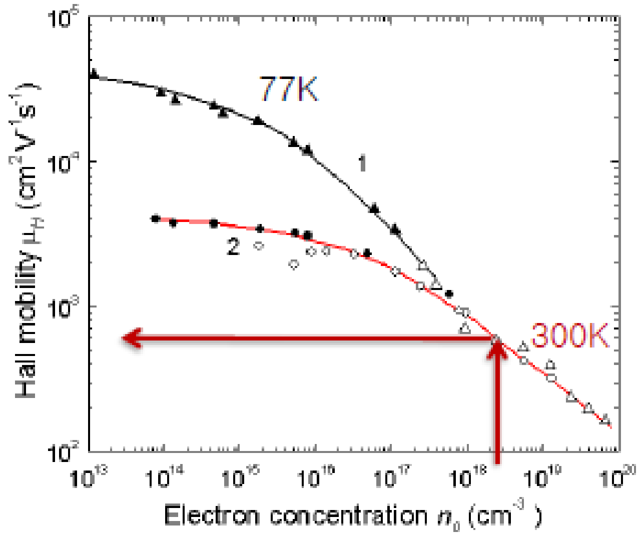
280% Faster Than Silicon (Si=220 vs. SiGe=616)

Standard n-type Silicon



Jacoboni, C., C. Canali, G. Ottaviani, and A. A. Quaranta, *Solid State Electron.* **20**, 2(1977) 77-89.

Standard n-type Germanium



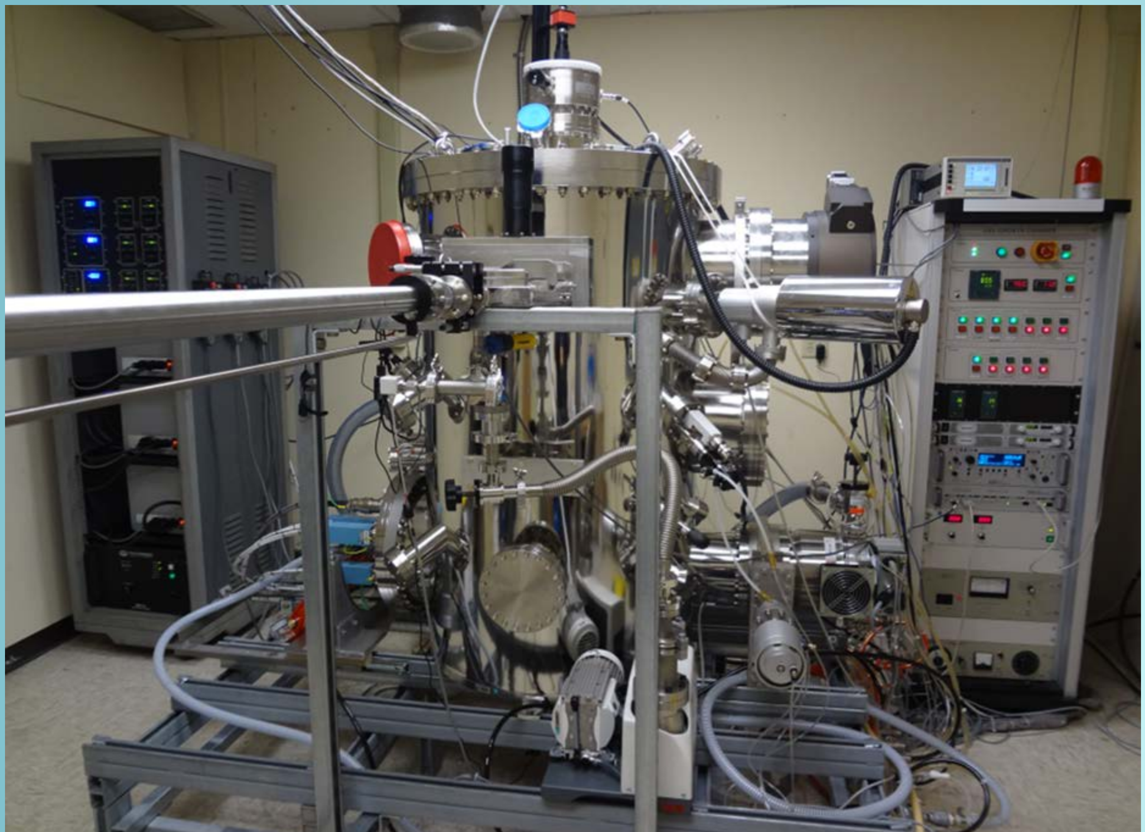
Fistul V. I., M. I. Iglitsyn, and E. M. Omelyanovskii, Sov. Phys. Solid State **4**, 4 (1962) 784-785.

220 cm²/V·s at 1.5×10^{18}/cm³ doping

780 cm²/V·s at 1.5×10^{18}/cm³ doping

Note: Our Thin Rhombohedral SiGe Sample#2 has **616 cm²/V·s** at 1.5×10^{18}/cm³ doping **which is 2.8 times higher electron mobility** than single crystalline Silicon wafer at the sample doping level. **μ_{SiGe} is 2.8 times higher than μ_{Si}**

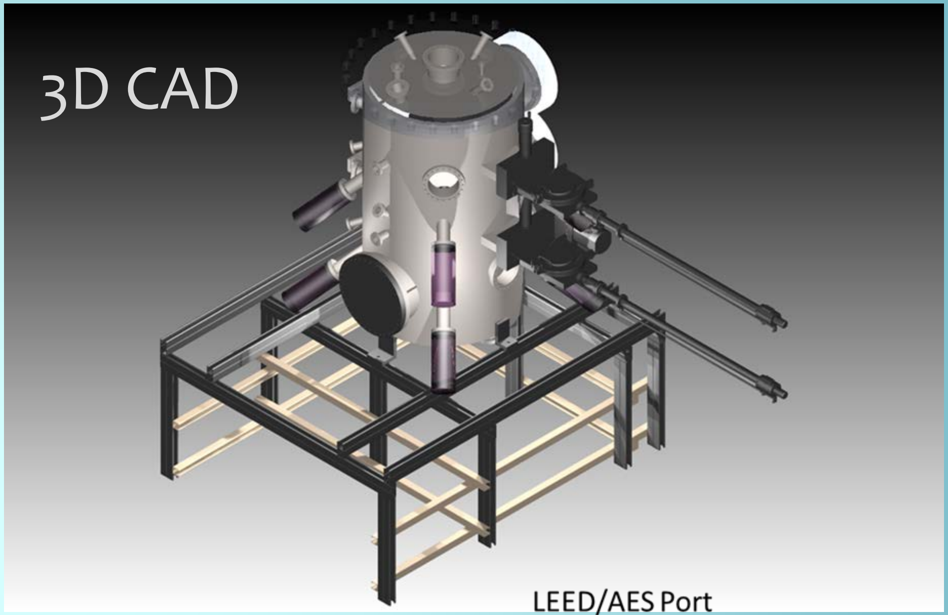
Super Hetero Crystal Growth Chamber

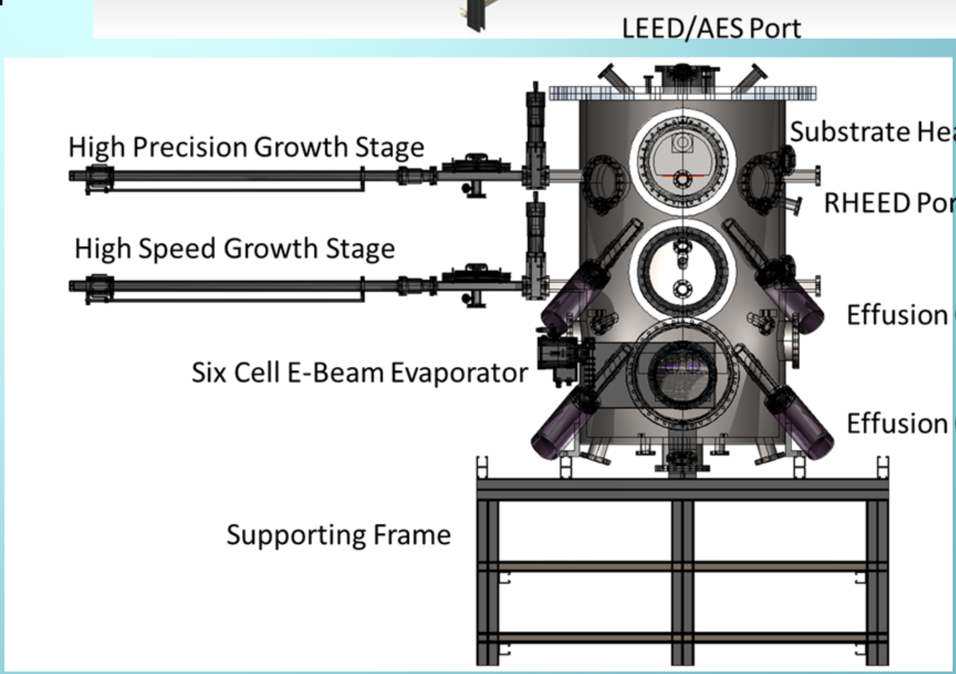


- About $1 Million was invested to build the super hetero-crystal crystal growth chamber. Additional financial support was made from Department of Transportation (DoT).
- The system can accept standard 2”~6” wafers with a load-lock.
- The system is ready for full computer control.

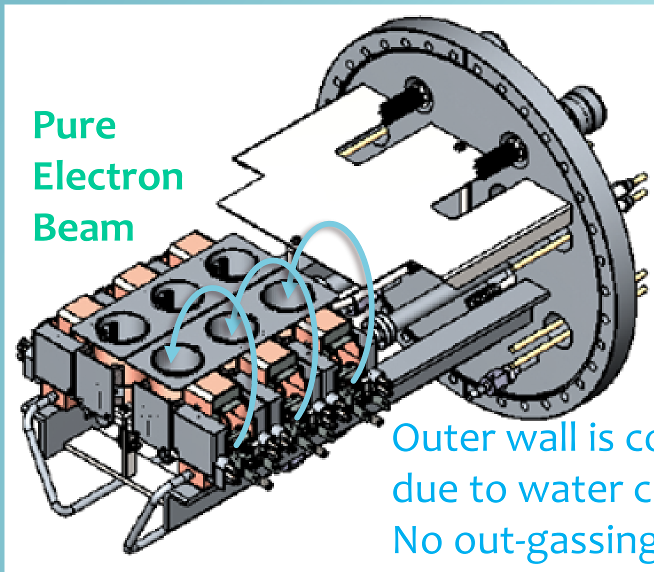
Super Crystal Structure Growth Chamber Designed by NASA Langley Team

- New atomic resolution growth machine was designed and built by NASA Langley Team.
- Unique two stage design to support (1) High Precision Growth Mode, (2) High Speed Growth Mode.
- Six cell E-beam evaporator to evaporate source materials up to 8130°F (4500°C).
- Multi effusion cells for dopants
- Reflective High Energy Electron Diffraction (RHEED) system to monitor in-situ growth.
- Low Energy Electron Diffraction (LEED) system with Auger Electron Spectroscopy (AES).



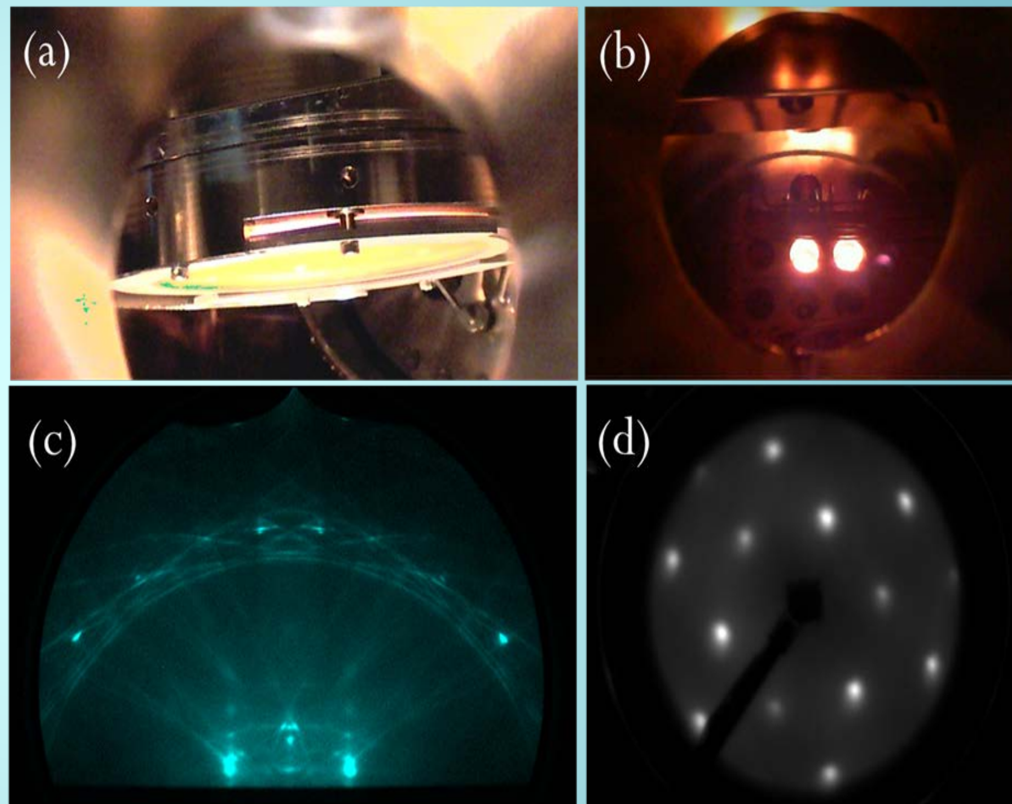


Functions of Super Growth Chamber

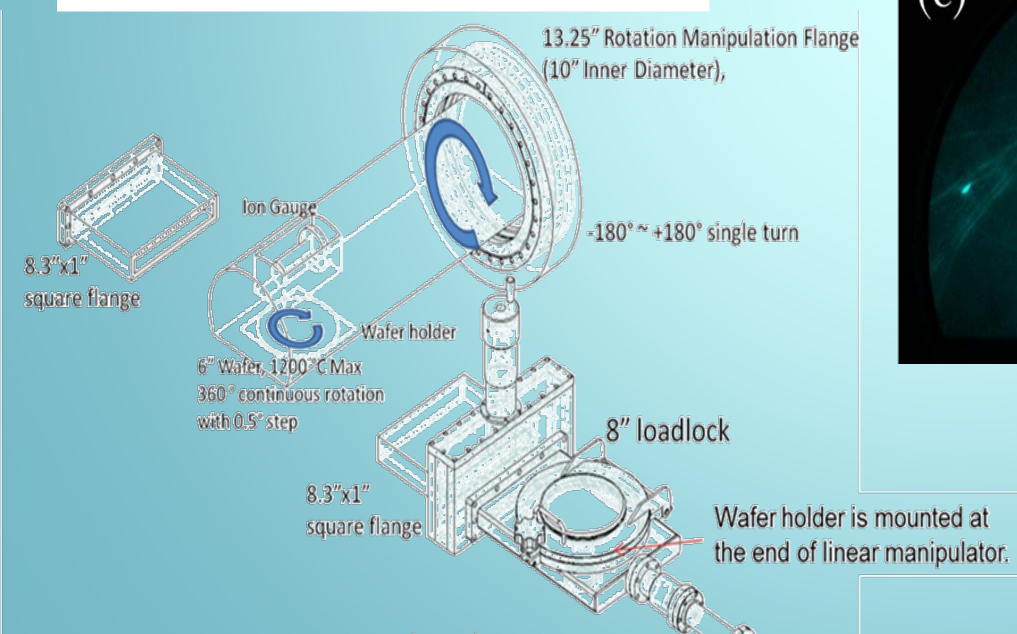


Outer wall is cold
due to water cooling.
No out-gassing!

6” Wafer Heater | 6-Cell E-Beam Evaporator

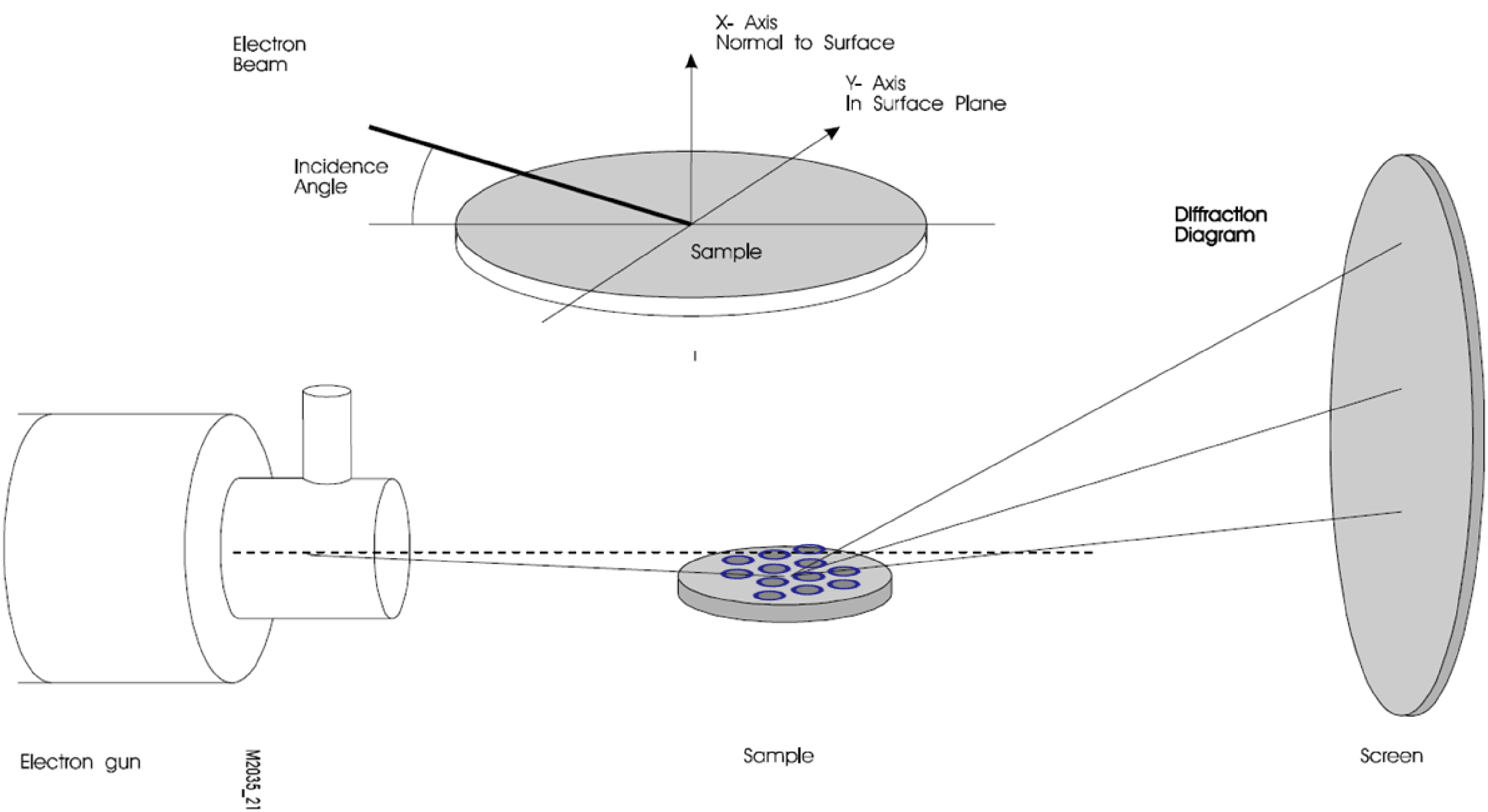


RHEED Monitoring | LEED Monitoring



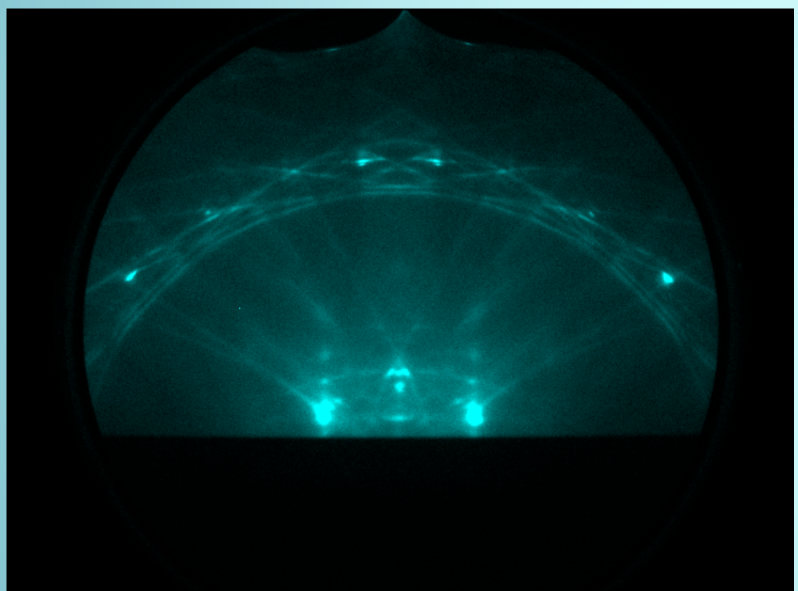
In-Vacuum Sample Exchange

Reflective High Energy Electron Diffraction (RHEED) System Configuration

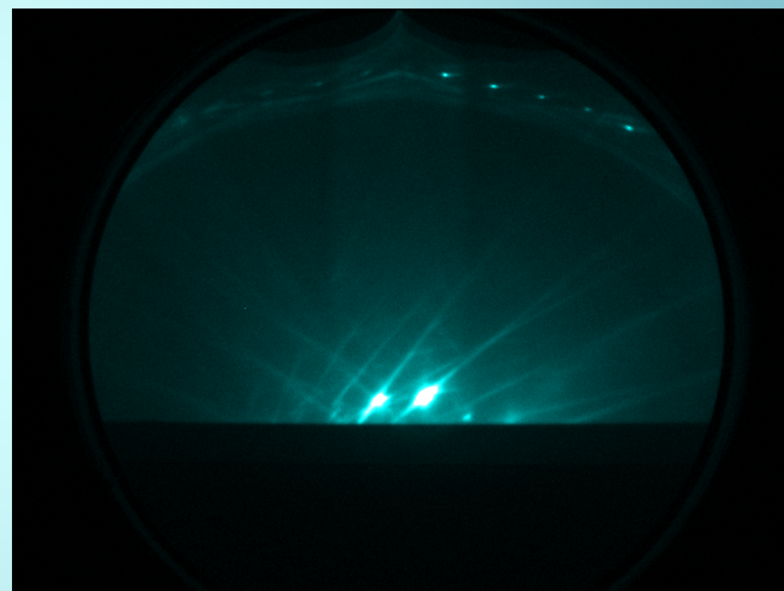


Atomic Precision In-Situ Growth Monitoring

RHEED patterns obtained from Sapphire (0001) surface

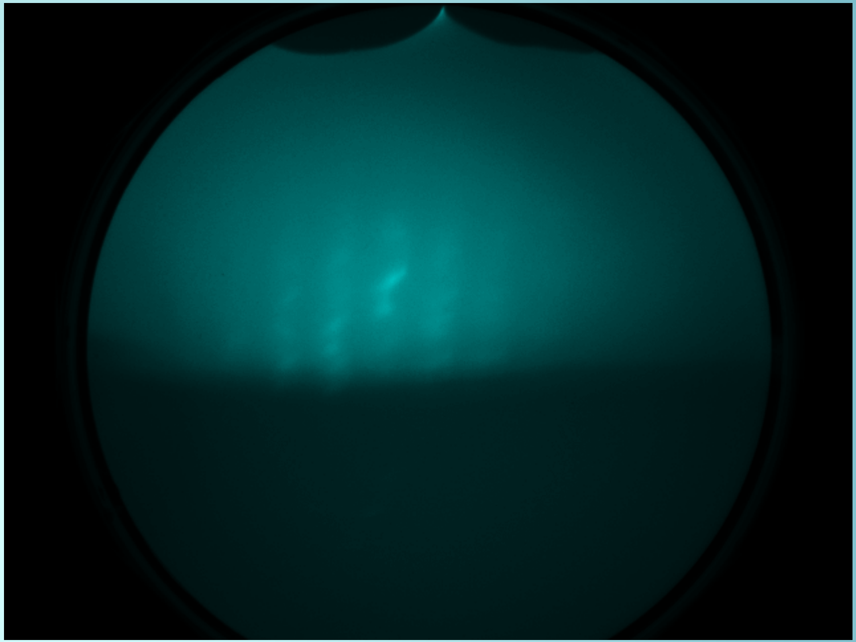


$[2\bar{1}\bar{1}0]$ Direction



$[1\bar{1}00]$ Direction

RHEED Pattern of SiGe Epi-Layer



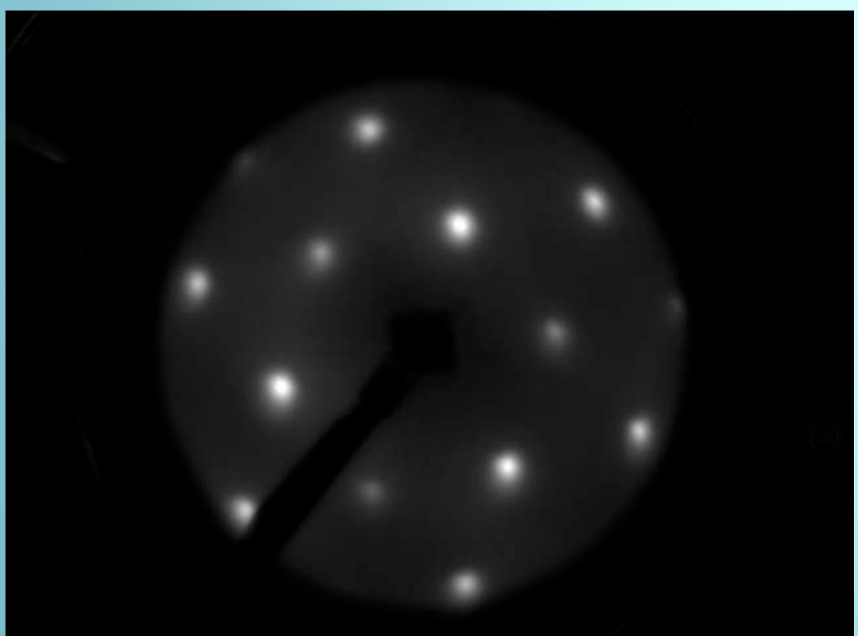
RHEED Pattern of
SiGe Epitaxial Layer

*Fuzzy lines are due to 60Hz noise from AC current substrate heater.

Atomic Precision Substrate Surface Monitoring

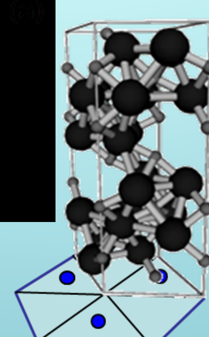
Low Energy Electron Diffraction (LEED)

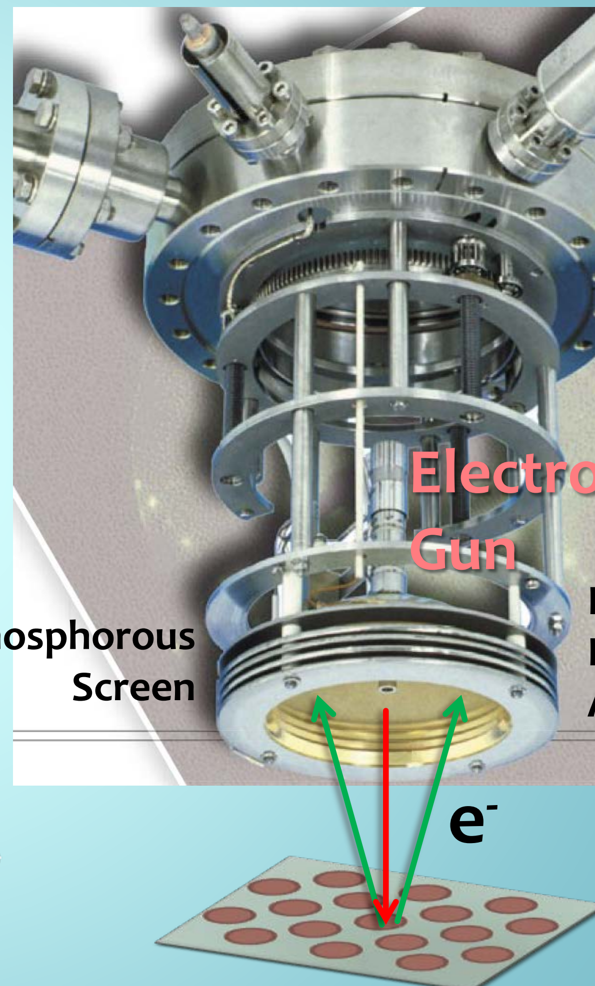
- Three bright spots and three dark spots indicate the atomic surface of trigonal symmetry. As the substrate temperature and gas condition change many new LEED patterns appear as different surface reconstructions occur.



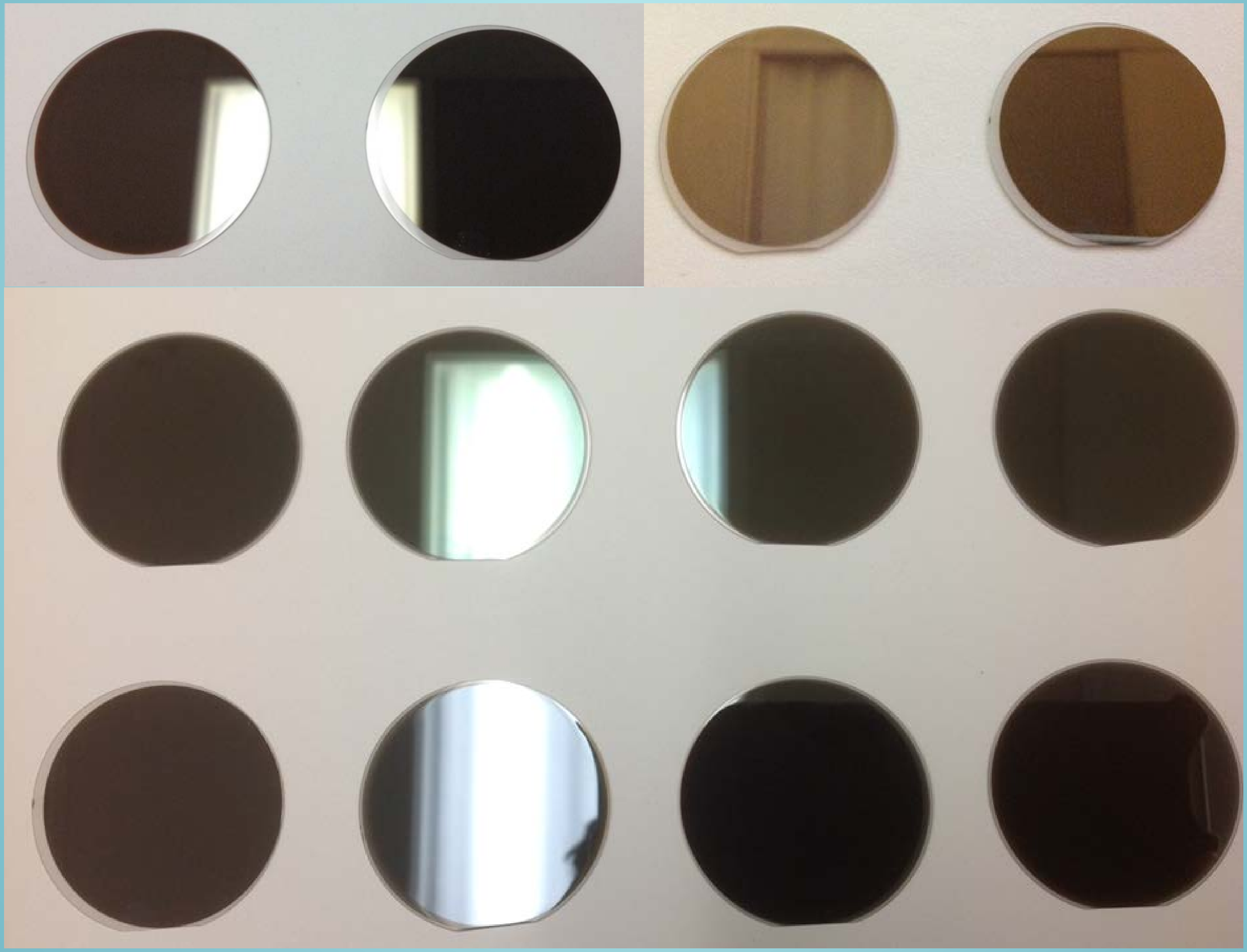
100eV LEED Pattern

Trigonal Substrate

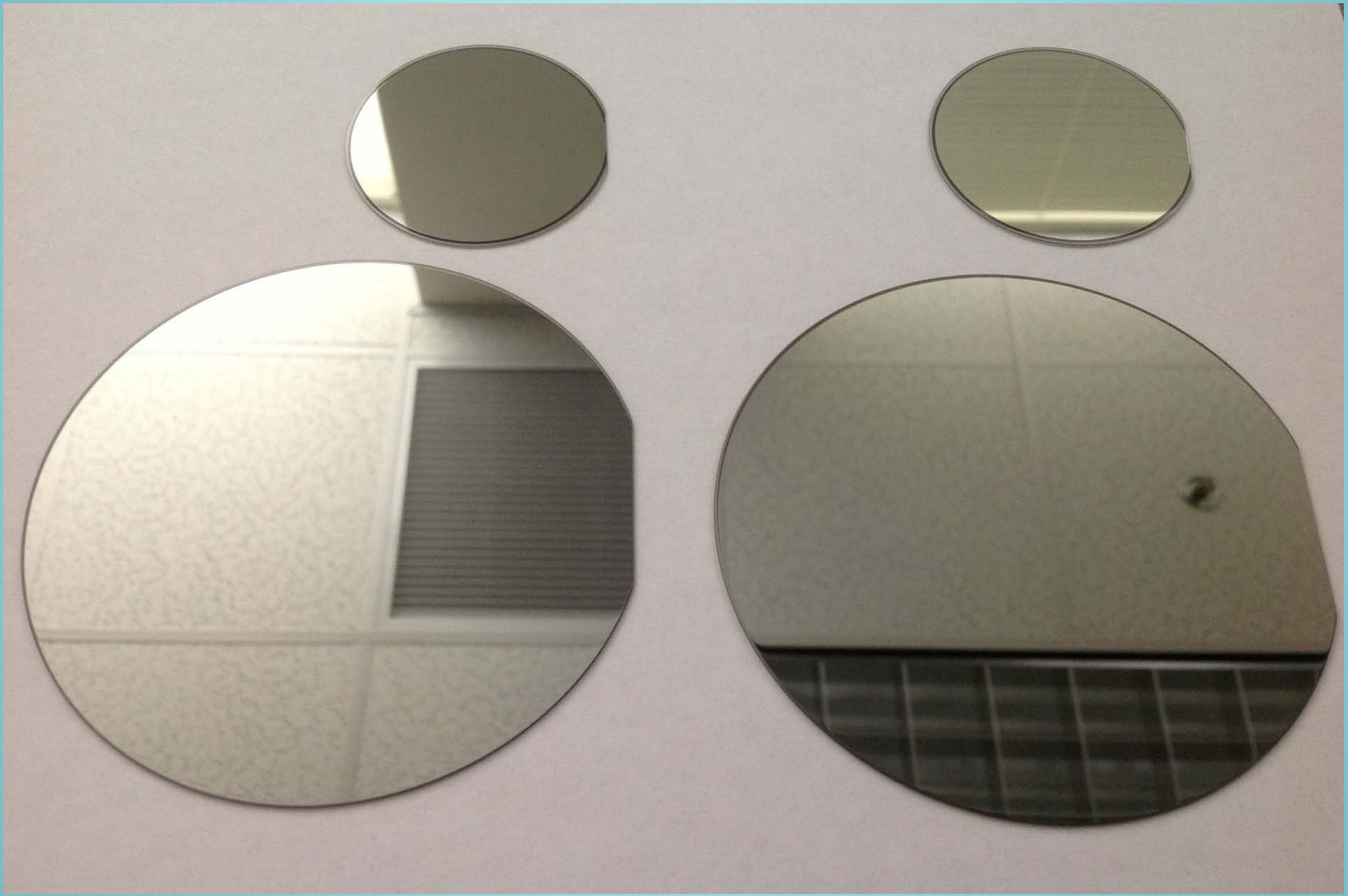




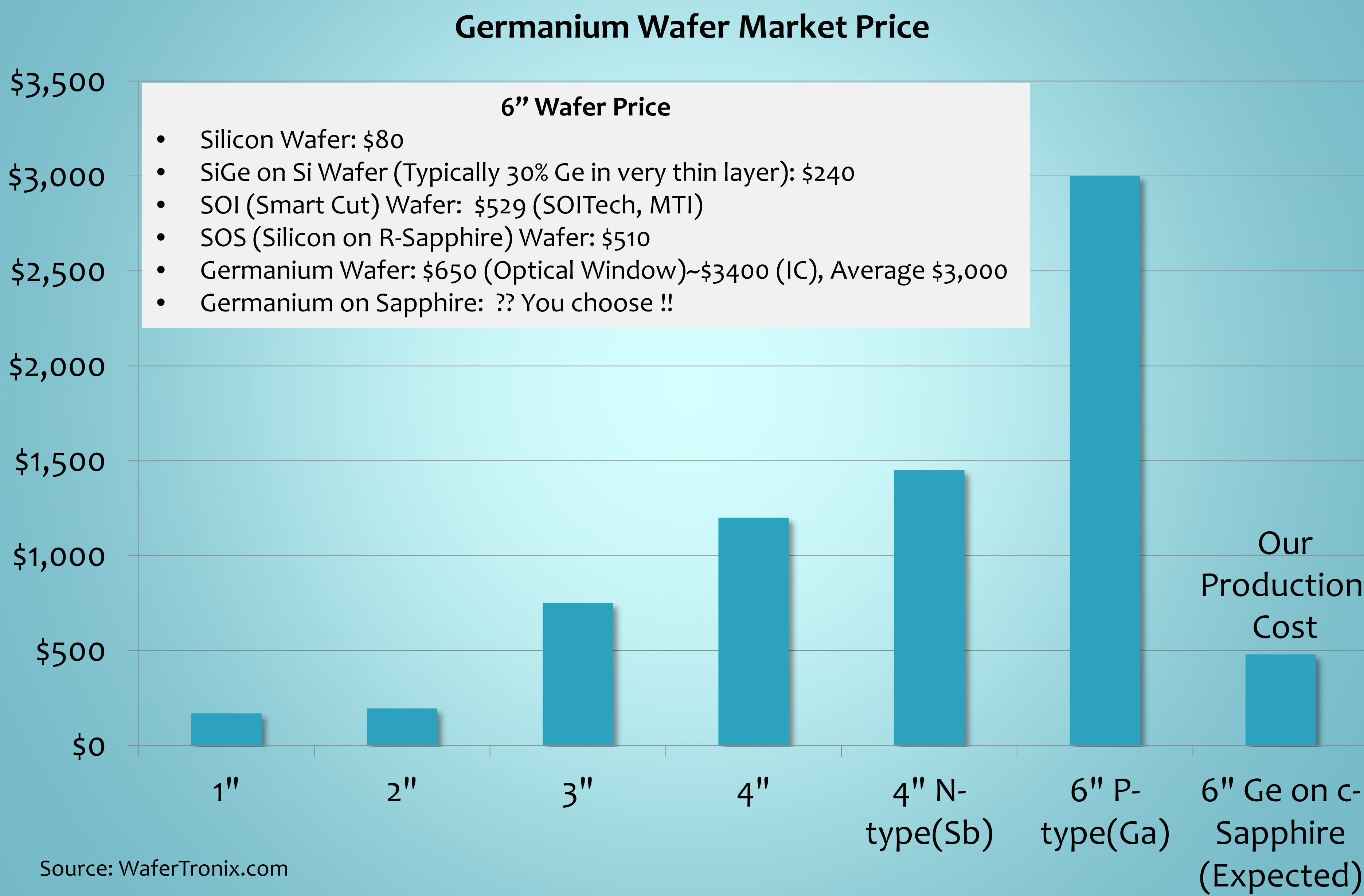
2" SiGe on c-Sapphire Samples



4" SiGe on c-Sapphire Samples



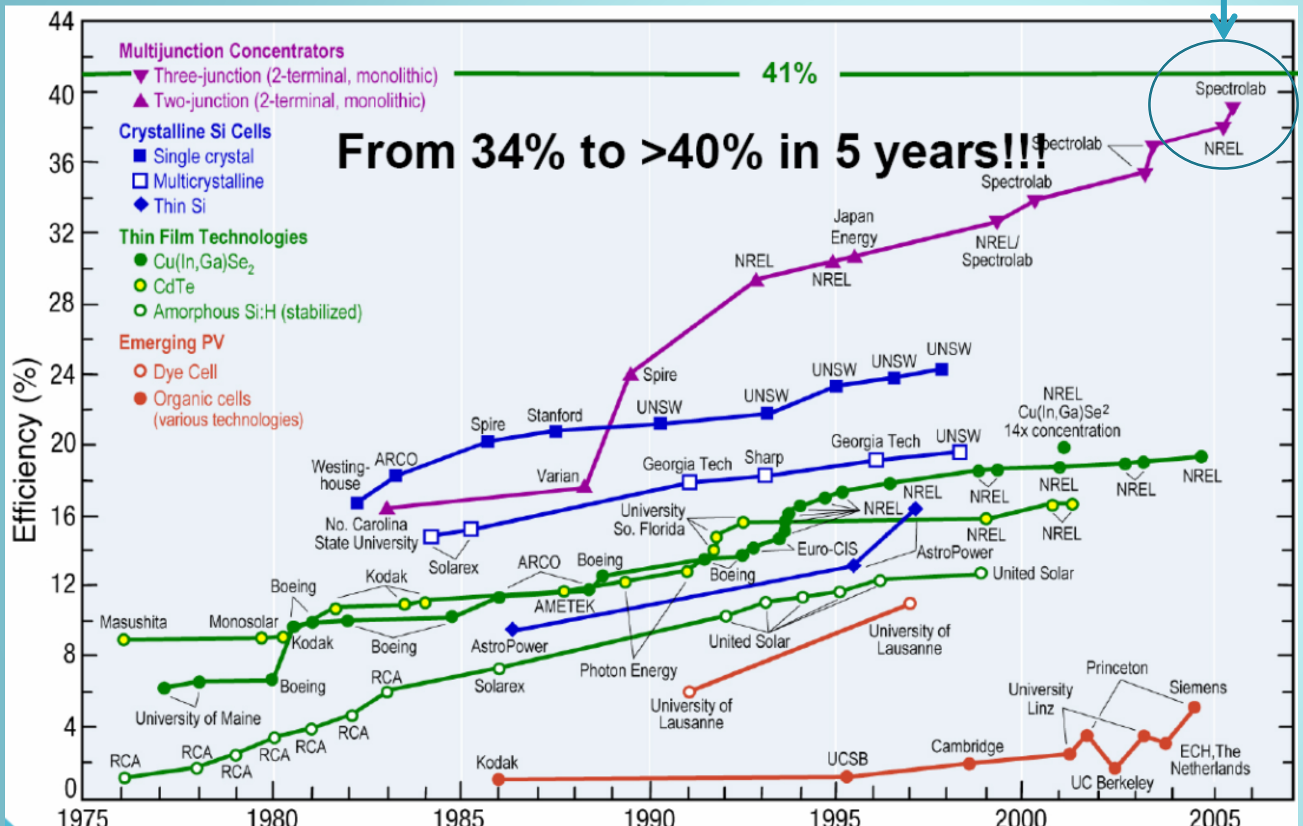
2013 Germanium Wafer Market



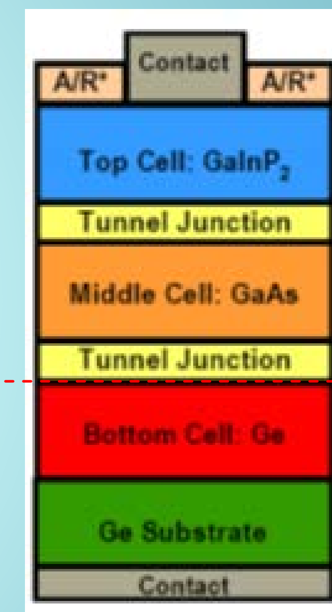
Source: WaferTronix.com

Toward The World's Best Solar Cell

The World's Highest Efficiency Solar Cell: III-V Multi-Junction Cells on Ge/Si Wafer (44%)



III-V Multi-Junction Solar Cell On Germanium Solar Cell Wafer



Commercial 6" Germanium Wafer is about $3,000.
NASA's new technology can make 6" SiGe/Sapphire under $300.
Our SiGe on Sapphire uses transparent substrate: It can receive light in both sides.
Our Goal: 40% Efficiency with 1/10th of price.

Summary

- Rhombohedral super-hetero-crystal epitaxy technology is invented. The world's first triangular crystal-plane epitaxy technology can combine cubic semiconductors with trigonal crystals.
- Germanium-rich single crystal SiGe layers on c-Sapphire are fabricated with high reliability (>99.9% single-crystal).
- US Patents: #8,257,491. #8,226,767. #7,906,358. #7,769,135. #7,558,371. #7,514,726 and so on.
- Super growth chamber was designed and manufactured to fabricate highly sophisticated quantum well solar cells and devices.
- Characterization shows single-crystalline SiGe layers on c-Sapphire with some residual defects. Surface morphologies are being improved with the reduction of RMS roughness.
- Rhombohedral Hybrid Bandgap (RHB) Technology expansion to III-V, III-Nitride and II-VI is underway.
- Pre-processor for high yield and Post-processor for high quality are under development.