RHOMBO-TRIGONAL EPITAXY OF SiGe ON c-SAPPHIRE

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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
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

(a) Trigonal Substrate

(b) SiGe (Diamond Structure)

(c) 2” SiGe on trigonal substrate

(d) Twin crystal to each other
1st Key:

XRD Integral Twin Density Measurement

(4-a) SiGe (111) 99.9%
Substrate (0006)
Substrate (0 0 0 12)

(4-b) Phi scan of SiGe (220)
99.7%
0.3%

(4-c) Phi scan of Sapphire (10-14)
New Rhombohedral SiGe Semiconductor Epitaxy

Single Crystalline SiGe Atomic Layers on Sapphire

NASA patented XRD methods, materials, and fabrication processes.
(US Patent # 7341883, 7558371, 7769135, 7906358, 8226767 and more.)
**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
- : Double Position Defect at Stepped Interface

- Twin detection XRD works
- Twin detection XRD does not work
New Rhombohedral Semiconductor Epitaxy
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
Atomic Resolution TEM Image of Rhombohedral-Trigonal Super Structure

SiGe (111)

Sapphire (0001)
**Comparison of Etch-Pit Densities**

**Threading Dislocation Pit Density after Secco Etching**

- **IBM’s SiGe**: Si(100)
- **NASA Langley’s SiGe**: Sapphire(0001)

**SiGe on Si substrate**
- 35% Ge

**SiGe on sapphire substrate**
- 78% Ge

- **TDP density**: $3.90 \times 10^4$ cm$^{-2}$
- **LD density**: $1.73 \times 10^4$ cm$^{-1}$
- **Cross-hatch pattern**

- **TDP density**: $1.9 \times 10^2$ cm$^{-2}$
- **LD density**: 0 cm$^{-1}$
- **No Cross-hatch pattern**

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

(Etch rate: 25 nm/sec)
Hole (p-type) Mobility of SiGe

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

P-type Silicon’s Mobility vs. Doping

- Silicon
  - N=7.3E+17/cm^3
  - Mobility: 105

P-type Germanium’s Mobility vs. Doping

- Germanium
  - 300 K
  - N=7.3E+17/cm^3
  - Mobility: 532.6
Electron (n-type) Mobility of SiGe

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

220 cm²/V·s at 1.5×10¹⁸/cm³ doping

780 cm²/V·s at 1.5×10¹⁸/cm³ doping

Note: Our Thin Rhombohedral SiGe Sample#2 has 616 cm²/V·s at 1.5×10¹⁸/cm³ doping which is 2.8 times higher electron mobility than single crystalline Silicon wafer at the sample doping level. \( \mu_{\text{SiGe}} \) is 2.8 times higher than \( \mu_{\text{Si}} \)
• 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.
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.

Functions of Super Growth Chamber

Pure Electron Beam

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

6” Wafer Heater
6-Cell E-Beam Evaporator

(a) RHEED Monitoring
(b) LEED Monitoring

13.25° Rotation Manipulation Flange
10” Inner Diameter)

-180° ~ +180° single turn

Wafer holder is mounted at the end of linear manipulator.
Reflective High Energy Electron Diffraction (RHEED) System Configuration
RHEED patterns obtained from Sapphire (0001) surface

[2110] Direction

[1100] Direction
*Fuzzy lines are due to 60Hz noise from AC current substrate heater.
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.
2” SiGe on c-Sapphire Samples
Germanium Wafer Market Price

6” Wafer Price

- Silicon Wafer: $80
- SiGe on Si Wafer (Typically 30% Ge in very thin layer): $240
- SOI (Smart Cut) Wafer: $529 (SOITech, MTI)
- SOS (Silicon on R-Sapphire) Wafer: $510
- Germanium Wafer: $650 (Optical Window)–$3,400 (IC), Average $3,000
- Germanium on Sapphire: ?? You choose !!

Source: WaferTronix.com
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

**From 34% to >40% in 5 years!!!**

- 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.**
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.