Development of SiC Large Tapered Crystal Growth

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APE027

Overview

Timeline

- Funding start: Dec. 2009
- Project end: Dec. 2013
- Percent complete: 70%

Budget

- Total project funding

  (4 years Labor + Procurement)
  - DOE: $2M
  - NASA: $1.3M ($600K FY13)
- $400K from DOE for FY12
- $400K from DOE for FY13

Barriers

- Advanced Power Electronics and Electric Machines (APEEM)

Table 2.1-4. Technical Targets for Electric Traction System

	2010[a]	2015[b]	2020[b]
Cost, $/kW	<19	<12	<8
Specific power, kW/kg	>1.06	>1.2	>1.4
Power density, kW/L	>2.6	>3.5	>4.0
Efficiency (10%-100% speed at 20% rated torque)	>90%	>93%	>94%

Partners

- NASA Glenn (Lead)
- Ohio Aerospace Institute
- Sest, Inc.
- NASA Postdoctoral Program (Oak Ridge Assoc. Universities)
- Stony Brook University
- Free Form Fibers, Inc.

Objectives

- SiC power semiconductor devices should theoretically enable vastly improved power conversion electronics compared to today's silicon-based electronics.
  - 2-4X converter size reduction and/or 2X conversion loss reduction (theoretical performance gains vary with system design specifications).
  - Fundamentally improved implementation of smart grid, renewable energy, electric vehicles, aircraft and space power systems.
- SiC wafer defects and cost inherent to existing SiC material growth approach presently inhibiting larger benefits from becoming more widely available.
- **New but unproven NASA "Large Tapered Crystal" (LTC) SiC growth concept proposed to lower SiC material defect and cost technology barrier.**

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Vehicle Technologies Program Multi-Year Program Plan (2011-2015)

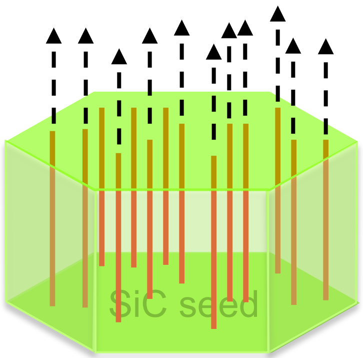
Table 2.1-6 Tasks for Advanced Power Electronics and Electric Motors R&D

Task	Title	Barriers Addressed
Task 1	**Power Electronics Research and Development** *New Topologies*- achieve significant reductions in PE weight, volume, and cost, and improve performance: • Reduce need for capacitance by 50%–90%, to yield 20% – 35% inverter volume reduction and cost reduction • Reduce part count by integrating functionality, to reduce inverter size and cost, and increase reliability • Reduce inductance, minimize electromagnetic interference and ripple, and reduce current through switches, all resulting in reduced cost *WBG semiconductors* - higher reliability and higher efficiency, and enable high-temperature operation	A, B, C, D, E, F

Approach/Strategy

Present SiC Growth Process

(Vapor transport)



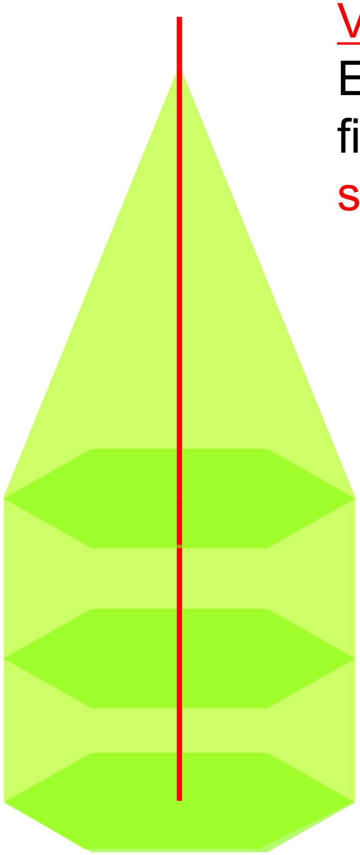
Vertical (c-axis) growth proceeds from top surface of large-area seed via thousands of dislocations. (i.e., dislocation-mediated growth!)

Crystal grown at T > 2200 °C
High thermal gradient & stress.

Limited crystal thickness.

Proposed LTC Growth Process

(US Patent 7,449,065 OAI, Sest, NASA)



Vertical Growth Process:
Elongate small-diameter fiber seed grown from single SiC dislocation.

Lateral Growth Process:
CVD growth to enlarge fiber sidewalls into large boule.
- 1600 °C, lower stress
- Only 1 dislocation

Vertical & Lateral growth are simultaneous & continuous (creates tapered shape).

Radically change the SiC growth process geometry to enable full SiC benefit to power systems.

Objectives

Overall Objectives (Longer Term)

- Open a new technology path to production of large-diameter SiC and GaN wafers with 100-1000 fold total crystal defect (dislocation) density improvement at 2-4 fold lower cost. (Present SiC wafers ~ 10^3-10^4 total dislocations per cm^2.)
- Enable leapfrog improvement in wide bandgap power device capability and cost to enable game changing improvements in electric power system performance (higher efficiency, smaller system size).

Funded Project Objectives (Shorter Term)

- Demonstrate initial feasibility of radically new “Large Tapered Crystal” (LTC) approach for growing vastly improved large-diameter SiC semiconductor wafers.
- Verify LTC growth physics in laboratory setting:
    - Growth of long, small-diameter single-crystal 4H-SiC fibers.
    - Lateral “M-plane” enlargement of 4H-SiC fibers into boules.

Milestones

SiC experimental demonstrations of the two critical growth actions required for Large Tapered Crystal (LTC) process.

Month/Year*	Milestone
September 2012	Demonstrate epitaxial radial (lateral) growth of a 5 mm diameter boule starting from a simulated SiC fiber crystal.
September 2013	Demonstrate laser-assisted fiber growth of a SiC fiber crystal greater than 10 cm in length.

LTC is **NOT** viable without success of BOTH processes.

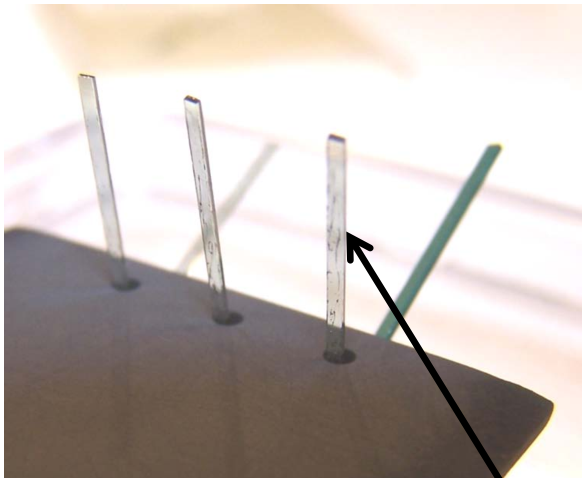
As discussed in this presentation, neither above quantitative milestone challenges have been met within the original project schedule.

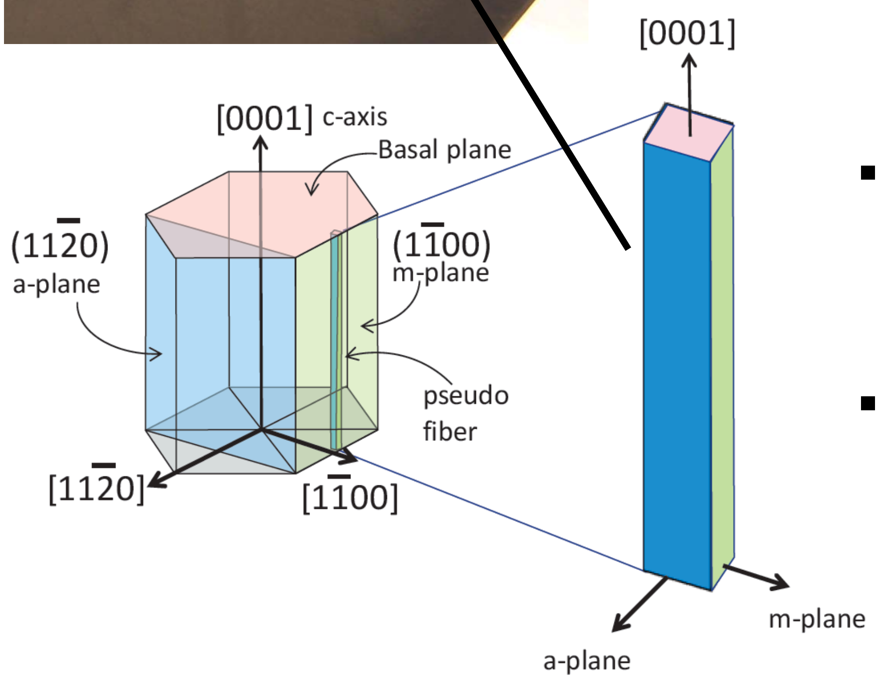
* Interagency Agreement Amendment #2 Executed June 2012.

Technical Accomplishments and Progress

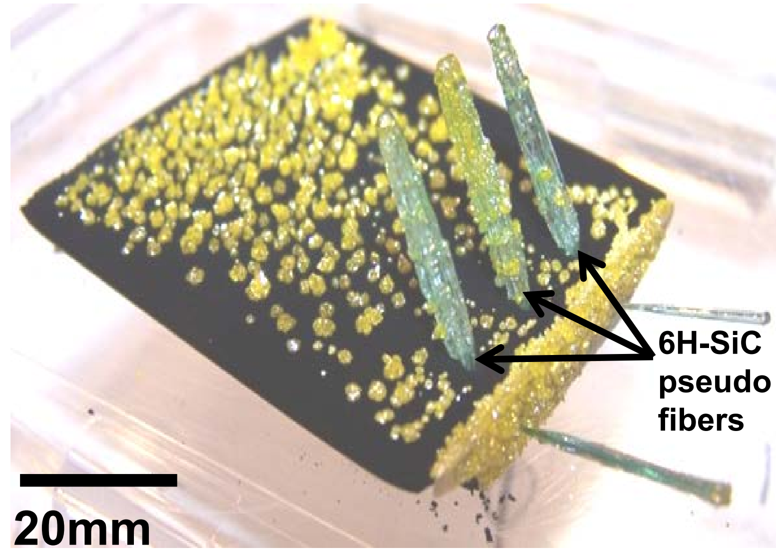
Radial/Lateral CVD Epi-Growth (viewgraph from FY12 Review)

4H/6H SiC a/m-plane slivers prior to growth





Slivers after 8 hours of CVD epitaxial growth

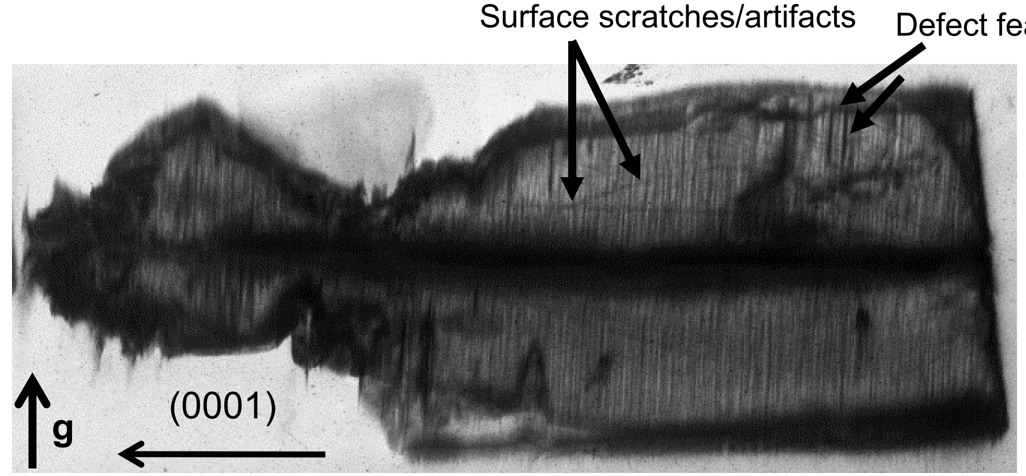


- Post-growth crystals are translucent and exhibit lateral expansion (a/m-face growth).
- 3C-SiC crystallites (yellow) undesirably nucleated in some areas.

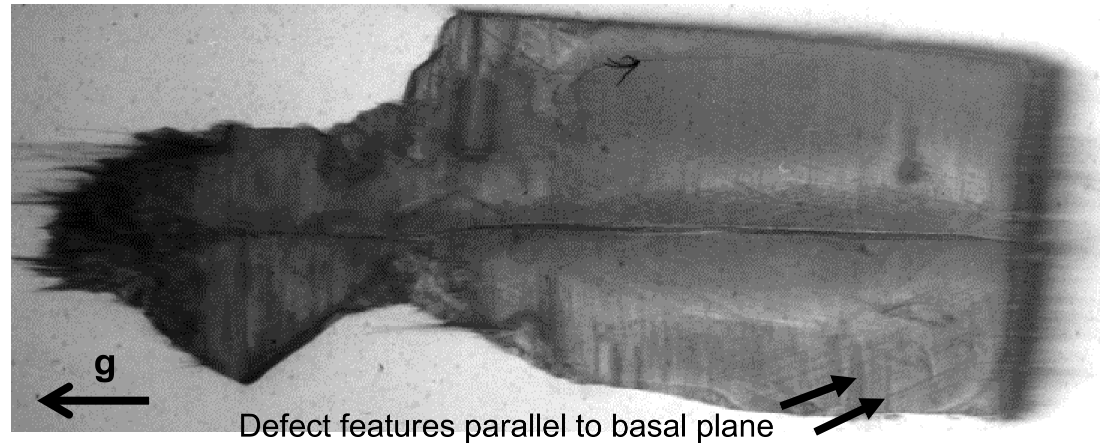
Technical Accomplishments and Progress

Radial/Lateral CVD Epi-Growth

X-Ray Topography of Initial Radial Epilayer Mini-Boules
(Stony Brook University using Synchrotron Source at Brookhaven National Laboratory)

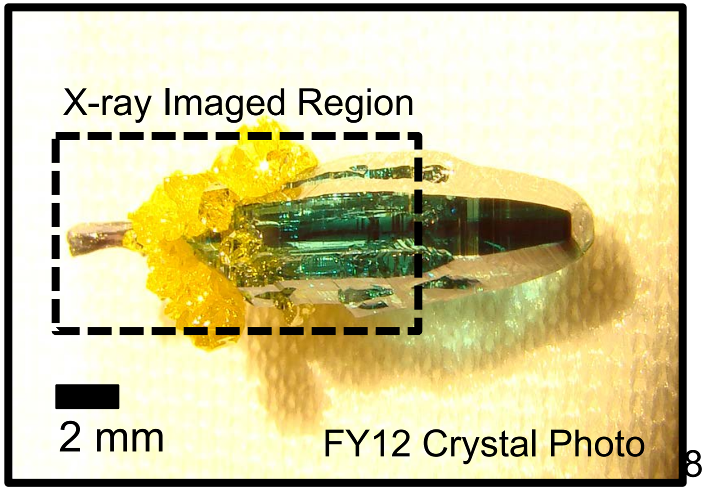


Transmission topograph (g = 1-100)



Transmission topograph (g = 0006)

- 4 mm radial epilayer “mini-boule” was sectioned and polished for X-ray topography.
- The 1-100 topographs reveal defect features running along the basal plane directions. **Vast majority of these defects originate in the seed sliver, but a few also appear to nucleate in the radial epilayer.**



Technical Accomplishments and Progress

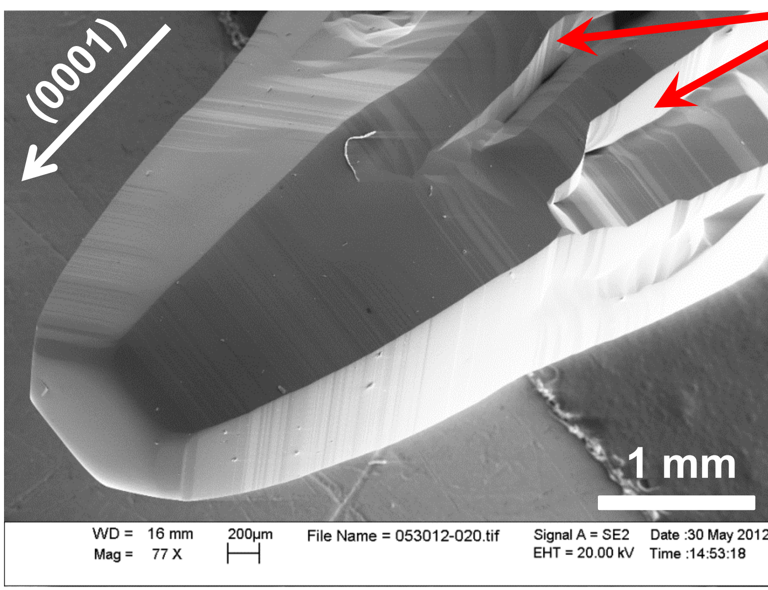
Identified Extrinsic (Correctable) Sources of Radial Layer Defects

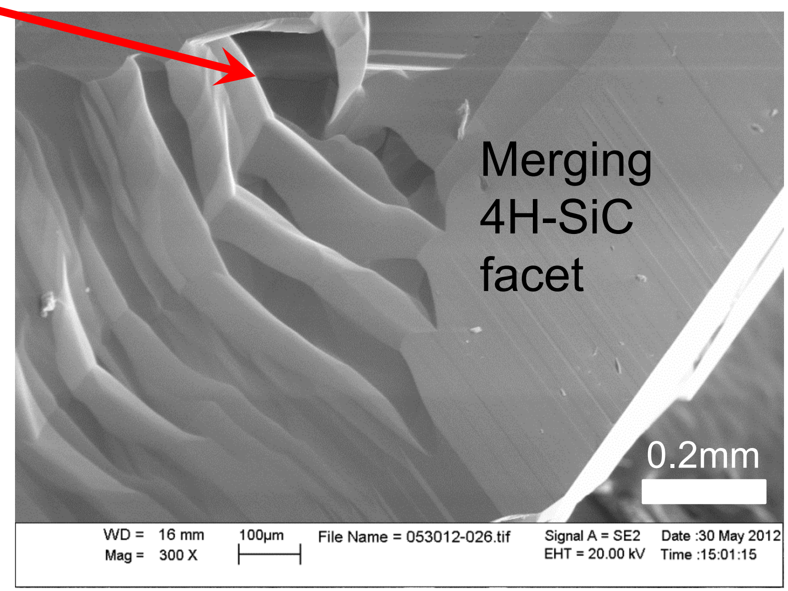
- Seed sliver basal plane dislocations propagate into epilayer (slide 8).
  Best Solution: Succeed at high-quality fiber growth, use those as seeds!

- Disordered coalescence from rectangular seed radially growing into hexagonal crystal (below).
  Best Solution: Succeed at high-quality fiber growth, use those as seeds!
  Less-ideal Solution: Polish seed slivers into hexagonal cross section.

- Parasitic 3C nucleation dominant in seed sliver base holder region (slide 7).
  New sample holder installed to suppress 3C-SiC nucleation near base.
  Adjust growth conditions, better optimize growth rate vs. film quality tradeoffs.

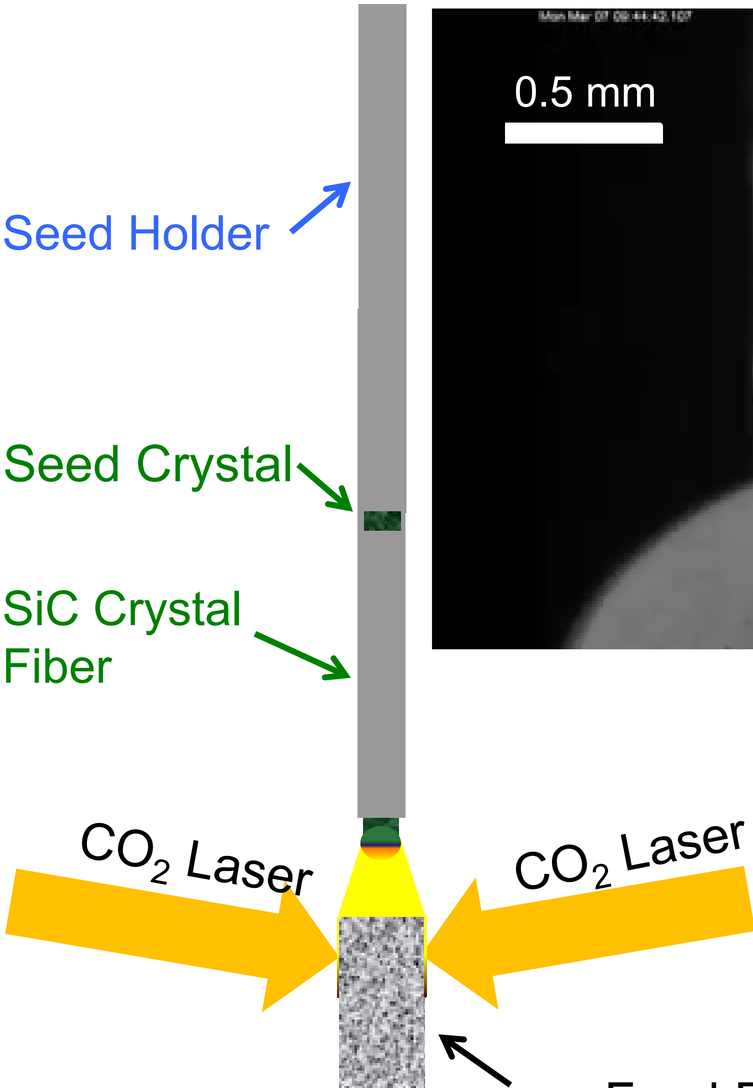
Scanning electron micrographs of disordered merging & voids in two radial growth fronts.

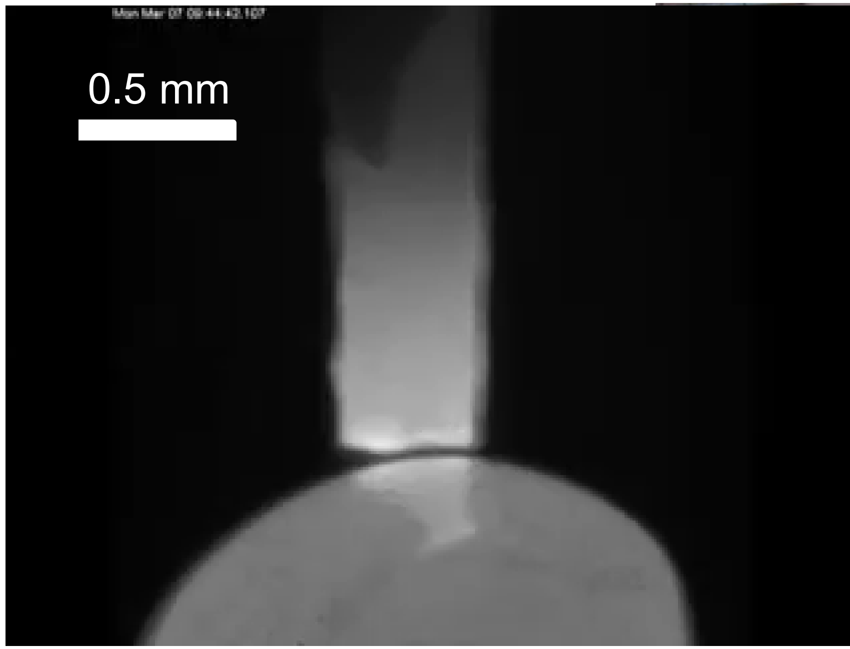


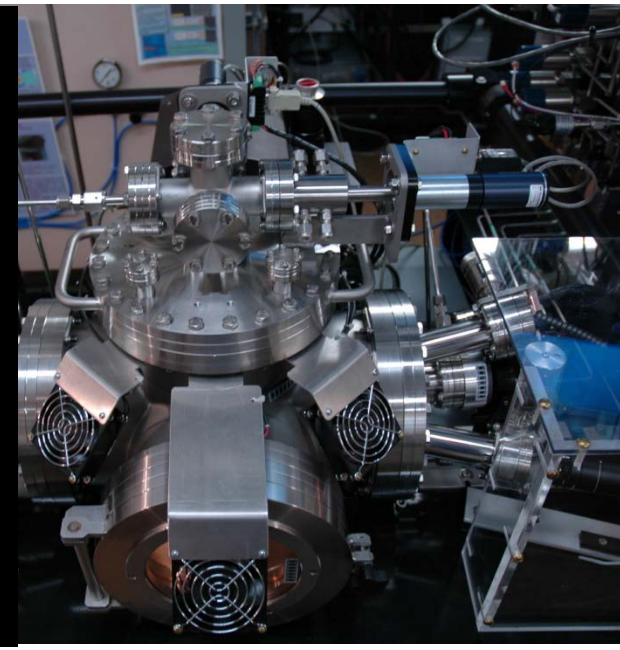


Approach/Strategy

(Solvent-LHFZ) - A New and Unique SiC Fiber Growth Method







Combines the advantages of Traveling Solvent Method (TSM) & Laser Heated Floating Zone (LHFZ)

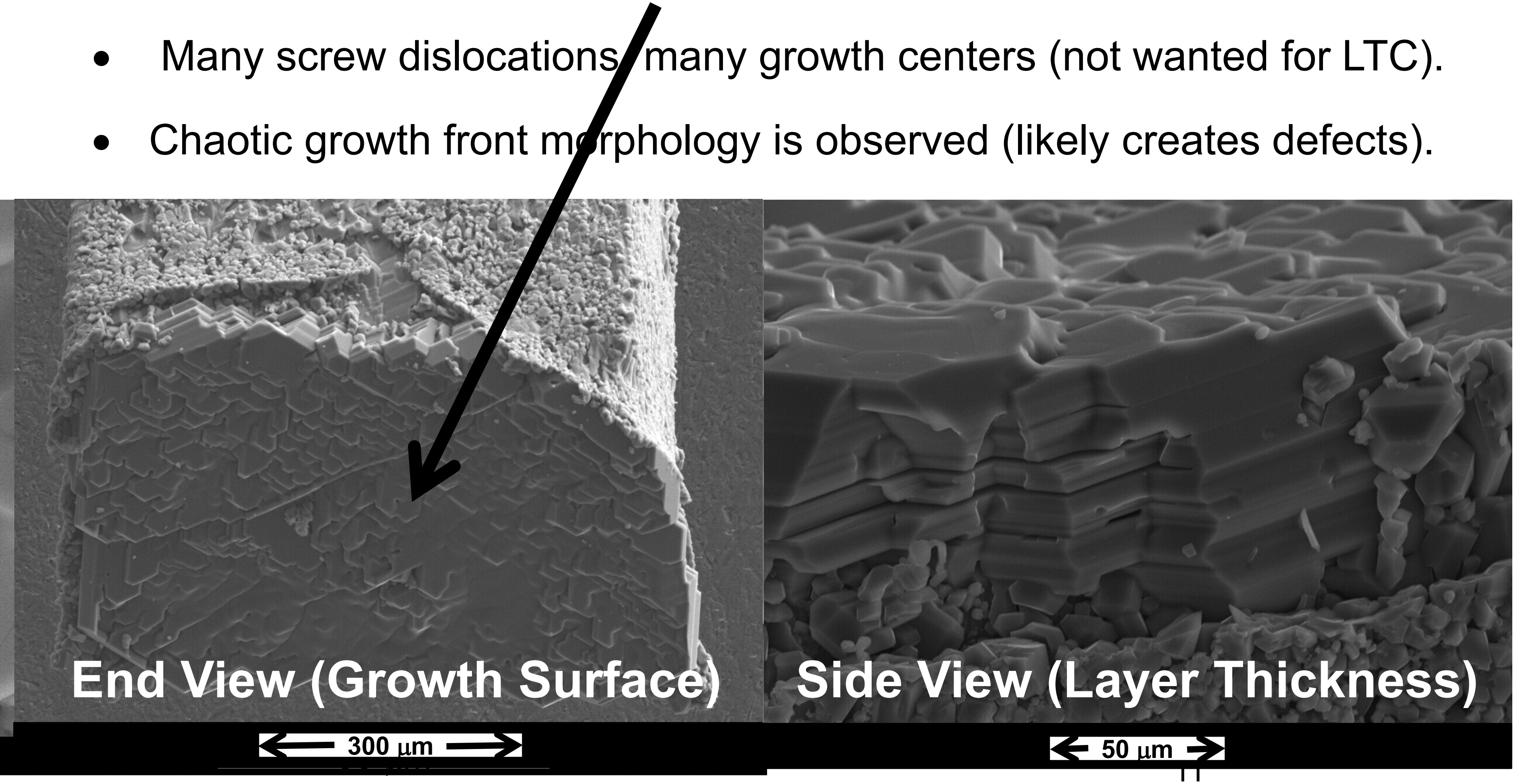
- TSM: Known SiC growth method
- LHFZ: Semi-infinite growth material

Feed Rod with Si + C + Solvent
(Non-Crystalline Source Material)

Technical Accomplishments and Progress

Solvent-LHFZ SiC Fiber Growth (viewgraph from FY12 Review)

- Layer polytype confirmed via X-ray topography (Prof. Dudley @ SUNY)
- Non-ideal "cut seed" crystal growth front is large (~ 0.5 mm^2).
  - Many screw dislocations, many growth centers (not wanted for LTC).
  - Chaotic growth front morphology is observed (likely creates defects).

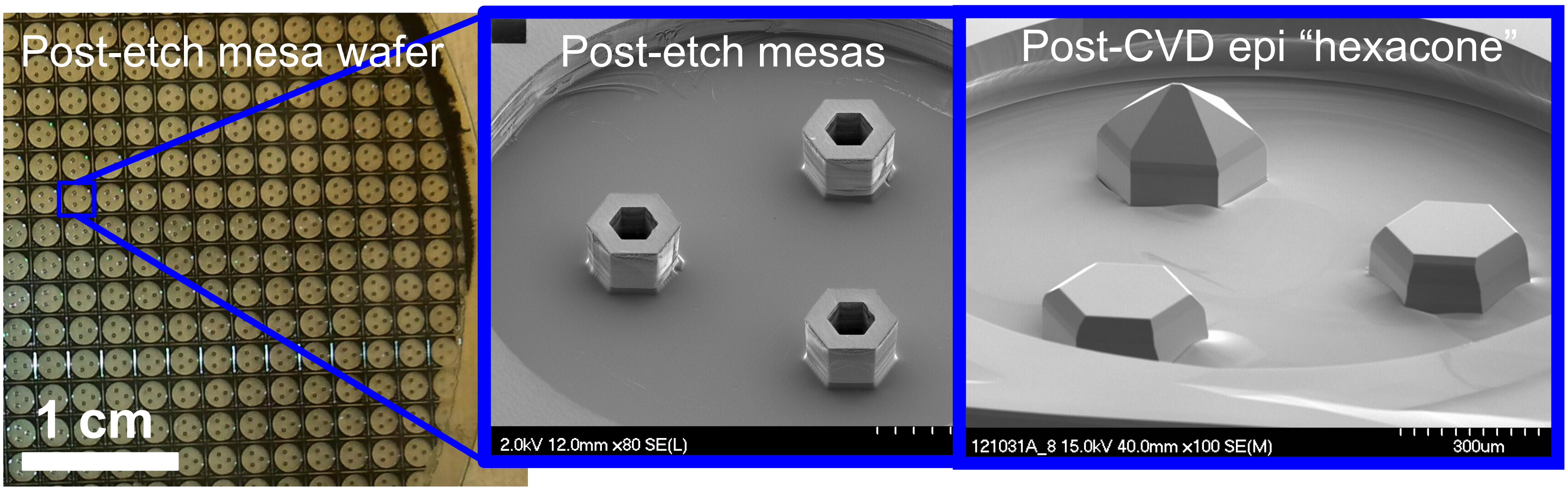


Technical Accomplishments and Progress

“Hexacone” Mesa Seed Development

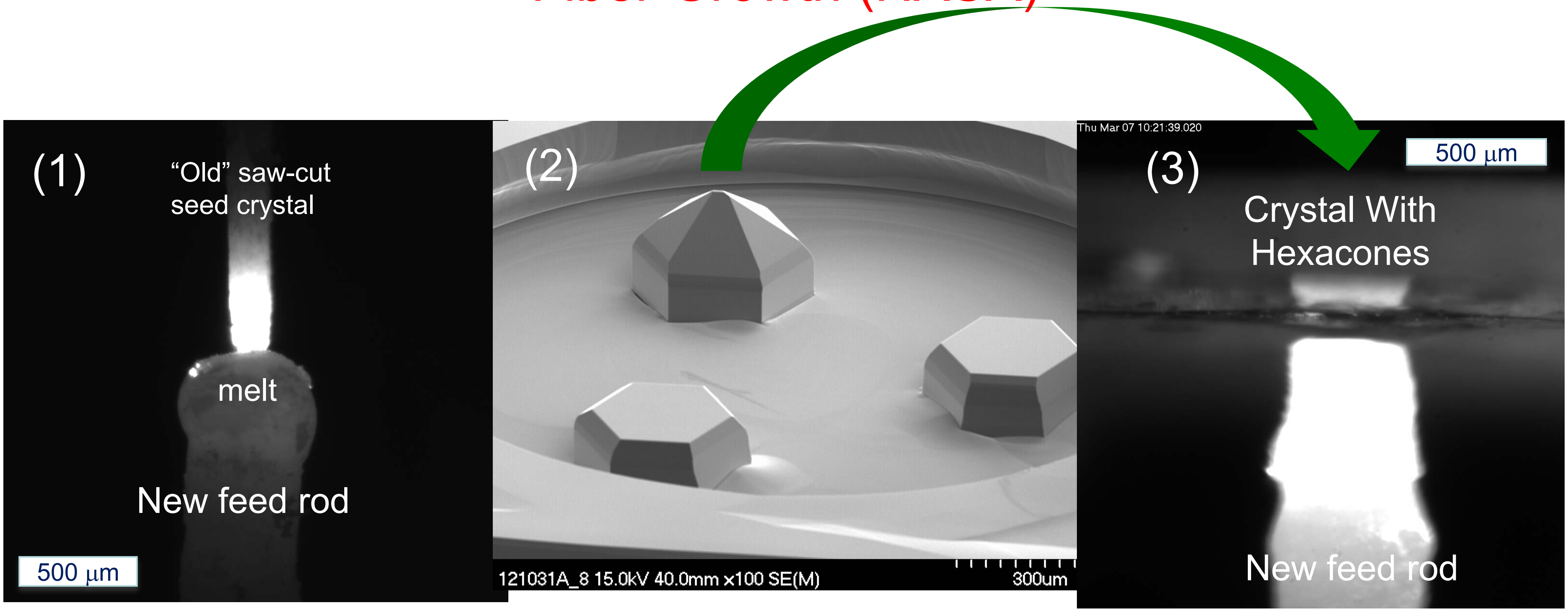
As described in LTC patent (US 7,449,065), both laser-solvent (NASA) and laser-CVD (FFF) fiber-growth approaches require (start from) a small initial 4H-SiC seed mesa with centrally located screw dislocation. **Nominal mesa seed for fiber growth is a pointed “hexacone” achieved via pure stepflow CVD homoepitaxy on mesa-etch patterned etched 4H-SiC wafer.**

Significant effort this year on refining deep dry etching and hot-wall CVD process for growing arrays of 4H-SiC mesa “hexacones” for seeding fiber growth.



Technical Accomplishments and Progress

Fiber Growth (NASA)



(1) New 4X smaller-diameter feed rods for solvent fiber growth developed.

(2) Improved SiC "hexacone seeds" needed to advance fiber development work grown via CVD epitaxy (delivered to Solvent-LHFZ lab & SBIR contractor).

(3) First Solvent-LHFZ experiments using (1) and (2) initiated (March 2013).

Fundamental Challenge: Can solvent process yield a stable single-domain growth front needed to realize a long 4H-SiC single-crystal fiber?

Technical Accomplishments and Progress

Laser-CVD at Free Form Fibers (FFF) LLC, Saratoga Springs NY

NASA-funded SBIR Phase III for Laser-Assisted CVD Growth of 4H-SiC Single-Crystal Fibers was Awarded June 2012.

Significant modifications to Laser-CVD system installed, followed by first experiments on NASA-provided 4H-SiC mesa samples in November 2012.

4H-SiC single-crystal fiber growth has not yet been achieved at FFF, but important (proprietary) experimental insights have been learned.

NASA Glenn providing technical assistance (interactive research collaboration).
- Seed crystal samples, characterization, consulting, & equipment loan.
- Recent OMB travel restrictions have prevented additional desired site visits to FFF.

SBIR contract scheduled to conclude June 2013.

Proposed Future Work

Radial growth of larger (> 5mm diameter) mini-boules to retire original project metric will be undertaken soon.

- Until 4H-SiC fibers become available, radial growth will continue to be seeded by non-ideal saw-cut slivers.
- Larger samples with less 3C should make it easier to resolve if any intrinsic defects are present in radial epilayers.

Majority of NASA effort will be transitioning to fiber growth research.

- Grow sufficient inventory of "hexacones" for seeding all fiber growth work.
- Explore Laser-solvent fiber growth using hexacone 4H-SiC seeds.
  - Push from "layer growth" to "fiber crystal growth"
- Assist Free Form Fibers Laser-CVD SBIR Phase III effort.
  - Modeling, growth, and sample characterization.
- **Systematically attack experimental condition control (including hardware) needed to achieve 4H-SiC fiber growth breakthrough demonstration.**

Collaboration and Coordination with Other Institutions

- NASA Glenn Research Center (Prime)
  SiC crystal growth and ceramic fiber growth research branches
    - Ohio Aerospace Institute (Non-Profit)
    - Sest, Inc.
    - NASA Postdoctoral Program (Oak Ridge Assoc. Universities)

- State University of New York at Stony Brook – Brookhaven NY and Argonne IL X-ray sources (Dept. of Energy).
    - Prof. Dudley's group - recognized leader in X-Ray topographic mapping characterization of SiC crystals and defect structure.

- Free Form Fibers LLC (NY) – SBIR Phase III (NASA Funded $100K) for laser-assisted SiC fiber growth using gas precursors.
  - Small business laser-growing **polycrystalline** SiC fiber shapes.
  - Parallel path (risk mitigation) to realize **single-crystal** SiC fiber growth if technical challenges of Solvent-LHFZ approach cannot be overcome.

Summary

Progress continues towards SiC Large Tapered Crystal growth feasibility demonstration, albeit behind original schedule.

Radial growth feasibility milestone likely to be completed soon.
- Crystal will contain defects from understood non-idealities.
- High quality fiber needed to obtain best crystal quality.

Fiber growth feasibility remains toughest challenge of LTC.
- "Hexacones" for seeding fiber experiments have been produced.
- No "breakthrough" fiber crystals yet at NASA or Free Form Fibers.
- Additional fundamental experiments & understanding required.
- Fiber growth milestone unlikely to be met during FY 2013.

Going forward, effort and resources will be more focused on fiber growth, with likely increased emphasis on CVD-based approach.

Technical Acknowledgements

NASA LTC Co-Investigators:
Andrew Woodworth (NPP/NASA),
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Michelle Mrdenovich (Sierra Lobo Inc),
Scott Panko (Vantage Partners),
Chuck Blaha, Frank Lam & Kelly Moses (Jacobs Technology),
and Ed Sechkar (Zin Technologies Inc).

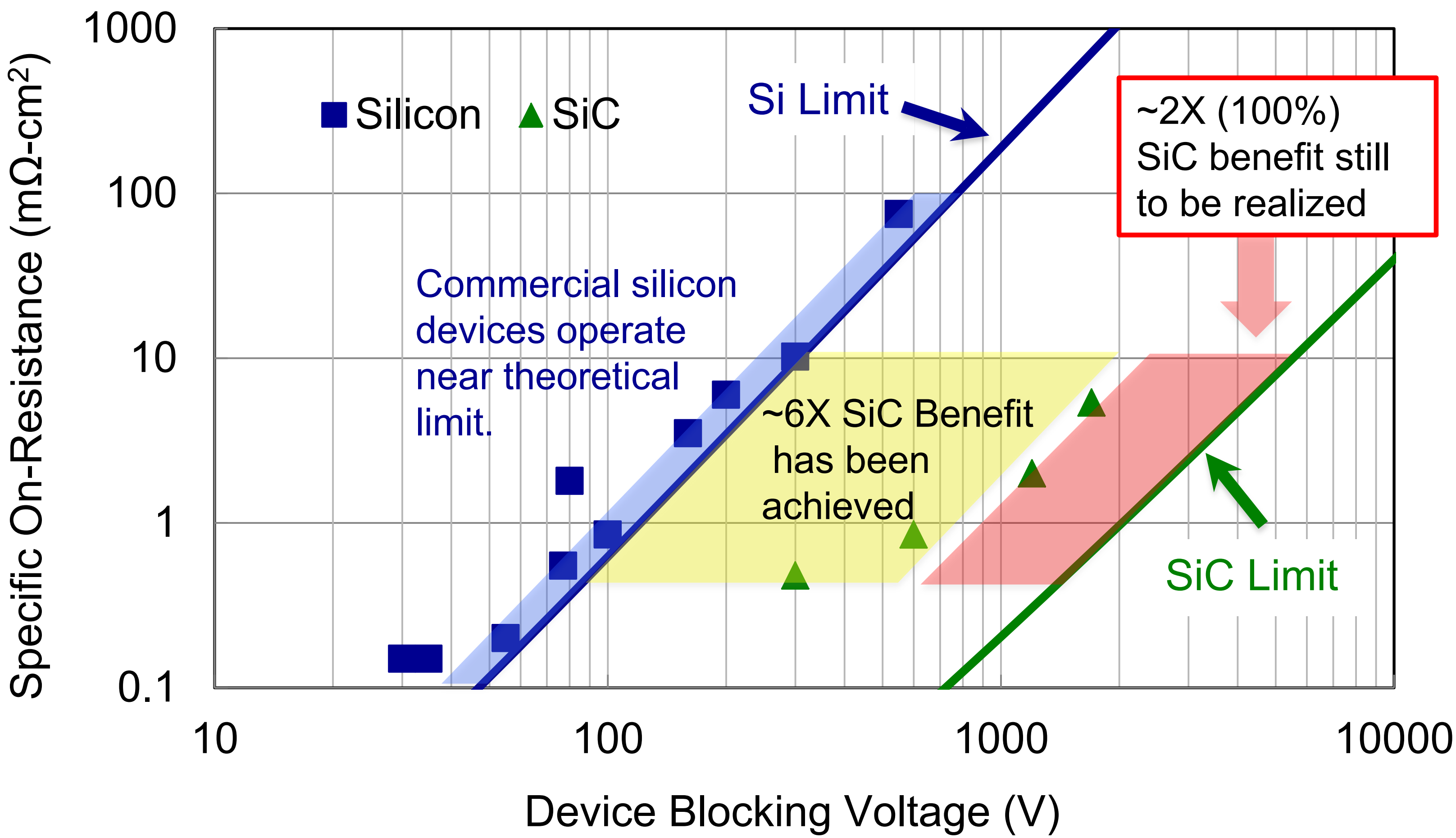
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Unipolar Power Device Comparison

(Volume Production Commercial Devices)

SiC devices are ~2X voltage or current-density **de-rated** from theoretical material performance.



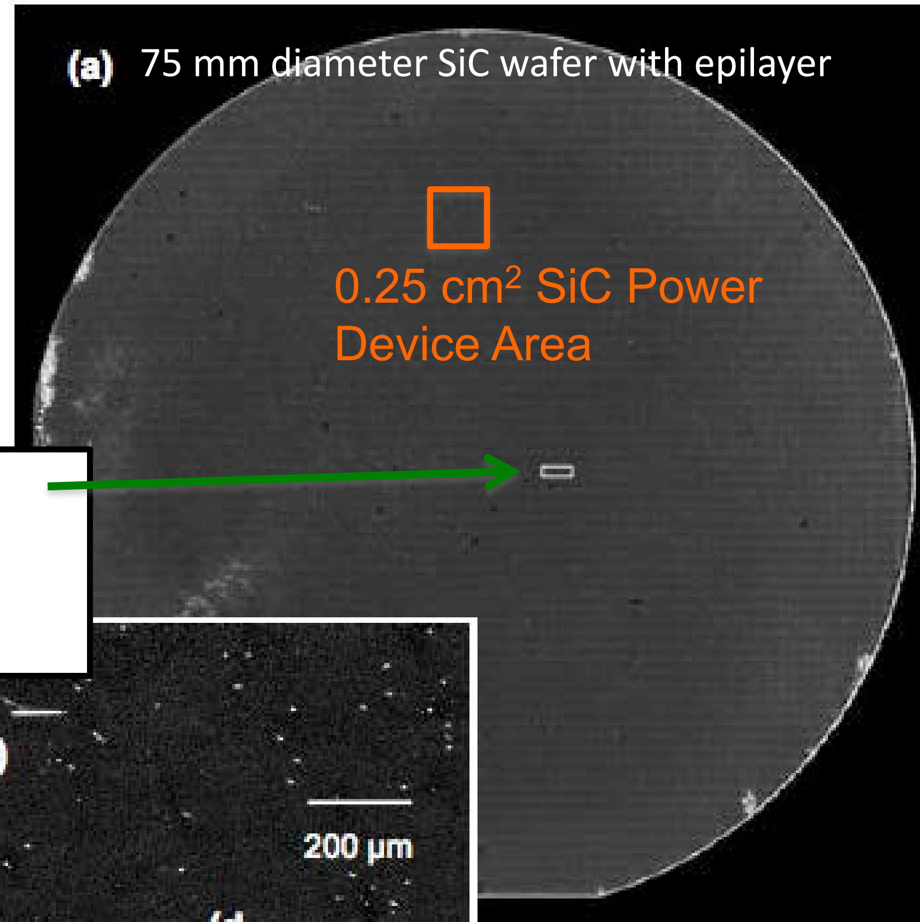
Above comparison does NOT take yield, cost, other relevant metrics into account.

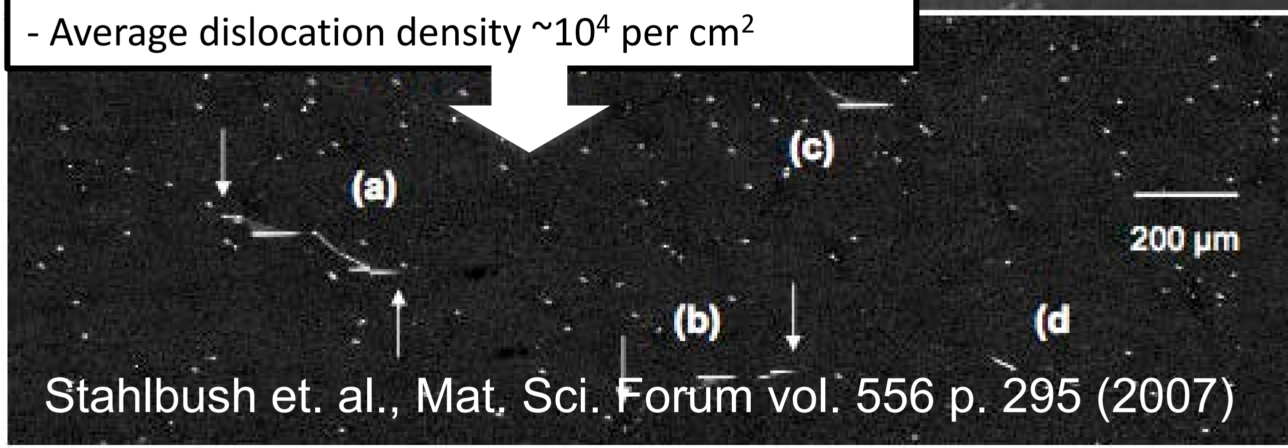
SiC Wafer Material Defects

Over the past decade there have been numerous studies (including NASA GRC) linking degraded SiC power device performance, yield, and reliability to the presence of defects in the SiC wafer crystal.

Magnified view small area in middle of wafer imaged by Ultra-Violet Photoluminescence

- Each white dot or line is a dislocation defect!
- Average dislocation density ~10^4 per cm^2

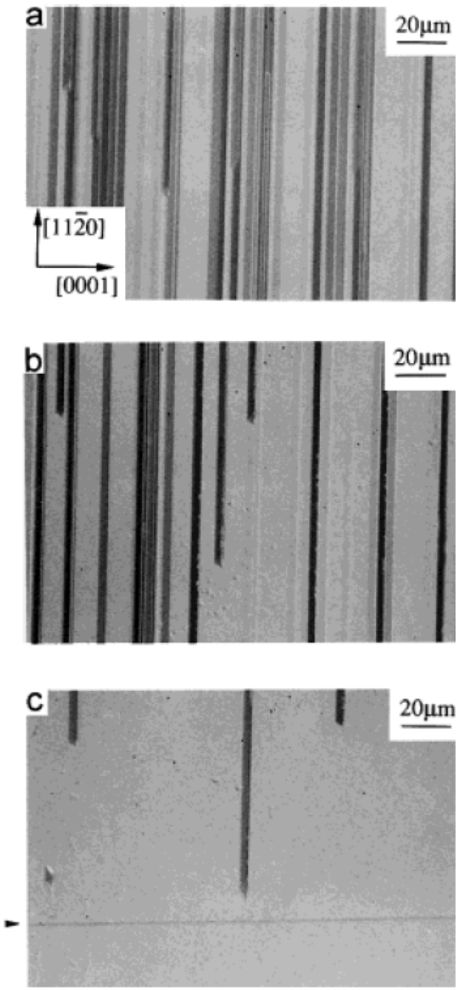




Stahlbush et. al., Mat. Sci. Forum vol. 556 p. 295 (2007)

Prior a-face/m-face SiC Growth Research

Takahashi & Ohtani, Phys. Stat. Solidi B, vol. 202, p. 163 (1997).

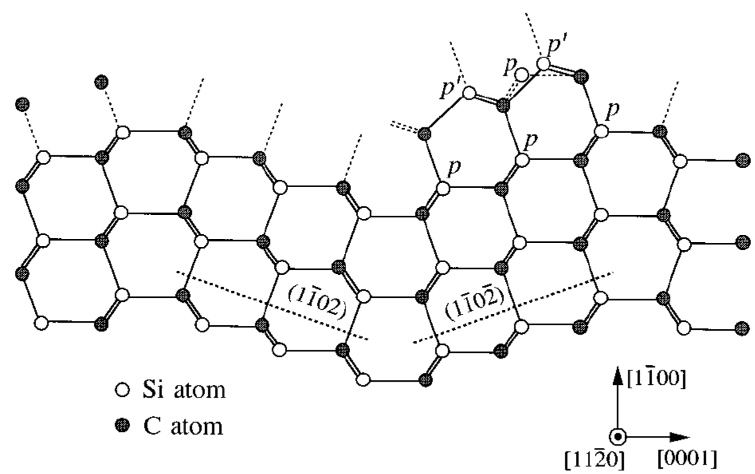


Defects were found to increase as a-face growth proceeded.

Attributed to low energy difference between stacking configurations on the growth surface.

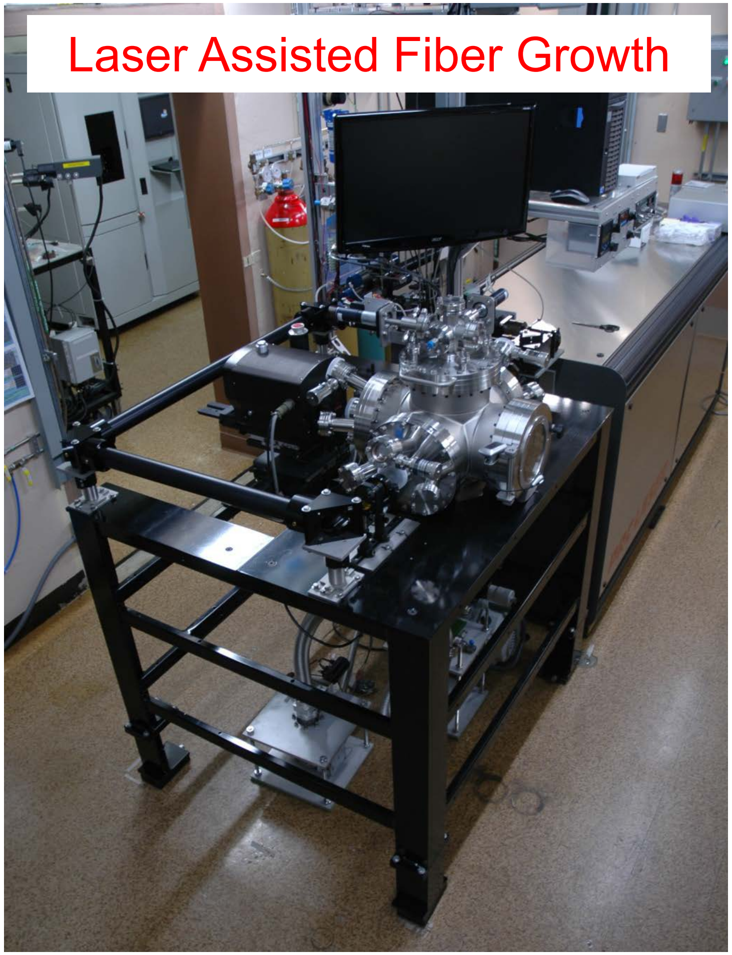
BUT – This prior work was physical vapor transport (PVT) growth at T > 2000 °C, high thermal gradient.

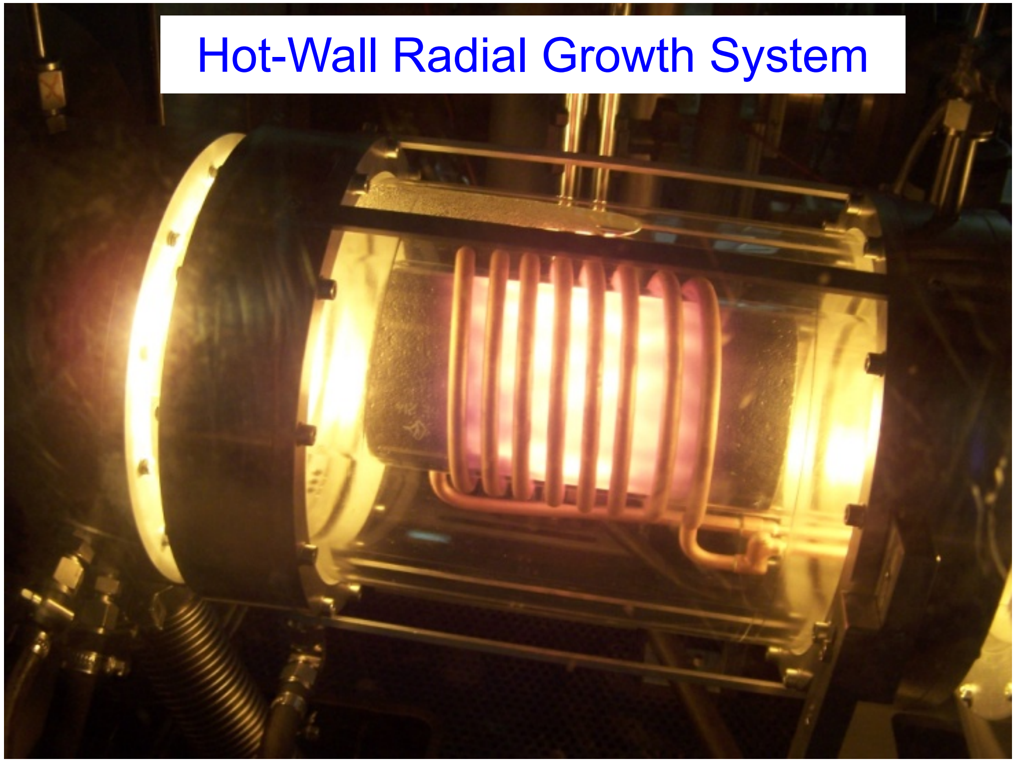
Key LTC feasibility question – will stacking faults form in CVD, isothermal, T ~1600 °C?



Technical Accomplishments and Progress

Previously reported build-up and safety reviews of laser-assisted fiber growth and radial epitaxial growth hardware **<u>are now complete.</u>**





(Photos previously presented at FY11 VTP Kickoff Meeting)

Both systems are now <u>operational and growing</u> experimental SiC crystals!