Development of SiC Large Tapered Crystal Growth

Philip G. Neudeck

NASA Glenn Research Center

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Project ID # APE027

Overview

Timeline

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

Budget

- Total project funding
  - DoE: $1600K
  - NASA: $700K ($500K FY12)
- $700K from DOE in FY11
- $200K from DOE in FY12

Barriers

- Advanced Power Electronics and Electric Machines (APEEM)

SiC expense and material quality inhibiting higher density and higher efficiency EV power electronics.

Table 1. Technical Targets for Electric Traction System

	2020[b]
Cost, $/kW	<8
Specific power, kW/kg	>1.4
Power density, kW/L	>4.0
Efficiency	>94%

Partners

- NASA Glenn (Lead)
- Ohio Aerospace Institute
- Sest, Inc.
- NASA Postdoctoral Program (Oak Ridge Assoc. Universities)

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

Objectives

Overall Objectives (Longer Term)

- Open a new technology path to 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 in turn enable leapfrog improvements in electric power system performance (higher efficiency, smaller system size).

Funded Project Objective (Shorter Term)

- Demonstrate initial feasibility of radically new "Large Tapered Crystal" (LTC) approach for growing vastly improved large-diameter SiC semiconductor wafers.
- Verify needed (never experimentally demonstrated) 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

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

Month/Year	Milestone
May 2011	Demonstrate epitaxial radial (lateral) growth of a 5 mm diameter boule starting from a simulated SiC fiber crystal.
December 2011	Demonstrate laser-assisted fiber growth of a SiC fiber crystal greater than 10 cm in length.

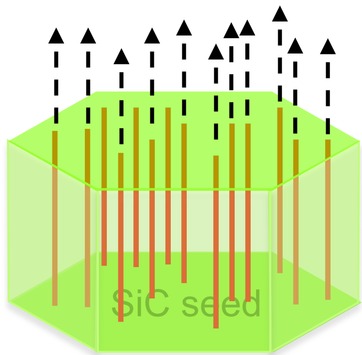
LTC is **NOT** viable without success of BOTH processes.

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

Approach/Strategy

Present SiC Growth Process

(Vapor transport)



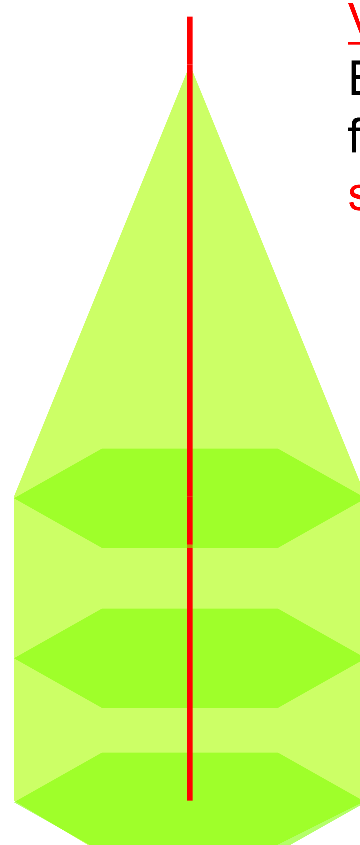
Vertical (c-axis) growth proceeds from top surface of large-area seed via thousands of dislocations. (i.e., dislocation-mediated growth!)

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)



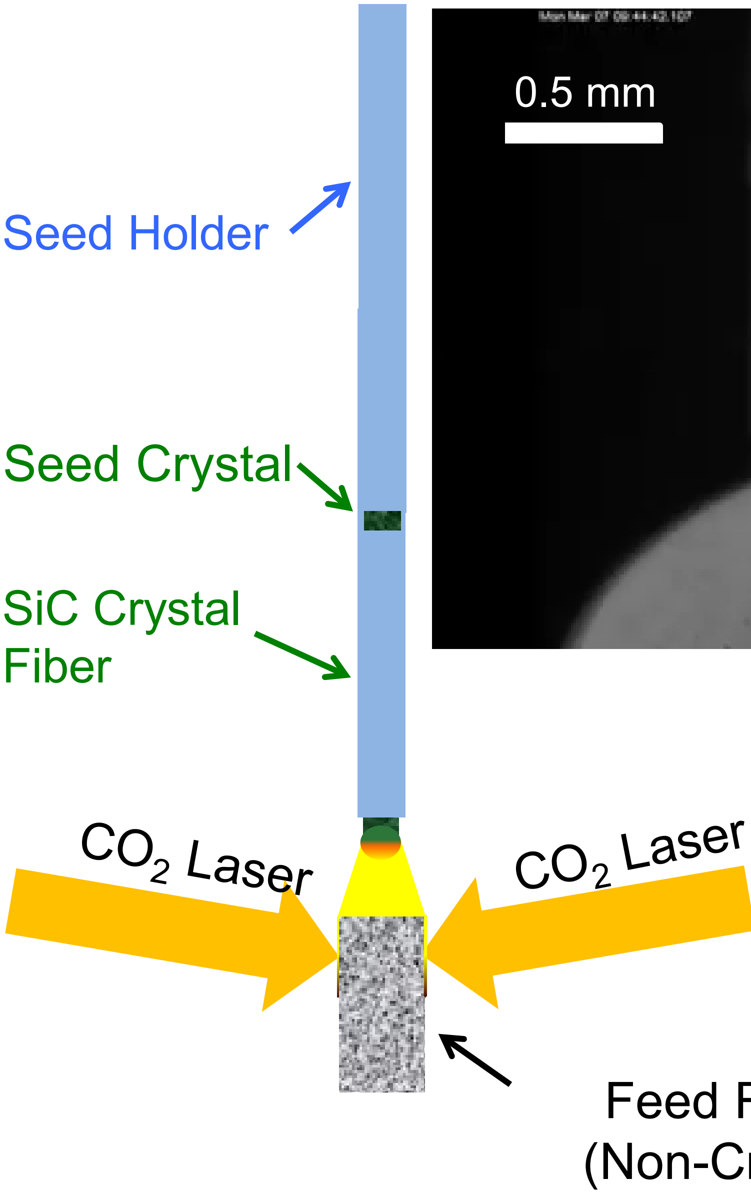
Vertical Growth Process:
Elongate small-diameter fiber seed grown from single SiC dislocation.

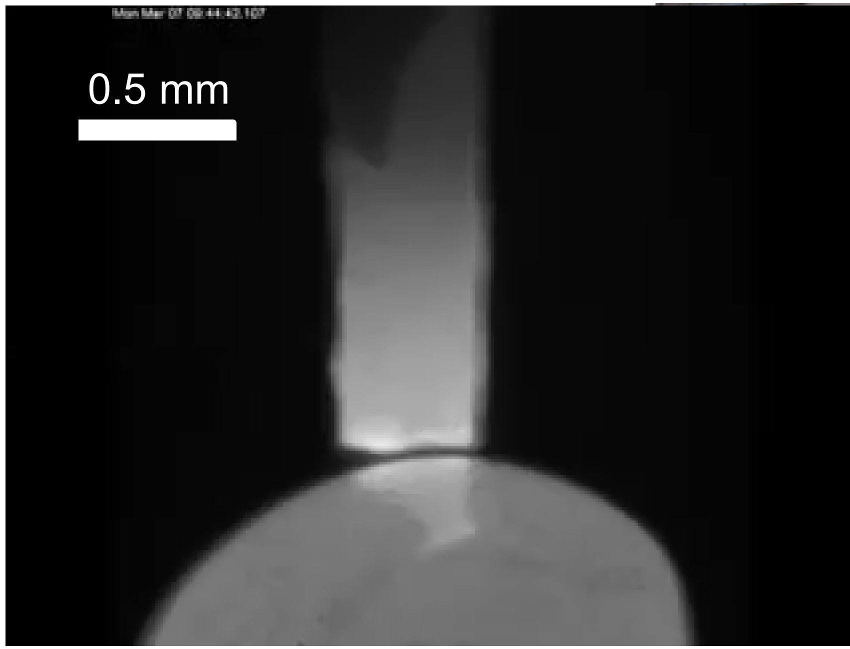
Lateral Growth Process:
CVD grow to enlarge fiber sidewalls into large boule.
- 1600 °C, lower stress
- Only 1 dislocation

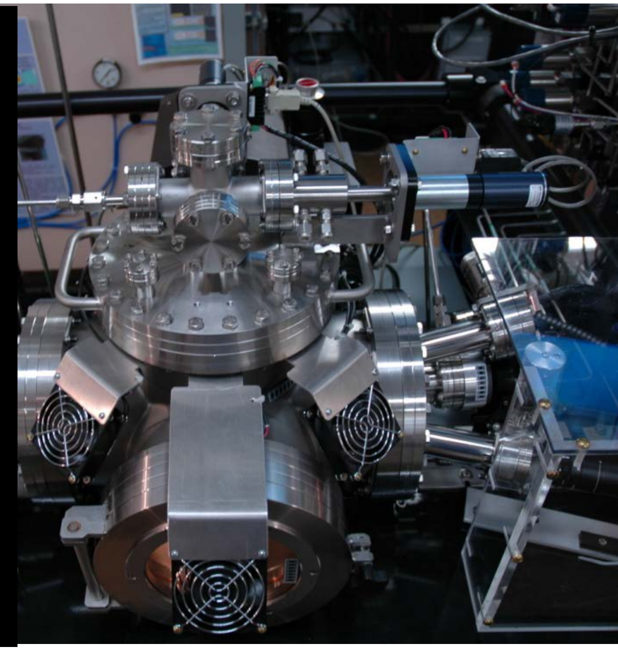
Lateral & vertical growth are simultaneous & continuous (creates tapered shape).

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

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

Technical Accomplishments and Progress

- 88 Experimental Solvent-LHFZ runs since 2011 Review.
- 10 Changes to feed rod processing technique, 5 feed rod material compositions tested, 5 seed crystal configurations tested.
- Have achieved single crystal growth rates >100 µm/hour (polycrystalline > 400 µm/hour)
- **Demonstrated control over growth rates.**

Experimental Conditions* (M.P. = Feed Rod Melting Point)			**Growth Rates (µm/hour)**		
Fe/Si	**C (at.%)**	**M.P. (ºC)**	**M.P.+90 ºC**	**M.P.+190 ºC**	**M.P.+325 ºC**
Fe/Si~0.35	**8**	**1170**	**4**	**40**	**135+**
	16	**1195**	**50**	**120**	**N/A**
Fe/Si~1.9	**8**	**N/A**	**No growth**		

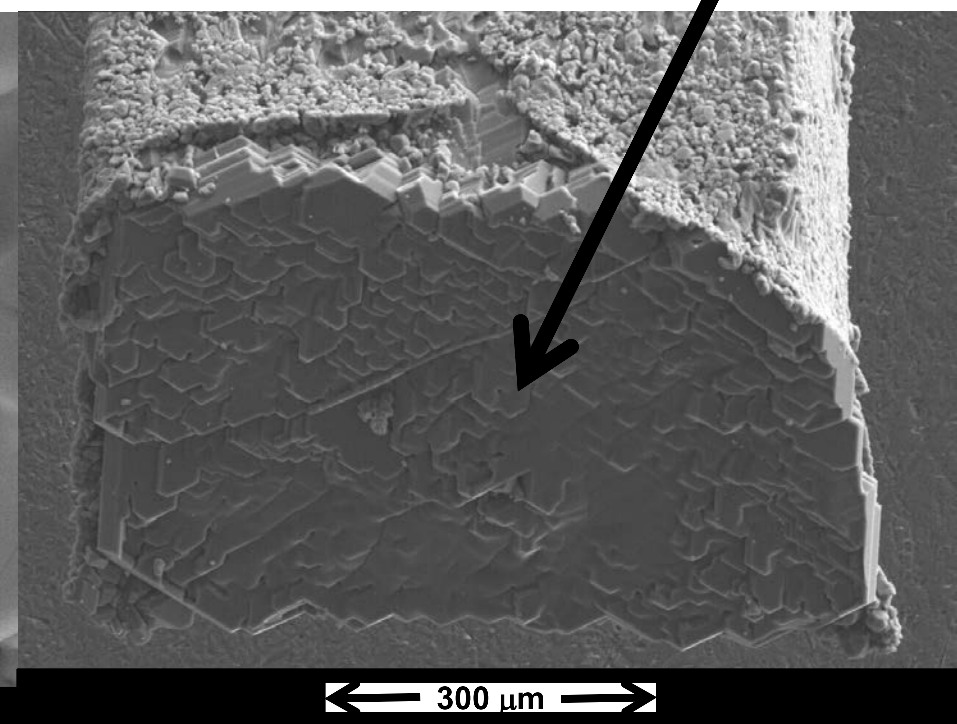
* Temperatures not corrected for emissivity.

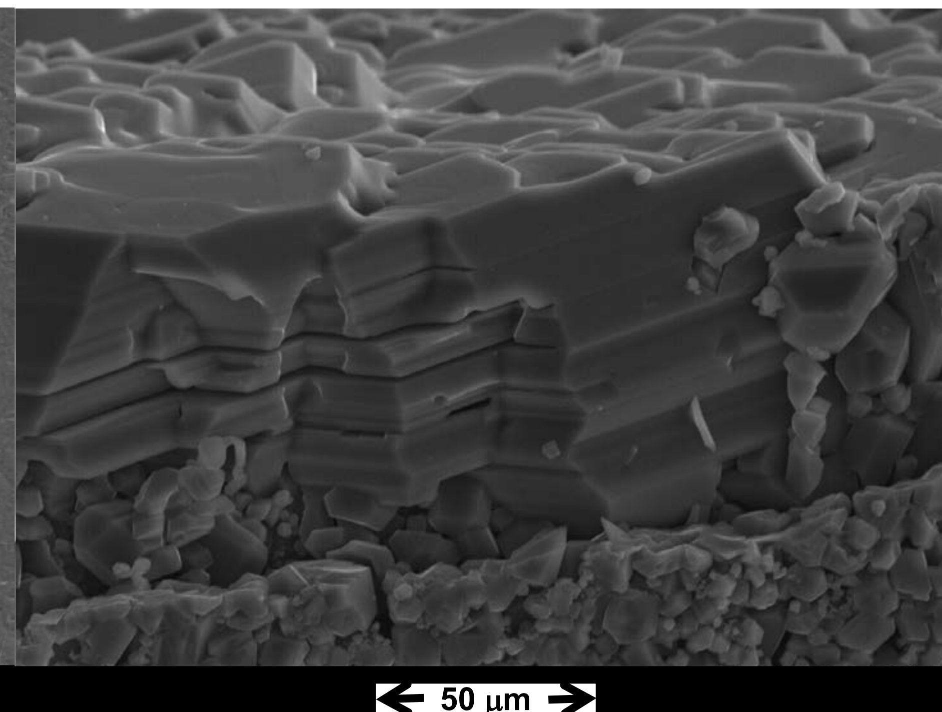
Woodworth et al., ICSCRM 2011

Technical Accomplishments and Progress

Solvent-LHPG SiC Fiber Growth

- 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).

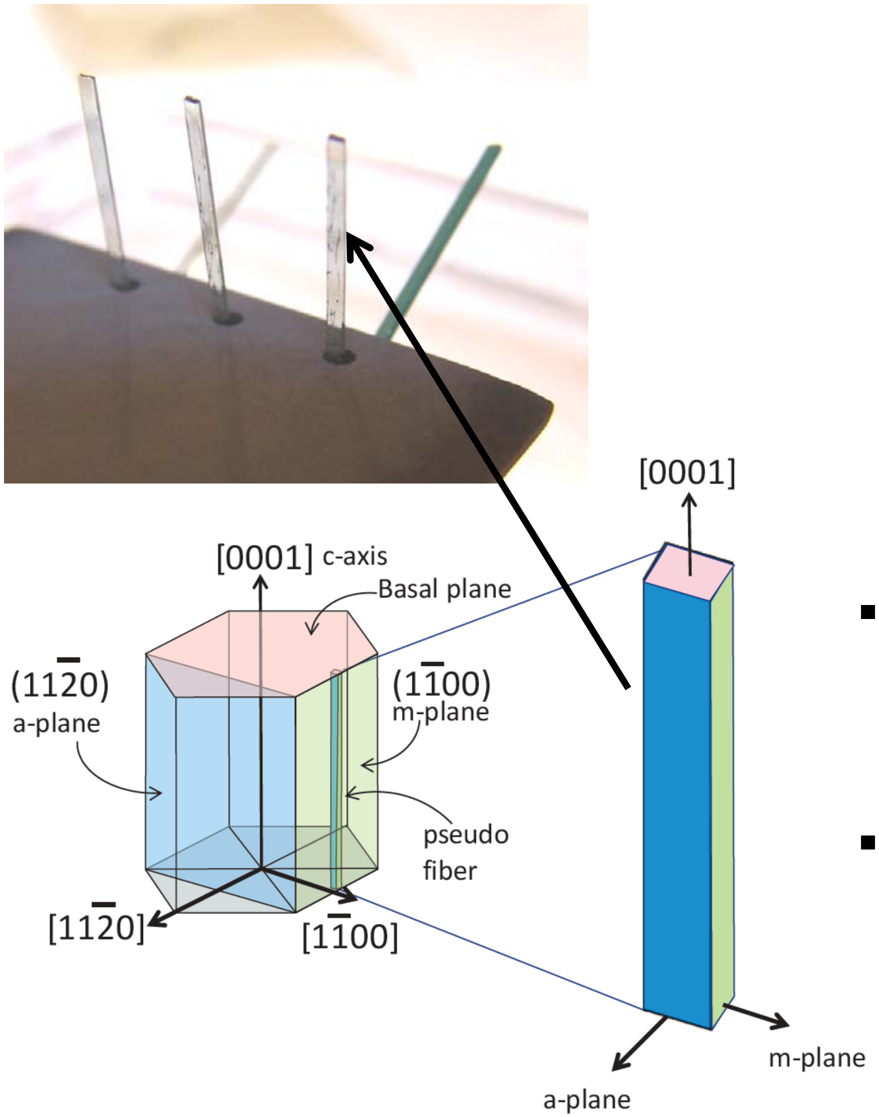




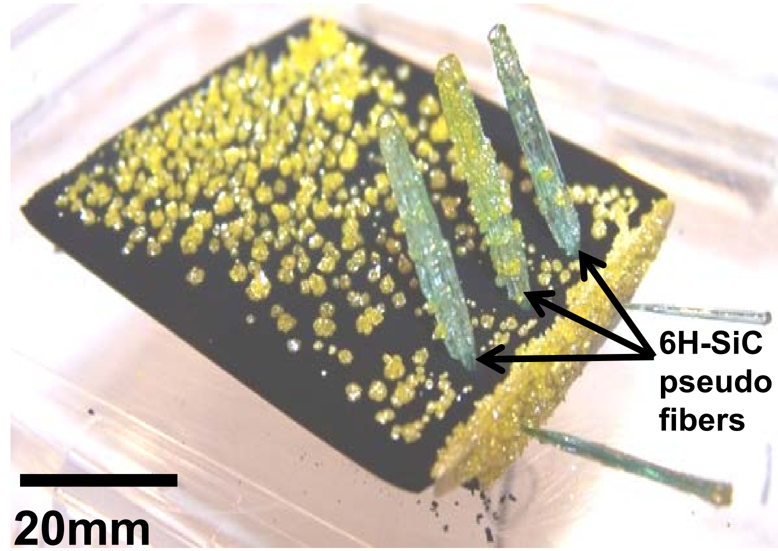
Technical Accomplishments and Progress

Radial/Lateral CVD Epi-Growth

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



Slivers after 8 hours of CVD epitaxial growth

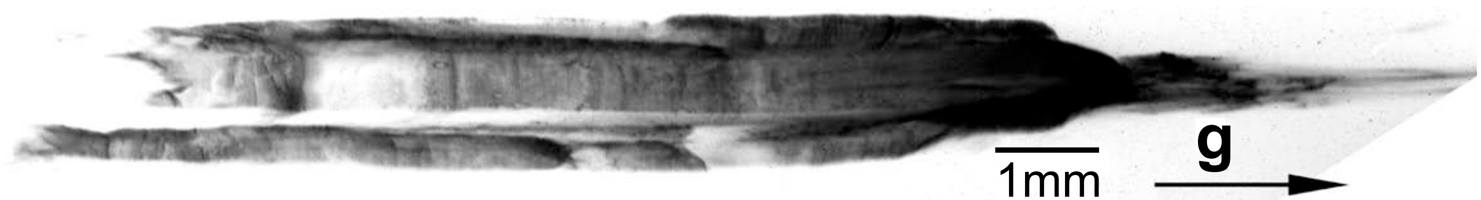


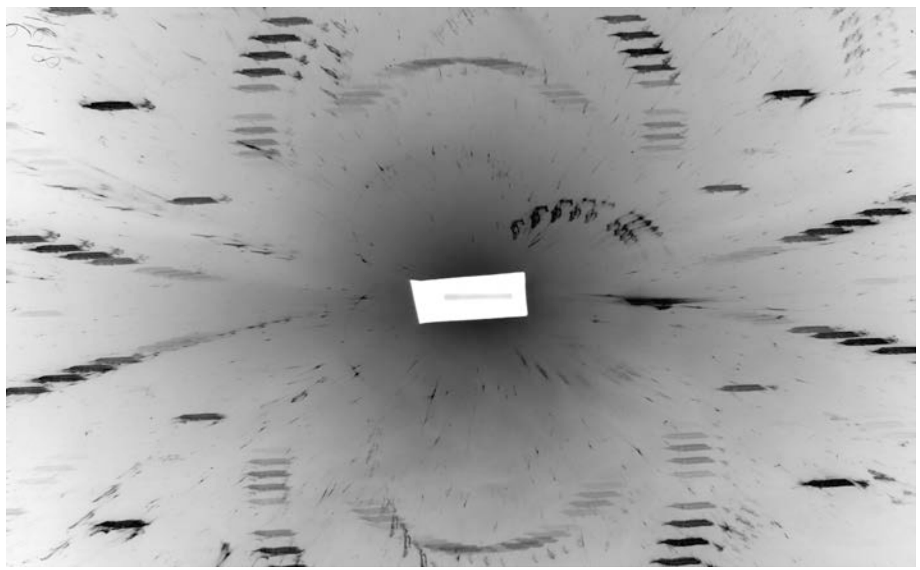
- Post-growth crystals are translucent and exhibit lateral expansion (a/m-face growth).

- 3C-SiC crystallites (yellow) undesirably nucleated in some areas.

Technical Accomplishments and Progress

Synchrotron white beam X-ray topograph (top) and diffraction pattern (bottom) of sliver after 8 hours of growth (from Prof. Dudley's group at Stony Brook U.)



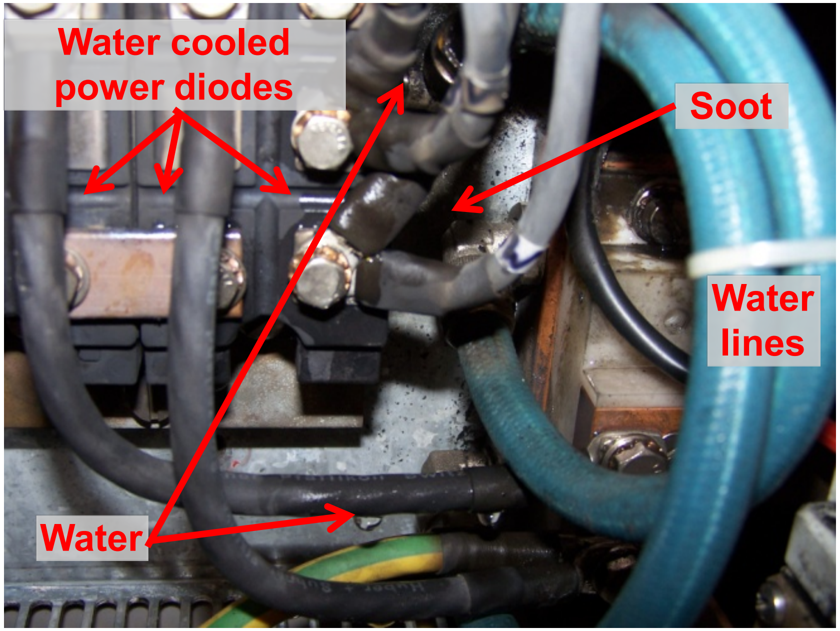


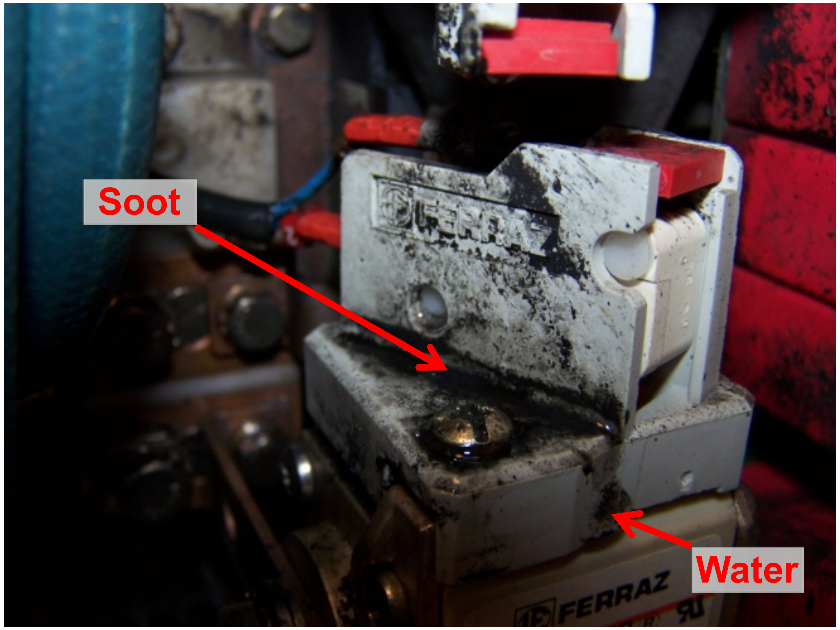
Confirmation of hexagonal polytype replication and low strain during CVD growth (for "clean" regions where parasitic 3C-SiC nucleation did not occur).

Technical Accomplishments and Progress

Radial/Lateral CVD Epi-Growth

NASA Glenn SiC CVD Growth System
Major Equipment Failure
(RF Generator) on August 12, 2011

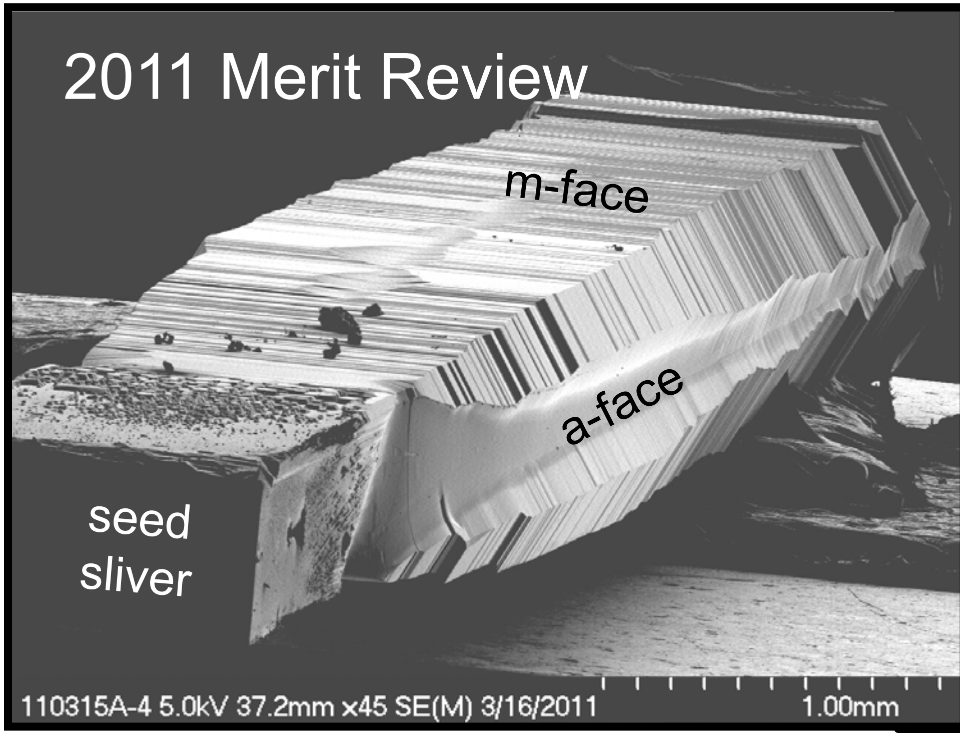


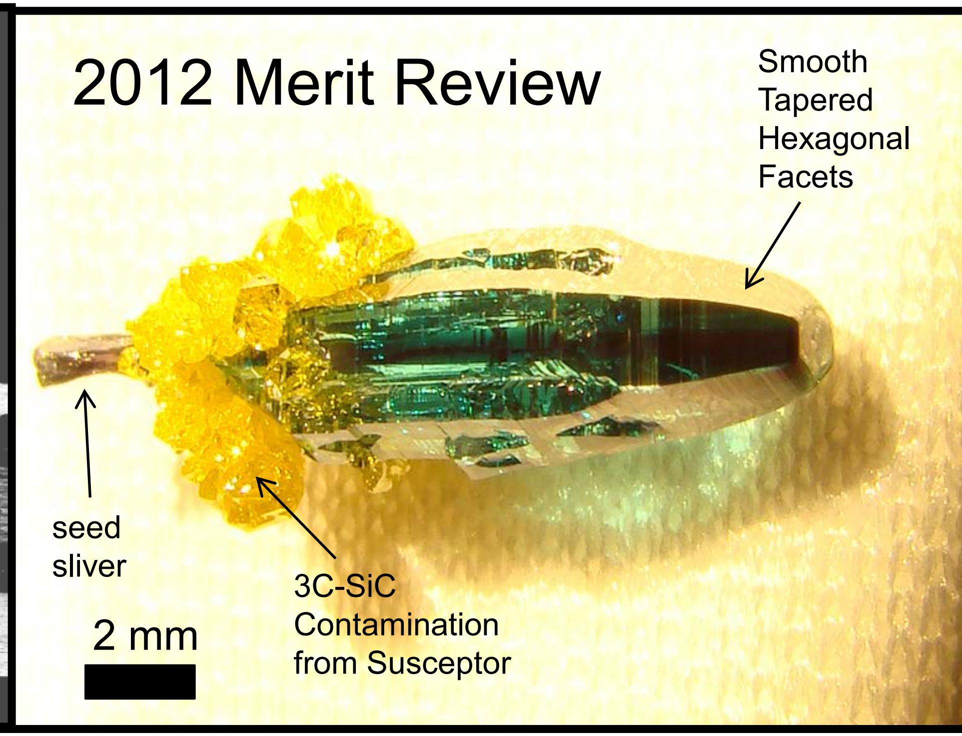


- Heavily damaged sub-system returned to manufacturer for replacement/repair.
- New RF generator procured (using $100K of NASA funds).
- **All lateral CVD SiC epitaxial growth work suspended for > 5 months.**
- Delayed new/improved seeding of Solvent-LHFZ growths.
- Operations resumed using repaired sub-system on January 23, 2012.
- 22 operational runs conducted in 36 working days following repairs.

Technical Accomplishments and Progress

Radial/Lateral CVD Epi-Growth



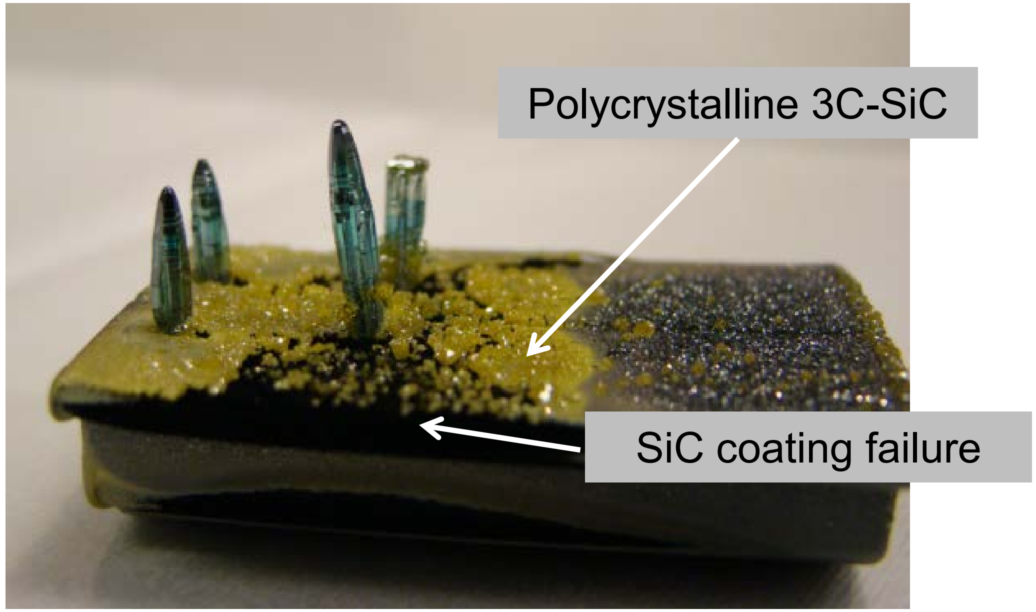


Epi Growth Rate: ~80 μm/hour
Max. Film Thickness: ~0.15 mm
Max Diameter: ~1 mm (mostly seed)
Rough grown surfaces/mini-facets

Epi Growth Rate: ~ 120 μm/hour
Max. Film Thickness: ~2 mm
Max Diameter: ~4 mm (mostly epi)
(80% of 5 mm Quantitative Milestone)
Smooth Tapered Hexagonal Facets!

Proposed Future Work

Radial/Lateral CVD Epi-Growth



Carry out detailed characterization of larger mini-boules.

- Including X-ray Topography by Prof. Dudley’s group at SUNY.
- Answer critical question: Are stacking faults produced during thick radial CVD?

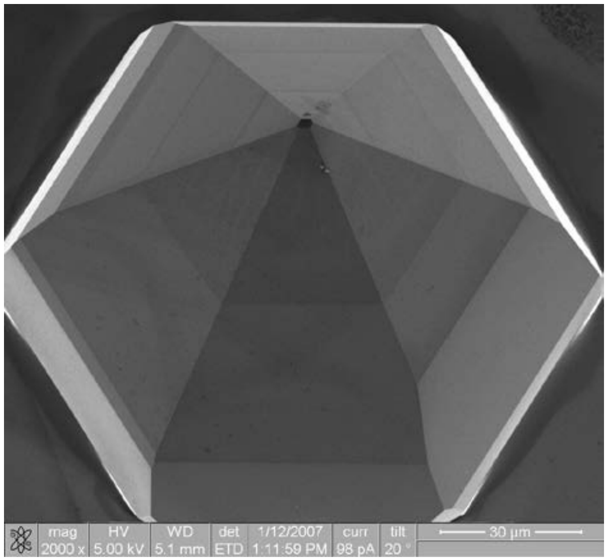
CVD growth hardware & crystal mounting modifications to suppress 3C-SiC.

Grow and characterize increasingly larger mini-boules.

Proposed Future Work

Fiber Growth

Smaller, well-ordered seed with pointed tip is needed for fiber growth.



P. Neudeck, 2009 DRIP Conf.

Transition to micro-patterned "single screw hexacone" (produced by patterned etching followed by CVD epi as described in LTC patent).

Further refinement of seed rods (materials, smaller diameter) and solvent-LHPG growth process.

In addition to solvent-LHPG growth, LTC patent also describes laser-assisted vapor-growth methods for growing long single-crystal fiber (from same "hexacone" SiC seeds).

Free Form Fibers LLC (NY) – Initiating SBIR Phase III (NASA Funded $100K) for laser-assisted <u>SiC fiber growth using gas precursors</u>.

- Small business presently 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.

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. – SiC Crystal Characterization
  - NASA Postdoctoral Program (Oak Ridge Assoc. Universities)

- State University of New York at Stony Brook – National Synchrotron Light Source at Brookhaven National Laboratory (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) – Initiating 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

- Experiments to investigate feasibility of revolutionary new "Large Tapered Crystal (LTC)" SiC growth approach are behind schedule, but significantly progressing towards demonstration goals.

Technical Area	2011 Status	2012 Status
Radial Growth	System build-up complete First layers documented ~ 1 mm diameter ~80 μm/hour growth rate	First "Mini-boules" grown ~ 4 mm diameter ~125 μm/hour growth rate Desired hex facet evolution
Fiber Growth	System build-up complete First Solvent-LHFZ layers	Solvent-LHFZ > 100 μm/hour Laser-CVD Effort Initiating

- Developmental acceleration expected with addition of NASA resources, expanded LTC development team.

Technical Acknowledgements

NASA LTC Co-Investigators:
Andrew Woodworth (NPP), Ali Sayir (NASA), Fred Dynsys (NASA), Andrew Trunek (OAI), David Spry (NASA), and J. Anthony Powell (Sest)

NASA LTC Support Team:
Tom Sabo, Michelle Mrdenovich, Beth Osborn, Kelly Moses, Chuck Blaha, Kimala Laster, Jim Mazor, Wentworth John, and Frank Lam

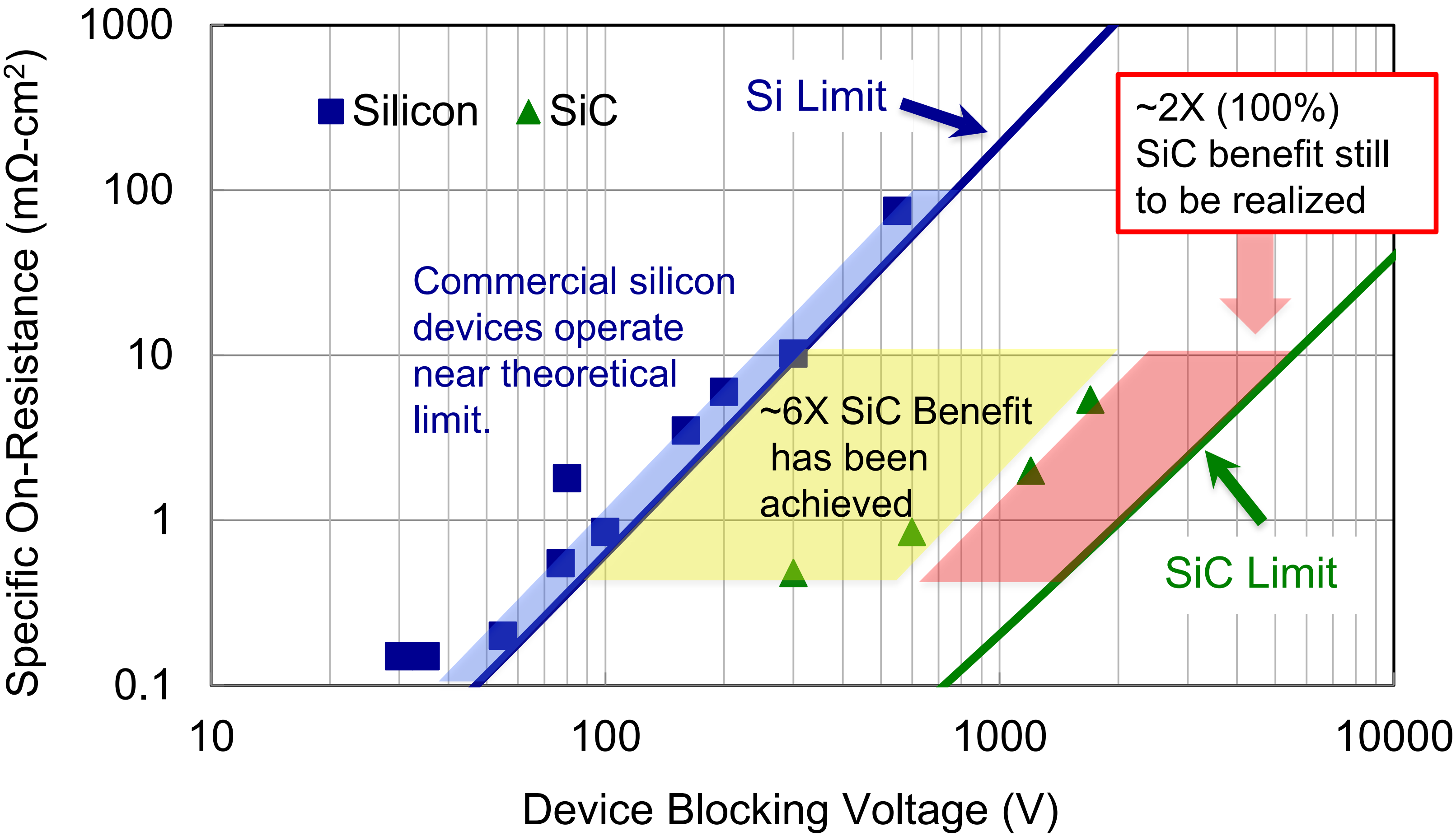
Technical Back-Up Slides

(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)

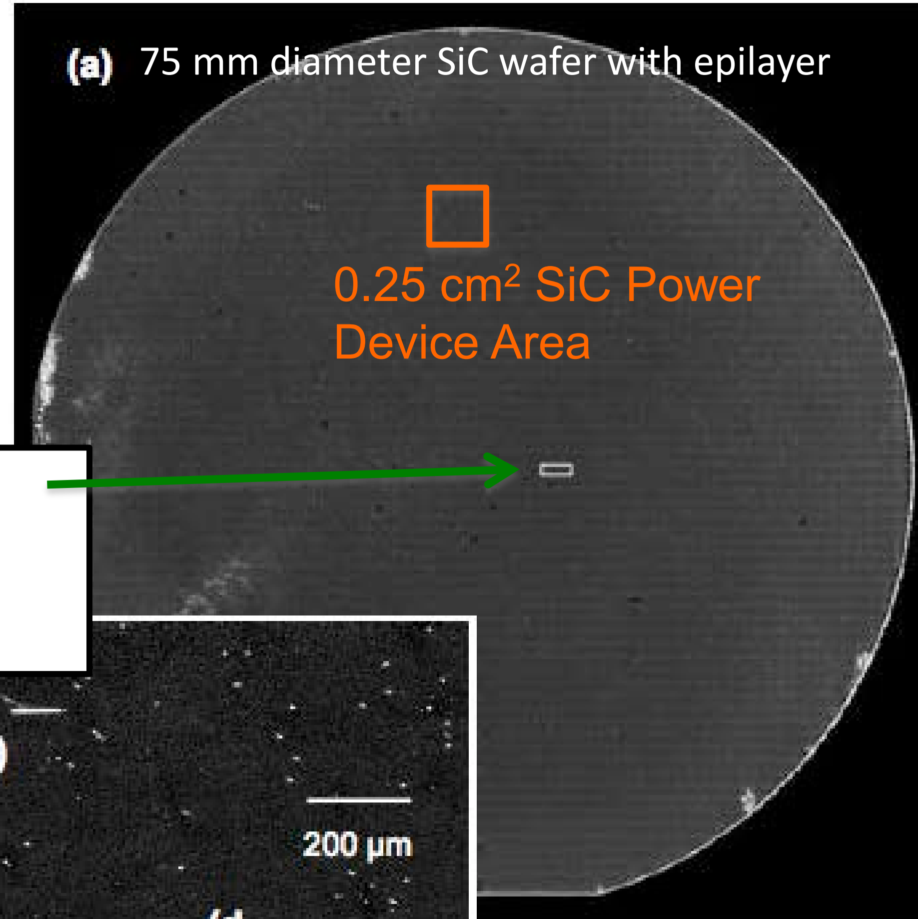
SiC devices are ~2X voltage or current-density **de-rated** from theoretical material performance.



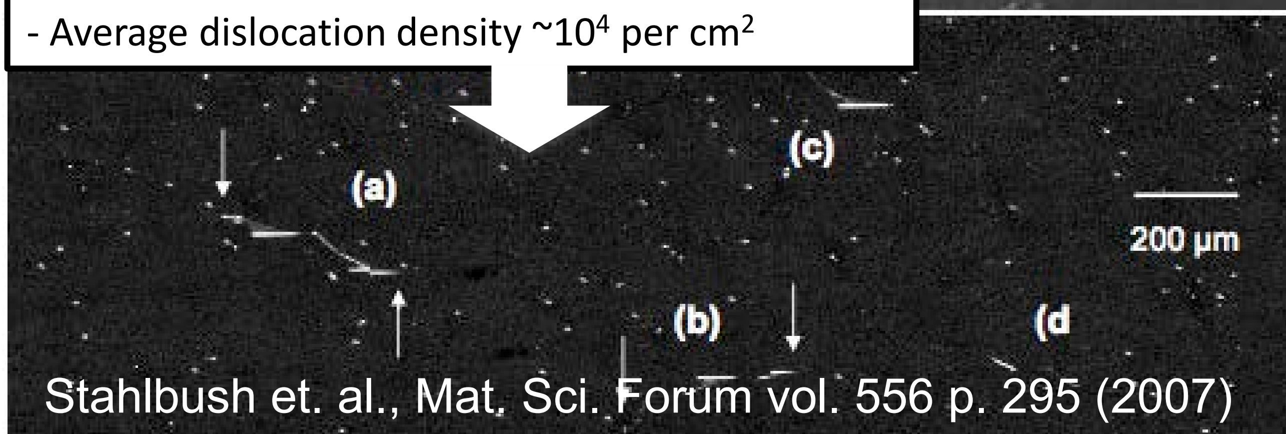
Above comparison does NOT take yield, cost, other relevant metrics into account.

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.



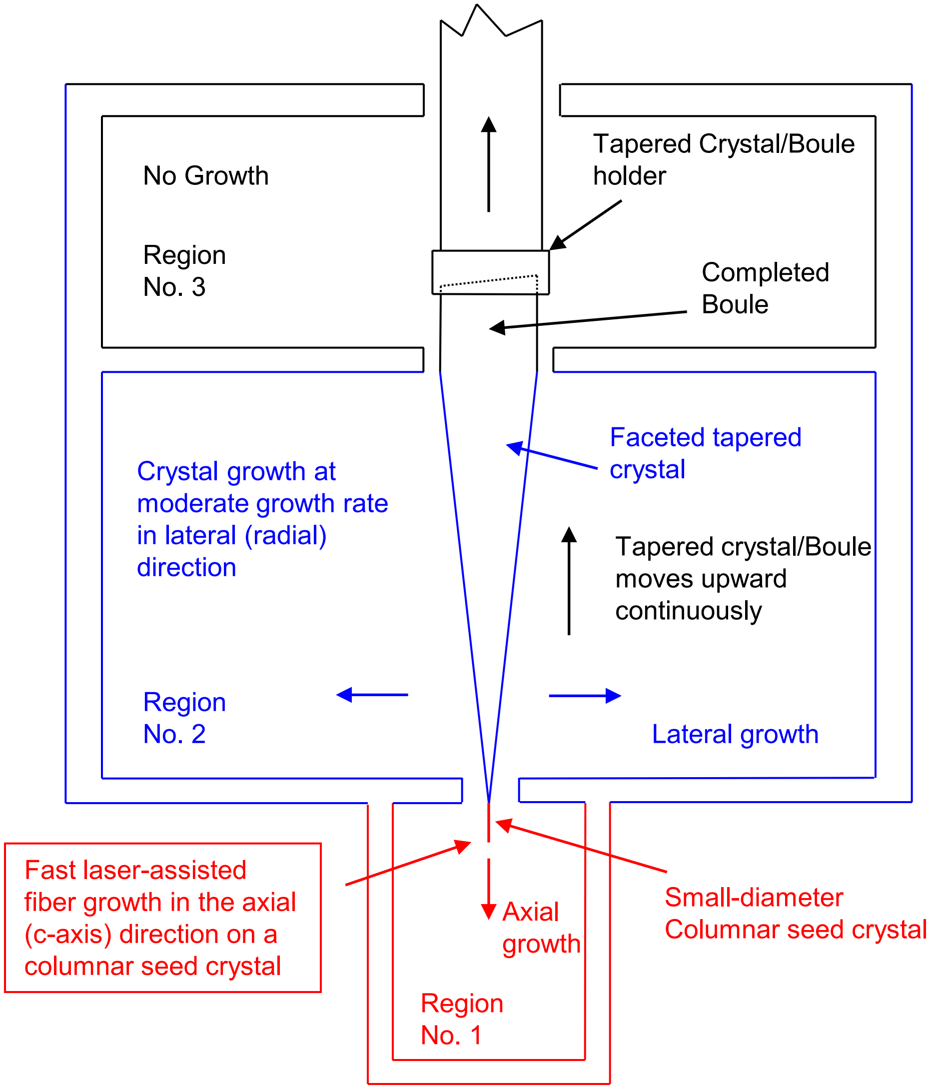
Magnified view small area in middle of wafer imaged by Ultra-Violet Photoluminescence
- Each white dot or line is a dislocation defect!
- Average dislocation density ~10^4 per cm^2



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

Production LTC SiC Growth System

Simplified Schematic Cross-Sectional Representation

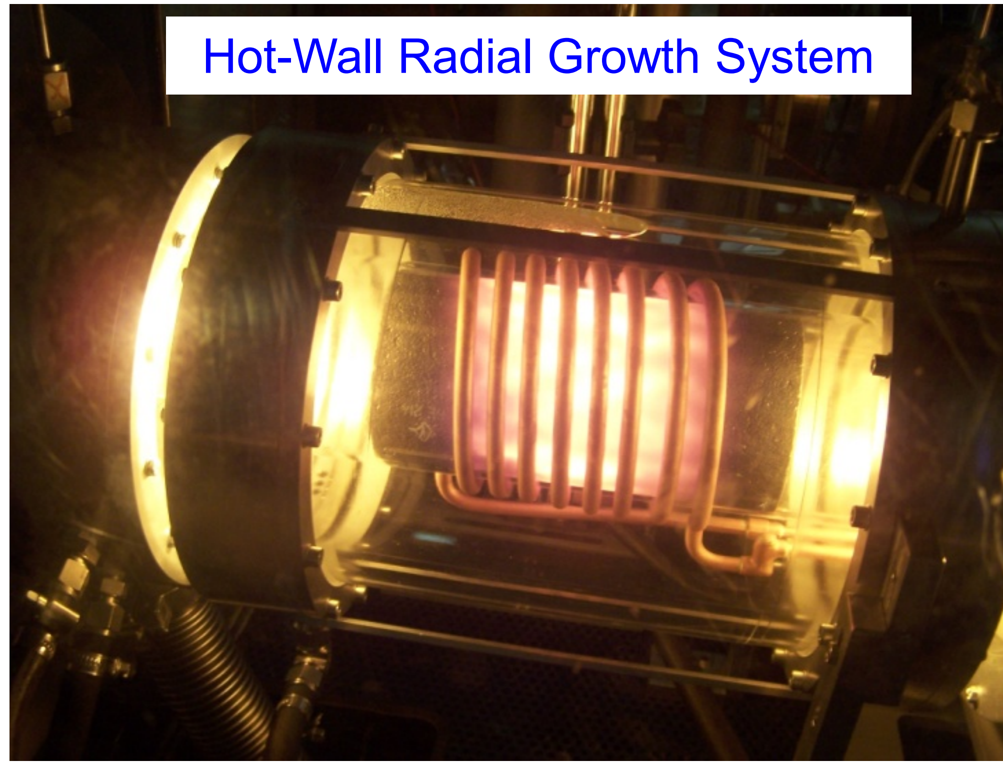


<u>Features (one embodiment):</u>

1. **3-Region growth apparatus for 3 different growth actions.**
2. **Region 1: Vertical (c-axis) growth on a <u>very small diameter</u> columnar portion ("Fiber Growth").**
3. **Region 2: Lateral (m-direction) growth on fiber & tapered portion ("Lateral Growth").**
4. **Region 3: No growth after LTC boule reaches desired diameter.**
5. **Growth rate of boule in c-axis direction equals fast growth rate of columnar seed crystal.**
6. **Boule contains only one dislocation along its axis; the remainder of the boule is nominally defect-free.**

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>**

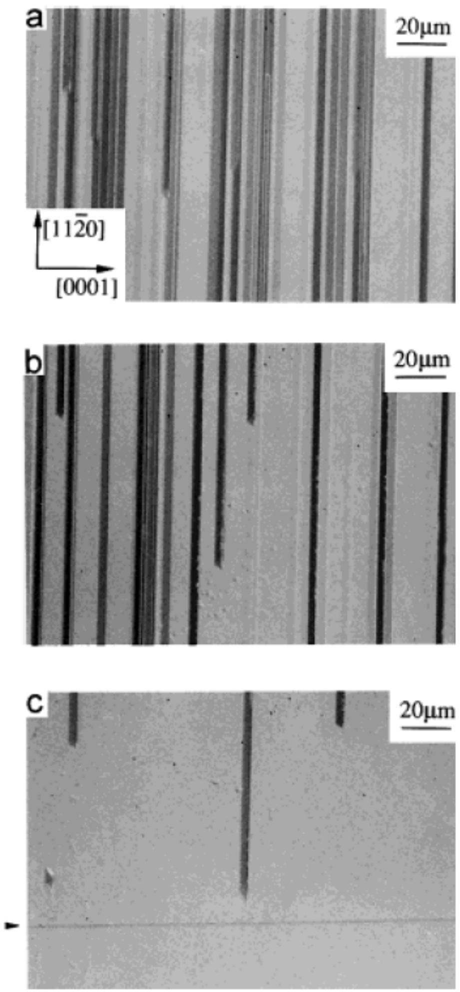


(Photos previously presented at FY11 VTP Kickoff Meeting)

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

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?