Development of SiC Large Tapered Crystal Growth

Dr. Philip G. Neudeck
NASA Glenn Research Center

10 May 2011

APE027

Overview

Timeline

- Funding start: Dec. 2009
- Project end: Dec. 2011
- Percent complete: 70%

Budget

- Total project funding
  - DoE: $1200K
  - NASA: $180K
- $700K received in FY10
- $400K received in FY11

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 Research Center
- Ohio Aerospace Institute
- Sest, Inc.
- 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 widely & reliably available.
- New but unproven NASA "Large Tapered Crystal" 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)

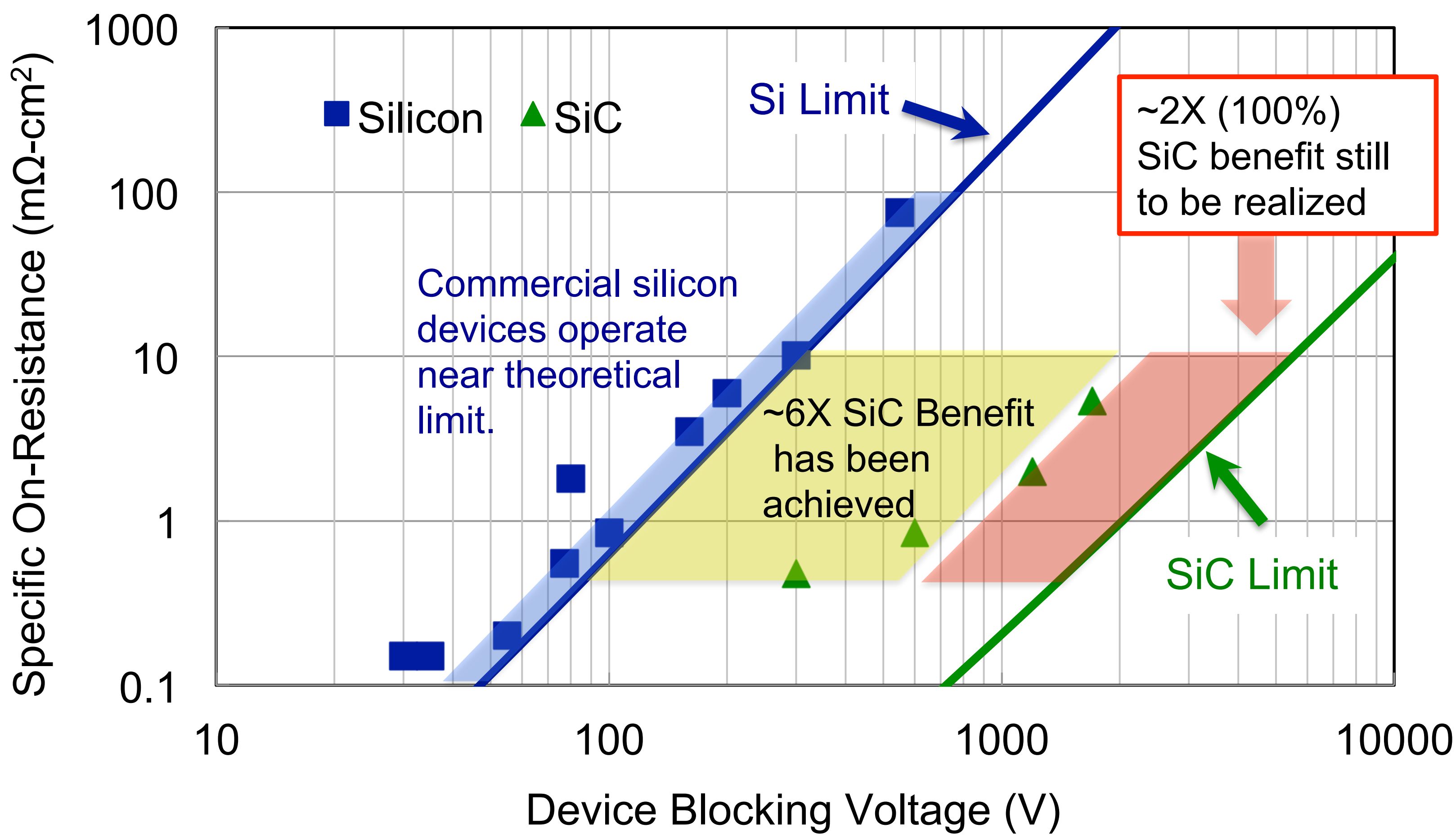
Table 2.1-6 Tasks for Advanced Power Electronics and Electric Motors R&D

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

Unipolar Power Device Comparison

(Volume Production Commercial Devices)

SiC devices are ~2X (100 %) voltage or current-density **de-rated** from theoretical material performance.



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

Objectives

FACT: Majority of large benefits (of significantly higher efficiency and power density) theoretically enabled by wide bandgap (WBG) semiconductor (e.g., SiC and GaN) power devices to power systems (including electric/hybrid vehicles) have **not** been realized/ commercialized.

High cost and high dislocation defect density of starting SiC & GaN wafer material are widely recognized as major inhibitors to realizing wide bandgap power devices for large system benefits.

Overall Objectives

- Open a new technology path to large-diameter SiC and GaN wafers with **100-1000 fold defect density improvement at 2-4 fold lower cost.**
- Enable leapfrog improvement in wide band gap power device capability and cost to in turn enable leapfrog improvements in electric power system performance (higher efficiency, smaller system size).

Funded 2-Year Project Objective

- Demonstrate initial feasibility of radically new “Large Tapered Crystal” (LTC) approach for growing vastly improved large-diameter SiC semiconductor wafers.

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.

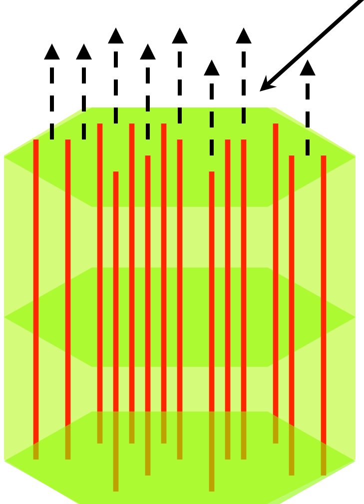
LTC is **NOT** viable without success of BOTH processes.

Note that throughout this presentation, issues related to "Lateral Growth" milestone are highlighted in blue, while issues relating to "Fiber Growth" milestone are all highlighted in red.

Approach/Strategy

Commercial SiC Wafer Growth Approach

(Sublimation growth or High Temperature CVD)



C-axis (vertical) growth proceeds from top surface of large-area seed crystal via thousands of screw dislocations.

Vertical growth rate would not be commercially viable (i.e., would not be high enough) without high density (> 100 cm^{-2}) of screw dislocations.

Crystal enlargement is vertical (up c-axis). Negligible lateral enlargement.

Thermal gradient driven growth at T > 2200 °C
High thermal stress/strain.

Limited crystal length (# of wafers) per run.

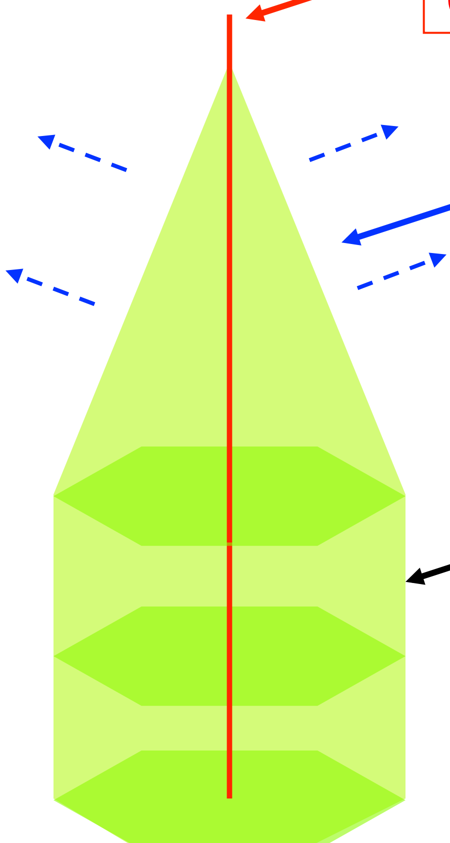
Fundamental Flaw: Abundant screw dislocation defects are needed for present SiC wafer growth approach, yet these same defects harm SiC power device yield and performance (cause blocking voltage de-rating, leakage, etc.).

- High thermal stress also generates dislocations.

Approach/Strategy

New Approach - Large Tapered Crystal (LTC) Growth

(US Patent 7,449,065 Owned by OAI, Sest, Inc., with NASA Rights)



Vertical Growth Process:
Fiber-like growth of small-diameter columnar tip region (from single screw dislocation)

Small-diameter c-axis fiber from single screw dislocation at mm/hour rate.

Lateral Growth Process:
CVD growth enlargement on sidewalls to produce large-diameter boule (T = 1500 - 2000 °C)

MOST of crystal grown via epitaxy process on laterally expanding taper **at significantly lower** growth temperature **(lower thermal stress)** and growth rate.

Completed boule section
Ready for slicing into wafers

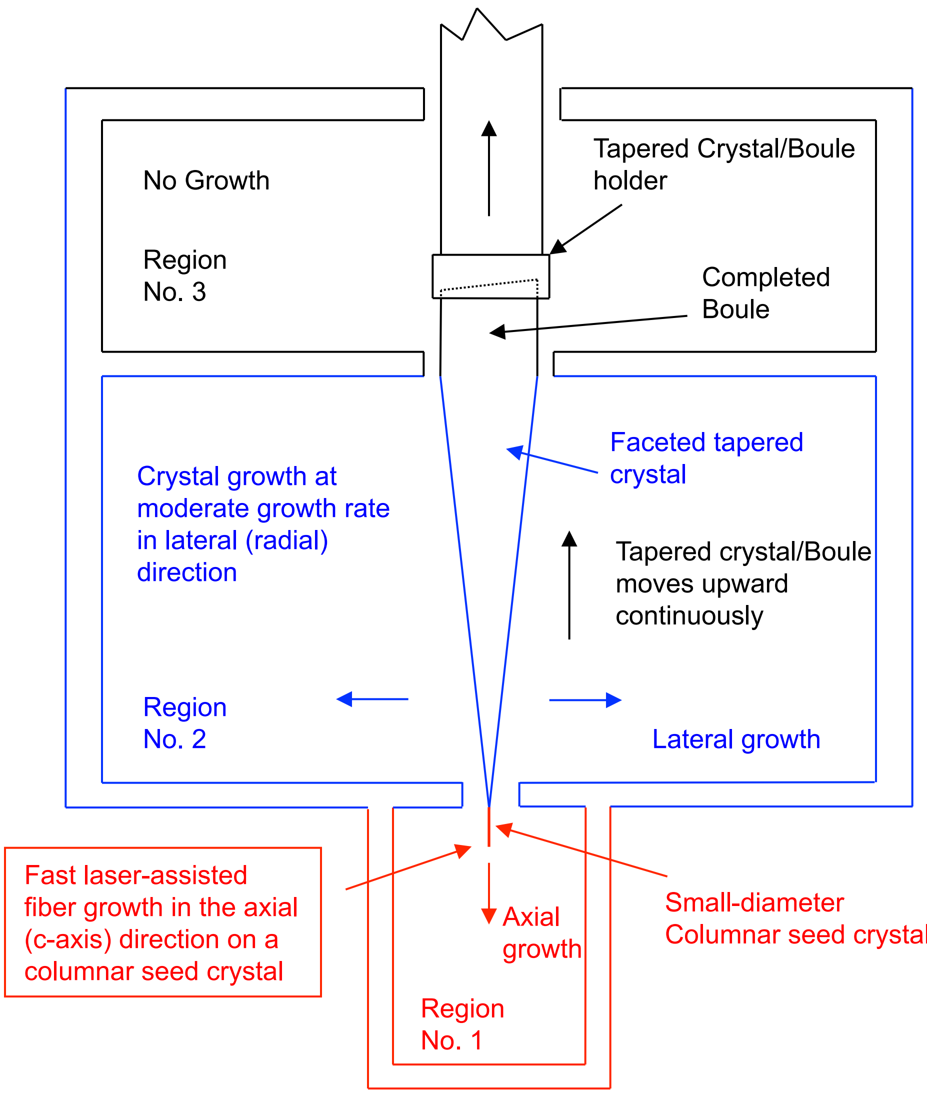
Large diameter wafers yielded at mm/hour (wafers/hour) growth rate! Much longer boule length (# of wafers) possible.

Tapered portion is then re-loaded into growth system as seed for subsequent boule growth cycle.

Approach/Strategy

Large Tapered Crystal (LTC) Growth Method

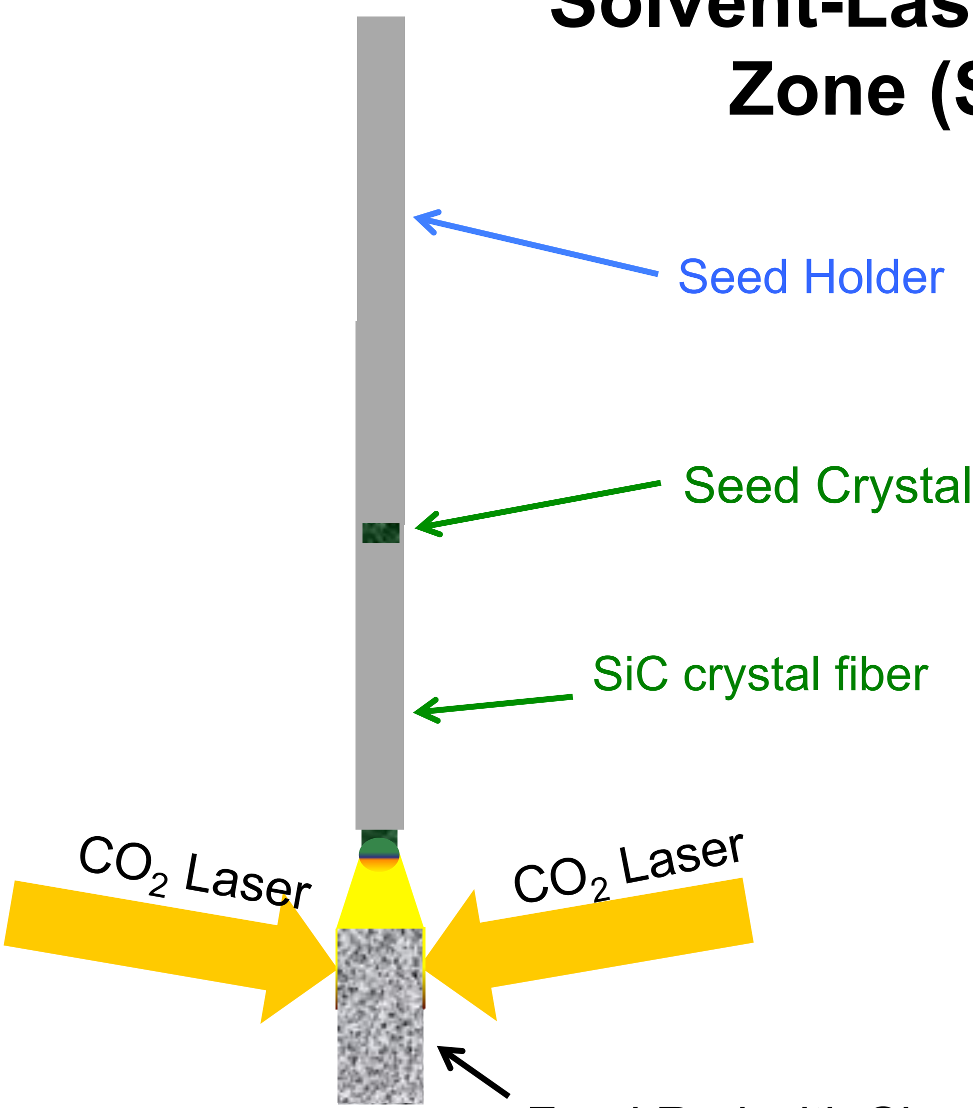
Simplified Schematic Cross-Sectional Representation



<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" Year 2 Milestone).**
3. **Region 2: Lateral (m-direction) growth on fiber & tapered portion ("Lateral Growth" Year 1 Milestone).**
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.**

Approach/Strategy
Solvent-Laser Heated Floating Zone (Solvent-LHFZ)

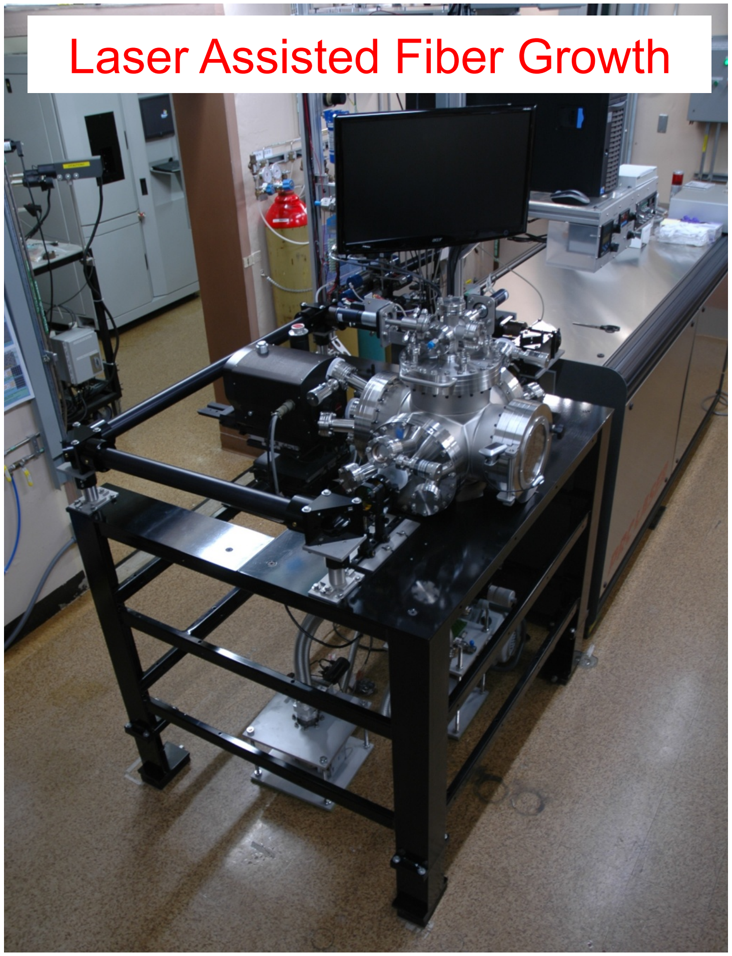


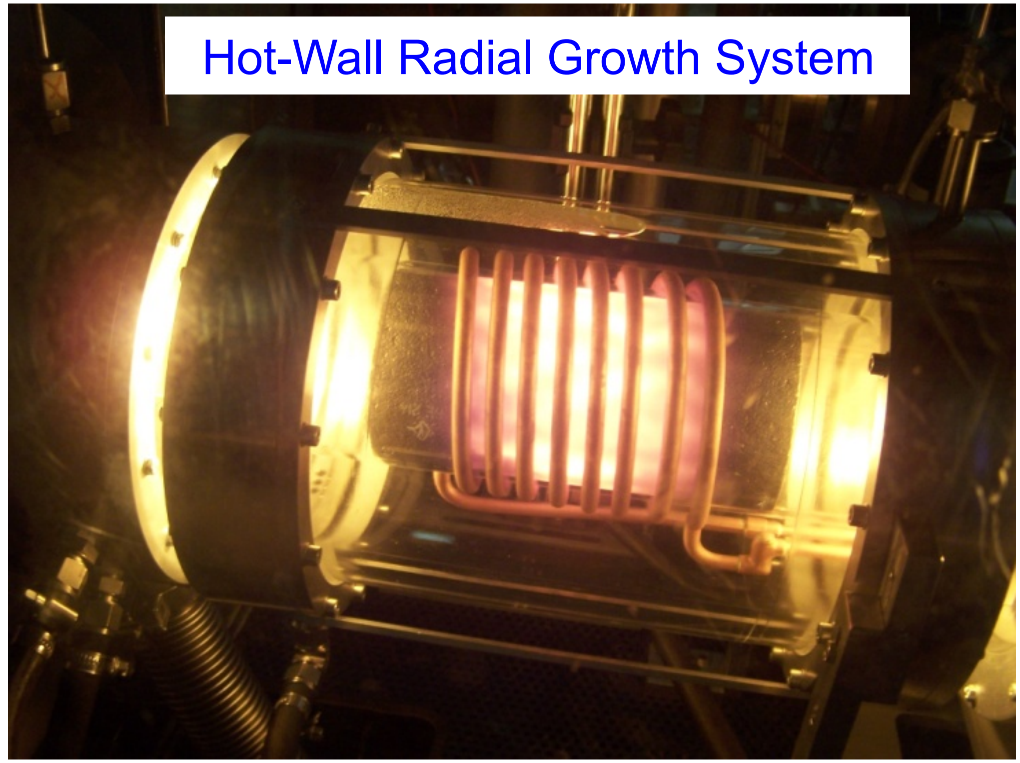
Totally new approach to SiC crystal (fiber) growth

Combines the advantages of Traveling Solvent Method (TSM) & Laser Heated Floating Zone
- TSM: known SiC growth method
- LHFZ: semi-infinite growth material

Technical Accomplishments and Progress

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





(Photos previously presented at FY11 VTP Kickoff Meeting)

Both systems are now operational and growing experimental SiC crystals!

Technical Accomplishments and Progress

All Technical Accomplishment slides following this one represent completely new results.

Technical Accomplishments and Progress

Laser-Assisted SiC Fiber Growth

- Process of creating source feed rods has been developed and refined.
- Stable laser-heated melt of source feed material established in system.
- Wetting of the seed crystal and stable floating zone established.
- **Initial experiments have demonstrated Solvent-LHFZ SiC growth.**
- Sustained stable melt demonstrated (> 6 hours).

Items in red represent positive experimental answers to some of the important technical assumptions/questions on LTC fiber growth!

Results obtained with “shakedown run” quality (i.e., non-optimized) source feed rods and SiC seed crystals.

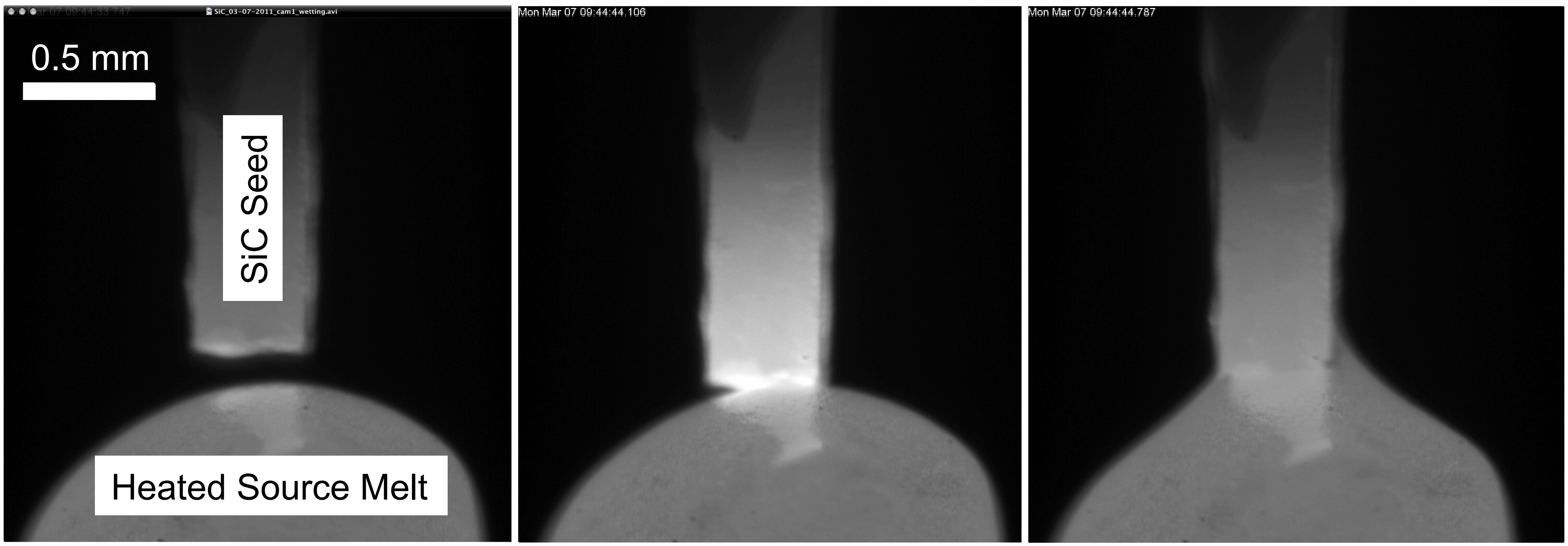
Technical Accomplishments and Progress

First Solvent Laser Heated Floating Zone Growth of SiC

Images recorded by CCD camera (special optics)

Start of laser-heated growth run.

Pre-contact | Initial Contact | Wetting



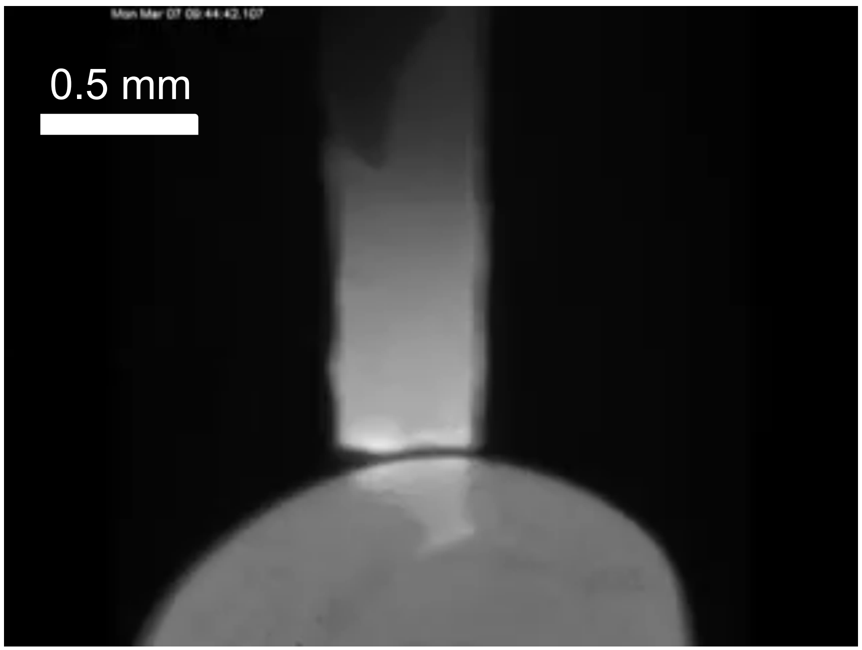
- Desired control of source and seed positioning.
- Desired control of laser power, position, and focus to melt top tip of source rod.
- Desired wetting of laser-heated source melt and SiC seed crystal.

Technical Accomplishments and Progress

First Solvent Laser Heated Float Zone Growth of SiC

Movies recorded by CCD camera (special optics) during laser-heated growth run.

Start of Run



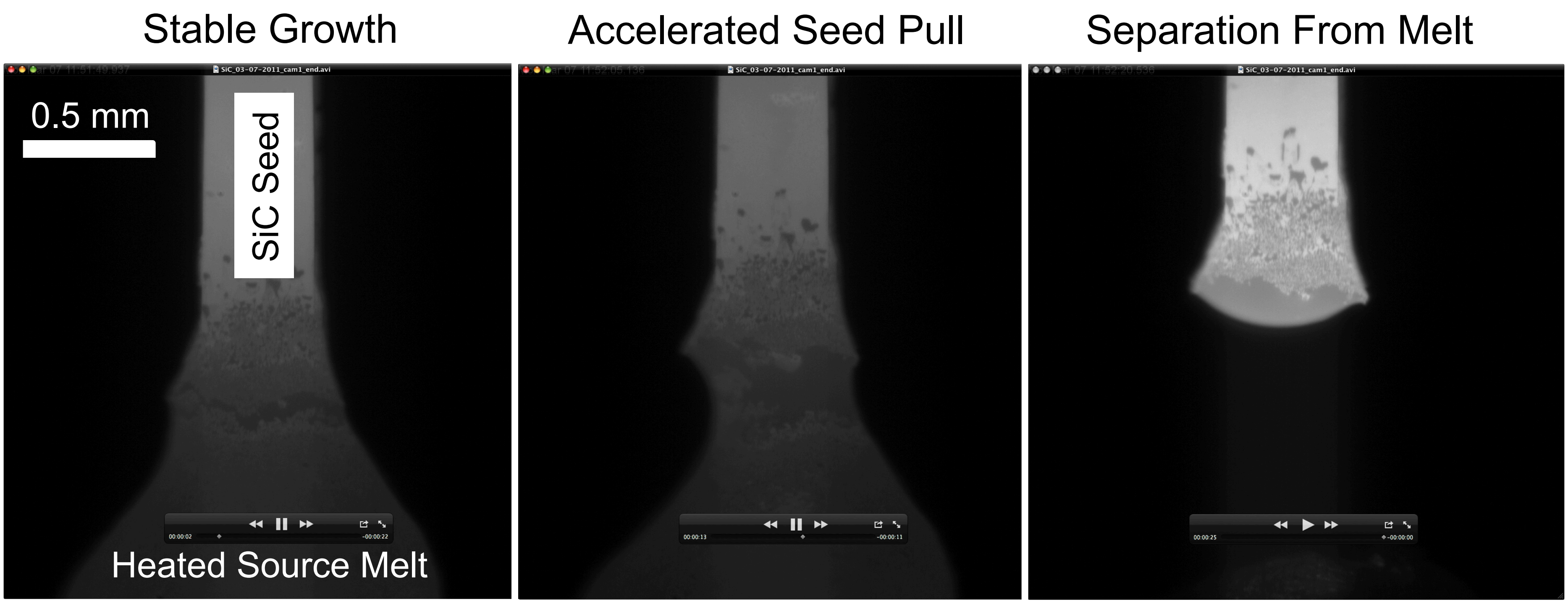
End of Run

Technical Accomplishments and Progress

First Solvent Laser Heated Float Zone Growth of SiC

Images recorded by CCD camera (special optics)

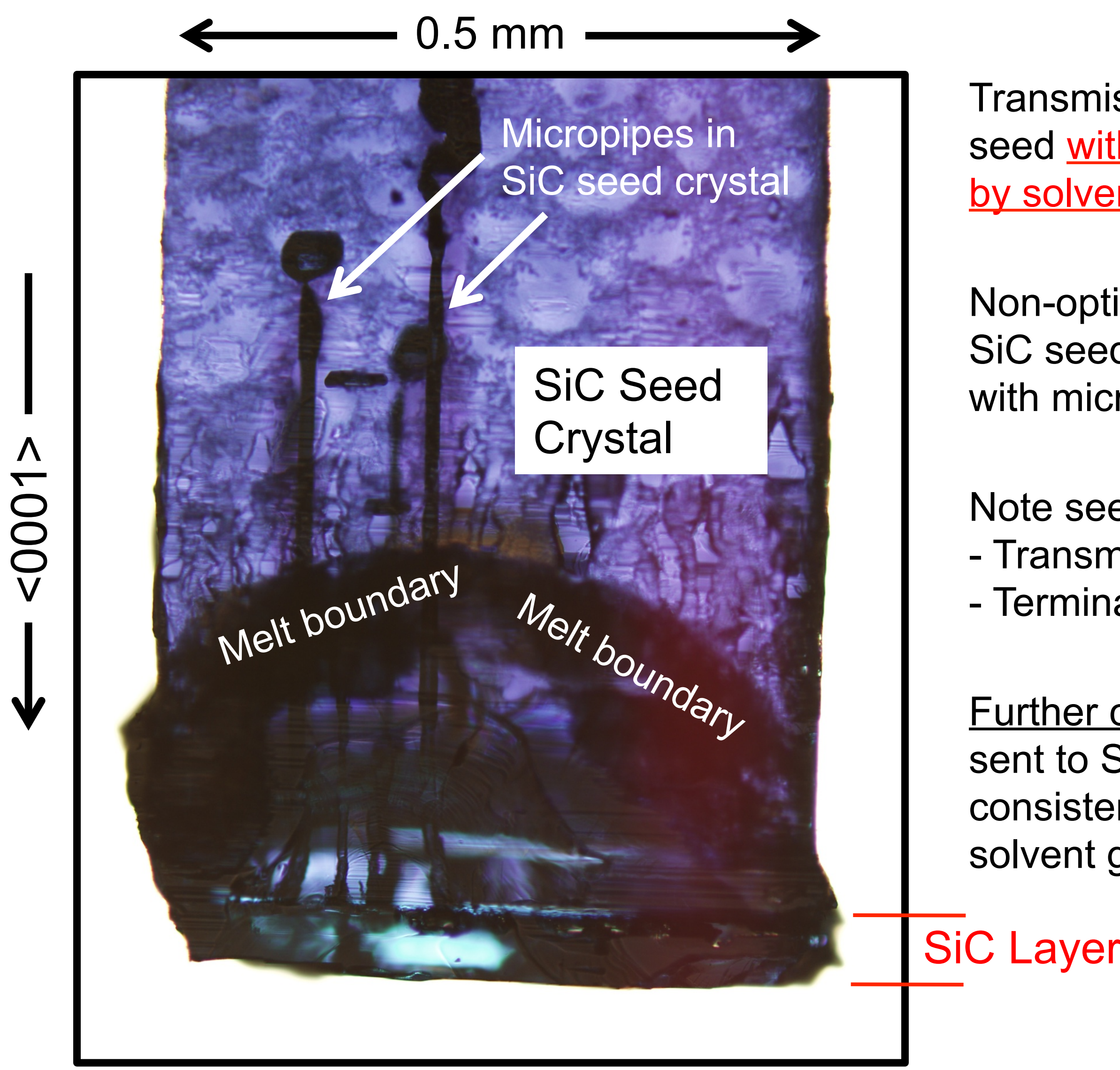
End of laser-heated growth run.



- End of run separation of crystal from melt via withdrawal.
- Wetted melt solution material covers SiC crystal bottom tip following run.
- Wet chemical etching used to remove non-SiC melt solution left on crystal.

Technical Accomplishments and Progress

First Solvent Laser Heated Float Zone Growth of SiC



Transmission optical micrograph of SiC seed with ~ 50 μm thick SiC layer grown by solvent-LHFZ along bottom.

Non-optimized “shakedown run” quality SiC seed crystal (cut from a-face wafer) with micropipes.

Note seed/layer interface features:
- Transmission color difference
- Termination of most micropipes

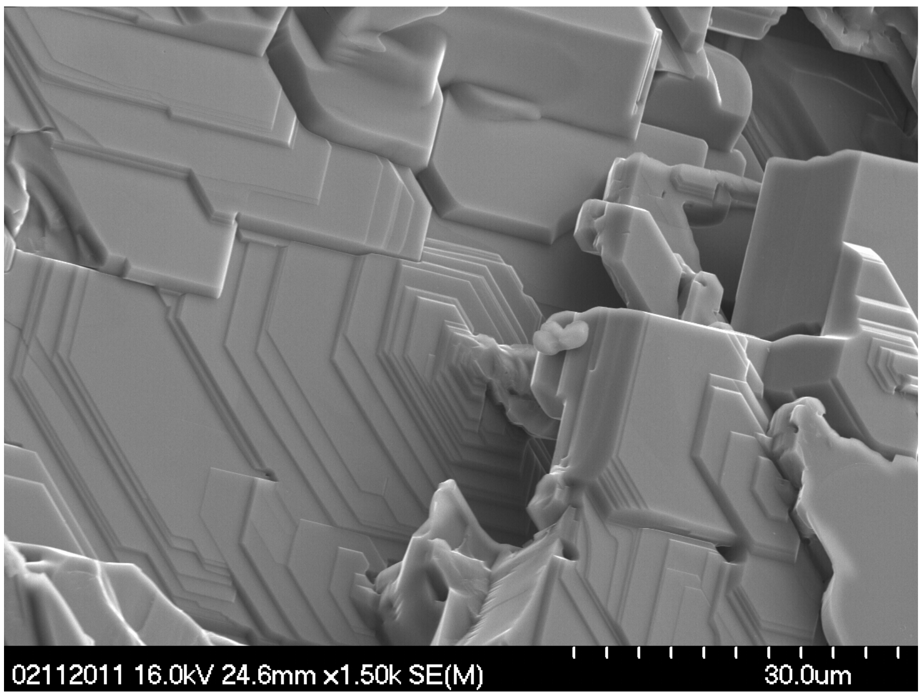
Further characterization on-going (crystal sent to SUNY), but these observations are consistent with previous (non-laser) SiC solvent growth observations.

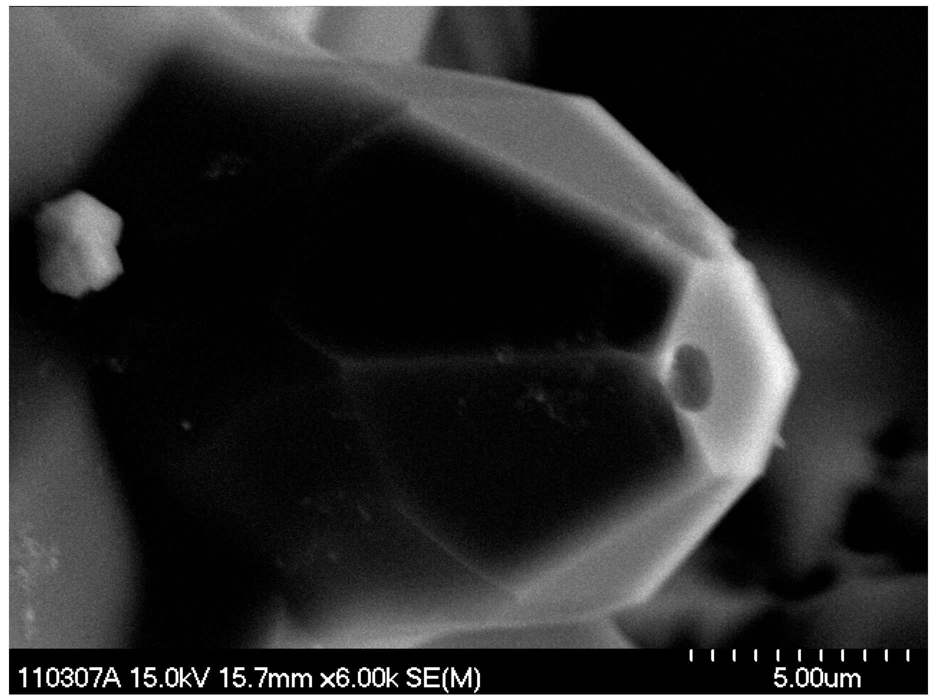
Technical Accomplishments and Progress

First Solvent Laser Heated Float Zone Growth of SiC

Growth morphologies and surface composition analysis conducted to date (March 2011) are consistent with expected SiC growth behavior and crystallography.

SEM images from two Solvent-LHFZ SiC samples (different process conditions).



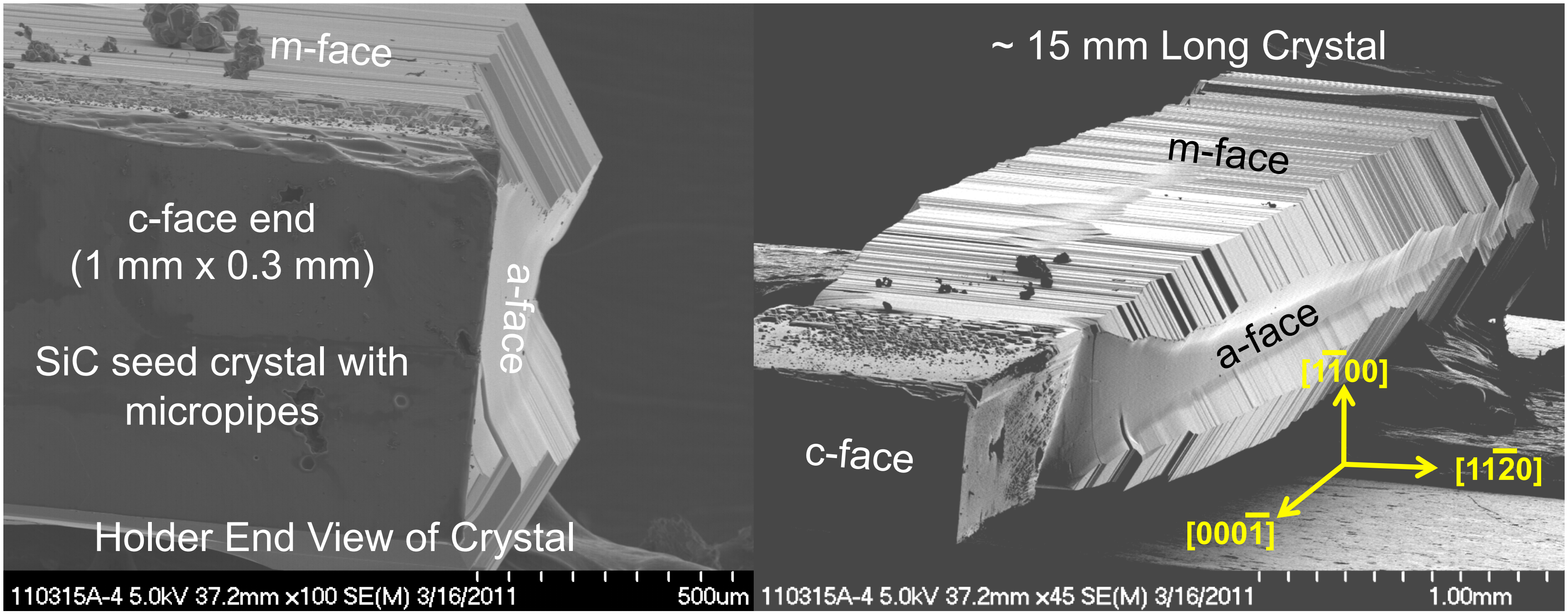


Much further characterization of samples are on-going.

Technical Accomplishments and Progress

Radial Epitaxial SiC Growth

Growth obtained with "shakedown run" quality (i.e., non-optimized)
15 mm x 1mm x 0.3 mm seed crystal saw-cut from m-face SiC wafer.



- Up to 200 μm thick deposition grown during initial runs.
- Growth faceting evolves crystal from rectangular to hexagonal shape.
- High density of ridges possibly due to saw-cut seed crystal preparation?
- X-Ray topography to be carried out at SUNY (Prof. Dudley's group).

Collaboration and Coordination with Other Institutions

- NASA Glenn Research Center (Prime – 2 Research Organizations)
  - Sensors & Electronics Branch (RHS) – "Lateral Growth"
    - Two decades of SiC epitaxial crystal growth experience.
  - Ceramics Branch (RXC) – "Fiber Growth"
    - Decade of laser-assisted ceramic fiber growth experience.
  - NASA On-Site
    - Ohio Aerospace Institute (Non-Profit) – Radial Epi Growth
    - Sest, Inc. – SiC Crystal Characterization
    - NASA Post-Doctoral Fellow (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.

Proposed Future Work

- Now that crystals are being grown, perform detailed characterization on selected crystals.
  - NASA: Optical, SEM, AFM, KOH Etching, micro-Raman, SIMS, etc.
  - X-Ray topographic analysis (Prof. Dudley – SUNY).

- Now that new hardware is running, develop and improve LTC growth processes (fiber and radial).
  - Improve growth initialization process (including SiC seed quality).
  - Increase growth rate (first), then increase growth time to demonstrate larger crystals on path to meeting milestone metrics.

- If both fiber and radial growth processes demonstrated as viable in this project, initiate follow-on project (with more development partners and funding) to build and demonstrate "full-up" LTC boule production prototype.

Summary

- SiC material defects, inherent to commercial SiC crystal growth process, are directly & indirectly (cost & de-rating) hindering beneficial insertion of more efficient SiC power electronics into systems.

- Experiments to investigate feasibility of revolutionary new "Large Tapered Crystal (LTC)" SiC growth approach are now fully underway!
  - New experimental growth system build-ups have been completed.
  - Prototype SiC crystals are being grown via LTC processes.
    - First demonstration of Solvent Laser-Assisted Floating Zone SiC growth.
    - Initial demonstration of CVD radial epitaxial growth enlargement.
  - Demonstrations to date are starting to answer key LTC technical feasibility questions.

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, Mark Dieringer, Michelle Mrdenovich, Beth Osborn, Trevor Hempel, Kelly Moses, Chuck Blaha, Kimala Laster, Jim Mazor, Wentworth John, and Frank Lam