



Floating Silicon Method (FSM) DOE Progress Report – May, 2010

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Floating Silicon Method (FSM)

PV Program Team

Presenter

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VSEA (non-confidential)

Timeline

- Project Start Date: 8/01/2009
- Project End Date: 7/31/2012
- Percent Complete: 22%

Budget

- Total project funding
 - DOE share: \$3.0M
 - Contractor share: Per Contract
- Funding received in FY09
 - \$339K
- Funding for FY10
 - \$1,564K

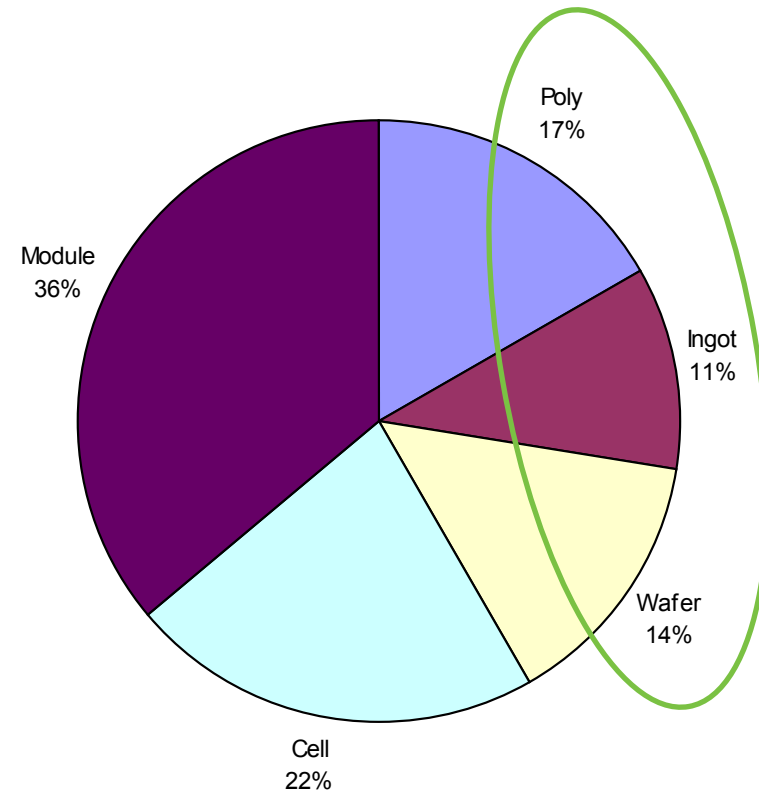
Barriers

- Solar power is not cost-competitive with conventional sources of electricity
- Costs of existing silicon wafer manufacturing processes are high

Partners

- A US based solar manufacturer will produce solar cells from FSM wafers for performance evaluation, and evaluate an FSM system for production.

- Solar energy \$/watt is too expensive
 - Not yet at grid parity
- Wafer production is >40% of module cost
 - Large lever on \$/watt
- Disruptive wafer manufacturing technology will:
 - Reduce material costs (gram/watt)
 - Increase conversion efficiency
 - Increase throughput
 - Increase yield



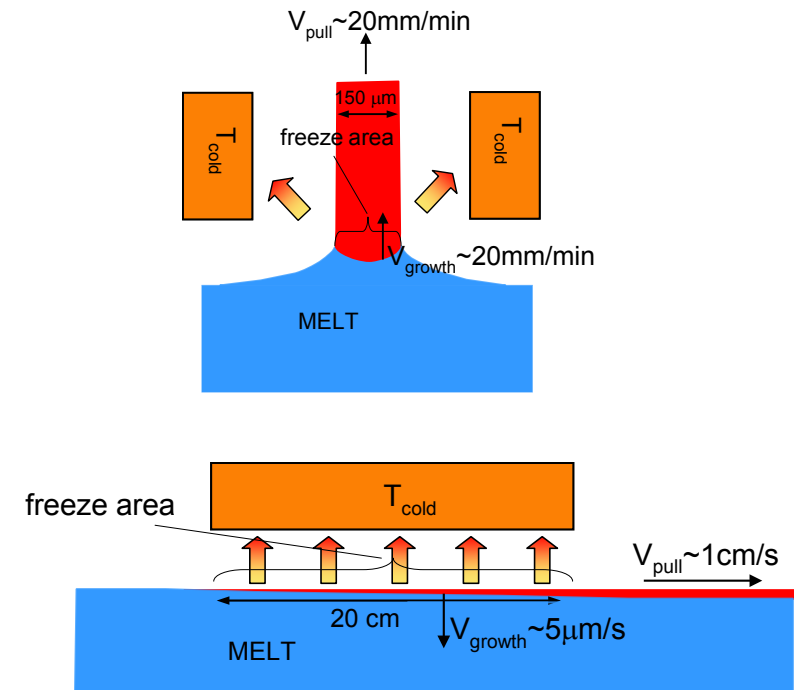
Low cost, high efficiency wafering technology is needed!

- VSEA is developing a system which will produce sheets of single-crystal silicon at high throughput and low cost.
 - Kerfless wafering → Low material cost, high yield
 - Single crystal, high quality → Cz equivalent efficiency
 - Horizontal ribbon growth → High throughput
- Our tool will deliver a drop-in 156mm Solar wafer substrate, enabling fast adoption by existing PV manufacturers
 - Capable of future evolution to thinner and wider substrates
- VSEA is a \$1B US based supplier of equipment for precision materials modification, and the world's leading supplier of ion implantation equipment.
 - VSEA will leverage its global business systems and support infrastructure to quickly proliferate FSM technology

FSM addresses all major issues with existing wafer manufacturing practices

Floating Silicon Method Background

- Vertical Ribbon Growth
 - Heat removed over small area
 - Large T gradients result in dislocations and poor quality Si sheets
 - Pull rate (low) = growth rate (high)
- Horizontal Ribbon Growth (HRG)
 - Heat removed over large area
 - Small thermal gradients enable high quality
 - Pull rate is high, Growth rate is low
 - Thickness is independently controllable
- HRG History:
 - Early attempts by Bleil, Jewett, Kudo (1980s)
 - Existence proof of single crystal dislocation free HRG (JCG, 50(1980) 247-259)
 - Never became commercially viable

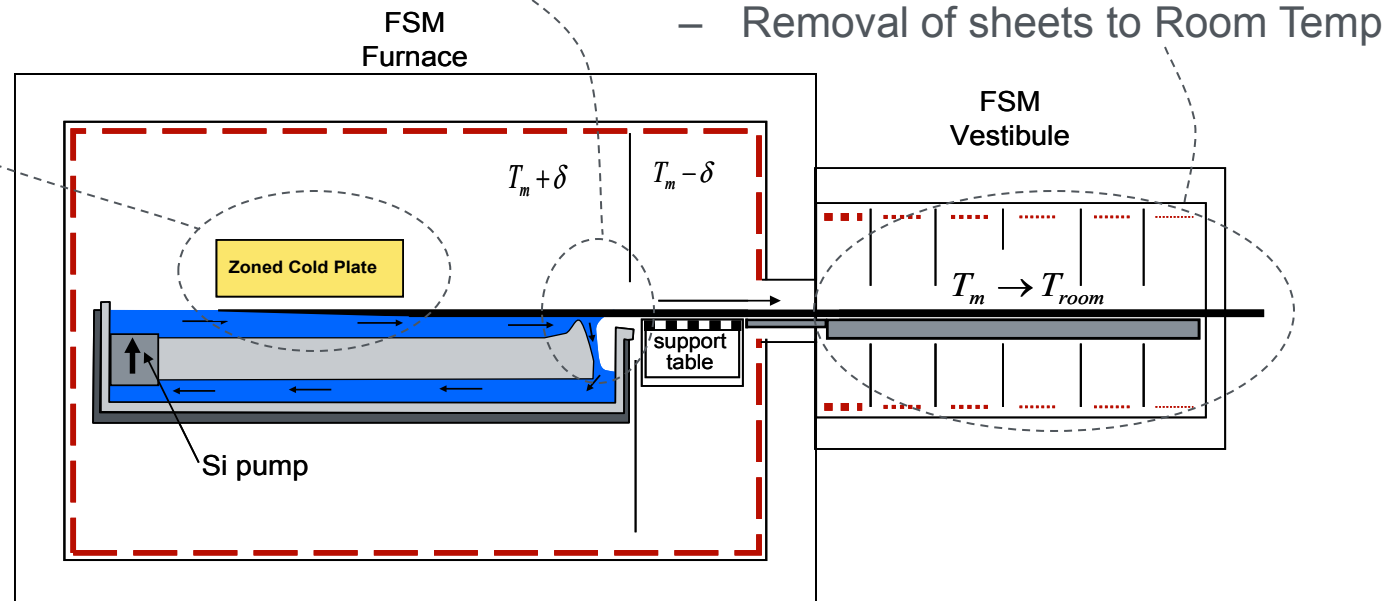


High speed, single crystal, HRG was previously demonstrated but never matured into production

Floating Silicon Method Elements of FSM

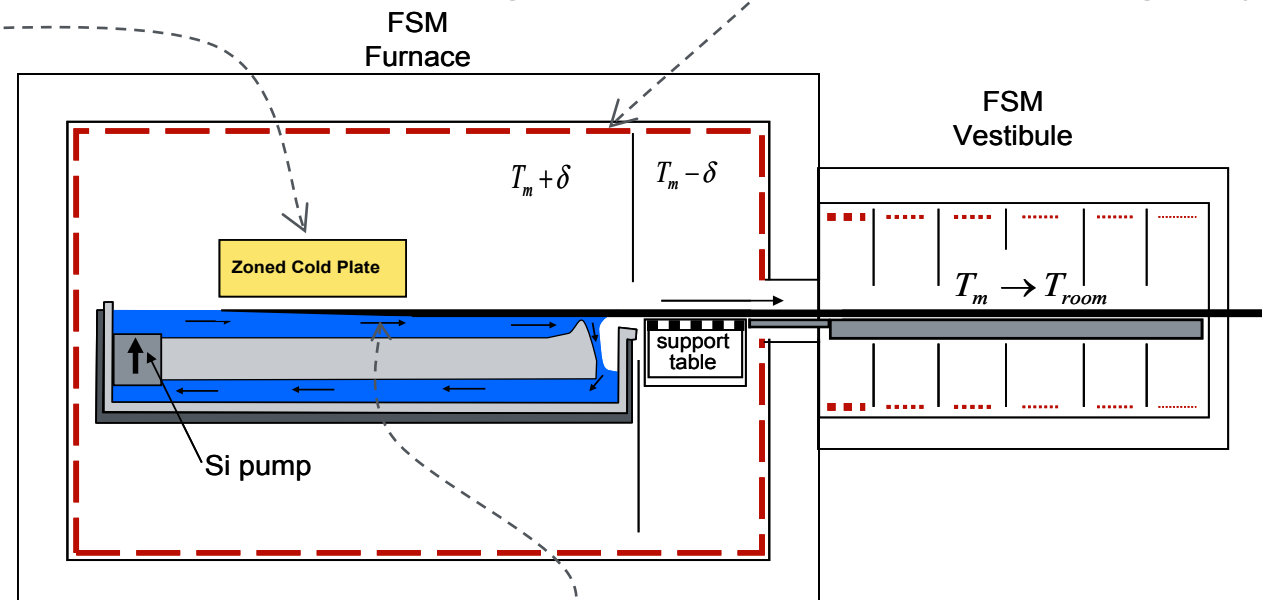
- FSM addresses the limitations of early HRG attempts with several novel approaches
- 1) Separate regions for:
 - Si Sheet Crystallization

– Separation of sheet from Melt



– Separate functions are independently controllable → robust process

- 2) “Isothermal” FSM Furnace
 - Minimal thermal gradients enables thin and wide sheets
- 3) Zoned cold plate for single crystal initialization
 - Two dimensional equivalent to “Dash” necking down process in Cz enables single crystal initialization



- 4) Flowing melt
 - Solute flushing stabilizes crystallization without large thermal gradients and enables fast, wide pulling of single crystal

FSM resolves the problems with previous HRG experiments

Accomplishments

Team Assembled in 11/09

- > 35 years experience in EFG Si crystal growth
- > 30 years experience in EFG, String Ribbon Si crystal growth
- > 10 years experience in crystal growth and fluid/thermal modeling
- Frederick Carlson > 30 years experience in crystal growth and thermal engineering
- Brian Helenbrook > 15 years experience in fluid numerical simulation
- Tom Surek > 35 years experience in Si crystal growth and photovoltaics
- **Greg Thronson Program Manager**
- **Peter Kellerman Physicist, Principal Investigator**
- **Marketing**
- **Physicist, Crystallographer**
- **Systems Engineer**
- **Thermal Systems Engineer**
- **Crystal Growth, CFD Modeling Engineer**
- **Mechanical Design Engineer**
- **Control Systems Engineer**
- **Software Engineer**
- **Technician**
- **Finance**
- **IP Counsel**
- **Science Concepts, Inc.**
- **Surek PV Consulting, LLC**

VSEA has assembled a world-class team

- R&D Approach: Parallel development
 - Analysis: calculations and computational modeling
 - Engineering: development of required system components
 - Experiment: multiple test stands to accelerate learning
- Planned Milestones for 2010-2011
 - **6 months (3/10)**
 - **FSM team – Identify and fill skills gap**
 - **FSM facilities – Set up laboratory and develop first test stand**
 - **Models and analysis – Demonstrate feasibility of FSM**
 - 1 year (9/10)
 - Test stand demonstrating ability of FSM to pull Si sheet continuously
 - 2 years (9/11)
 - Alpha tool capable of demonstrating commercial viability of FSM process

Parallel path risk retirement in 2010
Demonstration of commercial viability in 2011

Floating Silicon Method R&D Approach

FY10

Proof of Concept

Understand and prove the physics

FY11

Alpha Development

Get the process and engineering right

FY12

Beta Development

Get the product right

Sand Box 1

High temperature engineering

- Component and sub-system development
- Evaluation of materials
- Control system development
- Model verification and refinement

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Sand Box 2

Sheet solidification

- Development of key process steps and control algorithms
- Demonstration of high anisotropic freeze rate

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POC Test Stand

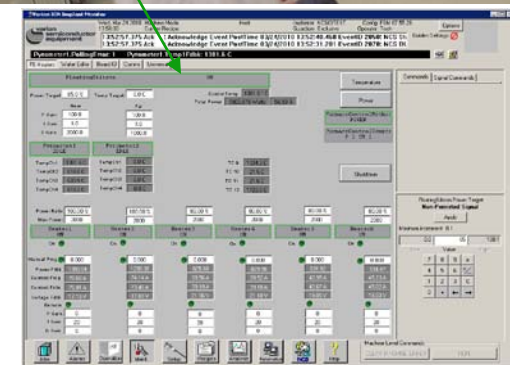
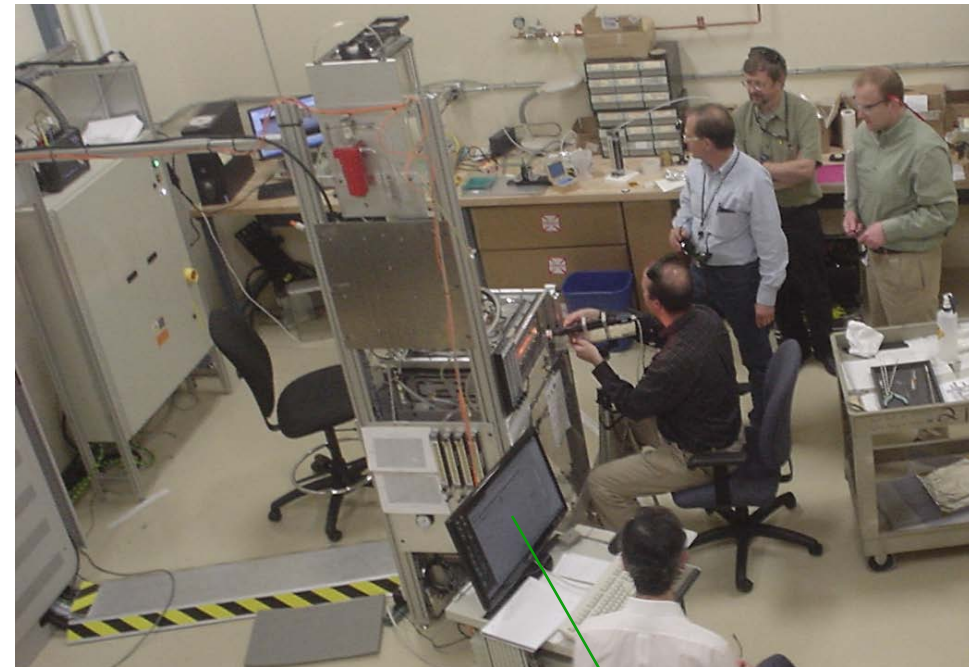
Process Test Stand

- System level integration and optimization
- Proof-of-Concept demonstration

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VSEA has a proven systematic approach to product development

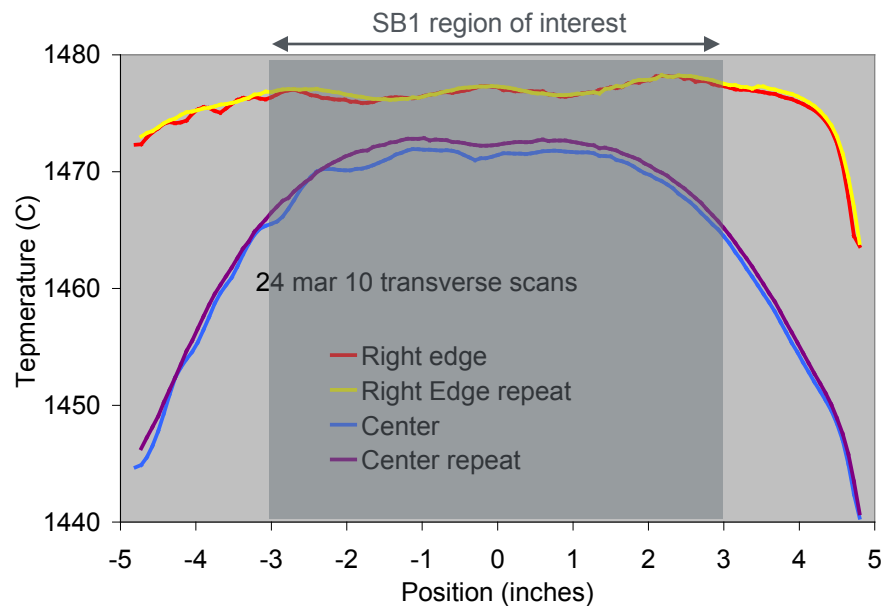
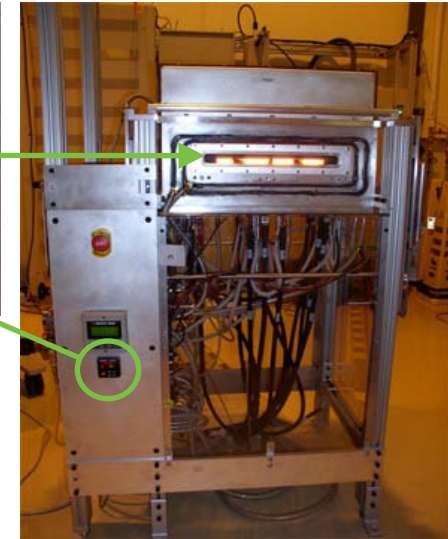
- Leverage VSEA core competencies
 - Varian Control System (VCS) controls – Flexible, powerful and proven control system
 - Mature Engineering Processes
 - Extensive infrastructure and facilities for high tech development
- Sandbox 1 Capabilities
 - Custom designed furnace
 - VCS controls: PID loops, data logging, interlocks
 - Temperature scans using travelling thermocouples
 - Accurate T measurements using pyrometers
 - Windows for visualization with minimal thermal impact



Lab and test stand up and running in only 4 months!

Accomplishments Laboratory Operational

- First Si melt on 3/25/10
 - Temperature scans using travelling thermocouple
 - Accurate temperature control using pyrometers
 - Ability to visually discern melt/solid interface on surface of melt in crucible



3/25/10: Uncontrolled freeze → solid-liquid interface visible

Rapid learning curve → Gaining expertise needed for feasibility test stand development

- Different aspects of FSM require different approaches
- Solidification of sheet (heat flow and phase transition)
 - First order calculations
 - Computational Fluid Dynamics (CFD) two phase (solid, melt) model
- Thermal environment
 - CFD model – Heat flow, radiation and convection
- Si flow, pumping and meniscus stabilization:
 - CFD two phase FEM model (gas, melt)
 - Fixed mesh approach
 - Adaptive mesh approach (Helenbrook)
 - First order calculations for pumping of molten silicon
 - First order calculations for sheet flexure and buoyancy effects

Extensive modeling and analysis is being performed to develop FSM technology

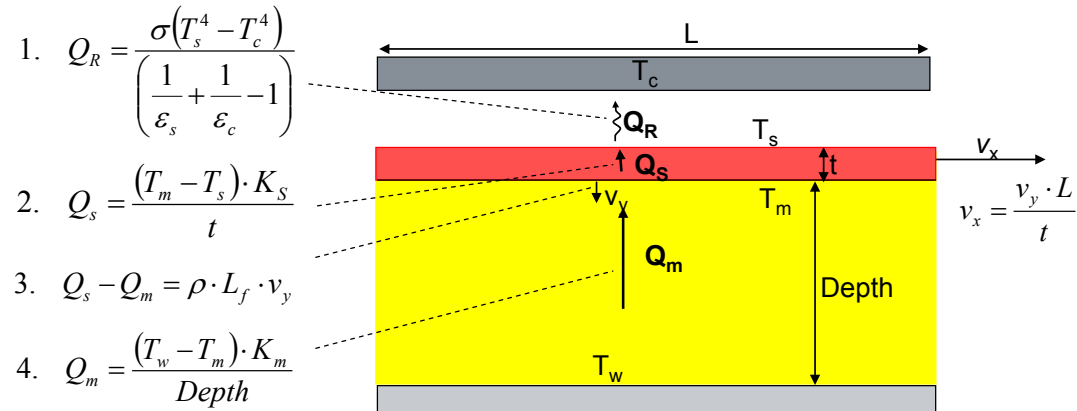
- First order calculations

- Example:

$$V_x = 1 \text{ cm/s}$$

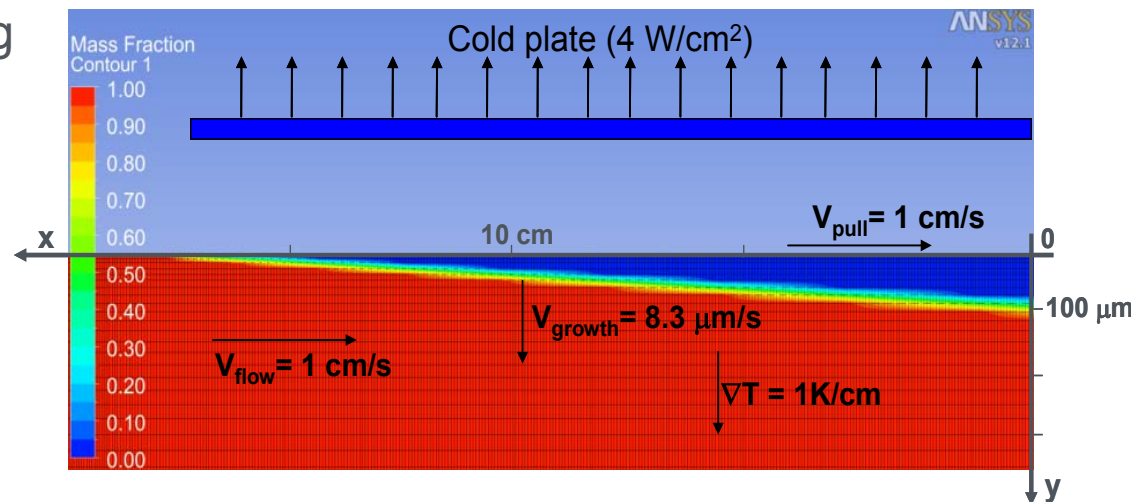
$$Q_R = 4 \text{ W/cm}^2 \rightarrow V_y = 7.6 \text{ } \mu\text{m/s}$$

$$\nabla_y T = 1 \text{ K/cm}$$



- CFD Model

- 2-phase FEM model showing solidification
- Includes heat flow, radiation, fluid flow
- Using same conditions as above $\rightarrow V_y = 8.3 \text{ } \mu\text{m/s}$



Detailed model supports initial calculations.

Accomplishments: Modeling and Analysis Thermal Environment in Furnace

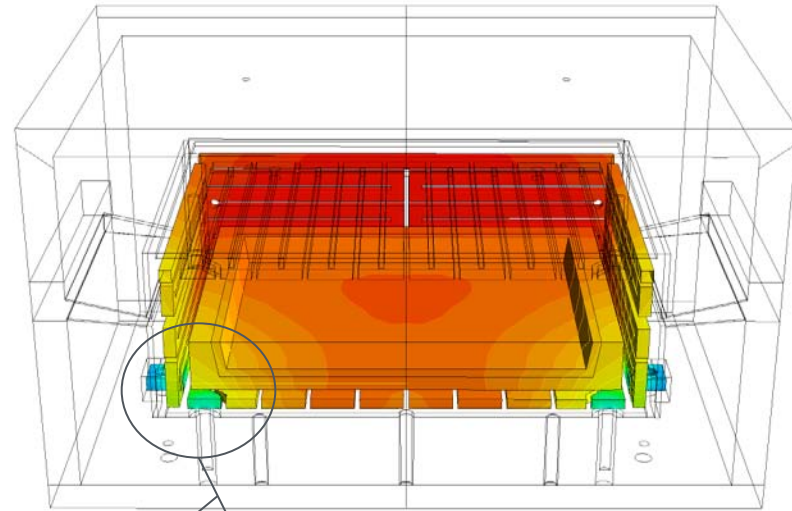
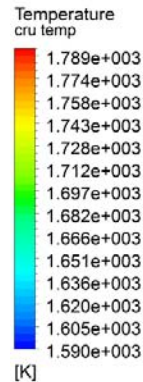
- 3D Model derived from engineering design matches experimental data qualitatively



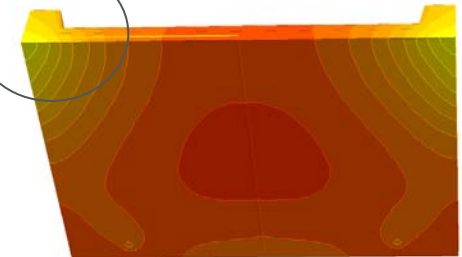
Viewing tunnel

Graphite Insulation

- Effect of viewing tunnel and heater posts can be seen
- Model can guide engineering solutions



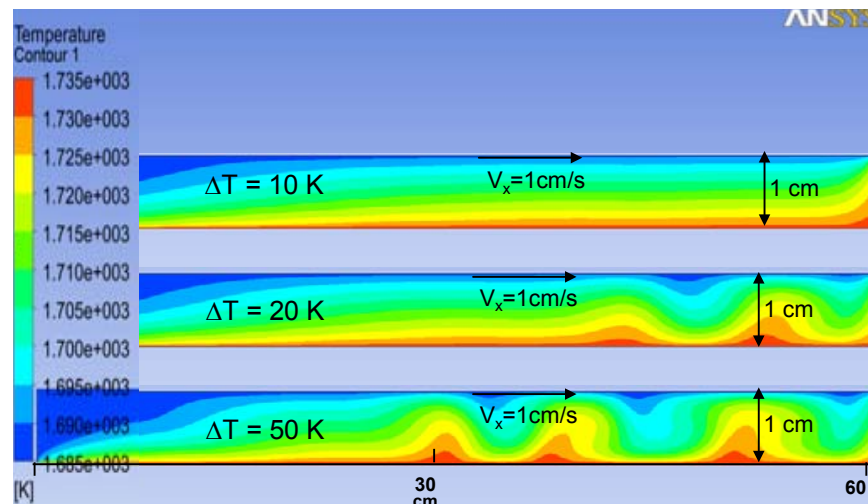
3 heater posts in close proximity add conductive loss



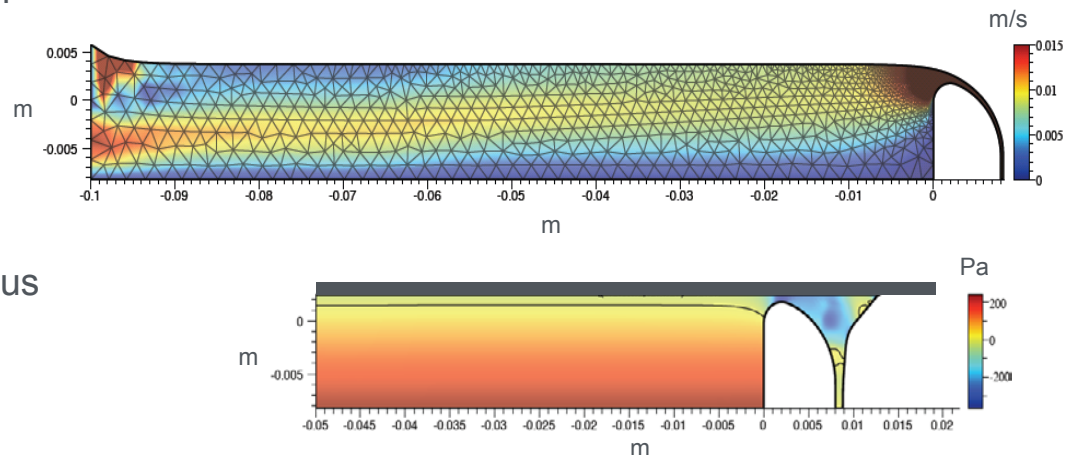
Crucible bottom

**Refining model with test stand data.
Models will guide furnace optimization.**

- Laminar flow of Si melt
 - To get forced laminar flow under the cold plate, thermal (buoyancy) driven convection must be minimized
 - Relative magnitudes of forced and thermally driven flow are determined by flow rate, vertical temperature gradient, viscosity, and density
 - For surface flow speed of 1cm/s, forced flow dominates as long as the vertical temperature gradient $\nabla_y T < 10\text{K/cm}$
 - Planned $\nabla_y T$ for FSM crucible is $\sim 1\text{K/cm}$

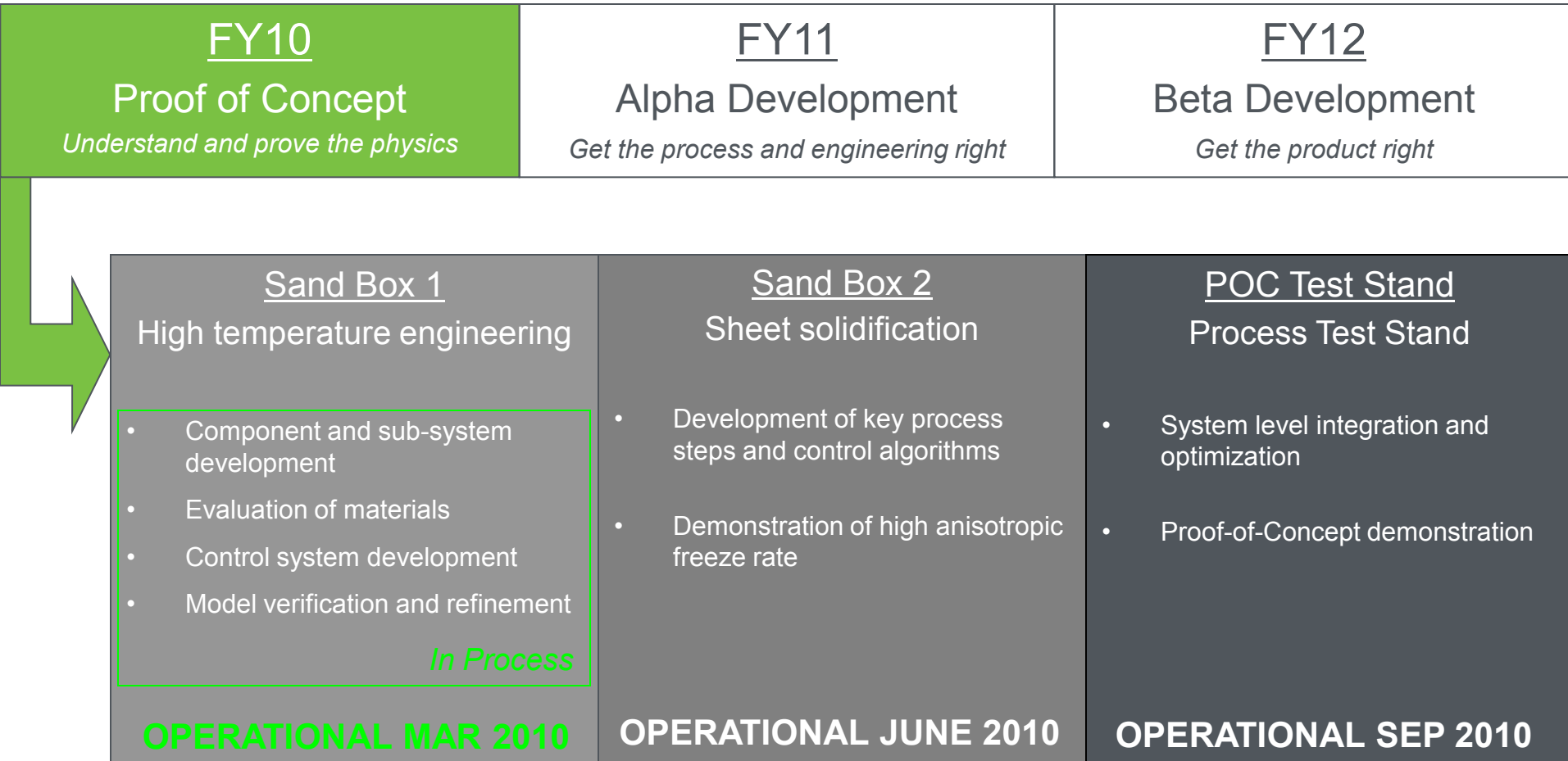


- Separation of sheet from melt
 - Flow over weir: Helenbrook's adaptive mesh model for open channel flow over weir
 - Addition of moving sheet- Stable meniscus forms
 - Model can guide optimization of weir geometry



Detailed flow model being used for crucible optimization.

Future Plans (FY 2011 and beyond)



All Test Stand Activities Progressing On Schedule

- VSEA is the world's leading supplier of ion implantation equipment
- VSEA is active in the solar market. Planned shipment of first solar doping tool in 2010.
- Collaborating with a US based solar manufacturer on FSM development. They will:
 - Manufacture and evaluate solar cells using FSM substrates
 - Evaluate an FSM tool for production

VSEA is positioned to rapidly fan out FSM

- FSM is transformational, and will reduce cost of c-Si substrates by a factor of 3
- FSM is novel with several challenges
- VSEA has the team and facilities to meet these challenges
- FSM team at VSEA is on target for achieving set goals
 - **6 month goals (3/10)**
 - **FSM team – Identify and fill skills gap ✓**
 - **FSM facilities – Set up laboratory and develop first test stand ✓**
 - **Models and analysis – Demonstrate feasibility of FSM ✓**