Floating Silicon Method

Photovoltaic Supply Chain and Cross

Cutting Technologies Award DE-EE0000595

Final Technical Report
December, 2013

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Executive Summary

The Floating Silicon Method (FSM) project at Applied Materials (formerly Varian Semiconductor Equipment Associates), has been funded, in part, by the DOE under a "Photovoltaic Supply Chain and Cross Cutting Technologies" grant (number DE-EE0000595) for the past four years.

The original intent of the project was to develop the FSM process from concept to a commercially viable tool. This new manufacturing equipment would support the photovoltaic industry in following ways: eliminate kerf losses and the consumable costs associated with wafer sawing, allow optimal photovoltaic efficiency by producing high-quality silicon sheets, reduce the cost of assembling photovoltaic modules by creating large-area silicon cells which are free of micro-cracks, and would be a drop-in replacement in existing high efficiency cell production process thereby allowing rapid fan-out into the industry.

The conception of the FSM process (back in 2009), and our belief in its success, was based on the current understanding of Horizontal Ribbon Growth (HRG) or Low Angle Silicon Sheet (LASS) process at that time. According to the work of Kudo, Bleil, and Jewett, the continuous growth of the leading edge (balancing the pull rate) occurs over the length of the heat removal device, forming a "solidifying wedge" with very small inclination angle. The growth is mostly vertical and very slow, close to equilibrium; the fast horizontal growth occurs due to the "sinθ" effect. With the belief that this wedge goes to a point with no limit to the attachment rate at that "triple point", one could increase the pull speed without limit; the wedge would just get more acute and the ribbon thinner. The reported success of Kudo in pulling single crystal Si ribbons at speeds up to 7mm/s was, in fact, taken to be a "Proof of Concept" for the FSM approach.

The FSM process was conceived as an optimization of this LASS process, overcoming the existing challenges of pulling ribbons that are both wide and uniform. With some fundamental innovations, we were expecting to pull single crystal sheets at up to 10mm/s, as thin as 100um, and arbitrarily wide (several 156mm widths). Among these innovations were:

- Floating the Si sheet, which allowed independent zones offering optimization of the different functions of solidification of the leading edge, thickness control, and separation of the sheet from the melt
- Single crystal widening (2 dimensional Dash Effect)
- Separation from the melt using elasticity and buoyancy

These patents were granted (along with others), and form the cornerstone of our strong IP position.

The plan was to build a series of test stands to lead us from initial learning (furnace engineering, and solidification process) to a production worthy prototype. The three planned phases were:

- Phase 1:
    - Develop the team and engineering approaches needed for FSM (Learning),

  - o Verify the process- start pulling (in limited way) sustained single crystal ribbon,
  - o Develop models to support the furnace engineering and solidification process.
- Phase 2:
  - o Develop a Test Stand that can demonstrate our ability to pull single crystal ribbon at production speed, width, and thickness:
  - o Refine models to further optimize equipment and process
  - o Verify material quality by making a solar cell
- Phase 3:
  - o Apply all learning to building a production worthy tool, or “Early Learning Tool” (ELT), capable of sustaining ribbon growth at production speed, width, and thickness.

During Phase 1, we assembled a world-class team of experts, including Tom Surek, Marty Glicksman, Brian Mackintosh, Brian Helenbrook, Fred Carlson; each having more than 30 years’ experience in the field of silicon growth. With this team, we developed furnace engineering techniques in our “Sandbox” test stand, including calibrated pyrometric temperature measurements. But the experiments carried out in the Sandbox clearly demonstrated that the concepts assumed by our predecessors were, in fact, wrong: the leading edge wedge (going to a point) is a myth. We discovered that the leading edge of single crystal ribbon always ends with a (111) facet, and since this facet forms a large angle (55°) with the surface, it requires an intense amount of heat removal to support even a moderate steady state pull rate of .5 mm/s. So although the results of Kudo could be considered an “Existence Proof” of being able to pull single crystal ribbon as fast as 7mm/s, his concepts were wrong, thus necessitating our adding a true “Proof of Concept” phase to our FSM program. That is, although we could glean a lot of information from Kudo’s work, key points were clearly missing. Kudo did not have the sophisticated instrumentation required to accurately measure his thermal fields and he based his heat flow estimates on incorrect theory. It is at this point in the project that our focus evolved from “engineering production equipment” to research and discovery of the fundamental solidification physics of single crystal horizontal ribbon growth. It is only by developing such an understanding that we would then be able to develop the optimal tool for growing wide, thin, single-crystal ribbon at production rates.

Phase 2 was devoted to developing the best approaches to exploring this new subject of rapid solidification of single-crystal ribbon with a faceted leading edge. In order to make rapid progress, we utilized a process of “concurrent science and engineering”. This was a sort of “bootstrap” process, in that in making progress in the theory required experimental results, but doing the experiments required engineering that depended on the theory. While the complexity of developing a mathematical model describing the observed combined faceted and roughened growth was being worked out, we developed heuristic models, which could at least provided pictures and language that allowed us to discuss our results and make progress.

We developed a new test stand (TS1) that had more than 20 heater zones, each on a closed loop temperature control with its own pyrometer, cross-calibrated with a 500 wavelength spectro-pyrometer. With this test stand, we entered into an intense period of research, combining experiments, developing new heat flow devices based on computational fluid dynamic (CFD) models, and developing the solidification physics of combined faceted and roughened growth for FSM. This led to punctuated discoveries and breakthroughs. Among them were:

- Single-crystal HRG is a highly non-equilibrium process requiring intense heat removal. This led to the development of a series of “water cooled, Helium jet” devices, with which we demonstrated our ability to pull single crystal at steady state pull speeds up to 2mm/s, and widths up to 16cm
- Attachment kinetics, including an anisotropic attachment coefficient, is necessary to describe the solidification process with combined facet and roughened interfaces (at the continuum thermodynamic level).
- Single crystal ribbon growth always exhibits surface facet lines, indicating a more complex process involving a limit-cycle
- The thermal stability of this non-equilibrium process is key to pulling fast.

During this phase of the project, we realized that, given the evolved research focus of the project, we could not fulfill our original project objectives in 3 years, and so negotiated a NCTE with the DOE. The NCTE was also was also necessary due to a reduced spend rate resulting from combining several test stands as well as not having achieved sufficient performance to pursue the development of a production system.

In Phase 3, we extended the capabilities of TS1 (TS1+), enabling us to pull ribbons with a full cell width (16cm), as well as providing continuous replenishment. The original DOE goals were modified (along with the NCTE) to focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the original engineering milestones (continuous puller, etc.). With a new water cooled He device, the “Water Cooled Sustainer”, we reached pull speeds up to 2mm/s. Our consultant Brian Helenbrook developed a solidification finite element model, including anisotropic attachment kinetics, which provided a description of the observed combined faceted and roughened growth. The agreement with the pull speed data from TS1 was a major accomplishment. The theory predicted that, given the heat removal rates achievable by the WCS, we should be able to reach a pull speed of 4mm/s, yet we found that we could not get above 2mm/s before the ribbon growth suddenly switched to faceted dendrites. We concluded that the real limitation in pulling > 2mm/s is not in merely providing the intense heat removal, but rather in maintaining stability. This conclusion was supported by the theoretical work of Helenbrook, who generalized linear stability theory to include the combined faceted and roughened kinetics. The thrust of our current work is in understanding the causes of instability, and developing the devices that allow high pull speeds while avoiding this instability.

After the end of the DOE grant period (2013 Q3), the executives at AMAT-VSE have continued to fund the program, striving to solve this final problem of maintaining single growth stability at pull speeds > 2mm/s. The ultimate goal of developing a commercial FSM system may still be achieved.

AMAT-VSE would like to thank the US Department of Energy for supporting the FSM project with its grant (DE-EE0000595). It was this support that allowed VSE to initiate the FSM program, and continue uninterrupted during the R&D phase. We feel that the FSM project was very successful during this time; achieving many discoveries which led to true scientific breakthroughs, leaving FSM “tantalizingly close” (quoting Marty Glicksman) to providing the kerfless wafering that will transform the solar industry.

Actual Time Line

Date	Phase	Key Events
2009-Q4	1	Assembled team
2010-Q1	1	SB1 build
2010-Q2	1	Defined test stands SB1, SB1+, TS1
2010-Q3	1	SB1+ functioning
2010-Q4	1	Sprouted first single crystal
2011-Q1	1	First WCI designed
2011-Q2	1	First sustained pull- dendritic
2011-Q3	1	WCI-3 designed
2011-Q4	1	First sustained single crystal (s.c.) with WCI-3
2012-Q1	2	TS1 build with WCI-4
2012-Q2	2	-Sustained s.c., 6cm wide, .8mm/s -NCTE requested
2012-Q3	2	WCI-7 designed; NREL cell results
2012-Q4	2	WCS, H8 designed
2013-Q1	3	-Sustained s.c., 16cm wide -Keyence data
2013-Q2	3	-WCS experiments -NCTE granted, Phase 3 redirection
2013-Q3	3	-Pull speeds up to 2mm/s -Steady State Facet model

Overview

Project Title:	Floating Silicon Method
Covering Period:	July 1, 2009 to September 30, 2013
Date of Report:	December 21, 2013
Recipient:	Applied Materials, Varian Semiconductor Equipment
Award Number:	DE-EE0000595

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Project Objective:

VSEA will develop a system to manufacture silicon sheet using a VSEA method known as the Floating Silicon Method (FSM). This process will be developed from a rough concept to a point that the technology will be verified for commercialization.

This new manufacturing equipment will support the photovoltaic industry in these ways:
• eliminate kerf losses and the consumable costs associated with wafer sawing,
• allow optimal photovoltaic efficiency by producing high-quality silicon sheets, and
• reduce the cost of assembling photovoltaic modules by creating large-area silicon cells which are free of microcracks.

Background:

VSEA will perform detailed analysis and testing to validate the feasibility of FSM technology. This will be accomplished through extensive computational modeling, and experimentation on a test stand. VSEA will then optimize the FSM process and develop a scaled-up system demonstrating full specification capabilities. This will be accomplished through additional computational modeling and extensive testing. VSEA will further optimize the process, and develop additional capabilities, which will result in a preliminary demonstration tool.

Phase 1: Floating Silicon Method Proof of Concept

From SOPO:

- **Task 1.0 – Simulation and Feasibility Testing for the Floating Silicon Method (FSM)**

VSEA will perform detailed analyses and testing to validate the feasibility of FSM technology. This will be accomplished through extensive computational modeling, and experimentation on a test stand.

  - **Subtask 1.1 – Computational Modeling**
    Create computational models to verify previous analytical first order calculations. Simulate and verify the transient multidimensional mass, momentum, and energy transport of the process. Use this tool to further the design and operation of FSM technology.
  - **Subtask 1.2 – Test stand development**
    Complete the engineering and design of a test stand to demonstrate horizontal ribbon growth. The test stand will have the capability of flowing Si sheet in a controlled and continuous manner for short periods of time. Limited controls capability and sheet handling/cooling capability will be developed for the test stand.
  - **Subtask 1.3 – Model verification**
    Numerous aspects of the process will be measured and/or monitored on the test stand, and results will be compared with computational models. Empirical data will be incorporated into the models to improve their predictive capabilities.
  - **Subtask 1.4 – Feasibility testing**
    Extensive feasibility testing will be conducted on the test stand, including process initiation and characterization of limits of rate and stability of sheet flow.

- **CRITICAL MILESTONE 1**: Simulations that demonstrate a system capable of growing silicon sheet in a continuous mode.
- **CRITICAL MILESTONE 2**: Preliminary feasibility testing to verify the ability to flow silicon sheet in a controlled and continuous manner.

Phase 1 Technical Accomplishments

The most important initial task of this program was to assemble the best team. We were able to engage some of the top engineers and scientists in the field:

- Brian Mackintosh (Systems Engineer) with > 35 years' experience in EFG Si crystal growth (Schott, Mobil Tyco)
- David Harvey (Mechanical Engineer) with > 30 years' experience in EFG, String Ribbon Si crystal growth (Evergreen, Mobil Solar)
- Dawei Sun (Crystal Growth Engineer, Modeler), with > 10 years' experience in crystal growth and fluid/thermal modeling (Saint Gobain, Purdue U., SUNY Stony Brook)
- Fred Carlson (Crystal Growth Engineer) with > 30 years' experience in crystal growth and thermal engineering (Clarkson University)
- Brian Helenbrook (CFD, Solidification Modeler) with 15 years' experience in fluid numerical simulation (Clarkson University)
- Tom Surek (Solidification Physicist) with > 35 years' experience in Si crystal growth and photovoltaics (NREL, Harvard, Mobil Tyco)
- Marty Glicksman (Solidification Physicist) with > 40 years' experience in crystal growth and thermal engineering- received Frank award in Beijing, 2010

Brian Mackintosh, David Harvey, and Dawei Sun were hired as full time employees, while Fred Carlson, Brian Helenbrook and Marty Glicksman were engaged as consultants.

Once our team was assembled, we immediately embarked on the design of our first test stand, which we called "Sandbox 1" (SB1). Although Brian Mackintosh and David Harvey each came with a great deal of Si furnace experience in terms of materials and controls, there were new challenges to be overcome with FSM. Part of the function of SB1 was to provide a platform for testing and optimizing solutions to these challenges.

One of the most important patented features of FSM is its zoned capability which is enabled by the floating ribbon, and which, in turn, enables the optimization of the different functions of: leading edge growth, thickness and uniformity control, and separation from the melt (see Figure 1). This zone capability created several challenges: engineering the zoned heaters, providing the temperature feedback for each zone's control, and calibration. The heaters (resistive) were fabricated from SiC coated graphite with specially designed heater posts that generate the exact power that is lost via conduction to the outside of the furnace. Between the heaters and the crucible was a SiC coated liner, known as the "isoliner", or sarcophagus. At each heater location there was a pyrometer target; the pyrometer providing the temperature control feedback for that heater. The computer control of all these zones was provided by the VCS (Varian Control System). This is the same control system designed to control ion implanters, and with its flexible architecture, allowed straightforward adaptation to the FSM furnace control. The pyrometers for the zones were single wavelength pyrometers, requiring emissivity input in order to get a temperature output. In order to calibrate these, we used a 500 wavelength spectro-pyrometer, capable of

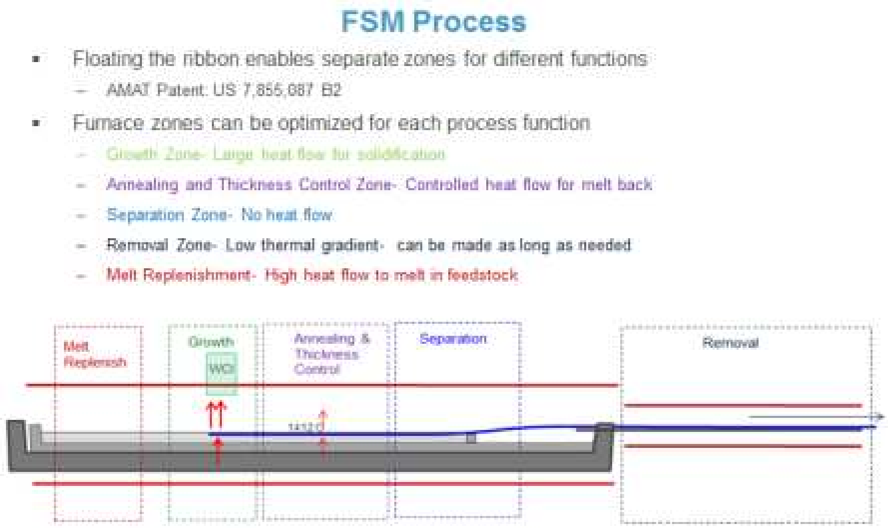


Figure 1 Depiction of Floating Silicon Method showing zones.

measuring both emissivity and temperature, with a temperature accuracy of ~1C. We also utilized a calibrated black-body source as further calibration check.

Another challenge for FSM came from the use of quartz as a crucible material. Quartz is the only material that allows single crystal quality (both EFG and String Ribbon used graphite crucibles). But quartz dissolves (very slowly) in Si melt, releasing SiO gas, which condenses to a solid powder below ~1150C, so any cold surfaces would get coated. This solid SiO can clog exhausts, and if it gets into the melt can cause nucleation of faceted dendrites. Avoiding these outcomes required careful Ar flow engineering. All cold surfaces (e.g. windows, cold devices used in solidifying the leading edge of the ribbon) required Ar purging to prevent SiO from condensing. The chamber used for inserting and extracting ribbon (referred to as the “vestibule”) needed special purging to prevent both air from diffusing into the furnace, as well as SiO from diffusing into the cold area of the vestibule. This was accomplished by flowing Ar near the center of the vestibule and controlling the furnace exhaust to force a determined flow rate into the furnace.

Much of our initial discussions were focused on the stabilization of the meniscus which is formed when separating the ribbon from the melt, as well as the mode of motivation for the ribbon (both insertion and pulling). We originally envisioned using the flow of Si melt, flowing over a weir. The idea was that the falling melt would provide the required negative pressure to stabilize the meniscus, as well as providing the motivation of the ribbon. It was quickly ascertained, however, that the high surface tension of Si requires a much higher pulling force than could be supplied by the viscosity of the flowing melt, and so we developed a new concept of seeding and pulling. In order to insure that we grew our single-crystal ribbon in the desired crystal orientation, we decided to used electronics grade Si wafers (with [100] orientation) as our seed material, inserted and pulled using a mechanical pulling device. The negative pressure needed to stabilize the meniscus could be obtained while pulling horizontally by utilizing the elasticity and buoyancy of the solid Si ribbon. This concept was codified in patent (US application 20110272115, still pending). We used SB1+ (with vestibule) to test this concept, and found that it worked successfully. (see Figure 2)

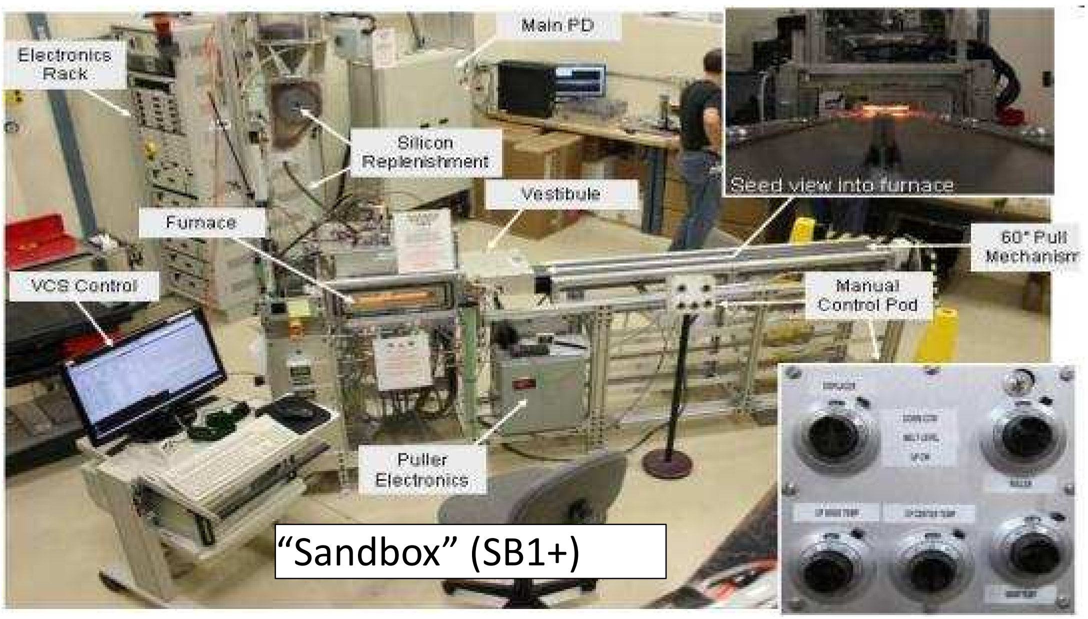


Figure 2 "Sandbox 1" test stand, shown with vestibule and puller mechanism.

By the end of 2010 we were ready to start our pulling experiments. Our initial concepts concerning the required heat flows were based largely on the work of Kudo (JCG 50(1980), 247-259), who reportedly pulled single-crystal ribbon at speeds up to 7mm/s. (see Figure 3) According to Kudo, the continuous growth of the leading edge (balancing the pull rate) occurs over the length of the heat removal device, forming a "solidifying wedge" with very small inclination angle. The growth is mostly vertical and very slow, close to equilibrium; the fast horizontal growth occurs due to the "sinθ" effect. With the belief that this wedge goes to a point with no limit to the attachment rate at that "triple point", one could increase the pull speed without limit; the wedge would just get more acute and the ribbon thinner. In fact, Kudo expressed the opinion that lower heat flow in the melt would be advantageous, which would then require less heat removal. Based on this, our first heat removal device was a conductively cooled "cold plate", and relied only on radiative coupling between the bottom surface of the cold plate and the ribbon. We controlled the net heat removal by balancing the conduction with additional heaters in the cold plate, thereby obtaining control of the freeze rate.

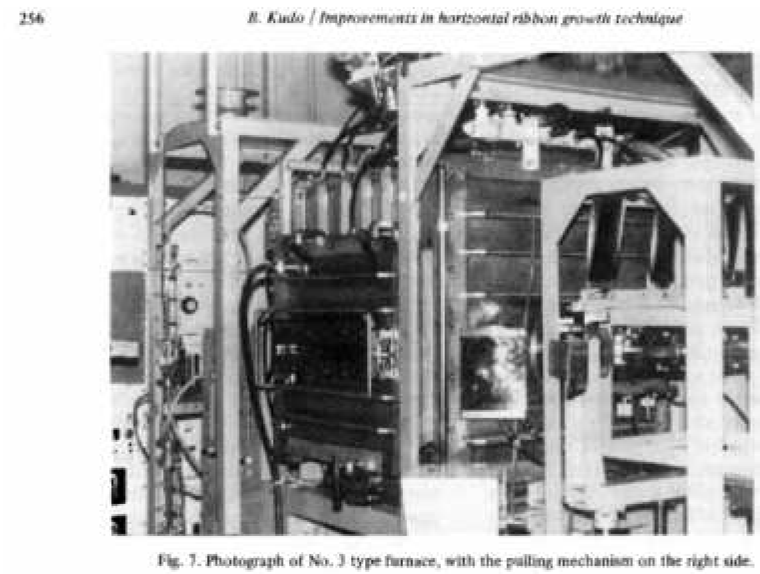


Figure 3 Photo of Kudo's LASS furnace (JCG, 50 (1980) 247-259).

In order to determine the heat flows in our furnace, we had to connect our observable temperatures on the isoliner boundary (as measured at points by the pyrometers) to the heat flows within the Si melt. This was done using our 3-dimensional FLUENT furnace models (see Figure 4).

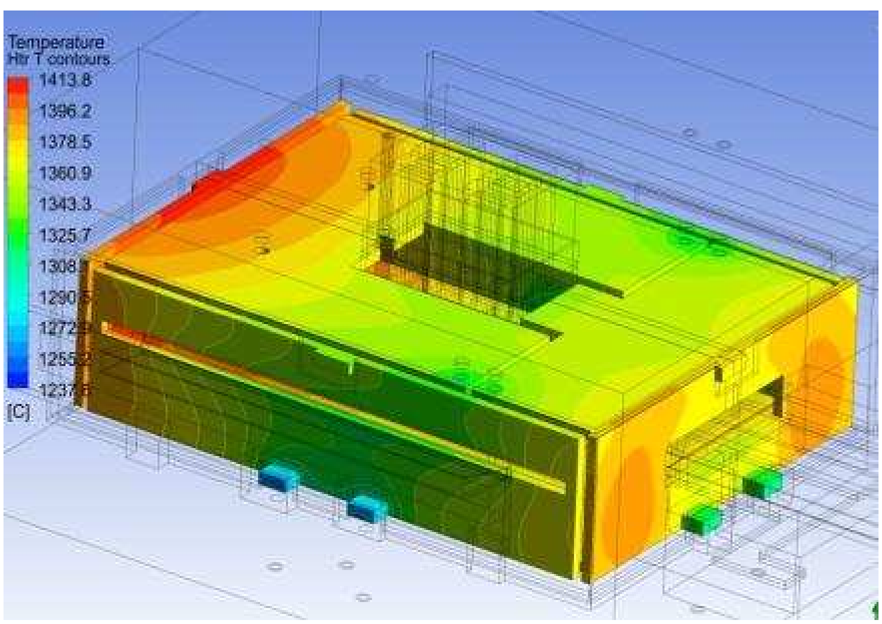


Figure 4 Example of FLUENT furnace model for SB1+.

By December 2010, we were able to successfully insert a [100] seed under the cold plate, sprout new growth, and extract the seed and sprouted growth (using our seeding and meniscus stabilization techniques). By the shape of the sprouted crystal, we deduced that the sprouted crystal was the same [100] crystal orientation as the seed. This was later confirmed using XRD measurements at Boston University. However, with the heat removal afforded by the radiation cooling of the cold plate (< 12 W/cm^2 from the solid), we could not sustain this sprouted growth even at very low pull speeds. Based on this, as well as our theoretical understanding, we concluded that we needed a more intense, though narrow, heat removal device, and embarked on developing a series of new devices using water cooling to provide a very cold surface within the furnace.

Meanwhile, we advanced our theoretical understanding of the horizontal ribbon growth solidification problem. Dawei Sun developed an in-house solidification model using FLUENT which uses a fixed mesh approach, while Brian Helenbrook used his own code with an adaptive mesh approach (see Figure 5). Both approaches described heat flow including radiation and convection, but assumed roughened growth at the interface; that is, no faceted attachment kinetics. Both of these approaches predicted that a minimum radiative heat extraction was necessary to obtain sustained growth due to the difference in emissivity between the solid and the melt. This placed a condition on how cold the bottom of the cold plate had to be, and it was based on this requirement that we decided to design our first Water Cooled Initializer, which would provide a very cold surface close to the melt in a very narrow region, a kind of "cold knife", so that the leading edge could be initialized with minimal subsequent thickening of the ribbon.

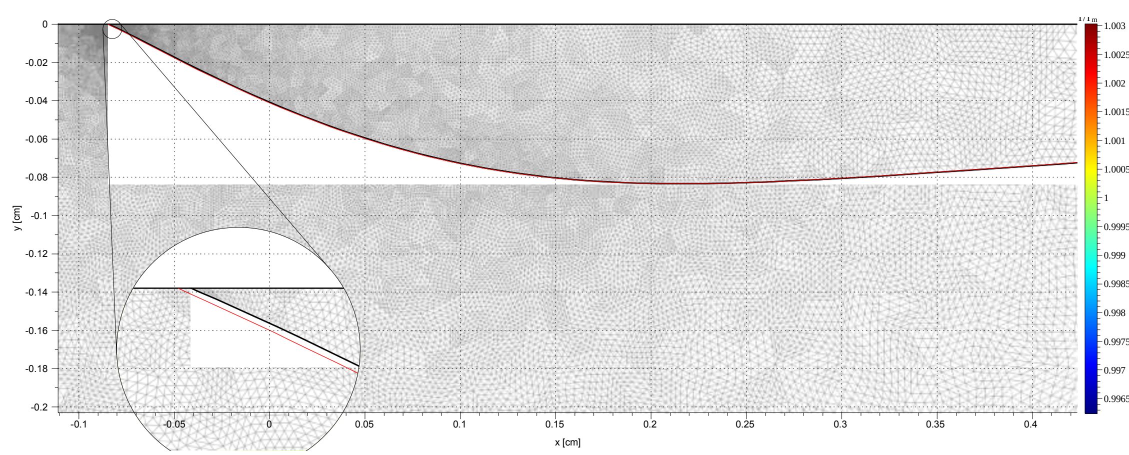
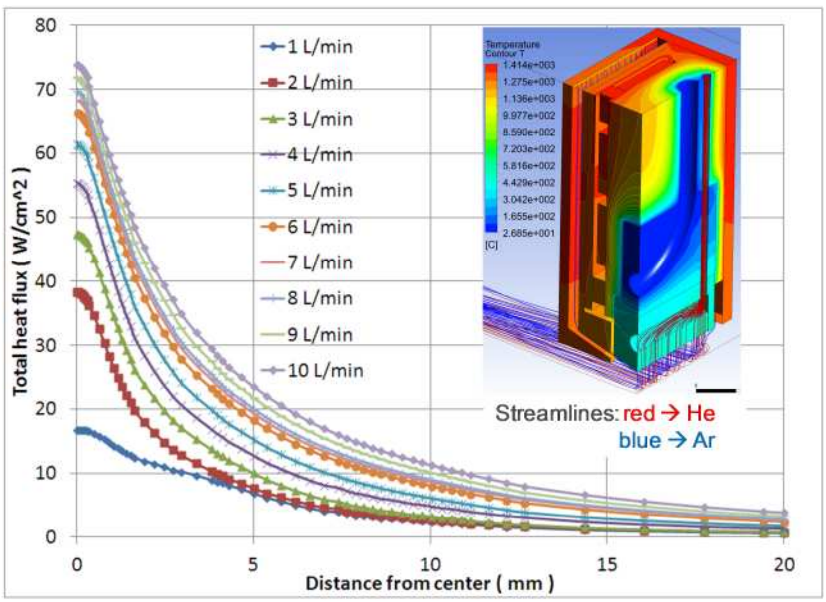


Figure 5 Example of Brian Helenbrook's adaptive mesh solidification Finite Element Model.

After experimenting with a series of water cooled devices, we finally achieved sustained growth but at far higher heat removal than expected, requiring convective He flow. Our initial sustained growth was dendritic, however. It was not until the end of 2011 that we finally achieved the sustained single crystal growth. This was using our third iteration of water-cooled devices, WCI-3, which had integrated heaters, hot Ar purge (to keep the water cooled tip clear of SiO), and a slit jet of He. The optimization of this device required a great deal of modeling in FLUENT, involving 2-gas flows in 3-dimensions (see Figure 6). This model provided us with the surface cooling flux (for different He flows), which could then be used in our solidification models to further our understanding.



Surface heat removal rate increases with helium flow rate.

Figure 6 FLUENT model relates He flow with heat extraction from melt surface.

In December of 2011, we successfully pulled a series of single-crystal ribbons the width of the WCI-3 (~2cm) for a length of ~10cm, and a pull speed ~.5mm/s. (see Figure 7)

By analyzing these ribbons, it became clear that the leading edge was indeed a (111) facet, rather than roughened growth. This, then, finally provided the explanation why we needed the intense heat removal (> 30W/cm^2) to initiate and sustain the single-crystal growth. This was the piece of information that was missing in Kudo's work.

Figure 7 Picture of single-crystal ribbon growth. Left side is a (111) facet.

It also became clear that a solidification model that could predict our observations would have to contain facet kinetics, so at this point we charged Brian Helenbrook to begin incorporating kinetics into his model. Note that it would have been much more difficult to try to incorporate new physics into a commercial code such as FLUENT.

SUMMARY OF TASK STATUS

Task #	Task Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
1.1	Computational Modeling	Create Computational Models	COMPLETE. Completed the following models: thermal system model, flow over weir with sheet separation, heat extraction via cold plate and gas-lift pumping. Models will be continually updated with design changes and refined with test data per plan.
1.2	Test Stand Development	Design and Systems Engineering of Test Stand	COMPLETE: Completed component testing in first test stand. Second test stand for growth experiments is operational. Architecture of fully integrated test stand is defined, engineering design and parts procurement is in process.

1.3	Model Verification	Verify Models	COMPLETE. Finished refinement of thermal model. Completed verification of CFD models for flow and pumping with the room temperature test apparatus. Models have proven their predictive capabilities.
1.4	Feasibility Testing	Conduct Preliminary Feasibility Tests	COMPLETE. Demonstrated the repeatability of sprouting single crystal growth with [100] orientation. Demonstrated sustained growth of a sheet. Feasibility has been demonstrated.

SUMMARY OF MILESTONE STATUS

Milestone #	Milestone Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
1	System Capability Simulations	Conduct System Capability Simulations	COMPLETE. Completed the following models: thermal model of system, flow over weir with sheet separation, heat extraction via cold plate and gas-lift pumping.
2	Preliminary Feasibility Testing	Conduct Preliminary Feasibility Tests	COMPLETE. Demonstrated ability to: achieve temp. uniformity, remove heat for solidification, pump molten silicon, and repeatably grow Si crystals from a seed with extraction to room temp. Demonstrated sustained [100] single crystal growth.

Phase 2: Floating Silicon Method Process Optimization & Prototype Development
From SOPO:

Task 2.0 – Optimization of process and design and build of a prototype system

VSEA will optimize the FSM process and develop a scaled-up system demonstrating full specification capabilities. The FSM process will be optimized through additional computational modeling and extensive testing on the test stand. Additional components needed for continuous sheet production will be engineered and tested on the test stand. Results are expected to include improved computational modeling efforts, a working Si pumping system, a solar cell produced using Si sheet from the test stand, and a prototype tool capable of continuous production flow rates of silicon sheets at thicknesses of interest to the PV industry.

Subtask 2.1 –Refine computational models

Computational models will be updated using empirical data from the test stand. Simulations will be used in the design and engineering of components for the prototype tool to further optimize the process.

Subtask 2.2 – Systems Engineering of Prototype Tool

The system design will be optimized based on updated models and empirical results from the test stand. System engineering efforts will be completed on the design and engineering of the prototype tool. Examples of these system engineering efforts include handling and cooling of the Si sheet, design of hardware and software for process control, and design of all required support facilities.

Subtask 2.3 – Produce sample solar cells from test stand Si sheet

Solar cells will be produced by two major solar cell manufacturers using Si sheet grown on the test stand. Collection efficiency will be measured and reported.

Subtask 2.4 – Verify Cz equivalent Si quality from test stand Si sheet

Si sheet produced on the test stand will be characterized. Numerous properties will be characterized, including: grains size and orientation, impurity levels, and majority and minority carrier lifetimes.

Subtask 2.5 – Demonstrate capabilities on prototype system

Specification capabilities will be demonstrated on the prototype system. Crystal structure of the Si sheets will be correlated with both the flow rate and the temperature profiles within the system. Sheet thickness, sheet width, and the rate of sheet production will be optimized with various process parameters.

CRITICAL MILESTONE 3: Demonstrate the ability to build solar cells with from sheet produced on the test stand. (18 months)

CRITICAL MILESTONE 4: Verify Si sheet quality produced on the test stand. (24 months)

CRITCAL MILESTONE 5: Demonstration that the scaled-up prototype system meets or exceeds test stand capabilities. (30 months)

Phase 2 Technical Accomplishments

While we were doing our first pull experiments in SB1, we were concurrently designing our next test stand, TS1. This test stand incorporated all the learning from SB1 and was considerably larger and more complex, having more than 20 independently controlled heater zones and the capability of pulling a ribbon up to 1m long and 16cm wide. Other important features of TS1 include enhanced Argon flow control (using MFCs and pressure monitors), an elongated vestibule with graded heaters, and precision vertical control of the entire vestibule unit.

The first quarter of 2012 was dedicated to bringing TS1 on-line and characterizing it. This was done by running “fake-melts”, using a graphite slab with a Mo sheet surface to simulate (thermally) a Si melt. These experimental results (pyrometer temperatures and heater powers) were used to verify 3-D FLUENT furnace models which were run on our new 192 cluster computer.

Figure 8 Photo of TS1 test stand.

The first cooling device used in TS1 was WCI-4, the next iteration in our series of water-cooled He jet devices, capable of pulling ribbon up to 8cm wide. This device demonstrated the widening capability during initialization, as described in our patent (US Patent 7,816,153 B2). Incrementally increasing the effective width of the He jet (by switching on additional He feeds), allowed us to start with the initial width of our seed (2cm) and monatonically widen the single crystal ribbon, affecting a 2-dimensional version of the Dash Effect used in Cz growth. (see Figure 9)

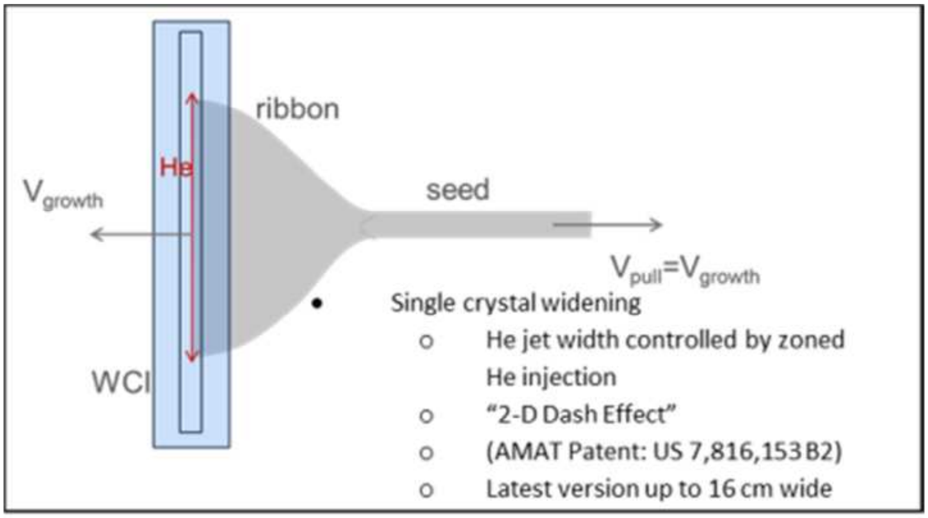


Figure 9 Depiction of WCI monatonic widening, or 2D Dash Effect.

During the first quarter of 2012 we also increased our ribbon characterization capability. We obtained the capability to cut and polish samples within our FSM lab, enabling us to consistently prepare sections of our ribbons so that comparisons could be made from run to run. We characterized ribbons grown in December (SB1) using XRD, SIMS, and Etch-Microscopy analysis. Our FSM team member, Dr. Sudhir Ranjan, began work with with Prof. Vinod Sarin at Boston University. Prof. Sarin is in charge of the Material Science Laboratory within the Mechanical Engineering Department at BU. Besides the X-Ray Diffraction (XRD) capability which determines crystal orientation, we also began processing samples to determine point defects and dislocations in the crystal. This involves sawing, polishing and etching, along with both Optical and Scanning Electron Microscopy (SEM). (see Figure10) The results showed that the first few ribbons grown were high quality single crystal, and in some respect (oxygen) better than Cz:

- (100) single crystal (same as the seed) with defect density ~ $1e4/cm^2$ (about the same as Cz).
- The oxygen content was nearly an order of magnitude lower than Cz. (This had been expected due to the large surface area (relative to the quartz wetted area) than in Cz.)
- The carbon concentration was much higher than Cz (~50x). This was due to the high CO concentration in the SB1 furnace, which was due to the way in which Ar flows in the FSM furnace. This is a problem that could be resolved in future systems, and is not inherent to the FSM process.

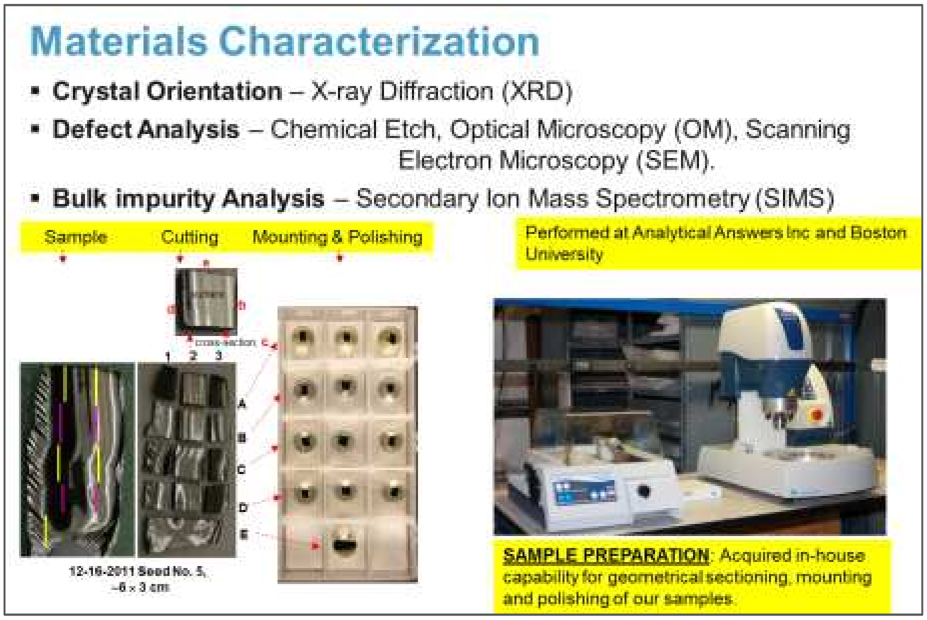


Figure 10 FSM Ribbon characterization capability.

During the second quarter, we intensified our experimentation in TS1. We averaged about one crystal growth experiment per week, exploring how to grow single crystal ribbon faster, thinner and wider. The goal of each week's crystal growth experiment focused on some aspect of the crystal growth conditions (furnace heat flow, or Water Cooled Initializer (WCI4) settings) in order to grow ribbons both for further material analysis (crystal morphology and electrical characterization) , as well as directly advance our understanding of the solidification physics. We were able to go from repeating the sustained ribbon growth results from the Sandbox (2 cm wide, 2 mm thick, 12 cm long) to growing single crystal (100) ribbons up to 6 cm wide, 1-2 mm thick, and over 30cm long. Reaching these ribbon-pulling metrics clearly demonstrated our ability to sustainably grow wider single crystal ribbons; growing faster and thinner became our major challenge. But with the heat flow capability of TS1 and WCI-4, we were not able to pull faster than .8mm/s with a thinness of 1mm.

We performed material characterization on these new ribbons (at Boston University), and found that all ribbons were single crystal with (100) orientation using XRD measurements. Using Etch-pit microscopy, we found that the defect density became lower as the ribbon got longer. After ~10cm of growth, we measured the defect density at <3e3/cm^2 (lower than Cz, which is ~1e4/cm^2). Note that this was expected, in that the defect density improves as the ribbon grows since the dislocations "heal out". Our measured oxygen content remained commensurate or lower than Cz, the boron content was also commensurate with Cz wafers. We started performing electrical measurements of the ribbons (at Varian's in-house cell characterization facility), obtaining resistivity measurement of 1.3 ohm-cm (commensurate with Cz solar wafers), and lifetime measurement of 1.5 μs (similarly prepared Cz wafers yielded a lifetime of 2.5-3.5 μs). The life time measurement proved to be very challenging, requiring effective surface passivation. We began using oxide passivation in order to obtain meaningful lifetime measurements.

Solar cells were fabricated at NREL's PDIL (their standard POCL diffusion 1cm^2 test cells). A CZ substrate was used as a control. The FSM cell efficiency was measured (by PDIL) to be 15.8% compared to 17.4% for the CZ substrate. Subsequent measurements (PL mapping after "dark soak") revealed that the predominant limitation on minority carrier lifetime was Fe contamination. A root-cause analysis for the Fe contamination in our FSM TS1 test stand, revealed several likely causes, which were incorporated into the design of the wider WCI-7 and wide vestibule. The few remaining "fixes" can be left as part of the on-going furnace design optimization/continuous improvement effort.

Another important feature of our pulled ribbons was analyzed at this time, first with standard optical microscopy, and then using a Keyence laser-scanning microscope. The top surface of our ribbons exhibit "facet lines", which are an imprint of the leading edge (111) facet as the ribbon is being grown. These facet lines are always perfectly straight and oriented such that they can only be explained as a result of the leading (111) edge facet. From a material quality issue (for solar cells), the presence of these

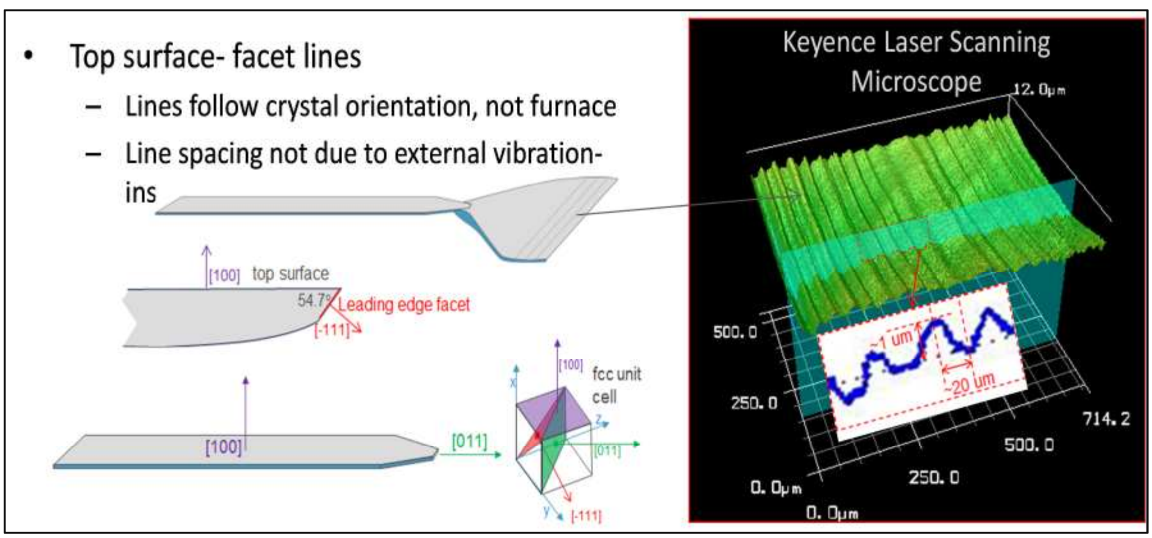


Figure 11 Facet lines with Keyence laser scanning microscope image.

lines is not important, in that they would not affect the efficiency of the cell. But from a crystal growth perspective, the presence of these lines is an important clue as to what is happening directly at the leading edge, and so must be incorporated into any complete theory describing the solidification of FSM ribbons.

At this point in the project, we realized that, given the evolved research focus of the project, we could not fulfill our original project objectives in 3 years, and so submitted a request for a No-Cost Time Extension (NCTE) for the FSM program on 2 July, 2012 which included the rationale and updated spend plan. This 14 month no cost extension (through September 30, 2013) was necessary for VSEA to achieve program milestones per the SOPO in conjunction with the revised spend plan that approaches the original committed cost share for the project. The primary reason given for this request was that there have been multiple unforeseen technical challenges while developing the FSM process. Addressing these challenges prevented us from completing the program within the current period of performance (end date: 31 July, 2012). As described in the NCTE justification, the technical issues that were not anticipated prior to the start of this project were: 1) Steeper temperature gradients were needed for solidification that originally anticipated; 2) Silicon Oxide (SiO) deposition on the heat removal device limited the ability to remove heat from the melt solidification, and also contaminated the melt; 3) Standard thermometry proved inadequate for the accuracy and repeatability required by the FSM process; 4) The second generation test stand (TS1) was delayed due to the technical issues mentioned above. In addition to this, Applied Materials-VSE's spending on the project has lagged when compared to the original plan. This was due to two primary reasons. The first was that we were able to extend the capabilities of our test equipment much further than was originally anticipated. The original plan called for five unique test stands. By hiring resource experts in furnace design, Applied Materials-VSE was able to architect the test stands to evolve through multiple generations instead of developing a unique test stand for each advancement of capability. The second reason being that we have gained a much better understanding of equipment requirements for the PV industry through the development of our solar doping tool and through our integration with Applied Materials. This additional knowledge and expertise has, and will continue to, contribute to the efficiency in which we develop this equipment. The impact of these two factors enabled us to predict accomplishing all of the project milestones in the SOPO using the two test stands that had already been developed. This fact has decreased the total spend on the project required to achieve the agreed upon goals; decreasing the cost share to ~78.4%. This cost share reduction was not expected to impact meeting the program milestones and deliverables per the existing SOPO.

The experiments on TS1 were driven by our theoretical considerations, while our theory was based on our observations of pulled ribbons. This "bootstrap" process was important to acknowledge, and drove our R&D process of “concurrent science and engineering”. Developing a complete mathematical theory to describe our leading edge faceted ribbon proved to be very challenging, and we needed a way of proceeding with the experimental side of the program while developing the theory. This led to the use of “heuristic” models, which allowed us to explore ideas relating what we knew about the crystal nature of the leading edge with heat flows (at least qualitatively). (see Figure 12) These models also provided a language that allows us to communicate our ideas to the larger community (including the DOE in reports), and drove the direction of engineering and innovation in terms of heat flow engineering. In conjunction with these heuristic models, Brian Helenbrook was working on a solidification Finite Element Model, based on his own adaptive mesh code, our in-house modelers were working on heat flow models using FLUENT (on our 192 core computer), and we all (including consultants) explored the literature for related theories that dealt with combined faceted and roughened crystal growth.

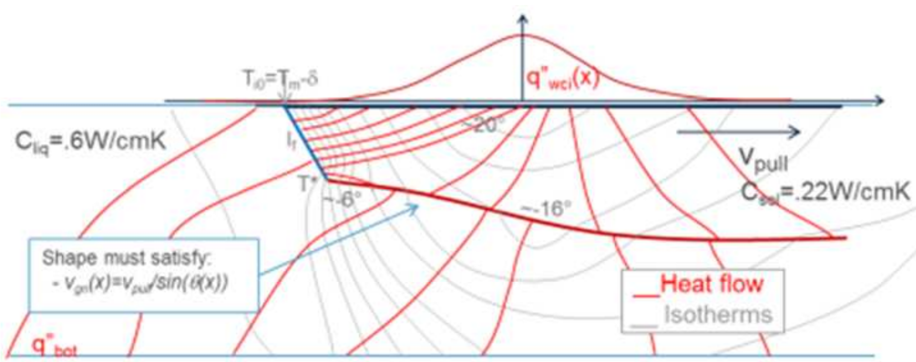


Figure 12 Example of heuristic model showing estimated heat flows with faceted leading edge.

Brian Helenbrook enriched his FEM solidification model to include many of the features of the heuristic description of the combined faceted and atomically rough growth processes seen in many of our grown ribbons. Assuming a 55° (111) facet at the leading edge, and also constraining the problem so that heat removal was only through the solid (for stability reasons), he was only able to obtain a solution (for the experimental heat removal from WCI-4) for a pull speed < .1mm/s, resulting in a ribbon > 5mm thick. (see Figure 13) (We observed ribbons pulled at speeds up to 1 mm/s and < 1mm thick). However, he was able to demonstrate fast steady state pull speeds if the leading edge was allowed to be small (i.e. the “wedge” case).

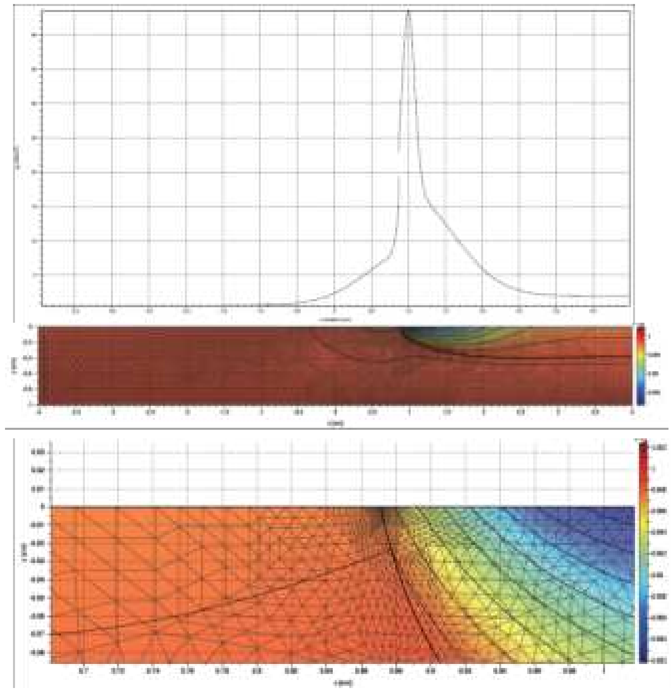


Figure 13 Example of Helenbrook's adaptive mesh solidification FEM

We were thus confronted with this puzzle: We observe faceted leading growth at speeds up to 1 mm/s (also observing facet lines), yet heat flow calculations (Brian Helenbrook's model) indicate that a facet cannot grow steady-state at these speeds with the current experimental heat removal from WCI-4. A steady-state facet model also does not predict the presence of facet lines. We attempted to resolve this by positing a new heuristic theory involving a limit cycle between faceted and atomically roughened growth. Much of the subsequent theoretical effort during this phase of the project was focused on understanding this limit cycle theory and its implications in how to overcome the currently observed pull speed limit and thereby achieving our entitled 7mm/s as observed by Kudo. We attempted to develop this new theory both on the heuristic level, as well as a rigorous mathematical level. This model needs to include kinetic theory (with combined roughened and faceted growth), as well as a new facet nucleating mechanism.

With the insights gleaned from our theoretical considerations, we proceeded with more experiments on TS1 with WCI-4, reaching pull speeds up to 1.1 mm/s and thinness of 1mm. Attempting to pull faster resulted in the growth suddenly transitioning to faceted dendrites. Based on these models, observations, and work of Kudo et.al, we believe that a necessary factor to get to single-crystal high pull speed is high vertical heat flow in the melt at the leading edge. (Kudo had >10x more heat flow than we had in TS1.) This motivated a new engineering effort to design localized heater and a "water cooled sustainer (WCS)" providing localized heat flow, to be superimposed on the low heat flow (isothermal) conditions provided by TS1. This involved significant modeling as well as design effort. In addition, a wider WCI-7 was designed, which would allow pulling ribbons up to 16cm wide.

SUMMARY OF TASK STATUS

Task #	Task Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
2.1	Refine Computational Models	Refine Computational Models	COMPLETE. Models developed to investigate initialization for sustained, anisotropic growth. 3D models completed and being used for trade-off studies.
2.2	Systems Engineering of Prototype Tool	Systems Engineering of TS1 Test Stand	COMPLETE: Systems Engineering and Design of prototype TS1 tool and WCI-4 has been completed.
2.3	Produce Sample Solar Cell	Produce Sample Solar Cell	COMPLETE: Silicon sample preparation and solar cell fabrication has been completed. NREL testing revealed a 15.8% cell efficiency and 1.5 microsecond lifetime measurement.
2.4	Verify Material Quality	Verify Cz Si Quality	COMPLETE: Material characterization work on TS1 silicon ribbon samples confirmed single crystal and [100] orientation. Results showed a steady improvement in quality (with material quality approaching Cz quality). Areas of improvement to reduce Iron and Carbon content have been identified and will be implemented in the next set of TS1 design modifications.
2.5	Demonstrate Capability of Prototype System	Demonstrate Capability of TS1 Test Stand	COMPLETE: TS1 capabilities have significantly increased when compared to the SB1+ test stand. The TS1 test stand has demonstrated ribbon widening capability (8.5 cm) while increasing speed to 1.1 mm/sec and reducing thickness to ~1.0 mm. TS1 design enhancements are under way to further reduce thickness while increasing speed and width (156 mm).

SUMMARY OF MILSTONE STATUS

Milestone #	Milestone Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
3	Demonstrate Ability to Build Sample Solar Cell	Demonstrate Ability to Build Sample Solar Cell	COMPLETE: NREL completed effort to fabricate and test solar cells. NREL testing revealed a 15.8% cell efficiency and 2.0 microsecond lifetime measurement.
4	Verify Material Quality	Verify Si Sheet Quality	COMPLETE: Material characterization work on TS1 silicon ribbon samples confirmed single crystal and [100] orientation. Results showed a steady improvement in quality (with material quality approaching Cz quality). Areas of improvement to reduce Iron and Carbon content have been identified and will be implemented in the next set of TS1 design modifications.
5	Prototype System Demonstration	Demonstrate Scaled-Up Prototype System	COMPLETE: TS1 capabilities have significantly increased when compared to the SB1+ test stand. The TS1 test stand has demonstrated full-width (WCI 7: 15.6 cm) ribbon widening capability. Pull speeds of 2 mm/sec and ribbon length of 95 cm have also been demonstrated.

Phase 3: Floating Silicon Method Process Verification and Tool Demonstration

From SOPO:

Task 3.0 – Final process verification and tool demonstration

The FSM process will be further optimized and incorporated into a preliminary demonstration tool. The design will be completed and a demonstration tool meeting all specifications and requirements will be developed.

Subtask 3.1 – Systems engineering of demonstration tool

The system design will be optimized using acquired knowledge from updated models and empirical results from the test stand and prototype system. System engineering efforts will be continued in all areas to further refine the design.

Subtask 3.2 – Tool demonstration

A preliminary tool will be developed and verified and made available for qualification in different processes.

CRITICAL MILESTONE 6: Demonstration tool verified to meet simulation and prototype specifications and performance. (36 months)

Phase 3 Technical Accomplishments

The first quarter of Phase 3 was devoted to upgrading TS1 to enable wide ribbon growth. This involved building, installing, and testing the new water cooled initializer WCI-7, as well as the wider vestibule. Much higher Ar flow was required to accommodate the wider ribbon removal, which had a wider opening to the furnace. This required new Mass Flow Controllers and modified control algorithms. More valves (and controls) were also needed to accomplish the monotonic He widening in the WCI-7. We installed components for the continuous replenishment system, although this was not tested until Q4 of 2013.

Figure 14 Ribbon (16 cm width) grown with WCI-7. Top surface shown.

In Feb and March, we pulled many ribbons 16cm wide, with top and bottom morphologies suitable for solar cell production. This verified our patented concepts related to the “two-dimensional Dash Effect”. However, the intensity of He flow, as well as heat flow in the melt,
could only sustain pull speeds < .8 mm/s (as expected from WCI4 experiments). See Figure 15 for a summary of pull speeds up to 2013Q1.

In Q2 and Q3 we re-built T1 once again to accommodate the “localized H8” and “water cooled sustainer (WCS)”. These devices were designed to allow us to encompass the experimental space of Kudo et.al. (higher heat flow in melt), and allow us to perform experiments exploring the limits of ribbon pull speed and thinness.

Over the summer we entered into an intense mode of performing a ribbon pulling

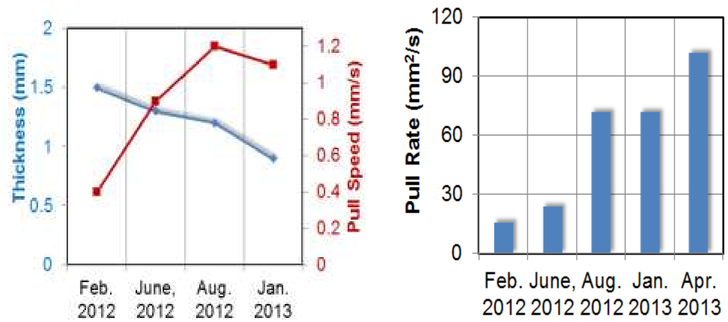


Figure 15 FSM ribbon pull speed and areal pull rate as of 2013Q1.

experiment every week, exploring the range of heat flows that we imagined Kudo might have achieved, searching for a possible "other fast mode" of single crystal growth (heat removal up to ~30W/cm^2, and heat flow up to ~10W/cm^2). We did not find any new modes of growth, and in July decided to switch from "Kudo searching" to systematic furthering our understanding of the combined facet/rough ribbon growth we do observe. Experiments varying the He cooling width (WCS had this capability) resulted in our concluding that even more intense peak heat removal is required to extend our pull speed. We developed new experimental techniques of observing the leading edge position (relative to the He jet) by using video techniques in conjunction with our Varian Control System data (heater powers, He flow, puller speed, etc.). We also addressed several issues that could cause fluctuations leading to the triggering of faceted dendrites. By pushing the WCS He cooling jet capability to much higher peak heat removal than previous WCI devices (though with a ribbon width < 5cm), we were able to achieve single-crystal ribbon pull speeds up to 2mm/s by the end of August.

In Q2, the NCTE was officially approved, and we met with Doug Hall in Gloucester on 4/25. At that meeting, it was decided to redirect the final work of the project to focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the original engineering milestones (continuous puller, etc.). This discussion was codified in the memo of Dan Stricker dated 5/15/2013.

Concurrent with the intense experimental work on TS1 (with WCS), the modeling and theoretic effort also made huge advances. In order to relate experiments with theory, we needed to relate He flow (for the given WCS geometry) to peak heat removal at the melt/ribbon surface. This was achieved by running FLUENT CFD models at particular values of parameters and then optimizing a general expression relating peak heat removal at the surface with experimental parameters (e.g. He flow, WCS height, slit width), so that particular experimental values could be related to parameters within the solidification model. This exercise was facilitated by our 192-core dedicated computer.

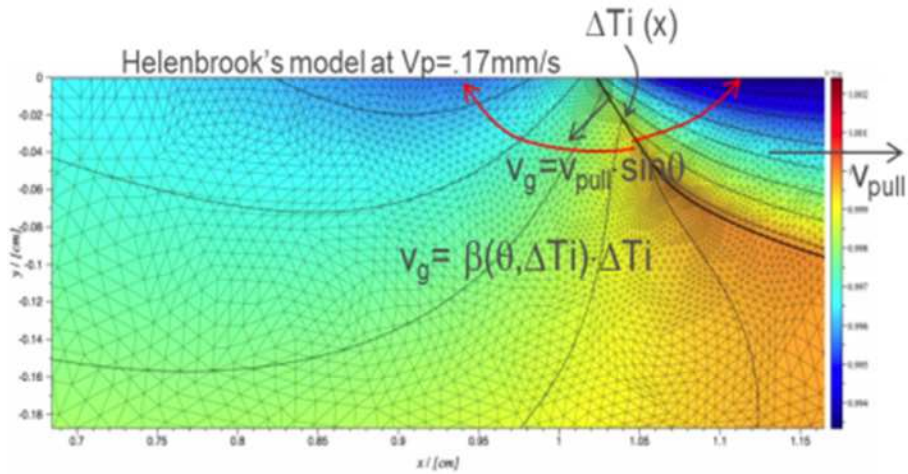


Figure 16 Example of Helenbrook's solidification FEM with Brandon/Weinstein kinetics, showing combined faceted and roughened interface.

Brian Helenbrook incorporated the anisotropic facet kinetics of Brandon/Weinstein

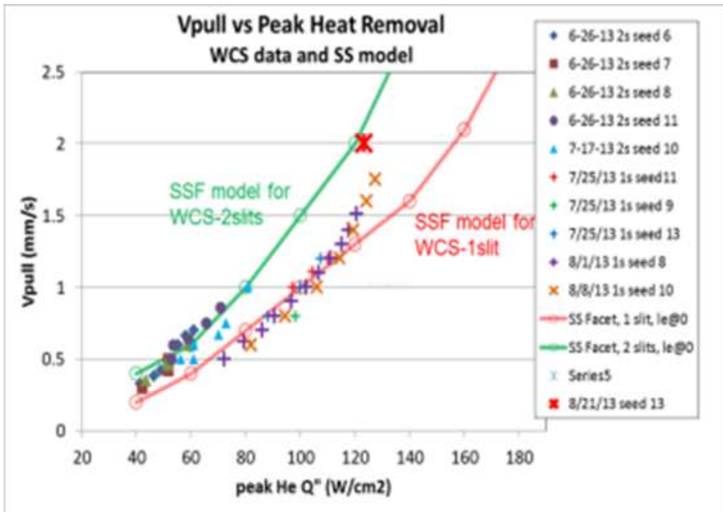


Figure 17 Comparison of pull speed data (TS1 with WCS-1slit) with Helenbrook's model prediction.

(JCG, 2005) into his adaptive mesh code. (see Figure 16) By relaxing the requirement of not super-cooling the melt, he was able to achieve steady state pull solutions with pull speeds of several mm/s, commensurate with what we were observing in the lab. (see Figure 17) This breakthrough forced us to rethink the controversy between this Steady-State Facet (SSF) model and our heuristic Limit-Cycle Theory (LCT). Although the LCT can explain the presence of facet lines (whereas the SSF model cannot), the SSF model seemed to be a good enough approximation in terms of heat flow, to be able to predict pull speeds. Our reconciliation was to, indeed, consider the SSF model to merely be a reasonably good approximation, and although the leading edge facet may actually grow via a saccadic process (LCT), the SSF model can approximate pull speeds, provided the average leading edge angle remains close to the (111) facet angle of 55°, which is probably the case until we get to pull speeds > 4mm/s. By accepting this assumption, we can glean insights from this (working) model regarding the heat flow conditions needed to get to faster pull speeds, which can then guide the engineering and experimental efforts. The validity of this approximation will be tested by those experiments. Since implementing the LCT within Brian Helenbrook's FEM would require scaling several major hurdles, we decided to postpone that effort to a later date.

The SSF theory predicts that, given the heat removal rates achievable by the WCS, we should be able to reach a pull speed of 4mm/s, yet we found that we could not get above 2mm/s before the ribbon growth suddenly switched to faceted dendrites. We concluded that the real limitation in pulling > 2mm/s is not in merely providing the intense heat removal, but rather in maintaining stability.

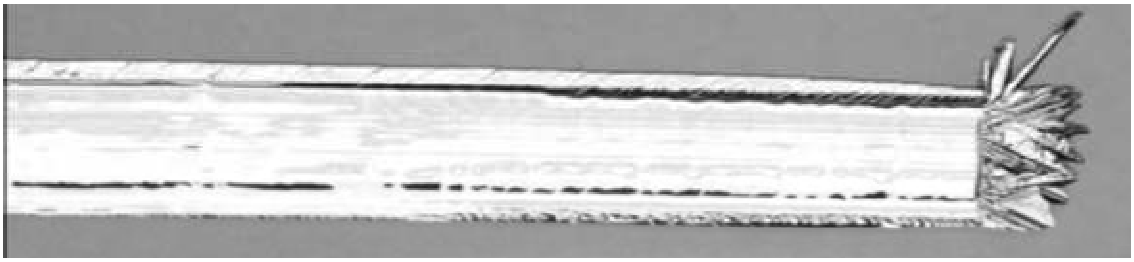


Figure 18 Example of ribbon suddenly going dendritic at a certain pull speed (for given heat flow conditions).

This conclusion was supported by the theoretical work of Helenbrook, who generalized linear stability theory to include the combined faceted and roughened kinetics, and found that the facet provides further stabilization, thereby allowing additional heat to be removed via a supercooled melt. This is, in fact, what allows the fast growth of the leading edge facet via intense heat removal on the surface. It is interesting that it is the facet that hinders the fast growth of the leading edge wedge, and it is also the facet that provides the stability that allows the necessary intense heat removal on the high angle facet. This is the final challenge for FSM: finding the optimal combination of intense heat removal and intense heat flow that allows fast single crystal pull speeds while maintaining stability. The thrust of our current work is in developing the devices that will allow high pull speeds while avoiding the transition to unstable growth.

On Aug. 14-15, we had a very productive meeting with our team of consultants (Brian Helenbrook, Tom Surek, Marty Glicksman, and Fred Carlson). We reached agreement that the close agreement between observed pull speeds and Brian’s SSF model (within this regime of < 2mm/s) demonstrates that the SSF model represents a good approximation to the required heat flows required to solidify a faceted ribbon at these fast rates, and that our pull speeds are heat flow limited, not kinetically limited. Marty Glicksman remarked that we are “tantalizingly close to reaching the point of process scalability”, and that the insights we achieved regarding the combined faceted and roughened growth ribbon growth were “a true scientific breakthrough in the physics of Si crystal growth”.

At the end of the DOE grant period (2013 Q3), there was an executive program review for FSM, and it was decided to continue funding the FSM project at a sufficient level to continue scientific progress, with the 6 month goal of achieving a pull speed of 4mm/s and a thinness of 200um, and a 12 month goal of developing an ELT with an outside partner. This funding depends on FSM success as well as business constraints.

We had our final DOE technical on-line meeting with Doug Hall, Dan Stricker, and Scott Morgan on September 19. It was concluded that we have fulfilled all of our contractual obligations.

SUMMARY OF TASK STATUS

Task #	Task Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
3.1	Systems Engineering of Demonstration Tool	Systems Engineering of Demonstration Tool	COMPLETE: Completed design and testing of a wider (15.6 cm) version of the WCI (WCI7) and vestibule. Completed the Water Cooled Sustainer (WCS), melt-back heater, quartz diffusion barrier designs to improve thermal profile. In addition, the continuous feeder was installed onto TS1.
3.2	Tool Demonstration	Develop and Verify Demonstration Tool	This milestone was modified per DOE memo so that the remaining project resources can focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the engineering milestones (continuous puller, feeder, etc.) and fabrication milestones (full width solar cell, etc.). Reference DOE letter 2013-05-15 Stricker - MemoToFile 5_14_13

SUMMARY OF MILSTONE STATUS

Milestone #	Milestone Description	Initial Negotiated Deliverable / Milestone	Actual Deliverable / Milestone
6	Demonstration Tool Performance Verified	Verify Demonstration Tool Meets Prototype Specifications and Performance	This milestone was modified per DOE memo so that the remaining project resources can focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the engineering milestones (continuous puller, feeder, etc.) and fabrication milestones (full width solar cell, etc.). Reference DOE letter 2013-05-15 Stricker - MemoToFile 5_14_13

Deliverables (Summary Table)

Phase	SOPO Task #	Item: Task = T Milestone = M Deliverable = D	Task Title or Milestone/Deliverable Description	Task Completion Date				Progress Notes
				Original Planned	Revised Planned	Actual	% Com-plete	
1	1.1	T	Computational Modeling	3/31/2010		3/31/2010	100%	COMPLETE. Completed the following models: thermal system model, flow over weir with sheet separation, heat extraction via cold plate and gas-lift pumping. Models will be continually updated with design changes and refined with test data per plan.
1	1.2	T	Test stand development	6/30/2010	9/1/2011	9/23/2011	100%	COMPLETE: Completed component testing in first test stand. Second test stand for growth experiments is operational. Architecture of fully integrated test stand is defined, engineering design and parts procurement is in process.
1	1.3	T	Model verification	9/30/2010		########	100%	COMPLETE. Finished refinement of thermal model . Completed verification of CFD models for flow and pumping with the room temperature test apparatus. Models have proven their predictive capabilities.
1	1.4	T	Feasibility testing	9/30/2010		6/30/2011	100%	COMPLETE. Demonstrated the repeatability of sprouting single crystal growth with [100] orientation. Demonstrated sustained growth of a sheet. Feasibility has been demonstrated.
1	1	M	Simulations that demonstrate system capabilties and feasibility	3/31/2010		3/31/2010	100%	COMPLETE. Completed the following models: thermal model of system, flow over weir with sheet separation, heat extraction via cold plate and gas-lift pumping.
1	2	M	Feasibility testing	9/30/2010	12/30/2011	########	100%	COMPLETE. Demonstrated ability to: achieve temp. uniformity, remove heat for solidification, pump molten silicon, and repeatably grow Si crystals from a seed with extraction to room temp. Demonstrated sustained [100] single crystal growth.
2	2.1	T	Refine computational models	12/31/2011		6/30/2011	100%	COMPLETE. Models developed to investigate initialization for sustained, anisotropic growth. 3D models completed and being used for trade-off studies.
2	2.2	T	Systems Engineering of Prototype Tool	12/31/2011		1/31/2012	100%	COMPLETE: Systems Engineering and Design of prototype TS1 tool and WCI-4 has been completed.
2	2.3	D	Produce sample cells from test stand product	3/30/2011	8/31/2012	9/30/2012	100%	COMPLETE: Silicon sample preparation and solar cell fabrication has been completed. NREL testing revealed a 15.8% cell efficiency and 1.5 microsecond lifetime measurement.
2	2.4	T	Verify material quality	9/30/2011		9/30/2012	100%	COMPLETE: Material characterization work on TS1 silicon ribbon samples confirmed single crystal and [100] orientation. Results showed a steady improvement in quality (with material quality approaching Cz quality). Areas of improvement to reduce Iron and Carbon content have been identified and will be implemented in the next set of TS1 design modifications.
2	2.5	T	Demonstrate capabilities on prototype	3/31/2012		9/30/2012	100%	COMPLETE: TS1 capabilities have significantly increased when compared to the SB1+ test stand. The TS1 test stand has demonstrated ribbon widening capability (8.5 cm) while increasing speed to 1.1 mm/sec and reducing thickness to ~1.0 mm. TS1 design enhancements are under way to further reduce thickness while increasing speed and width (156 mm).
2	3	M	Demonstrate ability to build cells from test stand product	3/31/2011		9/30/2012	100%	COMPLETE: NREL completed effort to fabricate and test solar cells. NREL testing revealed a 15.8% cell efficiency and 2.0 microsecond lifetime measurement.
2	4	M	Verify material quality	9/30/2011		9/30/2012	100%	COMPLETE: Material characterization work on TS1 silicon ribbon samples confirmed single crystal and [100] orientation. Results showed a steady improvement in quality (with material quality approaching Cz quality). Areas of improvement to reduce Iron and Carbon content have been identified and will be implemented in the next set of TS1 design modifications.
2	5	M	Prototype system demonstration	3/31/2012	3/31/2013	9/30/2013	100%	COMPLETE: TS1 capabilities have significantly increased when compared to the SB1+ test stand. The TS1 test stand has demonstrated full-width (WCI 7: 15.6 cm) ribbon widening capability. Pull speeds of 2 mm/sec and ribbon length of 95 cm have also been demonstrated.
3	3.1	T	Systems Engineering of Demonstration Tool	6/30/2012	6/30/2013	9/30/2013	100%	COMPLETE: Completed design and testing of a wider (15.6 cm) version of the WCI (WCI7) and vestibule. Completed the Water Cooled Sustainer (WCS), melt-back heater, quartz diffusion barrier designs to improve thermal profile. In addition, the continuous feeder was installed onto TS1.
3	3.2	T	Tool demonstration	9/30/2012	9/30/2013		N/A	This milestone has been modified per DOE memo so that the remaining project resources can focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the engineering milestones (continuous puller, feeder, etc.) and fabrication milestones (full width solar cell, etc.). Reference DOE letter 2013-05-15 Stricker - MemoToFile 5_14_13
3	6	M	Demonstration tool performance verified	9/30/2012	9/30/2013		N/A	This milestone has been modified per DOE memo so that the remaining project resources can focus on understanding the fundamental science to achieve faster and thinner single crystal ribbon growth rather than trying to meet the engineering milestones (continuous puller, feeder, etc.) and fabrication milestones (full width solar cell, etc.). Reference DOE letter 2013-05-15 Stricker - MemoToFile 5_14_13

Presentations:

1. 6/14/2012- DOE Sunshot Conference, Denver, CO- Poster Presentation: “Floating Silicon Method (FSM)” (Peter Kellerman)

2. 6/7/2013- AMAT ET Conference, Monterey, CA- Oral Presentation: “Floating Silicon Method for Single Crystal Kerfless Wafering- Observations and Theory” (Peter Kellerman)

Patents:

Issued Patents:

1. US 8,064,071 B2, Nov.22, 2011, Rowland et al. FLOATING SHEET MEASUREMENT APPARATUS AND METHOD

2. US 8,226,903 B2, Jul. 24, 2012, Kellerman et al. REMOVAL OF A SHEET FROM A PRODUCTION APPARATUS

3. US 7,990,224 B2, Aug. 16, 2011, Kellerman, et al. REMOVAL OF A SHEET FROM A PRODUCTION APPARATUS

4. US 7,816,153 B2, Oct. 19, 2010, Kellerman et al. METHOD AND APPARATUS FOR PRODUCING A DISLOCATION-FREE CRYSTALLINE SHEET

5. US 7,855,087 B2, Dec. 21, 2010, Kellerman et al. FLOATING SHEET PRODUCTION APPARATUS AND METHOD

Filed Applications (pending):

1. 20110272115 A1, Nov. 10, 2011, Kellerman, et al. REMOVING A SHEET FROM THE SURFACE OF A MELT USING ELASTICITY AND BUOYANCY

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3. 201130213295 A1, Aug. 22, 2013, Mackintosh et al. METHOD FOR ACHIEVING SUSTAINED ANISOTROPIC CRYSTAL GROWTH ON THE SURFACE OF A MELT

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