Market Progress Evaluation Report

Silicon Crystal Growing Facilities, No. 2

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Final Report

SILICON CRYSTAL GROWING FACILITIES: MARKET PROGRESS EVALUATION REPORT #2

Funded By:

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Acknowledgements

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EXECUTIVE SUMMARY

The Northwest Energy Efficiency Alliance is a non-profit group of electric utilities, state governments, public interest groups and industry representatives committed to bringing affordable, energy-efficient products and services to the marketplace. The Alliance was incorporated and began funding projects in 1996.

Siemens Solar Industries (SSI) submitted a proposal to the Northwest Energy Efficiency Alliance (the Alliance) in 1997 to develop an innovative process for growing silicon crystals. As the only US grower of silicon crystals for the solar industry, they would be willing and able to publish the results of their experience in industry forums, thus potentially influencing silicon crystal growing firms throughout the semiconductor industry.

SSI has successfully met all internal objectives in their proposal during the project period. They estimate that they saved 6 million kWh between February 1999 and February 2001. With current monthly savings at about 45,000 kWh, annual savings could be as high as 500 MWh. These savings are only the tip of the iceberg for silicon crystal growers in the Pacific Northwest (PNW). If semiconductor-grade silicon crystal growers in the PNW adopt the processes developed by SSI during the Alliance project, the energy savings could be many times greater than what SSI achieved.

The energy savings achieved in the project pale in comparison to the productivity gains and improved ingot quality SSI accomplished. It is these non-energy benefits that have really caught the attention of other silicon crystal growers in the PNW.

On their own, semiconductor firms in the PNW have implemented many process improvements to the hot zone and have developed their own recharge processes. But the SSI improvements demonstrate opportunities that these firms have not yet explored. Adoption of these improvements, however, is not assured. There remain several specific barriers:

- Semiconductor firms doubt that crystal purity can be maintained using the SSI methods. This is a concern because semiconductor silicon crystals have much higher purity requirements than solar silicon crystals.
- Semiconductor firms need access to a commercially competitive polysilicon feedstock that will work with the recharge process. Currently there is only

one supplier of the granular polysilicon used by Siemens. The supplier also uses the granular polysilicon in their own process, making its supply at risk in times of high demand.

- Semiconductor firms are reluctant to make changes to processes that already work well for them.

The Alliance is currently working to address the first two of these barriers and the industry, through its own process, is working on the later. First, the Alliance provided funding to SSI for independent tests of the purity of the SSI ingots. The results have shown that the SSI process does produce a high quality yield.

Second, the Alliance is funding a project with ASiMI to develop a dendritic polysilicon feedstock. SSI and two local semiconductor-grade silicon crystal-growing companies are going to be involved in testing and using the feedstock. It is anticipated that ASiMI will subsequently be able to develop a granular polysilicon project that is cost competitive and readily available.

Finally, semiconductor-grade silicon crystal growing firms anticipate that the technological experience of the SSI project will affect their development of the 300mm silicon crystal growing processes more than change their current procedures. They are just now beginning to move into 300mm crystal growing. The next five years will see this process move forward, and likely incorporation of these ideas, especially given the current increased concerns for rising energy costs.

We therefore make the following four recommendations to monitor progress and ensure that these processes are more likely to be adopted:

1. Continue to monitor the semiconductor-grade crystal growers' awareness of, and interest in, the SSI results.

2. Monitor semiconductor-grade crystal growers' and equipment producers' awareness of, and interest in, the dendritic polysilicon feedstock project.

3. Consider providing support to JAX Industries to develop a business plan for marketing the recharge equipment and to obtain chemical engineering support to address semiconductor industry concerns for impacts on product purity.

4. Consider providing some additional support to a local semiconductor company to test the integration of the SSI experience into their 300 mm processes.

1. INTRODUCTION

OVERVIEW

This introductory chapter presents an overview of the project, describes the evaluation approach and summarizes the first market progress evaluation report.

PROJECT OVERVIEW

The Northwest Energy Efficiency Alliance (the Alliance) is a non-profit group of electric utilities, state governments, public interest groups and industry representatives committed to bringing affordable, energy-efficient products and services to the marketplace. The Alliance was incorporated and began funding projects in 1996.

In 1997, Siemens Solar Industries (SSI) submitted a proposal to the Alliance in response to a request for proposals (RFP). The SSI proposal requested financial support for the research and development of an innovative process for growing silicon crystals that could provide energy and non-energy benefits to SSI and to other silicon crystal-growing firms in the solar, semiconductor and microelectronics industries.

The Alliance Board of Directors agreed to provide $1,000,524 to fund the project, with equal funding coming from SSI. The contract was signed and the project began in April 1998. Project implementation proved very successful. Modifications to the hot zone were largely completed in 1998. The hot-zone modifications met most of the goals for the project, but they also reduced the capacity of the crucible, leading to a request for continued support as SSI developed a hot top-off recharge process to enable expanded crystal growth.

The recharge activities also proceeded successfully and in August 2000, the contract for the project was allowed to lapse.[1] During the contract period, all internal project goals were achieved or exceeded, with the market transformation goals still in the process of evolving. Table 1 displays the goals and achievements for the project.

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1 Memo from Blair Collins to Margie Gardner, August 7, 2000.

Table 1

PROJECT GOALS ACHIEVEMENT

GOALS	ACHIEVEMENT
Reduce power consumption by 40% per run (kWh/kg)	Reduced power consumption by 51% per run (kWh/kg)
Reduce argon consumption by 50% perrun (cf/kg)	Reduced argon consumption by 85% per run (cf/kg)
Increase productivity by 15% (mm/day)	Increase productivity by 20% (mm/day)
Improve or maintain the quality of ingot produced	Improved quality 5% higher valued solar cells, better axial Oi
Transform the market place, specifically, semi-conductor crystal growers in the Pacific Northwest, into lower consumers of power and argon	Business-to-business marketing. Active dialogue and demonstrations with Mitsubishi Silicon America and Wacker-Siltronic. A new Alliance project with Advanced Silicon Manufacturing Inc. was initiated in 2001 to develop lower power consuming polysilicon feedstock materials.
No yield goal set	Achieved 5% higher yields

EVALUATION APPROACH

In 1998, the Alliance contracted with TecMRKT Works to conduct an evaluation of the SSI Solar project. The first market progress evaluation report (MPER) was completed in August 1999. The first MPER focuses on project start-up and market perceptions of the project during the first year of implementation. A summary of that report is provided below.

In November 2000, the Alliance contracted with Research Into Action, Inc. (RIA) to continue the evaluation of the venture. The purpose of this second MPER is to update the history of the project and assess market response to the project in early 2001.

The evaluation method includes review of Alliance and SSI reports and briefing materials, as well as interviews with key silicon crystal growing firms in the Pacific Northwest and suppliers of polysilicon materials and crystal growing equipment.

Interview guides are provided in Appendix A and a list of contacts is provided in Appendix B. Table 2 displays the number of interview contacts per category.

Table 2

INTERVIEW CONTACTS

ACTIVITY	CONTACTS
Alliance and SSI staff	3
Crystal Growing Equipment	2
Polysilicon materials	2
Silicon crystal growing companies	2

In addition, we conducted a limited patent search of patent applications for hot-zone modifications and hot top-off recharge modifications. The purpose of this patent search was to determine whether any modifications similar to those implemented by SSI had been patented.

The interviews with SSI and Alliance staff began in February 2001. The interviews with industry contacts were conducted in April and May 2001.

The economic context surrounding the interviews, it should be noted, is quite different than that for the first MPER. In summer 2000, California energy consumers began to experience price shocks and rolling brownouts and blackouts resulting from an electricity supply shortfall and the increased cost of natural gas. These price shocks continued into the winter. By May 2001, the entire West Coast anticipates electricity shortages and price increases due to supply constraints. These price shocks and supply shortfalls are expected to last for multiple years and have made energy, and specifically electricity consumption, a serious issue for each of the firms we spoke with.

SUMMARY OF THE FIRST MPER

The first MPER[2] focused on a characterization of the market during the project's early stages, before influence had begun, and on the technical goals of the project. The MPER provides a fairly detailed description of the hot-zone modifications and includes the results of interviews with 26 industry contacts.

Within the first year of the project, SSI had achieved or nearly achieved several of its goals:

- Power consumption had been reduced 51%
- Cycle times had been reduced by 20% to 40%
- Argon flows had been reduced by as much as 85%
- Crystal growth yields had been increased by 4%
- Pot scrap at the end of the run had been cut from 4 kg to 1 kg
- Amperage output per wafer showed a 4% to 6% improvement
- A recharge system was being developed to increase the number of ingots that could be pulled from a single growth
- SSI had committed to implementing changes on all growers at their Vancouver facility.

The opportunity for market transformation, however, rested on whether the quality of the silicon ingots produced by the SSI project could be equivalent to semiconductor-grade ingots.

Specifically, the MPER reported that:

- The grower hot-zone modifications were not new and had been adopted by many other companies already where possible; furthermore, these modifications were not applicable to all growers.

2 Reed, John H., Andrew d. Oh and Nicholas P. Hall (1999). *Market Progress Evaluation Report: Silicon Crystal Growing Facilities, No. 1 (E99-034).* Northwest Energy Efficiency Alliance.

- Due to the different types of growers in use, industry contacts reported they would selectively implement the innovations based on their own needs and processes.
- The recharge process looked promising and could be widely adopted.
- Data on the quality of the ingots is needed by firms to determine the impact of the modifications.
- The business-to-business approach used by SSI to introduce other firms to the project is effective and firms who had been briefed on the project were impressed.
- If the results were published using technical benchmarks, they could be more widely considered.

Several recommendations were provided based on these results. The recommendations included:

- Continued support for the recharge process
- Encouragement to obtain purity tests on ingots from other crystal-growing firms.
- Continued presentation of results and business-to-business marketing, as well as possible development of additional formats for presentations to appeal to different audiences.
- Consideration of a project to demonstrate the transferability of the results to semiconductor-grade crystal growing.

STRUCTURE OF THIS REPORT

This report contains three additional chapters. Chapter 2 documents the progress of the SSI project in 2000, as well as their future plans. Chapter 3 documents the industry's response and the results of our patent search. Chapter 4 presents an assessment of project progress relative to the indicators identified by the Alliance, and provides our conclusions and recommendations.

1. Introduction

2. PROJECT PROGRESS

OVERVIEW

This chapter reviews the technology of crystal growing, the history of SSI's interest in working with the Alliance, and the status of the project during its three-year funding cycle.

THE CRYSTAL GROWING PROCESS

The process by which silicon becomes a wafer for use in electronic equipment, or for solar photovoltaics, begins with the feedstock – polysilicon. Polysilicon is manufactured through an energy intensive process that begins with metallurgical-grade silicon. The process hydrogenates and distills the metallurgical-grade silicon to silane, which is then used to create rods of electronic-grade polysilicon.[3] The rods are broken into chunks for use in the crucible.

The most common crystal growing process, the Czochralski (Cz) method, uses a seed crystal of silicon dipped into the melted polysilicon chunks in the crucible. Melted polysilicon deposits on the seed and the crystal is pulled from the crucible until the polysilicon material is consumed, the impurities collect at the tail of the pull resulting in a very pure silicon crystal.[4] The size of the pulled crystal is primarily limited by the volume of polysilicon that can be melted in the crucible during the period of the crystal-pulling process.

SIEMEN'S GOAL FOR THE PROJECT

As noted in MPER 1, the solar market is a small proportion of the total market for silicon crystals, accounting for only 5% of all the single silicon crystals grown. The SSI silicon crystal growing facility is the world's largest silicon growing facility

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3 This link provides an excellent overview of the polysilicon manufacturing process used by AsiMI: http://www.asimi.com/polytech.html

4 This link provides an excellent overview of the silicon growing process: http://www.techfak.unikiel.de/matwis/amat/elmat_en/kap_5/backbone/r5_1_2.html

solely devoted to the solar photovoltaics industry. Most solar manufacturers purchase their silicon crystal ingots from semiconductor silicon manufacturers. Thus, SSI is in the unique position of being able to publish information about its technology without affecting any direct competitors. If SSI achieves advancements in silicon growing activities, these advancements have the potential to be made more widely available than would normally occur in the industry.

This situation led SSI to propose a project to the Alliance in 1997 to reduce energy consumption in the crystal-growing process. The initial project focused on modifications to the hot-zone and the argon gas usage in the crucible. The hot-zone and argon modifications were successful and were completed within the first year of the project. However, the modifications to the hot zone reduced the volume of crystal that could be produced in a single run. The crystal growing staff at SSI was aware that some semiconductor crystal growers use a technique called recharge that enables them to increase the length of the crystal pulled during any single run. SSI explored this process and identified a procedure to test. The Alliance agreed to support SSI's efforts to develop a viable recharge process.

PROJECT PROGRESS

At the end of 1999, SSI had successfully demonstrated the ability of a recharge process using a feeder system and polysilicon rod. Yield and throughput in the experimental runs had been very promising, with one run achieving an 88% yield and productivity of 41 mm/hour, compared to average non-recharge runs with yields of 76.2% and 31 mm/hour.[5]

With the successful experimental runs, SSI also began exploring the use of granular polysilicon in place of polysilicon rods broken into chunks. Granular polysilicon (GPS) offered several advantages: the manufacturing process is less energy intensive than for polysilicon rods and the labor costs involved in converting rod to chunk would be eliminated. In addition, with the emergence of larger 300-millimeter ingot diameters as the anticipated growth area for the semiconductor industry, GPS is viewed as the optimum feedstock for larger diameters, especially for recharge, if it can be demonstrated.

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5 Mihalik Greg and Bryan Fickett 2000. *1999 Annual Report*: Efficiency Opportunities in Silicon Crystal Growing Facilities. Redesign of Crystal Grower Hot Zones (00-050). Northwest Energy Efficiency Alliance.

Project Activities in 2000

In 2000, SSI was able to successfully implement the recharge process using GPS. Twenty-four crystal-growing furnaces were fully retrofit with the hot-zone and recharge systems by the end of 2000. During 2001 and 2002, an additional 31 units are planned for conversion.

The conversion process focused first on new growers, then on 14-inch growers. The 16-inch growers will be done last, as there are additional costs due to the different geometry of the larger crucible.

Internal studies by SSI, as well as others by third parties, found the ingots to be of high enough quality for semiconductor use.

The project-specific results have been much greater than anticipated:

- A 51% reduction in power consumed to make one kg of a 155-mm diameter ingot.
- A reduced payback ratio of gross energy consumed across both direct and indirect materials from 3.3 years to 2 years.
- Productivity increased due to a reduction in the time required to clean and cycle the crucible, reduced from one turn per day to one turn per seven days. (The recharge process allows a pull to last seven days instead of one.)
- A 85% cf/kg reduction in argon use. (Argon is a greenhouse gas.)
- Increased yield through reduced post-pull scrap materials, and more defect-free ingots.
- A reduced number of crucibles consumed per month from 250 to 50.

Market Activities in 2000

Market efforts also proceeded well during 2000. Beginning in 1999, SSI crystal growing staff began submitting papers and making presentations about the project. Five papers were presented at conferences including *IEEE Photovoltaic Specialists Conference 28th* (2000), *Crystal Growth 211* (2000), *American Association for Crystal Growth and Epitaxy 11* (1999), and the *Ninth* and *Tenth Workshops on Crystalline Silicon Solar Cell Materials and Processes*, NREL (1999 & 2000). One article was published in *Fabtech 10th Edition* (1999).

Business-to-business meetings were held at SSI with several local semiconductor-grade crystal growing firms including Wacker-Siltronic, S E H, and Mitsubishi Silicon America. The purpose was to introduce these firms to the project and provide a tour of the crystal growing facility.

By all accounts the business-to-business meetings were the most effective way to reach other crystal growers. In at least one case, the semiconductor firm had not heard about the project and sent a variety of staff to the meeting, including facilities and crystal growing staff. While the facilities staff found the meeting relatively useless, the crystal growing staff was enthusiastic and intrigued by the presentation, and they are continuing to work with SSI.

Future SSI Activities

SSI is continuing to convert crystal growers with the hot-zone and hot-top-off processes. SSI is also offering to license the processes to other companies and permits them to market them as they see fit.

The next activity emerging from this project concerns the polysilicon feedstock. Granular polysilicon (GPS) proved to be the most effective recharge material tried by SSI. However, MEMC Electronic Materials, Inc. is the sole manufacturer of GPS. MEMC consumes about 90% of the GPS for their own wafers when the market for semiconductor wafers is good. As a consequence, SSI and other crystal growing companies are hesitant to make a commitment to purchase MEMC's GPS. If another company manufactured GPS, the use of GPS for recharge would increase. Furthermore, the manufacturing process for GPS consumes less energy than the process for making polysilicon rods, resulting in lower energy costs for the entire process.

SSI will be working with a PNW supplier of polysilicon (Advanced Silicon Materials Inc., ASiMI) to test a new dendritic polysilicon product in their recharge process. The dendritic polysilicon product is a step toward GPS, and if successfully developed may result in ASiMI being able to produce GPS.

SUMMARY

SSI successfully completed their project with the Alliance in 2000. All project targets that were internal to SSI were achieved and efforts were taken to increase market awareness and familiarity with the project.

SSI estimates that they saved 6 million kWh between February 1999 and February 2001. With current monthly savings at about 45,000 kWh, annual savings could be as high as 500,000 kWh.[6]

6 Mihalik, Greg and Bryan Fickett 2001. "Efficiency Opportunities in Silicon Crystal Growing Facilities: Redesign of Crystal Grower Hot Zones" *2000 Annual and Final Report*. (pp 2.)

2. Project Progress

3. INDUSTRY ACTIVITIES

OVERVIEW

In this chapter we discuss the response by PNW semiconductor crystal growing firms to the SSI project, discuss perceptions by manufacturers of interest in the recharge modifications, discuss response by PNW semiconductor crystal growing firms to the pending ASiMI dendritic polysilicon project, and present results from a limited patent search.

INDUSTRY RESPONSE TO THE SSI PROJECT

The market transformation theory of the SSI crystal growing hot-zone and recharge modifications is that SSI can and will make the changes to their process public, and thus influence semiconductor crystal growers to make similar changes to their processes.

We spoke with staff from three semiconductor-grade silicon crystal growing companies located in the Pacific Northwest. All three of these companies are aware of the SSI project. Their staff have visited the SSI facility, been provided with copies of the data and reports on the project, and have continued to have contact with staff at SSI since the initial meetings.

In general, all three crystal growers find the results of work at SSI "intriguing." Two of them noted that the hot-zone modifications were very similar to things that had been done by semiconductor firms already; one thought the modifications were nearly identical to a patent they were aware of. All three have some skepticism about direct transferability of the hot-zone modifications. They believe that the materials used in the hot-zone modification could affect the purity of semiconductor-grade silicon and therefore the effects may be difficult to replicate.

The recharge process is the most interesting aspect. As with the hot-zone modifications, all three have some skepticism about direct transferability of the recharge process. As discussed above, they also believe that the recharge process could affect the purity of semiconductor-grade silicon. One noted that MEMC has been doing recharge for eight to ten years using GPS. Though their wafers are high quality, their GPS product has not been of good enough quality to warrant others using it. Tests using it were not satisfactory. Also, there is a problem with competitive supply. MEMC currently sells their recharge equipment to try to increase use of GPS. Yet for these three contacts, the fact that there is only one supplier of GPS limits their willingness to try the GPS recharge process.

One of the contacts noted that they believe that SSI uses a lower grade of GPS than a semiconductor firm would use. This was also suggested by MEMC. Access to a steady supply of electronic-grade GPS, as well as the development of recharge equipment that could assure the levels of purity required, would be necessary before any of these firms will increase their use of recharge. However, two of three indicated that they were experimenting. One noted that they are also looking at the hot-zone modifications, as they may facilitate the recharge process, though he doubted that it would be possible to get as much out of the recharge process for semiconductors as for solar.

Two of the three contacts noted that this is a good time to be working on these changes.

- First, the semiconductor industry is confronting increased energy costs; thus it is a good time to consider changes that will reduce these costs.
- Second, and perhaps most important, changes to the hot-zone and recharge systems are best made when a process is first being developed. The move to manufacture 300mm crystals for wafers is just beginning. As new crystal growers are put in place, it is likely that especially those familiar with the SSI project will adopt hot-zone modifications and recharge activities.

These contacts all think that the experience of SSI provides a benchmark and will inspire semiconductor-grade silicon growers to attempt to do the same thing in order both to keep energy costs down and to increase the material that can be manufactured in one pull.

MARKET INTEREST IN THE RECHARGE EQUIPMENT

We spoke with a representative of Kayex, the manufacturer of the growers used by SSI in their crystal growing process, and JAX Industries, an Oregon machine shop that manufactured the system used for the recharge modifications.

Kayex manufactures around 50% of the growers purchased commercially. They also manufacture an add-on for their growers to permit recharge using chunk polysilicon. The main barrier to use of their recharge system is its cost. Kayex, however, is considering a new design based on some of what they learned in working with SSI on the recharge and hot-zone modifications. This new design will likely have a lower cost.

JAX Industries is a small specialty research and development machine shop that focuses on high-tech companies. They are located in Oregon and have many contacts with semiconductor and other high-tech companies. JAX Industries designed and manufactured the recharge unit SSI uses. The company would like to sell the recharge unit over the Internet. They will be attending a crystal growers' conference in 2001 to demonstrate their product and see if they can obtain some interest. They do not currently have any production-line units, but would like to see this product take off.

The barrier to recharge from the view of both of these equipment manufacturers is similar. Fundamentally, the recharge process developed by SSI is perceived to be primarily applicable to the solar industry. Current interest is highest among Kayex's solar crystal growing customers, with a firm in the Ukraine and a firm in India either pursuing modification on their own or seeking to license the process from SSI.

Semiconductor firms typically express concern that the recharge process, such as that used by SSI, has not been demonstrated to result in a high enough quality ingot for them to pursue. Kayex noted that semiconductor firms typically do some recharge, but not on the scale done by SSI. Since recharge processes usually use rod or chunk polysilicon, the crucibles tend to be damaged after one to three recharge runs. While MEMC can demonstrate a high quality recharge process using GPS (and sells recharge equipment for GPS), few companies are willing to commit to purchase GPS and the recharge equipment because of lack of competitive supply.

JAX Industries noted that their focus is on the mechanical issues. If chemical questions arise regarding the purity of the product as a result of the recharge equipment, they are not necessarily able to answer those concerns. The semiconductor industry focus is on product quality and purity. This means that sales to the semiconductor industry are likely to be slow for JAX.

Kayex also noted that with the increased focus on energy costs, there would likely be additional modifications to the growers by different manufacturers. Currently energy-efficient options are available, but they are rarely purchased. With the SSI results and the increased energy costs, the demand for these more energy-efficient growers is likely to increase.

INDUSTRY RESPONSE TO THE DENDRITIC POLYSILICON PROJECT

All of the companies we spoke with were aware of, and enthusiastic about, the dendritic polysilicon project being funded by the Alliance in 2001-2002. They all have a high confidence that dendritic polysilicon will be produced. If the dendritic polysilicon can be provided at high enough purity, then it has some potential for recharge for semiconductor crystal growing. However, most of the contacts believe that the larger market is for solar crystal growing.

One company noted that there are at least five companies with which they are familiar who are trying to develop a lower-cost feed stock for the solar industry. The dendritic polysilicon is viewed as more likely to fit that niche.

Silicon rod remains the comparison feedstock for the semiconductor industry. Its low surface area means that contamination is less likely. The higher surface area to volume of both GPS and dendritic polysilicon mean contaminants are more likely. The need, however, for a better feedstock for recharge and the desire to expand the number of suppliers has all contacts supportive of the project.

With two of the three largest semiconductor silicon growing companies in the world (Wacker-Siltronic and S E H) participating in the Alliance project, success could lead to significant changes in the industry worldwide.

SILICON CRUCIBLE PATENT SEARCH

We undertook a narrowly-focused search of World Wide Web (www) sites to determine whether any individuals or corporations had filed patent claims which modified exiting single silicon crystal growth processes or apparatus used in the Czochralski (Cz) method. Sites searched and the terms used in each site's search engine are included in Appendix C.

Description of the Search Process

To conduct the search we identified five modifications to target. These modifications included:

- Adding insulation to the crucible apparatus or "hot zone."
- Isolating any part of the crucible or hot zone to minimize or prevent conduction or convection of heat away from the zone.
- Adding a shield at the top of the apparatus.

- Adding or modifying any method designed to introduce silicon pellets or other raw silicon into the melt chamber.
- Changing the flow path of argon gas.

Search Results

Each of the modifications could be researched in greater depth. The "first pass" through the search sites revealed that each of the subject areas has interested some manufacturers, though no single patent filing appears to have approached all of the subject areas comprehensively. Additionally, none of the identified patent filings state an interest in making modifications to the process or apparatus with the express intent of conserving energy.

Several patents claim changes to the insulation of the crucible wall, describe designs doubling the chamber construction (Sumitomo Sitix Corporation US5919306), or make claims relating to addition of thermal layers or external heat-regulating elements situated about the crucible (Sumitomo Electric Industries US5733371).

None of the patents we found introduce a top to the shielded portion of the crucible apparatus.

We identified patents on a variety of materials handling systems for the introduction of silicon into the crucible area. Methods such as conveyors, hoppers and evacuated (vacuum coupled) canisters have been considered since at least the late 1970's (Siltec Corporation US4036595). Ebara Solar of Large, Pennsylvania, filed a claim for a silicon pellet feed system in early 1997 (US5997234). Since no design deals with the issues of placing a top on the crucible area, we could not tell if any of these attempts to recharge the silicon in the melt were similar to the SSI redesign.

Several modifications to gas flow and path are available, but time did not permit a thorough study to determine if the filings are similar.

We also examined US Patent Class 117, which is concerned with processes and apparatus used in the production of ingots or crystals of silicon. No one filing appears to have approached all of the SSI subject areas comprehensively. We found 15 patents with some relevance to the SSI modifications. Eleven of these are similar to each other in that they all possess elements of basic crucible construction. Four offer some form of double crucible construction that related to: 1) insulation of the crucible, and 2) options for feeding the melt.

Eight patents turned up which may have bearing on production efficiencies. However, the primary claim in each is concerned with end-product quality not process efficacy. The claims center on ingot shape, application of magnetic fields to stabilize crystal growth, adjustments to the rotation of the crucible, and changes to the pulling operation. None of the selected filings claim the modifications to process or apparatus are proposed to conserve energy. Table 3 displays the patents in Class 177 that could be relevant to the project.

Table 3

US PATENTS FOR CLASS 177: SILICON CRYSTAL GROWTH PROCESSES & APPARATUS THEREOF

DIRECT INTEREST [COPIED]	DOUBLE CRUCIBLE FEED MECHANISM	NOT DIRECTLY RELEVANT	UNSURE OF RELEVANCE
4036595	5021118	5868835	5948163
5471943	5873938	5858087	5895527
5474022	5871581	5948163	
5683507	5779792	5882398	
5720809		6007625	
5733371		5938836	
5900055		5876495	
*5919306		5779791	
5954875			
*5968261			
5997234			

Patents with Similar Approaches

US Patent 005919306 proposes a change to basic crucible construction by adding a U-shaped carbon ring "inserted into an upper portion of the quartz crucible and the carbon crucible capping both of them." This patent granted in July 1999, to Sumitomo Sitix Corporation of Amagaski, Japan, is the only one found which mentions any type of cap or top modification to the crucible. It also proposes a double crucible structure, which in other instances (not this patent) suggests a thermal insulating quality and opportunities for feeding the silicon melt.

US Patent 005968621 from October 1999, granted to Northrop Grumman Corporation of Los Angeles, California, is of interest because it mentions placement of an “insulating jacket around said crucible” in its first of six claims.

Of the patents that claim to make changes to the crucible wall or that describe designs doubling the chamber construction, several mention a method where the melt is fed from the outer crucible to the inner crucible. Such a modification may relieve the need for any type of hopper, conveyor, or chute to introduce silicon pellets to the main crucible.

Summary of Limited Patent Search

This limited look at recent patent filings for modifications to the process and/or apparatus used in silicon crystal growth yielded no one filing that addressed all of SSI’s proposed changes. It did turn up evidence that interest in insulating the crucible or using thermal controls around the melt apparatus is common in the industry.[7]

Continuing effort in the crystal growing sector toward improving the nature of continuous crystal growth process and apparatus is evident.

The focus on Class 117 revealed two patents that incorporate some aspect of the SSI modifications. One locates a carbon ring at the top of a double crucible, though the claimant does not specifically state that the cap is useful for thermal insulation of the hot zone. The second proposes a jacket to insulate the crucible and does not state that the insulation is placed to aid energy conservation.

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7 This search was limited to information available from the Internet. It is further limited by factors attributed to use of site-specific search engines. In the effort to look at Section 117 patents, we attempted to investigate applications for patents filed with the United States Patent Office (USPTO). In order to preserve the confidentiality of claims that are being processed, the office does not disclose information about application filings while they are pending review. It appears that a two-to-four year turn around can be expected between the time an application is filed and a patent is granted. A more comprehensive search would disclose the specific limitations of those search engines and would not rely upon one source (the Internet) for answers.

SUMMARY

The industry contacts are enthusiastic about the SSI project. They see the project as having demonstrated some striking results. However, they are uncertain as to whether the project will translate to the semiconductor industry.

The solar industry has many factors that make it different. The purity requirements are lower, the solar companies are forced to keep costs low so they do not pursue high purity options, nor do they use as high a quality feedstock as semiconductor firms. This makes all the contacts we spoke with, while enthused, unwilling to commit as to how far they think changes in the semiconductor industry will go.

Contacts also noted that much of what SSI did, had been demonstrated before, though on a lesser scale and with less dramatic results. Yet they all note that the lengths SSI was able and willing to go with these modifications exceeded what had been done before and demonstrated to other silicon crystal growing firms that more is possible. They see this effort as providing a benchmark for semiconductor-grade silicon growing firms to strive toward.

The availability of a feedstock for use in recharge appears to be a real hurdle that all of the contacts believe must be overcome for the semiconductor silicon crystal growing industry to more willingly experiment in the same way SSI did.

There appear to be three components that will facilitate the market transformation of the semiconductor silicon crystal growing industry to adopt the SSI results:

- The Alliance funded dendritic polysilicon project is important because it may provide a viable feedstock for recharge.
- The move to 300mm crystal growing will open the door for experimentation and attempts to develop hot-zone and hot-top-off solutions similar to those developed by SSI.
- The Alliance encouraged active communication between semiconductor-grade silicon crystal growing firms located in the PNW and SSI, and SSI's active promulgation of their experience at industry forums has led to a transfer of information that would not have happened otherwise.

4. ASSESSMENT OF PROGRESS CONCLUSIONS AND RECOMMENDATIONS

OVERVIEW

This section provides an assessment of the progress to date relative to the Alliance's definition of success and progress indicators, and presents our conclusions and recommendations.

ASSESSMENT

The project definition of success as published at the Alliance project website[8] is:

> Successful development and demonstration of new efficient furnace technology followed by retrofitting all of the furnaces at the current Siemens facility. Adoption of the energy saving technologies created by the project into existing and future semiconductor grade silicon ingot manufacturing plants region-wide.

The progress indicators identified at the project's inception, and located at the project coordination website, are presented below. We have included an assessment of achievement relative to each indicator for the project period.

- Development of an accurate modeling tool for current and future hot zone designs.
    - Successfully completed at the end of 1999.

- Successful design of a more efficient hot zone that meets or exceeds the technical criteria (reducing the furnace hot-zone energy consumption by at least 40%, reducing cycle-time by at least 15%, reducing argon consumption by at least 50%, while improving or maintaining ingot quality).
    - Successfully completed at the end of 1999.

8 http://nwalliance.org/coordination

- Successful construction of the new hot-zone design.
  - Successfully completed at the end of 1999.

- Installation of all new and retrofitted hot zones within the Siemens facility.
  - At the end of the project, SSI has retrofit all of the furnaces in their plant with the hot-zone modifications. The process is continuing in 2001 with the recharge modification, plans are to complete the retrofit all 14-inch crucibles in 2001, and 16-inch crucibles as soon as possible.

- Industry-wide dissemination of project results, in conjunction with furnace manufacturers.
  - SSI presented papers at five international conferences, published one article in an international journal for the semiconductor industry, and held business-to-business meetings with three large semiconductor grade silicon crystal growing firms located in the PNW.

- Adoption of the optimization methods used in the Northwest plants of one or more semiconductor manufacturers.
  - Adoption of the energy savings technologies in semiconductor grade silicon ingot manufacturing plants region-wide is possible, but is limited by three factors:
    - Semiconductor firms doubt the purity can be maintained using the SSI methods.
    - Semiconductor firms need access to a commercially-competitive polysilicon feedstock that will work with the recharge process.
    - Semiconductor firms are reluctant to make changes to processes that already work well for them.

    The Alliance is currently working to address the first two of these factors. First, the Alliance provided funding to SSI for independent tests of the purity of the SSI ingots. These tests were conducted by several independent testing labs. The results were very good and suggest that the process is producing high-grade quality ingots. Testing by semiconductor wafer manufacturers will be necessary to obtain their concurrence in these results.

Second, the Alliance is funding a project with ASiMI to develop a dendritic polysilicon feedstock. SSI and two local semiconductor grade silicon crystal growing companies are going to be involved in testing and using the feedstock.

Finally, semiconductor grade-silicon crystal growing firms anticipate that the technological experience of SSI will affect their development of 300mm crystal growing processes more than change their current procedures. They are just now beginning to move into 300mm crystal growing. The SSI project provides a benchmark for these firms. The next five years will see a move to 300mm crystals and likely incorporation of these ideas.

CONCLUSION

Siemens Solar Industries (SSI) estimates that they saved 6 million kWh between February 1999 and February 2001. With current monthly savings at about 45,000 kWh, annual savings could be as high as 500 MWh. These savings, plus the achievement of all internal project objectives, demonstrate that the SSI Silicon Growing Hot Zone Modifications Project has successfully met all of its internal objectives during the project time period. The market transformation objectives, however, are still being realized.

On their own, the semiconductor firms in the PNW have implemented many process improvements to the hot zone and have developed their own recharge processes. But the SSI improvements demonstrate opportunities that these firms have not independently achieved. These firms now have a benchmark to strive towards. Adoption of these improvements however, is not assured. There remain several specific barriers to adoption as noted above:

- Semiconductor firms doubt crystal purity can be maintained.
- Semiconductor firms need access to a commercially competitive polysilicon feedstock for recharge.
- Semiconductor firms are reluctant to make changes to processes that already work well.

The Alliance dendritic polysilicon feedstock project is an effort to increase the potential for market transformation resulting from the SSI project. An important step will be to monitor the interest in, and awareness of, the SSI process by PNW semiconductor-grade silicon crystal growers over the next three to five years. During this time period they will be converting to 300mm silicon crystal growers and participating in the dendritic polysilicon feedstock project. This time period should help clarify the degree of adoption of the SSI process that does occur.

RECOMMENDATIONS

1. Continue to monitor semiconductor-grade crystal growers' awareness of and interest in the SSI results.

The project met all internal goals during the project time period. Market transformation goals, however, are still being achieved. Contacts with silicon crystal growers in the PNW indicate that initial efforts to reach the market appear to have been effective. The monitoring should continue as the industry moves towards increased production of 300mm silicon crystals and response to the energy price increases.

2. Monitor semiconductor-grade crystal growers' and equipment manufacturers' awareness of, and interest in, the dendritic polysilicon feedstock project.

The SSI project began with a focus on hot-zone modifications and then expanded to include recharge to the hot zone with a hot-top-off process. Both of these efforts were successful. However, a market barrier was then identified to adoption of the recharge process. The Alliance has therefore funded a project to develop a more satisfactory polysilicon feedstock for this purpose.

The semiconductor silicon crystal growing industry claims that this feedstock could improve their ability to implement a recharge process similar to that developed by SSI. It will be important for the Alliance to monitor response to the dendritic polysilicon feedstock project to assess market response. Market response may come from other feedstock manufacturers or other manufacturers of crystal growing equipment, as well as semiconductor and solar-grade silicon crystal growing companies.

3. Consider providing support to JAX Industries to develop a business plan for marketing the recharge equipment and obtain chemical engineering support to address semiconductor industry concerns for impacts on product purity.

JAX Industries will likely not be able to move to production of the recharge equipment without substantial capability growth. They do not have a business plan, they have not conducted a market assessment, they do not have the chemical engineering capability to address semiconductor firm concerns with purity, and they have limited contacts in the semiconductor crystal growing industry. The Alliance could provide support to JAX Industries to develop some of this capability, thus increasing the probability that PNW semiconductor firms will have access to the recharge modifications developed for SSI.

4. Consider providing a local semiconductor silicon crystal grower with support to test the integration of the SSI experience into their development of 300 mm crystal growing processes.

All three contacts from the local semiconductor grade silicon growing firms we spoke with expect to incorporate the SSI experience into their development of 300 mm crystal growing processes. However, it is uncertain how far they will be willing to go. If one of the firms is willing to consider a bold test of hot zone modifications and recharge using a variety of polysilicon feedstock, the Alliance may want to consider supporting this project.

7. Assessment of Progress Conclusions and Recommendations

APPENDICES

APPENDIX A

Interview Guides

Appendix A

SIEMENS SOLAR EVALUATION
INTERVIEW GUIDE FOR INDUSTRY MEMBERS

Date ________________________

Name ____

Company ____

Phone ____

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1. What is the nature of your company's business and what aspects of the silicon crystal growing process is your firm involved in?

2. Were you aware of the Siemens Solar research and development project? If so, when and how did you learn about the Siemens Solar recharge and hot top-off and hot zone crucible (shielding, insulation, argon) modifications?

3. What was your initial reaction to these modifications?

4. Has your perception of these modifications changed? If so how?

5. Have you considered incorporating any of the findings from the Siemens project into your business? If so, what changes are you considering and what is the likely hood of their implementation?

6. Within the bounds of confidentiality, what type of response have you had from other silicon growing firms?

7. What type of response do you anticipate in the next year?

8. How do you anticipate these products evolving over the next two to five years?

9. Are you aware of how the Siemens Solar research project was funded?

10. Have you heard of the Northwest Energy Efficiency Alliance?

SIEMENS SOLAR EVALUATION
INTERVIEW GUIDE FOR ALLIANCE STAFF

Date ______________________

Name ______________________

Company ______________________

Phone ______________________

Who should we talk to at S E H?

1. What do you think will be the major benefits of the Siemens' Solar project?

2. What have you done to promote or publicize the project?

3. Is your perception that Greg and Brian knew they would need to try to include recharge in their project at the outset, or was that an evolving idea? If evolving, what led them to recharge?

4. What is your perception of the difference between solar-grade silicon ingots and semiconductor-grade ingots?

5. How much recharge and hot zone insulation do you think is commonly done in the semiconductor industry silicon growing process?

6. What type of response have you had from other silicon growing firms?

7. What is the purpose of the ASIMI project?

8. Why do you believe that the materials produced by ASiMI can work for the semiconductor industry?

9. What type of response have you had from other silicon growing firms? Has the response been different since the energy crisis hit?

10. What type of response do you anticipate in the next year?

11. What other projects do you anticipate will be needed to make the market transformation work?

APPENDIX B

List of Contacts

Appendix B

LIST OF CONTACTS

Blair Collins, Northwest Energy Efficiency Alliance

Alan Cox, JAX Industries

Howard Dawson, ASiMI

Byan Fickett, Siemens solar Industries

Jameel Ibrahim, MEMC

Tom Kurassch, Wacker-Siltronic Corp.

Greg Mihalik, Siemens Solar Industries

Haresh Siriwardane, Mitsubishi Silicon America

Robert Stevenson, Kayex

Darren Tai, S E H

APPENDIX C

Silicon Crucible Patent Search Criteria

Appendix C

SILICON CRUCIBLE PATENT SEARCH CRITERIA

World Wide Web Search of the Following Sites:

- United States Patent and Trademark Office: Patent Bibliographic Database
- IBM Intellectual Property Network
- Siemens Process News
- Semiconductor Subway
- Semiconductor Supersite
- SEH America

Search Terms – *used singly and in combination with each other*

Silicon:

- Crystal Processing
- Crystal Manufacturing
- Pellets
- Single Crystal
- Crystal Growing
- Materials Recharge

Growth Methods:

- Czochralski (Cz)
- Horizontal Magnetic Cz (HMCZ)

- Heat Exchanger Method
- Liquid Encapsulated Cz (LEC)

Patent Classes and Subclasses

- 110 - Furnaces
  - 110-110 Doors and Casings
- 293 - Supply Hoppers and Magazines
- 117 - Single Crystal, Oriented Crystal and Epitaxial Growth Processes and Non-Coating Apparatus
  - 117-200 Apparatus
  - 117-900 Apparatus Characterized by Composition or Treatment Thereof
- 198 - Power-driven Conveyors
- 414 - Material or Article Handling

Principal Corporate Filers

- *Ebara Solar*, Large, Pennsylvania, USA
- *Komatsu Electronics Metals*, Japan
- *Shin Etsu Handotai Company, Ltd.*, Tokyo, Japan
- *SEH America*, Vancouver, Washington, USA
- *Siltec Corporation*, Menlo Park, California, USA
- *Sumitomo Electrical Industries*, Osaka, Japan
- *Sumitomo Sitix Corporation*, Amagasaki, Japan