PRODUCTION VIABILITY OF GALLIUM DOPED MONO-CRYSTALLINE SOLAR CELLS

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ABSTRACT

Results of efforts at Shell Solar to implement the use of gallium dopant as a commercial solar cell production process are presented. Both small area cell results and production related activities and results are discussed. Many researchers have demonstrated that gallium effectively eliminates light induced degradation (LID) of the bulk lifetime, but less effort has been dedicated to implement gallium dopant into a commercial production process. Shell Solar has worked in this direction and expanded past research activities to demonstrate that the full range of resistivity values produced from a gallium-doped crystal can be used to successfully fabricate high efficiency cells. In addition, Shell has produced significant numbers of gallium-doped cells in their production facility and characterized process results from crystal growth to module build. This paper discusses additional subjects essential to production viability, such as gallium metal availability, silicon feedstock availability and management specific to a gallium process and overall cost effectiveness.

INTRODUCTION

Today's mono-crystalline solar cells are typically manufactured on silicon wafers doped with boron. While boron has the advantage of providing minimal resistivity variation in the grown crystal, it brings with it a significant disadvantage for solar cell performance. Boron, paired with oxygen, creates a defect, which causes a bulk lifetime degradation when the solar cell is exposed to light [1]. Light Induced Degradation can reduce a solar cell's efficiency by 2 to 5% (relative). Many efforts have been made to eliminate, or at least minimize, this light induced degradation [2,3,4]. Since both the dopant and the oxygen are added during crystal growth, many of the efforts to overcome the LID effect involve changes to the crystal growth process. The strategy of these efforts has been to lower the concentration of either the oxygen or the boron through a variety of techniques. These techniques include Magnetic Confined Czochralski (MCZ) to lower the oxygen content, use of float zone substrate to eliminate the oxygen, a higher resistivity target to lower the concentration of boron and N-type substrate to eliminate the boron. One of the more promising methods is to use gallium, which is an alternate P-type dopant, to totally eliminate the boron [5]. Most of the recent investigation of the use of gallium as a dopant has characterized the LID effect and the electrical performance of the solar cell. Once these technical challenges are met, there remains major cost and logistical hurdles to implement the gallium process into a production operation.

METHODOLOGY

Successful implementation of a commercial gallium-doped solar cell process hinges largely on one factor: cost. If the use of gallium as a dopant does not reduce the $/Watt of the final product, there is no compelling reason to develop the process. A reasonable first impression of the technology is that it can reduce cost simply by eliminating the LID and boosting final power output by 2 to 5%. There are, however, substantial cost disadvantages, which must be overcome to meet the goal of reduced cost and these challenges defined our development efforts. These are:

1) Characterize the quality and the LID behavior of gallium crystal grown at Shell Solar.
2) Characterize the crystal growth process with respect to yields, resistivity control and bulk lifetime.
3) Characterize the electrical results and the LID effect on cells fabricated using the Shell Solar production process.
4) Demonstrate that the full range of resistivity values produced from a gallium-doped crystal can be used to fabricate a quality solar cell.
5) Produce modules from gallium-doped cells and demonstrate reduced LID.
6) Complete module environmental testing.

RESULTS AND DISCUSSION

Crystal Growth

The crystal growth process appears to be transparent to the use of gallium dopant. We experienced no problems with growth control, melt contamination or increased structure loss. Maintaining the rate of structure loss is especially important for cost control since it is typically the highest loss category in a Czochralski crystal growth process. While we found that no changes to the crystal growth process were necessary to achieve similar yields, targeting the resistivity required some effort. The segregation of any impurity in a solidification process is determined by its segregation coefficient. Figure 1 illustrates the different axial resistivity profile of boron vs. gallium dopant of a Czochralski (CZ) grown ingot, which results in the resistivity distribution shown in Figure 2. The marked difference results from boron having a segregation coefficient of 0.8, compared to 0.008 for gallium. Clearly, a gallium-doped crystal cannot maintain the same resistivity tolerance as a boron-doped crystal. If the solar cell fabrication process cannot tolerate the wider resistivity distribution, a significant yield loss in the

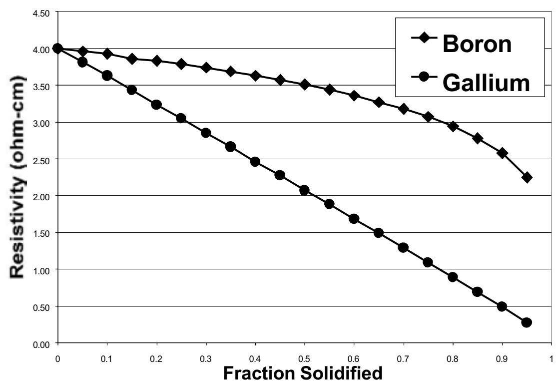

Figure 1. Theoretical Resistivity Axial Profile of CZ Grown Silicon for Boron and Gallium Dopant

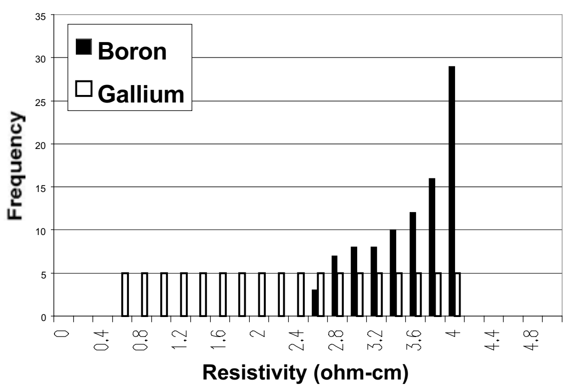

Figure 2. Theoretical Resistivity Distribution of CZ Grown Silicon for Boron and Gallium Dopant

crystal growing process would result, which, of course, would add substantial cost to the final product. Therefore, demonstration that the entire resistivity range from a gallium-doped crystal is usable to produce a quality solar cell is fundamental to its implementation. Crystal growth run-to-run control of resistivity has not yet been demonstrated due to the low number of crystals produced and the differing resistivity targets and initial charge compositions used during development. We have demonstrated, however, the unique doping behavior of gallium on recharge runs and on runs where the initial charge used gallium remelt. Due to the very low segregation coefficient of gallium, greater than 99% of the gallium remains in the melt at the end of a typical run. Recharge runs, where virgin silicon (and typically dopant) are added to the melt during a run, no additional gallium was necessary to maintain the resistivity target. On remelt runs, on the other hand, where previously used gallium-doped silicon was added to the initial charge, so little dopant was contributed to the run from the remelt that it could be doped as though it was all virgin silicon.

LID and Cell Efficiency Characterization

Tests made at the Georgia Institute of Technology using gallium-doped wafers produced at Shell Solar measured pre and post degradation lifetimes using contactless

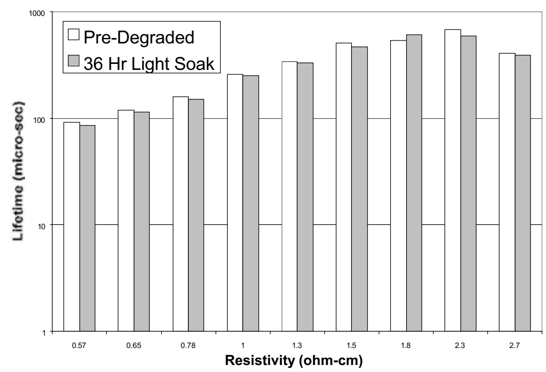

Figure 3. Lifetime Values of Gallium-doped Wafers Before and After Light Soak

Material	Resistivity (ohm-cm)	Efficiency (%)	Voc (mV)	Jsc (mA/cm^2)	Fill Factor
Gallium Doped Cz	0.57	16.8	629.4	34.53	0.771
	0.65	16.8	628.7	34.43	0.774
	0.78	16.8	627.6	34.57	0.772
	1.00	16.9	624.5	35.10	0.771
	1.30	17.0	623.7	35.36	0.769
	1.50	16.9	620.9	35.45	0.769
	1.80	16.9	618.7	35.71	0.765
	2.30	17.0	618.7	35.67	0.770
	2.70	16.9	617.5	35.70	0.767
Float Zone	1.30	17.2	624.9	35.67	0.771

Table 1. Electrical Results of Full Resistivity Range of Gallium-doped Crystal

photoconductance decay. Again, the full range of resistivity produced from a gallium-doped crystal was studied. Lifetime results are presented in Figure 3 and illustrate that LID is eliminated at every resistivity value. Using a screen-printed, aluminum back side field, texture etched, SiN antireflective front surface process, the Georgia Institute of Technology fabricated small area cells for analysis. Table 1 shows results of the study. Cell efficiency after light soak ranged from 16.8% to 17.0% demonstrating that high efficiency cells can be fabricated from the full resistivity range of a gallium-doped crystal.

Production Tests

Using a screen-printed, boron back surface field, texture etched, SiN antireflective front surface process, Shell Solar fabricated cells on wafers obtained from multiple gallium-doped crystals. Electrical results for the full group of gallium-doped cells are shown in Figure 4. Electrical results for standard boron-doped cells are shown in Figure 5 for comparison.

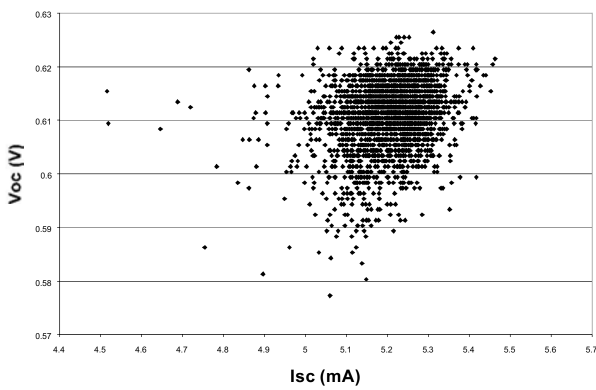

Figure 4. Voc vs Isc Characteristics of Gallium-doped Cells

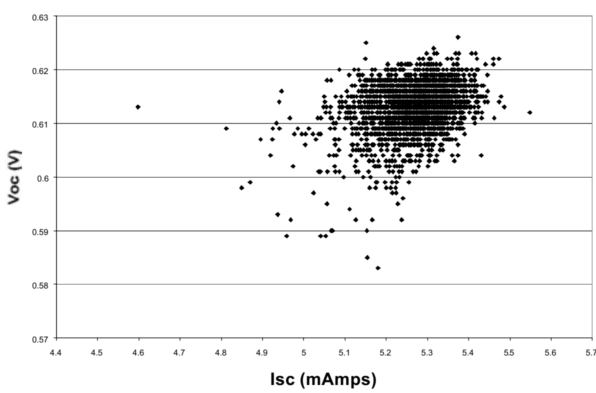

Figure 5. Voc vs Isc Characteristics of Boron-doped Cells

Module Tests

Four modules using gallium-doped cells were built and tested for LID. These were compared with modules built using standard boron-doped cells and with boron-doped cells obtained from crystals grown with the MCZ process. All cells and modules were fabricated in Shell Solar's standard production line in a split test. Gallium modules exhibited an average LID value of 0.18% power loss demonstrating that the reduction in LID holds true at the module level. LID losses for the standard boron-doped modules averaged 1.15% power loss, which is quite low when compared with Shell Solar's historical power loss. The MCZ modules had an average power loss of 0.93%. Additional modules were fabricated in Shell Solar's standard production line using gallium-doped cells. Eighteen modules have been sent to Arizona State University for environmental testing. Tests are conducted according to IEC standards and involve thermal cycling and damp heat tests. No results are yet available.

Polysilicon Feedstock Management

Managing one's feedstock supply of PV polysilicon has always been somewhat chaotic, requiring of a lot of attention paid to the silicon market. PV silicon is obtained from myriad sources, including virgin suppliers, brokers, IC crystal manufacturers, recycle houses and internally recycled remelt and comes in a variety of purities and geometries. A typical material flow chart for a CZ operation is shown in Figure 6. Figure 6 presents a simplified version of the feedstock management system as it does not depict the varying process steps necessary to deal with different remelt resistivity and dopant species, different types of contamination within or attached to the surface of the remelt or the different remelt geometries.

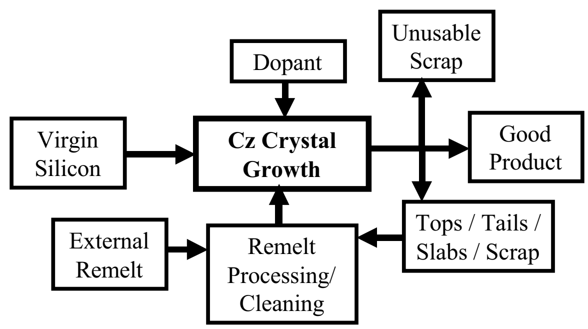

Figure 6. Typical Silicon Feedstock Flowchart for CZ Operation

Using gallium dopant exclusively further complicates the task of managing silicon feedstock, since most CZ based solar cell manufacturers rely on externally supplied remelt or potscrap. No gallium-doped remelt is available on the open market. This situation likely necessitates the recycling of internally produced remelt, subsidized with virgin silicon. Relying on virgin suppliers is not a cost effective option and creates a significant amount of risk since the availability and more importantly the cost of virgin silicon fluctuate greatly, driven largely by the semiconductor industry. Recycling one's own Ga doped remelt, either through reclaim services or internally, becomes a necessity. One potential option to alleviate some risk, is to use N-type remelt in the gallium process, which we have not explored. Gallium metal availability, although not as much a concern, also deserves consideration. Worldwide shortages of gallium have been projected since the late 1990's during periods of high growth rates of the GaAs opto-electronics and IC industries, which consume 95% of gallium produced [5,6].

CONCLUSIONS

Shell Solar and the Georgia Institute of Technology have demonstrated that high efficiency solar cells can be fabricated from the entire resistivity range of a gallium-doped CZ ingot. This conclusion satisfies one critical requirement for cost effective implementation into a commercial process. In addition, we have demonstrated positive results for modules built with gallium-doped cells and that these modules fabricated with Shell Solar's standard production process, benefit from the LID reduction provided by the gallium dopant. The question remains, however, as to how silicon feedstock to a gallium crystal growth process is obtained and managed. Resolution of this question must be established in order to implement gallium as a viable production process.

REFERENCES

[1] S.W. Glunz, S. Rein, J. Y. Lee and W. Warta, "Minority Carrier Lifetime Degradation in Boron-doped Czochralski Silicon”, *Journal of Applied Physics, Volume 90, Number 5, 2001.*

[2] NB Mason, TM Bruton, S Gledhill, KC Heasman, O Hartley, C Morilla and S Roberts "The Selection and Performance of Monocrystalline Silicon Substrates for Commercially Viable 20% Efficient LID-Free Solar Cells”, *19th European Photovoltaic Solar Energy Conference, 2004.*

[3] S.W. Glunz, S. Rein, W. Warta, and J. Knobloch, “Stable Czochralski Silicon Solar Cells Using Gallium- Base Material”, *16th European Photovoltaic Solar Energy Conference, 2000*

[4] Jianhua Zhao, Aihua Wang, Pietro P. Altermatt, Martin A. Green, "High Efficiency PERT Cells on N-type Silicon Substrates”, *Journal of Applied Physics, Volume 90, Number 5*

[5] *2001*A. Metz, T. Abe and R. Hezel, "Gallium-doped Czochralski Grown Silicon: A Novel Promising Material for the PV-Industry”, *16th European Photovoltaic Solar Energy Conference, 2000.*

[6] Deborah A. Kramer, “Gallium”, *U.S. Geological Survey Minerals Yearbook, 2002*

[7] Scott Davis, Capacity Issues in the Material Supply Chain”, *GaAs MANTECH, Inc, 2001.*