Cost-effective industrial n-type bifacial and IBC cells with ENERGi™ P and B ion implantation

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ABSTRACT: Industrial ion implantation with Intevac ENERGi ion implant tool provides a major processing advantage and cost reduction. Currently, Intevac’s ENERGi ion implant system has processed millions of wafers in production with better Cost of Ownership (CoO) than POCl3 diffusion process. ENERGi ion implant has successfully demonstrated a production cell of 19.95% with 646mV Voc with a standard screen printed processing. ENERGi is now capable of boron implantation which enables high efficiency bifacial industrial production. We present JOE and JO, lifetimes and implied Voc of symmetric and bifacial structures with implanted B-emitters and P-BSF structures that are co-annealed as well as 670 mV implied Voc for boron emitters. With ENERGi ion implantation, the cost of doping and co-annealing an n-type bifacial cell is below $0.02/Wp, a significant improvement over diffusion process flows. For other cell architectures such as IBC, the ability to pattern dopants with ENERGi ion implant dramatically reduces process complexity and cost. We also discuss PID improvement with implant, introduce graded doping for I2R reduction in emitters, and show the compelling short payback time for ENERGi ion implant.

Keywords: Ion Implantation, Boron, PERC, PERT, PERL, IBC

1 INTRODUCTION

For module manufacturers, future profitability and growth increasingly depends on improved module efficiency and long term reliability. For standard front contact Ag paste cell manufacturing, there is a trade-off between a low contact resistance vs. low phosphorus concentration in the emitter. (The former increases FF and the later increases Voc and Isc.) While front Ag pastes have improved, allowing for higher sheet resistance emitters (lower peak concentration resulting in high Voc), obtaining the full benefit of new pastes, or the benefits of advanced non-paste metallization, requires the ability to tailor phosphorus profiles beyond what is possible with a single step POCl3 diffusion.

Existing manufacturing lines can be upgraded with ENERGi ion phosphorus or boron implantation systems for an efficiency increase, tightening of efficiency distribution, improved PID resistance, and with a pay back time of below 1.5 years (see discussion). The ENERGi ion implantation system has already produced millions of cells in production with an industrial partner, CSUN. Champion cells at CSUN reach up to 19.95% efficiency using the production screen print process. ENERGi has also demonstrated ≥20% efficiency cells on a PERC structure with a different industrial partner. Ion implanted emitters also show improved PID resistance which is thought to be related to the solid phase epitaxial regrowth.

While standard cell designs are improving, more advanced and higher efficiency cells are also being introduced to the market. Many advanced cell designs are at or above 20.5% efficiency and utilize highly optimized phosphorus and/or boron profiles. The commercialization for a number of advanced designs is challenged by difficulties regarding 1) control and uniformity of dopant profiles, 2) single sided doping, 3) boron doping, and 4) patterning of dopants. Ion implantation solves these issues and thus has been considered for solar since the 1960’s. [1,2,3] Historically, however, ion implantation has been too costly with low throughputs for industrial production of solar cells.

2 INTEVAC ENERGi ION IMPLANTATION SYSTEM

Intevac is a 23 year old equipment manufacturer which has delivered production-proven deposition systems in hard disk drive industry, and is expert at developing high volume and cost sensitive tools. The ENERGi ion implantation system was conceptualized and designed from the start for solar applications. ENERGi provides high productivity and competitive CoO for industrial high efficiency phosphorus and boron doping requirements. The unique, patented ion source allows for a small footprint (24m²) and high throughput. High beam current is maintained even at low implant energies for
phosphorus and boron doping. ENERGi operates at 3000 wph for both P and B doping from over 200 Ω/□ down to 35 Ω/□.

3 BORON IMPLANTATION

With furnace diffusion of boron, an undesirable boron-rich-layer (BRL) is often formed. Kessler et. al. [4] describe the BRL as a continuous or discontinuous layer of a $B_xSi$ compound where $x$ is thought to be between 4 and 6. The BRL formation (or reduction) is determined by the balance of O or B species arriving at the BSG/Si interface which is difficult to control uniformly throughout the diffusion process. The BRL is linked to lifetime degradation and is resistant to chemical etches. These issues have hampered the industrialization of B doping for solar cells. For most boron implant and anneal processes, BRL formation is typically avoided. Unlike diffusion, the boron implant alone determines the boron dose, rather than the particular chemistry and phase conditions at the BSG/BRL/Si boundary condition. An intentionally grown thin oxide during the B drive-in anneal can add improved passivation.

We have demonstrated high quality boron emitters with Intevac facilities. Industrial 156x156mm, n-type, textured, Cz wafers of 2 Ω-cm ($\tau_{\text{bulk}} < 500\text{us}$) were cleaned and implanted with boron on both sides. After implantation, the samples were annealed in a tube furnace without any cleaning process between implant step and the anneal. These wafers then received plasma-assisted ALD $Al_2O_3$ and PECVD $SiNx$ passivation layers. After a forming gas anneal (FGA), the wafers were characterized using a QSSPC (Sinton Tester). An implied $V_{\text{oC}}$ of 670mV was obtained for an ~100 $Ω/□$ emitter as described in Table 1.

The significance of this result is that such high quality boron emitters are now industrially possible with high uniformity and repeatability at ≥3000 wph, and CoO under 1¢/Wp (U.S.D.).

Table 1: Example of properties of an ENERGi boron implanted emitter in a fully textured n-type Cz wafer without a cleaning step between implant and anneal.

<table>
<thead>
<tr>
<th>$R_{\text{sheet}}$</th>
<th>$J_{\text{OE}}$</th>
<th>MCL at 0.1 sun (us)</th>
<th>Implied $V_{\text{oC}}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104 $Ω/□$</td>
<td>38 fA/cm$^2$</td>
<td>330</td>
<td>670</td>
</tr>
</tbody>
</table>

4 PHOSPHORUS IMPLANTATION

High quality phosphorus doped layers are also required for advanced cells. For standard cells (front Ag paste and rear Al-alloyed BSF) the three important considerations for optimization are a) emitter sheet resistance for lateral conduction of carriers, b) emitter recombination, and c) the contact resistance of the emitter to the Ag paste. Lower emitter sheet resistance reduces $I^2R$ losses, improves fill factors, and/or allows for wider spacing of Ag fingers. A wider finger pitch reduces emitter shading and requires less Ag. Cooper et. al. [5] illustrated how an optimized lower sheet resistance phosphorous profile with a lower $J_{\text{OE}}$ (deeper junction with lower concentration of P at the surface) could result in 40% to 60% reduction in Ag paste usage.

$V_{\text{oC}}$ is strongly influenced by the total recombination in the emitter. This recombination is due to three main mechanisms; 1) Surface recombination velocity (SRV), 2) Auger recombination, and 3) SRH recombination within the emitter.
All three mechanisms are improved with lower phosphorus concentrations.[6] POCl₃ diffused emitters typically have higher recombination and thus lower Voc than implanted emitters due to the typically higher phosphorus surface/peak concentrations above >5x10²⁰ P/cm³. Increasingly, cell designs and processes are being demonstrated and commercialized which do not use Ag pastes. Instead, metals such as Ni, Ti, or Al contact the silicon. Such metals can form ohmic contacts at significantly lower doping levels than Ag pastes. Cuevas and Russell [7] show that based on contact resistance and grid optimizations, that titanium fingers between 28μm and 150μm wide would have highest efficiencies with peak phosphorus below 10¹⁹ P/cm³ and junction depths exceeding 1μm. Similar aluminum contacts would be optimized at peak phosphorus concentrations 2 to 4x10¹⁹ P/cm³. Such phosphorus profiles can be achieved most easily with ion implantation. Low dose profiles with POCl₃ diffusion would require a costly multi-step process.

An example of a high efficiency phosphorus emitter is shown in Table 2. A 156mm p-type fully textured wafer (1.5Ω-cm) was symmetrically implanted with phosphorus and annealed without a clean process between the implant and anneal. A thermal oxide was grown during the anneal. A PECVD SiNx was applied on top of the oxide, followed by a FGA.

<table>
<thead>
<tr>
<th>Rsheet</th>
<th>JOE</th>
<th>MCL at 0.1 sun</th>
<th>Implied Voc (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>51</td>
<td>100</td>
<td>663</td>
</tr>
</tbody>
</table>

Table 2: Symmetrically phosphorus implanted and annealed sample passivated with a thermal oxide grown during the anneal, and with PECVD SiNx, followed by FGA.

Such high performance layers can be industrially realized using ENERGi with CoO below $1/W_p$ (U.S.D.) including the implant and an anneal with the oxide passivation.

The ENERGi implantation system has processed millions of production wafers and has demonstrated >99.97% wafer yield, improved efficiency, and tighter efficiency binning. An example of 2013 industrial data from CSUN is shown in Figure 2 and illustrates the narrow binning. Cells meet $R_{shunt}$ and $I_{rev2}$ specifications for mass production. Recent champion data on 210mm diagonal wafers run in the CSUN production line show 19.95% efficiency with a $V_{oc}$ of 646m and FF of 80.2%. With a different industrial customer, ENERGi implantation also demonstrated over 20% efficiency and $V_{oc}$ >652mV on PERC cells.

Figure 2: Results from 2013 production run of ENERGi showing narrow binning of cells.

5 IMPLANTED BIFACIAL AND CO-ANNEAL

With the ability of both P and B implantation at low CoO, an obvious high efficiency and industrially viable design is the n-type PERT cell or n-type bifacial cell. Because of the one-sided doping nature of ion implantation, streamlined manufacturing process for such designs is now possible. One possible process sequence with ENERGi implantation is shown in Figure 3, and features a CoO under $2/W_p$ (U.S.D.) for the doping and annealing steps. In order to use a front ALD $Al_2O_3$, any front oxide from the anneal should be etched while leaving the rear oxide on the P-BSF. The initial results of such a process are shown in Table 3. This is a promising result for early stage development. We are confident that greater than 650mV can be achieved on this process flow with additional optimization given the results from Tables 1 and 2.

Figure 3: One possible sequence to fabricate n-PERT or n-type bifacial cells. The doping and annealing sequence combined have a CoO less than $2/W_p$ (U.S.D.) with ENERGi implantation.
6 DOPANT PATTERNING FOR IBC AND ADVANCED CELLS

A crucial capability for advanced cell designs has been the patterning of dopants. For example, selective emitters, PERL cell, EWT/MWT, and IBC feature patterned doping. Patterning often requires application, patterning, and removal of a sacrificial barrier layer. This adds cost and yield risk. With ENERGi implantation, patterned doping is easily implemented using either a stationary mask or a traveling mask. For example, with the single pass design of the ENERGi implanter, both selective and homogeneous doping of a selective emitter can be implemented in the same single pass through the implanter. Similarly, IBC designs based on 1D and 2D patterns can also be implemented in the ENERGi implanter at high throughputs.

An example of the capabilities of ENERGi implanter for patterned doping is shown in Figure 4.

Table 3: Parameters of bifacial cell following the implant, anneal and passivation scheme described in Figure 3.

<table>
<thead>
<tr>
<th>Rsheet B-Emit</th>
<th>Rsheet P-BSF</th>
<th>J0</th>
<th>MCL at 0.1 sun (us)</th>
<th>Implied Voc (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>56</td>
<td>65</td>
<td>130</td>
<td>650</td>
</tr>
</tbody>
</table>

7 ADDITIONAL ASPECTS FOR FRONT CONTACT PHOSPHOROUS EMITTER CELLS

**Thin Oxides:** Higher surface phosphorus concentrations are needed to form low resistance contacts to Ag paste metallizations which increases J0E. The optimization of low J0E sheet resistance, and P dose for Ag paste cell designs has been explored by many and is understood. [8,9] An additional advantage of using implantation process is the growth of a thin high quality oxide during the anneal. This oxide not only improves passivation of the phosphorus emitter, but also appears to improve contact with Ag pastes. [10,11] This may be due to the formation of a crude passivated contact where tunneling from the Si to the Ag through SiO2 becomes more prevalent across the wafer.

**Potential Induced Degradation (PID):** PID has severely constrained the trend to higher string voltages in installed systems and the realization of cost savings on inverters and cabling. The main culprit appears to be Na migrations to stacking faults in the emitter of the cell. [12] The primary solutions so far to PID mostly involve strategies that block Na from the emitter of the cell. These include measures such as low sodium glass (added $), higher resistivity encapsulant (added $), deeper emitter (added $ and/or lower $), modified SiNx (added $ and/or lower $). [13] Ion implanted cells may be inherently PID free or resistant. Some reports [14] point to the thin oxide layer (see above) as the solution for PID. However, PID resistance may also be a result of the Solid Phase Epitaxial Regrowth (SPER) process which results from P implantation. During implantation, P atoms collide and displace Si lattice atoms. When enough Si atoms are displaced, crystal structure is lost, resulting in an amorphous Si region. During annealing, the amorphized region will re-crystalize epitaxially starting at the aSi-cSi boundary and moving to the surface. [15] This recrystallized layer is characterized by an extremely low level of point defect and no extended defects which may be responsible for the observed PID resistance of implanted wafers. ENERGi ion implanted cells in CSUN’s QSAR commercial modules have passed TUV 1500V 85C 85RH for 96hrs as well as the test conditions of 60ºC / 85% RH / -1000V/96 hours with the module front surface immersed in water.

**Graded Doping:** In the previous section, dopant patterning has been demonstrated. ENERGi ion implantation can also form graded doping patterns. The ENERGi implant tool can create not only high and low doped regions, but gradients of doping as well. This could be used to increase efficiencies on standard Ag front contact cells. Consider, the lateral current density in the emitter is highest nearest the fingers (current crowding).
...and lowest at the center point between two fingers. This results in high I^2R losses in the regions of current crowding. Higher efficiency cells with typically lower bulk doping, will have very high current densities in the emitter and suffer from high I^2R losses. Presently, the only solution is to reduce the finger pitch which results in higher Ag consumption and shading losses.

With graded doping, the sheet resistance could be allowed to be very high, e.g. 300 Ω□, where there is low current densities, such as near the center point between fingers. The sheet resistance could be graded from the center point to perhaps 65 Ω/□ near the Ag fingers. With proper tailoring of the lateral sheet resistance of the graded emitter, J_{OE} and I^2R losses are simultaneously optimized. This is not to be confused with selective emitter which has a step function profile and is designed primarily to improve the contact with the Ag paste at the fingers as well as to reduce Ag/silicon interface recombination velocity. The graded emitter proposed here does accomplish the goals of the selective emitter and additionally would have much looser alignment tolerances. Depending on the exact relationship between J_{OE} and sheet resistance, the gains can be >0.3% absolute according to PC2D simulations.

Graded doping would allow wider spacing of Ag fingers which would reduce Ag consumption as well as lower shading losses. Graded doping is useful where ever there is current crowding in a cell of any design.

8 ECONOMICS OF ION IMPLANT

We calculate the cost of ownership of ENERG\textsuperscript{i} implant + anneal to be competitive with POCl\textsubscript{3} + PSG wet etch, while achieving higher cell efficiencies. This combination of competitive cost of ownership in ENERG\textsuperscript{i} emitter formation compared to POCl\textsubscript{3}, and the higher ENERG\textsuperscript{i} cell efficiency results in a total cost of ownership ($/Watt) reduction for the cell manufacturing process. Further benefits of ENERG\textsuperscript{i} implant are realized from tighter cell efficiency distribution and improved PID performance. Both are an important added value that is not included in this cost analysis. PID is often improved in ways that reduce efficiency by 0.1% to 0.2% (absolute). Even without including tight distribution and PID, the cost calculations show that ENERG\textsuperscript{i} implant has one of the fastest times to payback of any PV manufacturing equipment.

9 CONCLUSION

ENERG\textsuperscript{i} ion implantation provides excellent doped layers at high throughputs and low CoO. The ENERG\textsuperscript{i} implantation system has processed millions of production wafers with an industrial partner, CSUN. Recent champion data on 210mm diagonal wafers run in the CSUN production line show 19.95% efficiency with a V_{oc} of 646mV and FF of 80.2% with a standard screen printed processing. The excellent initial boron implantation results make ENERG\textsuperscript{i} the platform of choice for future advanced cell designs. With ENERG\textsuperscript{i} ion implantation, the cost of doping and co-annealing an n-type bifacial cell is below $0.02/Wp, a significant improvement over diffusion process flows. The ability to pattern dopants with ENERG\textsuperscript{i} ion implant dramatically reduces process complexity and cost in other cell architectures such as PERL and IBC. The collaboration between Intevac and CSUN move forward to the industrial high efficiency solar cell (bifacial, PERL, IBC) with Intevac ENERG\textsuperscript{i} P and B ion implantation, for example the industrialization of bifacial cell with the efficiency >20% and PERL cell with the efficiency >22%.
REFERENCES


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Enabling the rapid shift in the solar technology roadmap using ENERGI™ ion implantation

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ABSTRACT: Competition among solar cell manufacturers is driving innovation and the adoption of new technologies and process flows. Leading PV manufacturers are now making strategic modifications that will enable more rapid shifts to higher cell efficiencies and lower costs per watt. The cell roadmap is accelerating and new innovative cell process equipment will be required. ENERGI ion implantation is a key vehicle for the future cell line and will enable these rapid shifts to occur. Early indications of the advanced capability of ENERGI ion implant is the ability to quickly tune a line to higher cell efficiency, with fewer steps and lower cost than a diffusion line. Additional values of ENERGI are a very stable narrow cell efficiency distribution and greatly improved PID resistance. With millions of cells processed in commercial modules, ENERGI ion implant technology has proven successful in high volume solar manufacturing and is now being tested for more advanced cell technologies. Key to the advanced cell architectures is the addition of boron implantation capability and patterning capability. All new cell technologies will demand more ion implantation use since step count reduction and subsequent cost reduction is more pronounced with advanced cells. This paper will highlight the ever improving cost advantages of ENERGI ion implant vs. diffusion using a detailed cost of ownership analysis technique for advanced cells starting with high efficiency p-Mono, n-PERT, Bi-facial, and IBC cells.

Keywords: Ion implant, cost of ownership, payback time

1 INTRODUCTION

The solar industry is going through a significant transition on a global scale from being a niche market to becoming a major source for cost effective, zero emissions energy supply. The rapid scaling in manufacturing over the last decade has driven costs to a point where multiple countries are now implementing solar energy, rather than fossil fuel or nuclear based energy, because it is the lowest cost and most easily scalable electricity generation source. Expectations for the coming decade are for the adoption rate of solar energy to continue. The solar market is predicted to grow substantially and, as the industry progresses on the cost learning curve [1], prices are forecasted to continue to lower cost per watt. The drivers for this are additional scaling, higher efficiency modules, and improvements in balance of systems area (including soft costs). As the industry grows to ever larger proportions, the focus on the technology roadmap will become more intense. Recently a key area of focus for the cell technology roadmap has been with ion implanted cells versus the older approach of diffusion technology. The technology transition from diffusion to ion implantation has already occurred many years ago in the semiconductor industry. The advantages of ENERGI ion implant for solar are now beginning to be better understood by the manufacturers and ENERGI ion implantation is being implemented on a high volume scale. The benefits include the following: higher cell efficiencies, lower process costs, fewer process steps, narrower cell efficiency distribution, high PID resistance, and much greater extendibility to new cell architectures such as n-type bi-facial, PERL, and IBC solutions. [2]

2 INTEVAC ENERGI ION IMPLANTATION SYSTEM

Intevac is a 23 year old equipment manufacturer which has delivered production-proven deposition systems in hard disk drive industry, and is expert at developing high volume and cost sensitive tools. The ENERGI ion implantation system was conceptualized and designed from the start for solar applications. ENERGI provides high productivity and competitive CoO for industrial high efficiency phosphorus and boron doping requirements. The unique, patented ion source allows for a small footprint (24m²) and high throughput. High beam current is maintained even at low implant energies for phosphorus and boron doping. ENERGI operates at 3000 wph for both P and B doping from over 200 Ω/□ down to 35 Ω/□.
3 COST OF OWNERSHIP

A detailed analysis of total cost of ownership and complete modeling is a critical aspect required to drive the design and improvements of solar process equipment and competing process flows [3]. Aggressive cost roadmaps drive the need for high accuracy in modeling. The models are continuously being updated and improved as more details are established. Cost of ownership analysis requires use of standards (SEMI E-35 and SEMI E-10) to provide systematic methods of design and allow transparency between suppliers and customers. The accuracy of our cost model is continuously improved as internal data is incorporated and customers provide feedback from auditing our model. Once a cost of ownership model is fully established for a certain process flow and equipment set it becomes a very powerful tool both in demonstrating capability and in driving new improvement programs internally at the equipment supplier.

4 ENERG\textasciitilde ION IMPLANTATION COST REDUCTION

For the ENERG\textasciitilde ion implant system the emitter is formed at a much more rapid rate with higher precision and repeatable than diffusion furnaces can attain. The flow is also simplified due to ion implantation ability to dope single sided. There is no need for the acid glass etch steps or edge isolation steps used in traditional flows. ENERG\textasciitilde ion implant system basic emitter process flow solution includes the implant system followed by a simple oxide anneal system. See process flows in Figure 1.

Figure 1: Emitter process flows p-type with costs in U.S. cents / watt.

The difference between process flows requires the need to understand the cost and efficiency impact of the steps involved in each flow. From an efficiency standpoint cells made with ion implant are usually higher by 0.1 to 0.3%, based on the ENERG\textasciitilde ion implant’s more tunable dopant profile capability and ability to optimize the concentration through dose control [2]. The ENERG\textasciitilde ion implant cost of ownership is well understood. In today’s high volume p-type front contact cell lines with efficiency at 19.3%, ion implant can raise the efficiency in the line above 19.5% average and exhibit a comprehensive CoO of < 0.8 U.S. cents/watt [2]. This cost is actually lower than many diffusion furnaces flows (0.9 U.S. cents/watt). When the full diffusion flow is considered with a wet etch that costs $0.8 U.S. cents/watt in addition to doping step, it can be seen that the ENERG\textasciitilde ion implant flow is not only higher in efficiency but also lower in cost/watt. The flows in Figure 1 also show the limitation of staying with a furnace line. To achieve the higher efficiencies as demanded by the market, an additional oxidation step is required for the diffusion flow. This approach could raise the efficiency but at additional cost which was proven to be an uneconomic approach. As cell process technology is driven toward 20% cell efficiency and higher with more complex flows such as n-type, bifacial or IBC, the opportunity for ion implant to reduce process steps and costs is even greater. A table of advanced cell flows, process step reduction and cents / watt saving is shown in Table 1.

Table 1: As cell types grow more complex ENERG\textasciitilde ion implant reduces steps and cost.

5 PAYBACK CALCULATION

In addition to the cost of ownership comparisons that can be made to simply compare the manufacturing costs for different process flows another calculation should be used in the case where efficiency increases are made. This is the payback calculation. This calculation takes into account the additional profit per year by adding an efficiency increasing process step such as ENERG\textasciitilde ion implant to the line. Increasing the cell efficiency of a solar cell process line increases the overall watts out per line. In doing so a manufacturer can make two basic profitable steps to return more revenue, the first is based on
equivalent cell price where the manufacturer simply ships more cumulative watts due to the increase in cell efficiency while using the same production cost per wafer. The second is based on the higher sales price ($/Wp) of higher efficiency modules. This results in higher pricing power with higher efficiency achieved on each cell. An example of this calculation is shown in Table 2. It can be seen from the table and the following chart that increasing efficiency even as small as 0.1% or 0.2% has high price value. Moreover, if value pricing of the cell is added into the increase in plant watts, (also on a conservative scale) the payback time is affected even more, thus a payback time of one year is achievable with a 0.2% gain with a slight increase in cell pricing due to the value of efficiency to the cell manufacturers end market customer (Figure 3).

<table>
<thead>
<tr>
<th>PAYBACK CALCULATION</th>
<th>UNITS / CALCULATIONS</th>
<th>0% GAIN</th>
<th>0.1% GAIN</th>
<th>0.2% GAIN</th>
<th>0.3% GAIN</th>
<th>0.4% GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Diffusion Efficiency</td>
<td></td>
<td>19.3%</td>
<td>19.3%</td>
<td>19.3%</td>
<td>19.3%</td>
<td>19.3%</td>
</tr>
<tr>
<td>Efficiency Gain</td>
<td>%</td>
<td>0.00%</td>
<td>0.10%</td>
<td>0.20%</td>
<td>0.30%</td>
<td>0.40%</td>
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<tr>
<td>Increase Output</td>
<td>%</td>
<td>0</td>
<td>533,169</td>
<td>1,066,338</td>
<td>1,599,507</td>
<td>2,132,676</td>
</tr>
<tr>
<td>Cell Price</td>
<td>Watts / Year</td>
<td>$0.460</td>
<td>$0.460</td>
<td>$0.460</td>
<td>$0.460</td>
<td>$0.460</td>
</tr>
<tr>
<td>Cell Price (Value of Efficiency)</td>
<td>$</td>
<td>$0.460</td>
<td>$0.461</td>
<td>$0.462</td>
<td>$0.463</td>
<td>$0.464</td>
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<tr>
<td>Increased Revenue / Year</td>
<td>$</td>
<td>$-</td>
<td>$245,258</td>
<td>$490,516</td>
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<tr>
<td>Increased Revenue (Value) / Year</td>
<td>$</td>
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<td>$348,693</td>
<td>$698,451</td>
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<tr>
<td>Implant Investment</td>
<td>$</td>
<td>$2,700,000</td>
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<tr>
<td>Investment Cost Saved (Wet Etch)</td>
<td>$</td>
<td>$1,562,500</td>
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<tr>
<td>Investment (Implant - Wet Etch)</td>
<td>$</td>
<td>$1,137,500</td>
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<tr>
<td>Running Costs</td>
<td></td>
<td>$390,119</td>
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<tr>
<td>Increase in Profit</td>
<td>Revenue - Running Costs ($)</td>
<td>$390,119</td>
<td>$635,376</td>
<td>$880,634</td>
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<td>Revenue - Running Costs ($)</td>
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<td>$738,811</td>
<td>$1,088,570</td>
<td>$1,439,395</td>
<td>$1,791,287</td>
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<tr>
<td>Payback Time (Efficiency)</td>
<td>Investment / Increase in Profit (Yrs)</td>
<td>2.92</td>
<td>1.79</td>
<td>1.29</td>
<td>1.01</td>
<td>0.86</td>
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<tr>
<td>Payback Time (Efficiency + Value)</td>
<td>Investment / Increase in Profit (Yrs)</td>
<td>2.92</td>
<td>1.54</td>
<td>1.04</td>
<td>0.79</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 2: Impact of higher cell efficiency and value pricing on payback time.

Figure 3: Payback chart with impact of efficiency gain and value pricing.

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6 ADDITIONAL VALUE OF ION IMPLANT

Other values of ion implant are still being explored to determine the real values for the differentiation offered by ion implant technology. The most obvious but as yet least studied values are listed below:

6.1 TIGHTER CELL EFFICIENCY DISTRIBUTION

The benefits of ion implant do not stop with efficiency and cost. In addition to increasing cell efficiency ion implant offers a much tighter cell efficiency distribution than a regular diffusion line.

6.2 REMOVE WET ETCH PROCESS STEPS AND CHEMICALS FROM THE PROCESS LINE

As factories scale to the GW scale, more thought has to be put into reducing the volumes of acid, other chemicals and DI water that are needed as additional factory consumable costs. Acids also need to be neutralized with additional volumes of liquids which also take up more factory space and cost. This cost needs to be studied more in the solar Giga-scale factory of the future and balance the impact versus ENERGi ion implant that utilizes gases only and therefore more economic.

6.3 LOW PID

The data published on ion implant suggests that potential induced degradation (PID) can be lower with ENERGi ion implanted cells [2]. PID has become an issue recently as large utility scale systems have increased the module string voltage. A higher string voltage saves cost of the inverter as well as cabling, thus reducing total BOS cost. The main issue appears to be Na migrations due to stacking faults in the emitter of the cell. [4] The primary solutions so far involve strategies that block Na from the emitter of the cell. These include measures such as low sodium glass (added $), higher resistivity encapsulant (added $), deeper emitter (added $ and/or lower η), modified SiNx (added $ and/or lower η). [5] These costs or efficiency degradations are not included in this cost model. Ion implanted cells may be inherently PID free or resistant. ENERGi ion implanted cells in commercial modules have passed TUV 1500V 85C 85RH for 96hrs as well as Chemitox Severity IV standard.

7 CONCLUSION

The solar industry is now entering a rapid transition phase to become a mainstay of the future global energy supply. Manufacturing industry roadmaps are accelerating. Strategic players are now looking to invest in approaches that will allow swift moves toward higher efficiency and lower cost per watt in order to differentiate themselves in a highly competitive field. The industry has recognized ENERGi ion implantation technology as one of the manufacturing processes with higher efficiency, lower cost per watt and greater extendibility. A detailed cost of ownership methodology and model along with payback analysis has shown the potential for increased return on investment for solar cell processing lines choosing to use ion implantation.

REFERENCES

[1] International Technology Roadmap for Photovoltaic (ITRPV) 2013 Results Revision 1, 24 March 2014, pp7


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