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Research

SHORT COMMUNICATION

Laser Isolation of Shunted Regions in Industrial Solar Cells

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This paper provides proof of concept for a technique that uses laser-ablated grooves to locally isolate shunted regions in industrial silicon solar cells. The shunted regions are located using photoluminescence imaging and then isolated from the active cell area with a Nd:YAG laser. By applying this shunt isolation technique, we demonstrate that a strongly shunted 9·6% efficient industrial screen-printed solar cell could be recovered to 13·3%. With further development this technique could be applied in an industrial environment to mitigate yield losses and improve average cell efficiencies. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: laser processing; shunt; photoluminescence; lock-in thermography

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INTRODUCTION

Efficiency loss due to regions of low shunt resistance is one of the major challenges currently facing PV manufacturers. Shunted cells significantly reduce average efficiencies, result in modules with poor low light performance and reduce the total yield. This problem is particularly pronounced in cells fabricated on cheaper forms of silicon where material induced defects present many different sources of shunting[1] and is therefore expected to become worse in the future given the current shortage in silicon feedstock. In many cases, the source of low shunt resistance is highly localized, one example is conductive SiC inclusions which are typically only 5–10 μm in size.[2] Although the shunted region itself is highly localized, the lateral conductive path formed by the emitter and by metal contacts generally causes much larger areas of the solar cell to be affected. This paper presents a technique to mitigate the influence of localized shunted regions by isolating them from the majority of the cell with a laser groove. In doing so we provide a proof of concept for a technique that can be used to improve the performance of industrial solar cells and reduce the yield loss due to shunting.

It is well established that laser grooves can be used to isolate the shunted regions that exist at the edge of many industrial solar cells.[3–5] Such laser edge isolation techniques are already used routinely in modern industrial manufacturing. In this case the location of the shunt is well known *a priori* and highly repeatable. A single scribe from a laser creates a trench which intercepts the lateral conductive path to the edge for one type of carrier and

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thereby mitigates recombination or current flow towards the edge. Other variations of this technique have incorporated excimer lasers[6] and water jet technology.[7]

Additional material or processing induced shunts are located within the active cell area however their position is not known. Experimental techniques are therefore required to localize the position of shunted regions in order to be able to apply similar laser isolation techniques to those shunts. For such techniques to be applicable in an industrial environment, the localization of the shunts must be accomplished in about one second per cell. Electroluminescence (EL) imaging[8,9] and photoluminescence (PL) imaging[10,11] have recently been introduced as fast characterization tools for silicon solar cells and silicon wafers with typical data acquisition times on the order of 1s per measurement. It has been shown that luminescence imaging techniques can be efficient process monitoring tools[12–14] that are applicable to different types of silicon substrates[15] and that can be used to obtain high resolution images of the minority carrier lifetime.[10] The localization of regions with enhanced series resistance by EL imaging and by the combination of PL imaging with EL imaging has also been demonstrated.[11,16]

The spatially resolved detection of shunts with luminescence imaging techniques was proposed in Reference 10. The fact that luminescence based shunt detection techniques are not expected to be as accurate and quantitative as lock-in thermography (LIT) techniques[17] was pointed out in Reference 18 and soon thereafter confirmed experimentally.[13,19,20] However, at present the data acquisition time of LIT techniques is longer than that achieved with luminescence techniques which make luminescence techniques more appropriate for use in industrial inline applications. Point like shunts that are typical for multicrystalline silicon material were observed with luminescence imaging and the comparison with LIT confirmed that these types of shunts can be localized reasonably accurately with luminescence imaging techniques.[13,19] Based on these experimental results, several possible industrial applications of PL- and EL imaging to reduce the impact of shunts on average cell efficiency were suggested.[19] Here we demonstrate the feasibility of some of these methods experimentally.

EXPERIMENTAL

The technique to isolate shunted regions with a laser is developed in two stages. In the first part, the influence of the laser settings are investigated by scribing a typical industrial screen-printed cell with relatively high shunt resistance and examining the impact on the cell's electrical properties. This step is necessary because the laser processing, rather then removing existing shunts, could potentially lead to additional shunting. In the second part the laser settings that are identified to have a small effect on the performance of good cells are applied to a strongly shunted industrial cell.

The laser processing presented in this work uses a 1064 nm Q-switched Nd:YAG laser with a pulse width of 200 ns. The laser system incorporates a nitrogen shield gas to protect the optics during the ablation process. An average laser power of 400 mW with a pulse spacing of 10 μm is used to produce pulses that are then focused onto the work piece to a spot size of 20–30 μm diameter. An isolation trench through the emitter and through metal grid lines is formed by overlapping these pulses to produce a continuous groove.

PL imaging is used to detect the location of shunted regions on the solar cell.[19,20] In this technique an 815 nm/25 W laser is used to excite carriers within the sample and a CCD camera captures the emission of photons. All images presented here were taken with data acquisition times of 1s or less. Neglecting photon reabsorption within the sample and optical inhomogeneity across the sample, the local luminescence intensity is proportional to the local carrier density (integrated over the thickness) within the sample. Regions of high minority carrier lifetime therefore appear bright and poor regions appear dark. Luminescence intensities can also be interpreted as a local voltage.[21,22] Because a shunt reduces the voltage locally and in its surroundings, it appears as a region of reduced luminescence intensity.[23]

An important aspect of this work is to determine whether the laser processing electrically isolates the shunted region from the cell. This is accomplished using a recently described method based on PL imaging of finished cells, with simultaneous extraction of current,[11,16] in which regions of high series resistance (i.e. isolated regions) appear bright while regions that are well connected to the metal contacts appear dark. To more

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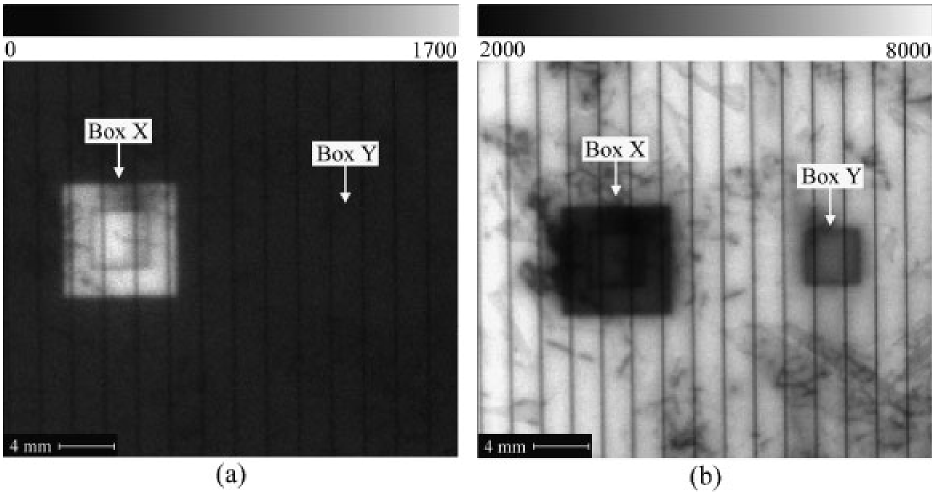

Figure 1. Photoluminescence images of a laser processed surface region on a silicon solar cell under 1 Sun equivalent illumination; (a) with 3·6A current extraction and (b) at open circuit

accurately assess the impact of laser scribes, the LIT technique is used to examine shunting in the laser-processed regions.

Influence of laser processing

The laser processing must electrically isolate a region without introducing excessive recombination or causing additional junction shunting. This is particularly important when the laser scribe crosses a contact finger since the metal forms a very low resistive path that connects the laser scribe to the rest of the cell. The presence of metal during laser scribing is also a critical factor since incorrect laser settings can result in driving the metal into the bulk of the silicon, producing very low shunt paths across the junction.

Photoluminescence images, shown in Figure 1, demonstrate the influence of laser settings on achieving electrical isolation. In this case 'Box X' is scribed with high shield gas flow and two laser passes, 'Box Y' is scribed with no shield gas and only one pass. The square on the left (labeled 'Box X') appears white in the image with current extraction (Figure 1a). This indicates that the grooves scribed with these laser settings have successfully isolated the region within the box from the contacts of the cell. The square on the right (labeled 'Box Y') is not at all visible on the image with 3·6A current extraction. In this case the region is poorly isolated and the carriers are drained from the region during current extraction. Both boxes appear dark in the open circuit PL image (Figure 1b), box X has less counts (~2500) than box Y (~4000) and both are less than the surrounding cell area (~7000 counts). This indicates that the laser scribe has introduced some damage. The number of counts within box X is further reduced by the fact that it is electrically isolated from the surrounding areas. In this case the box becomes a separate solar cell with an area of 1 cm^2 surrounded by a larger cell with an area of 155 cm^2. Assuming the laser scribe introduces an equal resistive path (shunt) across the junction on either side of the groove leads to an area shunt resistance (Ωcm^2) that is approximately 155 times lower within the small cell and which therefore has a much more dramatic effect compared to the large cell. As a result the small cell reaches a lower open circuit voltage for the same illumination conditions and thereby emits a lower luminescence signal. In the case of box Y the small cell is still connected to the large cell through a resistor and current is able to flow from the large cell into the small cell, thereby increasing its voltage and reducing the contrast between the areas inside and outside the groove. Box X contains a smaller square, scribed with the same laser settings, within the larger square. The larger square was required to observe any impact on the Suns-V_{oc} curve presented in Figure 2 below.

The impact of scribing on the shunt resistance of solar cells is investigated using Suns-V_{oc} measurements[24] and the LIT technique. As shown in Figure 2a, scribing box X with 'good' laser settings results in a slight

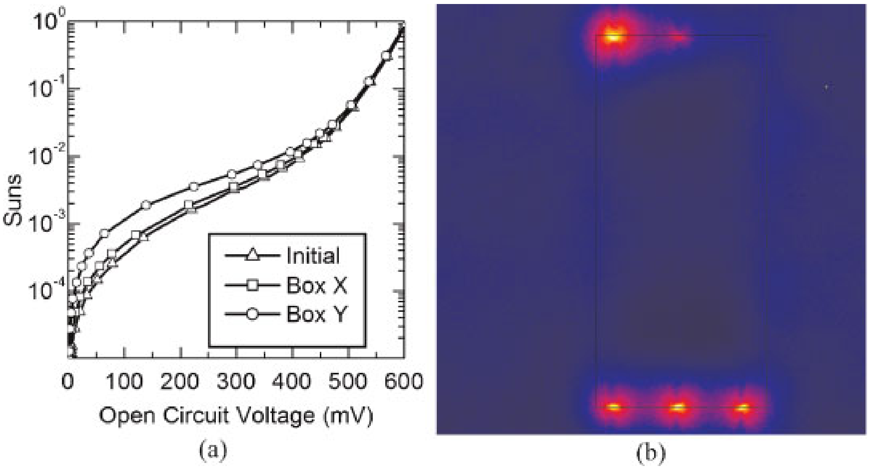

Figure 2. (a) Suns V_{oc} curve of a 156 cm^2 solar cell taken after various laser process; (triangle) no laser scribe, (square) after 10×10 mm box with 'good' laser settings and (circle) after 4×4 mm box with 'poor' laser settings. (b) Lock-in thermography image of a laser processed region, laser scribe marked with black line

increase (∼10% reduction in voltage at 10^{-3} Suns) in recombination at lower voltages and marginally reduces the shunt resistance of the cell, indicating some damage due to the scribe. In comparison, box Y introduces significantly more damage (∼50% reduction in voltage at 10^{-3} Suns) and significantly lowers the shunt resistance of the solar cell. LIT measurements, shown in Figure 2b, of a second solar cell scribed with similar laser settings to box X, indicate that the source of shunting is primarily located at the point where the laser scribe crosses metal fingers. Interestingly, not all such points are shunted regions. This result suggests that it may be possible to further optimize the laser processing to greatly reduce the shunting introduced by the laser scribe. Another alternative is to incorporate advanced laser technologies such as the water jet technique[7] or laser-assisted thermochemical etching.[25] Poor laser settings reduce the performance of the solar cell without providing any isolation of shunted regions.

These results indicate that solar cells with a shunt resistance that is worse than that introduced by the laser processing itself will benefit from laser isolation of those regions. It should be noted that removing sections of the solar cell will also affect the short circuit current and series resistance of the cell. However, due to the localized nature of most shunts the total area of isolated regions can generally be small, on the order of only one to two per cent of the total cell area. In a fully optimized process a cell could be assessed in terms of its potential to improve based on increased performance due to removal of poor regions and the decrease caused by the total area removed (perimeter of laser damage and area of poor current collection). The next section demonstrates the improvement in cell efficiency that we achieved with the laser isolation technique. The laser isolation is sequentially applied to different shunted regions in a strongly shunted cell and the cell is characterized after each laser step with PL imaging and Suns-V_{oc} measurements.

Cell recovery

The cell used to test the technique is an industrial 156 cm^2 solar cell that was rejected at the IV testing stage due to its extremely low fill factor (53·1%), resulting in a one Sun efficiency of only 9·6%. PL imaging of the finished cell, shown in Figure 3a, indicates several badly shunted regions in the center of the device. Where these regions intersect with a metal contact finger the influence of the voltage reduction can be seen extending along the affected fingers. There are also some regions close to the right edge of the cell in Figure 3 that appear as localized shunted points that exist between contact fingers.

The optimized laser settings from above were used to scribe boxes or circles around the affected areas. After the laser processing, Figure 3b, the influence of the high recombination is contained within the scribed boxes. These areas now represent isolated dead regions which do not contribute to the operation of the device. They

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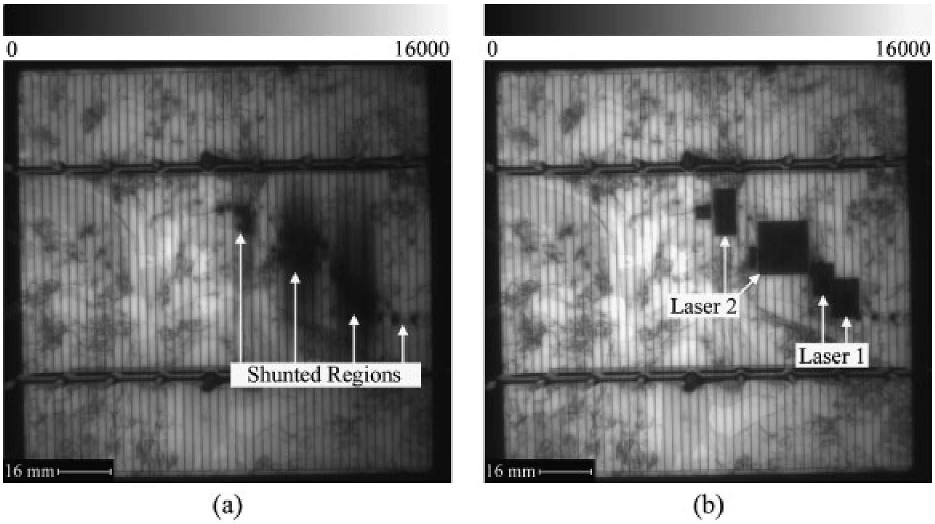

Figure 3. PL image of a 156 cm^2 silicon solar cell (a) before any laser processing and (b) after laser isolation of shunted regions

represent approximately 3·5% of the total cell area, leading to an expected reduction in short circuit current of 1 mA/cm^2. Importantly, carriers generated throughout the rest of cell are electrically disconnected from the shunted regions located inside the scribed boxes and circles and are no longer able to recombine there. Because the metal fingers are disconnected by the laser scribes, the shunted regions can no longer affect the voltage (and thus luminescence intensity) along those fingers outside the isolated regions as seen in Figure 3b. The higher average luminescence intensity in Figure 3b, that is, after the laser processing, indicates an improved open circuit voltage.

The Suns-V_{oc} measurements after individual laser isolation steps, shown in Figure 4a, clearly demonstrate the benefits of removing the shunted regions. Pseudo IV characteristics, shown in Figure 4b, were generated from the Suns-V_{oc} curves, assuming the same short circuit current density of 30·8 mA/cm^2 in order to get a quantitative estimate of the efficiency improvement after each step. The electrical data of the cell at various laser processing stages determined from the Suns-V_{oc} measurements are summarized in Table I. As more isolation boxes are added the fill factor and open circuit voltage increase significantly. After all laser processing (labeled ‘Final’ in

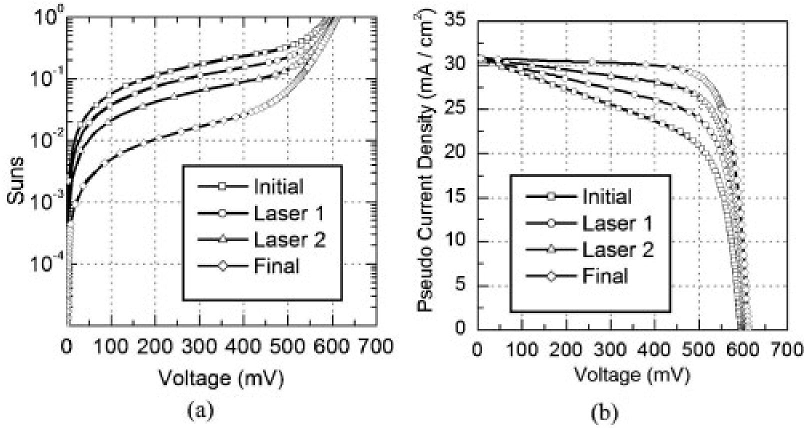

Figure 4. Electrical properties of a 156 cm^2 silicon solar cell after various amounts of laser isolation; (a) Suns-V_{oc} curves and (b) pseudo-IV curves

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Table I. Summary of pseudo IV characteristics, measured using Suns-V_{oc}, after various laser processes

Laser process	Thickness (μm)	Area (cm^2)	V_{oc} (mV)	Assumed-J_{sc} (mA/cm^2)	Pseudo-FF (%)	Rshunt (Ω.cm^2)	Pseudo-η (%)
Initial	300	156	594	30·8	57·2	35	10·5
Laser 1	300	156	604	30·8	64·5	52	12·0
Laser 2	300	156	608	30·8	71·2	98	13·3
Final	300	156	611	30·8	77·4	390	14·6

Table II. Summary of one Sun IV characteristics before and after application of the laser isolation process

Laser process	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
Initial	590	30·76	53·1	9·6
Final	605	30·00	72·9	13·3

Figure 4) the pseudo fill factor of the cell, as determined from the Suns-V_{oc} data, has increased from 57·2% to 77·4% and the open circuit voltage by 16 mV, leading to an increase in pseudo efficiency from 10·5% to 14·6%, that is, an improvement by 4·1% absolute.

Calibrated one Sun IV measurements of the cell, summarized in Table II, were carried out at Deutsche Cell prior to and after laser processing at UNSW. Both the open circuit voltage and fill factor of the device have increased significantly. The values for the fill factor are lower than those measured by Suns-V_{oc} since the light IV measurement includes the effects of series resistance. It should be noted that the impact of disconnecting fingers on the series resistance would be enhanced for regions not located between the busbars. The value for the short circuit current has decreased, leading to less of an improvement in efficiency than that predicted by the Suns-V_{oc} measurement. This is due to the area lost by the laser isolation resulting in a reduction in J_{sc} that is slightly less than the predicted amount of 1mA/cm^2 discussed above. Future improvements in the process will reduce this loss through more accurate removal of shunted regions rather than coarsely writing large squares around the shunted areas. Accounting for the reduced short circuit current density, the efficiency improvement by 3·7% absolute is in good agreement with the results from the Suns-V_{oc} measurements.

The improvement in the electrical properties of this cell demonstrates the potential of the proposed technique. The results indicate that further investigation into the application of the technique, involving a larger number of samples, is of interest. Future studies will attempt to further improve the technique by reducing the damage introduced by the laser scribing, particularly in the regions where the laser groove cuts metal grid fingers, and reduce its impact on the short circuit current through better localization of shunted regions. To be relevant to industry it is also necessary to perform hot spot testing to ensure that shunting in the cells has been reduced enough to avoid damaging modules. For the cell examined here a further reduction in the laser-induced damage will be required to achieve this. By examining a larger sample set (including more moderately shunted solar cells) it should be possible to better evaluate the tradeoff between the potential gains and the inevitable laser induced losses in cell performance. The potential gains that can be expected from this technique on moderately or weakly shunted cells will depend on the further improvement of the laser process and also depends on the specific cell design and on the exact nature of the shunt (e.g. extended shunts versus localized shunts).

CONCLUSION

The combination of PL imaging and laser scribing can provide an industrially applicable technique to reduce the impact of shunted regions in poor quality solar cells. The technique works by using a laser scribe to electrically isolate localized shunted regions from the device, thus reducing the impact of such regions. Here we have used

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the technique to increase the efficiency of a badly shunted solar cell from 9·6% to 13·3%. Future optimization of the laser parameters and identification of shunted regions may lead to even greater improvements in solar cell efficiencies. With imaging capture times of 1s and laser processing times less than 10s it would be a feasible process to integrate into a production line as a technique to increase average cell efficiencies and reduce yield losses due to shunting. While the experiments here were limited to shunted regions, we will also investigate the possibility to improve cell efficiencies by isolating local high recombination areas, such as local defect rich regions or local regions with high density of recombination active grain boundaries.

Here a proof of concept of the technique has been demonstrated on one solar cell. In order to fully assess the effectiveness of the technique, further work should be performed to investigate the application of the technique on a larger number of samples, including more moderately shunted cells. This assessment should also include hot-spot testing to ensure that the shunt resistance of the laser-processed cell is adequately reduced to avoid damage to modules.

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