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# Study of dark lines on the polycrystalline silicon solar cell and their influence on cell electrical properties

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## ABSTRACT

The aim of this work is to study the effects of dark lines on the face of polycrystalline silicon solar cells. The formative processes of dark lines were observed by laser scanning microscopy. Following the initial appearance of a few etch pits on the surface of the cells, extending the etching time saw these etch pits increase in size, eventually merging to form a single line, known as a 'dark line.' Dark lines are lines that are linked together by a series of contiguous dislocation outcrops and have the potential to reduce silicon wafer lifetime, adversely affect both the electroluminescence and the quantum efficiency of a solar cell, and have resulting negative effects on the cell's electrical properties.

## Introduction

Of the two types of silicon solar cells in commercial production – silicon-based film solar cells and crystalline silicon solar cells – the latter looks set to capture a major market share and to continue to hold the top spot over the next 10 years [1]. These cells can be further classified into monocrystalline silicon and multicrystalline silicon solar cells. Although the latter have lower efficiencies than monocrystalline silicon solar cells, the low production cost of the starting material for multicrystalline silicon cells brings with it greater potential for cost reduction.

Research is ongoing regarding the various methods of increasing the efficiency of multicrystalline silicon solar cells and enhancing the sector's market competitiveness. This research has involved such investigations as texturing, rapid thermal process (RTP), gettering processes and surface and body passivation [2]. However, improving the properties of multicrystalline silicon is the most vital factor behind increasing the efficiency of the resulting solar cells. 'Defect engineering' in multicrystalline silicon [3–9], which improves the macroscopic properties of Si by artificial microscopic control of structural elements, has come to be regarded as one of the most promising approaches to the development of crystal growing. This technique of manipulating defects to yield high-quality multicrystalline Si ingots is one that is being extensively pursued throughout the industry.

The $HNO_3/HF/H_2O$ solution system is currently the most widely used method of multicrystalline silicon wafer texturing in the industry. These dark lines tend to appear in an arbitrary distribution on the surface of multicrystalline silicon wafers after texturing. Preliminary studies suggest that the lines have a direct bearing upon the electrical properties of these cells, prompting the authors to carry out this study on the formative processes, mechanisms and essence of dark lines and their influence on the electrical properties of cells.

## The formation process of dark lines

For the purposes of observing the formation of these dark lines, four sister wafers were prepared for comparative analysis. The four wafers each feature similar grain shape and distribution, and were etched in a $HNO_3/HF/H_2O$ solution system for 30, 60, 90 and 180 seconds, respectively. Laser scanning microscopy (LSM) was used to observe the differences between the dark lines that formed on the wafers with respect to their different etching durations.

Fig. 1(a) shows the surface topography of the wafer that was etched for 30 seconds. At the beginning of the etching process, some etching pits were visible; however, these pits

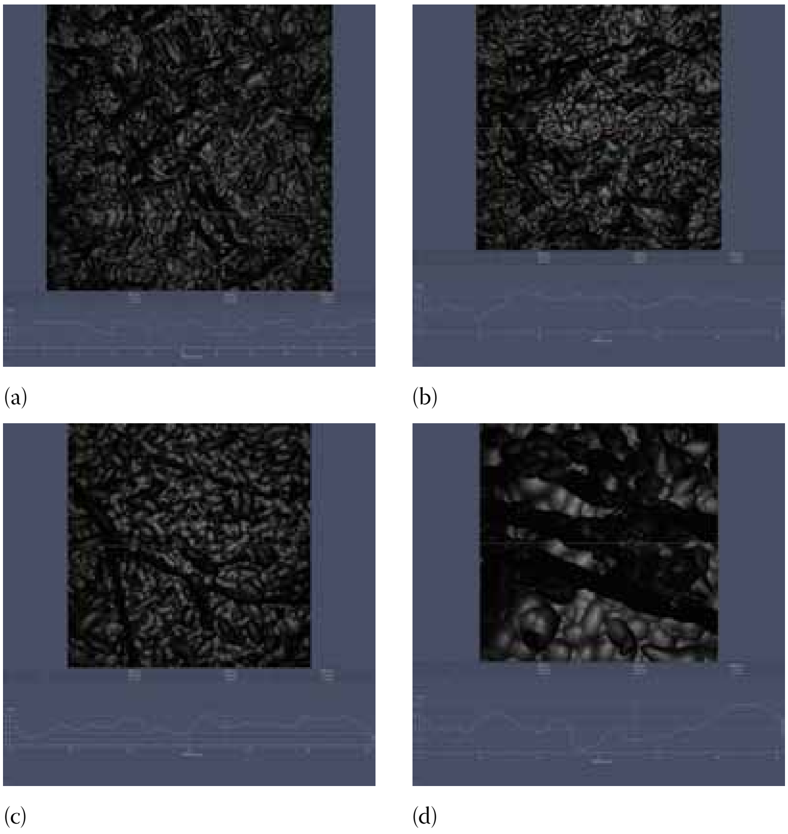
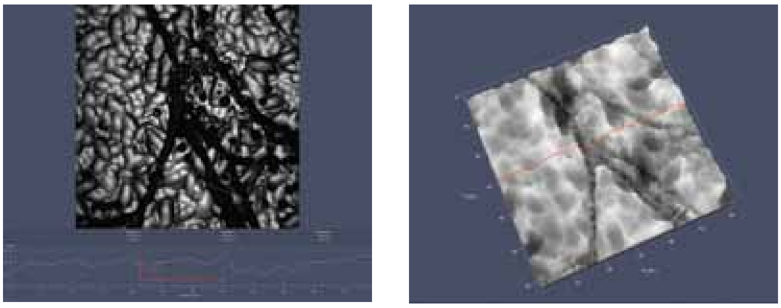
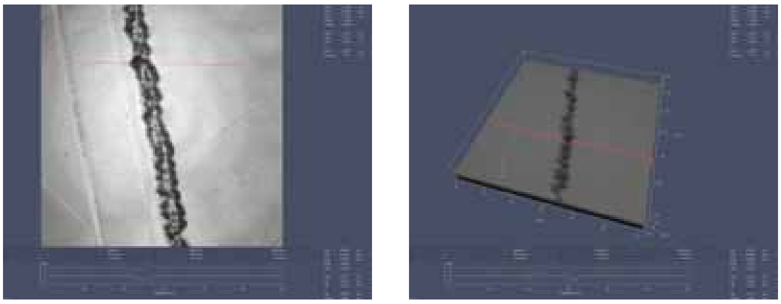


**Figure 1. Formative processes of dark lines on surfaces of wafers etched for (a) 30 seconds; (b) 60 seconds; (c) 90 seconds and (d) 180 seconds.**



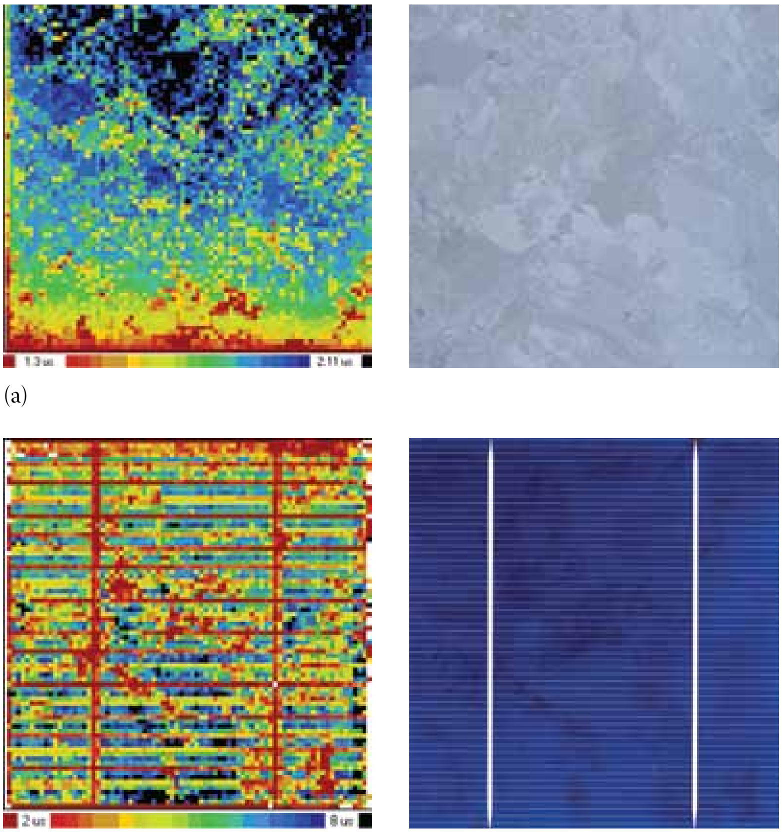
(a) (b)

Figure 2. Dark lines on multicrystalline silicon wafers in 2D (a) and 3D (b).



(a) (b)

Figure 3. Low angle grain boundary on monocrystalline silicon wafers 2D (a) and 3D (b).



(b)

Figure 4. Lifetime scanning images of a multicrystalline silicon wafer (a) and cell (b). Wafer: avg: 1.822µs; min: 0.646µs, max: 2.33µs; cell: avg: 4.418µs, min: 0.254µs, max: 94.963µs.

were in close proximity but not attached to each other. Fig. 1(b) shows the surface topography of the wafer etched for 60 seconds. As the etching time was extended, the pits expanded, and some proceeded to link together to form a line, but some of these dark lines were not fully developed.

The image in Fig. 1(c) shows the surface topography of the wafer that was etched for 90 seconds. On comparing this image with the images in Figs. 1 (a) and (b), it is clear to see that the lines in image (c) have become deeper and wider. There are also some underdeveloped dark lines, while several of the scattered etching pits have become clearer. This resulting surface topography is extremely similar to that found in large-scale production. Fig. 1(d) shows the surface topography of the fourth wafer, this time etched for 180 seconds. In this sample, the dark lines and pits were over-etched, while the dark lines themselves were too deep and wide for the wafers to have been used in a conventional solar cell manufacturing process.

## The formative mechanism of dark lines

As can be seen from the formative processes of dark lines, etching pits are the 'stepping-off point' for the study of the formation mechanisms behind dark lines. Firstly, the etching pits were more easily etched than any other areas of the multicrystalline silicon wafers in question, regardless of the degree of etching. Secondly, many scattered etching pits were visible, and they feature the same variation trend as the etching pits that eventually linked together to become the dark lines. Thirdly, the dark lines and etching pits were the same on both sides of the multicrystalline silicon wafers, so it can be deduced that these lines are the outward manifestations of the wafers' internal structures.

> “Etching pits are the 'stepping-off point' for the study of the formation mechanisms behind dark lines.”

Figs. 2 and 3 show dark lines on a multicrystalline silicon wafer and a low angle grain boundary on a monocrystalline silicon wafer, respectively. Comparing these 2D and 3D LSM images shows that the two have very similar microstructures, both consisting of an amount of etching pits linked together to form a line.

Contiguous dislocation, a feature that is easily etched along the dislocation line, and the etching pits on the face of multicrystalline silicon wafers form the dislocation outcrops after the acid etching step. Dark lines, then, are lines that are linked together by a series of contiguous dislocation outcrops, frequently occurring in the grain – very different from the composition of high angle grain boundary.

Kun Huang's *Solid-state physics* explains the phenomenon as follows: "There are different areas in one grain, and the angles between crystal lattices are very small. It may be taken for granted that the low angle grain boundaries in one grain are formed by the arrangement of a series of contiguous dislocations" [10], leading us to the conclusion that low angle grain boundaries take the form of dark lines after acid etching.

## Influence of dark lines on electrical properties of cells

### Wafer and cell lifetime

Fig. 4 shows lifetime scanning images of a multicrystalline silicon wafer (a) and cell (b). It is clear from these images that low lifetime areas correspond with the areas that feature dark lines, and that both the wafer and the cell are in accordance with this situation. The extent of the influence is different owing to the differences between the type and concentration of impurities and defects in question. However, generally speaking, the areas with dark lines tend to have lower lifetime, even taking into account the presence of $SiN_x$ passivation film.

### Electroluminescence (EL)

Considering the danger these dark lines can pose to the lifetime of wafers and cells, the next logical step was to investigate the level of damage inflicted by them on the cell's electrical properties. Six sister wafer sets were arranged according to the quantity and distribution of their dark lines, with the quantity of lines increasing from wafer (a) to wafer (f). The wafers were then made into cells and subjected to tests for electrical properties and EL.

Fig. 5 shows EL images of the different cell classes. The dark areas within the EL images correspond to the areas that showed the presence of dark lines. It was also found that the degree of luminescence within these zones is much lower than other areas that did not feature the dark lines. It can be concluded, therefore, that the areas that formed the dark lines have weaker electroluminescence properties, and consequently, these areas are lower in efficiency.

Table 1 shows the electrical properties of the different cell classes under investigation in this study. As the number of dark lines increases, cell electrical properties such as $V_{oc}$, $I_{sc}$ and FF decrease gradually, a pattern that fits the trend of EL. Furthermore, the distribution of these dark lines has as great an effect as these electrical properties. Similar quantities of decentralized dark lines are far less harmful to the cell than dark lines that cluster together.

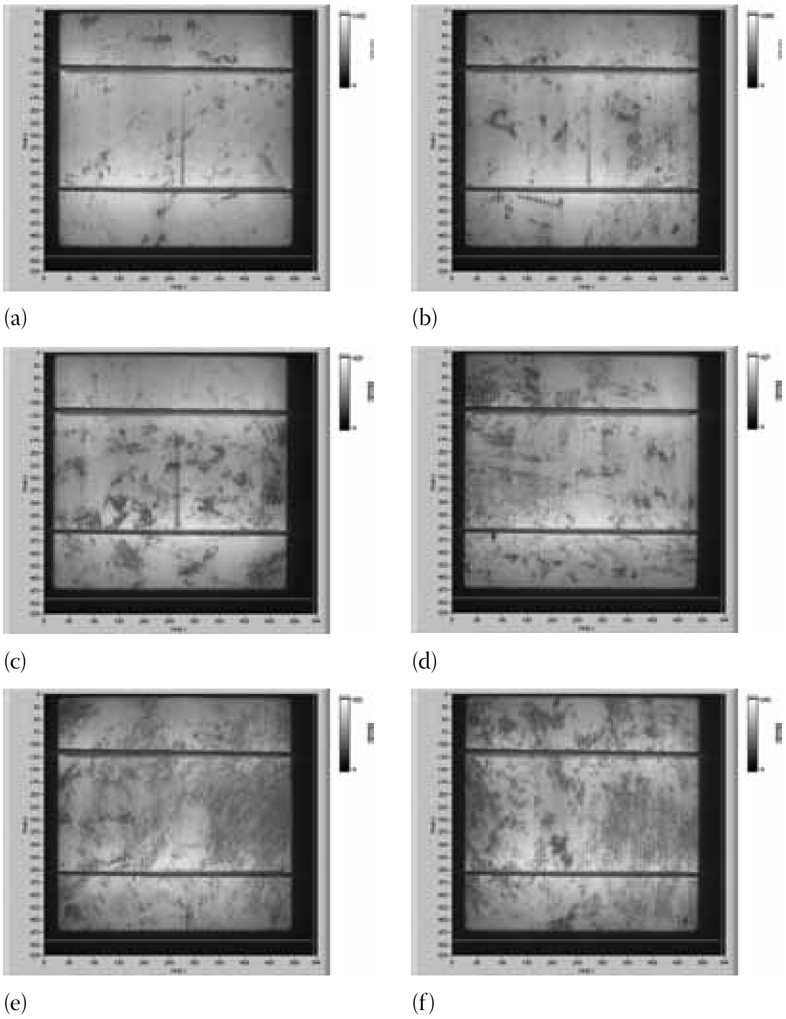


Figure 5. EL images of six different cell classes (see data in Table 1).

### Quantum efficiency (QE)

As a result of this relationship between the quantity and distribution of dark lines and the resulting cell's electrical properties, it is safe to state that dark lines form one of the most vital factors in terms of determining the cell's electrical properties. The impurities and defects that gather together and form these dark lines lead to a drop in electrical properties of the solar cell.

Fig. 6 shows the quantum efficiency (QE) and reflectivity result of the areas with and without dark lines. It can be seen from the graph that the area with dark lines has lower reflectivity in the 300–600nm wavelength, while in the 600–1100nm wavelength, both areas have almost the same reflectivity. As regards IQE, the 300–1100nm wavelength area shows lower values than the area without dark lines. This gap is seen to get wider from 700nm to 1100nm, a direct result of the increase in impurities and wafer defects. As a result of the effects of reflectivity in the 300–600nm wavelength, the areas with and without dark lines have the same EQE. In the 600–1100nm range, the EQE of the area with dark lines is lower due to the disadvantage

| | $J_{sc}$/mA/cm$^2$ | $U_{oc}$/v | FF/% | $N_{cell}$/% |
|---|---|---|---|---|
| a | 34.97 | 0.629 | 77.14 | 0.1696 |
| b | 34.74 | 0.623 | 77.91 | 0.1687 |
| c | 34.56 | 0.622 | 77.12 | 0.1658 |
| d | 34.17 | 0.623 | 76.70 | 0.1632 |
| e | 34.02 | 0.619 | 76.38 | 0.1609 |
| f | 33.56 | 0.618 | 76.47 | 0.1586 |

Table 1. Electrical properties of the six different cell classes.

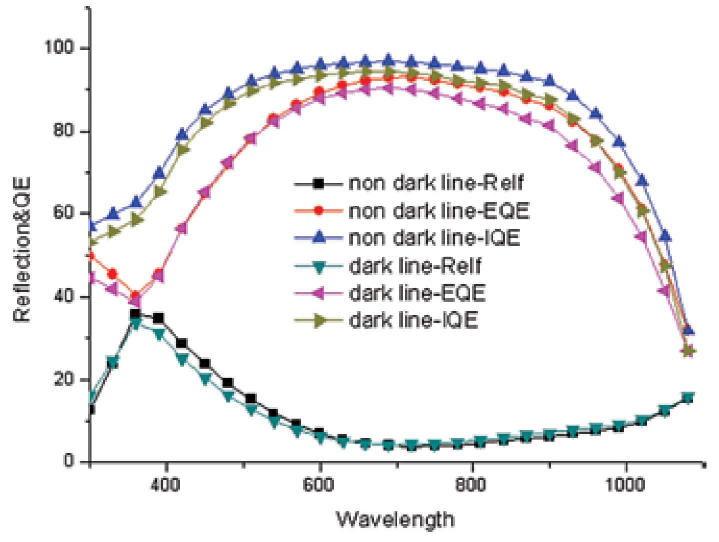


**Figure 6. Quantum efficiency and reflectivity results of the areas with and without dark lines.**

of IQE; however, this range does not have the benefit of reflectivity.

## Summary

The study conducted in this paper arrived at a series of conclusions. The formative processes of dark lines were observed by LSM, showing the appearance of several etch pits on the surface. As etching time increased, these etch pits became bigger, some linking together to form one line, now known as a dark line, or lines that are linked together by a series of contiguous dislocation outcrops.

Dark line were found to have the potential to reduce the lifetime of silicon wafers, while also having an adverse effect on electroluminescence, quantum efficiency and various other electrical properties. The quantity and distribution of these dark lines is one of the most crucial factors in improving the electrical properties of multicrystalline silicon cells. It is possible that this problem can be addressed by the development of a crystal growth technique that is capable of manipulating such defects, allowing the creation of high-quality multicrystalline Si ingots, which are the building blocks of high efficiency multicrystalline silicon solar cells.

## Acknowledgements

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