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current topics in solid state physics

Material effects in manufacturing of silicon based solar cells and modules

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The performance and efficiency of solar cells depends strongly on influence of materials. Key topics for solar cell optimisation are presently silicon material properties and materials for cell metallisation. Optimisation of silicon is focussed e.g. on material properties such as impurity content, density of dislocation and grain boundaries in multi-crystalline silicon which influence parameters like carrier lifetime, and therefore the cell efficiency. Improved characterisation methods of solar cells like electroluminescence and photoluminescence are combined with techniques such as thermography and LBIC to improve production process and materials. As a result cell efficiency will be increased. Optimisation of cell metallisation and module interconnects is strongly related to progress in paste materials for front side metallisation. Improved materials enable the use of higher emitter resistance and the printing of smaller metal lines, while reducing the series resistance of the solar cell. Progress in paste materials leads to increased solar cell efficiency for the standard cell process. The introduction of new metal pastes has to be combined with careful optimisation of the process window in soldering during module built-up.

1 Introduction The target of solar cell and module manufacturing is to achieve highest efficiency at lowest cost per Watt peak.

Silicon wafers as substrate material for solar cells contribute 30-40% to the cost of a solar cell. Material properties of multi crystalline silicon, e.g. intrinsic defects like dislocation networks and grain boundaries and extrinsic defects like impurities, affect the minority carrier lifetime and have a key influence on solar cell efficiency [1-4]. Characterisation techniques like μ-PCD (Microwave PhotoConductance Decay), LimoLIT (Light modulated Lock-in Thermography), VomoLIT (Voltage modulated Lock in Thermography), LBIC (Light Beam Induced Current) and EL (Electroluminescence) are essential to get data on silicon material properties, which can be correlated with the solar cell performance.

The relatively high cost of silicon for solar cells has caused a high focus on technological progress in silicon crystallisation, which may affect concentration and distribution of impurities and crystal defects. Therefore a good understanding of silicon characterisation and the relationship between silicon material properties and solar cell efficiency is crucial to reduce the costs per Watt peak even further.

The metallisation of silicon solar cells is also a major contributor to cell efficiency and cost effectiveness. Cell metallisation is widely based on screen printing of metal pastes on front and back side of the cells. On the back side an Al metal layer provides the contact and the back surface field. The front side metallisation consists of an Ag based metal layer which is formed by printing and firing of silver containing metal paste.

The paste has to provide low contact and series resistances while the metal lines have to be as small as possible to avoid shadowing of the solar cell at its sunny side. Because of conflicting requirements of good contact and series resistance and small lateral dimension of the metal fingers the front side paste is a key topic for cell optimisation. Although the screen print technology is challenged by new developments like metal plating it is the mainstream metallisation technology up to now. The progress in paste technology combined with smaller metal lines on the front side extends this dominating role of screen print in solar cell production.

This paper describes key influences of mc-silicon material and metal pastes on solar cell performance.

2 Experimental For solar cell processing, a conventional cell process was used including screen print for Al back surface field and Ag front side metallisation. Commercially available B-doped mc-silicon wafers with a thickness of 180-200 µm served as starting material.

The analysis of the silicon substrate material was carried out on as-grown wafers as well as on solar cells. µ-PCD was used to determine the lifetime of minority carriers of as-grown wafers. Completely processed cells were characterised by LimoLIT (carrier recombination in silicon), VomoLIT (shunt analysis), EL (defect analysis) and LBIC (diffusion length of charge carriers).

For front side metallisation commercially available Ag pastes with different rheologies and print conditions were investigated.

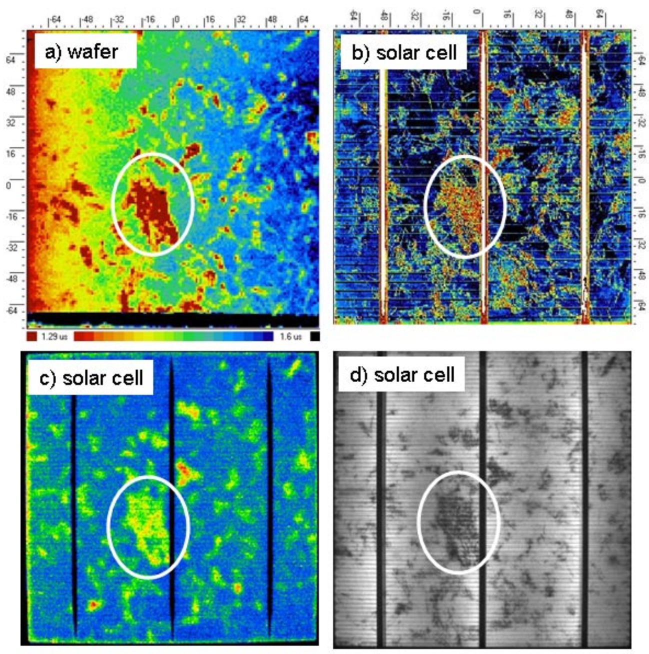

Figure 1 a) µ-PCD-map of a mc-wafer, b) LBIC-map, c) LimoLIT-map and d) EL-map of a mc-solar cell. a), b), c) Red regions indicate low wafer/cell performance; blue regions indicate high wafer/cell performance. d) Dark regions indicate low cell performance; light regions indicate high cell performance. White circles mark a region with high dislocation density.

3 Results and discussion

3.1 Effect of dislocations The quality of the substrate material has a strong impact on the efficiency of mc-Si solar cells. Contaminated intrinsic crystal defects e.g. dislocations and grain boundaries are recombination centres for charge carriers reducing their lifetime and diffusion length. The characterisation of wafers and solar cells by different methods shows a clear correlation between the occurrence of dislocations, carrier lifetime and solar cell efficiency.

Figure 1 summarizes the results of four different measurements on wafers (µ-PCD) and cells (LBIC, LimoLIT, EL). In all four pictures local areas with dislocation clusters can be clearly distinguished from the rest of the cell (marked by white circle). The existence of dislocation networks was confirmed by SEM (samples prepared by defect etch).

The dislocation networks change the local properties of the material in the following way:
Areas with a high dislocation density:
- have lower lifetimes (Fig. 1a)
- have lower diffusion lengths (Fig. 1b)
- show increased recombination (Fig. 1c)
- are less luminescence-active (Fig. 1d)

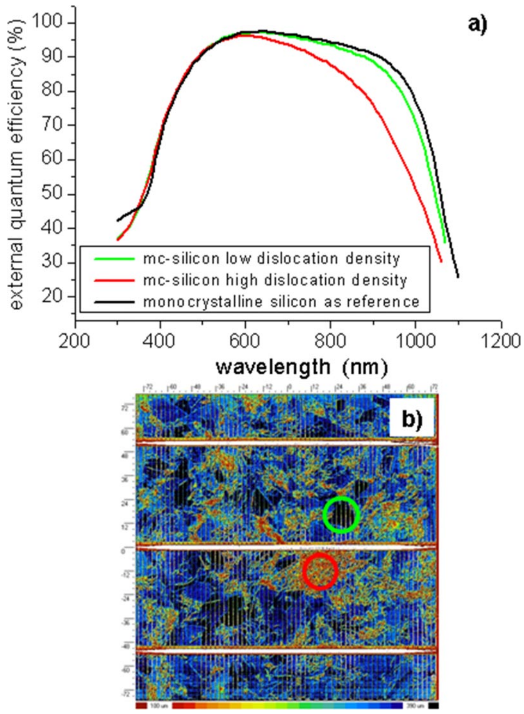

Figure 2 a) Quantum efficiency (QE) as function of wavelength for mc-silicon areas with high dislocations density (red curve) and low dislocation density (green curve). QE of monocrystalline silicon solar cell is shown as reference (black curve). b) LBIC map of solar cells for areas shown in QE (a) green circle: low dislocation density red circle: high dislocation density.

The areas of high dislocation density show also a different external quantum efficiency (EQE) compared to areas with low dislocation density (see Fig. 2). While for wavelengths < 600 nm EQE is similar to a dislocation-free area, it is reduced for larger wavelengths. This gives evidence that dislocations are mostly affecting the bulk of the solar cell. Areas with high dislocation density reduce the short circuit current and therefore deteriorate the efficiency of the solar cell.

The comparison of different methods reveals that electroluminescence is a reliable method to detect dislocation cluster in silicon. Since EL characterisation only takes a few seconds, it is valuable technique for defect characterisation in high-volume production.

Statistical analysis of EL data from volume cell production gives strong evidence for a correlation between cell efficiency and density of dislocations. Figure 3 shows the percentage of cells with dislocation networks covering a significant part of the cell area for different efficiency classes. The evaluation of the analysis shows that for 80-100% of low-efficiency cells a high dislocation density is the main reason for their poor efficiency. By contrast, less than 10% of high-efficiency cells exhibit dislocation networks with significant size.

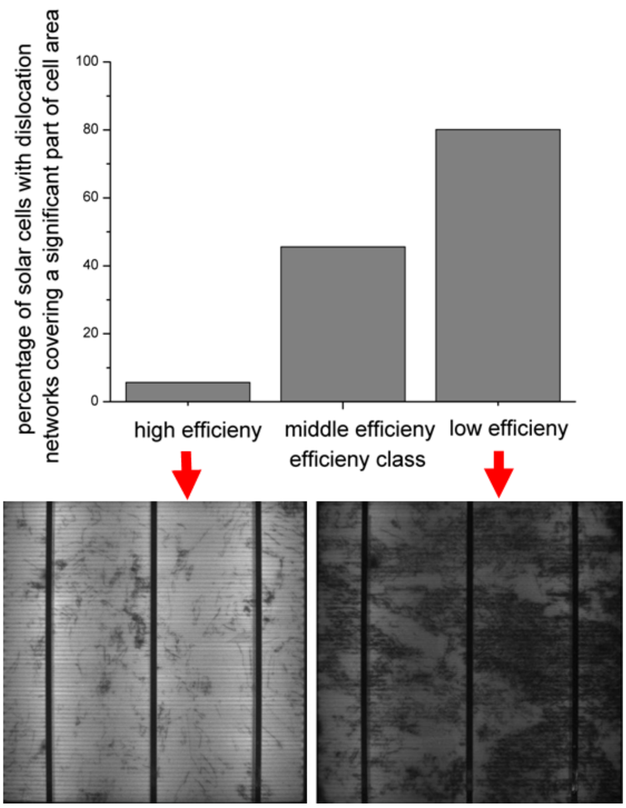

Figure 3 Percentage of solar cells with significant cell area covered by dislocations for different cell efficiency classes. Below EL pictures of representative cells are shown.

3.2 Effect of impurities In addition to intrinsic defects, the quality of the solar cell is also influenced by impurities. Here, metallic and non-metallic impurities are distinguished.

In this work we investigate the effect of carbon as one major non-metallic contamination which influences the wire sawing process as well as the performance of solar cells. SiC may occur in the upper part of mc-silicon ingots in form of clusters and filaments [5-7]. Large SiC clusters cause saw marks [8] which lead e.g. to a deterioration of the metal printing process. In addition saw wires can be damaged. Figure 4a shows an example of a typical saw mark. Investigations with SEM and EDX reveal SiC as root cause of this saw mark (see Figs. 4b and c).

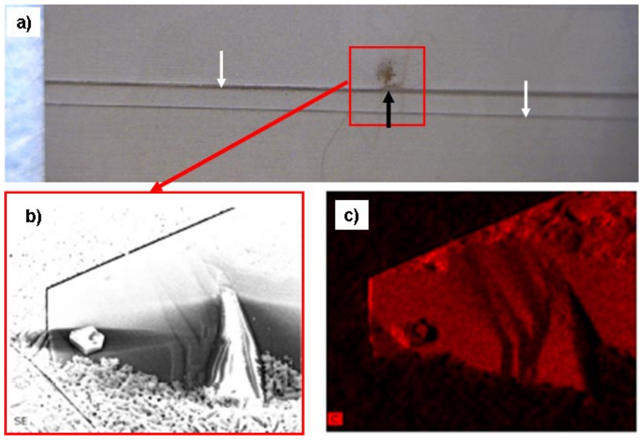

Figure 4 a) Saw marks on the surface of a wafer (indicated by white arrows). The inclusion is marked by a black arrow. b) SEM-image of the inclusion decorated with Secco etch. c) Carbon mapping with EDX from the same inclusion.

SiC inclusions also deteriorate solar cells by Ohmic shunts [9, 10] and reduce the cell efficiency. Again, characterisation techniques like LimoLIT are very powerful to detect such type of defect of the solar cell (see Fig. 5).

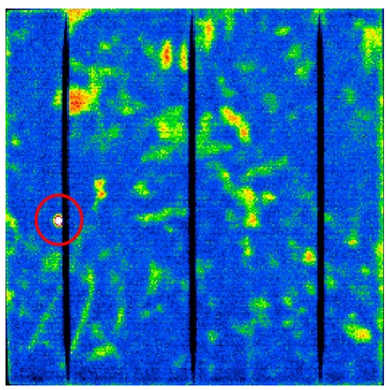

Figure 5 Ohmic shunt caused by a SiC precipitate (red circle) as visible in LimoLIT analysis. VomoLIT has been used to verify the Ohmic shunt behavior.

3.3 Optimisation of screen printing For the front side of the solar cell the printing of fine metal lines with high aspect ratio is important. Finer lines reduce shadowing of the solar cell, high aspect ratios allow better lateral resistance. Together with these requirements the paste has to be designed for good contact resistances, especially for higher emitter resistances.

Over the last years the development of new Ag based pastes improved contact properties which enabled the introduction of higher emitter resistances (up to 80 Ohm/sq) into cell production. At the same time the print process got more attention.

Figure 6a shows a SEM of a metal finger made by standard printing process which was subject of optimisation. The right combination of paste and screen printing process results in finger widths lower than 60 µm, while the height of the line was improved to 30 µm (see figure 6b). This result could be achieved by using a single print step process. The trend to a higher aspect ratio of metal finger formation will continue and even include the use of advanced screens [11].

Together with the introduction of new pastes the optimisation of the soldering process in module production gains importance, to prevent a reduced process window in soldering by additional stress between cell and ribbon interconnect. Again electroluminescence evolved as key technique for defect characterisation.

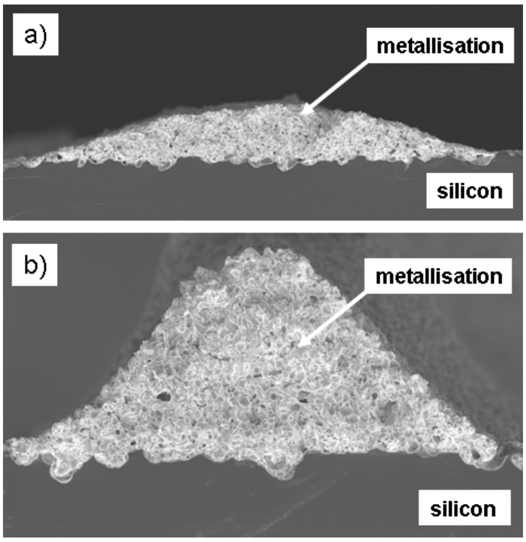

Figure 6 SEM of front side metal fingers. a) standard paste, b) paste with improved rheology combined with optimisation of print conditions.

4 Conclusion In this paper key material influences on solar cell performance were discussed. One of the main reasons for low efficiency of solar cells is the quality of the silicon material. A high density of dislocations in the silicon reduces the short circuit current in the bulk of a solar cell. SiC clusters are disadvantageous due to sawing mark generation and the formation of Ohmic shunts. Electroluminescence measurements allow a good and fast characterisation of material effects on solar cells and show consistent results to other characterisation methods.

By optimisation of front side metallisation (paste and print conditions) a higher aspect ratio of metal fingers has been achieved to improve the solar cell performance.

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References

[1] C. Donolato, J. Appl. Phys. **84**, 2656 (1989).
[2] M. Bertoni, C. Colin, and T. Buonassisi, Solid State Phenom. **156**, 11 (2010).
[3] M. Kittler, W. Seifert, and K. Knobloch, Microelectron. Eng. **66**, 281 (2003).
[4] J. Chen, B. Chen, W. Lee, M. Fukuzawa, M. Yamada, and T. Sekiguchi, Solid State Phenom. **156**, 19 (2010).
[5] J. P. Rakotoniaina, O. Breitenstein, M. Werner, M. Hejjo Al Rifai, T. Buonassisi, M. D. Pickett, M. Gosh, A. Müller, and N. L. Quang, Proceedings of the 19th European PVSEC, (2004).
[6] M. Hejjo Al Rifai, O. Breitenstein, J. P. Rakotoniaina, M. Werner, A. Kaminski, and N. L. Quang, Proceedings of the 19th European PVSEC, (2004), p. 632.
[7] A. K. Søiland, E. J. Øvrelid, T. A. Engh, O. Lohne, J. K. Tuset, and Ø. Gjerstad, Mater. Sci. Semicond. Process. **7**, 39 (2004).
[8] G. Du, N. Chen, and P. Rossetto, Semicond. Sci. Technol. **23**, 055011 (2008).
[9] O. Breitenstein, J. P. Rakotoniaina, M. H. Al Rifai, and M. Werner, Prog. Photovolt, Res. Appl. **12**, 529 (2004).
[10] O. Breitenstein, J. Bauer, and J. P. Rakotoniaina, Semiconductors **41**(4), 440 (2007).
[11] J. Hoornstra and B. Heurtault, Proceedings 24th European PVSEC (2009), p. 989.