ELECTRICAL INVESTIGATIONS ON SiC PRECIPITATES FOUND IN BLOCK-CAST SOLAR SILICON

Jan Bauer[1*], Otwin Breitenstein[1], Michael Becker[1], Jörg Lenzner[2]

[1]Max Planck Institute of Microstructure Physics Halle
Weinberg 2, D-06120 Halle (Saale), Germany
[*]phone: +49 345 5582979, electronic mail: jbauer@mpi-halle.mpg.de

[2]Universität Leipzig, Institut für Experimentelle Physik II
Linnéstraße 5, D-04103 Leipzig, Germany

Abstract In multicrystalline silicon solar cells linear shunts were found, which were caused by silicon carbide precipitates. These silicon carbide preciptitates have been isolated from the bulk material to investigate their electrical properties and to investigate the shunt mechanism. Current-voltage characteristics and four-point probe measurements were performed on the silicon carbide precipitates. In addition to the investigations on isolated silicon carbide preciptitates, current-voltage and capacitance-voltage characteristics were measured on precipitates, which were still embedded in the silicon bulk material. The results show that the silicon carbide precipitates are highly n-conductive, and a simulation of the shunt shows that the shunt current flows inside the silicon carbide material. Photoluminescence and cathodoluminescence measurements on the silicon carbide precipitates reveal that they emit green light and therefore should be detectable by luminescence methods.

1. Introduction

In solar cells, which were made of block-cast multicrystalline (mc) silicon, one finds shunts decreasing the efficiency of the affected solar cells. A well-known technique to detect shunts in every kind of silicon solar cells is dark lock-in thermography DLIT[1]. Briefly, a pulsed bias of 0.5 V (which corresponds approximately to the working point of a commercial silicon solar cell) is applied to the cell. A thermo camera detects local heat sources, which occur on the cell. These local heat sources correspond to shunts. Different shunt types, which were detectable with LIT are known and were described elsewhere[2]. A so-called linear or ohmic shunt is given, if the signal, detected by the camera at 0.5 V forward bias at a certain area on the cell, has the same magnitude as the signal, which is detected at -0.5 V reverse bias at the same area.

In further studies[3,4] it was found that in block-cast multicrystalline silicon for solar cells several precipitates occur and are responsible for shunting. We have found silicon carbide (SiC) cluster, silicon nitride (Si_3N_4) rods and SiC filaments. There are SiC filaments, which grow from SiC clusters within the crystallites, and SiC filaments, which grow in grain boundaries.

Al-Rifai et al.[3] showed that SiC filaments may cause linear shunts, but nothing was known about the electrical properties of the SiC and the linear shunt mechanism at this stage of investigation. It was assumed that an inversion channel is formed at the interface between the solar cell substrate material (p-type silicon) and the SiC precipitates[2] and that the shunt current flows in this inversion channel, but the correct shunt mechanism was not clear so far.

The main aim of this paper is to describe investigations of the electrical properties of SiC precipitates in mc solar silicon, to describe a model of the linear shunt mechanism and to show a new possibility how to detect SiC precipitates in mc silicon wafers.

2. Experimental

The first problem to investigate the SiC precipitates separately is to isolate them from the bulk material. To find the precipitate positions we use DLIT to detect all linear shunts in mc Si solar cells. The shunted areas of the cell are cut out and polished from both sides. After that we image the sample with an infrared microscope and can identify different precipitates, which are shown in Fig 1a).

To perform different electrical measurements on the precipitates, it was necessary to isolate them from the bulk. For that we use a 1:3 mixture of HF (50%) and HNO_3 (65%), where we put in the Si sample containing the precipitates in a Teflon funnel. Since SiC and Si_3N_4 are chemically resistant against the HF-HNO_3 mixture, they remain in the acid mixture and can be separated from the liquid. A scanning electron microscope (SEM) image of the different precipitates is shown in Fig. 1b).

The second problem to investigate the SiC precipitates was that their diameter is in the range of some micrometers. For this we use two nanomanipulators within a SEM. These manipulators give us the opportunity to probe the precipitates very carefully. Each manipulator is equipped with a platinum-iridium (Pt-Ir) tip to contact the SiC filaments electrically. The manipulators can be also equipped with a four-point probe to get information about the doping type of the precipitates. To get the voltage-current (I-V) characteristics we use a picoamperemeter with an internal voltage source (Keithley 6487, $\leq$2 fA noise). For the voltage-capacitance (C-V) measurements we use a Booton 7200 capacitance meter and the four-point measurement was performed by a Veeco FPP-5000. Electron beam induced current (EBIC) measurement on SiC filaments, which are still embedded in Si bulk material, were performed with a self made amplifier and show us the electronic structure of the heterojunction SiC – Si. To test the ability of the detection of SiC precipitates in Si wafers by luminescence measurements, we used cathode luminescence (CL) measurements in a SEM and performed photo luminescence (PL) measurements in a Raman spectrometer.

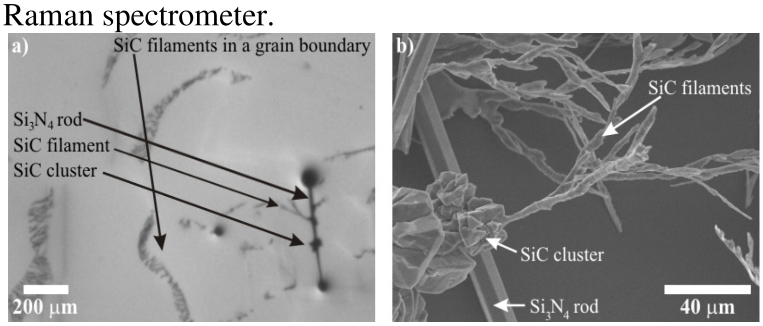

Fig. 1: SiC and Si_3N_4 precipitates found in a mc Si solar cell wafer after polishing the shunted area of the cell a), SEM image of SiC filaments, SiC cluster and Si_3N_4 rods after isolation from the bulk b).

3. Results

The two-point probe measurements of the SiC filaments, which can be seen in Fig. 2a), shows a linear behavior, and a resistance in the order of 15 Ω can be calculated from the slope of the curve (Fig 2b). By using the geometric dimensions of the SiC filaments, the specific resistance ρ can be calculated to be ρ = 0.002 Ωcm. To find out the doping type of the SiC filaments, a four-point probe measurement was performed on several SiC filaments (see Fig. 2c). It turns out that all the SiC filaments are n-type doped. Using ρ and a carrier mobility of 400 V/cm^2 for the electrons, the carrier density of the SiC can be estimated to be in the order of 8 x 10^{18} cm^{-3}.

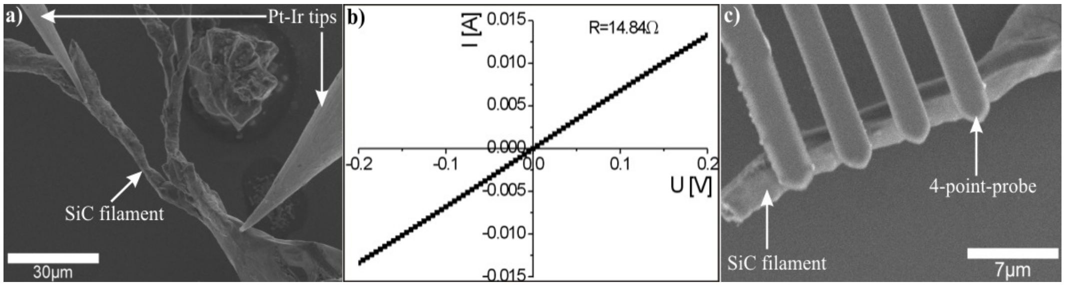

Fig. 2: Two-point probe measurement of a SiC filament with two Pt-Ir tips a), I-V characteristic of the SiC filament b), and four-point probe measurement of a SiC filament c).

Since the SiC filaments are embedded in the p-type solar cell material, it would be interesting to measure the electrical behavior of the heterojunction n-SiC to p-Si (here, n stands for n-type doped and p for p-type doped material). Figure 3c) shows the I-V measurement of the heterojunction. The I-V curve is rectifying and behaves like a p-n junction, as expected. By performing a C-V measurement on the heterojunction and extrapolating the $1/C^2$-view of the C-V curve to $1/C^2=0$, the diffusion voltage was determined to be $U_D = 1.1$ V. In Fig. 3b) an EBIC image of the interface between n-SiC and p-Si is shown. The EBIC signal at the interface leads to the conclusion that there is a barrier for the electrons.

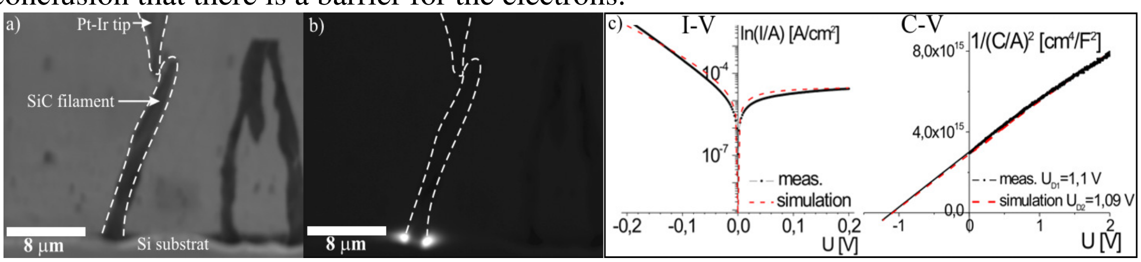

Fig. 3: SEM image of a contacted SiC filament, which is still embedded in the bulk a), EBIC image of the same SiC filament b), and I-V & C-V characteristics of the system SiC – Si with simulated curves c).

We performed cathodoluminescence (CL) and photoluminescence (PL) measurements to check whether the SiC filaments emit light. The image in Fig. 4a) shows SiC filaments, the corresponding CL measurement can be seen in Fig 4b). A broad peak of the CL intensity appears with a maximum at about 2.4 eV. In Figure 4c)-e) a PL measurement at a grain boundary, which contains SiC filaments, is shown. The PL intensity in the Si area is negligible, only the Si Raman shifted peak at 500 nm is observable, but the PL intensity of SiC the filaments is strong. A maximum of the PL intensity appears at 2.4 eV, which corresponds to a light wavelength of about 508 nm (green light) and is consistent with the CL measurement.

4. Discussion

Since the SiC filaments are highly doped and therefore highly conductive, they may cause ohmic shunts in solar cells by short-circuiting the emitter with the backside contact of the solar cell. We have to mention that the SiC is doped by nitrogen, which acts as a shallow donor in SiC. The existence of N in the material is proven by the appearance of Si_3N_4 precipitates in Si bulk material.

The question, whether the shunt current flows in the filaments or in an inversion channel around them[2], can be answered by simulating the electrical properties and electronic structure of the heterojunction and regarding the simulated band diagram. We simulate the I-V and C-V curves of the system n-SiC – p-Si with AFORS-HET[5]. In Fig. 3c) one can see a quite good correlation between the measured and simulated I-V and C-V curves. With the parameter set, that shows this good correlation, we simulated the band structure of the heterojunction. It turns out that there is a very low positive conduction band offset at the interface. Since the barrier is very low (some ten meV) and very narrow, because of the highly doped SiC, the electrons can overcome or tunnel through this barrier very easily and no inversion channel will be formed on the interface between SiC and Si.[6]

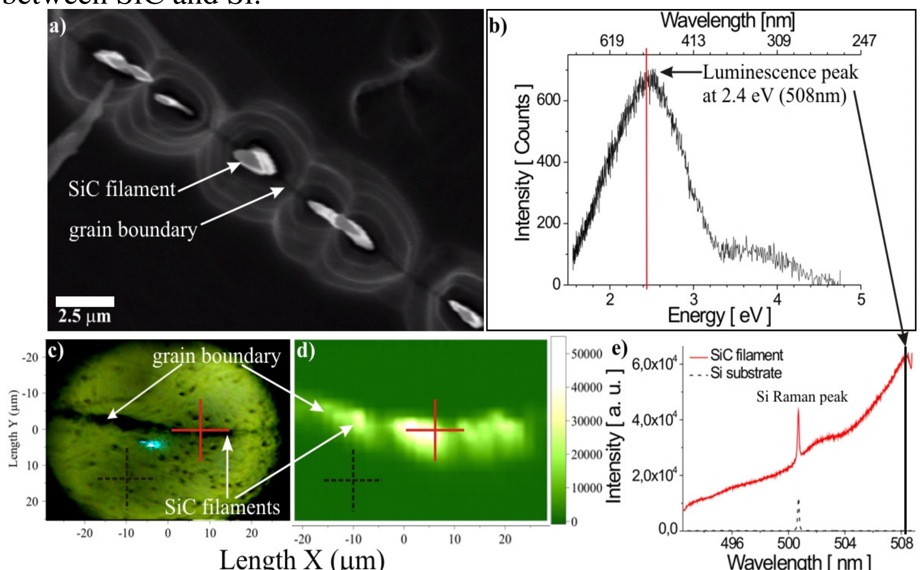

Fig. 4: SiC filaments in a grain boundary a), and the corresponding CL spectra with a peak at 508 nm b), light microscope image of a grain boundary containing SiC filaments c), and the corresponding PL mapping d). In e) the PL spectra of the cross-marked points are shown. The PL spectra of the Si shows only the Si Raman peak (black dotted line), the PL spectra of the SiC filament (red solid line) shows a broad peak at 508 nm. For PL a Laser with λ=488 nm was used.

5. Conclusion

Ohmic, material induced shunts in mc Si solar cells are often caused by SiC filaments, which grow in mc Si blocks. The SiC filaments are highly n-doped by nitrogen and are highly conductive. Our model of the shunt mechanism shows that the shunt current flows in the SiC filaments. SiC filaments emit green light if they were exited by photons or electrons during CL or PL measurements. Therefore PL and CL measurements are methods to detect SiC filaments in mc Si wafers and maybe for avoiding shunts.

References

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