COMPARISON OF SPATIALLY RESOLVED CARRIER LIFETIMES IN mc-Si WITH SOLAR CELL AND MATERIAL CHARACTERISTICS

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ABSTRACT

We introduce a novel application of modulated free carrier absorption (MFCA) for measuring minority carrier lifetimes in multicrystalline silicon with high spatial resolution. The improved lateral resolution compared to other contactless techniques allows the correlation between these lifetime maps and solar cell characteristics as well as microscopic properties, like dislocations, precipitates, oxygen concentration, etc.. Comparisons of the lifetime maps measured on the starting material and light beam induced current (LBIC) maps exhibit a very good qualitative correlation of the structures observed in both cases. In addition, correlations to microscopic characteristics like high dislocation density in regions with low lifetimes are investigated and a comparison with spatially resolved FT-IR measurements of the interstitial oxygen concentration is performed.

INTRODUCTION

Knowledge about the lateral spatial distribution of silicon quality is essential in analysing semiconductor device performance. In solar cells the minority carrier lifetime is a crucial parameter for obtaining high energy conversion efficiencies. For multicrystalline material an integral lifetime value is not sufficient; only a lateral lifetime distribution gives the necessary information for solar cell and crystal growth technology. Solar cell processing steps like phosphorous diffusion, oxidations and the related gettering effects and temperature stress are all expected to change the local volume lifetime in different ways [1],[2],[3]. We used a newly developed lifetime mapping technique with high spatial resolution and optical detection, modulated free carrier absorption (MFCA), to determine lateral lifetime distributions. Compared to conventional techniques (e.g. microwave detected PCD), MFCA extends the resolution range of contactless lifetime measurements into the range of microscopically imaging methods like EBIC or LBIC without requiring a collecting junction. In contrast to a resolution enhancement in a µW-PCD setup by focussing the generation spot the method locally probes the excess minority carrier distribution generated over a wider area.

Clarifying the mutual relation of lifetime and the resulting solar cell current distributions (measured with LBIC), as well as crystal parameters like the dislocation density or the interstitial oxygen concentration \([O_i] \) is of great interest for improving material quality. In the first part of this paper the relevance of the local lifetime variations measured with MFCA for the solar cell is established. In a second step it is investigated if a correlation between microscopic characteristics, like etch pit densities and interstitial oxygen concentration, with lifetime maps could be observed.

METHOD OF APPROACH

Lifetime measurements using modulated free carrier absorption (MFCA) [4],[5] can be extended to obtain high resolution lifetime maps [6]. The method uses a focused IR-beam \((\lambda = 3.4 \ \mu m)\) which transmits the sample to detect the local excess carrier density photogenerated over a wider range of about 1 cm\(^2\) by a sine modulated laser.

Fig. 1. Modulated free carrier absorption (MFCA) setup
diode ($\lambda = 780$ nm). The detection spot size is presently about 200 $\mu$m representing a good compromise between spatial resolution and data collection and handling time. The resolution can be easily enhanced to about ten micrometers. The phase shift between the photogeneration and the detecting IR-beam is determined by the recombination parameters as described in detail elsewhere [5]. For the measurements of multicrystalline material the high detection sensitivity achieved by the lock-in technique is essential: carrier densities less than $10^{14}$ $\text{cm}^{-3}$ can be detected with the present setup.

After the lifetime mapping, solar cells were fabricated usually featuring an oxide passivated emitter and aluminum back surface field. Light beam induced current (LBIC) maps are measured with a spatial resolution of about 100 $\mu$m. On selected samples also etch pit densities are counted using a Kontron optical image processing system.

Measurements of the local oxygen content are obtained with a maximum resolution of 20 $\mu$m using a Bruker 113v FT-IR spectrometer with an attached IR-microscope (Fig. 2). In order to improve the signal to noise ratio and reduce the data collection time, the wavelength range entering the Michelson interferometer is limited to a narrow band centered around the dominant peak for interstitial oxygen using a specially selected filter. Great care is taken in defining the base line and accounting for contributions of the silicon phonons to the spectra.

![Fig. 2. FT-IR spectrometer with an attached IR-microscope](image)

**COMPARISON OF MFCA AND LBIC MAPS**

The silicon used was a p-type, multicrystalline block cast material with a thickness of about 345 $\mu$m and a base resistivity of approximately 1 $\Omega \cdot \text{cm}$. A low pressure chemical vapour deposition oxide was formed at a temperature of 550°C in order to reduce the surface recombination velocity. A MFCA lifetime map (shown in Fig. 3) was measured, taking into account the residual surface recombination for the calculation of the bulk lifetime [6].

![Fig. 3. Lifetime map measured with modulated free carrier absorption (MFCA), resolution 200 $\mu$m](image)

On the same sample a solar cell with an oxide passivated emitter and aluminum back surface field was processed. Fig. 4 shows the corresponding LBIC map.

![Fig. 4. Light beam induced current (LBIC) map performed on a solar cell fabricated on the identical sample as seen in Fig. 3, measured with a resolution of 100 $\mu$m](image)

A very good structural correlation between the maps is obvious. In this case the solar cell process does not seem to change the quality of the starting material inhomogeneously across the area of the cell. This qualitative conclusion is supported by determining the volume lifetime in the solar cell from an evaluation of the internal quantum efficiencies (IQE) measured at different spots on the solar cell. Taking into account surface recombination and optical reflection at the rear surface [7], the volume diffusion length was extracted. The value for the surface recombina-
tion velocity at the Al-BSF was determined to be 2500 cm/s on a solar cell processed with the same rear surface treatment on FZ material by photocurrent and -voltage decay (PCVD)[8]. For example, on a high current spot of the LBIC map (marked "A" in Fig. 2) $\tau_B$ was determined to be 14.3 $\mu$s. At a low current spot (marked "B") $\tau_B$ was found to be 1.4 $\mu$s. In this case the solar cell process tended to deteriorate the high lifetime regions by about 30%.

COMPARISON OF LIFETIME, INTERSTITIAL OXYGEN CONCENTRATION AND ETCH PIT DENSITY

We have compared two different aspects of the lateral [O] distribution: (i) the strong concentration increase towards the bottom of a cast block (called "macroscopical variation" in the following) and (ii) minor variations between grains with different structural defects ("microscopic variation").

Macroscopic variation

A wafer cut vertically with one edge close to the bottom of the cast block (thickness around 2 mm) was polished and thermally oxidized at a temperature of 1050°C in order to reduce surface recombination. A MFCA lifetime map was performed over the full wafer area (Fig. 5). Towards the bottom of the block the lifetime decreases strongly, as was expected [9]. In parallel, the overall [O] map (Fig. 6) shows an increase towards the bottom.

Microscopic variation

Figs. 7, 8 and 9 show a high resolution lifetime map, an etch pit image and a 3D-plot of the interstitial oxygen concentration, respectively, taken on a selected small area of the identical wafer. A decrease of [O] at the grain boundaries and in regions with high dislocation density is obvious. This decrease of [O] around structural defects is consistent with an increase of the total oxygen concentration at grain boundaries measured with SIMS [10]. In a region of high defect density the lifetime decreases strongly. Within the same region also the interstitial oxygen concentration is lowered.

The influence of dislocations on the effective lifetime was modelled and experimentally investigated e.g. by El Ghitani et al. [11]. A strong decrease of the lifetime with increasing dislocation density is reported. On a multi-grained FZ ingot also the dependence of lifetime on decreasing grain area and on the dislocation density was measured [12].

Our observations show that oxygen is depleted in between structural defects and segregates most likely into them. Whether the oxygen decoration is responsible for the high recombination activity of dislocations can not be determined presently. On the other hand, the knowledge of the amount of oxygen contained in the crystal matrix appears to be essential for predicting the efficiency of phosphorous gettering [13]. These very interesting questions will be further investigated.