QUANTITATIVE ANALYSIS OF GRAIN BOUNDARY RECOMBINATION IN MULTI-CRYSTALLINE SILICON WAFERS

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ABSTRACT

Grain boundary recombination is one of the mechanisms limiting performance of multi-crystalline silicon solar cells. We aim at low grain boundary recombination in the finished cells and want to find out which mechanisms affect grain boundary recombination. We describe a new quantitative analysis to extract accurate values of the grain boundary recombination velocity, from 2-D maps of the minority carrier lifetime made with the MFCA (modulated free carrier absorption) technique.

1. ANALYSIS OF 2-D LIFETIME MAPS

In the MFCA technique the sample is illuminated with harmonically modulated light in order to generate carriers. Infrared light detection light is shone through the wafer and the phase shift of the absorption of this light with respect to the generation is measured. The bigger the phase shift is, the longer the lifetime.

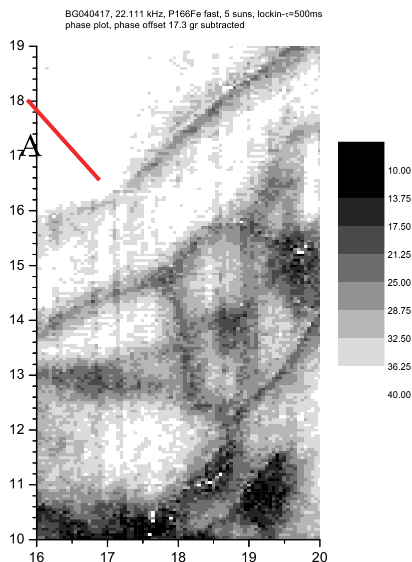

Figure 1: MFCA phase shift map (at 22 kHz) of an Fe implanted mc-Si wafer. The grain boundaries are visible as regions of lower phase shift. We analyse the phase shift along line A.

We analyse neighbouring multi-crystalline wafers, some of which were implanted with iron and subsequently annealed. Prior to measurement, the front- and rear surfaces passivated with a SixNy:H coating. In Figure 1 we see a 2-D map of phase shifts on an Fe implanted wafer, where the grain boundaries (GB) are clearly visible.

For a homogeneous sample there is a simple relation between phase shift and lifetime, but for an inhomogeneous sample such as Fig. 1 much more information can be extracted using a full solution of the 2-D minority carrier transport equations under the used excitation.

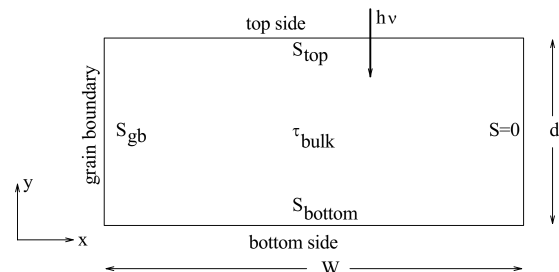

Figure 2: the geometry of the simulation. A sample of wafer thickness d is considered, the grain boundary is at the left hand side. A region of finite width W is simulated.

We consider the minority carrier transport equations for a cross-section of a wafer as illustrated in **Figure 2**, leading to a 2-D partial differential equation. Because the illumination is harmonic with frequency ω, the solution becomes harmonic as well. The minority carrier concentration – in this case a complex quantity – is given by the following equation:

$$\vec{\nabla} \cdot \left(D(x,y) \vec{\nabla} n(x,y) \right) - n(x,y) \left(i\omega + \frac{1}{\tau_{\text{bulk}}(x,y)} \right) + g(x,y) = 0$$

Here D(x,y) and τ_{bulk}(x,y) are the diffusion constant and the minority carrier lifetime respectively for minority carriers. g(x,y) is the generation by illumination. The different recombination velocities enter through the boundary conditions. We employed finite difference methods to calculate the minority carrier distributions.

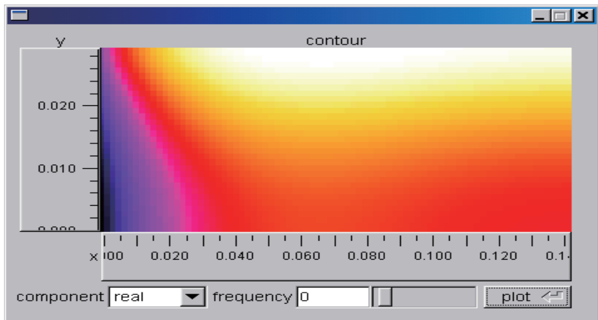

Figure 3: contour plot of minority carrier concentration. This plot represents a cross-section of the wafer as in **Figure 2**. *Left*: grain boundary, *top*: front (illuminated) side *bottom*: rear side of wafer.

Figure 3 shows a calculated minority carrier concentration in a cross section of the wafer for the 3.1 kHz frequency. We can observer a lower (dark color) carrier concentration near the GB and a higher (bright color) carrier concentration at the top where the carriers are generated. From the minority carrier concentration the phase shift of the detection light can be calculated. This calculated phase shift is fitted to the measured phase shift.

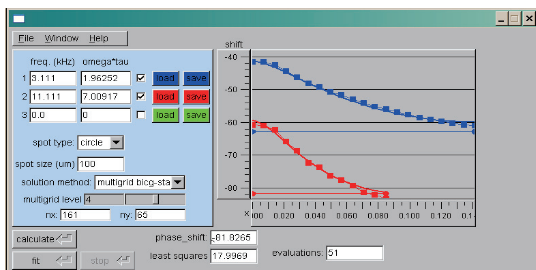

Figure 4: Fit to line scans from line A (3.1 kHz and 11 kHz)

Figure 4 shows two phase shift measurements (blue and red squares) along line A, measured at two different illumination frequencies, as a function of the distance of the detection light from the grain boundary. Use of measurements at multiple frequencies improves the reliability of the fit. A simultaneous fit is done to these two curves by which the following parameters are extracted: GB recombination velocity, front- and rear surface recombination velocity and bulk minority carrier lifetime.

We have found that the Fe impurities result both in a reduction of the bulk recombination lifetime and an increase of the recombination at grain boundaries. In Fig. 2 the grain boundary s is 2000 cm/s with an estimated uncertainty of 10 %.

[1] J.D. Zook, "Effects of grain boundaries in polycrystalline solar cells", *Applied Physics Letters 37* (1980)

[2] C. Donolato, "Theory of beam induced current characterisation of grain boundaries in polycrystalline solar cells", *Journal of Applied Physics 54* (1982)