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Device architecture and lifetime requirements for high efficiency multicrystalline silicon solar cells

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Abstract

We present a numerical simulation study of different multicrystalline silicon materials and solar cell architectures to understand today's efficiency limitations and future efficiency possibilities. We compare conventional full-area BSF and PERC solar cells to future cell designs with a gallium phosphide heteroemitter. For all designs, mc-Si materials with different excess carrier lifetime distributions are used as simulation input parameters to capture a broad range of materials. The results show that conventional solar cell designs are sufficient for generalized mean lifetimes between 40 – 90 μs, but do not give a clear advantage in terms of efficiency for higher mean lifetime mc-Si material because they are often limited by recombination in the phosphorus diffused emitter region. Heteroemitter designs instead increase in cell efficiency considerable up to generalized mean lifetimes of 380 μs because they are significantly less limited by recombination in the emitter and the bulk lifetime becomes more important. In conclusion, to benefit from increasing mc-Si lifetime, new cell designs, especially heteroemitter, are desirable.

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1. Introduction

The energy conversion efficiency of multicrystalline silicon (mc-Si) solar cells depends strongly on the quality of the wafer material and of the chosen device architecture. The quality of mc-Si wafers has increased significantly in the past decades, especially in the last few years through the refinement of the directional solidification often resulting in higher and more uniform lifetimes across the ingot [1]. An open question is to which degree increased

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lifetimes will translate into higher cell efficiencies, especially as new solar cell device architectures, like carrier selective contacts or heteroemitter designs [2, 3] are developed.

We presented earlier [4] that generalized mean values of mc-Si excess carrier lifetime distributions can be used as a quality criterion. Equation (1) shows the formula for a generalized mean value M_p of $\tau_1,\dots\tau_n$ lifetime values. The exponent p characterizes the mode of mean, e.g. $p = 1$ for the arithmetic mean, or $p = 0$ for the geometric mean. We showed in [4] that no universal p exists to describe mc-Si quality for all materials and device architectures, each mc-wafer and each device architecture have their individual p values. However, the differences are rather small and p = -0.835 is a good approximation for various materials and devices. In other words, to decide which one of two different mc-Si wafers results in a better solar cell performance, Equation (1) with a p of -0.835 can be applied to their excess carrier lifetime distributions.

$$M_p(\tau_1, \dots, \tau_n) = \left(\frac{1}{n}\sum_{i=1}^{n} \tau_i^p\right)^{1/p} \quad (1)$$

To simulate the specific behavior of mc-Si solar cells, the model described in [4] is used here. To predict solar cell efficiencies for different device architectures, numerical simulation models can be used [3-6]. We will focus in this paper on a conventional full-area BSF solar cell architecture, a PERC design with local rear contacts, and a PERC design with a high efficiency heteroemitter made of gallium phosphide [3, 6].

We will use the simple Equation (1) and the more sophisticated simulation models to show limitations of bulk lifetime and device designs.

2. Simulation models

To simulate mc-Si solar cells, the following approach is used [4]: Excess carrier lifetimes from a mc-Si wafer are discretized in a lifetime histogram having a number n of bins with different lifetime values τ_n with corresponding areas A_n. We then simulate a sequence of n monocrystalline Si cells, having a homogenous SRH bulk lifetime $\tau_n = \tau_{n0} = \tau_{p0}$ and obtain their I-V curves $I(V)_{mono,n}$. To obtain the I-V curve of the mc-Si cell, $I(V)_{multi}$, these simulated $I(V)_{mono,n}$ curves are connected in parallel in a numerical spice circuit model, using A_n as area factors.

The wafer's τ_n values are alternatively generated with a random algorithm [4] using MATLAB. Each wafer has 10^6 different lifetime values between 1 – 600 µs, as typically measured. To capture a broad range of possible materials, three generated distributions are used: low quality with M_p = 49 µs, high quality with M_p = 254 µs, and very high quality with M_p = 443 µs, where M_p is calculated using Equation (1) with p = -0.835.

Three different cell architectures are simulated. First, a "standard cell" consisting of a conventional silicon solar cell with a full-area Al-BSF and conventional phosphorus diffused emitter. Second, a "PERC cell" with local laser-fired BSFs and improved phosphorus diffused front emitter. Third, the "GaP/Si cell" [3], which is a c-Si solar cell with the same local laser fired BSFs as in the PERC cell, but a heteroemitter, made of gallium phosphide at the front side. This heteroemitter is highly n-doped and the resulting band structure allows electrons from the Si bulk material to enter the front contact but blocks the holes due to an high valence band offset (holes are the minority carrier in n-type GaP). We like to point out, that this GaP/Si cell represents a cell with an almost ideal emitter and that major technical issues have to be solved to produce these heteroemitters in mass production. The surface recombination velocities for the different devices are: 2.0×10^7 cm/s for the standard cell, 2.5×10^5 cm/s for the PERC cell and 1.0×10^3 cm/s for the GaP cell. The interface recombination velocity between GaP and Si is set to 1.0×10^2 cm/s. We discussed in Ref. [3] the influence of different recombination velocities for the GaP/Si cell and reported that the device efficiency is not strongly influenced for values up to 1.0×10^6 cm/s. These three cell architectures are simulated for 180 µm thick p-type wafers with a boron base doping of 7.2×10^{15} cm^{-3}.

For each cell in the respective cell design, the SRH bulk lifetime τ_i is ramped from 1 µs to 600 µs in steps of 1 µs (hence, we simulate a sequence of n = 600 monocrystalline solar cells, assume homogeneously distributed lifetimes in the Si bulk with $\tau_i = \tau_{n0} = \tau_{p0}$). The high end of this range of lifetimes is achievable in mc-Si after effective gettering of dissolved iron and otherwise low contamination levels, i.e. oxygen and carbon especially [7]. We use this sequence of cells for the above described mc-Si simulation model ($\tau_i = \tau_n$) and to show the individual device efficiency as a function of τ_i SRH bulk lifetime.