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THE ORIGIN OF IDEALITY FACTORS $n > 2$ OF SHUNTS AND SURFACES IN THE DARK I-V CURVES OF SI SOLAR CELLS

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ABSTRACT: So far, a general model for the explanation of non-linear shunts and edge currents, often showing ideality factors $n > 2$, has been missing. Non-linear shunts like scratches and edge currents are the major source of the recombination current of industrial crystalline silicon solar cells. Moreover, the reverse current of such cells behaves always linear or even superlinear instead of saturation-type, as expected. We propose that the edge recombination current and other non-linear shunts can be described as regions that are highly disturbed, even amorphous, crossing the pn-junction. The recombination within such regions needs model descriptions that go beyond the SRH approximation, because the density of defects is so high that carriers recombine via more than one defect (so-called multi-level recombination). Two variants of coupled defect level recombination, both leading to ideality factors larger than 2, are realistically modelled by Sentaurus simulations. Under reverse bias, the high local density of states in the defective material enables hopping conduction, which explains the linear reverse characteristics.

Keywords: Fundamentals, Silicon, Simulation, Shunts.

1 INTRODUCTION

The Shockley-Read-Hall (SRH) recombination theory, which assumes recombination via isolated point defect levels, predicts an ideality factor of the recombination current of $n = 2$ or less (see e.g. McIntosh et al. [1]), and saturation-type reverse characteristics. Industrial crystalline solar cells usually deviate from this prediction. Their recombination current is much higher than expected for the given lifetime and often shows an ideality factor larger than 2 at relative low voltages. Moreover, their reverse characteristic is linear or even superlinear. Especially the large ideality factors have attracted attention already very early [2] and are still under discussion. Previous explanations of a high ideality factor were based on trap-assisted tunneling or field-enhanced recombination [3] via isolated point defect levels. However, realistic simulations have shown that the electric field in the depletion region is too low to enable effective single-level trap-assisted tunneling. Only if two-level recombination implying at least one shallow level is considered, which becomes probable only for high defect concentrations, trap-assisted tunneling becomes effective and indeed may lead to large ideality factors [4]. Another explanation of high ideality factors was based on the emitter series resistance between the contacts and the recombination site [5]. We will show in the following that this series resistance is not sufficient to explain large ideality factors at the observed low voltages.

A key for the understanding of large ideality factors is the fact that such recombination currents are flowing not homogeneously in the cell, but always at local sites, e.g. in extended defects. For example, it had been realized by many authors that, in the absence of other defects, the major source of currents with $n > 2$ is the edge, where the pn-junction crosses the surface. By lock-in thermography investigations it had been proven that, besides the edges, there are local non-linear shunts

anywhere in the cell area that are responsible for current with $n > 2$ [6]. We propose that already the elementary recombination process at the extended defects may be saturable, which leads to the observed high ideality factors. For explaining this saturation, models beyond the SRH approximation have to be considered, which becomes probable if recombination occurs via extended defects [7]. Results of the simulation of two special cases of defect pair recombination, both leading to high ideality factors, will be introduced.

2 EXPERIMENTAL RESULTS

2.1 Artificial shunts, dark forward characteristics

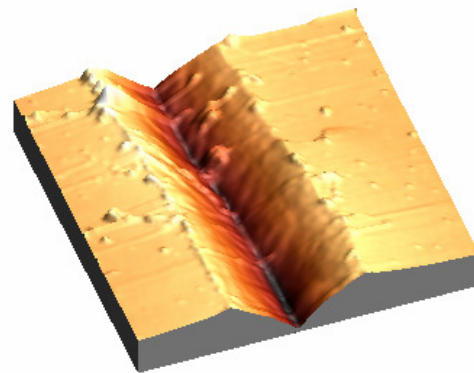


Fig. 1: AFM image of a 25x25 μm sized region of the scratch with 27 g load. The scratch is about 1 μm deep.

Planar, monocrystalline silicon solar cells with the edge of the pn-junction lying well-passivated below an oxide layer ("PERL"-type cells), behave like "ideal" cells, i.e. they don't show a recombination current with an ideality factor larger than 2. By cleavage [7, 8] or

scratching, typical non-linear shunts can be produced in a controlled manner. Here we have made 1 mm long scratches at the front surface of several 1 cm² sized "ideal" cells with well-defined loads from 6 to 27 g by using a Vickers indenter at room temperature. In Fig. 1, an AFM image is shown of a scratch performed with 27 g load. It is apparent that, even for this scratch with the highest load, the material still was deformed plastically. In Fig. 2 the dark I-V characteristic and in Fig. 3 the bias-dependent ideality factor of an "ideal" (virgin) cell are shown, together with characteristics of 3 equivalent cells, which had been diamond-scratched over 1 mm length using three different loads. The virgin cell shows an ideality factor below 1.5 over the whole bias range. The scratch with 6 g load clearly increased the forward current and the ideality factor, but the ideality factor did not exceed $n = 2$. The scratches with 9g and 27 g load generated a further increase both of the recombination current and of the ideality factor, exceeding $n = 2$ already for biases below 0.1 V. Since our scratches of 1 mm length are all lying in the middle between two grid lines having a distance of 1 mm in a 100 Ω/\square emitter, the emitter series resistance to the scratch R_s is well known to be 25 Ω . So the characteristics can be R_s -corrected, which is shown for the 27 g load as dotted lines in Figs. 2 and 3. The R_s -correction slightly reduces the ideality factor for biases above 0.3 V, but the general behavior remains. This proves that here the series resistance is not the primary reason for a high ideality factor.

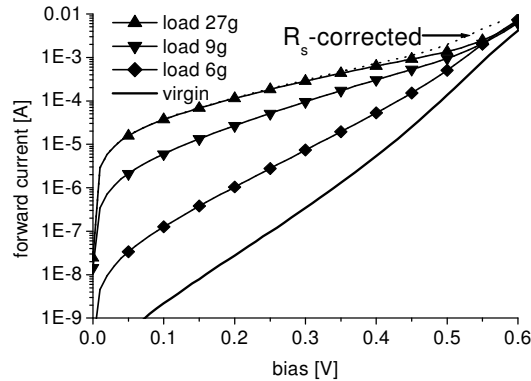


Fig. 2: Measured forward I-V characteristics of a virgin "ideal" cell and 3 equivalent cells, which are diamond scratched with different loads. Dotted: R_s -corrected curve for the 27 g load.

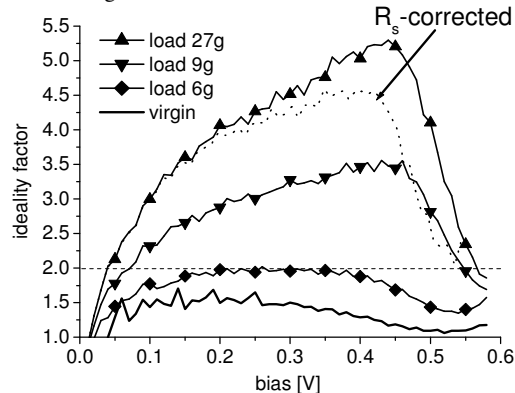


Fig. 3: Bias-dependent ideality factors of the characteristics shown in Fig. 2. Dotted: R_s -corrected

curve for the 27 g load.

2.2 Artificial shunts, reverse characteristics

Fig. 4 shows the room temperature reverse characteristics of the cells of Figs. 2 and 3 in linear scale. Both the virgin and the 6g scratched cell show a negligible reverse current. We see that the reverse conductivity strongly correlates with the magnitude of the recombination current under forward bias: the higher the recombination current, the higher is the reverse conductivity. The characteristics are nearly linear up to 5 V.

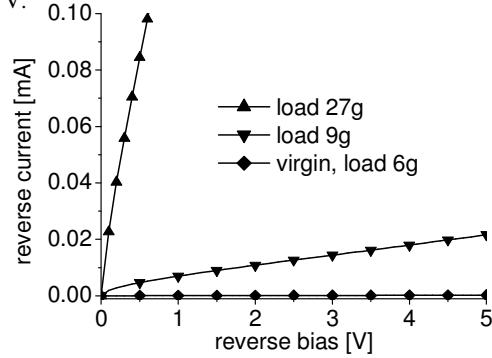


Fig. 4: Reverse characteristics of cells of Fig. 1

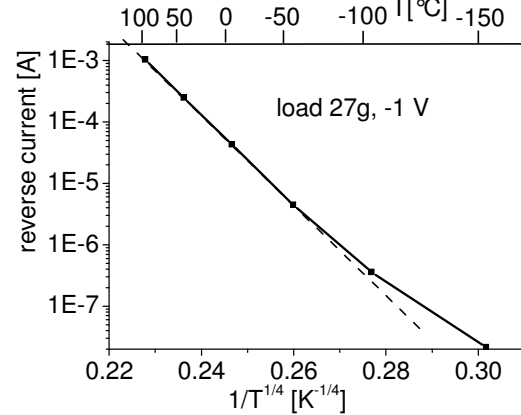


Fig. 5: T-dependence of the reverse current of the cell scratched with 27 g load, measured at -1 V reverse bias

The temperature dependence of the I-V characteristics may point to the conduction mechanism. In Fig. 5 the T-dependence of the reverse current of the cell with the 27 g scratch measured at -1V is shown. This dependence is displayed logarithmically over $1/T^{1/4}$. It is found that, at least in the range between -50°C and +100°C, this plot produces a straight line. It is well known that such a dependence is expected for variable range hopping conduction in a constant density of states near the Fermi level according to Mott's theory [9]. This type of conductivity has been observed regularly for highly disturbed semiconductors and insulators, like nano- and microcrystalline silicon layers [10].

3 MODELLING

A general theory for recombination via coupled defect levels is not available yet. However, we present the simulation using two special cases of recombination via two levels: Schenk's Coupled defect level model [4] and

the Deep donor-acceptor-pair (DAP) recombination proposed recently [7]. In both cases recombination paths according to Fig. 6 are assumed, where the usual SRH recombination paths via two neighboring defect levels are extended by an inter-defect transfer path described by the transfer coefficient c_{12} and a thermal emission rate e_{12} [4].

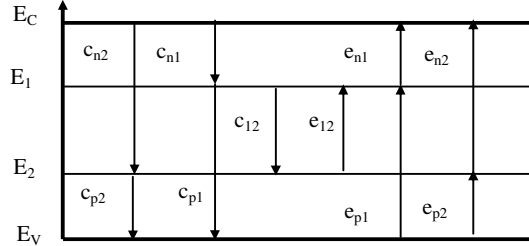


Fig. 6: Recombination scheme including inter-level recombination and emission

3.1 Simulations with the Coupled defect level model

A basic assumption of the coupled defect level model is that the inter-level transfer coefficient c_{12} is so large that it is not rate-limiting. If at least one of the two energy levels is shallow [4], its wave function is sufficiently extended in space so that trap-assisted tunneling becomes the dominant mechanism for its free carrier capture process, which is assumed to be rate-limiting [11]. This capture mechanism does not require large electric fields and is strongly field-dependent, leading to a saturation of this recombination path with increasing forward bias, corresponding to decreasing field strength. Fig. 7 shows Sentaurus [12] simulations using this model to compute the dark I-V characteristics together with the bias-dependent ideality factor for various defects in the pn-junction, having various energies of the shallow trap level E_t and various defect lifetimes τ [7].

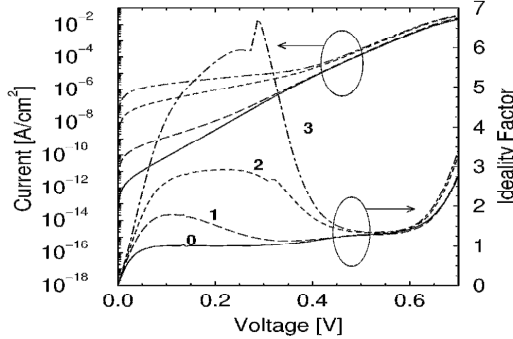


Fig. 7: Simulated forward I-V characteristics and ideality factors of a PERL cell with a defect modelled by the coupled defect level model [4]. 0: $E_t = 50$ meV, $\tau = 1e-4$ s, 1: $E_t = 90$ meV, $\tau = 8e-7$ s, 2: $E_t = 145$ meV, $\tau = 6e-8$ s, 3: $E_t = 190$ meV, $\tau = 4e-8$ s [7].

3.2 Deep donor-acceptor-pair recombination

This model assumes that capture and emission of free carriers in a single level follows the usual SRH theory, but that the captured carriers can be transferred to a neighboring defect. For creating a saturation effect, we have to assume a distinct asymmetry between the electron and hole capture coefficients, so that the recombination occurs via a donor-acceptor-pair (DAP). Until now, DAP

recombination has only been observed in luminescence of shallow levels. In our case also deep donors and acceptors are considered. Their wave function is much more localized than that of shallow levels. However, deep defects that are charged have sufficiently extended wave functions such that their local concentration may be high enough in extended defects that inter-level transfer becomes probable. Under forward bias, in the middle of the depletion region, for each isolated level the capture of carriers with the lower capture coefficient would be rate-limiting. Here the inter-level recombination may provide an alternative recombination path bridging this bottleneck, which leads to an increased recombination rate compared to single levels. However, this inter-level recombination path is saturable, because the density of recombination partners is limited. This is the basic reason for the saturation behaviour in the Deep DAP recombination model. In Fig. 8 results of our Sentaurus simulations are shown. The donor and acceptor energies were set to midgap, and the smaller of the two capture coefficients was set to zero for both levels. We vary the transfer coefficient c_{12} [cm³s⁻¹]. For small c_{12} a maximum of the ideality factor appears at low voltage, and with increasing c_{12} it shifts to higher voltages. The second smaller maxima around 0.5 V are due to the series resistance to the defect. The experimental results are not perfectly modelled in this simple model. Simulations with variable energy of the levels have shifted the maximum of the ideality factor to even higher voltages. For further refining this model, an ensemble of defect pairs with various energies and transfer coefficients has to be assumed.

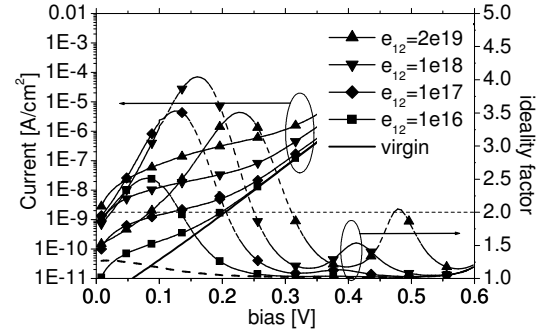


Fig. 8: Simulated forward I-V characteristics and ideality factors (dashed) of a cell with a defect modelled by the Deep DAP recombination model. Both levels are assumed to lie at midgap.

4 DISCUSSION AND CONCLUSIONS

We are presenting a unified explanation for all aspects of the non-ideal behavior of the dark I-V characteristics of most industrial silicon solar cells, which are a high magnitude and ideality factor of the recombination current and an essentially ohmic reverse characteristic. These non-ideal current contributions are all due to extended defects like the cell's edge or other defects in the cell area like scratches crossing the pn-junction. If these extended defects have a low local density of defect states, they behave according to the SRH recombination theory of isolated point defects, and the I-V characteristics have $n < 2$. However, if the extended defects have a high local density of defect

states, multi-level recombination becomes probable, which may show an intrinsic saturation behavior as demonstrated here in two special cases. Moreover, for a high density of defect states, hopping conduction in the defect volume may govern the reverse conductivity of the devices. Our experimental results on scratches with different loads, which are typical examples of extended defects with controlled densities of states, strongly support this hypothesis.

In a general theory for multi-level recombination at extended defects, a basic question is how these recombination levels can be described. Here we propose that they should be modelled in analogy to the defect levels in amorphous silicon. Indeed, usual edge opening procedures like laser cutting, dicing, and reactive ion etching may generate an amorphous layer at the surface. Even cleaving causes plastic deformation at the cleave-tip, and also scratching implies plastic deformation in micro-regions (see Fig. 1), which converts crystalline silicon into highly disturbed (up to amorphous) material. Non-hydrogenated amorphous silicon is characterized by a very high defect density in the order of 10^{20} cm^{-3} . This high defect density makes both multi-level recombination (as the dominant recombination mechanism under forward bias) and hopping conduction (as the dominant conduction mechanism under reverse bias) very probable. Note that for such a high defect density the Fermi level is pinned, hence free carrier conduction is improbable in this material. Our measured T-dependence of the reverse conductivity of the scratched solar cells strongly supports the hypothesis that this conductivity is due to amorphous or at least highly disturbed silicon material bridging the pn-junction.

Until now, only special cases of multi-level recombination have been modelled, and well-known DAP recombination features like Coulomb interaction and the influence of the pair distribution function of neighbouring defects have not been considered. Therefore, our modellings do not exactly reproduce the experimental results. So a general theory for describing the electronic influence of highly disturbed regions crossing a pn-junction, which describes both forward and the reverse characteristics, is still awaiting completion.

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