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POTENTIAL-INDUCED DEGRADATION ON CELL LEVEL: THE INVERSION MODEL

Pierre Saint-Cast, Henning Nagel, Dirk Wagenmann, Jonas Schön, Peter Schmitt, Christian Reichel, Stefan W. Glunz,
Marc Hofmann, Jochen Rentsch and Ralf Preu
Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, 79110 Freiburg, Germany
Email: pierre.saint-cast@ise.fraunhofer.de
Phone: +49 761 4588 5614

ABSTRACT: The field effect model for potential-induced degradation of p-type crystalline silicon solar cells postulates an inversion of the emitter surface. The electrical properties of the inversion layer was evaluated based on theoretical considerations and the effect of the inversion layer on the solar cell device was modeled. Finally, our theoretical model was compared to experimental data. As a result, the inversion layer alone cannot explain the observed shunting of the solar cells.

Keywords: Potential-induced degradation, reliability, inversion layer, solar cells, theoretical model.

1 INTRODUCTION

Potential-induced degradation of solar cells is a common but mysterious phenomenon. PID was first observed for SunPower modules with rear-junction *n*-type solar cells. This degradation was provoked when a high positive voltage was applied between the solar cells and the front surface or the frame of the modules (ground potential) [1]. This phenomenon can be explained by negative charges trapped on the surface of the solar cell, decreasing the surface potential of the front surface field that provide the front passivation of rear contacted solar cells[1]. The presence of negative charges is not very surprising, as negative ions are attracted by the positive potential of the front surface of the solar cells [1]. In Ref. 1, the degradation was explained by a field effect model.

PID is not only observed on rear junction *n*-type solar cells, but also on front junction *p*-type solar cells [2]. In this case, it occurs for high negative voltage bias between the solar cells and the front surface (ground) of the module. The degradation is caused by a shunt and more than 80% of the initial efficiency might be lost [2]. In analogy to the problem observed for SunPower modules, several models explain the shunts as an inversion region at the surface of the emitter [3-6].

2 FIELD EFFECT MODEL

As explained in the introduction, the PID is characterized as a shunt, that appears when the module-surface is grounded (0 V) and the (front-emitter *p*-type-base) solar cell has a negative potential (-1000V). Shunts are usually not reversible. However, the PID degradation can be cured by inverting the polarity on the module. Phenomena related to trap charging or to field effect are known to be reversible depending on the electric polarity; this is probably the origin of the field effect model.

In literature, other models of the physical causes of potential-induced degradation have been proposed, and more models based on new experimental results will probably come up [7, 8]. In order to be complete, the model should at least explain the following experimental observations:

- The electrical behavior of the degradation is a shunt, with strong losses even at low voltage [2],
- The degradation is fully reversible by inversing the polarity [2],
- The degradation is local, induced by microscopic shunts present on the surface, and these shunts are also correlated with the presence of positive Na ions [3].
- A degradation can be obtained with other positive ions for example positive corona charges [6].

2.1 Overview on the field effect model

This model has been already presented in different form [3-6]. The common point in these models is that negative charges on (or in) the dielectric induces an inversion layer on the surface of the emitter or a full depletion of the emitter. The inversion layer or the depletion is responsible for the shunt behavior. By changing the polarity of the electrical potential the inversion layer could vanish which would explain the reversibility.

In this paper, the possibility to have negative charges on (or in) the dielectric is discussed. Subsequently, the electrical properties of such an inversion layer are studied. Then, the inversion layer is included in a solar cell model. Finally, the calculated impact of the inversion layer on the solar cell is compared to the impact of a PID degradation observed experimentally.

2.2 Negative charges

The direct measurement of negative charges on *p*-type solar cells in correlation with a PID has not been reported so far. The negative charges have been postulated because they might induce an inversion of the emitter (see section 2.3).

The potential applied on the module has the tendency to drive positive ions like Na^+ from the glass to the surface of the solar cell. Indeed, on a microscopic scale, a local excess of Na was observed on degraded areas [9]. These observations are in favor of the accumulation of positive charges on the solar cell's surface. Therefore, in order to obtain an inversion layer on *n*-type emitter, the *positive* charges need to be over-compensated by the *negative* charges.

Several hypotheses about the nature of the negative charges were proposed. Nagel suggested that the negative charges could be stored in the K-centers of the SiN_x antireflection coating layer (ARC) [5]. Indeed, the K-centers of SiN_x can be charged positively or negatively. The charging occurs, when an electrical field is applied to SiN_x [10, 11]. After the electrical field vanishes, a part of the charges remains in the K-centers, which makes SiN_x very suitable for memories (e. g. EPROM).

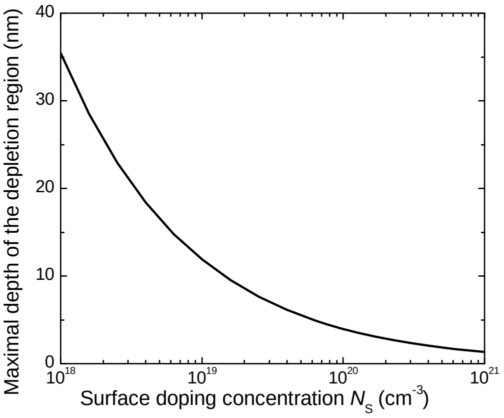

Fig. 1. Maximum depth of the depletion region as a function of the surface doping concentration.

It was proposed that the electrical field formed by the Na^+ on the solar cells surface induce negative charging of the K-centers [5]. However, the negative charges in the K-centers cannot over-compensate the positive charges which caused them.

In this paper, we propose that a negatively charged layer might be formed in a two-steps process:

1. As proposed earlier, Na+ ions accumulate on the solar cell surface (at the outside surface of the SiNx ARC) forming an electrical field which induces negative charging of the K-centers.
2. When a large quantity of Na^+ already accumulates on the SiN_x, a breakdown of the dielectric occurs. Around the breakdown region, the dielectric is more conductive and a current neutralization of the Na^+ ions occurs. The positive charges are neutralized and only the negative charges stored in the K-centers remain.

As it will be seen in the next section, a negative charge density of about 10^{14} cm^{-2} is needed in order to invert a typical solar cell emitter (75 Ω / sq.). This amount of charges would correspond to an electric field strength of about 25 MV/cm which is higher than the typical electrical strength of SiN_x (~10 MV/cm) [10]. It is therefore improbable that such a high amount of charges in the silicon nitride is stable.

2.3 Inversion layer

So far, for *p*-type solar cells, no-direct measurement of an inversion region on the emitter in correlation with a PID has been published. The inversion region has been postulated in order to explain the shunts observed on the degraded solar cells (see section II.C).

Several opinions exist concerning the inversion of the emitter that could be involved in the degradation. In the references [6] and [9], the emitter is considered to be completely inverted (or depleted). In contrast, in reference [5] the emitter is only inverted on the surface of the solar cell.

At equilibrium, the space charge region stops growing when an inversion layer is formed. Therefore, there is a maximum size of the depletion region, which depends on the doping concentration. The inverted region itself is very thin (limited by quantum confinement, about 1-2 nm). In Fig. 1, the maximal depth of the depletion region (W_{dep}) is ploted as a function of the surface doping concentration. A detail of the calculations can be found in [12, 13].

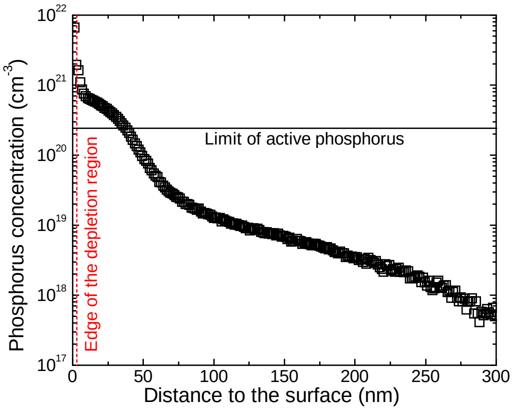

Fig. 2. Phosphorus concentration as a function of the distance to the wafer surface. This emitter profile was obtained using secondary ion mass spectroscopy (SIMS). The limit of active phosphorus and the edge of the front depletion region are indicated.

For a typical industrial emitter the surface doping concentration is higher than 2×10^{20} cm^{-3} which corresponds to a depletion region of less than 3 nm in thickness. The emitter thickness is about 400-500 nm and the high doping region ($N_D > 10^{20}$ cm^{-3}) is typically larger than 30 nm. For such highly doped emitter there is no chance that the emitter is fully inverted (or depleted). In Fig 2, the doping profile of the emitter used for the experiment is plotted. The theoretical limit of the depletion region is also shown.

The amount of charges density in the depletion region corresponds to the integrated doping concentration in the depletion region. This charge density corresponds also to the density of negative charges needed in order to obtain an inversion of the emitter (detail of the calculation can be found in Ref. 13). For an industrial emitter ($N_S > 2\ 10^{20}$ cm^{-3}), the negative charge density needs to be at least 10^{14} cm^{-2}.

The depletion layer is very thin, therefore it is very probable that current can tunnel through it (detail of the calculation can be found in Ref. 13). In Fig 4, the tunnel resistivity is plotted as a function of the surface doping concentration. For high surface doping concentrations ($N_S > 10^{20}$ cm-2) the tunnel resistance is very low ($< 10^{-6}$ Ω cm^2). Therefore, it seems clear that if there is an inversion layer on the surface of the emitter, the *p-n* junction between the inversion layer and the emitter is shunted due to the low tunnel resistance.

2.4 Modeling of the device

The inversion of the surface of the emitter has been postulated and its electrical properties have been studied (see last section). The goal of this section is to model the effect of an inversion layer on the solar cell device. For this, a model for the dark current voltage (IV) characteristic will be derived.

From the last section, it is clear that the inversion layer is only at the surface of the emitter. There is therefore no direct contact between the *p-n* junctions between bulk and emitter (solar cell junction) and the *p-n* junction between emitter and the inversion layer (inversion junction). Then, the potential at the solar cell junction and at the inversion junction can be set independently, like in a *p-n-p* transistor (an alternative demonstration using *p-n-p* transistor is presented in ref. 13).

In section 2.3, it was calculated that the inversion junction is shunted by the very low tunnel resistance. Therefore, the potential at the inversion junction needs to be very small. If the potential difference at the junction is very small than the excess hole density is also almost zero. This boundary condition is equivalent as setting the front surface recombination velocity of the solar cell to infinity.

It means that the solar cell with an inverted emitter on the front surface will behave like a solar cell with infinite recombination velocity on the front surface. Therefore the dark current ($J_{\text{dark,inv}}$) of such a solar cell can be written

$$J_{dark,inv}(V) \approx J_{dark}(V) + J_{0e,\infty}\exp\left(V/V_{th}\right), \quad (1)$$

where J_{dark} is the dark current of the solar cell without inverted region and $J_{0\text{e},\infty}$ is the emitter saturation current if the front surface recombination velocity is infinite. In the next part, the predicted losses for inverted emitters will be compared to experimental tests on solar cells with PID.

3 EXPERIMENTAL

Al-BSF solar cells have been fabricated, laminated in a one cell mini-module and a PID stress was applied. For the fabrication of the solar cells the following steps were carried out:

1. Alkaline texture,
2. Diffusion of a 75 Ohm/sq. phosphorus emitter,
3. PSG etching,
4. Deposition of an anti-reflection coating (ARC) SiN_x,
5. Screen-printing of Al on the rear, of Al-Ag solder pads on the rear, of an Ag metal grid on the front,
6. Co-firing of the contacts.

In step 4, the anti-reflection coating was chosen for its sensitivity to PID, however this layer is representative to the ones used in industrial solar cell production. For the fabrication of the mini-module a standard ribbon, a standard EVA and a standard soda-lime solar glass has been used.

For the PID stress an Al foil was disposed on the glass. The test was carried out at a temperature of 50°C, the Al foil was grounded and a potential of -1000 V was applied on the solar cell. These conditions were applied during 72 hours.

A measurement of the current voltage characteristic in the dark was carried out before and after the PID stress. These measurements are shown in Fig. 4. The principal difference between the dark current voltage characteristics before and after degradation is a drastic decrease of the shunt resistance (from 12k Ohm cm^2 to 27 Ohm cm^2), leading to an increase of the current of more than two orders of magnitude in the low voltage range (< 300 mV).

In order to evaluate of the current due to an inverted region we need to evaluate $J_{0\text{e},\infty}$ for our emitter. It was calculated using PC1D simulations [14]. The doping concentration profile of the emitter was needed as input parameter of the simulation (see figure 2) and the surface recombination velocity on the emitter surface was varied. The calculated emitter saturation current density ($j_{0\text{e}}$) as a function of the surface recombination velocity is plotted in Fig. 3. For very high surface recombination velocities the $j_{0\text{e}}$ saturates limited by the diffusion of the minority carriers through the emitter. This saturation corresponds to $J_{0\text{e},\infty}$.

$J_{\text{dack,inv}}$ is than calculated as a function of the voltage

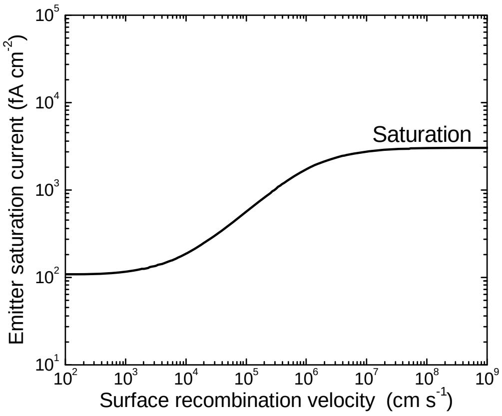

Fig. 3. Emitter saturation current density as a function of the surface recombination velocity

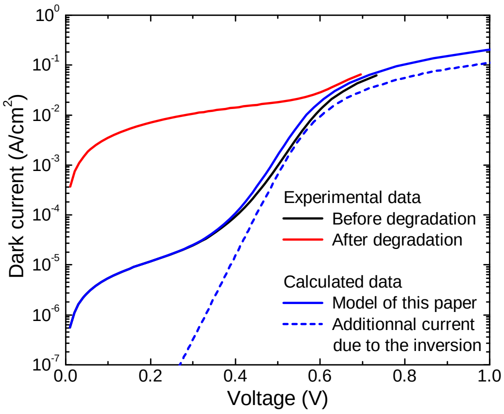

Fig. 4. Dark current voltage characteristic before and after potential-induced degradation (PID), calculated IV degradation using the model of inverted region. The calculated data includes the experimental data before degradation plus the maximum current due to the degradation according to Eq. 11.

and added to the experimental data before degradation (Fig. 4). The additional current due to the inversion layer is not sufficiently high to explain the dark current after degradation, especially in the low voltage range, where it is negligible. In deed, the losses due to the inversion of the emitter would correspond to a increased recombination not to a shunt like in the case of PID. Therefore, the inverted model cannot explain the PID.

4 SUMMARY

We have shown that a sufficient negative charge density would lead to an inversion of the emitter surface rather than a full inversion of the emitter. The inverted front surface can be modelled by an infinitely recombining surface. However, these additional recombination losses cannot explain the PID on the experimental level. Therefore, we conclude that an inversion layer cannot explain the potential-induced degradation.

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