Solid-State Electronics 76 (2012) 36–39

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Hard breakdown mechanisms of compensated *p*-type and *n*-type single-crystalline silicon solar cells

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ARTICLE INFO

Article history:
Received 14 December 2011
Received in revised form 14 May 2012
Accepted 18 May 2012
Available online 1 July 2012

The review of this paper was arranged by S. Cristoloveanu

Keywords:
Silicon
Breakdown
Dopant
Solar cell

ABSTRACT

The hard breakdown behaviors of boron–phosphorus compensated *p*-type and *n*-type Czochralski silicon solar cells were studied as functions of the type of conductivity, the net doping concentration and the temperature. We showed as expected from previous studies that the hard breakdown was governed by avalanche mechanisms (impact ionization) and that for a given net doping concentration the hard breakdown voltage was almost the same for both *p*-type and *n*-type solar cells, despite the different reported values for the electron and hole impact ionization coefficients. The studied compensated materials offered the opportunity to determine the hard breakdown voltages for samples with the same net doping concentration but different total amount of doping species. However no major effects of the dopant compensation were observed, the experimental data being described by the empirical expressions used for uncompensated silicon samples.

1. Introduction

Upgraded Metallurgical-Grade Silicon (UMG-Si) is a promising material for the future of the PhotoVoltaic (PV) industry. Compared to Electronic-Grade Silicon (EG-Si) this Silicon (Si) features lower purification cost, a weaker environmental impact associated to the purification processes, and significantly reduced energy payback time. High efficiency solar cells can be obtained from such a material [1–3]. UMG-Si generally contains high densities of dopants mainly Boron (B) and Phosphorus (P). Furthermore the material is compensated (it contains similar amount of both acceptor and donor species). These high amounts of dopants are generally presented as the main limitation of these new materials as the dopants affect both the transport and recombination properties of the charge carriers, and the forward and reverse current–voltage characteristics of the finished solar cell [4].

The present study focuses on the absolute value of the hard breakdown voltage (V_{bd}) of the solar cells processed from such material. The hard breakdown is related to the part of the reverse current–voltage (I–V) curve where the current suddenly sharply increases upon lowering the reverse bias. The current of this breakdown type governs the global I–V curve at high reverse bias (in absolute values). The V_{bd} is a crucial parameter since it governs the long-term performance of a solar module. Indeed when a cell within the module is shaded, it induces a loss of the global power of the panel which is mitigated by the presence of protection diodes [5]. However for a large size standard module of about 60 cells these protection diodes mitigate the power loss only if the V_{bd} value of the shaded cell is higher than 12–13 V. Thus the influence of the high amount of compensated dopants on this critical parameter has to be studied.

To discriminate the influence of dopants from the effect of other defects (mainly metal impurities and extended defects) a single-crystalline Czochralski (Cz) ingot was grown from an EG-Si feedstock which was intentionally doped and compensated by both B and P. The physical mechanisms behind the junction hard breakdown were identified via studies at different temperatures (T). Then the effects of the net doping concentration (p_0), the substrate conductivity type and the dopant compensation were investigated.

2. Experiment

A single-crystalline Czochralski (Cz) ingot was grown from an EG-Si feedstock which was intentionally doped and compensated by both B and P in order to observe a change in the type of conductivity located at 76% of the ingot's height. The B and P concentrations (respectively [B] and [P]) along the ingot's height were accurately determined by the combination of various chemical – Glow Discharge Mass Spectroscopy (GDMS) and Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) – and electrical (Hall Effect at various T) analyzes. From [B] and [P] the majority carrier

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0038-1101/$ - see front matter
http://dx.doi.org/10.1016/j.sse.2012.05.033

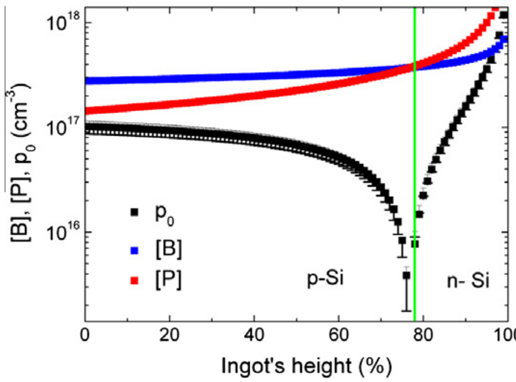

Fig. 1. [B], [P] and p_0 variations along the ingot's height. The vertical green line shows the change in the type of conductivity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

densities (noted p_0 independently of the type of conductivity) were computed, including the incomplete ionization of the B atoms in *p*-Si and that of the *P* atoms in *n*-Si. Details regarding this computation are given in [4]. Fig. 1 presents the variation of [B], [P] and p_0 along the ingot's height. We can notice that due to the different partition coefficients of *B* and *P*, the p_0 values vary strongly on the height of the ingot and that the influence of the type of conductivity on the V_{bd} values can be studied for given p_0.

Some wafers were selected to process both *p*-type and *n*-type solar cells. The *p*-type cells were industrial-like cells and the *n*-type cells were aluminum emitter rear junction cells (details about the cell process can be found in Ref. [6]). Thus the same processing steps – particularly the same alkaline texturization and the same high *T* annealing – were used for the processing of both types of cells [6]. The V_{bd} were extracted from reverse dark current–voltage (*I–V*) measurements in two different ways: the first based on the determination of the maximum curvature point of the *I–V* curve, the second based on the voltage value corresponding to a pre-defined reverse current. The *T*-coefficients of the V_{bd} values (β) were determined in the 25–60 °C *T* range.

3. Identification of the physical mechanisms governing the junction hard breakdown

Two major hard junction breakdown mechanisms generally occur in n^+p or p^+n diffused junctions: the avalanche effect (impact ionization) and the tunneling effect through the Space Charge Region (scr) [7]. When the breakdown is governed by the avalanche effect, the V_{bd} values increase as the *T* increases (the accelerated free carriers within the scr lose part of their energy to optical phonons). When the breakdown is governed by the tunneling effect, the V_{bd} values decrease as the *T* increases (this is mainly due to the decrease of the semiconductor energy band gap) [7].

Figs. 2 and 3 present the reverse *I–V* curves measured at various *T* for compensated *p*-type and *n*-type Si solar cells. For both studied cells the V_{bd} values (voltage corresponding to a given reverse current, higher than 40 mA.cm^{-2}) increase as the *T* increases. The V_{bd} values vary linearly with the *T*. Fig. 4 reports the variation with the p_0 values of the β coefficient (equal to V_{bd}/T). For all studied cells, β is positive. Consequently, in good agreement with the previous study of Kwapil et al [8], the hard breakdown voltage of the studied cells is predominantly governed by the avalanche effect, whatever the net doping concentration and the type of conductivity. This is also in good agreement with the published literature for non-compensated Si, which mentions that the tunneling effect govern the junction breakdown for p_0 values higher than about

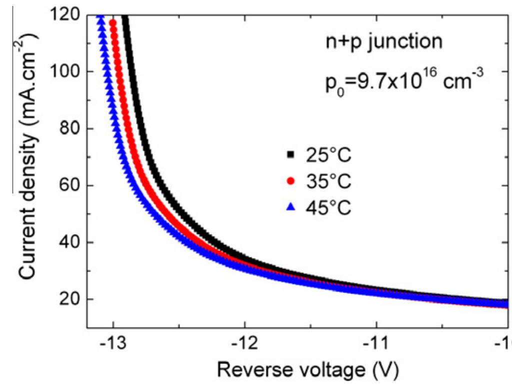

Fig. 2. Dark reverse characteristics of a B–P compensated *p*-type solar cell at various temperatures.

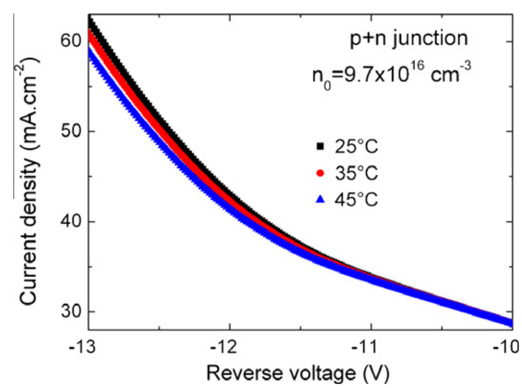

Fig. 3. Dark reverse characteristics of a B–P compensated *n*-type solar cell at various temperatures.

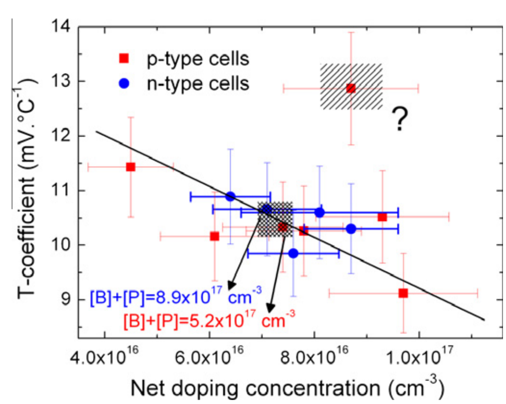

Fig. 4. Variation of the *T*-coefficient of the V_{bd} with the net doping concentration. Data within the shaded square corresponds to *p*-type and *n*-type cells with the same net doping concentration but different total dopants concentrations. The black line is only a guide to the eyes. Notice that the data within the shaded circle was off-centered compared to the others but not satisfactory explanations were proposed for this result.

3×10^{17} cm^{-3} (the higher the p_0, the thinner the scr and consequently the higher the possibility of tunneling conduction across the junction) [7].

We can notice in Fig. 4a slight decrease of the β values as p_0 increases. Such a decrease of β with increasing p_0 is in good agreement with the computations of Crowell and Sze [9], Chang et al. [10] dedicated only to the avalanche effect in non-compensated Si, done by the use of a modification of Baraff's theory. Particularly Chang reported β values equal to 10 mV °C^{-1} and 6 mV °C^{-1} for p_0

respectively equal to 4.5×10^{16} cm^{-3} and 9.7×10^{16} cm^{-3} whereas for the same p_0 our β values are equal to 11.5 mV °C^{-1} and 9.1 mV °C^{-1}. This good agreement shows first that the observed slight decrease of β with increasing p_0 is only due to the avalanche effect (not due to the combination at high p_0 of both the avalanche and tunneling effects). Secondly this comparison between our data and those computed by assuming a standard non-compensated material shows that the dopants compensation has no significant effect on the *T*-variation of the V_{bd}. This consideration is reinforced by the fact that as pointed out in Fig. 4, *p*- and *n*-type solar cells having the same p_0 but different total dopants concentrations have the same β.

4. Variation of the hard breakdown voltage with the net doping concentration

Figs. 5 and 6 present the reverse dark *I–V* curves for the *p*- and *n*-type solar cells processed from wafers from the previously presented Cz ingot. From these curves the V_{bd} (defined in this case as the voltage at the point of maximum curvature of the reverse *I–V* curve) were extracted. We notice first that the V_{bd} values increase as the p_0 values decrease. This tendency was expected. Indeed, as previously shown, the hard breakdown is due to the avalanche effect. Yet the higher the p_0, the higher the electric field within the scr and consequently the possibility of impact ionization of the Si atoms by the free carriers.

Fig. 7 reports the variation of the V_{bd} with p_0. We notice that for a given p_0, the V_{bd} are almost the same for both *p*- and *n*-type cells (for the studied cells architectures). At first this result was rather unexpected because the hole and electron ionization rates are significantly different in Si [11]. However we recently conducted a theoretical study [12], based on the computation of the ionization integrals, which shows that for given emitter profiles and carrier densities, identical V_{bd} are expected for both *p*- and *n*-type cells, in agreement with our experimental data.

It is worth noticing that for the studied cells, the V_{bd} are the same for both *p*- and *n*-type cells (for a given p_0) despite some strong differences regarding the total dopants concentration (as pointed out in Fig. 7). Furthermore our experimental V_{bd} are compared with those computed from the empirical model of Van Zeghbroeck [13], built from experimental data obtained with standard non-compensated Si. For high p_0, the computed data are in very good agreement with the experimental values despite the surface texturation of the processed cells. Both results confirm again that the effects of the dopants compensation on the V_{bd}, if they do exist, are very weak.

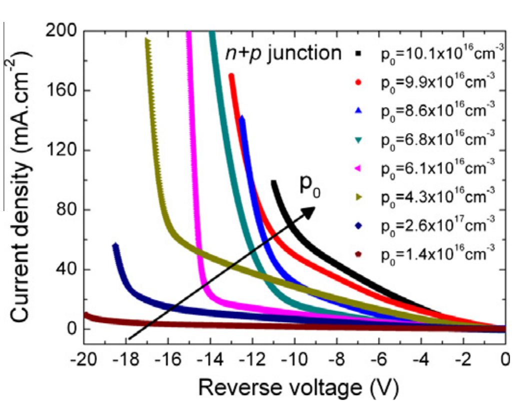

Fig. 5. Dark reverse characteristics of B–P compensated *p*-type solar cells measured at 25 °C for various net doping concentrations.

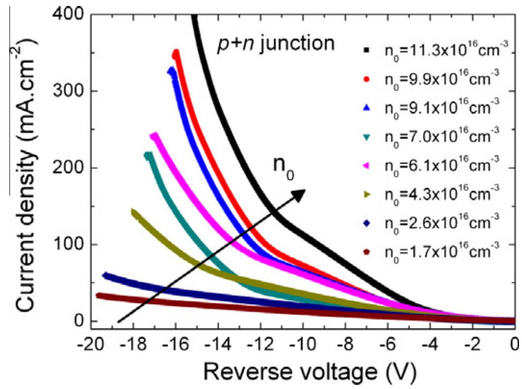

Fig. 6. Dark reverse characteristics of B–P compensated *n*-type solar cells measured at 25 °C for various net doping concentrations.

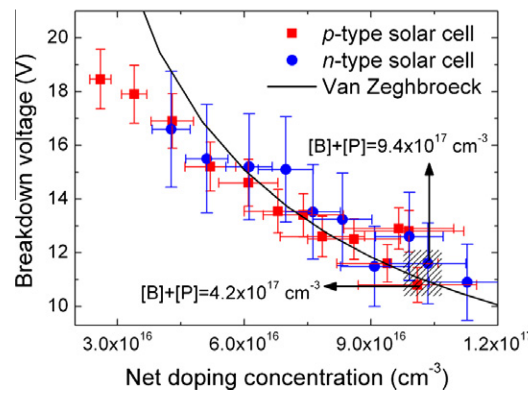

Fig. 7. Variation of the V_{bd} with the net doping concentration for both *p*-type and *n*-type B–P compensated solar cells. The black curve represents the data computed from the Van Zeghbroeck's model. Data within the shaded square corresponds to *p*-type and *n*-type cells with the same net doping concentration but different total dopants concentrations.

Notice that the difference between the computed V_{bd} (from Van Zeghbroeck's expression) and the experimental values for the lowest p_0 (below 5×10^{16} cm^{-3}) is unclear but could be due to the surface texturation (the presence of sharp kinks in the shape of the *pn* junction plane enhances locally the electric field within the scr and consequently the breakdown) or due to the metallization (parasitic junctions below the metallic electrodes which could locally increase the bands curvature and consequently the junction breakdown) [14].

In terms of application, the fact that at high p_0 the V_{bd} values correspond to those computed from Van Zeghbroeck's model is useful since this mathematical expression can be used in order to predict from a p_0 value the corresponding V_{bd}. Also a specification regarding the p_0 value in order to get V_{bd} higher than 12 V (cells encapsulated in large size modules) can be extracted, namely p_0 values have to be lower than 8.5×10^{16} cm^{-3} for both *n*-type and *p*-type *Si* solar cells, whatever the compensation level.

5. Conclusion

The hard breakdown behaviors of B–P compensated *p*-type and *n*-type Cz-Si solar cells were studied as functions of the type of conductivity, p_0 and *T*. First we showed, as expected from previous studies, that the hard breakdown was governed by avalanche mechanisms (impact ionization) and that for a given net doping concentration the hard breakdown voltage was almost the same for both *p*-type and *n*-type solar cells, despite the different reported values for the electron and hole impact ionization coefficients. The studied compensated materials offered the opportunity to determine the hard breakdown voltages for samples with the same p_0 but different total amount of doping species. For given p_0, no effects of the dopants compensation were observed on the V_{bd} whatever T. In addition both the V_{bd} and their T-coefficients were almost the same as the experimental or computed values, extracted from standard non-compensated materials. Thus all this results show that in the ranges of p_0, [B] and [P] investigated, no effects of the dopants compensation on the hard breakdown were observed. Also as the experimental data are well described for p_0 higher than $5 \times 10^{16}\,\mathrm{cm}^{-3}$ by the empirical expressions of Van Zeghbroeck, this shows that despite the dopants compensation the V_{bd} can be predicted simply from the knowledge of p_0. In order to fabricate cells encapsulated in a standard large size module without using additional protection (by-pass) diodes or modifying the solar cell fabrication process, the p_0 values should be below $8.5 \times 10^{16}\,\mathrm{cm}^{-3}$.

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