Solar Energy Materials & Solar Cells 124 (2014) 24–30

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Analysing the lateral series resistance of high-performance metal wrap through solar cells

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ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
7 January 2014
Accepted 20 January 2014
Available online 8 February 2014

Keywords:
Silicon
Solar cell
Metal wrap through
Series resistance
Simulation

ABSTRACT

In back-contact solar cells, both external polarities are located at the back surface of the device, which allows for higher photocurrent generation on cell level and reduced series resistance on module level, leading to higher energy conversion efficiencies compared to conventional solar cells and modules. However, the majority charge carriers, which are generated near the back emitter, have to flow laterally *e.g.* through the base in order to reach the external majority carrier contact. In the present work, we analyse the lateral series resistance by means of measurement and simulation for high-performance metal wrap through (HIP-MWT) solar cells. We compare theoretical models and experimental methods to extract the effective series resistance from simulated and measured current–voltage characteristics and show that lateral voltage variations significantly increase the local recombination current. If the width of the gap between the external majority carrier contacts is reduced from the typical value of 3.5 mm to ideally 0 mm, we expect an increase of the energy conversion efficiency of approximately 0.1% abs. for cells with three continuous rear emitter contacts on 125 mm × 125 mm large silicon wafers. In a simulation study, the bulk doping concentration N_A and the bulk lifetime are varied yielding an optimal base resistivity of 0.6 Ω cm–1.5 Ω cm for HIP-MWT solar cells based on Czochralski-grown silicon in the degraded state of the boron–oxygen defect and an optimal resistivity of less than 1.0 Ω cm for the case of bulk lifetimes larger than ~300 μs.

1. Introduction

The metal wrap through (MWT) solar cell concept [1] has several advantages compared to the conventional H-pattern cell concept. The most important are the reduced shading at the front side and reduced cell-to-module losses [2,3]. Both external polarities, the *n*- and *p*-type contact of metal wrap through solar cells are located side by side at the back surface, which induces a contribution to the total series resistance of the device, which can significantly reduce the fill factor compared to conventional H-pattern devices [4–6]. It was shown by Fellmeth et al. that the analytical formula for the lateral series resistance proposed by Clement ([3] and [7, pp. 201]) does not fit to measured data [4]. However, in this and other works, the presence of a shunted emitter at the back of the cells, which additionally reduces the fill factor, obscured the effect of the series resistance [4,5]. Recently, Thaidigsmann et al. presented the high-performance MWT (HIP-MWT) concept, which features a simplified processing sequence compared to conventional MWT-PERCs (passivated emitter and rear cells [8]), but the same energy conversion efficiencies [9]. In HIP-MWT cells, there is neither an emitter at the back surface of the cell which may be possibly shunted nor are other sources of shunts more pronounced than in conventional MWT-PERCs [10]. Therefore, this cell concept allows for a precise analysis and optimisation of the lateral series resistance of MWT cells based on measurements and numerical and analytical calculations, which is the focus of the present work.

2. Experimental

In order to study the impact of the lateral resistance of the base in the region of the rear *n*-type contacts, the following experiment is carried out. A HIP-MWT solar cell (see Fig. 1) is manufactured on a five-inch (125 mm) *p*-type Czochralski-grown silicon wafer with a specific resistance of approximately 1.8 Ω cm using the TOPAS (thermal oxide passivated all sides [11]) approach. This approach results in a thin thermal silicon oxide passivation at the front and the rear of the wafers. A SiN_x anti-reflection coating at the front and further rear surface passivation layers are deposited with the PECVD technique. The front, via and rear metallization are screen printed. The front metal-semiconductor contact is formed during a firing step in a belt furnace. The rear metal-semiconductor contact to the base of the devices is formed stepwise with the laser-fired

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http://dx.doi.org/10.1016/j.solmat.2014.01.032

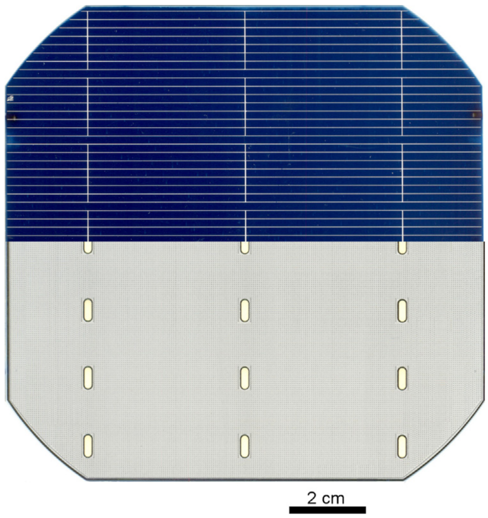

Fig. 1. The photograph shows the front (top) and rear side (bottom) of a HIP-MWT solar cell including the nearly elliptical pads for the *n*-type contact.

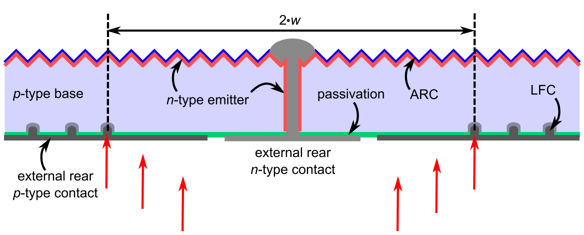

Fig. 2. The cross-sectional sketch of the stepwise LFC processing of the HIP-MWT cells shows the lines of LFC point contacts at the bottom that are subsequently added as indicated by the red arrows leaving an uncontacted stripe of width 2*w* around the rear *n*-type contact. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contact (LFC [12,13]) approach (cf. Fig. 2): In a first step, only a part of the rear is contacted leaving three uncontacted stripes where the front metallization is wrapped through the via holes to the back surface of the wafer. At this stage, the uncontacted stripes are 7.5 mm broad, including the 3 mm broad rear *n*-type contact stripes. By subsequently adding row after row of LFCs parallel to each of the three stripes of the rear *n*-type contacts of the HIP-MWT cells, the effective width 2*w* of the uncontacted stripes at the rear is reduced stepwise from 7.5 to 3.5 mm. Accordingly, the lateral resistance is reduced. In order to separate the contribution of the lateral current in the base $R_{lat}(w)$ from the remaining contributions R_{rem}, which arise from the front metallization fingers, the metal-semiconductor contact resistance, the emitter sheet resistance and the spreading resistance of the LFC point contacts to the base, a quasi-full-area LFC-pattern is applied as final stage of the experiment. Instead of three 3.5 mm broad stripes, this contact pattern leaves only three rows consisting of seven approximately 3.5 mm × 6 mm small elliptical areas uncontacted at the rear side (see Fig. 1). Furthermore, this quasi-full-area LFC pattern features a spatial LFC distance that is reduced by 50% in the first row directly adjacent to the elliptical areas, *i.e.*, the density of LFCs is twice as high around the *n*-contacts compared to the remaining rear areas. This minimizes the contribution of the lateral resistance R_{lat} of the base to the total series resistance R_s. In the following, the series resistance of the quasi-full-area LFC pattern is identified with $w=0$, and a possible remaining contribution of $R_{lat}(0)$ to $R_s(0)$ is completely neglected ($R_{lat}(0)=0$), which allows the effective series resistance $R_s(0)$ to be identified with the contributions of all remaining components R_{rem}. Furthermore, it follows that the difference of the measured total series resistance at an *n*-type contact width $w>0$ and the measured total series resistance at $w=0$ equals the lateral series resistance contribution from the base R_{lat}

$$R_s(w)=R_{rem}+R_{lat}(w). \quad (1)$$

For measurements of the current–voltage characteristics, the solar cell is contacted with a chuck matching the cell layout [14] and is unaffected by the LFC-patterns applied, since the *n*-type probes of the chuck are contacting only the *n*-type pads of the cell.

From lifetime measurements on parallel processed samples, the surface recombination velocity of the passivation ($S_{pass}=35$ cm/s) is determined. Assuming the parameterization for the effective surface recombination of the LFCs given by Wolf et al. [15] and the pitch of 500 μm of the LFC points, we derive an effective rear surface recombination velocity $S_{eff}=160$ cm/s including the passivation and the LFC metallization according to the model for S_{eff} of Fischer [16]. From further lifetime samples the effective emitter saturation current density $j_{0e}=160$ fA/cm^2 is deduced, which is the mean of the metallised and non-metallised parts of the emitter weighted by the respective areas. The spectral hemispherical reflectance of the finished cell is measured with a Varian Cary500 spectrophotometer equipped with an integrating Ulbricht sphere. After each LFC step, the relevant current–voltage characteristics of the device are measured giving amongst others the efficiency and the total effective series resistance. The area-related, effective series resistance, given in Ω cm^2, can be determined by different methods. In order to highlight possible differences between the methods, which are reported in the literature [17,18] and observed in our lab [19], the three most common experimental methods are compared here:

1. Method 1: By comparing the current–voltage curves measured at three illumination intensities (0.8, 1.0 and 1.2 suns) giving R'_{3i} [20,21].
2. Method 2: By comparing the current–voltage curve measured under 1-sun illumination and the suns V_{oc} curve giving R'_{is} [17,20].
3. Method 3: By comparing the current–voltage curves measured under 1-sun illumination and in the dark according to Eq. (5) in Ref. [19] giving R'_{id}.

These experimental methods are accompanied by two purely theoretical methods to calculate the series resistance in Section 3.

3. Numerical simulations and analytical model

The HIP-MWT cell is modeled using the software Sentaurus TCAD [22]. For the optical part, we assume a 70 nm thick SiN_x antireflection coating and a 10 nm thin SiO_2 passivation on the alkaline textured front side. The Phong model [23] is used to model the rear surface instead of the tilted-mirrors model [24] since the rear surface morphology was not measured and the focus in the present work is on the electrical part. With the Phong parameters $R_0=0.93$ and $\omega=40$, the measured spectral hemispherical reflectance is well reproduced. The two-dimensional symmetry element for the electrical simulation is sketched in Fig. 3. The width of the symmetry element is chosen to be $w_{se}=125$ mm/(3 × 2)=20.83 mm and the wafer thickness is assumed as 155 μm according to the measured thickness after emitter diffusion. The emitter doping profile is measured with secondary ion mass spectroscopy (SIMS) on planar reference samples. The finite solubility of phosphorous in silicon is accounted for according to Solmi et al. [25], giving a surface concentration of 2.75×10^{20} cm^{-3}. The emitter depth is approximately 0.5 μm. The effective saturation current density $j_{0e}(25\,°C)$