Solar Energy Materials & Solar Cells 133 (2015) 143–147

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Application and modeling of single contact electron beam induced current technique on multicrystalline silicon solar cells

L. Meng [a,b], A.G. Street [a], J.H. Phang [a], C.S. Bhatia [a,b,*]

[a] Centre for Integrated Circuit Failure Analysis and Reliability (CICFAR), Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, 117576 Singapore, Singapore
[b] Solar Energy Research Institute of Singapore (SERIS), National University of Singapore, 7 Engineering Drive 1, 117574 Singapore, Singapore

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form
22 October 2014
Accepted 3 November 2014

Keywords:
Single contact electron beam induced current
SCEBIC
EBIC
Solar cell
Characterization
PSPICE simulation

ABSTRACT

The first demonstration of single contact electron beam induced current (SCEBIC) technique on multicrystalline silicon (mc-Si) solar cells is reported. A lumped single-diode analytical model is also proposed to theoretically explain the SCEBIC phenomenon within solar cells as well as the current transient characteristics of the major model parameters, such as shunt resistance R_{sh}, junction capacitance C_j and parasitic capacitance C_s. The accuracy of the analytical model is then verified using PSPICE simulations, which show a close match with the experimental results. It is found that a large value of parasitic capacitance C_s is necessary to achieve good SCEBIC signal strength with a relatively low signal-to-noise ratio (SNR), and this is realized experimentally by adopting a metal enclosure in the measurement setup. In addition, an advantage of SCEBIC over the conventional double-contact method is also demonstrated by characterizing partially processed solar cells, which clearly illustrates the high degree of flexibility of SCEBIC in solar cell characterization.

1. Introduction

Electron beam induced current (EBIC) has been widely used for characterizing semiconductor materials and microelectronic devices as a useful technique for p–n junction imaging, as well as localization of defects and doping inhomogeneities [1,2]. Conventionally, EBIC requires electrical contacts to both the p- and n-type regions of the p–n junction. Such convention is also adopted in this paper and, unless stated otherwise, EBIC refers to the double-contact technique. To overcome the double-contact EBIC requirement, single-contact EBIC (SCEBIC) was subsequently developed [3]. As the name suggests, SCEBIC requires only one electrical contact to either the p- or n-type region. It differs from EBIC primarily by being an AC technique that takes advantage of the parasitic capacitance between a floating contact and ground. This single-contact technique proves to be extremely convenient, for instance, for imaging multi-layer integrated circuits (ICs), where both connected and unconnected junctions can be clearly captured [4,5], thus allowing high flexibility for imaging and characterization of semiconductor devices and ICs.

Recently, there has been increasing popularity in applying EBIC in solar cells to study extended crystallographic defects such as dislocations, grain boundaries, microcracks and breakdown sites in photovoltaic devices [6–9]. EBIC is also employed to characterize local electrical properties of solar cells, such as minority-carrier current collection efficiency, characteristics of the p–n junction, as well as local recombination sites in the semiconductor materials [10,11]. While the double-contact EBIC has been gaining increased traction for characterizing solar cells, application of its single-contact counterpart, SCEBIC, has remained elusive. In particular, one of the main difficulties in implementing SCEBIC on solar cells is that the time-dependent SCEBIC transient signals are highly sensitive to the junction and parasitic capacitances of the devices [12]. Unlike ICs, where the junction areas and thus the corresponding junction capacitances are relatively small, photovoltaic devices tend to have large junction areas, which in turn result in SCEBIC transient signals with a poor signal-to-noise ratio (SNR). This makes it difficult to separate the real signals from noise.

In this work, the first demonstration of SCEBIC measurement on a single p–n junction multicrystalline silicon (mc-Si) solar cell is reported. It is shown that by using a novel technique of employing a metal enclosure in the SCEBIC setup, SCEBIC imaging with accuracy and resolution comparable to the conventional double-contact EBIC can be established on mc-Si solar cells. A theoretical explanation of the SCEBIC phenomenon in solar cells as well as the importance of having a large value of C_s in obtaining good SCEBIC signal strength

---

[*] Corresponding author at: Centre for Integrated Circuit Failure Analysis and Reliability (CICFAR), Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, 117576 Singapore, Singapore. Tel.: +65 6516 7216.
E-mail address: elebcs@nus.edu.sg (C.S. Bhatia).

http://dx.doi.org/10.1016/j.solmat.2014.11.003

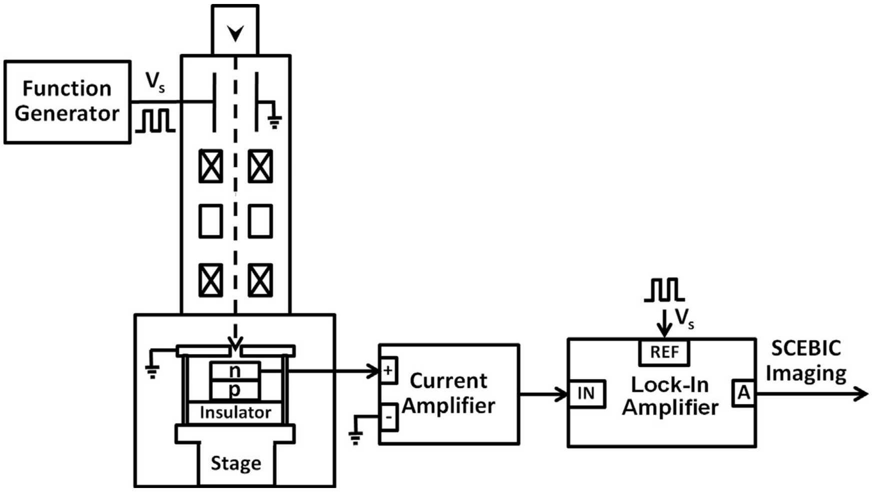

Fig. 1. SCEBIC system experimental setup. The p-type region is left floating and only the n-type region of the sample (top metal finger) is connected to the external circuit.

are also explained using a lumped single-diode analytical model and supported by PSPICE simulations. Lastly, SCEBIC characterization of partially processed solar cells is also demonstrated, clearly illustrating the higher degree of flexibility of SCEBIC in solar cell characterization and an advantage of SCEBIC over the conventional double-contact EBIC.

2. SCEBIC setup and experiment

The SCEBIC imaging was carried out in a scanning electron microscope (SEM) with a beam blanker to achieve an intensity-modulated electron beam, (i.e. a pulsed electron beam). Fig. 1 shows the experimental setup of the system. A function generator was used to drive the beam blanking plates and also to provide the reference signals of the lock-in amplifier (LIA). As shown in the setup, the p-type region was left floating and only the n-type region of the sample (top metal finger) was directly connected to the external circuit. As the induced current signals are very weak (in the range of nano-amperes), a low-noise current amplifier was employed to improve the signal-to-noise ratio of the transients. The resulting signals were then fed into the LIA and an imaging acquisition system that synchronized the scan generator with the LIA output. The image acquisition system also controlled the position of the electron beam on the sample and generated the SCEBIC images. An important difference between our experimental setup and previous SCEBIC work is the addition of a metal enclosure that acts as a shield against noise and increases the parasitic capacitance in the SCEBIC circuit.

For all the SCEBIC measurements in this work, a 200-μm thick commercial mc-Si solar cell was used. The active n$^+$–p area of the sample is approximately 1 cm^2. The contact to the n$^+$ region was established by using electrically conductive silver paste.

3. Results and discussion

Fig. 2a is a secondary electron (SE) image showing the general surface morphology of the mc-Si solar cell. The textured surface is typical of mc-Si solar cells and is a result of the multicrystalline nature of the silicon and the saw-damage etch (SDE) process. Fig. 2b shows a corresponding conventional EBIC image from the same location. This image clearly demonstrates the defect localization capability of EBIC as several defects are visible. When combined with SE and other techniques as reported earlier [13,14], EBIC allows easy correlation and accurate analysis of the nature of the defects. As also mentioned previously, SCEBIC imaging on solar cells is difficult due to poor SNRs and this is apparent from the very noisy image depicted in Fig. 2c. This image was made by connecting only the n-type region of the sample to the external circuit and leaving the p-type region floating (i.e. using the conventional SCEBIC [3] without a grounded metal enclosure). The addition of a grounded metal enclosure close to the sample surface significantly increases the SNR of the circuit, generating a clear SCEBIC image (Fig. 2d) of comparable quality to the conventional EBIC image. Based on our best knowledge, such successful application of SCEBIC represents the first demonstration of SCEBIC on solar cell characterization.

While the capabilities of SCEBIC and the effectiveness of the metal enclosure are clearly demonstrated in Fig. 2, it is important to understand the physical and electrical effects of the metal enclosure. Fig. 3a and b shows the configuration of a typical p–n junction solar cell and its equivalent circuit diagram of the SCEBIC measurements, respectively. A lumped single-diode model is used in this case since it has been used to provide a simple yet reasonably accurate physical picture of device operation under electron-beam excitation [15]. The solar cell is represented by a diode with a shunt resistance R_{sh} and a junction capacitance C_j in parallel [16]. For ICs, the value of R_{sh} is typically very high owing to the relatively low density of defects and well-passivated p–n junction edges. Because of this, R_{sh} is usually omitted in the SCEBIC model of ICs. However, in the case of solar cells, the p–n junction is much leakier, making R_{sh} a necessary parameter in the model. The series resistance R_s refers to the total contact resistance, and the parasitic capacitance C_s is the capacitance that exists naturally between a floating contact (the p-type region of the solar cell in our particular setup) and ground. When the pulsed high-energy electron beam impinges the sample surface, electron-hole pairs are generated and separated by the internal electric field within the space-charge region of the p–n junction as the holes drift to the floating p-type region and the electrons move to the n-type region. This induced current can be effectively modeled by a current source I_g. In the conventional double-contact EBIC, I_g can be readily measured and is commonly known as the generation current. Although there is no physically closed loop in the SCEBIC model, the parasitic capacitance C_s will charge up and discharge as the pulsed electron beam interacts with the device, leading to a complete AC SCEBIC current path. This allows the pulsed current, $I_{SCEBIC}(t)$, to pass through and to be measured by the current meter between the unconnected p-region and ground.

To understand the importance and the effect of the different parameters on the SCEBIC transient response, PSPICE simulations are carried out assuming typical values of each parameter.