Revisiting the theory and usage of junction capacitance: Application to high efficiency amorphous/crystalline silicon heterojunction solar cells

Jean-Paul Kleider *, José Alvarez, Aurore Brézard-Oudot,
Marie-Estelle Gueunier-Farret, Olga Maslova

*Laboratoire de Génie Electrique de Paris, CNRS UMR 8507, SUPELEC, Univ. Paris-Sud, Sorbonne Universités-UPMC Univ. Paris 06,
11 rue Joliot-Curie, Plateau de Moulon, F-91192 Gif-sur-Yvette Cedex, France*

ARTICLE INFO

ABSTRACT

We briefly review the basic concepts of junction capacitance and the peculiarities related to amorphous semiconductors, paying tribute to Cohen and to his pioneering work. We extend the discussion to very high efficiency silicon heterojunction (SiHET) solar cells where both an amorphous semiconductor, namely hydrogenated amorphous silicon, and heterojunctions are present. By presenting both modeling and experimental results, we demonstrate that the conventional theory of junction capacitance based on the depletion approximation in the space charge region, cannot reproduce the capacitance data obtained on SiHET cells. The experimental temperature dependence is significantly stronger than that of the depletion-layer capacitance, while the bias dependence yields underestimated values of the diffusion potential, leading to strong errors if applied to the determination of band offsets using the procedure proposed precedingly in the literature. We demonstrate that this is not related to the amorphous nature of a-Si:H, but to the existence of a strongly inverted c-Si surface layer that requires minority carriers to be taken into account in the analysis of the junction capacitance.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

In recent years silicon heterojunctions (HET) combining crystalline silicon (c-Si) wafers with thin layers of hydrogenated amorphous silicon (a-Si:H) have received much attention in the world of photovoltaics due to their ability to build high efficiency solar cells. Indeed, many research groups have demonstrated cells with more than 22% conversion efficiency [1–5], and the new world record for silicon cells has been reached in April 2014 by Panasonic, with a value of 25.6% based on Si-HET and rear contacting concepts [6]. Despite these impressive results there is still a lot to learn about this kind of heterojunction cells. In particular, the assessment of the band diagram parameters at the heterojunctions, the role of the a-Si:H properties, the choice of the charge collection electrodes and the characterization of interfaces need to be further investigated in order to further improve the cell performance. This necessitates the collection and analysis of results from various characterization techniques. Space charge spectroscopy using capacitance and conductance measurements is one of the useful techniques that can be deployed to this purpose. Silicon HETs associate a very high quality and almost defect free crystalline semiconductor with a defect rich amorphous one. Space charges have different origins and different behaviors in these two very different materials.

The theory of junction capacitance in crystalline semiconductors can be found in textbooks on the physics of semiconductor devices (see for instance [7]) and is usually based on the depletion approximation. On the other hand, strong efforts have also been deployed to analyze capacitance measurements of junctions formed on a-Si:H. We want here to pay homage to the pioneering work of Cohen [8,9]. In this paper we briefly recall the fundamentals of capacitance spectroscopy in both crystalline and amorphous semiconductors. We then emphasize the failure of the usually accepted and almost universally used depletion layer approximation for the junction capacitance. This is demonstrated both for the use of the $C–V$ method that could in principle be used to extract band offsets, and also for the temperature dependence. We provide the physical explanation of this failure that is not due to the amorphous nature of the emitter, but to the existence of a strong inversion layer at the c-Si surface.

2. Samples and procedures

We measured the capacitance on high efficiency ($\eta > 21\%$) solar cells coming from EPFL-IMT and INES that were fabricated on n-type crystalline silicon of similar doping density ($\approx 10^{15} \text{ cm}^{-3}$) [4,5]. These solar cells were not intended for bi-facial illumination
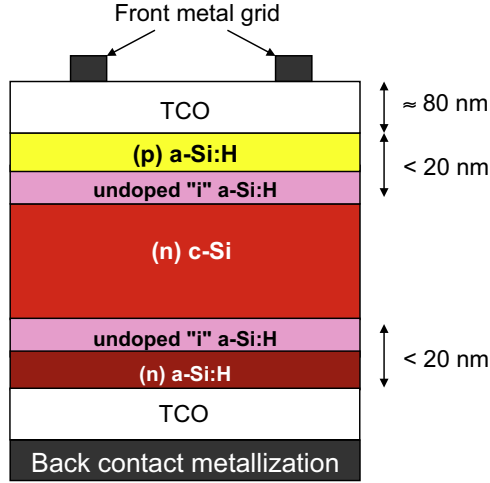
Fig. 1. Schematic view of the investigated silicon heterojunction solar cells (texturing has been omitted for simplicity).
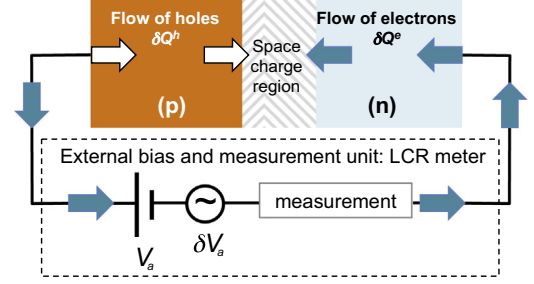

Fig. 2. Principle and schematic circuit of the capacitance measurement. Arrows indicate the charge flows following a small positive change in the bias applied to the p–n junction.

so the non-illuminated side was metallized on the whole wafer area (Fig. 1). Small pieces (between a few mm^2 up to 0.5 cm^2) were cut inside larger area solar cells. We first measured the current–voltage characteristics in order to check that the samples were not affected after cutting in particular with regards to shunts from the edges. The capacitance was then measured using Agilent 4284A and E4980A precision LCR meters at different DC biases (from -2 V to $+0.5$ V) and frequencies (20 Hz–1 MHz). Measurements were performed in two different cryogenic systems: one under nitrogen gas exchange in the range 90–320 K and the other with a cold finger chamber pumped down to 10^{-6} mbar in the range 90–420 K. We verified that measurements performed in either cryostat were reproducible and repeatable, crosschecked measurements performed in both cryostats and found that the results were identical within 5%.

3. Elements of junction capacitance theory

3.1. What do we really measure?

It is well known that charges of opposite sign develop at equilibrium in each side of a p–n junction (defining the space charge region) due to the difference in work function of the two materials in contact. These charges are modified by an external bias applied to the junction through an external circuit. Following a slight positive change in applied bias $\delta V_a = \delta(\varphi_p - \varphi_n)$, φ_p and φ_n being the electrochemical potential on the p- and n-side, respectively, a small quantity of electrons will flow from the n-side into the space charge region, giving a charge variation δQ^e (which is thus negative for a positive change in applied bias considering the negative charge of electrons) while a small quantity of holes will enter the space charge region from the p-side, producing a charge variation δQ^h of opposite sign, $\delta Q^h = -\delta Q^e$, as depicted in Fig. 2.

The instrument used to measure the capacitance only "sees" the flow of electrons that circulate in the external circuit, and the capacitance is thus given by

$$C = -\frac{\delta Q^e}{\delta V_a} = +\frac{\delta Q^h}{\delta V_a}. \tag{1}$$

We emphasize that this is the general and correct definition of the measured capacitance. It is more often used that $C = -\delta Q_n/\delta V_a = +\delta Q_p/\delta V_a$, where δQ_n and δQ_p are the charge variations within the n- and p-side of the space charge region, respectively. This only corresponds to the correct expression if

$\delta Q^e = \delta Q_n$ and $\delta Q^h = \delta Q_p$. These equalities are true in the depletion layer approximation that assumes that the density of both types of carriers can be neglected compared to that of dopants within the space charge region. Indeed, in that case after a small positive bias change electrons entering the space charge region from the n-side will just compensate some of the positively charged donors that determine Q_n; similarly holes entering the space charge region from the p-side will just compensate some of the negatively charged acceptors that determine Q_p. However these equalities do not hold for strongly asymmetrical p–n homojunctions (p$^+$–n or p–n$^+$) or in some cases of heterojunctions. For instance, as we will detail later, for p$^+$–n junctions and for the (p) a-Si:H/(n) c-Si heterojunction solar cells the flow of holes entering the space charge region from the p-side will also produce an increase in the charge of holes located on the n-side of the junction, very close to the junction interface where the density of holes may be larger than that of donors. Noticing that δV_a is equal to the variation in total electrostatic potential drop, $\delta V_a = \delta(V(-\infty) - V(\infty))$, and integrating twice Poisson's equation, we obtain

$$\delta V_a = -\int_{-\infty}^{\infty} \frac{x \delta \rho(x)}{\varepsilon(x)} dx, \tag{2}$$

where $\varepsilon(x)$ is the dielectric permittivity at position x, and $\delta \rho$ is the change in space charge density.

We express the variation in charge density

$$\delta \rho(x) = \delta \rho^h(x) + \delta \rho^e(x), \tag{3}$$

where $\delta \rho^h$ and $\delta \rho^e$ are the variations of space charge densities due to exchanges with holes and electrons, respectively. If we assume that the dielectric permittivity is the same in a-Si:H and in c-Si, $\varepsilon(x) = \varepsilon$, then a simple expression can be obtained for the junction capacitance

$$C = \frac{\varepsilon A}{\langle w \rangle}, \tag{4}$$

where A is the junction area and

$$\langle w \rangle = \langle x^e \rangle - \langle x^h \rangle, \tag{5}$$

is the separation between the first momentum of charge variation due to exchanges with electrons and that due to exchanges with holes

$$\langle x^e \rangle = \frac{\int_{-\infty}^{\infty} x \delta \rho^e(x) dx}{\delta Q^e}, \tag{6}$$

and

$$\langle x^h \rangle = \frac{\int_{-\infty}^{\infty} x \delta \rho^h(x) dx}{\delta Q^h}. \tag{7}$$