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Variable light biasing method to measure component *I–V* characteristics of multi-junction solar cells

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ABSTRACT

We present a new technique to measure component current–voltage (*I–V*) curves of individual sub-cells integrated in a monolithic multi-junction solar cell. This new approach, compared to all previously reported ones, is well suited for thin-film silicon p–i–n structures where the so-called shifting approximation, which supposes that illumination only shifts the *I–V* curve without changing its shape, is not valid. Moreover, the proposed method is particularly resistant to problems related to electrical shunts. The principle of this method lies in coupling the level of a selective light bias with the level of measured electrical current in order to fix the voltage of a selected sub-cell while sweeping over the current axis. When one of the sub-cells has a fixed voltage, it is then possible to get the *I–V* characteristics of the second one, shifted by a fixed voltage value. This measurement procedure is simple and requires no modeling. The accuracy of the method is evaluated by numerical simulations of a thin-film silicon p–i–n photodiode. Our technique is then successfully experimentally tested on a specially prepared three-terminal amorphous/microcrystalline silicon tandem solar cell.

1. Introduction

The multi-junction structure is a proven way to increase device efficiency in many solar cell technologies. In the thin-film silicon technology, one of the most common approaches is to combine an amorphous (a-Si:H) silicon cell and a microcrystalline (μc-Si:H) silicon cell into a so-called micromorph tandem solar cell structure [1]. The advantage of such a structure is the ability to absorb more efficiently a larger part of the solar spectrum by stacking materials with different bandgaps. For cell and module diagnostics, both in research and production, the current–voltage (*I–V*) measurement is the most common characterization tool. However, due to the monolithic integration of the two sub-cells, only measurements of the multi-junction's overall *I–V* are currently common. Although many *I–V* separation methods have already been reported [2–9], due to their complexity or limitations, none of them has become a standardized method of evaluation of the *I–V* performance of separate sub-cells in multi-junction devices. In this article we introduce a new and promising technique.

1.1. Effect of illumination

A common approach in the variety of reported methods [2–9] is the application of additional selective illumination. Indeed, the sub-cells are sensitive to different parts of the light spectrum. Thus, using selective illumination is the only non-destructive way of accessing individual sub-cells. In this part we first analyze theoretically the effect of the illumination on p–i–n solar cell *I–V* characteristics.

In the simplest model, the electrical performance of the solar cell can be described by Eq. (1) that takes into account the diode behavior, the parasitic serial resistance R_s and the shunt resistance R_{sh}. The symbols I, V, I_{ph}, I_s, n, k, and T respectively correspond to current and voltage on terminals, photogenerated current, saturation current, ideality factor, Boltzmann constant, and temperature:

$$I = -I_{ph} + I_s\left(\exp\left(\frac{V-IR_s}{nkT}\right)-1\right)+\frac{V-IR_s}{R_{sh}} \quad (1)$$

The simplified assumption that the illuminated *I–V* characteristic is equivalent to the dark *I–V* ($I_{ph}=0$) shifted by the photogeneration I_{ph} along the vertical axis, called the shifting approximation [10], is valid only under restricted conditions. As shown already by Wolf and Rauschenbach [11], this assumption is violated by the presence of serial resistance R_s that introduces the current I also to the right side of Eq. (1). Apart from this effect of

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the serial resistance, the shifting approximation has been attributed to the superposition principle of solving linear differential equations and has been critically analyzed for p–n junction solar cells [10,12]. Even in the case of crystalline silicon solar cells, the introduction of processes such as surface recombination can invalidate the shifting approximation. For thin-film p–i–n junctions, this approximation has been dismissed for both empirical [13] and fundamental reasons (presence of amphoteric recombination centers in the i-layer). This is expressed in Merten's model [14] by the addition of a new voltage-dependent recombination term I_{rec} (2) to the right side of Eq. (1):

$$I_{rec} = I_{ph} \frac{d^2}{(\mu\tau)_{eff}(V_{bi} - V + IR_s)} \quad (2)$$

Here, d, $(\mu\tau)_{eff}$, and V_{bi} indicate the thickness of the intrinsic layer, the effective mobility–lifetime product, and the built-in potential, respectively. We present a method that does not depend on the shifting approximation directly, thus significantly reducing the error.

By recording the evolution of the short-circuit current (I_{SC}) versus the open-circuit voltage (V_{OC}) when going from dark to full illumination, the so-called pseudo-*I–V* curve [11,15] can be obtained. For p–n junctions, such a curve is often interpreted as approximately the dark *I–V* of the given cell, but without the effect of serial resistance R_s. The exact difference between the pseudo and dark *I–V* curves in p–n junctions is now being considered as more complex [16]. Again, for thin-film silicon p–i–n structures, such an interpretation would mean an even poorer approximation, because of the presence of the recombination term (2). From this brief overview we can conclude that any measurement technique giving an illuminated *I–V* curve must be—in the case of thin-film p-i-n silicon cells—also performed at this illumination.

The explanation of the effect of illumination on the *I–V* curve of a multi-junction solar cell relates to the analysis of individual operating points of the individual sub-cells [11]. At any condition, the operation of any sub-cell is fully defined by the (operating) point that lies on its respective *I–V* curve and that fulfills all additional physical conditions. Thus the operating points of cells connected in series must be at the same current. The total voltage is then the sum of the voltages of all points. The selective illumination of one sub-cell can shift its respective *I–V* curve, while the vertical position of the operating point will still be determined by the level of the common electrical current. Voltage as a function of current will be a sum of voltages of two operating points lying at the same current level (see Fig. 1).

1.2. State of the art

Several *I–V* separation methods aim at measuring the *I–V* characteristics of one sub-cell by fixing the voltages of the other ones. Fixing the voltage of a given sub-cell can be done by using a constant selective light bias [2–4] that shifts its respective *I–V* characteristic downward and, since the operating point must stay at the same current, it will be moved along the *I–V* curve and can be moved to its steep part. If the slope of the steep part (its lower bound corresponds to R_{OC}^{-1}, defined e.g. in [14]) is high enough, the voltage on the illuminated sub-cell can be assumed to be constant. In Fig. 1, the effect of light biasing on the bottom sub-cell of a tandem cell is shown. The lowest lying red curve corresponds to the constant light bias method. When the *I–V* curve of the device is then measured, the voltage contribution of the light-biased sub-cell corresponds to the V_{OC} plus a variation given by the slope of its *I–V* curve (see the trajectories of the operating points denoted by black circles and dashed lines in Fig. 1). To obtain the component *I–V* curve, this voltage contribution has to be subtracted. Either a value of V_{OC} is simply assumed [2,4] or a default shape is used [3]. In order to take into account the real shape of the voltage variation, some more advanced methods that use several intensity levels of constant light bias exist. However, a complex mathematical analysis that is again based on the shifting approximation has to be used to recover the component *I–V* curves [5,7] or their basic parameters [6]. Determining a sub-cell's individual V_{OC} is a specific problem of some of the latter methods. In some of them [4–6,9] the V_{OC} is obtained directly from the method; however in other ones [2,3,7] it is a necessary input.

Another possibility is to perform spectrally selective suns–V_{OC} measurements [15] to obtain separate pseudo-*I–V* curves for individual sub-cells [8,9]. V_{OC} is measured by applying selective illumination with intensity varying from dark to the equivalent of 1 sun. The current is calculated from the sub-cell's I_{SC} at 1 sun, measured by the integral of the external quantum efficiency (*EQE*) and from the assumption of its linear dependence on intensity [15]. As discussed before, pseudo-*I–V* curves are difficult to be interpreted as illuminated *I–V* characteristics. Nevertheless this method can still be useful for obtaining V_{OC} because both pseudo-*I–V* and illuminated *I–V* curves go through the same V_{OC} point [11]. However, this approach requires perfectly selective illumination because even a very small parasitic generation in an unbiased sub-cell can vastly corrupt the results. We recently developed an algorithm to obtain reliable V_{OC} values for

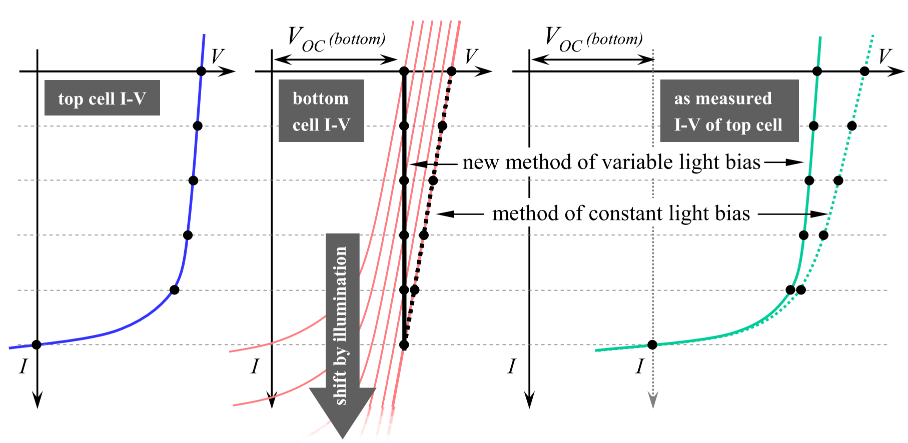

Fig. 1. Measured *I–V* curves (on the right) as a product of summation in voltage domain of the top cell voltage (on the left) and the voltage of the light biased bottom cell (in the middle). Light bias shifts the *I–V* curve vertically. Dotted lines represent attempt to eliminate the variation of voltage on the bottom cell by vertical shift of its *I–V* curve due to a constant light bias. Full lines represent new method of a variable light bias where the vertical shift scales with the level of current. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).