

Detailed investigation of TLM contact resistance measurements on crystalline silicon solar cells



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ARTICLE INFO

Article history:

Received 15 February 2017

Received in revised form 28 April 2017

Accepted 4 May 2017

Keywords:

Contact resistance

TLM method

c-Si wafer solar cell

ABSTRACT

The transmission line method (TLM) is often used in characterizing the contact resistance of c-Si solar cells by cutting cells into strips parallel to the busbars. When applying this method to industrial solar cells, we found various problems that have not been sufficiently explained in prior work. In this paper, we investigate different factors that influence the accuracy of this measurement, using both simulation and experimental methods. The following factors are shown to influence the extracted contact resistivity and are investigated in this work: (1) strip width; (2) edge shunting; (3) current flow through the intermediate unprobed fingers; (4) non-uniform contact resistance; and (5) non-uniform sheet resistance. In cases where the contact resistivity values determined from the TLM measurements and simulations were found to be inaccurate, we introduce correction procedures and measurement guidelines that reduce error. For example, when strip width is a factor, the measurement error of a 30 mm sample is reduced from 95.5% to 4.5% using a correction procedure validated by simulation. Furthermore, the methods are also shown to be very effective when applied to industrial solar cells. TLM measurements have an important role to play in both cell R&D and factory quality control, and this work can serve as a guide towards more accurate contact resistivity measurements.

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1. Introduction

Optimized solar cell performance is critically dependent on the nature of the metal contacts joined to the semiconductor absorber. Accurately measuring the contact resistivity of the metal contacts is therefore very important. The most common method used to calculate the contact resistivity of crystalline silicon (c-Si) solar cells is the transmission line method (TLM). This method was originally proposed by Shockley (1964) and further developed by Berger (1972a,b, 1969). It is important not to confuse the transmission line method with the transfer length method, a similar type of contact resistivity measurement. The TLM mentioned in this paper only refers to transmission line method. In order to prepare a test structure from a solar cell, either a special structure is fabricated with variable spacing between the contacts (Pysch et al., 2009; Untila et al., 2017), or a standard solar cell is cut into strips parallel to the busbars (Zeng et al., 2012; Willsch et al., 2015; Vinod, 2011). The latter approach is more commonly applied, since the measure-

ment can be easily performed on a finished solar cell, which is very convenient and achievable. By measuring the resistance between pairs of contacts with different spacing, the TLM can be applied to calculate the contact resistivity and the sheet resistance of the underlying semiconductor. Much of the literature focused on solar cell characterization uses this method to measure contact resistivity. In (Reeves and Harrison, 1982), the TLM plot was modified according to the sheet resistance under the contact. In (Meier and Schroder, 1984), the influence from actual contact resistance values on the accuracy of the TLM measurement was investigated.

Despite these existing works investigating the TLM method for c-Si solar cells, many problems found with this measurement still remain unresolved. For example, our experiments have shown that the measured contact resistivity changes significantly depending on the width of the sample cut from a standard solar cell (Gabor et al., 2016). The measured contact resistivity is often artificially high for sample widths that are either too large or too small. It is also found that the transfer length extracted from the TLM plot varies significantly with the strip width, and this phenomenon is not explained by TLM theory. In this work, we explain how and why these problems, and others, occur and propose solutions. To do this, we introduce some basic theory behind the TLM approach

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and the simulation methods used in this work. We then present the key factors influencing the contact resistivity values measured from TLM and offer correction procedures and measurement guidelines to reduce error. The key factors addressed in this paper are: (1) strip width; (2) edge shunting; (3) current flow through the intermediate unprobed fingers; (4) non-uniform contact resistance; and (5) non-uniform sheet resistance.

2. Theory and method

2.1. Applying TLM in solar cell characterization

Basic TLM theory has been explained in many publications (Berger, 1969; Reeves and Harrison, 1982; Schroder, 2006). Here, we only give a brief introduction of the method. When performing the TLM technique, the total resistance R_T between two contacts with length (Z) and width (L) is measured and plotted as a function of contact spacing d (shown in Fig. 1). Three parameters can be extracted from this plot: the contact resistance (R_c), the sheet resistance (R_{sh}), and the transfer length (L_T). As contact spacing d increases, the effect of the sheet resistance on the total resistance measurement increases, thus creating the slope of the TLM plot (k). Therefore, the value of sheet resistance can be extracted using:

$$\frac{\Delta R_T}{\Delta d} = \frac{R_{sh}}{Z} = k \quad (1)$$

Thus R_{sh} can be calculated by $k \cdot Z$.

The transfer length indicates the average distance along L over which current transfers from the semiconductor into the metal and vice versa. It is defined as:

$$L_T = \sqrt{\rho_c / R_{sh}} \quad (2)$$

The value of the total resistance at the y-intercept of the plot is $2 R_c$. R_c can be deduced according to the potential distribution underneath the contact and is represented by:

$$R_c = \frac{\rho_c}{L_T Z} \coth\left(\frac{L}{L_T}\right), \quad (3)$$

where ρ_c is the contact resistivity or specific contact resistance. When $L \geq 1.5 L_T$, which can be the case for c-Si solar cells with very good contact resistivity, Eq. (3) can be approximated as:

$$R_c = \frac{\rho_c}{L_T Z} \quad (4)$$

Here, the effective contact area is $L_T Z$ and therefore the contact resistivity can be approximated as effective contact resistivity:

$$\rho_{c-\text{eff}} = R_c L_T Z. \quad (5)$$

Another common scenario seen in c-Si solar cells occurs when $L \leq 0.5 L_T$. In this case Eq. (3) can be approximated as:

$$R_c = \frac{\rho_c}{LZ}. \quad (6)$$

Here, the effective contact area is the entire interfacial area of the contact LZ and the contact resistivity is calculated as:

$$\rho_{c-\text{eff}} = R_c LZ. \quad (7)$$

In this study, Eq. (5) is applied to calculate the contact resistivity of solar cells. When applying this method for c-Si solar cell characterization, usually a strip is cut from a finished solar cell without any special test structures. The voltage between variably spaced pairs of fingers is measured one by one, and thus the total resistance between each finger pair is calculated ($R_1, R_2, \dots, R_n$). Depending on the distance between each finger pair, a plot similar to the one shown in Fig. 1 can be constructed and the contact resistivity can be extracted.

2.2. Simulation method

In order to investigate the TLM method in detail, we use two simulation models in this work. One method is a circuit model implemented in the open-source software LTspice (Engelhardt, 2011). The implementation of this model is based on procedures presented in Guo et al. (2012a,b). The circuit model constructed in this work represents a small strip cut from a solar cell. The model is a 2-D network of circuit elements, and each unit element is based on the one-diode model which includes a current source, a diode, a shunt resistance and a series resistance. Additional elements represent the front metal grid and the contact resistance between the grid and the solar cell. The model parameters for each unit are assigned according to their position in the TLM structure and the model geometry. Fig. 2 shows the circuit model of the simulated solar cell strip and the structure of the intersection between two fingers.

Another model used for studying the TLM method is a device model implemented in Silvaco Atlas[®], a device simulator. This TCAD software allows users to define the physical structure, the physical models, and the bias conditions (Atlas User's Manual, 2015). It has been widely used in solar cell simulation (Michael, 2005). Silvaco Atlas[®] requires that each structure be defined on a mesh that covers the physical simulation domain. In order to get accurate results, it is important that the mesh is defined properly. Therefore, a very fine mesh is defined near the metal-semiconductor interface and then made coarse away from the contacts for the sake of computational efficiency. Table 1 summarizes the input parameters used in both the circuit model and in the TCAD model.

2.3. Experiment setup

In this work, a semi-automatic tool, the *ContactSpot* from BrightSpot Automation, is used to measure the contact resistivity of solar cells. Fig. 3 shows a photo of two *ContactSpot* units. This unit includes a sample platform and microscope with translation

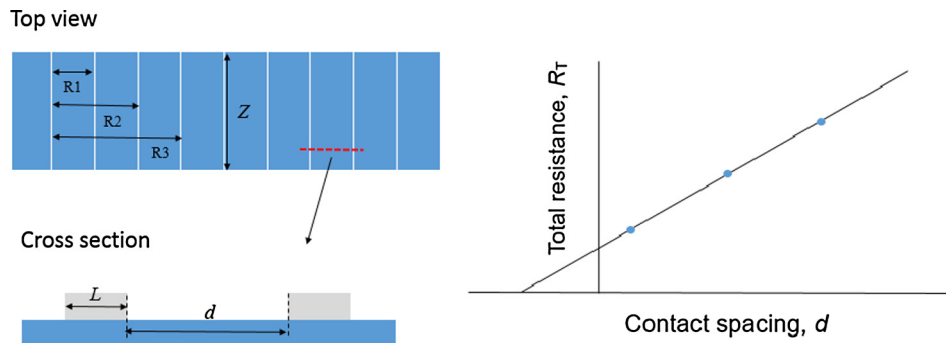


Fig. 1. (a) Typical TLM structure used for characterizing c-Si solar cells. (b) Fitted curve of total resistance versus contact spacing.

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