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Physics and Statistics of Non-Ohmic Shunt Conduction and Metastability in Amorphous Silicon p–i–n Solar Cells

Sourabh Dongaonkar, Karthik Y., Souvik Mahapatra, Senior Member, IEEE, and Muhammad A. Alam, Fellow, IEEE

Abstract—In this paper, we present a physical model of the non-Ohmic shunt current $I_{SH}$ in amorphous silicon (a-Si:H) p–i–n solar cells and validate it with detailed measurements. This model is based on space-charge-limited (SCL) transport through localized p–i–p shunt paths. These paths can arise from n-contact metal incorporation in the a-Si:H layer, causing the (n)a-Si:H to be counterdoped to p-type. The model not only explains all the electrical characteristics of preexisting shunts but also provides insight into the metastable switching that is observed in the shunt-dominated region of dark current as well. We first verify the SCL model using simulations and statistically robust measurements, and then use it to analyze our systematic observations of nonvolatile switching of the low-bias dark characteristics. This study interprets broad experimental observations regarding shunt behavior, and suggests possible techniques for alleviating shunt-induced performance and reliability issues.

Index Terms—Amorphous silicon, photovoltaic (PV) cells, shunt, thin films.

I. INTRODUCTION

Improvement of parametric yield, through the reduction of process variability, is critical for the commercial success of thin-film photovoltaic (PV) technologies [1]. One of the most important variability concerns is variable shunt leakage in solar cells. It has been identified as one of the major factors responsible for the significant gap between panel and cell efficiencies [2], [3]. Despite its importance in determining the panel output, the physics of shunt formation is not as well understood as that of the solar cell itself, and most studies of $I_{SH}$ are empirical in nature. Some shunts at the panel level have been correlated with localized, macroscopic (up to millimeters) nonuniformities (e.g., pinholes), which are caused by particulate debris on the panel surface [3], [4]. These “extrinsic” shunts can be minimized by the better control of deposition conditions. However, significant shunt currents are observed even in cells fabricated with excellent process control, which are generally free from the “extrinsic” defects. These “intrinsic” shunts cannot be traced to any visible defect on the surface but show up in dark lock-in thermography images as bright spots [4].

The intrinsic shunts introduce considerable performance variation among nominally identical cells, and in this paper, we will focus on the physical mechanisms of their formation, conduction, and nonvolatile switching. We find that unlike the Ohmic extrinsic shunts, the intrinsic shunts show non-Ohmic voltage dependence [5]. Moreover, these shunt currents also show an abrupt threshold switching behavior on application of reverse voltages [6], [7]. This threshold switching is known in the PV industry and is used for electrical shunt removal/reduction (shunt busting) [8]. However, we find that the switching behavior is actually metastable, and cell $I_{SH}$ can also increase on application of reverse bias. This has important implications for long-term panel reliability, because during normal operation, partial shadowns on the panel can result in moderate-to-high reverse bias stress across shaded cells. And, any resulting increase in the shunt current because of this metastability can have a significant impact on the long-term panel output [9]. Therefore, understanding the formation of these shunts during fabrication and their metastability because of reverse bias is of great importance for design and development of a-Si:H PV technology. The goal of this paper is the development of such a model, which can lead to strategies for the reduction of the shunt loss in a-Si:H cells.

II. SPACE-CHARGE-LIMITED SHUNT CURRENT

A. Phenomenological Model

The identification of shunt conduction mechanism in as-fabricated a-Si:H solar cells is the critical first step in the development of a physical picture. We observed that $I_{SH}$, in a-Si:H cells, is characterized by three key empirical features, namely symmetry of shunt current about $V = 0$, non-Ohmic power-law voltage dependence $I \sim V^\beta$ [see Fig. 1(a)], and weak temperature dependence [see Fig. 1(b)] compared to the temperature-activated diode current component.

We had proposed a phenomenological space-charge-limited (SCL) current model to account for these features within a coherent framework [5]. SCL transport features single-carrier transport in a symmetric (e.g., metal/semiconductor/metal type)
characteristics showing weak temperature dependence of $I_{SH}$ (symbols, below 0.5 V), compared with the activated diode current (solid lines).

$V \sim A \varepsilon \mu c \gamma (1)$

Here, $A$ is the area, $L$ is the thickness, $\varepsilon$ is the dielectric constant, $\mu c (\gamma)$ is the effective carrier mobility, and parameter $\gamma$ is a function of trap distribution inside the band gap [10]. It is apparent from (1) that symmetry and non-Ohmic nature of $I_{SH}$ can be explained readily by SCL conduction. And, since the only temperature-dependent term in (1) is mobility, which is a weak function of temperature [11], the temperature dependence of $I_{SH}$ is also weak. While the electrical features of $I_{SH}$ can be understood from (1), the physical nature of shunt paths that are responsible for SCL conduction requires further analysis.

B. Localized $p-i-p$ Shunt Hypothesis

We now investigate a likely physical origin of the symmetric parasitic path that is responsible for an SCL shunt path. We propose that the parallel, symmetric shunt path is formed as a localized $p-i-p$ structure [see Fig. 2(b)]. For a typical a-Si:H $p-i-n$ cell that is deposited on fluorinated tin oxide (FTO) substrate, with aluminum-doped zinc oxide (AZO) top contact, such a path might form during cell fabrication, because of a local incursion of Al from the top AZO contact in the a-Si:H layer. This would result in a localized current path, in parallel to the bulk exponential diode current. This localized $p-i-p$ shunt hypothesis can be explored by numerical simulation. A self-consistent simulation of the 2-D structure in Fig. 2(b), using commercial Synopsys Medici software, readily reproduces the essential features of the SCL shunt [see Fig 2(c)]. The SCL current through the $p-i-p$ shunt region dominates in the lower bias regimes, while the exponential diode current through the $p-i-n$ region takes over at higher forward biases. This transition can be visualized using the quiver plots of the current in Fig. 2(c). As shown in (i), the current is localized to the $p-i-p$ shunt region. At higher forward biases however, the $p-i-n$ diode current takes over and the current distribution becomes more uniform across the bulk device, as shown in (ii).

Another useful insight from the quiver plots is that the shunt and diode currents are spatially separated and dominate the conduction in different voltage ranges. Therefore, we can avoid the computationally intensive 2-D simulations by the simulation of the 1-D $p-i-p$ shunt and $p-i-n$ diode separately [see Fig. 3(a)]. The total current is, then, given by $I_{Dark} = A_{cell}I_{pin} + A_{shunt}I_{pip}$. Here, $A_{cell}$ is the cell area, and $A_{shunt}$ is the sum of all shunt areas in a particular cell. Typically, we find $A_{shunt} \approx 10^{-4}-10^{-6}A_{cell}$, which is also consistent with the spot sizes in thermography images from the literature [12]. In Fig. 3(b), we show that a 1-D simulation of the $p-i-p$ shunt and $p-i-n$ diode matches the measured voltage and temperature dependences of the dark IV characteristics of the cell very well.

C. Formation of Preexisting Shunts

The most likely cause of $p-i-p$ shunt formation during cell fabrication is that Al from the top AZO layer diffuses into the (n)a-Si:H and counterdopes it to p-type [13]. Since the n-layer is only ~20 nm thick, even a small Al incursion can result in a local $p-i-p$ shunt path, which can occur in areas of AZO grain boundaries or regions of high void density in a-Si:H. Diffusion of Al in a-Si:H is a known concern for cell stability, because it can diffuse inside a-Si:H at relatively low temperatures (200–300°C) [13]. Therefore, it seems likely that during sputtering of
the top contact, Al may diffuse to sufficient depths (>20 nm) and destroy the n–i junction at some locations to form a parasitic shunt. Al migration is facilitated by vacancies that are created by diffusion of Si to AZO, especially at AZO grain boundaries. We simulated this interdiffusion of Si and Al, for moderate deposition temperatures and times, using reported values [14]. The diffusion coefficient of Al was enhanced based on the Si vacancy concentration. In Fig. 4(a), we show the results of this 2-D simulation, showing that Al can indeed reach past the n–i junction, especially near AZO grain boundaries, where Si diffusivity is increased. The extent of Al incursion can be significant to overcome the n–i junction at the grain boundary regions, as seen in Fig. 4(b). This simulation shows that a good approach to curb shunt formation would be reducing Al diffusion, possibly through the introduction of a barrier layer. Care must be taken however, to minimize any extra series resistance, which may be introduced by the diffusion barrier.

III. Validation of the p–i–p Shunt Model

While electrical features are reproduced well by the localized p–i–p shunt model, a conclusive confirmation of the model requires that its predictions be verified independently. Therefore, in the next sub-sections we investigate two important predictions of the SCL model with statistically robust measurements.

A. Confirmation of Hole Transport

SCL conduction requires single-carrier injection, and in the case of p–i–p shunt, holes that are injected in the i-layer will dominate the transport. We can indirectly establish the dominance of hole transport in ISH by examining the power exponent, i.e., \( \beta = \gamma + 1 \), of SCL conduction in (1). For the SCL current in materials with exponentially distributed shallow traps, it has been shown that the parameter \( \gamma = E_0/k_B T \), where \( E_0 \) is the characteristic energy of the trap distribution [10]. This feature of SCL current is well known and has previously been used to characterize the shallow band-tail states in a-Si:H [15]. Using this approach, we calculate the characteristic energy \( E_0 \) from the measured shunt current of 61 cells and find it to be about 40 meV [see Fig. 5(a)]. Note that the characteristic slope of the valence band tail in a-Si:H is \( \sim 40 \text{ meV} \), as opposed to the conduction band-tail slope of \( \sim 20 \text{ meV} \) [16]. This confirms that the SCL shunt current is indeed because of injection of holes in the i-layer, which is consistent with the hypothesis of the p–i–p shunt.

B. Thickness Dependence

Another prediction of the SCL shunt current expression from (1) is that ISH scales inversely with semiconductor layer thickness as a power law, i.e., \( I_{SCL} \sim 1/L^{2\gamma+1} \). To check this prediction, we measured 356 devices with i-layer thicknesses 140, 280, 560, and 1120 nm (89 devices each). In Fig. 5(b), the dark current at \(-2 \text{ V} \) (shunt-dominated region) versus the i-layer thickness is plotted for all measured devices. Here, each dot represents a separate device; the symbols are the geometric means with error bars showing the standard deviation. We find that the geometric mean of the data indeed shows a power-law behavior, with the power exponent \( \sim -2.8 \), broadly consistent with the SCL model. This statistically robust trend affirms the second prediction of the proposed p–i–p shunt model.

IV. Statistics of Shunt Formation

The large spread in the shunt-current magnitude, which is shown in Fig. 5(b), raises interesting questions about distribution of shunts on the cell surface. If we plot the shunt-current magnitudes (dark current at \(-2 \text{ V} \)) for the different i-layer thicknesses on a probability plot, as shown in Fig. 6(a), we find that the empirical distribution generally shows log-normal characteristics. Note that the lognormal lines describe the ISH data very well for the i-layer thicknesses of 280 and 560 nm. The deviation from lognormal for 1120 nm case reflects contamination due to the lower limit of measurement accuracy of \( \sim 100 \text{ pA} \). Therefore, the distribution shows a sharp cutoff near 100 pA value. On the other hand, for 140 nm case the reverse diode current is large enough to contaminate ISH, presumably due to enhanced tunneling [17]. On the removal of those contaminated data points, we find that ISH for all layer thicknesses follows the lognormal distribution very closely.
increases again (state caused by moderate reverse biases. A magnitude implies that only a handful of A IV ON VOLATILE magnitude and spot size I OFF transition, I ON − I OFF transition (red). A distribution is a consequence I ON and I OFF transition (green) switches to the low I OFF I is as a power law very closely. Therefore, we can > / Transitions L during the two I OFF because of metastability decreases abruptly by about 1–2 orders of magnitude (S I). Note, however, that the p–i–p model predicts only small Al in- attributing to a combination of spread in the area and thickness. Present data and simulations to show that the abrupt switching of shunts in a-Si:H solar cells, under reverse bias, has been reported in the literature and is used in industry for “shunt busting” [8]. However, our measurements show that this switching is actually metastable. That is to say that the shunt current of a cell can decrease or increase on application of reverse bias. We observe that during reverse voltage sweep, I SH decreases abruptly by about 1–2 orders of magnitude (OFF transition), analogous to the shunt busting [see Fig. 7(a)]. This change in the shunt current is nonvolatile during subsequent IV measurements. However, I SH increases again (ON transition), after a subsequent reverse current sweep, and stays at the higher value thereafter. The abrupt transitions of I SH during the two sweeps are shown in Fig. 7(b). Both these metastable states of the shunt current are nonvolatile and remain stable for many days under room temperature storage. In the following sections, we present data and simulations to show that the abrupt switching in the shunt-current magnitude is not because of metastability in a single shunt path but a consequence of the shunt formation physics and their statistical distribution.

V. NONVOLATILE SWITCHING

So far, we have showed that the proposed p–i–p shunt model with the SCL shunt current can explain the features of preexist- ing shunts in a coherent manner. We now discuss how this picture can also help us in understanding the nonvolatile switching in I SH caused by moderate reverse biases.

Threshold switching of shunts in a-Si:H solar cells, under reverse bias, has been reported in the literature and is used in industry for “shunt busting” [8]. However, our measurements show that this switching is actually metastable. That is to say that the shunt current of a cell can decrease or increase on application of reverse bias. We observe that during reverse voltage sweep, I SH decreases abruptly by about 1–2 orders of magnitude (OFF transition), analogous to the shunt busting [see Fig. 7(a)]. This change in the shunt current is nonvolatile during subsequent IV measurements. However, I SH increases again (ON transition), after a subsequent reverse current sweep, and stays at the higher value thereafter. The abrupt transitions of I SH during the two sweeps are shown in Fig. 7(b). Both these metastable states of the shunt current are nonvolatile and remain stable for many days under room temperature storage. In the following sections, we present data and simulations to show that the abrupt switching in the shunt-current magnitude is not because of metastability in a single shunt path but a consequence of the shunt formation physics and their statistical distribution.

A. Switching Thresholds for ON and OFF Transitions

In order to investigate the physical features of this switching behavior, we measured 16 nominally identical devices under reverse voltage and current stress. Consecutive voltage sweeps of −5, −6, and −7 V, and reverse current sweeps of 0.5, 5, and 50 mA were applied to all devices. Eight devices were subjected first to voltage sweeps followed by the current sweeps, and the other eight were stressed in the opposite order. The sweep rate was kept at the fastest possible, with the typical sweep time below 1 s (i.e., >10 V/s).
Of the 16 devices measured, eight did not exhibit any switching transition in $I_{SH}$. For the other eight, which show metastability, the switching showed distinct dependences for ON and OFF transitions. We found that the decrease in $I_{SH}$ (OFF transition) was determined by a power threshold $P_{\text{Critical}}$ [see Fig. 8(a)], and the increase in $I_{SH}$ (ON transition) was triggered at a threshold voltage $V_{\text{Critical}}$ [see Fig. 8(b)]. These thresholds were independent of the order of the sweeps (i.e., first voltage and then current, or vice versa). In Fig. 8(c), we show that the threshold voltage and power values for all the eight metastable shunts are $\sim 7.5$ V and $\sim 20$ mW, respectively. Finally, in Fig. 8(d), we compare the SCL power exponent $\beta$ of the shunt current in high- and low-current states, respectively, showing them to be roughly identical. This shows that the nature of $I_{SH}$ shunts does not change before and after switching.

B. Mechanism of ON Transition

The robust trends that are observed in our measurements show that this metastability in $I_{SH}$ is indeed a physical feature of shunt conduction. We now discuss how one can understand the metastable switching behavior, using the p–i–p shunt picture developed earlier. First, note that the ON transition is a voltage (analogously electric field)-driven process, as seen in Fig. 8(b). These observations suggest that the positively charged Al ions might be hopping through the a-Si:H matrix under the influence of the electric field and migrating into the a-Si:H layer. Second, we know, from Section II, that only a small Al incursion of $\sim 20$ nm is sufficient to create the local shunt. As Al gets past the thin n-layer, it will destroy the n–i junction locally and form a p–i–p shunt. Hence, the ON transition (driven by large voltage) would be very rapid, as observed in Fig. 7(b). In Fig. 9(a), we show the change in reverse current versus the distance of Al incorporation in a-Si:H, showing that even a small Al incorporation is sufficient to induce large change in the reverse current.

The voltage-driven contact metal migration in a-Si:H has been studied extensively in nonvolatile resistive switching memories made from a-Si. This in fact forms the basis of operation of the a-Si:H resistive RAM [19]. Direct evidence for Al migration in a-Si:H matrix under bias is also available in the memory literature [20]. Because of the similarities in materials (Al/a-Si:H) and the structures involved, it seems very likely that the similar physical processes are also driving the ON transitions in metastable shunts.

There is, however, an important distinction between the resistive memories and shunt metastability. In the case of a-Si:H-based memories, the program/WRITE electric fields are substantially higher and the conduction is Ohmic in the ON state. This is because, in memories, the metal migrates all the way through the bulk and forms a metallic filament [20]. However, for $I_{SH}$, we observe that $I_{SH}$ power exponent $\beta$ remains close to 2 before and after the ON transition, as seen in Fig. 8(d). This means that the shunt current continues to be SCL before and after the ON/OFF transition. Therefore, it appears that during the ON transition for $I_{SH}$, only a small incursion of the metal ions inside the bulk takes place (enough to overcome the n–i junction). Moreover, the shunt-current values after one ON and OFF transition are not necessarily the same. Based on this, we propose that the ON transition happens because of the formation of a new shunt path because of Al migration from the top AZO contact.

C. Mechanism of OFF Transition

Unlike the ON transition, the OFF transition is controlled by a power threshold, as seen in Fig. 8(a). This suggests that the most probable cause of the OFF transition is the dissolution of the small Al filament because of local heating. We discussed, in Section IV, that the largest shunt path in a cell carries most of the current. Moreover, since the sweep rates are high, the local heating at the largest shunt can be significant. In order to check this hypothesis, we simulated the 2-D shunt structure in Fig. 2(b) under moderate reverse bias. In Fig. 9(b), we show the
result of the complete simulation of electron–hole continuity equations that are coupled with the heat equation using Medici TCAD software. The reported values of a-Si:H thermal conductivity and heat capacity were used for the simulation [14]. Note that because of the localization of shunt current in reverse bias, the local temperature can increase by 300–400°C. While the exact temperature rise will depend on many other factors including the thermal properties of the contacts, which are not included in these simulations; this simulation demonstrates that the temperature rise can be significant. Therefore, it is likely that the largest Al filament might dissolve/disperse at these temperatures, resulting in the OFF transition. And, due to the lognormal distribution of shunt magnitudes, the total current is then determined by the next largest shunt, which is 1–2 orders of magnitude lower than the original shunt current, resulting in the OFF transition.

In summary, our data and analysis show that the OFF transition in shunt switching is related to local heating, and the ON transition is related to Al-ion migration with the electric field. While further measurements are needed to identify the exact mechanism, we have constructed a consistent picture for shunt metastability based on the physics of resistive switching memories and the statistical distribution of preexisting shunts. It appears that the understanding of the physical processes of metal incorporation in the a-Si:H matrix is key to understanding shunt formation in a-Si:H solar cells, and the metastability that is analyzed here can provide important insights for such studies.

We also note that the metastable behavior of shunt currents has also been observed in CdTe cells [21]. Since the SCL shunt model has been shown to be applicable to CIGS cells [22], and given the similar structures of CIGS and CdTe cells, the model that is developed here could in principle be extended to shunts in these cells as well.

VI. CONCLUSION

A physics-based model of shunt conduction has been developed and validated, which can explain the electrical and metastable features of shunts in a-Si:H p–i–n solar cells. A physical understanding of shunt behavior enables one to explore possible solutions for shunting problems. For example, since Al migration appears to cause shunt formation, it might be useful to put a barrier layer between AZO and a-Si:H to block this migration. Moreover, the understanding of the metastable shunt behavior will enable a better understanding of the degradation of panel performance over time, which is caused by the formation of new shunt paths. For example, the voltage-triggered \( I_{SH} \) increase suggests that techniques for avoiding large reverse voltages, which are caused by partial panel shading, would be very important to avoid shunt degradation during the panel operation. While further experiments are needed for the construction of a complete picture of shunt physics, the model that is presented here should provide useful guidance for any such investigations in the future.

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REFERENCES

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