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Isolation and optoelectronic characterization of Si solar cells microstructure defects

A Gajdos, P Skarvada, R Macku, N Papez, L Skvarenina, D Sobola
Department of Physics, Brno University of Technology, Brno 61600, Czech Republic

Abstract. This research article presents results of silicon solar cell defects optoelectronic characterization based on several experimental methods. These microstructure defects have their origin mainly in the production process, but also can be caused by mechanical stress. However, some defect related spots emit light when the cell is reverse biased. Therefore, electroluminescence (EL) method is used for macroscopic localization and scanning near-field optical microscopy (SNOM) combined with photomultiplier tube in order to scan topography of defective area in microscale. Moreover, elemental analysis of the defects related spots provided by energy-dispersive X-ray spectroscopy (EDX) is presented as well. Besides that, focused ion beam (FIB) was used to isolate the defective spots by 2 µm wide and 2 µm deep barrier. Isolation pattern around the defect is avoiding leakage current flow through it. Since leakage current does not flow through defect, solar cell parameters in reverse conditions are improved.

1. Introduction
Silicon solar cells are still commercially most used photovoltaic devices [1,2]. Even though silicon solar cell production technologies are well known and enhanced for many years, some defects in fabrication process may appear [3,4]. Solar cell uses the entire wafer sheet area for conversion of solar energy to electric one, for this reason defect-free wafers are necessary. However, the presence of defect with various types of breakdown mechanism can be determined by electrical measurement on fully fabricated cell. Nonetheless, not all inhomogeneities are shunts. There are many types of inhomogeneities such as inclusions, Schotky type shunts, cracks, crystal defects, etc [5]. To locate defect related spot, the fact that various defects emit a light in visible range whereas the sample is in reverse biased condition is used [6]. Methods for defects characterization can be also used for different types of solar cells [7].

2. Methods

2.1. Electrical measurement set-up
Measurements of electrical $I-V$ characteristics is performed by a source meter Keithley 2420 in thermally insulated box, which also provides basic shielding. Solar cell sample is placed between two electrodes with isolation layer in the middle to avoid electrical shunt. Thermal stability is realized by Peltier’s module cooled by water circuit, module is controlled by a source meter Keithley 2510-AT. Setup is controlled by PC via GPIB-USB interface and it allows fully automated measurement. This basic measurement had to be done for a detection of imperfection as well as an estimation of a suitable voltage bias which essential for next presented methods [8].
2.2. Macroscale localization set-up
Experimental set-up for macroscale imperfection localization is based on a CCD camera equipped by cooled 3.2MPx Si-chip which sensing radiation in a spectral range from 300 nm to 1100 nm (fig. 1a). Surface of solar cell is captured through macro lens with focal length 105 mm from minimum focusing distance 41 cm. Measurement is done in dark place, because the radiation from sample has very low intensity and it could not be visible in the daylight. Consequently, measurement is depended on voltage bias, because imperfection radiate from threshold level in reverse biased condition (determined by I-V measurement). A voltage bias is set by power supply Agilent E3631A.

2.3. Microscale localization set-up
Precise localization of imperfections is performed by SNOM combined with photomultiplier tube as well in reverse biased conditions (fig. 1b). Principle of this method is scanning surface of defective area by scanning probe and simultaneously detect the emitted radiation from imperfection by photomultiplier tube [9]. Nevertheless, radiation is glowing to all directions, thus scanning probe is placed between emitting spot and tube. While probe is scanning, amount of detected light by tube is affected. Emitted radiation is measured at each step of probe trajectory and as a result, probe forms a shadow map of defective area. Final topography with “shadow maps” is presented at fig. 3.

![Figure 1(a,b). (a) Macroscale localization set-up; (b) Principle Microscale localization of defects using SNOM.](image)

2.4. Defect-isolation method
To isolate microscopic imperfections dual-beam system (FIB-SEM) Tescan Lyra3 is used [10]. Localization of defective is possible, because of the know topography provided by SNOM. Localization only by SEM would be very difficult, since there are many microscopic inhomogeneities without effect on electrical properties of the solar cell. Even back-scattered electron (BSE) detector does not provide satisfying material contrast to enable microscopic localization of defective area. Isolation process is performed by ions of gallium that mill the potential barrier around the imperfection to avoid the leakage current flow through it. Isolation barrier is in order of tens micrometers.

3. Results and discussion
Mentioned characterization and isolation methods have been done on multiple samples, but in this article only result from one sample are presented. For investigation purpose the monocrystalline silicon solar cell is cut into small pieces (approximately 10 x 10 mm²) containing only few imperfections. Presented sample contains numerous imperfections, that provides parasitic current pathways which caused leakage current through the solar cell. A significant leakage current could be observed above the threshold reverse voltage bias $U_r > 6$ V from the red I-V characteristics before isolation process shown in fig. 2b. Every measurement was performed several times for a stability verification and time independence of the obtained results.
A sensitive CCD camera were used for raw localization process of imperfections on cell sample. Dominant radiation was observed from spot marked as “A” in fig. 2a when reverse bias reached voltage 6 V. However, silicon does not produce visible radiation by common recombination process, visible radiation can be observed during avalanche or Zener breakdown [9]. Topography and “shadow map” of radiation spot “A” performed by SNOM with photomultiplier tube in reverse bias higher than 6 V is shown in fig. 3a (top – shadow map; middle – topography; bottom – shadow map overlapped on topography). Combination of these two images provides location of radiation spot “A”. Imperfection related to radiation spot “A” founded by SEM (shown in Figure 4a) is common type of defect in monocrystalline silicon devices called pit defect [11]. The breakdown mechanism of this defect type is determined as avalanche type. This defect was successfully isolated by 2 µm wide circular barrier to depth of 2 µm with outer radius $R = 14$ µm and inner radius $r = 16$ µm. As a result, formed barrier prevents current flow directed to defect. Repeated I-V measurement (blue, fig. 2b) after defect “A” isolation shows that reverse current above breakdown voltage significantly decreased. Addition of parallel shunt resistance from fitted data for defect “A” is $R_{\text{defA}} = 970$ $\Omega$.

![Defects A and B](image)

Figure 2(a,b). (a) Electroluminescence image overlapped on solar cell sample image before defects isolation ($U_r = 6$ V, $t = 100$s, $T = 295$ K); (b) Current voltage curves “before” and “after” defects isolation. Shunt resistance of each defect is also presented. $T = 297$ K.

Even if reverse current after breakdown significantly decreased after defect “A” isolation, repeated measurement by CCD camera shows that radiation from spot “A” decreased, but defect “B” is now dominant when bias is still $U_r = 6$ V. The value of the breakdown voltage coincides with threshold value for radiation of spot “B”. Topography of radiation spot “B” with “shadow map” is presented in fig. 3b. Corresponding SEM micrograph of defective area to topography is in fig. 4b and it is visible that radiation spot “B” is also pit type with avalanche breakdown mechanism. Defect “B” is approximately same size as defect “A”.

Defect “B” was isolated by annulus with outer radius $R = 18$ µm and inner radius $r = 20$ µm milled to a depth of 2 µm in surface and successfully form a barrier for current flow directed to defect. Radiation intensity from defect “B” rapidly decreased after isolation. Decrease of reverse current after threshold voltage is almost same in case of defect “A” isolation. Addition of parallel shunt resistance is from fitted data for defect “B” is $R_{\text{defB}} = 1205$ $\Omega$. 

![Current-Voltage Curve](image)
Figure 3(a,b). Topography of defective area combined with “shadow map” for (a) defect A ($U_r = 6.1$ V); (b) defect B ($U_r = 6.1$ V).

Figure 4(a,b). SEM micrograph of isolated (a) defect A ($U_{HV} = 5$ kV, detector SE, tilt 0°); (b) defect B ($U_{HV} = 20$ kV, detector SE, tilt 0°).

Last set of figures 5(a-d) shows EDX analysis of defect “A”. This analysis proves that any metallic inclusions of are not involved in nature of defect. EDX analysis is not present for defect “B” because it can be observed similar results as in case of defect “A”.
4. Conclusion

The methods in this paper present the measurements for a detection and localization of the defects or inhomogeneities in the silicon solar cells. These methods could be applied as well on the different types of solar cells. Result from two localized defects on one sample are presented. Breakdown voltage in $I$-$V$ characteristics strongly correlates with radiation threshold voltage obtained by electroluminescence. Both of defects are isolated by experimental method using gallium ion milling. The process of FIB isolation has been successfully repeated on multiple solar cells samples. Electrical properties in reverse biased conditions of investigated sample has been improved. Parallel shunt resistance significantly decreased with each defect isolation. EDX analysis show that inhomogeneities around defects are not metallic inclusions.

Acknowledgments

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