Experimental Measurement of Lateral Transport in the Inversion Layer of Silicon Heterojunction Solar Cells

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***Abstract* — We performed two experiments to measure lateral flow of photoexcited charge carriers near the heterointerface in silicon heterojunction (SHJ) solar cells. Using light beam methods, we probed current extraction differences between areas of varying intrinsic layer thickness and the effective cross section of junction defects. Both measurements demonstrated a strong bias voltage dependence of lateral transport and transport lengths of tens to hundreds of microns as bias approached operating voltages. Lateral carrier flow near the heterointerface is proposed as one of the reasons that SHJ solar cells are extremely sensitive to interfacial defects.**

***Index Terms* — heterojunctions, photovoltaic cells, silicon.**

I. Introduction

Amorphous silicon/crystalline silicon heterojunction solar cells (SHJ cells) hold the potential to form high efficiency solar cells at low cost. Efficiencies above 23% have been achieved and open circuit voltages are the highest among silicon solar cells [1]. Furthermore, the a-Si:H emitter and back surface field depositions are performed at low temperatures, which has the potential to minimize processing costs.

Despite the fact that SHJ technology was developed more than 10 years ago, other research groups have been slow to approach the voltage records set by Sanyo [2]. The importance of maintaining a clean interface and avoiding conditions that allow epitaxial silicon deposition are well known. To fully understand the sensitivity to defects, the carrier transport around the heterojunction interface must be analyzed.

Due to band bending induced by the heterojunction, an inversion layer forms in the region just below the metallurgical junction [3]. In the n-type base, p-type emitter configuration that is commonly used, the c-Si/a-Si:H heterointerface presents a valence band offset of about 0.45 eV [4], which holes must pass through before being collected. Possible mechanisms include direct tunneling, hopping through band tail states, and thermionic emission across the barrier. Regardless of mechanism, there is a characteristic dwell time for carriers at the heterointerface [5]. Additionally, the high concentration of holes in the inversion layer allows for relatively high conductivity. These two parameters determine the characteristic lateral transport length of carriers in the inversion layer. Here we report results of two experiments performed to directly probe the carrier dynamics in the inversion layer.

II. Experimental

The experimental structure used was a SHJ emitter, in which an intrinsic a-Si:H thin film was deposited between the c-Si wafer and doped a-Si:H emitter. All a-Si:H depositions were performed at EPFL using plasma enhanced chemical vapor deposition (PECVD), as described elsewhere [6]. The thickness of the intrinsic layer was varied in the experimental structure using a series of patterning steps.

First, 300 nm of SiO_2 was deposited on a 4 ohm-cm n-type FZ silicon wafer by PECVD for use as an etch stop. This was patterned to the area that would become the lower contact by photolithography. A 5 nm thick initial a-Si:H(i) layer was deposited. Photolithography was again used to mask the entire sample surface except for the location of the lower contact. A XeF_2 etch was carried out for 10 s at 2000 mTorr to remove the small region of a-Si:H on top of the oxide. The oxide was

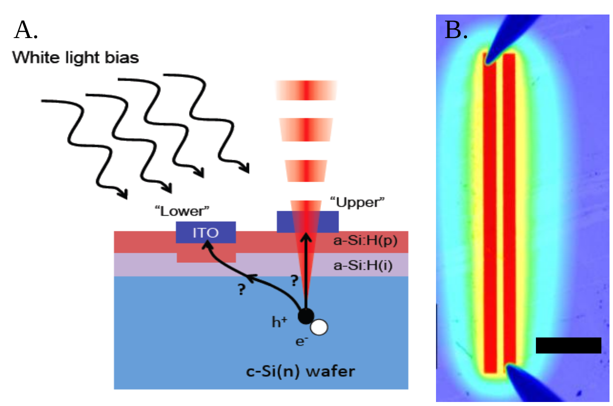

Fig. 1. A: Schematic of white light biased selected area illumination experimental setup. White light uniformly induces a known photovoltage across the junction while a pulsed optical excitation is applied and measured with lock-in amplification. B: Optical image enhanced by a scanning photocurrent measurement showing contact geometry. Scale bar is 200 microns.

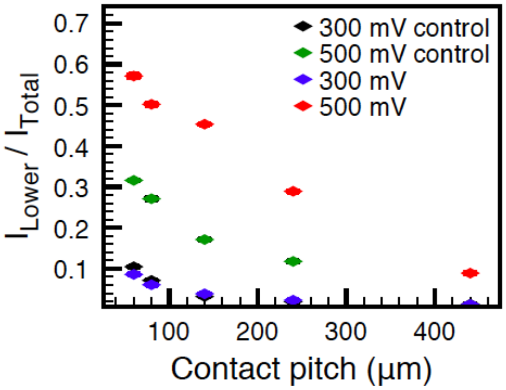

Fig. 2. Current splitting ratio in white light biased selected area illumination experiment when local excitation is focused above the upper contact. Under strong forward bias we observe that a significant fraction of photocarriers travel laterally and to be collected in a nearby contact.

then removed with an HF etch and the photoresist was removed with acetone. An oxygen plasma was used to clean any remaining organics. Following a brief HF immersion, A second intrinsic a-Si:H layer of thickness 5 nm was deposited immediately followed by a 5 nm a-Si:H(p) emitter and sputtered ITO top contact. A final photolithography step and HCl etch was used to remove the ITO from all regions that were not part of either contact. The resulting structures contained 80 µm wide contacts separated by varying distances above intrinsic layers of 5 and 10 nm. Control samples had the same contact geometry, but the intrinsic layer was not thinned.

A. Current Splitting Between Two Contacts

We performed a white light biased selected area illumination (WLB-SAL) experiment on the structure described above and depicted in Fig. 1B. White light from a halogen lamp was used to maintain a constant photovoltage over the entire cell and a chopped 635 nm diode laser was used to locally illuminate specific areas of the sample. Both contacts were held at the same voltage as the white light bias electrically with Keithley source meters. Current from the contact under test was fed through a transimpedance amplifier with a gain of 10^5 ohms to a Stanford Research Systems lock-in amplifier. A schematic of this experiment is shown in Fig. 1A. After recording current from both contacts, we calculated the current splitting ratio, which we define as the ratio of current collected at the opposite contact to total photocurrent extracted by the local excitation.

The current splitting ratio observed when the laser is positioned directly on the upper contact is shown in Fig. 2. A significant bias dependence is observed in this measurement, with a much higher degree of current splitting at 500 mV bias than 300 mV, in both the thinned and control samples. For the closest contact pitch, more current was collected from the lower contact than the upper contact under 500 mV bias, despite the laser illumination directly above the upper contact. As the pitch is increased, this ratio decreases.

The laser wavelength was chosen so that the local excitation is absorbed right around the depletion width edge, just a few microns into the material. We therefore expect carrier transport in the inversion region to be the dominant transport mechanism influencing our observations, rather than diffusion in the quasi-neutral region.

B. Lateral Transport Near a Defect

A second experiment was performed in order to probe the lateral transport length of carriers around defects. A 1 µm wide line was milled across the center of a single contact pad from the previous experiment to a depth of approximately 150 nm using a focused ion beam. This created a recombination active region in the center of the active area. This area was then probed with a light beam induced current (LBIC) measurement using a 633 nm HeNe laser source in a Zeiss scanning confocal microscope. Again, current was measured with a transimpedance amplifier and electrical bias was

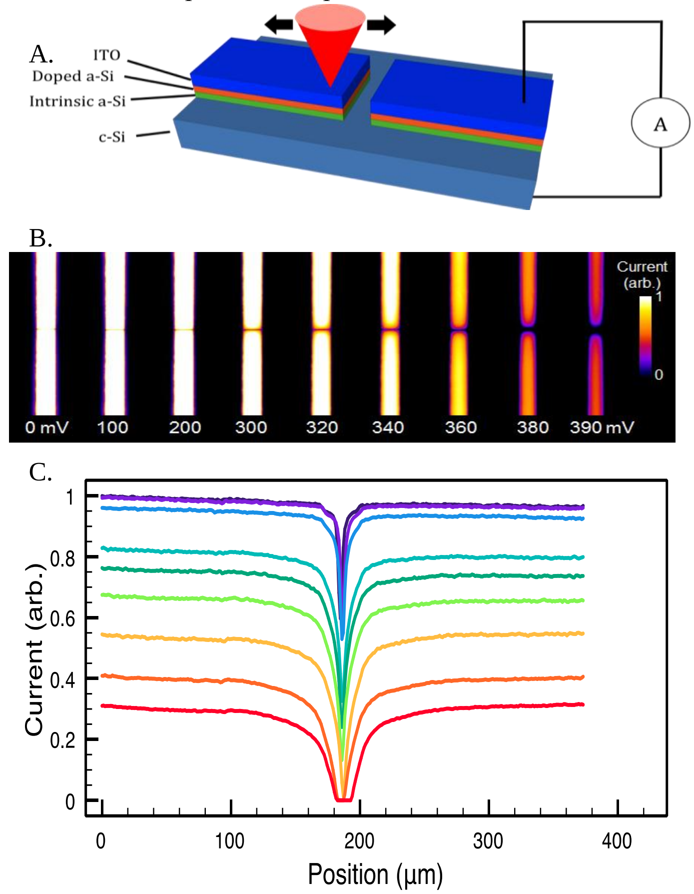

Fig. 3. A: Schematic of light beam induced current (LBIC) measurement around a FIB milled defect. B: LBIC maps at various voltages. C: Line scans extracted from these LBIC maps, increasing in bias from top to bottom showing the increase in the effective cross section of the junction defect at forward bias due to lateral carrier transport.

varied. The highest achievable bias voltage for which photocurrent was still observed was lower in this experiment, in which electrical bias was used, than in the previous because the local excitation must provide more current than the dark current from the whole cell in order to detect a signal. A schematic of this experiment is shown in fig. 3A.

The full width at half minimum was extracted from this measurement as a characteristic length, correlating with the exploration length. This varied from about 4 microns at short circuit to 31 microns at 390 mV.

III. DISCUSSION

Both experiments provide evidence of lateral transport near the heterojunction and it is possible to extract a characteristic collection length. This is not a diffusion length, but depends on both drift and diffusion in the inversion layer. The large hole population at the interface is able to support high currents given a fairly small gradient in the quasi-Fermi level. The gradients in the quasi-fermi level are provided by different sources in the two experiments and as a result, different magnitudes of lateral current are to be expected.

There are two likely explanations for the bias dependence observed in these experiments. At higher forward bias, the electric field across the intrinsic layer is reduced, which in turn reduces the driving force for transport across the intrinsic layer. It is likely that as a result of this, the dwell time in the inversion layer increases with forward bias. We saw in the first experiment that the sensitivity to intrinsic layer thickness increased in forward bias as well, as evidenced by the difference in current splitting ratios between the experimental and control samples. This supports the concept that the driving force for transport across the intrinsic layer is reduced at forward bias and the thicker intrinsic layer presents an increasingly difficult barrier to pass, resulting in a high current splitting ratio and long lateral transport lengths.

The second possible mechanism is a change in inversion layer mobility with bias. At positive forward bias it is likely that the occupation of band tail states changes, which may in turn change the hole mobility in the inversion layer. It is impossible to decouple the influences of the dwell time and mobility variation without a more complete model of transport or further experimentation.

IV. SUMMARY

Amorphous silicon/crystalline silicon heterojuction solar cells are capable of reaching extremely high open circuit voltages, but their full potential is difficult to attain due to sensitivity to defects at the interface. In order to fully understand this sensitivity, it is necessary to gain a better understanding of carrier dynamics in the inversion layer near the heterointerface. Two experiments were performed in order to directly probe the lateral movement of charge carriers. We found that characteristic lateral transport lengths are a strong function of device bias, and are on the order of tens to hundreds of microns near practical operating voltages. The lateral transport we observe is an important mechanism in SHJ device operation and elucidates the physics underlying the sensitivity these devices show to interface quality. Continued improvements in the understanding of the physics governing interfacial transport and charge collection at the a-Si:H/c-Si interface will benefit SHJ design and optimization.

ACKNOWLEDGEMENTS

This material is based upon work supported in part by the National Science Foundation (NSF) and the Department of Energy (DOE) under NSF CA No. EEC-1041895. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of NSF or DOE. Z.C.H, A.D., S.D.W., and C.B. acknowledge support from the European Union Seventh Framework Programme, Axpo Naturstrom Fonds, and the Swiss Commission for Technology and Innovation. We gratefully acknowledge critical support and infrastructure provided for this work by the Kavli Nanoscience Institute at Caltech.

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