A Novel Architecture for Photovoltaic Devices: Field-effect Solar Cells Using Screening-engineered Nanoelectrodes for Silicon and Earth Abundant Cuprous Oxide

Oscar Vazquez-Mena, William Regan, Steven Byrnes, Onur Ergen, Will Gannett, Feng Wang, Alex Zettl

Department of Physics, University of California, and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, U.S.A.

***Abstract* — We present a novel photovoltaic cell architecture based on the electric field effect that controls carrier concentration in semiconductors using screening-engineered nanostructured electrodes. The device operates in inversion mode, with a top gate that forms a depletion layer and a p-n junction, and with nanostructured electrodes that collect the photocurrent across the junction. This architecture does not require any doping process or a heterojunction, opening an alternative path to fabricate cells on hard-to-dope materials such as oxides or phosphides. As a proof of concept, we present a field effect solar cell made of Si. To demonstrate the potential of this configuration for alternative materials, we also present a field-effect solar cell made of cuprous oxide, which has a favorable band gap but that is difficult to dope. We control the behavior of the devices with the gate voltage that forms an inversion layer and hence a rectifying p-n junction.**

***Index Terms* — nanostructures, photovoltaic cells, solar energy, cuprous oxide, field effect**

I. INTRODUCTION

One of the main goals of sustainable energy technology is to achieve low cost and large scale energy from solar cells. A promising route is the use of low cost and earth abundant materials besides conventional silicon. Actually, it has been claimed that materials such as copper oxides and sulfide, zinc phosphide and iron sulfide can potentially produce more photovoltaic energy and at lower cost than crystalline silicon [1]. However, so far the efficiencies achieved from these materials have not matched the performance of Si or GaAs solar cells.

Most solar cells are based on p-n either homojunctions or heterojunctions. The most common material for homojunctions is Si, requiring an implantation process to create a p-n junction. In the case of heterojunctions, two materials with natural "p" and "n" doping are employed, such as "p" CdTe or CIGS and CdS as "n" material. The main limitation for homojunctions is the doping implantation process that is well controlled only for few semiconductors such as Si or GaAs. However, for other materials the doping process is still not well controlled. For heterojunctions, the main limitation is the quality of the interface between the two materials. Lattice mismatch and defects at the junction interface can produce recombination sites and affect the performance of the cell.

In this paper we present a novel configuration based on the field effect in semiconductors using a gate to control the carrier concentration in the semiconductor. This configuration does not require any doping implantation process or the formation of a semiconductor heterojunction between two different materials. This removes two main limitations for making solar cells with non-conventional materials from the semiconductor industry. We describe the configuration for field effect solar cells using a gate and screening-engineered nanostructured electrodes to collect the photocurrent [2].We also present a proof of principle of this configuration using conventional Si. As a new route for abundant materials, we present a field effect solar cell using cuprous oxide.

II. FIELD EFFECT SOLAR CELLS PRINCIPLE

Field effect solar cells were first demonstrated in 1979 based on the field-effect transistor (FET) principle [3]. However, the devices had a fast degradation at the insulator [4]. In this work we use a novel configuration for field effect solar cells based on screening-engineered nanoelectrodes demonstrated by Regan et al [2]. The principle of the field effect solar cells is shown in Figure 1. In a conventional FET, an inversion carrier layer is formed at the semiconductor-insulator interface when the gate voltage is above the threshold value. This forms a p-n junction and a conduction channel in the semiconductor without any doping or heterojunction (Figure 1.a). For a solar cell, this principle can be used by adding top and bottom electrodes to obtain a current across the junction (Figure 1.b). However, a fundamental issue is that the top electrode should not screen the gate field. To avoid such screening, we use nanostructured electrodes narrower than the depletion width of the semiconductor that allow a continuous depletion layer in the semiconductor under the nanostructured electrodes (Figure 1.c). If the electrodes are wider than the depletion width, then no inversion layer and hence no p-n junction will be formed under the nanostructured electrodes to separate charges.

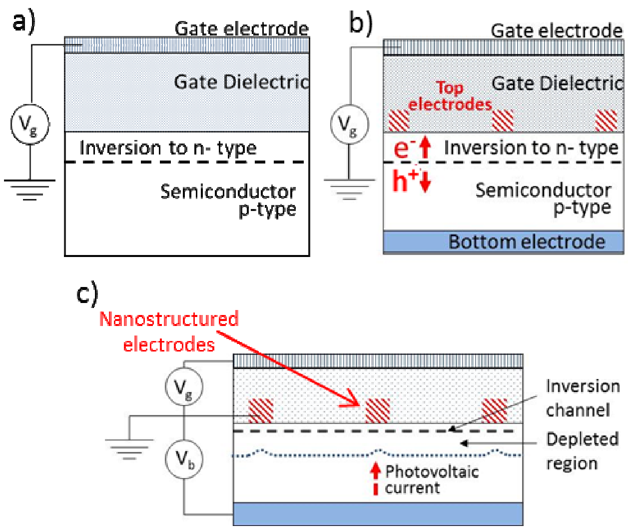

Fig. 1. Field effect solar cell principle (cross sections). a) Field effect in a semiconductor device in inversion mode, creating a junction under the gate dielectric. b) In a solar cell, top and bottom electrodes are added to extract the photocurrent across the p-n junction. To prevent the screening of the field, the nanostructured electrodes should not be wider than the depletion width in the semiconductor. c) Depleted region under the top electrodes when $V_G \approx V_{th}$.

III. Proof of Principle with Silicon

Figure 2 shows the results for a field effect solar cell made out of Si as a proof of the concept for solar cells described in Fig 1. It is based on a p-type Si wafer with $N_A \sim 1x10^{16}$ cm^{-3} with 250 nm wide Al nanostructured electrodes. The gate dielectric is 150 nm SiO_2 and a thin gate electrode of Cr/Au. As shown in Fig. 2, as V_G increases the photocurrent increases. When V_G increases, an inverted n- layer is formed under the gate dielectric forming a rectifying p-n junction. At V_G=3.2 V the efficiency is 1.4% with AM 1.5 illumination.

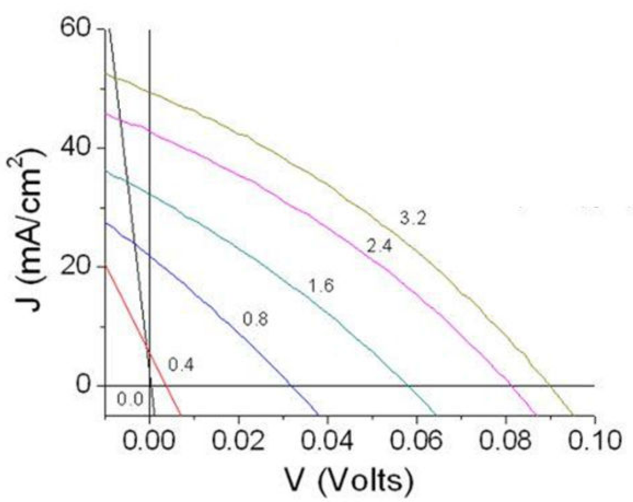

Fig. 2. I-V characteristics of a Si field effect solar cell showing the rectification due to induced p-n junction as gate voltage is increased forming an ‘n’ inversion layer in a ‘p’-silicon chip.

IV. Cuprous Oxide Cells

The same principle was applied for a Cu_2O solar cell made by reactive sputtering deposition with a copper metallic target with an oxygen flow. The fingers are made of Au, the gate dielectric is evaporated SiO_2 and the gate contact is sputtered ITO. Figure 3.a and 3.b show such a device with the nanostructured electrodes (nanofingers). The sputtered Cu_2O is p-type with a hole concentration ~$N_A \sim 2x10^{16}$ cm^{-3} as measured from capacitance/gate voltage measurements. The rectifying behavior is shown in Fig 3.c. When V_G=0, there is no photocurrent due to an ohmic contact between the semiconductor and the electrodes. When V_G=1.2, an inversion layer is formed under the gate dielectric. The n-p junction gives a diode behavior and a photocurrent is generated in the device under illumination (not solar simulated light).

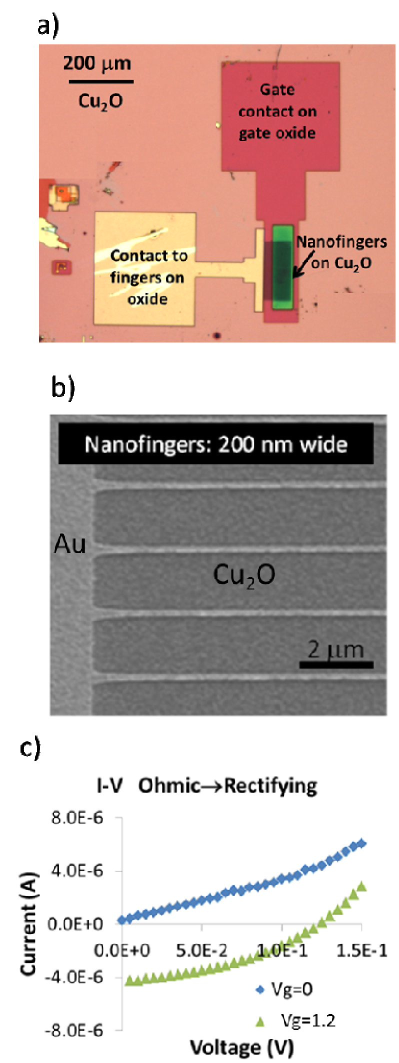

Fig. 3. a) Field effect solar cell made with Cu_2O with Au nanostructured electrodes (nanofingers) and ITO transparent gate. b) SEM image of the nanostructured electrodes. c) I-V characteristics of the Cu_2O field effect cell under illumination showing the transition from ohmic to rectifying behavior generating a photocurrent when V_G is increased. (Not solar simulated light)

V. CONCLUSION

The results herein presented demonstrate that the field effect configuration permits the realization of photovoltaic devices without any implantation process and with a single material avoiding a heterojunction. This opens a new window to realize solar cells with a broad range of materials like copper oxide that are hard to dope or hard to synthesize on a different material to form heterojuntions. Such type of materials can open a route to lower cost and larger scale production of photovoltaic energy. Currently we are working with the same architecture on other materials such as zinc phosphide and tin sulfide that are also earth abundant.

ACKNOWLEDGMENTS

This research was supported in part by the Director, Office of Energy Research, Materials Sciences and Engineering Division, of the US Department of Energy under contract No. DEAC02- 05CH11231 which provided for theoretical nalysis, design of the experiment, and characterization of the cells; by the National Science Foundation within the Center of Integrated Nanomechanical Systems, under Grant EEC-832819, which provided for Cu_2O synthesis; and by the Office of Naval Research (MURI) which provided for graphene synthesis and assembly. O. V. acknowledges support by the Swiss National Science Foundation (PBELP2-135864) W.R. acknowledges support through a National Science Foundation Graduate Research Fellowship.

REFERENCES

[1] C. Wadia, A. P. Alivisatos, and D.M. Kammen. "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment", *Environmental Science & Technology*, vol. 43, pp. 2072-2077, 2009

[2] W. Regan, S. Byrnes, W. Gannett, O Ergen, O. Vazquez-Mena, F. Wang, A. Zettl, "Screening-Engineered Field-Effect Solar Cells", Nano Letters, vol 12, pp. 4200-4204, 2012

[3] R. Godfrey, M. Green. "655mV Open circuit voltage, 17.6% efficient silicn MIS Solar Cells", *Applied Physics Letters*, vol 34, pp. 790, 1979.

[4] D.K. Yeh, T.A. DeMassa, A. L. "Computer Analysis of Induced-Inversion Layer MOS Solar Cells", *Solid-State Electronics*, vol 27, pp.283-292, 1984.