A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory

Innovation for Our Energy Future

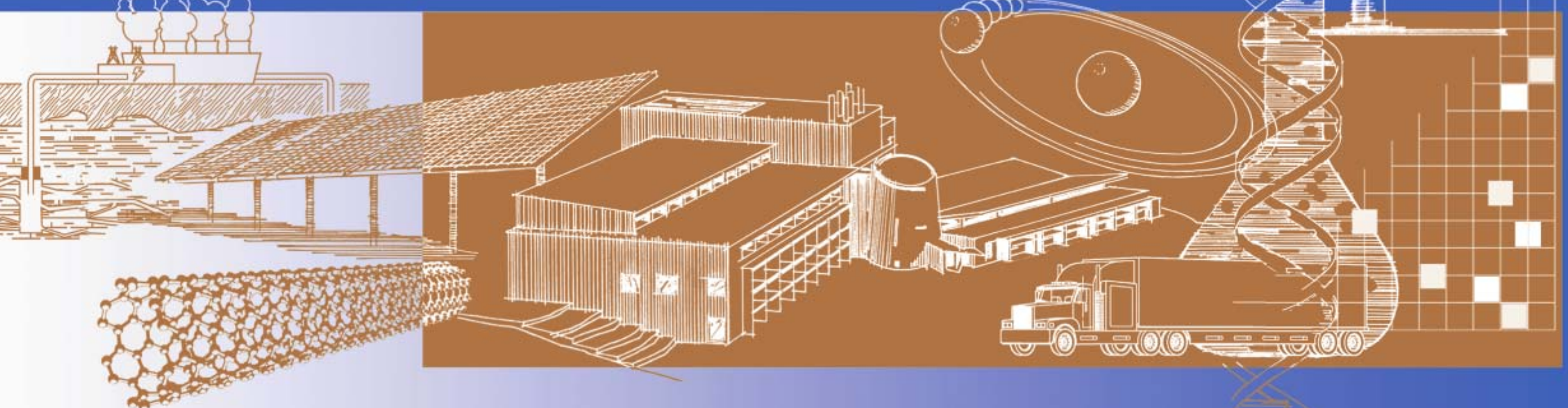
Conductive Atomic Force Microscopy of CdTe/CdS Solar Cells

Conference Paper
NREL/CP-520-37014
January 2005

H.R. Moutinho, R.G. Dhere, C.-S. Jiang, M.M. Al-Jassim, and L.L. Kazmerski

Presented at the 2004 DOE Solar Energy Technologies Program Review Meeting
October 25-28, 2004
Denver, Colorado

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Conductive Atomic Force Microscopy of CdTe/CdS Solar Cells

H.R. Moutinho, R.G. Dhere, C.-S. Jiang, M.M. Al-Jassim, and L.L. Kazmerski
National Renewable Energy Laboratory
1617 Cole Blvd., Golden CO 80401 USA
helio_moutinho@nrel.gov

ABSTRACT

Conductive atomic force microscopy (C-AFM) is a recently developed technique that applies an electric voltage between a very sharp tip and the sample, permitting the study of the electrical properties of the sample with very high spatial resolution. It also provides current-voltage measurements at well-defined spots. C-AFM is applied simultaneously with atomic force microscopy, providing topographic and current images of the same region. In this work, we analyze CdTe/CdS samples, before and after $CdCl_2$ treatment, and after bromine/methanol and nitric/phosphoric etches. The as-deposited samples show grains with different contrasts, indicating that the material is not electrically uniform. The $CdCl_2$ treatment resulted in less conductive grain boundaries, suggesting a relative decrease in the conductivity at these locations. After the bromine/methanol etch, the conductivity at grains boundaries was higher than inside the grains, whereas for the nitric/phosphoric etch the conductivity increased over the entire surface.

1. Objectives

The objective of this work is to introduce and demonstrate how C-AFM, a recently developed analytical technique, derived from atomic force microscopy (AFM), can be used to study the electrical properties of solar cell materials and devices. We used C-AFM to investigate CdTe/CdS solar cells, before and after $CdCl_2$ treatment, and after the standard etching processes used for device fabrication.

2. Technical Approach

The solar cells used in this work had the following structure: glass\SnO_2\CdS\CdTe. The CdS was grown by chemical-bath deposition and the CdTe by close-spaced sublimation. The cells were treated with vapor $CdCl_2$ for 5 min at 400°C. Some cells were etched in a 0.5% bromine in methanol solution (BM etch), for 2 s, and rinsed in methanol; other cells were etched in a phosphoric acid:nitric acid:deionized water (88:1:35) solution (NP etch), until bubbles started to form on the surface (between 30 and 45 s), and then rinsed in running deionized water.

The samples were analyzed before and after the treatments using C-AFM. C-AFM uses the same set up of an AFM, in which a very sharp tip is scanned over the sample surface. An electrical potential is applied between the tip and the sample surface, and the resulting current is measured [1,2], giving rise to a current image. Unlike conventional analytical techniques, C-AFM can provide information on the electrical properties of the samples with high spatial resolution. Another advantage is that the current image is simultaneously generated with a corresponding topographic image, which allows for a direct correlation between electric properties and topographic features. An additional capability of this technique is the acquisition of current-voltage (I-V) curves from very small areas of the surface.

3. Results and Accomplishments

For most samples, the small contact area between the tip and the sample surface resulted in the current flowing through a very small area of the surface, and spreading inside the CdTe. For this reason, the current was very sensitive to variations of the property of the CdTe film on the surface, and this was reflected in the current image.

The topography and current image of an untreated CdTe film can be observed in Fig. 1. Notice that, although the grain structure can be observed in both images, it is clear that the topography does not have a significant influence on the current image. This observation is very important, because it means that there are no artifacts in the current images caused by topographic features. The current image shows that the CdTe film is not electrically uniform, and that some grains conduct more than others. Furthermore, there is not a significant difference between the current at

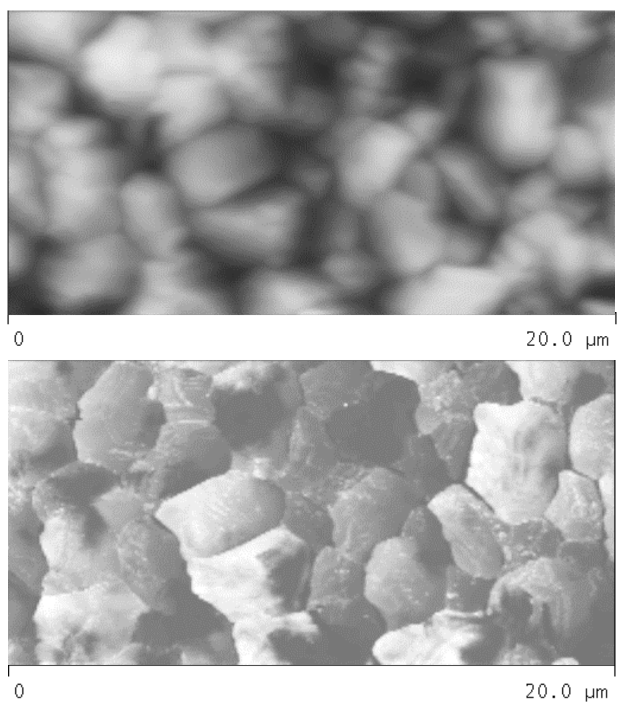


Fig. 1. Topographic (top) and current (bottom) images of an untreated CdTe/CdS solar cell.

grain boundaries and intragrain material. The changes in conductivity for different grains are probably related to different doping levels and/or different carrier mobilities, which are caused by differences in defect structure. I-V measurements indicated that there was a rectifying junction between the tip and the sample surface, probably due to the presence of an oxide layer.

After the $CdCl_2$ treatment, there were no striking changes in the current images. Nevertheless, there was a slight decrease in the current at grain boundaries. This is possibly related to a lower density of charge carriers at these locations, which has been previously observed by Visoly-Fisher et al. [3].

The BR etching process resulted in different current images, with a relative increase in the current at grain boundaries, when compared to the intragrain material (Fig. 3). This was probably caused by preferential etching of the grain boundaries, which had been observed by Danaher et al. [4]. Measurements with different polarities of the dc bias indicated that the contact between the CdTe surface and the tip was still rectifying, with the exception to grain boundaries. These results show that the BR etch, in the conditions performed here, is not suitable to produce a uniform ohmic contact on the film surface.

The results of the NP etching process are shown in Fig. 3. Contrary to the BR etch, this process increased the conductivity of the surface as a whole, resulting in a significant increase in the current in the C-AFM images. At the same time, it resulted in a decrease in the spatial resolution of the C-AFM images, because the current collected by the tip now comes from a larger area of the surface. The increase in the current is due to the formation of a highly conductive Te-rich layer on the CdTe surface after the NP etch [5]. I-V measurements performed in many spots resulted in a straight line, confirming the ohmic character of the surface. These results indicate that the NP etch is suitable for the formation of an ohmic contact on the surface of CdTe.

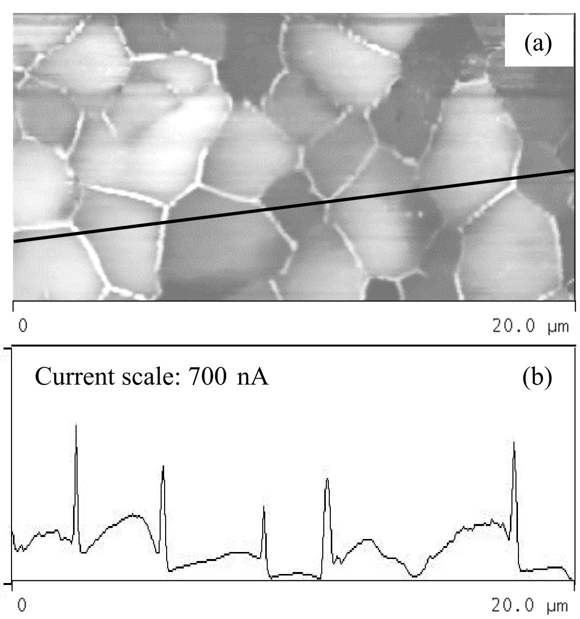


Fig. 2. (a) C-AFM image of a CdTe/CdS solar cell after BR etch. (b) Linescan taken at the line indicated in (a).

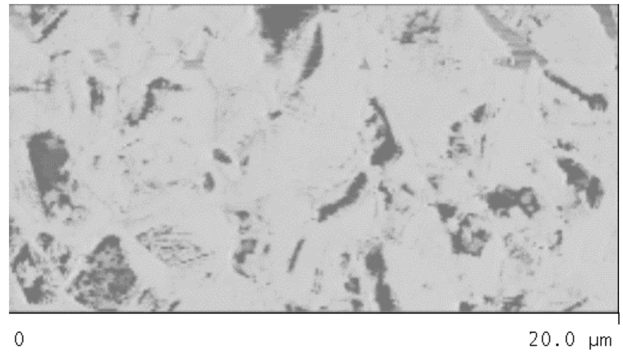


Fig. 3. C-AFM image of a CdTe/CdS solar cell after NP etch.

We have also noticed a strong effect of illumination on the current images of NP-etched samples, which was related to photo-generated carriers separated at the CdTe/CdS junction. These measurements can be used to measure the open-circuit voltage of the cells. Currently, we are investigating this effect, as well as performing C-AFM measurements on cross-sections of the cells, to investigate the effect of the etching process into the material.

4. Conclusions

We have demonstrated the applicability of C-AFM to study the electrical properties of CdTe/CdS solar cells with high spatial resolution.

As-deposited CdTe is not electrically uniform, with different grains having different conductivities. After the $CdCl_2$ treatment, the grain boundaries become less conductive than the intragrain material, but this effect was reversed at the surface after the BR etch. The NP etch promoted an increase in the conductivity, and created an ohmic contact over the whole CdTe surface.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337.

REFERENCES

[1] S. Kremmer, C. Teichert, E. Pischler, H. Gold, F. Kuchar, and M. Schatzmayr, Surf. and Interf. Anal. **33**, 168 (2002).

[2] J.V. Macpherson, J.-P.G. Mussy, and J.-L. Delplancke, Electroch. Sol.-St. Lett. **4**, E33 (2001).

[3] I. Visoly-Fisher, S.R. Cohen, and D. Cahen, Appl. Phys. Lett. **82**, 556 (2003).

[4] W.J. Danaher, L.E. Lyons, M. Marychurch, and G.C. Morris, Appl. Surf. Sci. **27**, 338 (1986).

[5] X. Li, D.W. Niles, F.S. Hasoon, R.J. Matson, and P. Sheldon, J. Vac. Sci. Technol. A **17**, 805 (1999).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. **REPORT DATE** *(DD-MM-YYYY)*	2. **REPORT TYPE**	3. **DATES COVERED** *(From - To)*
January 2005	Conference Paper	

4. **TITLE AND SUBTITLE** Conductive Atomic Force Microscopy of CdTe/CdS Solar Cells	5a. **CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. **GRANT NUMBER**
	5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** H.R. Moutinho, R.G. Dhere, C.-S. Jiang, M.M. Al-Jassim, and L.L. Kazmerski	5d. **PROJECT NUMBER** NREL/CP-520-37014
	5e. **TASK NUMBER** PVA53201
	5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	8. **PERFORMING ORGANIZATION REPORT NUMBER** NREL/CP-520-37014
9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**	10. **SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. **SPONSORING/MONITORING AGENCY REPORT NUMBER**

12. **DISTRIBUTION AVAILABILITY STATEMENT**
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*
Conductive atomic force microscopy (C-AFM) is a recently developed technique that applies an electric voltage between a very sharp tip and the sample, permitting the study of the electrical properties of the sample with very high spatial resolution. It also provides current-voltage measurements at well-defined spots. C-AFM is applied simultaneously with atomic force microscopy, providing topographic and current images of the same region. In this work, we analyze CdTe/CdS samples, before and after $CdCl_2$ treatment, and after bromine/methanol and nitric/phosphoric etches. The as-deposited samples show grains with different contrasts, indicating that the material is not electrically uniform. The $CdCl_2$ treatment resulted in less conductive grain boundaries, suggesting a relative decrease in the conductivity at these locations. After the bromine/methanol etch, the conductivity at grains boundaries was higher than inside the grains, whereas for the nitric/phosphoric etch the conductivity increased over the entire surface.

15. **SUBJECT TERMS**
PV; conductive atomic force microscopy (C-AFM); solar cells; electrical properties; current-voltage; spatial resolution; bromine/methanol etch; nitric/phosphoric etch; grain boundary;

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT**	b. **ABSTRACT**	c. **THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(12/2004)