

Profiling the Built-in Electrical Potential in III-V Multijunction Solar Cells

Preprint

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*Presented at the 2006 IEEE 4th World Conference on
Photovoltaic Energy Conversion (WCPEC-4)
Waikoloa, Hawaii
May 7–12, 2006*

Conference Paper
NREL/CP-520-39883
May 2006

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



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used in the air-AFM. For the Kelvin probe, a high-frequency ac voltage (~ 400 kHz) at the second resonant frequency of the cantilever [$V_{ac}\sin(\omega_{sr}t)$ in Fig. 1] is employed, instead of an off-peak low frequency that is used in the air-SKPM. This second resonant frequency enhances the energy resolution from ~ 50 mV of the air-SKPM to ~ 10 mV of the UHV-SKPM. The cantilever oscillation signal is separated to low- and high-frequency components by low- and high-pass filters, and these components are sent to the topographic and the Kelvin probe detection circuits, respectively. Comparing the air-SKPM, advantages of the UHV-SKPM are: (a) it keeps the fresh cross-sectional surface free of air molecule adsorption; (b) it uses a GaAs laser with a smaller photon energy of 1.4 eV for the AFM operation; and (c) energy resolution is improved. However, a disadvantage of the UHV-SKPM is that with the NC-AFM it is difficult to image a relatively rough thin-film surface with corrugations larger than ~ 50 nm, because it uses the frequency-modulation mechanism for z-feedback control.

RESULTS AND DISCUSSIONS

Figure 2 shows a SKPM potential and the corresponding AFM topographic images taken on the cross-section of the GaInP₂/GaAs tandem-junction cell. Because the potential distribution along the vertical direction is uniform, we averaged the potential along the direction and display the potential profile in Fig. 2(c). The profile shows three potential variations: the p-n junction at the top cell, the tunnel junction, and the p-n junction at the bottom cell. We note that this potential profile is different from the profile we previously measured in air on the same sample, where the 1.85-eV laser light was absorbed by the bottom cell, and the light absorption induced a potential flattening at the bottom junction and a potential enhancement at the top junction [1]. The potential measured by the air-SKPM is away from the

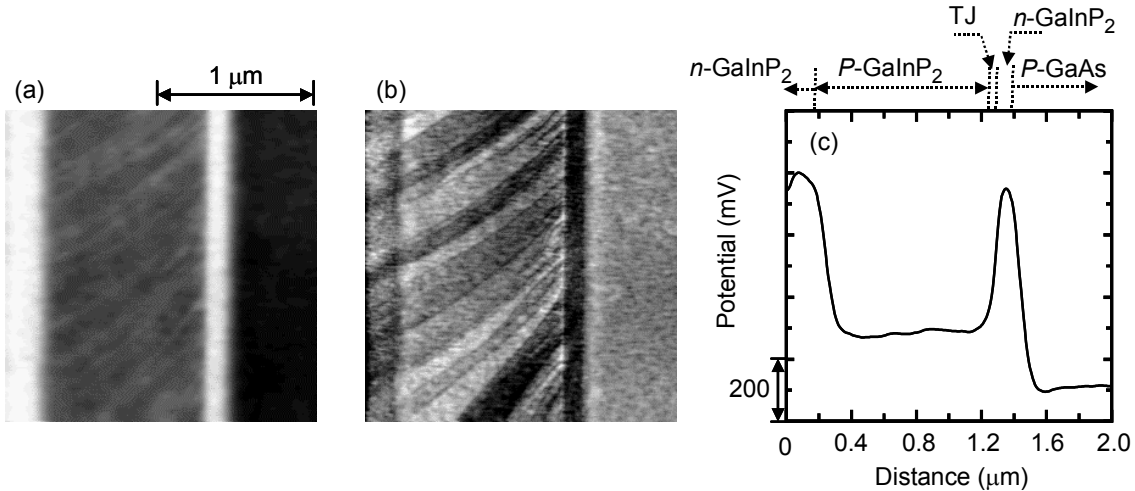


Fig. 2. (a) An SKPM potential and (b) the corresponding AFM topographic images taken on the cross-sections of GaInP₂/GaAs tandem-junction solar cells. (c) shows the averaged potential profile along the vertical direction in Fig. 2(a).

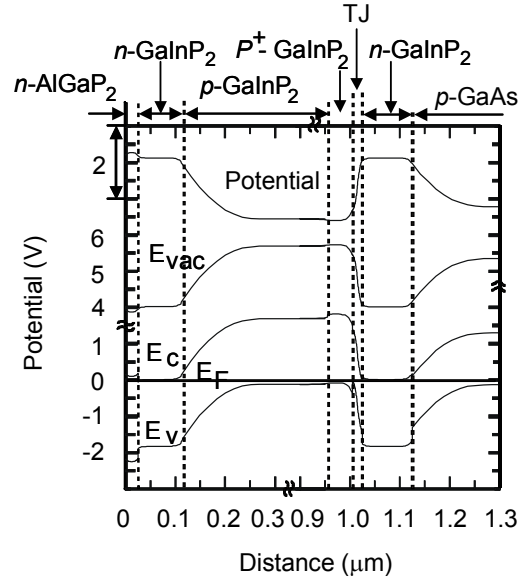


Fig. 3. A calculated band diagram in the bulk of GaInP₂/GaAs tandem-junction cell by solving Poisson's equation and using parameters of band offsets and bandgaps in the literature.

thermal equilibrium state. However, in the UHV-SKPM measurement, because the bandgap of the bottom cell approximately equals the photon energy, the effect of the laser light absorption should be weak or negligible. In this case, the sample is close to the thermal equilibrium state.

The band diagram (Fig. 3) in the bulk of the tandem cell is calculated by solving Poisson's equation and using parameters of band offsets and bandgaps listed in Table 1 [9-16]. There are three main potentials at the top, tunneling, and bottom junctions. The big potential drop at the top junction is close to the value of the GaInP₂ bandgap (~ 1.8 eV). The potential increase (1.56 eV) in

TABLE 1. Sizes and electronic properties of the multi-layers in the GaInP₂/GaAs tandem cell.

	Name	Material	Type	Thickness (nm)	Doping ($\times 10^{17}$)	E _g (eV)	Electron Affinity (eV)
Top cell	Window	AlInP ₂	n	25	10	2.35 ^[9]	3.78 ^[10]
	Emitter	GaInP ₂	n	90	10	1.85 ^[11,12]	4.01 ^[13]
	Base	GaInP ₂	p	840	1	1.81	4.01 ^[13]
	BSF	GaInP ₂	p	50	10	1.89 ^[11,12]	3.93 ^[13-15]
Tunneling Junction	p-layer	GaAs	p	10	100	1.42 ^[16]	4.07 ^[16]
	n-layer	GaAs	n	10	100	1.42 ^[16]	4.07 ^[16]
Bottom cell	Emitter	GaInP ₂	n	100	10	1.85 ^[11,12]	4.01 ^[13]
	Base	GaAs	p	350	1	1.42 ^[16]	4.07 ^[16]

the tunneling junction is slightly larger than the GaAs bandgap because of the conduction band offset (0.14 eV) between GaAs and the disordered p^+ -GaInP₂ back-surface-field (BSF) layer in the top cell. The potential drop in the bottom junction is close to the p-layer's bandgap (GaAs, ~ 1.42 eV). Although the n-layer of the bottom junction has a bigger bandgap (GaInP₂, 1.85 eV), it does not significantly affect the potential because the conduction bands are almost aligned ($\delta E_c \sim 60$ meV).

Comparing the measured profile in Fig. 2(c) with the

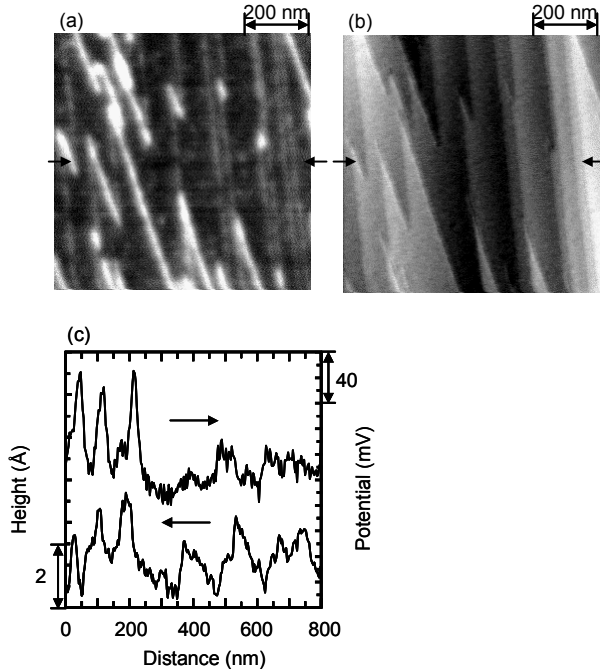


Fig. 4. (a) An SKPM potential and (b) the corresponding AFM topographic images taken on the cross-sections of GaAs substrate. (c) shows example line profiles along the arrows in (a) and (b).

calculated potential profile in Fig. 3, we found that the measurement qualitatively agrees with the calculation. Values of the potentials at the junctions are smaller than the calculation. This discrepancy is due to the effect of surface Fermi level pinning. Although the sample is cleaved in UHV and is free of air molecule adsorption, defects on the surface can be responsible for the Fermi level pinning [17,18]. From the measured potential values, we can propose Fermi level positions in the bandgap [1]. However, the potential measurement can give us only relative values between the Fermi level positions in these epitaxial layers of the cell. To deduce the Fermi level pinning positions, at least one Fermi level position in the layers has to be known as a reference. For GaAs(110), various surface Fermi level positions were reported, possibly depending on the nature of surface defects and doping types [17-21]. Because the relative values of the potential measured by the UHV-SKPM is different from the values measured by the air-SKPM [1], the Fermi level pinning positions should be different between the UHV- and air-cleaved (110) surfaces, due to the air molecule adsorptions.

On the SKPM image [Fig. 2(a)], one sees bright lines in the absorber layer of the top cell, which correspond to steps, as shown in Fig. 2(b). These lines show ~ 50 -mV higher potentials than on the terraces. The steps are single or a few atomic steps. The groove running along the tunneling junction is ~ 1 nm in depth, and the step along the vertical direction in the top junction is ~ 0.6 nm in height. The steps and the groove were created in the sample cleaving.

We also observed similar potential phenomena at atomic steps in the p-type GaAs substrate (Fig. 4), and found that the potential height depends on the step direction. To investigate the structure of the steps, we took STM images on the same sample area (Fig. 5). From the STM images, we know that there are angles between the atomic steps and the $[110]$ direction. The

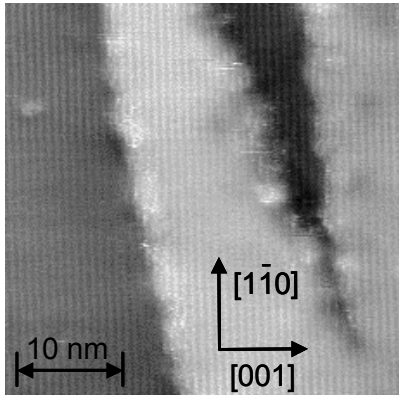


Fig. 5. A STM occupied-state image of the GaAs(110) surface taken in the same sample area as Fig. 4.

$[1\bar{1}0]$ direction is recognized by the atomic rows in Fig. 5. The steps in Fig. 4 are in two directions; the steps with the larger angle with respect to the $[1\bar{1}0]$ direction show the larger potential (~ 100 mV) than do the steps with the smaller angle (~ 30 mV). All the steps are single atomic steps [Fig. 4(c)]. This dependence of the potential on the step direction may relate to anti-site or vacancy defects at the steps, because the unbalance of cation and anion concentration on the surface directly results in surface charges, which causes the electrical potential at the steps. A larger work function at the atomic steps than on the GaAs (110) terraces for a n-type GaAs was reported by Sommerhalter et al. [21].

SUMMARY

We have observed three electrical potentials at the top, tunneling, and bottom junctions of $\text{GnInP}_2/\text{GaAs}$ tandem-junction solar cells by performing the UHV-SKPM measurement. The effect of laser illumination was avoided by using a GaAs laser with photon energy of 1.4 eV for the AFM operation. We also observed higher potentials at the atomic steps than on the terraces for both the p-type GaInP_2 epitaxial layer and p-type GaAs substrate, and found that the potential at steps of the GaAs substrate depends on the step directions.

ACKNOWLEDGEMENT

This work is supported or funded under DOE Contract No. DE-AC36-99GO10337.

REFERENCES

[1] C.-S. Jiang, H. R. Moutinho, D. J. Friedman, J. F. Geisz, and M. M. Al-Jassim, *J. Appl. Phys.* **93**, 10035 (2003).

- [2] C.-S. Jiang, D. J. Friedman, J. F. Geisz, H. R. Moutinho, M. J. Romero, and M. M. Al-Jassim, *Appl. Phys. Lett.* **83**, 1572 (2003).
- [3] C.-S. Jiang, F. S. Hasoon, H. R. Moutinho, H. A. Al-Thani, M. J. Romero, and M. M. Al-Jassim, *Appl. Phys. Lett.* **82**, 127 (2003).
- [4] C.-S. Jiang, H. R. Moutinho, M. J. Romero, M. M. Al-Jassim, Y. Q. Xu, and Q. Wang, *Thin Solid Films* **472**, 203 (2005).
- [5] C.-S. Jiang, H. R. Moutinho, Q. Wang, M. M. Al-Jassim, B. Yan, J. Yang, and S. Guha, *Mat. Res. Soc. Symp. Proc.* **808**, 587 (2004).
- [6] C.-S. Jiang, M. J. Romero, et al., unpublished.
- [7] J. M. R. Weaver and D. W. Abraham, *J. Vac. Sci. Technol.* **B9**, 1559 (1991).
- [8] A. Kikukawa, S. Hosaka, and R. Imura, *Appl. Phys. Lett.* **66**, 3510 (1995).
- [9] D. P. Bour, J. R. Shealy, G. W. Wicks, and W. J. Schaff, *Appl. Phys. Lett.* **50**, 615 (1987).
- [10] S.-H. Wei and A. Zunger, *Appl. Phys. Lett.* **72**, 2011 (1998).
- [11] S. R. Kurtz, P. Faine, and J. M. Olson, *J. Appl. Phys.* **68**, 1890 (1990).
- [12] A. Gomyo, T. Suzuki, and S. Iijima, *Phys. Rev. Lett.* **60**, 2645 (1988).
- [13] J. Chen, J. R. Sites, I. L. Spain, M. J. Hafich, and G. Y. Robinson, *Appl. Phys. Lett.* **58**, 744 (1991).
- [14] S. Froyen, A. Zunger, and A. Mascarenhas, *Appl. Phys. Lett.* **68**, 2852 (1996).
- [15] J. J. O'shea, C. M. Reaves, S. P. Debaars, M. A. Chin, and V. Narayanamurti, *Appl. Phys. Lett.* **69**, 3022 (1996).
- [16] M. E. Levinshtein and S. L. Rumyantsev, in *Handbook Series on Semiconductor Parameters Vol. 1*, Edited by M. Levinshtein, S. Rumyantsev, and M. Shur (World Scientific, River Edge, NJ, 1996), p77
- [17] Y. Ishikawa, N. Tsurumi, T. Fukui, and H. Hasegawa, *J. Vac. Sci. Technol.* **B16**, 2387 (1998).
- [18] S. Aloni, I. Nevo, and G. Haase, *Phys. Rev.* **B60**, R2165 (1999).
- [19] M. Kuball, M. K. Kelly, M. Cardona, K. Kohler, and J. Wagner, *Phys. Rev.* **B49**, 16569 (1994).
- [20] K. J. Choi and J.-L. Lee, *Appl. Phys. Lett.* **74**, 1108 (1999).
- [21] Ch. Sommerhalter, Th. W. Matthes, Th. Glatzel, A. Jager-Waldau, and M. Ch. Lux-Steiner, *Appl. Phys. Lett.* **75**, 286 (1999).