AIP Applied Physics

Rectification and tunneling effects enabled by Al_2O_3 atomic layer deposited on back contact of CdTe solar cells

,) ,) , , , , ,
, , ,)
Sc Ad a c d Ma a , P U S G ad a Sc , P U ,
S 518055, C a

(Received 22 April 2015; accepted 30 June 2015; published online 8 July 2015)

Atomic layer deposition (ALD) of Aluminum oxide (Al_2O_3) is employed to optimize the back contact of thin film CdTe solar cells. Al_2O_3 layers with a thickness of 0.5 nm to 5 nm are tested, and an improved efficiency, up to 12.1%, is found with the 1 nm Al_2O_3 deposition, compared with the efficiency of 10.7% without Al_2O_3 modification. The performance improvement stems from the surface modification that optimizes the rectification and tunneling of back contact. The current-voltage analysis indicates that the back contact with 1 nm Al_2O_3 maintains large tunneling leakage current and improves the filled factor of CdTe cells through the rectification effect. XPS and capacitance-voltage electrical measurement analysis show that the ALD-Al_2O_3 modification layer features a desired low-density of interface state of $8 \times 10^{10}\,cm^{-2}$ by estimation. [http://dx.doi.org/10.1063/1.4926601]

The performance of a CdTe thin film solar cell strongly depends on the nature of the back contact because it is challenging to compromise the CdTe material to most electrode materials.[1–3] To date, extensive efforts have been devoted to optimize the back contact based on nano-structures and physical concepts.[3–5] For example, we have shown previously that copper-nanowire back contact could be a controllable intermediate layer to enhance CdTe cell performances.[4] In the meantime, Al_2O_3 has been reported to be a promising candidate to passivate -type silicon (Si) material due to its good chemical and field-effect passivation, which is induced by the negative charge in the Al_2O_3 layer from Al vacancies, O interstitials, and extrinsic H.[6–11] Additionally, Al_2O_3 is a good candidate as an modification material for CdTe, because the lattice mismatch is only 3.7% between the unit cell of (0001) surface of Al_2O_3 and the unit cell of (111) surface of CdTe.[12] Therefore, a smooth interface of Al_2O_3/CdTe with strong chemical bonding and surface modification is expected to enhance the performance of CdTe solar cells.

Among the various methods for depositing Al_2O_3, atomic layer deposition (ALD) is attractive due to the ultra-thin film with excellent coverage. A 0.5–10 nm thickness is sufficient to tune the tunneling current by controlling the thickness.[7] In this letter, we demonstrate a nano-structured back contact of CdTe solar cells with Cu dopant and ALD-Al_2O_3 with thickness from 0.5 nm to 5 nm. The CdTe solar cells based on such Al_2O_3 ALD layer displays superior performance of efficiency due to the optimized rectification and tunneling effects.

CdTe solar cells were fabricated as following: 200 nm thick CdS window layers were grown by radio frequency magnetron sputtering (RF sputter), and then CdTe absorber layer was deposited by close space sublimation (CSS). For the back contact treatments, the ultrathin and uniform Al_2O_3 films were deposited by ALD using alternating pulses of $Al(CH_3)_3$ (Trimethylaluminium, TMA) and water as the precursors. Au was then evaporated as electrode. The procedure details were described in supplementary material, and the material properties are shown in Figures S1, S2, and S3.[20] The structure photo of CdTe solar cell is shown in Figure 1(a). The surface of ALD-Al_2O_3 CdTe layer shows smooth curvature, as shown in Figures 1(b) and S3, and the process is described in Figs. S1–S4.[20] From the XPS analysis (Figure 1(c)

the external quantum efficiency (EQE) of a series of CdTe solar cells with ALD-Al_2O_3 of different thicknesses. The cell with 1 nm Al_2O_3 presents more sensitive response at near infrared wavelength range (750 nm to 830 nm), as shown in the inset of Figure 2(b), which agrees well with the photocurrent J V characteristics. The high EQE at the visible wavelength range is mainly attributed to the reduced surface recombination by the ALD Al_2O_3.[4] The high FF of cells with Al_2O_3 is related to the enhanced holes collection of the back contact due to the negative charges from Al_2O_3, which neutralizes the positive charge in the surface of CdTe and eliminates the defect state in the interface. The estimated density of interface state (D_{it}) is below $8 \times 10^{10}\,cm^{-2}$ by fitting the C-V curve of 1 nm Al_2O_3 sample, as shown in Figure S4.[20]

f_{max} is the max response frequency. Obviously, the best S is achieved in the sample with 1 nm Al_2O_3, as shown in Table I and Figure S5.[20]

In order to evaluate the tunneling function of ALD-Al

[1]K. Zweibel, Science **32** , 699 (2010).
[2]L. Kranz, C. Gretener, J. Perrenoud, R. Schmitt, F. Pianezzi, F. L. Mattina, P. Blosch, E. Cheah, A. Chirila, C. M. Fella, H. Hagendorfer, T. Jager, S. Nishiwaki, R. U. Alexander, S. Buecheler, and A. N. Tiwari, Nat. Commun. **4**, 2306 (2013).
[3]S. G. Kumar and K. S. R. Koteswara Rao, Energy Environ. Sci. **7**, 45 (2014).
[4]J. Liang, H. Bi, D. Y. Wan, and F. Q. Huang, Adv. Funct. Mater. **22**, 1267 (2012).
[5]M. A. Matin, M. M. Aliyu, A. H. Quadery, and N. Amin, Solar Energy Materials & Solar Cells **4**, 1496 (2010).
[6]B. Hoex, J. J. H. Gielis, M. C. M. van de Sanden, and W. M. M. Kessels, J. Appl. Phys. **104**, 113703 (2008).
[7]P. Poodt, A. Lankhorst, F. Roozeboom, K. Spee, D. Maas, and A. Vermeer, Adv. Mater. **22**, 3564 (2010).
[8]B. Hoex, S. B. S. Heil, E. Langereis, M. C. M. Van de Sanden, and W. M. M. Kessels, Appl. Phys. Lett. , 042112 (2006).
[9]G. Dingemans, M. C. M. Van de Sanden, and W. M. M. Kessels, Electrochem. Solid-State Lett. **13**, 76 (2010).
[10]G. Dingemans, W. Beyer, M. C. M. van de Sanden, and W. M. M. Kessels, Appl. Phys. Lett. **7**, 152106 (2010).
[11]F. Werner, B. Veith, D. Zielke, L. Kuhnemund, C. Tegenkamp, M. Seibt, R. Brendel, and J. Schmidt, J. Appl. Phys. **10** , 113701 (2011).
[12]K. Meinander and J. S. Preston, Surf. Sci. **632**, 93 (2015).
[13]Y. Q. Liu, S. P. Shen, L. J. Brillson, and R. G. Gordon, Appl. Phys. Lett. , 122907 (2011).
[14]S. Lombardo, J. H. Stathis, B. P. Linder, K. L. Pey, F. Palumbo, and C. H. Tung, J. Appl. Phys. , 121301 (2005).
[15]J. Kruger, R. Plass, M. Gratzel, P. J. Cameron, and L. M. Peter, J. Phys. Chem. B **107**, 7536–7539 (2003).
[16]Y. D. Duan, J. X. Zheng, N. Q. Fu, Y. Y. Fang, T. C. Liu, Q. Zhang, X. W. Zhou, Y. Lin, and F. Pan, J. Mater. Chem. A **3**, 3066–3073 (2015).
[17]Y. D. Duan, J. X. Zheng, M. Xu, X. H. Song, N. Q. Fu, Y. Y. Fang, X. W. Zhou, Y. Lin, and F. Pan, J. Mater. Chem. A **3**, 5692–5700 (2015).
[18]S. Datta, *Q a T a : A T a* (Cambridge University Press, 2005), Chap. 9.
[19]S. M. Sze, *P c S c d c D c* , 2nd ed. (Wiley, New York, 1981), p. 286.
[20]See supplementary material at http://dx.doi.org/10.1063/1.4926601 for the detailed fabrication process and property characterizations of the CdTe solar cells.