Journal of The Electrochemical Society, **159** (5) H525-H528 (2012)
0013-4651/2012/159(5)/H525/4/$28.00 © The Electrochemical Society

Increasing Solar Efficiency of InGaN/GaN Multiple Quantum Well Solar Cells with a Reflective Aluminum Layer or a Flip-Chip Structure

Ming-Jer Jeng[z] **and Yu-Lin Lee**

Department of Electronic Engineering and Green Technology Research Center, Chang-Gung University, Taoyuan 333, Taiwan

Multiple quantum well solar cells (MQWSC) have the potential to be a highly efficient alternative to tandem or cascade systems. However, in conventional multiple quantum well solar cells, the quantum well layer does not usually receive and absorb enough light. To increase the absorption in the quantum well layer of an InGaN/GaN multiple quantum well solar cell, a reflective aluminum layer has been proposed and investigated here. We also studied the use of a flip-chip structure to increase the effectiveness of the heat sink and to prevent the shading loss that occurs in top contact metal of InGaN/GaN MQWSCs. We found that $In_{0.2}Ga_{0.8}N$/GaN MQWSCs with a reflective aluminum layer are 9.8% more efficient than those without a reflective aluminum layer. Meanwhile, $In_{0.28}Ga_{0.72}N$/GaN MQWSCs with a reflective aluminum layer are 4% more efficient than those without a reflective layer. $In_{0.28}Ga_{0.72}N$/GaN MQWSCs were expected by their lower well bandgap to be more efficient than $In_{0.2}Ga_{0.8}N$/GaN MQWSCs, but they are not. The lower efficiency enhancement in $In_{0.28}Ga_{0.72}N$/GaN MQWSCs is attributable to the greater number of defects or recombination centers in the film with higher indium content. $In_{0.2}Ga_{0.8}N$/GaN and $In_{0.28}Ga_{0.72}N$/GaN MQWSCs with a flip-chip structure exhibit efficiency enhancements of 1.4% and 1.1%, respectively, over those without a flip-chip structure.
 [DOI: 10.1149/2.009206jes]

Manuscript submitted December 14, 2011; revised manuscript received February 22, 2012. Published March 7, 2012.

The utilization of indium gallium nitride materials ($In_xGa_{1-x}N$) in the photovoltaic device applications has been extensively studied, due to their energy band gaps of between 0.7 and 3.4 eV.[1–8] The properties associated with the wide bandgap made such materials useful in fabricating high-performance multi-junction solar cells. Many theoretical calculations of the performance of InGaN-based solar cells have been made.[9,10] They have shown that a high solar efficiency could be achieved using a single material in the form of $In_xGa_{1-x}N$ with various indium contents. Unfortunately, no high-quality InGaN film with high indium content has yet been produced, because of the low miscibility of InN in GaN. One solution for fabricating high-quality InGaN films is the periodic growth of InGaN thin layers on a GaN surface to form multiple quantum well solar cells (MQWSCs). Multiple quantum well of thin films grown by this method are of high quality if their thickness is less than their critical thickness. That could afford MQWSCs the potential to be an alternative to the high efficient tandem or cascade solar cell systems.[11–16] The basic assumption is that in the cell, the barrier material with larger bandgap determines the open circuit voltage, while the quantum well material with a narrower bandgap determines the short circuit current. Consequently, the open circuit voltage and short circuit current can be independently optimized and the overall efficiency can be improved. However, the critical question here is that whether the increased short circuit current resulted from adding lower-bandgap quantum well materials can outweigh the voltage drop of an open circuit voltage caused by the recombination loss at the hetero-junction interfaces.

Although many theoretical calculations have demonstrated that a high solar efficiency could be achieved using a single $In_xGa_{1-x}N$ material with various indium contents, only a few relevant experimental results exist in the literature.[1,8] To study the properties of MQWSCs, two MQWSCs with different indium contents, $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$, are compared here. Additionally by considering the quantum well layer in MQWSCs that is usually too thin to receive and absorb enough light. Aluminum is known to reflect well at the wavelength of visible light. In the process of device fabrication, an aluminum metal layer is deposited on the back side of MQWSCs and functioned as a light reflective layer to increase the quantum well absorption further.[17,18] Moreover, III–V group solar cells are generally used in a concentrator system. Therefore a structure with a good heat sinking capability is very important. The flip-chip structure in light-emitting diodes provides a very effective heat sinking. In the conventional structures, the thermal conduction is through the top of GaN materials (thermal conductivity coefficient ~42 W/mK) and the bottom of sapphire materials (thermal conductivity coefficient ~35 W/mK) to air. In contrast, in flip-chip structures, the thermal conduction is through the gold (Au) stub bump (thermal conductivity coefficient ~320 W/mK) to AlN submount (thermal conductivity coefficient ~285 W/mK) and then to air. This new approach should yield a better heat conduction path. The flip-chip structure can also prevent shading loss by eliminating metal contact on the top surface.

Experimental

Two types of $In_xGa_{1-x}N$/GaN MQWSC were grown on c-plane sapphire substrates by metal organic chemical vapor deposition (MOCVD). The first contains 20% In ($In_{0.2}Ga_{0.8}N$), and the second contains 28% In ($In_{0.28}Ga_{0.72}N$). These solar cell structures consisted of a sapphire substrate, an undoped GaN buffer layer, a 1.7-μm-thick highly conductive n-type GaN:Si layer, an $In_xGa_{1-x}N$/GaN MQW layer, which consisted of five periods of a 7-nm-thick GaN barrier and a 3-nm-thick InGaN well, and a 0.1-μm-thick p-type GaN:Mg layer. The carrier concentration in the p-GaN and n-GaN layers was 5×10^{17} cm^{-3} and 1×10^{18} cm^{-3}, respectively. A mesa area was formed using an inductively-coupled-plasma (ICP) etcher to isolation the current. A thin Ni/Au (1.5 nm/3.5 nm) transparent contact layer was deposited by electron-beam evaporation on the GaN top layer, and then thermally annealed in oxygen for 10 minutes. The Ti/Al/Ti/Au metals for the p-GaN and n-GaN contact pads were deposited to form electrodes. Finally, all of the MQWSCs were cut to an area of 1×1 mm^2.

Figure 1 presents three approaches to fabricate MQWSCs with (a) conventional, (b) flip-chip and (c) reflective layer structures. In the conventional MQWSC structure, the light was incident from p-GaN and absorbed by the MQW. The flip-chip structure was formed by combining an inverted conventional MQWSC structure with a submount using gold pillars. Incident light was from the sapphire substrate, passing through the n-GaN buffer layer and absorbed by MQW, which reduced the reflection of incident light, because of the lower refractive index of sapphire as compared that of GaN. The heat generated in the MQWSCs can flow directly through the interconnect metal of the submount and improve the thermal conduction. Aluminum (Al) is a very favorable material for making metallic reflectors owing to its high reflectivity (>80%) in visible light range. The third structure was made by depositing an Al (200 nm) reflective mirror layer on

[z]E-mail: mjjeng@mail.cgu.edu.tw

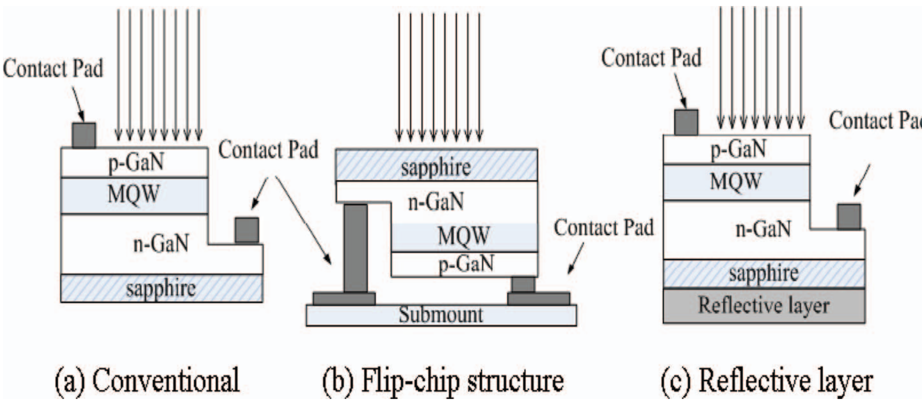

Figure 1. Three approaches to fabricate MQWSCs with (a) conventional, (b) flip-chip and (c) reflective layer structures.

the sapphire substrate to increase the optical path and absorption. A solar simulator YSS-50A (Yamashita DESO) was used as an air mass 1.5 (AM1.5 G, 100 mW/cm^2) light spectrum illumination. Dark and illuminated current-voltages (I-V) were measured using a Keithley 2400 meter.

Results and Discussion

Figures 2a and 2b present the current-voltage (I-V) characteristics of $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$ MQWSCs, respectively, with a conventional structure, a flip-chip structure and a reflective Al layer, illuminated by the AM 1.5G solar spectra. All current density curves were normalized to the short circuit current density (Jsc) of the MQWSC with a conventional structure. Table I presents the solar performance parameters. As is well known, the quantum well formed by lower bandgap materials can absorb more light, hence more photocurrent. Generally, a higher bandgap solar cell that has a lower QW energy bandgap will result in a higher efficiency and Jsc. Additionally, the open circuit voltage (Voc) can be increased by adjusting the bandgap of the P or N cladding layers with no or very few indium content. Theoretically, the V_{oc} of $In_{0.28}Ga_{0.72}N$ MQWSCs should equal to that of $In_{0.2}Ga_{0.8}N$ MQWSCs. Therefore, the solar efficiency of $In_{0.28}Ga_{0.72}N$ MQWSC should exceed that of $In_{0.2}Ga_{0.8}N$ MQWSC. However, as presented in Table I, the solar efficiency of $In_{0.28}Ga_{0.72}N$ MQWSCs is slightly less than that of $In_{0.2}Ga_{0.8}N$ MQWSCs. Attention should be paid to the reduction of Voc and the fill factor. The I-V curves in Fig. 2 show a large reduction in Voc and a worsening fill factor in $In_{0.28}Ga_{0.72}N$ MQWSCs as the forward bias increases. The large reduction in the Voc is attributed to the poor quality of the material with high indium content. A possible reason for the small fill factor is the decrease in the electric field and the conduction band offset (energy barrier, ΔE) in deep quantum wells.[8]

As shown in Fig. 2, the J_{sc} of $In_{0.2}Ga_{0.8}N$ MQWSCs with the flip-chip structure is 0.543 mA/cm^2, which is higher than 0.529 mA/cm^2 of the conventional structure and the Jsc of $In_{0.28}Ga_{0.72}N$ MQWSCs is 0.794 mA/cm^2, which is higher than 0.768 mA/cm^2 of the conventional structure. Notably, no anti-reflection layer was coated on any solar cell in this work. In Addition, the metallic contact pad in the conventional structure is required for the collection of photocurrent. These metallic contact pads suffer from shading loss. However, in the flip-chip structure, both metallic contact pads are located on the bottom side and will not cause shading loss. This configuration increases the effective absorption area and the conversion efficiency of the solar cell. The fill factor and V_{oc} of the flip-chip structure were slightly lower than those of the conventional structure, perhaps because of cracks or surface leakage in the flip-chip process. Generally, the leakage current increases slightly after the chip-flip process. There

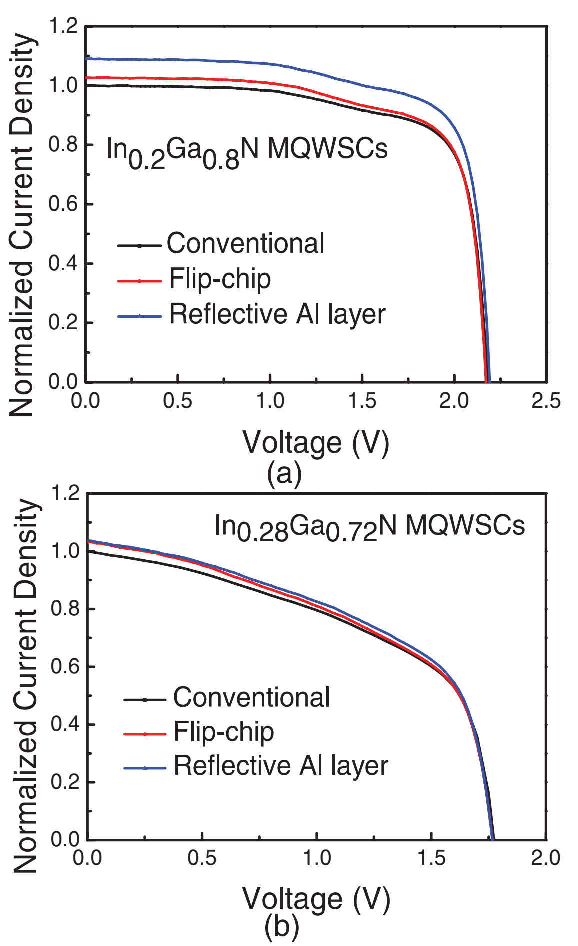

Figure 2. The current-voltage (I-V) characteristics of (a) $In_{0.2}Ga_{0.8}N$ and (b) $In_{0.28}Ga_{0.72}N$ MQWSCs with a conventional structure, a flip-chip structure and a reflective Al layer, illuminated by the AM 1.5G solar spectra.

Table I. Solar cell parameters of $In_{0.2}Ga_{0.8}N$/GaN and $In_{0.28}Ga_{0.72}N$/GaN MQWSCs

	Voc (V)	Jsc (mA/cm^2)	Fill Factor	Efficiency(%)
$In_{0.2}Ga_{0.8}N$ MQWSC				
Traditional	2.1812	0.529	0.7336	0.847
Flip chip	2.1725	0.543	0.7272	0.859
Al reflective layer	2.1922	0.577	0.7354	0.930
$In_{0.28}Ga_{0.72}N$ MQWSC				
Traditional	1.7763	0.768	0.5121	0.698
Flip chip	1.7669	0.794	0.5032	0.706
Al reflective layer	1.7669	0.797	0.5158	0.726

are two possible leakage paths in flip-chip structures. One is through the solar cell dies itself and the other is through the submount. It is known that the dies on the wafer may induce cracks during the dicing process.[19] The cracks in the dies will be worsened in flip-chip bonding process.[20] Through the top flipped dies (cracks induced by dicing damage and applied bonding force during flip-chip process), its thin active layers might have some cracks and cause the current leakage.[21] The other path is through the submount which was damaged in the flip chip procedure.[22] The increase of J_{sc} can outweigh the drop in FF and Voc, so the solar efficiency is still slightly higher in the flip-chip structure. The $In_{0.2}Ga_{0.8}N$/GaN and $In_{0.28}Ga_{0.72}N$/GaN MQWSCs with the flip chip structure are 1.4% and 1.1%, respectively, more efficient than those without the flip-chip structure. As for why the current improvement in flip-chip structures is not as expected as theoretical prediction, it could be owing to the following reason. The reflectivity of conventional structure(refractive index of GaN, 2.5) and flip-chip structures(refractive index of sapphire, 1.8) is about 18.4% and 8.2%, respectively, which is calculated from the simple reflective formula of $R = (1 - n)^2/(1 + n)^2$ (assuming air/one layer and normal incident light). It means that the short circuit current of MQWSCs with flip-chip structures will be 10.2% higher than that with conventional structures. For light shadowing by the pads, the area shaded by the contact metal line is 18.9% of cell area. It means that the short circuit current of MQWSCs with flip-chip structures will be 18.9% higher than that with conventional structures. For thermal effects, the Voc decreases and Jsc increases with increasing temperature. The net solar efficiency depends on the competition between the decreasing rate in Voc and the increasing rate in Jsc. The solar efficiency of MQWSCs in our previous works[8] exhibit no apparent variation in the temperature range from 25 to 130°C due to a near balance between the drop of Voc and the increase of Jsc. But, the solar efficiency drops drastically when the temperature is higher than 130°C. Thus, the solar cells with flip-chip structure will be greatly beneficial when higher operating temperature is required. If we don't include the thermal dissipation effects, the expected improvement in Jsc will be 28.9% theoretically. However, it should be noted that the light path is different between conventional and flip-chip structures. Some of light in flip-chip structures will be absorbed and wasted in buffer GaN and n-GaN layer. Thus, the enhancement of the short circuit current in flip-chip structures is not as expected as above value. If one can reduce the thickness of buffer GaN and n-GaN layer, the improvement of the short circuit current would be higher.

As is well known, Ag and Al are highly reflective in visible light range, and therefore are very good materials for fabricating metallic reflectors. Al metal was deposited as a reflective layer on the underside of the device to increase the optical path of light. The Voc and fill factor of $In_{0.2}Ga_{0.8}N$ MQWSCs equal those of the corresponding conventional device, but J_{sc} is increased from 0.529 to 0.577 mA/cm^2 and the corresponding conversion efficiency is increased from 0.847% to 0.93%. The efficiency enhancement over the cells without an aluminum reflective layer is 9.8%. Since the total thickness of the quantum well layer herein investigated is around 15 nm, this layer does not absorb enough incident light. Therefore, a reflective layer in an MQWSC can increase the optical path of light, hence increasing the solar efficiency. The J_{sc} and conversion efficiency of $In_{0.28}Ga_{0.72}N$ MQWSCs are increased from 0.768 to 0.97 mA/cm^2 and from 0.698 to 0.726%, respectively. The efficiency enhancement is 4% less than that of $In_{0.2}Ga_{0.8}N$ MQWSCs. Since theoretically the layer with high indium content would have more defects, the recombination rate should be higher than that in $In_{0.2}Ga_{0.8}N$ MQWSCs, and so the increase in J_{sc} and efficiency is less than that of $In_{0.2}Ga_{0.8}N$ MQWSCs. The short circuit current of the MQWSCs always includes two components; one is generated in the GaN layer and the other is generated in the InGaN layer. According to Brown's simulated results,[23] the p-GaN layer with a thickness of 100 nm can generate a photocurrent of 0.39mA/cm^2. This current represents a large portion of current in GaN/InGaN QW solar cells, which depends on the indium content in the well layer. It should be noted that very little light with energy larger than the bandgap of GaN will be reflected by Al layer due to the fact that

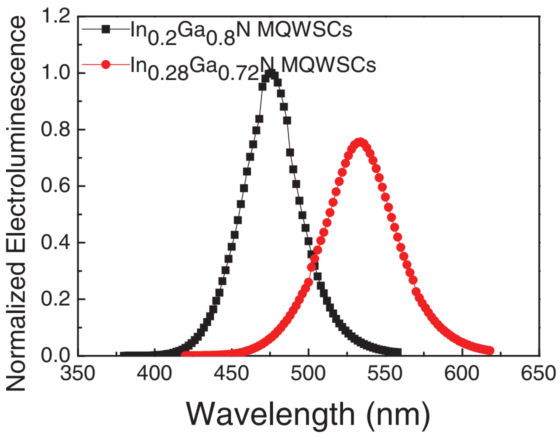

Figure 3. The EL emission spectra of the $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$ MQWSCs.

these lights will be absorbed totally at the p-GaN, n-GaN and GaN buffer layer. Only the light with the energy smaller than the bandgap of GaN will be reflected by Al layer. For example, if the current generated by the GaN layer occupies a half of total generation current, the theoretically expected improvement on the photocurrent will be 50% by the addition of a reflective layer. However, the GaN buffer layer is a nucleation layer and its quality is poor. It may also absorb some of these lights with the energy smaller than the bandgap of GaN. Thus, the reflective light with the energy smaller than the bandgap of GaN will be much weaker intensity than the incident light. In addition, the reflective light may reflect at the interface of sapphire and GaN, and cannot reach to QW layers again. These are the possible reasons for a less than 10% improvement of Jsc by the addition of Al layer. Based on the above reasoning, 9.1% and 9.8% improvement in Jsc and efficiency, respectively, are quite reasonable in $In_{0.2}Ga_{0.8}N$ MQWSCs. In $In_{0.28}Ga_{0.72}N$ MQWSCs, only 3.8% and 4% improvement in Jsc and efficiency, respectively, are observed due to the large number of defects or recombination centers in a higher indium content film.

The quality of the grown film can be easily characterized by electroluminescence (EL) measurements. Figure 3 presents the EL emission spectra of the $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$ MQWSCs. The peak wavelength and full-width at half-maximum (fwhm) of the emission spectra of $In_{0.2}Ga_{0.8}N$ MQWSCs were 476 nm and 37 nm, respectively, while those of $In_{0.28}Ga_{0.72}N$ MQWSCs were 534 nm and 47 nm, respectively. The EL peak wavelengths of grown MQWSC were in good agreement with the indium content of multi-quantum well (MQW) layers, and the values of the fwhm can be correlated to the crystal quality of InGaN layers. It is known that the fwhm is also affected by the spread of localized states in the quantum well and the built-in piezoelectric fields across the well. Since the strain and the piezoelectric fields are likely to increase in the sample with a higher indium fraction, so is the fwhm. However, the larger fwhm of the $In_{0.28}Ga_{0.72}N$ MQWSC indicated that its crystal quality was poorer. The EL peak intensity of the $In_{0.2}Ga_{0.8}N$ MQWSC exhibits stronger than that of the $In_{0.28}Ga_{0.72}N$ MQWSC under the same injection current of 50 mA. It also indicates that the film quality in the $In_{0.2}Ga_{0.8}N$ MQWSC is better than that in the $In_{0.28}Ga_{0.72}N$ MQWSC.

Figure 4 plots the dark I-V curves of $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$ MQWSCs. Clearly, the leakage current in $In_{0.28}Ga_{0.72}N$ MQWSCs exceeds that in $In_{0.2}Ga_{0.8}N$ MQWSCs, indicating that the quality of the film in $In_{0.28}Ga_{0.72}N$ MQWSCs is poorer than that in $In_{0.28}Ga_{0.72}N$ MQWSCs. The ideality factor of a diode is a measure for how closely the ideal diode equation describes the diode. The ideality factor is usually obtained from the slope of the dark I-V curve. The deviation of the ideality factor from unity reveals that either unusual recombination is occurring or the magnitude of recombination is changing. Therefore, the ideality factor is a powerful metric for examining

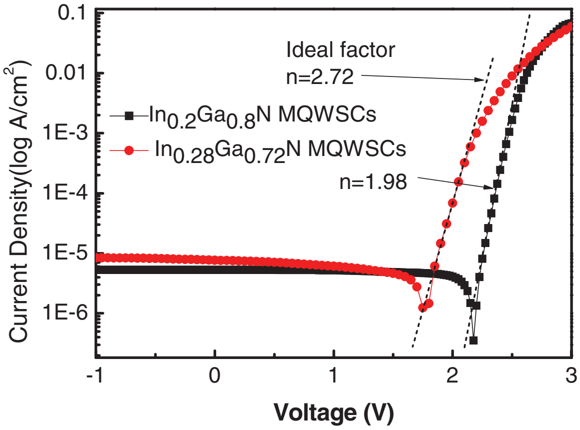

Figure 4. The dark I-V curves of $In_{0.2}Ga_{0.8}N$ and $In_{0.28}Ga_{0.72}N$ MQWSCs.

the recombination in a device. The ideality factor of $In_{0.2}Ga_{0.8}N$ MQWSCs is two, implying that the current transport is dominated by space-charge recombination.[24–26] However, the ideality factor of $In_{0.28}Ga_{0.72}N$ MQWSCs was much higher, 2.7. This difference is probably caused by the defect-assisted tunneling current at the interface of the MQWs, because many defects are present at the interface in the GaN/InGaN MQWs owing to the lattice mismatch especially when the InGaN film has a high indium content. This fact explains why the Voc of the $In_{0.28}Ga_{0.72}N$ MQWSCs is lower than that of the $In_{0.2}Ga_{0.8}N$ MQWSCs.

To study the effectiveness of heat sinking, a conventional MQWSC and a flip-chip MQWSC with an AlN submount are injected with various currents to generate heat, and compared. Figure 5 plots the average surface temperature as a function of injection current in a conventional MQWSC and a flip-chip MQWSC. The surface temperature of the samples was measured by thermal infrared microscopy. The average surface temperature is the average value of 1296 measured surface temperature values in an area of 1 mm^2. Higher injection current causes more heat to be generated. The average surface temperature of the conventional MQWSC and the flip-chip MQWSC increases with injection current with gradients of 0.4 and 0.24, respectively. Clearly, the slopes differ greatly, indicating that the flip-chip MQWSC can sink more heat than the conventional MQWSC. Notably, heat sinking effectiveness is important in the solar concentration systems.

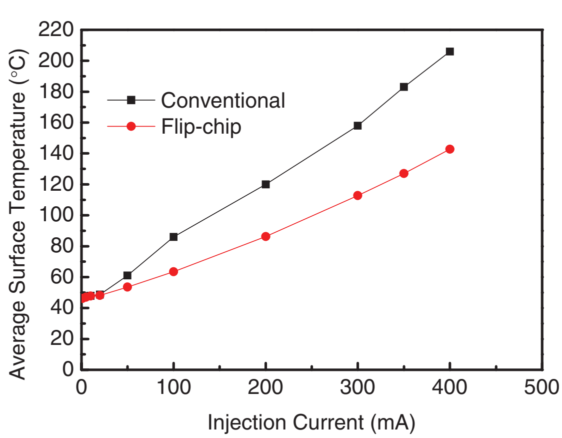

Figure 5. The average surface temperature as a function of injection current in a conventional MQWSC and a flip-chip MQWSC.

Conclusions

The photovoltaic characteristics of the $In_xGa_{1-x}N$/GaN MQWSCs with a flip-chip structure and a reflective metal layer are studied and compared with those of the conventional MQWSCs. The formers exhibit better solar performance than the conventional MQWSCs. As expected, the $In_xGa_{1-x}N$/GaN MQWSCs with a flip-chip structure and a reflective metal layer exhibit a larger photocurrent than the conventional MQWSCs. The $In_{0.2}Ga_{0.8}N$ MQWSCs with a flip-chip structure and a reflective metal layer have a 2.6% and 9.1% higher short circuit current density, respectively, than that of the conventional $In_{0.2}Ga_{0.8}N$ MQWSCs. Their corresponding efficiency enhancements are 1.4% and 9.8%, respectively. Furthermore, In0.28Ga0.72N MQWSCs with the flip-chip structure and a reflective metal layer have 3.4% and 3.8% higher short circuit current density, respectively. Their corresponding efficiency enhancements are 1.1% and 4%, respectively. It is interesting to note that the flip-chip MQWSC can sink greatly more heat than the conventional MQWSC. It is very suitable for the usage in a solar concentration system.

Acknowledgments

This work was supported by the National Science Council of Taiwan, R.O.C. (Project No. NSC98-2221-E-182-006) and Chang Gung University.

References

1. O. Jani, I. Ferguson, C. Honsberg, and S. Kurtz, *Appl. Phys. Lett.*, **91**, 132117 (2007).
2. C. J. Neufeld, N. G. Toledo, S. C. Cruz, M. Iza, S. P. Denbaars, and U. K. Mishra, *Appl. Phys. Lett.*, **93**, 143502 (2008).
3. R. Dahal, B. Pantha, J. Li, J. Y. Lin, and H. X. Jiang, *Appl. Phys. Lett.*, **94**, 063505 (2009).
4. X. Zheng, R. H. Horng, D. S. Wuu, M. T. Chu, W. Y. Liao, M. H. Wu, R. M. Lin, and Y. C. Lu, *Appl. Phys. Lett.*, **93**, 261108 (2008).
5. X. Chen, K. D. Matthews, D. Hao, W. J. Schaff, and L. F. Eastman, *Phys. Stat. Sol.*, **205**, 1103 (2008).
6. S. W. Zeng, B. P. Zhang, J. W. Sun, J. F. Cai, C. Chen, and J. Z. Yu, *Semicond. Sci. Technol.*, **24**, 055009 (2009).
7. B. W. Liou, *Jpn. J. Appl. Phys.*, **48**, 072201 (2009).
8. M. J. Jeng, Y. L. Lee, and L. B. Chang, *J. Phys. D:Appl. Phys.*, **42**, 105101 (2009).
9. H. Hamzaoui, A. S. Bouazzi, and B. Rezig, *Sol. Energy Mater. Solar Cells*, **87**, 595 (2005).
10. X. Zhang, X. Wang, H. Xiao, C. Yang, J. Ran, C. Wang, Q. Hou, and J. Li, *J. Phys. D:Appl. Phys.*, **40**, 7335 (2007).
11. K. Barnham, I. Ballard, J. Barnes, J. Connolly, P. Griffin, B. Kluftinger, J. Nelson, E. Tsui and A. Zachariou, *Appl. Surf. Sci.*, **113/114**, 722 (1997).
12. E. Aperathitis, A. C. Varonides, C. G. Scott, D. Sand, V. Foukaraki, M. Androulidaki, Z. Hatzopoulos and P. Panayotatos, *Sol. Energy Mater. Solar Cells*, **70**, 49 (2001).
13. N. G. Anderson, *J. Appl. Phys.*, **78**, 1850 (1995).
14. J. C. Rimada and L. Hernaadez, *Microelectronics J.*, **32**, 719 (2001).
15. H. Ohtsuka, T. Kitatani, Y. Yazawa and T. Warabisako, *Sol. Energy Mater. Solar Cells*, **50**, 251 (1998).
16. Y. Okada, N. Shiotsuka, and T. Takeda, *Sol. Energy Mater. Solar Cells*, **85**, 143 (2005).
17. C. L. Tsai, G. S. Liu, G. C. Fan, and Y. S. Lee, *Solid-State Electron.*, **54**, 541 (2010).
18. J. G. Adams, K. W. Barnham, J. P. Connolly, G. Hill, J. S. Roberts, T. N. Tibbits, M. Geen, M. Pate, *IEEE 33rd Photovoltaic Specialists Conference*, (2008) 1.
19. K. S. Seo and S. S. Song, US patent: 7,375,428 (2008).
20. J. A. West, P. D. Vincent, and R. A. Tuerck, US patent Application: 20100193918 (2010).
21. C. C. Lin, L. B. Chang, M. J. Jeng, C. Y. Yen, A. Das, C. Y. Tang, M. Y. Tsai, and M. J. Lai, *Microelectron. Reliability*, **50**, 683 (2010).
22. L. S. Lu, US patent Application: 20110014734 (2011).
23. G. F. Brown, J. W. Ager III, W. Walukiewicz, and J. Wu, *Sol. Energy Mater Solar Cells*, **94**, 478 (2010).
24. X. A. Cao, E. B. Stokes, P. M. Sandvik, S. F. LeBoeuf, J. Kretchmer, and D. Walker, *IEEE Electron. Dev. Lett.*, **23**, 535 (2002).
25. T. Markvart and L. Castaner, *Practical Handbook of Photovoltaics: Fundamentals and Applications*, (Amsterdam: Elsevier) **392** (2003).
26. J. Nelson, *Physics of thin film*, Eds. M. H. Francome and J. L. Vossen, (Academic Press, New York) **21** (1995) 251.