Projected Efficiency of Polarization-Matched p-$In_xGa_{1-x}N$/i-$In_yGa_{1-y}N$/n-GaN Double Heterojunction Solar Cells

Hsun-Wen Wang, Peichen Yu, *Member, IEEE*, Yuh-Renn Wu, *Member, IEEE*, Hao-Chung Kuo, *Senior Member, IEEE*, Edward Yi Chang, and Shiuan-Huei Lin

***Abstract*—Traditional p-GaN/i-InGaN/n-GaN double heterojunction solar cells have limited power conversion efficiency due to large polarization charges that accumulate at the heterojunction interfaces, leading to severe band bending that, in turn, hinders the carrier transport. In this study, we proposed the use of a p-type InGaN layer to reduce the polarization field and projected the power conversion efficiencies of p-$In_xGa_{1-x}N$/i-$In_yGa_{1-y}N$/n-GaN double heterojunction solar cells that are grown on a c-facet sapphire substrate with various indium components. Numerical simulations predict that a maximal power conversion efficiency that is close to 7% with a short-circuit current density of 4.05 mA/cm^2 and an open-circuit voltage of 1.94 V can be achieved with a p-$In_{0.2}Ga_{0.8}N$/i-$In_{0.2}Ga_{0.8}N$/n-GaN structure due to a polarization-matched p-i interface. Further efficiency enhancement with a higher indium composition over 20% is also possible via the redistribution of the built-in potential with n-GaN doping.**

***Index Terms*—InGaN solar cells, polarization effect.**

I. Introduction

InGaN ALLOYS have been widely used for making high-performance optoelectronic devices, including light-emitting diodes and laser diodes. Recently, InGaN materials have also become attractive for use in heterojunction solar cells for the following reasons. First, the ability to produce widely tunable direct bandgaps, ranging from 0.7 eV with InN to 3.4 eV with GaN, can cover the whole solar spectrum from ultraviolet to visible and infrared wavelengths [1], [2]. Second, the high absorption coefficient ($>10^5$ cm^{-1}) of InGaN-based materials permits strong optical absorption within a relatively thin active layer, which is desirable for light-weight solar cells [3]. These features may also make InGaN-based solar cells favorable for use in terrestrial applications. Currently, GaN/InGaN-based heterojunction p-i-n solar cells are normally grown on a c-facet sapphire substrate by metal–organic vapor phase epitaxy [4]–[6]. Due to epitaxial strain, the structures are generally composed of an intrinsic InGaN layer as the active region, with an indium content lower than 15%, and a thickness of 60∼300 nm, which is sandwiched in-between a n-GaN and p-GaN layer [7]–[9]. However, we note that the critical thickness of $In_xGa_{1-x}N$ that is grown on GaN is less than 10 nm for $x > 0.2$. Thicker growth results in strain relaxation through the formation of misfit dislocations, as well as compositional fluctuations, which adversely affect the electrical properties of the InGaN epilayer [10], [11]. The growth of a thick InGaN layer with a high indium composition is a challenge in real fabrication [12], [13]. Moreover, the i-InGaN epitaxial layer in this structure suffers from both a spontaneous and strain-induced piezoelectric polarization field [14]–[18]. The polarization mismatch effect also gives rise to strong band bending, which may hinder photogenerated carrier separation and transport, and lead to an inadequate power conversion efficiency of InGaN-based solar cells [19]. Previous studies have suggested that the growth of InGaN material on the nitrogen (N) face [20], [21] or insertion of a grading layer at the InGaN/GaN interface [22], [23] will minimize the influence of polarization and help the carrier escape the depletion region. Recently, the experimental implementation of heteroepitaxy and the p-type doping of InGaN are achievable at low indium composition conditions by using molecular beam epitaxy (MBE). However, obtaining high p-type doping in high indium composition is still very challenging [24]. In this study, we assume that the implementation of a p-InGaN layer is achievable. Therefore, we propose the use of a p-type InGaN layer to reduce the polarization field and investigate the projected efficiencies of p-$In_xGa_{1-x}N$/i-$In_yGa_{1-y}N$/n-GaN double heterojunction solar cells that are grown on the c-facet with various indium components. The growth of p-type InGaN materials has recently been demonstrated by MBE and metal–organic chemical vapor deposition [4], [5], [25]. Numerical simulations predict that maximal power conversion efficiency that is close to 7% can be achieved with a p-$In_{0.2}Ga_{0.8}N$/i-$In_{0.2}Ga_{0.8}N$/n-GaN structure, which is permitted by a polarization-matched p-i interface. Further efficiency enhancement with a higher indium composition over 20% is also possible by lowering the barrier at the n-GaN heterojunction with n-type doping.

Manuscript received August 17, 2012; revised December 10, 2012 and January 27, 2013; accepted March 1, 2013. Date of publication April 12, 2013; date of current version June 18, 2013. This work was supported in part by the National Science Council, Taiwan, under Grant NSC 101-3113-E009-002-CC2 and Grant NSC-100-2221-E-002-153-MY2.

H.-W. Wang and S.-H. Lin are with the Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: anniewangtw@gmail.com; lin@cc.nctu.edu.tw).

P. Yu and H.-C. Kuo are with the Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan (e-mail: yup@faculty.nctu.edu.tw; hckuo@faculty.nctu.edu.tw).

Y.-R. Wu is with the Institute of Photonics and Optoelectronics and the Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan (e-mail: yrwu@cc.ee.ntu.edu.tw).

E. Y. Chang is with the Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 300, Taiwan (e-mail: edc@mail.nctu.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JPHOTOV.2013.2252953

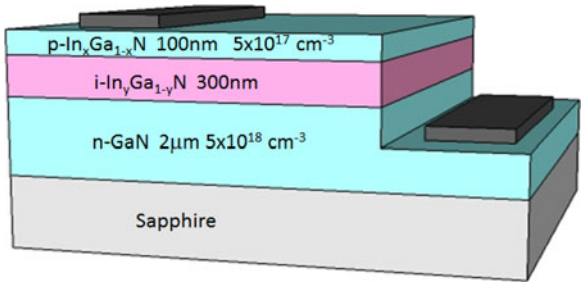

Fig. 1. Schematic layer structure of a p-$\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/i-$\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ solar cell.

II. Simulation and Method

The band structures and current density–voltage $(J$–$V)$ characteristics of InGaN-based heterojunction solar cells are investigated numerically by commercially available software, namely, Advanced Physical Models of Semiconductor Devices [26]. The simulated solar cell structure is composed of a 100-nm-thick Mg-doped $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$ layer with fully activated p-type doping of 5×10^{17} cm^{-3}, a 300-nm-thick strained intrinsic $\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ layer, and a 2-μm-thick Si-doped GaN bottom layer with n-type doping of 5×10^{18} cm^{-3}. To keep the depletion region large, the intrinsic doping density in this study is assumed to be 1×10^{16} cm^{-3}. In our testing, doping density smaller than 1×10^{17} cm^{-3} in the intrinsic region will give a close result. Fig. 1 illustrates the p-$\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/i-$\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ p-i-n double heterojunction solar cell's structure, which is similar to an experimental demonstration [4], [8]. Hereafter, we denote the indium compositions of a p-$\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/i-$\mathrm{In}_y\mathrm{Ga}_{1-y}\mathrm{N}$ structure as px-iy, for example, p-$\mathrm{In}_{0.05}\mathrm{Ga}_{0.95}\mathrm{N}$/i-$\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}\mathrm{N}$ as p0.05-i0.1. The device has an area of 300 μm $\times$ 300 μm and assumes ideal ohmic contacts. The unit cell is then discretized into 55 130 mesh points on the 2-D layout to minimize numerical errors and ensure convergence. Optical properties are first calculated based on the surface and internal reflection and the material absorption within each dielectric layer including the sapphire substrate. The distribution of the carrier generation rate under air mass 1.5 global (AM 1.5G) illumination condition is then obtained. Electronic properties are solved using the built-in 2-D self-consistent Poisson and drift-diffusion equations solver for electrons and holes transportation. Moreover, the band offset ratios between the conduction band and valance band are assumed to be 0.67 and 0.33 of the bandgap difference, respectively [27]. We also assume the diffusion length in p-InGaN to be 200 nm [28], which is larger than the layer thickness, and therefore, the additional absorption that occur in p-InGaN is still effective and contributes to the output photocurrent. The actual diffusion length assumption of the p-InGaN layer might be too long under this assumption. Thus, if the actual diffusion is short, we should reduce the p-InGaN/GaN layer thickness as well in order to avoid nonradiative recombination.

The polarization charges at the surfaces and interfaces with various indium compositions are calculated based on an ab initio model, which was developed by Fiorentini and coworkers [14], [18]. Equations (1)–(4), shown below, calculate the polarization charges of a ternary alloy layer, including spontaneous and piezoelectric polarization, P^{sp} and P^{pz}, respectively, using the relationship between composition x, bandgap, lattice constant a, and strain ε

$$p^{\mathrm{sp}}_{\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}} = -0.042x - 0.034(1-x) + 0.038x(1-x) \quad (1)$$

$$p^{\mathrm{pz}}_{\mathrm{InN}} = -1.373\varepsilon + 7.559\varepsilon^2 \quad (2)$$

$$p^{\mathrm{pz}}_{\mathrm{GaN}} = -0.918\varepsilon + 9.541\varepsilon^2 \quad (3)$$

$$\varepsilon(x) = [a_{\mathrm{subs}} - a(x)]/a(x). \quad (4)$$

The piezoelectric polarization can be expressed by Vegard's law as

$$p^{\mathrm{pz}}_{\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}} = x p^{\mathrm{pz}}_{\mathrm{InN}}[\varepsilon(x)] + (1-x)p^{\mathrm{pz}}_{\mathrm{GaN}}[\varepsilon(x)]. \quad (5)$$

We note that the strain is defined from the lattice constant of GaN, and other material parameters that are used in the calculation can be found in [22]. The nonlinear wavelength-dependent absorption coefficient of InGaN alloys was taken, as shown in [22]

$$\alpha(E) = 10^5\sqrt{a\cdot(E-E_g) + b\cdot(E-E_g)^2} \quad (6)$$

where E is the incident photon energy given in eV, and a and b are dimensionless fitting parameters. The parameters a and b are 3.52517 and -0.6571 when the indium composition equals 0%, and become 0.51672 and 0.468836, respectively, when the indium composition equals 50%; the fitting parameters of InGaN for indium compositions between 0% and 50% are obtained by linear interpolation.

In addition, we assume that the InGaN is ideally epitaxially grown without strain relaxation. Therefore, the ratio of polarization equals unity. Although a screening ratio between 0.4 and 0.6 is commonly used to fit the empirical data for InGaN-based light-emitting devices [29], we have calculated and found that the polarization charge induced at the interface under stain relaxation is still close to the unrelaxed case. This is because if the InGaN lattice is totally relaxed, the InGaN and GaN top layer would be still under tensile strain. However, if the top GaN layer experiences strain relaxation, the piezoelectric field is also reduced. Therefore, at the end of this paper, we discuss the dependence of the device characteristics on the ratio of polarization at the GaN/InGaN interface induced by strain relaxation.

III. Results and Discussion

To relieve the polarization effects using a p-doped InGaN layer, the current density–voltage curves of InGaN heterojunction solar cells with an intrinsic $\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}\mathrm{N}$ layer are first simulated for p-layers with different indium compositions, ranging from 0% to 10%, as shown in Fig. 2(a). The corresponding short-circuit current density J_{sc}, open-circuit voltage V_{oc}, fill factor (FF), and efficiency are plotted in Fig. 2(b)–(e), respectively. The cell, which is denoted as p0-i0.1, represents the reference cell with p-GaN, which has been experimentally demonstrated. With a slight indium composition in the p-layer, the photovoltaic characteristics are significantly improved over the reference counterpart. The J_{sc} increases and V_{oc} decreases with the

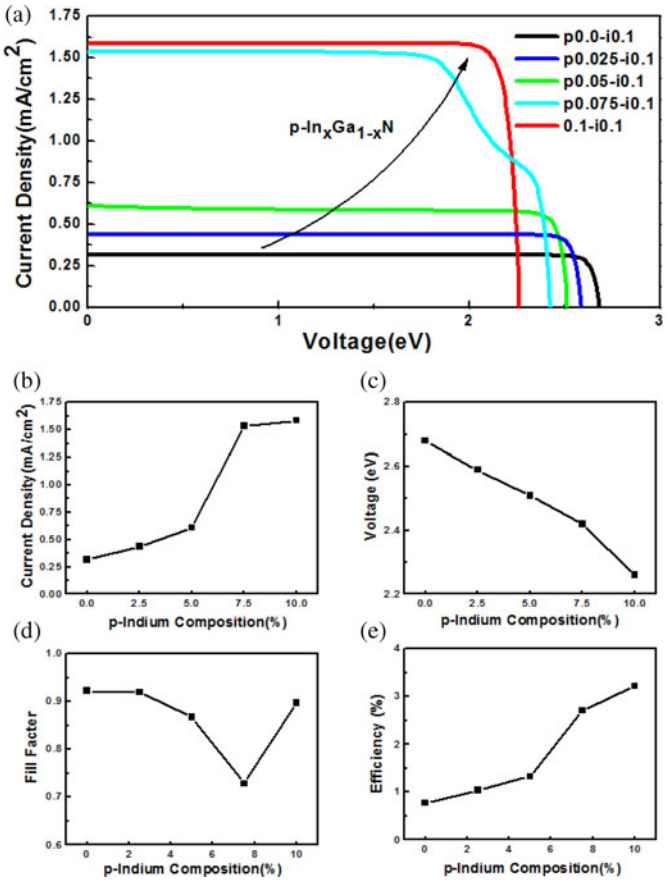

Fig. 2. (a) Current density–voltage characteristics for p-$In_xGa_{1-x}N$/i-$In_{0.1}Ga_{0.9}N$/n-GaN solar cells with varying indium compositions. The corresponding parameters are plotted as a function of the p-type indium composition: (b) Short-circuit current density J_{sc}, (c) open-circuit voltage V_{oc}, (d) FF, and (e) efficiency.

indium composition in the p-type layer monotonically due to decreased interface polarization charges. However, there is also a sudden increase in J_{sc} and decrease in FF with an indium composition of 0.075, due to a redistribution of the built-in field on the intrinsic layer, which will be further discussed later. The conversion efficiency of the p0.1-i0.1 cell is significantly enhanced by 4.14 times over the reference cell. The maximal conversion efficiency of p0.1-i0.1 achieves 3.22% with a V_{oc}, J_{sc}, and FF of 2.26 V, 1.59 mA/cm^2, and 89.8%, respectively. Results shown in Fig. 2(a)–(e) conclude that a p-InGaN layer can effectively mitigate the degradation of the conversion efficiencies due to polarization mismatch.

As we know, for an InGaN double heterojunction solar cell, three fields are applied in the system. One is a field due to the p-n-diode junction built-in potential, another is the polarization-induced field caused by fixed sheet charges at the heterointerface, and the final one is due to an applied voltage, which are denoted as the built-in field, polarization field, and applied field, respectively. Following the previous discussion, the increased indium content of the p-InGaN layer lowers the polarization charges at the p-i heterojunction interface, reducing the polarization field in the intrinsic layer and maintaining a depletion region for charge separation.

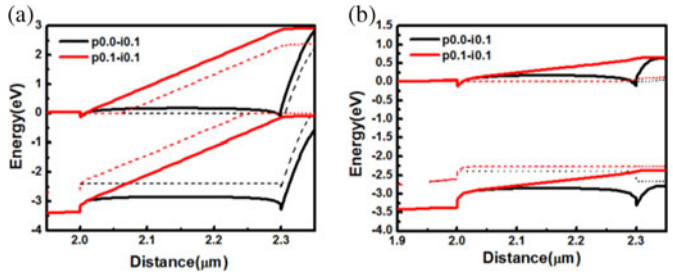

Fig. 3. Energy band diagrams of p0.0-i0.1 and p0.1-i0.1 structures under 1-sun solar radiation at near (a) short-circuit-current and (b) open-circuit-voltage conditions. The colored solid lines represent the positions of conduction and valence bands, and dashed lines denote the quasi-Fermi levels.

At the optimized conversion efficiency, the p-$In_{0.1}Ga_{0.9}N$ layer is polarization-matched to the i-$In_{0.1}Ga_{0.9}N$ layer when the polarization charges at the p-i interface are zero. To elaborate on the efficiency restrained by the polarization effect, Fig. 3 shows a comparison of the energy band diagrams of the p0-i0.1 and p0.1-i0.1 structures under 1-sun solar irradiance at near (a) short-circuit-current and (b) open-circuit-voltage conditions. As shown in Fig. 3(a), a large band bending in the p-GaN region caused by the fixed net polarization charges leads to a large dead layer in the intrinsic region. Moreover, the valence band discontinuity across the p-i heterojunction interface (at 2.3-μm distance) also gives rise to a small barrier for hole transport in the valence band. Both factors are responsible for the small photocurrent output. On the other hand, the p-$In_{0.1}Ga_{0.9}N$ is polarization-matched to the intrinsic layer, which ameliorates the distribution of the built-in field across the intrinsic region, and improves the photogenerated carrier separation and collection. Fig. 3(b) shows the activation energy under illumination and forward bias conditions, where the cell with p-$In_{0.1}Ga_{0.9}N$ obtains a lower V_{oc} than that with p-GaN. Since the V_{oc} is depicted by the separation of quasi-Fermi levels, it is therefore slightly limited by the difference in bandgaps between the n-GaN and p-$In_{0.1}Ga_{0.9}N$ layers. However, the increase in photocurrent output is sufficient to overcome the degradation of V_{oc} in order to observe a clear improvement in the power conversion efficiency.

Next, we calculate the efficiency map of ternary p-$In_xGa_{1-x}N$/i-$In_yGa_{1-y}N$/n-GaN solar cells with various indium compositions for both p-type and intrinsic layers. The projected efficiencies are plotted in Fig. 4 for $x = 0.00$–0.25, and $y = 0.10$–0.25. It is observed that the efficiencies of solar cells with a p-GaN layer are quite low due to the largely accumulated polarization charges at the p-i heterojunction interface. The electrons are generated near the p-i interface close to the surface, while holes easily accumulate at the p-i interface as a result of band discontinuity. Therefore, the situation leads to a very large recombination rate in the active region that lowers the carrier collection. By using the polarization match concept, the heterojunction solar cells with a p-$In_xGa_{1-x}N$ layer could considerably improve the power conversion efficiency. This is because the reduced interface polarization charges suppressed the band bending, which improved the distribution of the built-in field, as well as the hole transport. Therefore, when the indium

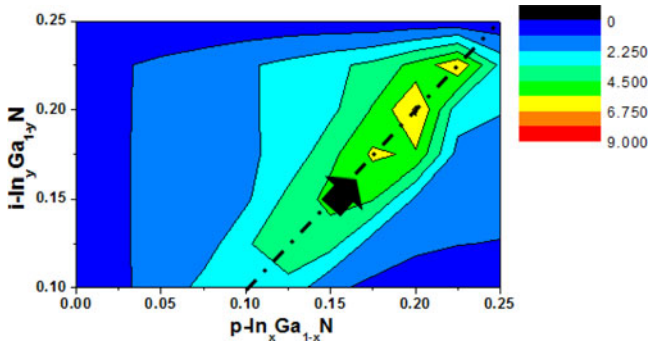

Fig. 4. Power conversion efficiency map of InGaN heterojunction solar cells consisting of p-$In_xGa_{1-x}N$ and i-$In_yGa_{1-y}N$ with various indium compositions. The dot-dashed line and arrow represent the polarization-matched combinations.

composition of the p-layer is higher than that of the intrinsic layer, polarization mismatch would also reduce the efficiency.

The polarization-matched structures are marked along the dashed line, as indicated in Fig. 4. The corresponding J–V curves on the dashed line are shown in Fig. 5(a), where the indium compositions of both p-type and intrinsic layers are the same. It appears that the efficiencies are enhanced with increasing indium content. Maximal power conversion efficiency occurs with approximately 20% indium composition. A peak efficiency of 6.93% is achieved with the p0.2-i0.2 structures, where $J_{\rm sc}$ is 4.05 mA/cm^2, and $V_{\rm oc}$ is 1.94 V. This indicates that the reduced polarization interface charges can boost the characteristics of InGaN solar cells. However, the efficiency of the p0.25-i0.25 cell structure is lower than that of p0.2-i0.2, which is not so intuitive. The energy band diagrams of p0.2-i0.2 and p0.25-i0.25 cells under illumination and without external bias are plotted in Fig. 5(b). Compared with the p0.2-i0.2 cell, which is shown in Fig. 5(c), the p0.25-i0.25 cell has a larger fixed negative polarization charge and larger band offset at the i-$In_{0.25}Ga_{0.75}N$/n-GaN interface. This results in a larger potential drop in the n-GaN layer instead of the intrinsic layer, which increases the recombination at the intrinsic layer. Therefore, as shown in Fig. 5(d), the electron and hole current output from the p and i layers are limited. From this viewpoint, increasing n-type doping can redistribute the built-in field for further efficiency enhancement [5]. These results suggest that p-type and intrinsic InGaN layers with an optimized indium composition of approximately 20% are desirable for monolithic growth on a GaN template.

Finally, we investigate the dependence of the device characteristics on the ratio of piezoelectric polarization at the GaN/InGaN interface by introducing a parameter "degree of relaxation" for the cap $In_xGa_{1-x}N$ layer, which is denoted by "$R_{\rm relax}$." By definition, $R_{\rm relax}$ equal to unity means 100% strain relaxation, corresponding to the case of no piezoelectric charges at the p-i interface. As the value of $R_{\rm relax}$ reduces, the piezoelectric polarization increases proportionally, while the spontaneous polarization remains unchanged. Therefore, Fig. 4 represents the case where $R_{\rm relax} = 0.0$. We further calculate the projected efficiency map for $R_{\rm relax} = 0.5$ and $R_{\rm relax} = 1.0$, as plotted in Fig. 6(a) and (b), respectively. It can be seen that maximal efficiencies for $R_{\rm relax} = 0.5$ and $R_{\rm relax} = 1.0$ of 9.10% and 9.12%, respectively, occurred in the p0.25-i0.25 structure. As the polarization charges at the p-i interface are reduced, we can expect a much-improved efficiency. However, we note that strain relaxation is often associated with the severe degradation of material quality. Therefore, the maximal efficiency with 100% strain relaxation is probably much worse than that without strain relaxation.

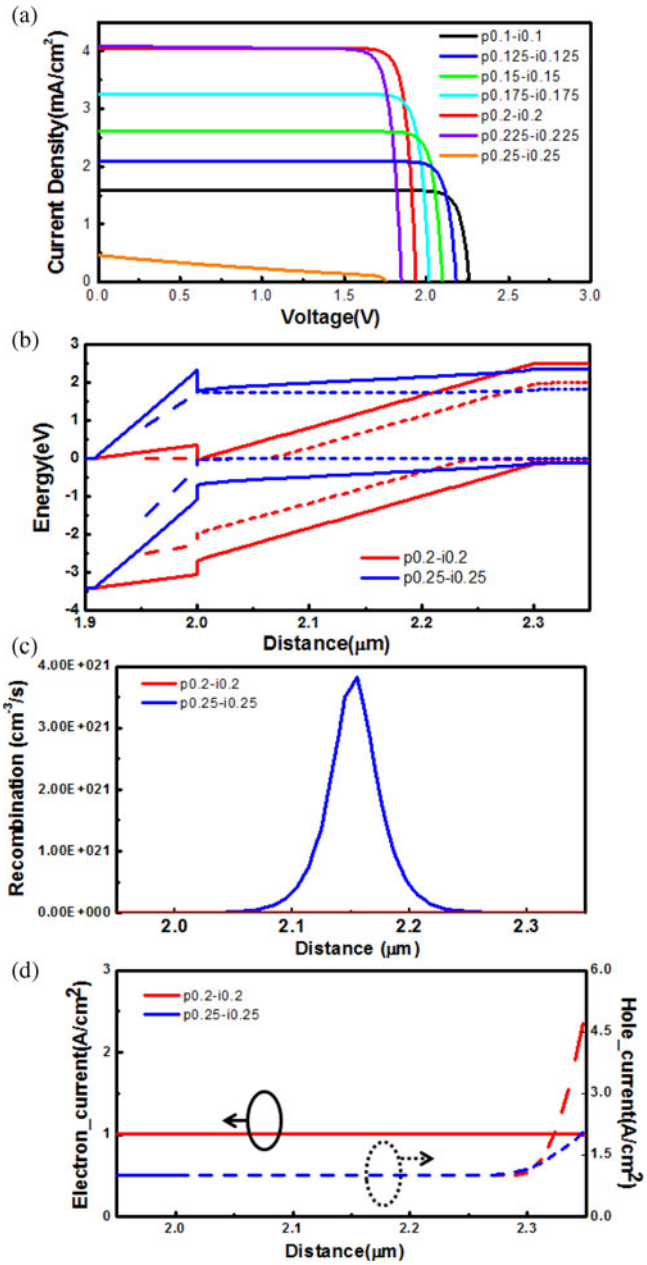

Fig. 5. (a) Current density–voltage characteristics of p-i polarization-matched InGaN heterojunction solar cells with various indium compositions. (b) Energy band diagrams. Colored solid lines represent the conduction and valence band, and dashed lines represent the quasi-Fermi levels. (c) Total recombination rates and (d) the electron and hole current density distribution of the p0.2-i0.2 and p0.25-i0.25 cell structures under illumination and without an external bias.

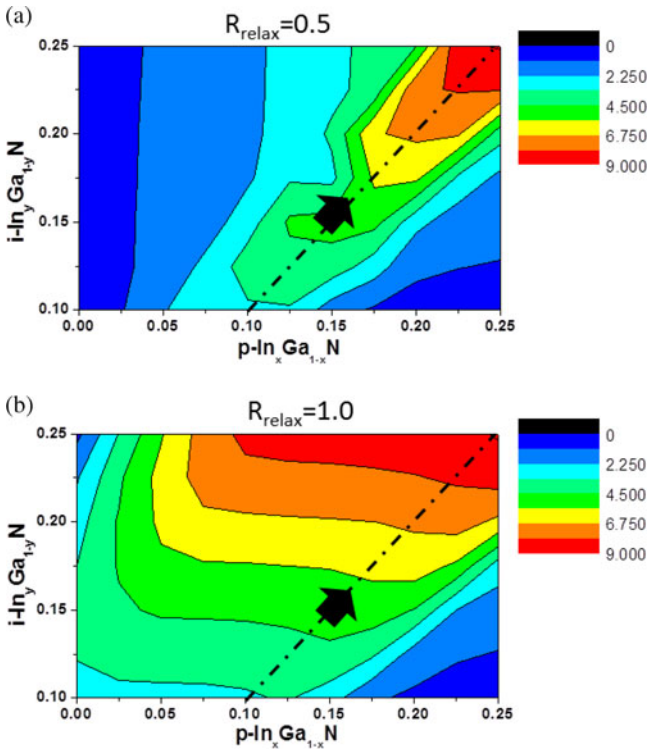

Fig. 6. Power conversion efficiency map of InGaN heterojunction solar cells consisting of p-$In_x Ga_{1-x}N$ and i-$In_y Ga_{1-y}N$ with various indium compositions for (a) $R_{\mathrm{relax}} = 0.5$ and (b) $R_{\mathrm{relax}} = 1.0$. The dot-dashed line and arrow represent the polarization-matched combinations.

IV. Conclusion

In summary, we have investigated the projected efficiencies of p-$In_x Ga_{1-x}N$/i-$In_y Ga_{1-y}N$/n-GaN double heterojunction solar cells with various indium compositions for monolithic growth on a c-facet sapphire substrate. The proposed p-type InGaN layer reduces the polarization charges at the p-i heterojunction interface, leading to a redistribution of the built-in potential and facilitating charge transport. We observe that an In content of 20% for a polarization-matched p-i interface is optimal and leads to a maximum power conversion efficiency that is close to 7% under the assumption of no strain relaxation. Further efficiency enhancement with a higher indium composition over 20% is also possible via the redistribution of the built-in field with n-GaN doping.

References

[1] J. Wu, W. Walukiewich, K. M. Yu, W. Shan, J. W. Ager, E. E. Haller, H. Lu, W. J. Schaff, W. K. Metzger, and S. Kurtz, "Superior radiation resistance of $In_{1-x}Ga_xN$ alloys: Full-solar-spectrum photovoltaic material system," *J. Appl. Phys.*, vol. 94, pp. 6477–6482, 2003.

[2] J. Wu, W. Walukiewicz, K. M. Yu, J. W. Ager, E. E. Haller, H. Lu, and W. J. Schaff, "Small bandgap bowing in $In_{1-x}Ga_xN$ alloys," *Appl. Phys. Lett.*, vol. 80, pp. 4741–4743, 2002.

[3] J. F. Muth, J. H. Lee, I. K. Shmagin, R. M. Kolbas, H. C. Caser, B. P. Keller, U. K. Mishra, and S. P. DenBaars, "Absorption coefficient, energy gap, exciton binding energy, and recombination lifetime of GaN obtained from transmission measurements," *Appl. Phys. Lett.*, vol. 71, pp. 2572–2574, 1997.

[4] X. Chen, K. D. Matthews, D. Hao, W. J. Schaff, and L. F. Eastman, "Growth, fabrication, and characterization of InGaN solar cells," *Phys. Status Solidi (a)*, vol. 205, pp. 1103–1105, 2008.

[5] S. W. Zeng, B. P. Zhang, J. W. Sun, J. F. Cai, C. Chen, and J. Z. Yu, "Substantial photo-response of InGaN p-i-n homojunction solar cells," *Semicond. Sci. Technol.*, vol. 24, pp. 055009-1–055009-4, 2009.

[6] J. Shim, S. Jeon, Y. Jeong, and D. Lee, "Improved efficiency by using transparent contact layers in InGaN-based p-i-n solar cells," *IEEE Electron Device Lett.*, vol. 31, no. 10, pp. 1140–1142, Oct. 2010.

[7] O. Jani, I. Ferguson, C. Honsberg, and S. Kurtz, "Design and characterization of GaN/InGaN solar cells," *Appl. Phys. Lett.*, vol. 91, pp. 132117-1–132117-3, 2007.

[8] C. J. Neufeld, N. G. Toledo, S. C. Cruz, M. Iza, S. P. DenBaars, and U. K. Mishra, "High quantum efficiency InGaN/GaN solar cells with 2.95 eV band gap," *Appl. Phys. Lett.*, vol. 93, pp. 143502-1–143502-3, 2008.

[9] E. Matioli, C. Neufeld, M. Iza, S. C. Cruz, A. A. Al-Heji, X. Chen, R. M. Farrell, S. Keller, S. DenBaars, U. Mishra, S. Nakamura, J. Speck, and C. Weisbuch, "High internal and external quantum efficiency InGaN/GaN solar cells," *Appl. Phys. Lett.*, vol. 98, pp. 021102-1–021102-3, 2011.

[10] K. Y. Lai, G. J. Lin, Y.-L. Lai, Y. F. Chen, and J. H. He, "Effect of indium fluctuation on the photovoltaic characteristics of InGaN/GaN multiple quantum well solar cells," *Appl. Phys. Lett*, vol. 96, pp. 081103-1–081103-3, 2010.

[11] Q. Dai, M. F. Schubert, M. H. Kim, J. K. Kim, E. F. Schubert, D. D. Koleske, M. H. Crawford, S. R. Lee, A. J. Fischer, G. Thaler, and M. A. Banas, "Internal quantum efficiency and nonradiative recombination coefficient of GaInN/GaN multiple quantum wells with different dislocation densities," *Appl. Phys. Lett*, vol. 94, pp. 111109-1–111109-3, 2009.

[12] D. Holec, P. M. F. J. Costa, M. J. Kappers, and C. J. Humphreys, "Critical thickness calculations for InGaN/GaN," *J. Cryst. Growth*, vol. 303, no. 1, pp. 314–317, May 2007.

[13] W. Zhao, L. Wang, J. Wang, Z. Hao, and Y. Luo, "Theoretical study on critical thicknesses of InGaN grown on (0 0 0 1) GaN," *J. Cryst. Growth*, vol. 327, pp. 202–204, 2011.

[14] V. Fiorentini, F. Bernardini, and O. Ambacher, "Evidence for nonlinear macroscopic polarization in III–V nitride alloy heterostructures," *Appl. Phys. Lett.*, vol. 80, pp. 1204–1206, 2002.

[15] A. E. Romanov, T. J. Baker, S. Nakamura, and J. S. Speck, "Strain-induced polarization in wurtzite III-nitride semipolar layers," *J. Appl. Phys.*, vol. 100, pp. 023522-1–023522-10, 2006.

[16] C. J. Neufeld, S. C. Cruz, R. M. Farrell, M. Iza, J. R. Lang, S. Keller, S. Nakamura, S. P. DenBaars, J. S. Speck, and U. K. Mishra, "Effect of doping and polarization on carrier collection in InGaN quantum well solar cells," *Appl. Phys. Lett.*, vol. 98, pp. 243507-1–243507-3, 2011.

[17] F. Della Sala, F. Bernardini, V. Fiorentini, R. Scholz, J. M. Jancu, A. di Carlo, and P. Lugli, "Free-carrier screening of polarization fields in wurtzite GaN/InGaN laser structures," *Appl. Phys. Lett.*, vol. 74, pp. 2002–2004, 1999.

[18] O. Ambacher, J. Majewski, C. Miskys, A. Link, M. Hermann, M. Eickhoff, M. Stutzmann, F. Bernardini, V. Fiorentini, V. Tilak, B. Schaff, and L. F. Eastman, "Pyroelectric properties of Al(In)GaN/GaN hetero- and quantum well structures," *J. Phys. Condens. Matter*, vol. 14, pp. 3399–3434, 2002.

[19] Y. K. Kuo, J. Y. Chang, and Y. H. Shih, "Numerical study of the effects of hetero-interfaces, polarization charges, and step-graded interlayers on the photovoltaic properties of (0001) face GaN/InGaN p-i-n solar cell," *IEEE J. Quantum Electron.*, vol. 48, no. 3, pp. 367–374, Mar. 2012.

[20] J. Y. Chang and Y. K. Kuo, "Simulation of N-face InGaN-based p-i-n solar cells," *J. Appl. Phys.*, vol. 112, pp. 033109-1–033109-5, 2012.

[21] Z. Q. Li, M. Lestradet, Y. G. Xiao, and S. Li, "Effects of polarization charge on the photovoltaic properties of InGaN solar cells," *Phys. Status Solidi (a)*, vol. 208, pp. 928–931, 2011.

[22] G. F. Brown, J. W. AgerIII, W. Walukiewicz, and J. Wu, "Finite element simulations of compositionally graded InGaN solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 94, pp. 478–483, 2010.

[23] A. T. M. G. Sarwar and R. C. Myers, "Exploiting piezoelectric charge for high performance graded InGaN nanowire solar cells," *Appl. Phys. Lett.*, vol. 101, pp. 143905-1–143905-5, 2012.

[24] M. H. Wong, F. Wu, J. S. Speck, and U. K. Mishra, "Polarity inversion of N-face GaN using an aluminum oxide interlayer," *J. Appl. Phys.*, vol. 108, pp. 123710-1–123710-6, 2010.

[25] J. J. Wierer, Jr., D. D. Koleske, and S. R. Lee, "Influence of barrier thickness on the performance of InGaN/GaN multiple quantum well solar cells," *Appl. Phys. Lett.*, vol. 100, pp. 111119-1–111119-5, 2012.
[26] APSYS, Crosslight Software Inc., Vancouver, BC, Canada. (2010). [Online]. Available: http://www.crosslight.com
[27] D. Zhu, A. N. Noemaun, M. F. Schubert, J. Cho, E. F. Schubert, M. H. Crawford, and D. D. Koleske, "Enhanced electron capture and symmetrized carrier distribution in GaInN light-emitting diodes having tailored barrier doping," *Appl. Phys. Lett.*, vol. 96, pp. 121110-1–121110-3, 2010.
[28] K. Kumakura, T. Makimoto, N. Kobayashi, T. Hashizume, T. Fukui, and H. Hasegawa, "Minority carrier diffusion lengths in MOVPE-grown n- and p-InGaN and performance of AlGaN/InGaN/GaN double heterojunction bipolar transistors," *J. Cryst. Growth*, vol. 298, pp. 787–790, 2007.
[29] C. H. Wang, C. C. Ke, C. Y. Lee, S. P. Chang, W. T. Chang, J. C. Li, Z.Y. Li, H. C. Yang, H. C. Kuo, T. C. Lu, and S. C. Wang, "Hole injection and efficiency droop improvement in InGaN/GaN light-emitting diodes by band-engineered electron blocking layer," *Appl. Phys. Lett*, vol. 97, no. 26, pp. 261103-1–261103-3, 2010.

Hsun-Wen Wang was born in Taipei, Taiwan. She received the B.S degree from Soochow University, Taipei, in 2001 and the M.S. degree in physics in 2009 from National Chung Cheng University, Hsinchu, Taiwan, where she is currently working toward the Doctor of Electrophysics degree. Her Ph.D. research includes simulation and measurement for high-efficiency solar cells.

Her focus is on high-efficiency si and III-V solar cells. She used APSYS simulation tools to simulate the performance of solar cells. She is the coauthor of four articles published in refereed technical journals and seven papers presented at specialized conferences.

Peichen Yu received the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2004.

From 2004 to 2006, she was a Design Engineer for the Advanced Design Group, Intel Corporation, Hillsboro, OR, USA. From 2006 to 2009, she was an Assistant Professor with the Department of Photonics and the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan, where she was promoted to Associate Professor in August 2009. Her research interests include the design and development of nanostructured solar cells, light emitting diodes, and silicon-based nano-devices. She is also actively engaged in the development of OPC and DFM solutions for CMOS 32-nm microlithography and beyond. She has published over 40 refereed technical papers in the above research areas. Her work has been published in the *Virtual Journal of Nanoscale Science & Technology* and highlighted by *SPIE Newsroom, NPG Nature Asia-Material*, etc.

Dr. Yu is a member of the IEEE Photonics Society and SPIE.

Yuh-Renn Wu (S'02–M'07) received the B.S. degree in physics and the M.S. degree in electrical engineering from the National Taiwan University, Taipei, Taiwan, in 1998 and 2000, respectively, and the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 2006.

He is currently an Associate Professor with the Institute of Photonics and Optoelectronics and the Department of Electrical Engineering, National Taiwan University. His area of research is in physics, the design of optoelectronic devices, and high-power electronics. His current research interests include the studies of nitride-based quantum wells, quantum wires, and quantum dot light-emitting diodes, high-power and high-speed electronics, ferroelectrics, and optoelectronic devices.

Hao-Chung Kuo (S'98–M'99–SM'06) received the B.S. degree in physics from National Taiwan University, Taipei, Taiwan, the M.S. degree in electrical and computer engineering from Rutgers University, New Brunswick, NJ, USA, in 1995, and the Ph.D. degree from the Electrical and Computer Engineering Department, University of Illinois at Urbana-Champaign, Urbana, IL, USA, in 1999.

He has an extensive professional career both with research and industrial research institutions that includes being a Research Assistant with Lucent Technologies, Bell Laboratories (1993–1995) and as a Senior R&D Engineer with the Fiber-Optics Division at Agilent Technologies (1999–2001) and LuxNet Corporation (2001–2002). Since October 2002, he has been with the National Chiao-Tung University (NCTU), Hsinchu, Taiwan, as a Faculty Member of the Institute of Electro-Optical Engineering. He is now with the Office of International Affairs, NCTU, as an Associate Dean. His current research interests include semiconductor lasers, VCSELs, blue and ultraviolet light-emitting diode lasers, quantum-confined optoelectronic structures, optoelectronic materials, and solar cells. He has authored and coauthored 300 internal journal papers, two invited book chapters, and six granted and 12 pending patents.

Prof. Kuo was an Associate Editor of the IEEE/OSA JOURNAL OF LIGHTWAVE TECHNOLOGY and the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS Special Issue on Solid-State Lighting (2009). He received the Ta-You Wu Young Scholar Award from the National Science Council Taiwan in 2007 and the Young Photonics researcher award from OSA/SPIE Taipei chapter in 2007. He was elected as an OSA Fellow in 2012.

Edward Yi Chang was with Unisys Corporation GaAs Component Group, Eagan, MN, USA, from 1985 to 1988 and with Comsat Labs Microelectronic Group from 1988 to 1992. He worked on the GaAs MMIC programs with both groups. He joined National Chiao-Tung University (NCTU), Hsinchu, Taiwan, in 1992. In 1994, he helped set up the first GaAs MMIC production line in Taiwan and become president of Hexawave Inc., Hsinchu, in 1995. He returned to teaching with NCTU in 1999, where he is currently the Head and Professor of the Department of Materials Science. His research interests include new devices and process technologies for Compound Semiconductor RFICs for wireless communication. He is a senior member and a Distinguished Lecturer of the IEEE Electronic Device Society.

Shiuan Huei Lin received the B.Sc. degree in electrophysics in 1990 and the M.S. and Ph.D. degrees in electro-optical engineering in 1992 and 1996, respectively, all from the National Chiao-Tung University, Hsinchu, Taiwan.

He is currently an Associate Professor with the Department of Electrophysics, National Chiao-Tung University. His research interests are in holographic storage, optical computing, optical devices, holographic materials, and holography for optical information processing.