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Enhanced conversion efficiency in wide-bandgap GaNP solar cells

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In this work, we demonstrate $\sim 2.05 \text{ eV}$ dilute nitride GaNP solar cells on GaP substrates for potential use as the top junction in dual-junction integrated cells on Si. By adding a small amount of N into indirect-bandgap GaP, GaNP has several extremely important attributes: a direct-bandgap that is also tunable, and easily attained lattice-match with Si. Our best GaNP solar cell ([N] $\sim 1.8\%$, $E_g \sim 2.05 \text{ eV}$) achieves an efficiency of 7.9%, even in the absence of a window layer. This GaNP solar cell's efficiency is $3 \times$ higher than the most efficient GaP solar cell to date and higher than other solar cells with similar direct bandgap (InGaP, GaAsP). Through a systematic study of the structural, electrical, and optical properties of the device, efficient broadband optical absorption and enhanced solar cell performance are demonstrated. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4933317]

Integration of III-V semiconductors and Si is a very attractive means to achieve low-cost high-efficiency solar cells. A promising configuration is to utilize a dual-junction solar cell, in which Si is employed as the bottom junction and a wide-bandgap III-V semiconductor as the top junction.^{1–3} The use of a III-V semiconductor as a top junction offers the potential to achieve higher efficiencies than today's best Si solar cell. By using this approach, dual-junction solar cells can potentially achieve a theoretical efficiency of 45% under AM 1.5G.¹

GaP is one of the major candidates for the top junction in dual-junction solar cells due to its small lattice mismatch with Si (0.37% at 300 K). Recent work on integration of GaP with Si has demonstrated that the nucleation-related defects (anti-phase domains, stacking faults, microtwins, and dislocations) can be entirely suppressed.^{4,5} However, GaP has an indirect-bandgap and, consequently, a low absorption coefficient. This disadvantage limits the efficiency of GaP to only a few percent, even in optimized designs.^{6–8} To remedy this situation, a small amount of N can be added to GaP, and this results in dilute nitride GaNP. A direct bandgap semiconductor, like GaNP or GaAs, exhibits an absorption coefficient of about 10^4 cm⁻¹ above the band edge. This is in contrast to indirect-bandgap GaP, which exhibits an absorption coefficient of between 10^2 and 10^3 cm⁻¹ above the band edge.^{9–11}

First, we addressed the problem of low optical absorption in GaP. By introducing a sufficient [N] into GaP, the resulting GaNP exhibits a direct-bandgap.^{12–17} As [N] increases, the energy of the Γ -band decreases faster than the energy of the X-band. At [N] of only ~0.4%, the energy of the Γ -band is lower than the energy at the X-band. Thus,

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GaNP becomes a direct-bandgap semiconductor at a [N] of ~0.4%.^{18,19} Significantly, a small change in the [N] allows the bandgap of GaNP to be tuned to optimize the dualjunction solar cell efficiency.²⁰ Second, this low [N] allows GaNP to be nearly lattice-matched to Si (lattice-matched to Si at [N] ~2%). This enables GaNP to be grown directly on the Si substrate without the need for a metamorphic buffer layer.^{21,22} Consequently, we can reduce the device complexity as well as the number of crystal defects associated with the nearly lattice-matched growth. This makes GaNP an ideal III/V candidate for the top-junction on Si substrates for low-cost solar cell applications.^{4,23,24}

As a first step toward the integration of GaNP on Si, we optimize and demonstrate ~2.05 eV GaNP solar cells on GaP (001) substrate. This GaNP layer is almost latticematched with Si. GaP was chosen as the substrate because its lattice constant is closer to the lattice constant of Si than any other III-V semiconductor. To explore the range of GaNP solar cell performance, we conducted a systematic study to correlate the GaNP material quality with their device figures of merit. Figure 1 shows a cross-section of our solar cell structures. The p-i-n GaP solar cell was used as the control sample. To compare GaP and GaNP, the second sample is identical to the control sample except that i-GaP was replaced with i-GaNP. For further improvement, the i-GaNP thickness of a third sample was increased to allow more efficient optical absorption. Henceforth, these three samples will be referred to as $\langle material \rangle - \langle i-layer \ thickness \rangle$: GaP-800, GaNP-800, and GaNP-2000, respectively.

Regarding our solar cell structures, highly doped p-type $(6.5 \times 10^{17} \text{ cm}^{-3})$ GaP (001) was chosen as the substrate to minimize series resistance to the back contact. The next layer, i-Ga(N)P, serves to enhance carrier collection by extending the built-in electric field across the absorbing undoped region. This intrinsic layer also aids the short

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FIG. 1. Cross-section of the solar cells presented in this work. Inset shows the measured x-ray diffraction (XRD) spectra. The XRD spectra of the GaNP samples confirm proper incorporation of N.

diffusion length of dilute nitride material.^{24–26} The following n-type layer was divided into two sub-layers: first, a standard 100 nm thick n-GaP sub-layer doped with Si at 4×10^{18} cm⁻³ to act as the emitter,^{27,28} followed by a 15-nm-thick highly doped (8×10^{18} cm⁻³) n⁺-GaP sub-layer, to reduce series resistances from the inner portions of the cell to the metal contacts and to create a thin tunneling barrier for ohmic-like contacts. The n+-GaP sub-layer was also kept very thin to minimize carrier loss by recombination due to its very short hole minority carrier diffusion length, which is below 190 nm.⁷ No window layer was used for any of the samples discussed in this work.

All samples reported in this work were grown on p-GaP (001) substrates in a Varian Gen-II molecular beam epitaxy (MBE) system modified to handle gas sources. Thermally cracked PH₃ at 1000 °C and radio frequency (RF) N plasma excited at 13.56 MHz were used for P and N sources, respectively. Solid elemental Ga was used to generate a Ga beam from an effusion cell. Solid Si was used as the n-type dopant. Prior to growth, native oxide was desorbed under P2 overpressure at 600 °C. The substrate temperature was then decreased to 570 °C to grow the i-Ga(N)P layer followed by the n-GaP layer. A substrate temperature of 570 °C was chosen because this is in the optimal growth temperature range to minimize N-related defects before phase separation in dilute nitride.²⁰ During growth, reflection high energy electron diffraction (RHEED) measurements of the samples in situ showed a streaky 2×4 reconstruction, indicative of a smooth surface. All layers were grown at $1 \,\mu$ m/h with V/III incorporation ratio ~ 2.5 , calibrated by Ga-induced RHEED intensity oscillation. The substrate was rotated at 5 RPM during growth to ensure uniformity.

Dilute nitride material often contains a significant number of defects, especially anti-site defects, due to the combination of N incorporation, relatively low growth temperature, and ion damage from RF N plasma.²⁹ This can be significantly suppressed by post-growth rapid thermal annealing (RTA).^{30–32} In our work, all GaNP samples were treated by RTA at 750 °C for 30 s in 95% N₂ and 5% H₂ forming gas ambient. This RTA condition was experimentally determined as the optimal condition providing the highest photoluminescence intensity—a higher intensity indicating lower non-radiative defects. Samples were then fabricated into 1 mm × 1 mm solar cells using photo-lithography and reactive ion etching (RIE). The Pd/Si front contact and the Zn/Au back contact were created using e-beam evaporation and thermal evaporation, respectively. This was followed by proper annealing processes to create good ohmic contacts.

X-ray diffraction (XRD) was performed to determine the [N]. An XRD $2\theta/\omega$ line scan on the (004) plane is shown in Figure 1(b) inset. The signals from GaP and GaNP, marked in the figure, are clearly seen in the right side of Figure 1(b) representing the dilute nitride composition. According to XRD measurements, our GaNP samples have a [N] of ~1.8%.

GaNP with [N] = 1.8% has a lattice mismatch f = 0.31%with GaP. Using the energy balance model for misfit strain relaxation,³³ and assuming 60° mixed dislocations typical for zincblende materials, we estimate a GaNP critical thickness of ~ 40 nm. This is well below the $\sim 1 \,\mu m$ optical absorption length in GaNP⁹ and below the thicknesses used in our cells. Therefore, full relaxation of misfit strain is expected in our structures. To characterize the structural integrity of the GaNP/GaP structures, we conducted detailed transmission electron microscopy (TEM) characterization on all three sample structures as shown in Figure 2. For the GaP-800 structure, an epitaxial defect free interface was obtained, as expected (Figure 2(a)). All GaNP/GaP samples exhibited epitaxial, yet defective interfaces with misfit defects that were often found to have edge dislocation components in the cross-sectional cut plane. Figure 2(b) shows the GaNP-2000 structure with clearly visible defect contrast at the GaP/GaNP interface. Aside from the interface, the GaNP layer is a single crystalline layer, as obtained by extensive selective area diffraction (SAD) characterization



FIG. 2. Transmission Electron Microscopy (TEM) images along the [001] zone axis with a g = [020] beam condition showing (a) defect free GaP-800 and (b) GaNP-2000 with misfit defects at the GaP/GaNP interface. (c) High resolution TEM (HRTEM) showing the crystalline i-GaNP layer in the region enclosed by the red square in (b). (d) and (e) Merged relatively high magnification TEM images at the GaP/GaNP interfaces showing the defect density of GaNP-800 and GaNP-2000, respectively.

and imaging in the $\langle 110 \rangle$ beam axis. Figure 2(c) shows a representative high resolution TEM (HRTEM) image at the center of the GaNP layer (area enclosed with a small red square in Figure 2(b)). Notably, we do not observe threading dislocations in the GaNP layers which is the key for the enhanced power conversion efficiencies in our cells. The contrast of misfit dislocations at the GaNP/GaP interface was observed for multiple g-vector orientations in TEM.

J-V characterization was performed under dark and AM 1.5G conditions. Figure 3 shows the J-V characteristics of GaP-800, GaNP-800, and GaNP-2000, respectively, and Table I lists key performance metrics extracted from the aforementioned graphs. We used the slope of the semi-log dark J-V curve to calculate the ideality factor (n-factor), of the devices. Despite series resistance effects that led to



FIG. 3. J-V characteristics of GaP-800, GaNP-800, and GaNP-2000 under AM 1.5G condition with and without AR coating.

nonlinear slope of the J-V characteristics, we estimate nfactor = 1.8 for GaP-800 and n-factor ≥ 2 for the GaNP cells. The n-factor of GaP-800 is similar to prior reported n-factor for GaP cells.³⁴ The higher n-factor of GaNP indicates that GaNP samples suffer higher Shockley-Read-Hall recombination in the depletion region when compared to GaP-800. This likely results from the GaP/GaNP defective interface.

By examining the GaP-800 and GaNP-800 samples in Figure 3 and Table I, the GaNP-800 sample exhibits a slightly lower fill factor (FF) as expected. This is due to its higher n-factor value. The lower FF in the GaNP-800 sample is more than compensated by a significant increase in J_{sc} and a slight increase in Voc. This results in a net efficiency of approximately twice that of GaP-800. However, because the bandgap of GaP-800 and GaNP-800 are not the same, a portion of the GaNP-800 J_{sc} can be attributed to its lower bandgap. To more accurately compare GaP-800 to GaNP-800, we define the J_{sc}-ratio,²¹ listed in Table I, as the measured J_{sc} over the maximum possible J_{sc} calculated by assuming external quantum efficiency (EQE) equal to 1 for all energies above the bandgap. By using this method, the J_{sc} -ratio of GaNP-800 is ~1.4× higher in comparison to the J_{sc}-ratio of GaP-800. This clearly indicates that adding N has a large impact on improving J_{sc} and, ultimately, solar efficiency. Consequently, we conclude that the interface defects seen in TEM observations do not have a significant adverse effect on the solar cell efficiency of the GaNP-800 sample.

We now investigate the effect of intrinsic layer thickness on solar cell performance. Examining GaNP-800 and GaNP-2000, J_{sc} increases with thickness, as expected, due to the larger light absorption length of the thicker samples and results in slightly elevated V_{oc} . With the J_{sc} and V_{oc} observations combined, the overall solar efficiency of GaNP increases as thickness increases. Furthermore, our work shows that efficiency is not yet limited by minority carrier diffusion length. Thus, this trend may continue beyond the maximum thickness, 2000 nm in GaNP-2000, studied in this work.

In addition to studying the impact of intrinsic layer thickness on solar efficiency, we also investigate the impact of surface reflection reduction on solar performance. To do so, we added a Si_3N_4/SiO_2 double-layer anti-reflection (AR) coating on the surface of each device.⁷ The AR layers were deposited by plasma-enhanced chemical vapor deposition (PECVD) with a thickness of 50 nm and 20 nm, respectively. The thicknesses of the layers were calculated to have a low reflectance, <5%, across wavelengths in the range of 400 nm-600 nm. Figure 3 shows the J-V characteristics of each device with and without an AR coating. The AR coatings enhance J_{sc} but have very little effect on V_{oc}. Accordingly, AR coatings increase overall solar efficiency for all devices studied. Combining all techniques mentioned thus far, our best solar cell, GaNP-2000, produces an efficiency of 7.9%.

To closely probe each material's solar cell performance, EQE measurements were performed. Figure 4 shows the measured 300 nm-700 nm EQE spectra for GaP-800, GaNP-800, and GaNP-2000. In Figure 4(a), the absorption edges of GaP-800 and GaNP-800 are \sim 540 nm and \sim 615 nm, respectively. This agrees with the GaP bandgap (2.26 eV) and

	Sample	J _{sc} (mA/cm ²)	$V_{oc}\left(V ight)$	J _{sc} -ratio (%)	FF (%)	η (%)	n-factor
Without AR	GaP-800	2.69	1.19	30	77	2.5	1.8
	GaNP-800	5.52	1.26	42	73	5.1	2.7
	GaNP-2000	7.80	1.31	60	71	7.3	2.0
With AR	GaP-800	3.17	1.19	35	76	2.9	
	GaNP-800	6.08	1.26	46	71	5.5	
	GaNP-2000	8.53	1.33	65	69	7.9	

TABLE I. Performance parameters of GaP-800, GaNP-800, and GaNP-2000 with and without AR coating.

GaNP bandgap (2.05 eV). Of particular note, GaNP-800 exhibits two EQE peaks. The short wavelength peak in the range of \sim 350 nm to \sim 450 nm is comparable to the peak of GaP-800 in the same region. We suggest that this characteristic is driven by the n- and p-type GaP layers of GaNP-800 cell structure. It follows, then, that the long wavelength peak in the range of \sim 450 nm to \sim 615 nm can be attributed to the GaNP layer and its lower bandgap. Additionally, the absorption edge of GaNP-800 increases more sharply than that of GaP-800 due to the direct bandgap of GaNP. This considerable advantage has a direct effect on solar efficiency within the wavelengths of interest. This is clearly reflected in the



FIG. 4. (a) EQE measurements with and without an AR coating of GaP-800 and GaNP-800. (b) EQE measurements with an AR coating of GaP-800, GaNP-800, GaNP-2000, and ME-GaP_{NW}.

improved J_{sc}-ratios listed in Table I. Finally, with respect to the effects of AR coatings on solar efficiency, while overall solar efficiency is increased as expected, we observed degradation of performance at shorter wavelengths. This is possibly due to the AR coating absorbing light in the shorter wavelengths, especially given that Si₃N₄ has a bandgap of $2.4-4.7 \text{ eV.}^{35}$

Examining the EQE of the GaNP devices (Figure 4(b)), we observe increased EQE at all wavelengths as the thickness is increased. With regard to our highest efficiency solar cell, GaNP-2000, its EQE is larger than 0.80 in the range of \sim 450 nm to \sim 560 nm and reaches its maximum value of 0.95 at 530 nm. This confirms that the photocurrent is not yet limited by the minority carrier diffusion length in the i-GaNP and p-GaP layers. In addition, high EQE at long wavelengths indicates little to no effect from rear surface recombination. With respect to front surface conditions, the EQE of all devices slowly decreases at short wavelength. This is indicative of poor surface conditions. This can be improved by (1) increasing the diffusion length in the emitter region (e.g., optimizing growth conditions), (2) optimizing the emitter thickness, and (3) reducing the front surface recombination velocity (e.g., passivating the front surface, implementing a window layer). Such improvements should be the focus of future work.

In addition to comparing our samples against one another, we also compare our results against the current most efficient GaP solar cell, which was reported to have a solar efficiency of 2.90% (Ref. 6) (ME-GaP_W) and 2.42% (Ref. 7) (ME-GaP_{NW}) with and without a window layer, respectively. Since none of our devices implemented a window layer, we performed comparisons against ME-GaP_{NW}. For GaP-800 and ME-GaP_{NW}, both absorption edges begin at \sim 550 nm due to their identical GaP material. The EQE of ME-GaP_{NW} then increases much faster than that of GaP-800 at the long wavelength range of \sim 460 to \sim 550 nm. This can be attributed to it being a much thicker device. However, utilization of a thinner emitter layer (shorter than the hole minority diffusion length) in GaP-800 results in significant gains in short wavelength EQE when compared to ME-GaP_{NW}. Comparing our most efficient sample, GaNP-2000, to ME-GaP_{NW}, GaNP-2000 exhibits considerably improved EQE performance across all wavelengths. To date, our GaNP solar cells exhibit higher efficiency than other wide bandgap solar cells grown on GaP substrate. InGaP²¹ (2.12 eV) and GaAsP³⁶ (1.92 eV) solar cells with active layer thicknesses of $\sim 2 \,\mu m$ achieve efficiencies of only 3.89% and 4.8%, respectively; the low efficiencies partly result from their lattice mismatch, which requires the growth of defective metamorphic buffer layers.

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In summary, these are some highlights of our materials and devices studies. First, the dilute nitride GaNP layers were grown by gas-source molecular beam epitaxy with [N] $\sim 1.8\%$ (2.05 eV), which is closely lattice-mated to Si. TEM shows epitaxial layers that have no observable defects under HRTEM in the volume of the GaNP layer above the interface. Most of the lattice-mismatch appears to stem from misfit dislocations in the plane of the GaNP/GaP interface. This is a significant observation because any threading dislocations in the volume of the GaNP layer would reduce the minority carrier lifetime. Second, the interface defects have some impact on n-factor and resulted in slightly lower FF, compared to GaP. Third, the reduction in FF was more than fully offset by the higher light absorption in the direct bandgap GaNP. This resulted in significantly increased solar efficiency as compared with pure GaP. Fourth, we conclude that we have not yet reached the optimal thickness of GaNP for solar cell applications. Thus, far in our studies, thicker GaNP layers exhibited significantly higher EQE across all wavelengths. It is likely that further increases in the layer thickness will provide additional gains in solar efficiency until the minority carrier diffusion length is exceeded. A more in-depth study of the effect of layer thickness on solar cell efficiency is required. Overall, we conclude that GaNP solar cells provide a significant increase in efficiency over their GaP counterparts. Experimentally, the best GaNP solar cell studied in this work delivers better efficiency (7.9%) than the most efficient indirect-bandgap GaP and directbandgap InGaP and GaAsP solar cells to date. These performance gains are expected to motivate further investigation into the integration of GaNP into future dual-junction solar cells on Si substrate.

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- ¹T. J. Grassman, J. A. Carlin, C. Ratcliff, D. J. Chmielewski, and S. A. Ringel, in *IEEE 39th Photovoltaic Specialists Conference (PVSC)* (2013), p. 0149.
- ²J. R. Lang, J. Faucher, S. Tomasulo, K. N. Yaung, and M. L. Lee, paper presented at the IEEE 39th Photovoltaic Specialists Conference (PVSC) (2013).
 ³J. R. Lang, J. Faucher, S. Tomasulo, K. N. Yaung, and M. L. Lee, Appl. Phys. Lett. **103**, 092102 (2013).
- ⁴T. J. Grassman, J. A. Carlin, B. Galiana, L. M. Yang, F. Yang, M. J. Mills, and S. A. Ringel, Appl. Phys. Lett. **102**, 142102 (2013).
- ⁵T. J. Grassman, M. R. Brenner, S. Rajagopalan, R. Unocic, R. Dehoff, M. Mills, H. Fraser, and S. A. Ringel, Appl. Phys. Lett. 94, 232106 (2009).

- ⁶L. Xuesong, H. Ruiying, M. Diaz, R. L. Opila, and A. Barnett, IEEE J. Electron Devices Soc. **1**, 111 (2013).
- ⁷L. Xuesong, S. Huang, M. B. Diaz, N. Kotulak, H. Ruiying, R. Opila, and A. Barnett, IEEE J. Photovoltaics **2**, 214 (2012).
- ⁸C. R. Allen, J. M. Woodall, and J. H. Jeon, Sol. Energy Mater. Sol. Cells **95**, 2655 (2011).
- ⁹G. Y. Rudko, I. A. Buyanova, W. M. Chen, H. P. Xin, and C. W. Tu, Solid State Electron. **47**, 493 (2003).
- ¹⁰V. K. Subashiev and G. A. Chalikyan, Phys. Status Solidi B 13, K91 (1966).
- ¹¹E. D. Palik, *Handbook of Optical Constants of Solids* (Academic Press, Burlington, 1997).
- ¹²W. Shan, W. Walukiewicz, K. M. Yu, J. Wu, J. W. Ager, E. E. Haller, H. P. Xin, and C. W. Tu, Appl. Phys. Lett. **76**, 3251 (2000).
- ¹³P. R. C. Kent and A. Zunger, Phys. Rev. B 64, 115208 (2001).
- ¹⁴J. Wu, W. Shan, and W. Walukiewicz, Semicond. Sci. Technol. 17, 860 (2002).
- ¹⁵S. Sukrittanon, Y. J. Kuang, A. Dobrovolsky, W. M. Kang, J. S. Jang, B. J. Kim, W. M. Chen, I. A. Buyanova, and C. W. Tu, Appl. Phys. Lett. **105**, 072107 (2014).
- ¹⁶S. Sukrittanon, Y. J. Kuang, and C. W. Tu, J. Vac. Sci. Technol., B 31, 03C110 (2013).
- ¹⁷Y. J. Kuang, S. Sukrittanon, H. Li, and C. W. Tu, Appl. Phys. Lett. 100, 053108 (2012).
- ¹⁸H. P. Xin, C. W. Tu, Y. Zhang, and A. Mascarenhas, Appl. Phys. Lett. 76, 1267 (2000).
- ¹⁹I. A. Buyanova, G. Pozina, J. P. Bergman, W. M. Chen, H. P. Xin, and C. W. Tu, Appl. Phys. Lett. **81**, 52 (2002).
- ²⁰W. G. Bi and C. W. Tu, Appl. Phys. Lett. **69**, 3710 (1996).
- ²¹S. Tomasulo, K. Nay Yaung, J. Faucher, M. Vaisman, and M. L. Lee, Appl. Phys. Lett. **104**, 173903 (2014).
- ²²J. Simon, S. Tomasulo, P. J. Simmonds, M. Romero, and M. L. Lee, paper presented at the IEEE 35th Photovoltaic Specialists Conference (PVSC) (2010).
- ²³T. J. Grassman, J. A. Carlin, B. Galiana, F. Yang, M. J. Mills, and S. A. Ringel, IEEE J. Photovoltaics 4, 972 (2014).
- ²⁴M. Da Silva, S. Almosni, C. Cornet, A. Létoublon, C. Levallois, P. Rale, L. Lombez, J. F. Guillemoles, and O. Durand, Proc. SPIE **9358**, 93580H (2015).
- ²⁵S. Kurtz, A. Ptak, S. Johnston, C. Kramer, M. Young, D. Friedman, J. Geisz, W. McMahon, A. Kibbler, J. Olson, R. Crandall, and H. Branz, paper presented at the 2005 DOE Solar Energy Technologies Program Review Meeting, Denver, Colorado, 7–10 November 2005.
- ²⁶S. L. Tan, C. J. Hunter, S. Zhang, L. J. J. Tan, Y. L. Goh, J. S. Ng, I. P. Marko, S. J. Sweeney, A. R. Adams, J. Allam, and J. P. R. David, J. Electron. Mater. **41**(12), 3393 (2012).
- ²⁷M. Vaisman, S. Tomasulo, T. Masuda, J. R. Lang, J. Faucher, and M. L. Lee, Appl. Phys. Lett. **106**, 063903 (2015).
- ²⁸Z. S. Bittner, D. V. Forbes, M. Nesnidal, and S. M. Hubbard, paper presented at the IEEE 37th Photovoltaic Specialists Conference (PVSC) (2011).
- ²⁹W. M. Chen, I. A. Buyanova, A. V. Buyanov, T. Lundstrom, W. G. Bi, and C. W. Tu, Phys. Rev. Lett. **77**, 2734 (1996).
- ³⁰M. Izadifard, I. A. Buyanova, J. P. Bergman, W. M. Chen, A. Utsumi, Y. Furukawa, A. Wakahara, and H. Yonezu, IEE Proc.: Optoelectron. 151, 335 (2004).
- ³¹D. Dagnelund, I. A. Buyanova, X. J. Wang, W. M. Chen, A. Utsumi, Y. Furukawa, A. Wakahara, and H. Yonezu, J. Appl. Phys. **103**, 063519 (2008).
- ³²Y. J. Kuang, S. W. Chen, H. Li, S. K. Sinha, and C. W. Tu, J. Vac. Sci. Technol., B **30**, 02B121 (2012).
- ³³B. A. Joyce, Adv. Mater. 5, 773 (1993).
- ³⁴C. R. Allen, J. H. Jeon, and J. M. Woodall, Sol. Energy Mater. Sol. Cells 94, 865 (2010).
- ³⁵S. V. Deshpande, E. Gulari, S. W. Brown, and S. C. Rand, J. Appl. Phys. 77, 6534 (1995).
- ³⁶S. Tomasulo, K. N. Yaung, J. Simon, and M. L. Lee, Appl. Phys. Lett. 101, 033911 (2012).