III-nitride disk-in-nanowire 1.2 μ m monolithic diode laser on (001)silicon

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Citation: *Applied Physics Letters* **107**, 191107 (2015); doi: 10.1063/1.4935614

View online: <http://dx.doi.org/10.1063/1.4935614>

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III-nitride disk-in-nanowire 1.2 μm monolithic diode laser on (001)silicon

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(Received 27 August 2015; accepted 2 November 2015; published online 12 November 2015)

III-nitride nanowire diode heterostructures with multiple $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ disks and graded InGaN mode confining regions were grown by molecular beam epitaxy on (001)Si substrates. The aerial density of the 60 nm nanowires is $\sim 3 \times 10^{10} \text{ cm}^{-2}$. A radiative recombination lifetime of 1.84 ns in the disks is measured by time-resolved luminescence measurements. Edge-emitting nanowire lasers have been fabricated and characterized. Measured values of J_{th} , T_0 , and dg/dn in these devices are 1.24 kA/cm^2 , 242 K, and $5.6 \times 10^{-17} \text{ cm}^2$, respectively. The peak emission is observed at $\sim 1.2 \mu\text{m}$.
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Silicon photonics is an important application area for an optical communication system, and both on-chip and inter-chip optical communications are envisaged in the future.¹ A suitable monolithic silicon-based laser, which is electrically pumped and reliable, is desired for this application and, in general, for large-scale optoelectronic integration. In the context of electrically pumped lasers, three technologies have been pursued. III-V quantum well and quantum dot lasers grown directly on silicon have been reported.^{2–4} The greatest drawback of this technology is the formation of anti-phase boundaries during epitaxy. The general solution to this problem—use of misoriented substrates (offcut (001)Si)—is not compatible with Si complementary metal-oxide semiconductor (CMOS) technology. Wafer bonded III-V lasers on silicon, with mode confinement and guiding either in silicon or the III-V heterostructure, have been investigated and reported.⁵ A tensile-strained and degenerately doped Ge-on-Si p-n-n diode laser has been reported with threshold current density and maximum output power equal to 280 kA/cm^2 and $\sim 1 \text{ mW}$, respectively.⁶ More recently, lasers with direct bandgap GeSn alloys are being reported,⁷ but electrical injection and room temperature operation have not been achieved with these devices.

III-nitride (Al, Ga, In)N nanowires and nanowire heterostructures are being grown on (001) silicon substrates for the fabrication of light-emitting diodes (LEDs) and lasers.^{8–15} The nanowires generally grow along the c-axis in the wurtzite crystalline form and are relatively free of extended defects due to the large surface-to-volume ratio. The radial relaxation of strain during epitaxy of the nanowires leads to a small polarization field in nanowire heterostructures. The diameter and aerial density of the nanowires can be varied in the range of 20–80 nm and 10^8 – 10^{11} cm^{-2} , respectively, by tuning the initial Ga flux, the substrate temperature, and the nitrogen flow rate. Most importantly, InGaN disks of varying alloy composition can be inserted in (Al, Ga)N nanowires, and the composition of the disk regions can be varied to tune the emission wavelength. In this letter, we report the characteristics of near-infrared InGaN/GaN nanowire edge-emitting lasers grown directly on (001)Si substrates. $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ disks inserted in the $\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ nanowires

form the gain media, and the peak emission wavelength of the lasers is $\sim 1.2 \mu\text{m}$.

Monolithic InGaN/InGaN disk-in-nanowires p-i-n heterostructures (Fig. 1(a)) were grown on n-type (001) Si by plasma-assisted molecular beam epitaxy (PA-MBE). 260 nm of Si-doped n-type GaN nanowire was first grown, followed by an n-type 150 nm graded cladding layer from GaN to $\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ in 10 equal steps (composition and thickness). Eight pairs of undoped $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ (3 nm) disks/ $\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ (12 nm) barrier were grown as the active region on top of the graded cladding layer followed by a 150 nm Mg-doped p-type GaN. The n-doped GaN region was grown at a substrate temperature of 819°C under nitrogen rich condition with a Ga flux of $1.17 \times 10^{-7} \text{ Torr}$. For the n-doped graded layer, the substrate temperature was varied from 819°C to 631°C , but the Ga and In fluxes were fixed at $1.1 \times 10^{-7} \text{ Torr}$ and at $4.03 \times 10^{-8} \text{ Torr}$, respectively. The InGaN disks were grown at 442°C with In flux of $6.04 \times 10^{-8} \text{ Torr}$ and Ga flux of $2 \times 10^{-8} \text{ Torr}$. The InGaN barriers were grown at the same substrate temperature as that of the disks, but with In and Ga fluxes of $3.01 \times 10^{-8} \text{ Torr}$ and $1.1 \times 10^{-7} \text{ Torr}$, respectively. The p-GaN region of the heterostructure was grown at a substrate temperature of 800°C with a Ga flux of $9.63 \times 10^{-8} \text{ Torr}$. The final 20 nm of p-GaN was grown with a higher Mg flux, thereby increasing the p-doping level. The entire growth was done at a fixed nitrogen plasma flowrate of 1 sccm. From scanning electron microscope (SEM) images (Fig. 1(a)), the average length and diameter of the nanowires are determined to be 700 nm and 60 nm, respectively, and the aerial density is $\sim 3 \times 10^{10} \text{ cm}^{-2}$. The mode intensity distribution for the p-GaN/active-region/graded-layer/n-GaN structure of Fig. 1(a) was simulated using the transfer-matrix-element method, considering continuous epitaxial structure and without scattering losses (Fig. 1(b)). The composition dependent refractive index profile in the figure was calculated from Ref. 16 or interpolated from measured values in Ref. 17. The optical confinement factor Γ of this heterostructure is the product of the electric field confined in the active region (mode confinement) simulated by the transfer matrix method (0.03) and the fill factor of the nanowires (0.85) derived from SEM

FIG. 1. (a) $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}/\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ disk-in-nanowire laser heterostructure. The inset shows scanning electron microscope image of the nanowires grown by MBE on (001)Si; (b) refractive index profile and near-field intensity in the nanowire laser structure; (c) X-ray diffraction profile of 120 nm $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ layer grown on GaN and graded $\text{In}_x\text{Ga}_{1-x}\text{N}$ layers ($x = 0-0.4$) on (001)Si substrate. Inset shows the control sample grown for the XRD measurements.

imaging. It may be noted that the optical mode leaks into the graded InGaN layer, as well as the p-GaN and n-GaN layers, consistent with the experimental near-field optical mode measurement discussed later. In order to confirm the alloy composition in the InGaN disk regions, a separate nanowire sample was grown on (001)Si, which consists of 260 nm Si-doped GaN followed by 150 nm graded $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x = 0-0.4$ in 10 equal steps) and then by 120 nm $\text{In}_x\text{Ga}_{1-x}\text{N}$ having the same composition ($x \sim 0.85$) as in the disk regions of the laser heterostructures. The x-ray diffraction (XRD) data from this sample are shown in Fig. 1(c). The alloy peak position confirms the composition in the disk material of the laser heterostructures. The relatively broad peak reflects the presence of mismatch-induced defects because of the 120 nm thickness. The tails observed in between the GaN and $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ peaks are believed to result from the graded InGaN region in the sample.

Temperature dependent photoluminescence (PL) measurements were performed with the laser nanowire sample housed in a He cryostat and excitation at 325 nm provided by a He-Cd laser. The PL data were analyzed by an Acton Spectrometer with a resolution of 0.03 nm and detected with a liquid nitrogen cooled Ge detector. The room temperature PL spectrum measured with an excitation intensity of 150 kW/cm^2 is shown in Fig. 2(a). The emission peak is at 0.85 eV ($1.46 \mu\text{m}$). The variation of the PL emission peak energy with temperature, shown in Fig. 2(b), can be analyzed by the Varshni equation¹⁸ with the parameters $\alpha = 0.42 \text{ meV/K}$ and $\beta = 615 \text{ K}$. The variation does not show any S-type behavior, generally attributed to multiple phases and clusters.¹⁹ The measured variation of the integrated PL intensity

with temperature is depicted in Fig. 2(c). The overall temperature dependence can be analyzed with activation energies of $E_1 = 23.6 \text{ meV}$ and $E_2 = 173.0 \text{ meV}$. The value of E_1 is in

FIG. 2. (a) Room temperature photoluminescence spectrum from $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ disk-in-nanowire laser heterostructure; (b) peak energy of disk-in-nanowire emission plotted as a function of temperature; (c) variation of the integrated photoluminescence intensity with temperature; (d) total carrier lifetime and its radiative and nonradiative components for an $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}/\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ disk-in-nanowire sample. The inset shows room temperature transient photoluminescence and analysis with stretched exponential model.

an excellent agreement with the X_A exciton binding energy, and the quenching of luminescence represents the deactivation of the free exciton.²⁰ The value of E_2 is much smaller than the band offset under flat-band conditions. However, due to the presence of the polarization field, the effective barrier from the ground state for electron escape by field-assisted emission or tunneling can be much smaller, and comparable to 173 meV. These electrons can then recombine non-radiatively in the barriers or other regions of the heterostructure. Indeed, deep level traps have been identified in GaN nanowires.¹¹ From the ratio of the PL intensity at room and cryogenic temperatures at an excitation level of 150 kW/cm², an approximate value of the internal quantum efficiency (η_i) of 17% is derived. In order to gain a better understanding of this low value, we performed temperature dependent time-resolved PL (TRPL) measurements with 267 nm excitation provided by a mode-locked Ti-sapphire laser. The transient luminescence signal was detected by a high speed ID Quantique id220 detector and was analyzed with the stretched exponential model. The radiative and non-radiative lifetimes, τ_r and τ_{nr} , as a function of temperature are determined from the measured recombination lifetime τ and η_i . These are shown in Fig. 2(d). The measured transient PL at room temperature is shown in the inset. Values of τ , τ_r , and τ_{nr} at room temperature are 0.3 ns, 1.84 ns, and 0.36 ns, respectively. The low values of η_i and the non-radiative lifetime are attributed to defects in the nanowire and disk regions. Extended defects can be caused by coalescing of nanowires during epitaxy²¹ either due to misorientation or due to increasing nanowire diameter at the low temperature of epitaxy. These defects behave electronically as non-radiative deep levels.¹¹ Defects can also be created due to the $\sim 5\%$ lattice mismatch between the disk and barrier regions. Alloy clustering in the disk region due to the high In flux can give rise to additional defects.

Edge-emitting broad-area nanowire lasers were fabricated by a combination of reactive ion etching, photolithography, and planarization with parylene. The latter also serves to passivate the nanowire and disk regions and to increase the relative IQE by $\sim 10\%$ – 12% .²² For example, an as-grown sample having a relative IQE of 40% attains a value of 50%–52% after parylene passivation. Details of the laser fabrication process steps have been published elsewhere.⁹ Two-step mesa etching was used to define the laser width of 50 μm in a ridge geometry and to form the n-contact with Al/Au (50 nm/200 nm) on the Si substrate surface. After planarizing the nanowires with parylene, an etch-back step was included to fully expose the tip of the p-GaN region of the nanowires. The p-contact was formed by the deposition and subsequent annealing of Ni/Au (5 nm/200 nm) followed by indium tin oxide (ITO) (250 nm). Lasers of lengths varying from 0.5 to 2 mm were defined by cleaving along the direction perpendicular to the cavity, followed by focused ion beam (FIB) etching and the deposition of 2 pairs of MgF₂/ZnSe (235 nm/130 nm) distributed Bragg reflectors (DBRs) to achieve a facet reflectivity of 0.68 at both ends. A series resistance of 25 Ω was derived from the laser diode current-voltage measurements.

A control nanowire sample was grown for waveguide loss measurements. The nanowire heterostructure is almost

identical to that grown for laser fabrication (Fig. 1(a)) with the waveguide region consisting of 120 nm of In_{0.4}Ga_{0.6}N without the In_{0.85}Ga_{0.15}N disks, to eliminate absorption of the 850 nm excitation light. Waveguide fabrication is also very similar to that of the lasers described above, with deposition of high-reflectivity DBRs replaced by the formation of dielectric anti-reflection (AR) coating on the facets. Waveguides of 50 μm width and varying length were end-fired, and the transmitted light intensity was measured (Fig. 3) with an infrared detector. A waveguide (cavity) loss of 9.3 dB/cm is derived from the measured data, which is comparable to that measured in InGaN/GaN quantum dot lasers with planar waveguide and cladding layers.^{23,24} This loss primarily results from the low mode confinement factor and contributes to an increase in the threshold current.

Light-current-voltage (L-I-V) measurements were made on 50 μm $\times$ 1 mm lasers under pulsed (5% duty cycle) bias conditions to avoid device heating. No special heat sinking or device mounting techniques were applied. The output characteristics measured at room temperature below and above threshold are shown in Fig. 4(a). The threshold current density is $J_{th} = 1.24 \text{ kA/cm}^2$, taking into account the fill factor of 0.85 of the nanowire ensemble. From these characteristics, a differential efficiency $\eta_d = 0.13 \text{ W/A}$ (12.8%) and a wall-plug efficiency of 0.07% are derived. The value of J_{th} is amongst the lowest for nitride-based quantum well and quantum dot lasers.^{24,25} The spectral characteristics of the electroluminescence at different biases were recorded by fiber-coupling the output to an optical spectrum analyzer. The spectral output at room temperature at an injection current of 600 mA ($1.13J_{th}$) is shown in the inset of Fig. 4(a), and the emission peak is at 1.17 μm . The blue shift of this peak from that of the photoluminescence peak at 1.46 μm is due to the quantum confined Stark effect (QCSE) arising from the polarization field in the In_{0.85}Ga_{0.15}N disks. From the measured variation of the spectral linewidth (full-width-at-half-maximum) with injection current density, the smallest recorded linewidth is found to be 6 $\text{\AA}$. The variation of the threshold current density with temperature was measured under pulsed bias (5% duty cycle) conditions with the help of a Peltier cooler. The measured variation, shown in

FIG. 3. Output intensity of nanowire heterostructure ridge waveguides as a function of waveguide length. The heterostructures were grown on (001)Si substrates.

FIG. 4. (a) Light-current characteristics of a broad area laser. Top inset shows a near-field image of the laser mode superimposed with the laser heterostructure schematic, and the bottom inset shows electroluminescence spectrum above threshold; (b) temperature dependence of the threshold current density; (c) measured variation of inverse differential quantum efficiency as a function of cavity length; and (d) measured variation of threshold current density as a function of inverse cavity length.

Fig. 4(b), was analyzed with the relation: $J_{th}(T) = J_{th0} \cdot \exp(T/T_0)$ from which a value of $T_0 = 242$ K was derived. This value is significantly higher than those measured for GaAs-based $\sim 1.0 \mu\text{m}$ quantum well lasers²⁶ and comparable to visible III-nitride nanowire lasers reported previously,^{12,27} indicating that the temperature stability of nanowire lasers is very promising. The high value of T_0 , in most part, is attributed to the large band offsets in the quantum disk heterostructure and the resulting reduction of carrier leakage. In order to study the mode propagation and emission of the device, we measured the near field image of the output at one facet with an Electrophysics microviewer and this is shown in the inset of Fig. 4(a). It is evident that there is some leakage of the propagating mode into the substrate, which accounts for the relatively large waveguide loss coefficient. Design and growth of nanowire heterostructures, which will enable better mode confinement, will reduce waveguide loss and laser threshold.

Finally, measurement of the laser output characteristics were made at room temperature for varying cavity length, L . Figures 4(c) and 4(d) depict the variation of η_d^{-1} versus L and J_{th} vs. $1/L$, respectively. Analysis of these data yields an IQE of 0.18, assuming unity injection efficiency, and a differential gain $dg/dn \sim 5.6 \times 10^{-17} \text{ cm}^2$, assuming a value of $\tau_r = 1.84 \text{ ns}$, as derived from TRPL measurements. It is instructive to compare this value of dg/dn with those reported for InGaAs/GaAs pseudomorphic quantum well and quantum dot lasers. Our measured value is approximately an order of magnitude smaller.^{28,29} We believe that the relatively large value of J_{th} measured here, compared to typical values $\sim 200 \text{ A/cm}^2$ for GaAs-based quantum well devices,²⁶ can be attributed to the smaller differential gain, a smaller

gain coefficient due to the polarization field induced reduction of the electron-hole overlap in the disks (~ 0.3 – 0.4),^{30,31} and the low quantum efficiency. Nonetheless, this demonstration opens the doors for improvement in performance of a truly monolithic electrically pumped laser on (001)Si.

Finally, it is important to make a comment on the nature of carrier confinement in the $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ disk region. It has been observed from direct transmission electron microscopy that a single island, which behaves electronically as a Volmer-Weber quantum dot, is formed³² in $\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ disks inserted in a GaN nanowire. It is possible that similar quantum dots are formed in the $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}$ disk regions of the current nanowire samples. However, in this case, it is more likely for the dots to be formed in the Stranski-Krastanov growth mode due to the large density of defects.³³ The increase of τ_r with temperature, seen in Fig. 2(d), is a trend characteristic of quantum dots^{29,32,34} and is not observed for bulk semiconductors, quantum wells, or quantum wires. In these materials, τ_r generally remains unchanged with temperature.

In conclusion, we have described the molecular beam epitaxy and characteristics of $\text{In}_{0.85}\text{Ga}_{0.15}\text{N}/\text{In}_{0.4}\text{Ga}_{0.6}\text{N}$ disk-in-nanowire edge-emitting $1.2 \mu\text{m}$ diode laser on (001)Si substrates. While the results are extremely encouraging, particularly in terms of the temperature stability of the threshold, there is room for improvement, such that the device can serve as a promising silicon-based coherent light source. The waveguide loss can be minimized by better design of the waveguide and cladding layer materials. An important factor that degrades the performance characteristics such as gain, differential gain and J_{th} is the high In content in the disks and the biaxial strain therein. The resulting piezoelectric polarization field in the disk needs to be minimized, while tuning the peak emission to $1.3 \mu\text{m}$ and beyond. Alloying with elements which can achieve both needs to be explored.

The work was supported by KAUST under Grant CRG-1-2012-001-010-MIC and the National Science Foundation, MRSEC program, under Grant DMR-1120923. The authors acknowledge the help provided by A. Bhattacharya, Z. Baten, and T. Frost.

¹B. Jalali and S. Fathpour, *J. Lightwave Technol.* **24**, 4600–4615 (2006).

²H. Z. Chen, A. Ghaffari, H. Wang, H. Morkoç, and A. Yariv, *Opt. Lett.* **12**, 812–813 (1987).

³Z. Mi, P. Bhattacharya, J. Yang, and K. P. Pipe, *Electron. Lett.* **41**, 742 (2005).

⁴A. L. Liu, C. Zhang, J. Norman, A. Snyder, D. Lubyshev, J. M. Fastenau, A. W. K. Liu, A. C. Gossard, and J. E. Bowers, *Appl. Phys. Lett.* **104**, 041104 (2014).

⁵D. Liang, G. Roelkens, R. Baets, and J. E. Bowers, *Materials* **3**, 1782–1802 (2010).

⁶R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, *Opt. Express* **20**, 11316–11320 (2012).

⁷S. Wirths, R. Geiger, N. von den Driesch, G. Mussler, T. Stoica, S. Mantl, Z. Ikonik, M. Luysberg, S. Chiussi, J. M. Hartmann, H. Sigg, J. Faist, D. Buca, and D. Grützmacher, *Nat. Photonics* **9**, 88–92 (2015).

⁸S. Gratečak, F. Qian, Y. Li, H.-G. Park, and C. M. Lieber, *Appl. Phys. Lett.* **87**, 173111 (2005).

⁹A. Kikuchi, M. Tada, K. Miwa, and K. Kishino, *Proc. SPIE* **6129**, 612905 (2006).

¹⁰W. Guo, M. Zhang, A. Banerjee, and P. Bhattacharya, *Nano Lett.* **10**, 3355–3359 (2010).

- ¹¹S. Jahangir, T. Schimpke, M. Strassburg, K. A. Grossklau, J. M. Millunchick, and P. Bhattacharya, *IEEE J. Quantum Electron.* **50**, 530 (2014).
- ¹²T. Frost, S. Jahangir, E. Stark, S. Deshpande, A. Hazari, C. Zhao, B. S. Ooi, and P. Bhattacharya, *Nano Lett.* **14**, 4535–4541 (2014).
- ¹³S. Arafin, X. Liu, and Z. Mi, *J. Nanophotonics* **7**, 074599 (2013).
- ¹⁴A. B. Greytak, C. J. Barrelet, Y. Li, and C. M. Lieber, *Appl. Phys. Lett.* **87**, 151103 (2005).
- ¹⁵Q. Li, J. B. Wright, W. W. Chow, T. S. Luk, I. Brener, L. F. Lester, and G. T. Wang, *Opt. Express* **20**, 16 (2012).
- ¹⁶C.-Y. Huang, Y.-D. Lin, A. Tyagi, A. Chakraborty, H. Ohta, J. S. Speck, S. P. DenBaars, and S. Nakamura, *J. Appl. Phys.* **107**, 023101 (2010).
- ¹⁷A. Hazari, A. Bhattacharya, T. Frost, S. Zhao, M. Z. Baten, Z. Mi, and P. Bhattacharya, *Opt. Lett.* **40**, 3304–3307 (2005).
- ¹⁸Y. Varshni, *Physica* **34**, 149 (1967).
- ¹⁹A. Bell, S. Srinivasan, C. Plumlee, H. Omiya, F. A. Ponce, J. Christen, S. Tanaka, A. Fujioka, and Y. Nakagawa, *J. Appl. Phys.* **95**, 4670 (2004).
- ²⁰B. J. Skromme, J. Jayapalan, R. P. Vaudo, and V. M. Phanse, *Appl. Phys. Lett.* **74**, 2358 (1999).
- ²¹K. A. Grossklau, A. Banerjee, S. Jahangir, P. Bhattacharya, and J. Mirecki-Millunchick, *J. Cryst. Growth* **371**, 142–147 (2013).
- ²²S. Jahangir, M. Mandl, M. Strassburg, and P. Bhattacharya, *Appl. Phys. Lett.* **102**, 071101 (2013).
- ²³A. Banerjee, T. Frost, E. Stark, and P. Bhattacharya, *Appl. Phys. Lett.* **101**, 041108 (2012).
- ²⁴T. Frost, A. Banerjee, K. Sun, S. L. Chuang, and P. Bhattacharya, *IEEE J. Quantum Electron.* **49**, 923 (2013).
- ²⁵S. Nakamura, M. Senoh, S.-I. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, *Jpn. J. Appl. Phys., Part 1* **35**, L74 (1996).
- ²⁶D. L. Huffaker, G. Park, Z. Zou, O. B. Shchekin, and D. G. Deppe, *Appl. Phys. Lett.* **73**, 2564 (1998).
- ²⁷S. Jahangir, T. Frost, A. Hazari, L. Yan, E. Stark, T. LaMountain, J. Mirecki-Millunchick, B. S. Ooi, and P. Bhattacharya, *Appl. Phys. Lett.* **106**, 071108 (2015).
- ²⁸D. Bimberg, N. Kirstaedter, N. N. Ledentsov, Zh. I. Alferov, P. S. Kop'ev, and V. M. Ustinov, *IEEE J. Sel. Top. Quantum Electron.* **3**, 196–205 (1997).
- ²⁹P. Bhattacharya, S. Ghosh, S. Pradhan, J. Singh, Z.-K. Wu, J. Urayama, K. Kim, and T. B. Norris, *IEEE J. Quantum Electron.* **39**, 952 (2003).
- ³⁰Y.-R. Wu, Y.-Y. Lin, H.-H. Huang, and J. Singh, *J. Appl. Phys.* **105**, 013117 (2009).
- ³¹G.-L. Su, T. Frost, P. Bhattacharya, and J. M. Dallesasse, *Opt. Express* **23**, 12850–12865 (2015).
- ³²S. Deshpande, T. Frost, L. Yan, S. Jahangir, A. Hazari, X. Liu, J. Mirecki-Millunchick, Z. Mi, and P. Bhattacharya, *Nano Lett.* **15**, 1647–1653 (2015).
- ³³K. Nakajima, T. Ujihara, S. Miyashita, and G. Sasaki, *J. Appl. Phys.* **89**, 146 (2001).
- ³⁴M. Braskén, M. Lindberg, M. Sopanen, H. Lipsanen, and J. Tulkki, *Phys. Rev. B* **58**, R15993(R) (1998).