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Small signal modulation characteristics of red-emitting ($\lambda = 610$ nm) III-nitride nanowire array lasers on (001) silicon

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The small signal modulation characteristics of an InGaN/GaN nanowire array edge-emitting laser on (001) silicon are reported. The emission wavelength is 610 nm. Lattice matched InAlN cladding layers were incorporated in the laser heterostructure for better mode confinement. The suitability of the nanowire lasers for use in plastic fiber communication systems with direct modulation is demonstrated through their modulation bandwidth of $f_{-3\text{dB,max}} = 3.1$ GHz, very low values of chirp (0.8 Å) and α -parameter, and large differential gain (3.1×10^{-17} cm²). © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4913317>]

III-nitride based nanowire array lasers, which can be grown monolithically on (001) silicon have many potential applications in the visible spectrum including in mobile-projectors, heads-up displays in automobiles, and in photodynamic therapy.^{1,2} Additionally, the possibility of fabricating a cheap laser on silicon makes these devices attractive for use in optical communications³ in the emerging plastic fiber communication systems which have transmission windows in the green to red. While current red-emitting lasers typically rely on InGaAlP active regions,⁴ these devices suffer from undesirable effects including large threshold current density (>6 kA/cm²) and poor temperature stability ($T_0 \sim 60$ K). On the other hand, InGaN/GaN nanowire heterostructures (which have previously been demonstrated with emission in the green) have been shown to have reduced threshold current densities (~ 2 kA/cm²) and very large values of T_0 (~ 240 K).⁵ These characteristics make them very suitable not only for use in communication systems but also in the display and medical applications listed above, which typically rely on planar InGaN/GaN quantum wells (QWs).^{6–8} The nanowire devices have further advantages of planar InGaN/GaN QW lasers which must be grown on expensive polar or non-polar GaN substrates, suffer from large defect densities, and from which emission can currently only reach green (~ 530 nm). The nanowire heterostructures, on the other hand, can be grown on cheap (001) or (111) silicon substrates.^{5,9–11} Furthermore, they grow with negligible extended defects^{12–16} with low surface state density¹⁷ and have reduced piezoelectric field and small measured values of Auger recombination.¹⁸ III-nitride based lasers having

(In)GaN/AlGaIn waveguides suffer from reduced modal confinement at longer wavelengths (red and beyond) due to the small refractive index difference between the (In)GaN waveguide and AlGaIn cladding layers. As an alternative, we have incorporated In_{0.18}Al_{0.82}N cladding layers (lattice matched to GaN), which provide more ideal mode confinement needed at these wavelengths. We report here a detailed investigation of the small signal modulation characteristics of edge emitting InGaN/GaN disk-in-nanowire array lasers emitting at 610 nm. Through the measurement of the laser linewidth enhancement factor, α , we show that the InGaIn disks in the nanowires behave as quantum dots electrically, which may explain the low threshold current density and high temperature stability of these devices, which are comparable with self-assembled quantum dot lasers.^{19–22} Through modulation experiments, we derive a differential gain of 3.1×10^{-17} cm² and measure a maximum modulation bandwidth of 3.1 GHz and chirp less than 1 Å.

The InGaIn/GaN disk-in-nanowire (DINW) array laser heterostructure, grown along the c -axis, is shown in Fig. 1(a) together with the calculated optical mode of the laser. Lattice-matched In_{0.18}Al_{0.82}N (to GaN), suitably doped n - and p -type with Si and Mg, has been incorporated as the lower and upper cladding layers, respectively. A lattice constant of $c = 5.16$ Å is derived from selective area diffraction (SAD) in a high-resolution transmission electron microscope (HRTEM) image, shown in Fig. 1(b), indicating excellent lattice matching with GaN. The gain medium consists of 6 In_{0.51}Ga_{0.49}N disks (2 nm) separated by 12 nm GaN barriers inserted in the center of the waveguide layer. The nanowire array laser heterostructure was grown on (001) silicon substrates in a Veeco Gen II plasma-assisted molecular beam epitaxy (MBE) facility. Substrate preparation and growth conditions have been described in detail in previous

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FIG. 1. (a) Schematic representation of the nanowire array laser heterostructure, with the calculated mode profile shown alongside; (b) HRTEM image of $\text{In}_{0.18}\text{Al}_{0.82}\text{N}$ nanowire showing relatively defect-free crystal structure along the growth direction. Inset shows the SAD pattern. (c) Light-current-voltage characteristics from a $10\text{ }\mu\text{m}$ by 1 mm laser at room temperature.

publications from our group.^{5,11} In brief, the GaN, $\text{In}_{0.18}\text{Al}_{0.82}\text{N}$, and InGaN disk regions of the nanowire are grown at 800°C , 510°C , and 545°C , respectively, under nitrogen rich conditions. The growth rate for GaN is 300 nm/h . The growth parameters are optimized by measuring the radiative efficiency of the InGaN disks. From photoluminescence measurements performed under saturation excitation conditions at 10 K and 300 K , the radiative efficiency η_r is calculated to be 41% , which increases to 52% upon passivation with parylene.^{11,23} This value of efficiency is excellent for luminescence in the red wavelength range, where no emission from InGaN/GaN quantum wells has been reported and typical InGaN/GaN self-assembled quantum dots have reported efficiencies around 40% .²¹ The average nanowire diameter, obtained by scanning electron microscope (SEM) imaging, is 60 nm , and the height of the nanowire laser heterostructure is $\sim 800\text{ nm}$. The nanowire density is $2 \times 10^{10}\text{ cm}^{-2}$, with an average spacing of $\sim 7\text{ nm}$ between adjacent nanowires, which are randomly distributed throughout the nanowire forest.

Ridge waveguide edge-emitting lasers were fabricated in much the same way as planar lasers with bulk semiconductors. Mesas for the ridge geometry were defined by dry etching of the nanowires. Parylene was deposited conformally at room temperature by physical vapor deposition to planarize and passivate the nanowires. It was ensured that a part of the top p-GaN region of the nanowires is exposed to facilitate formation of the p-ohmic contact. The latter is formed by the deposition of $5\text{ nm}/5\text{ nm}$ Ni/Au followed by 250 nm indium tin oxide (ITO). The n-ohmic contact is formed on the top surface of the Si substrate by deposition of Al. Laser fabrication is completed by cleaving the substrate along the direction perpendicular to the laser cavity, forming optically flat cavity facets with focused ion beam (FIB) etching and subsequent coating of these facets with $\text{TiO}_2/\text{SiO}_2$

distributed Bragg reflectors (DBRs) to attain reflectivities of ~ 0.35 and ~ 0.95 . The confinement and guiding of optical modes in the composite nanowire-parylene medium has been confirmed by finite difference time domain (FDTD) calculations by modeling the entire region as a hexagonal close-packed nanowire array.⁵ The average refractive index of the composite medium is 1.9 . The propagation loss in a similar nanowire-parylene waveguide on silicon has been measured to be 7.2 dB/cm .⁵

Lasers with cavity lengths in the range $400\text{ }\mu\text{m}$ to 0.2 cm and ridge widths in the range $4\text{ }\mu\text{m}$ to $40\text{ }\mu\text{m}$ (broad area) were measured in the course of this study. Figure 1(c) shows the light-current-voltage (L-I-V) characteristics measured for the output from the low-reflectivity facet with continuous wave (cw) biasing in a device with a ridge width and cavity length of $10\text{ }\mu\text{m}$ and 1 mm , respectively. The threshold current density, output slope efficiency, wall-plug efficiency, and series resistance under cw bias conditions are measured to be 2.9 kA/cm^2 , 2.5% ($\sim 0.1\text{ W/A}$), 0.2% , and $27\text{ }\Omega$ respectively. The output spectral electroluminescence characteristics below and above threshold are shown in Fig. 2(a). A maximum blue shift of 14.8 nm is recorded when the injection is increased from 1.4 kA/cm^2 to 3.6 kA/cm^2 . The smallest measured linewidth of the peak emission mode (at $\sim 610\text{ nm}$) is $9\text{ }\text{\AA}$. Temperature dependent L-I measurements were also performed under cw bias, from which a value of $T_0 = 234\text{ K}$ is derived by fitting the threshold current density to the formula $J_{\text{th}}(T) = J_{\text{th}}(0)\exp(T/T_0)$. The large value of T_0 indicates good thermal stability in these devices. This value of T_0 is comparable with those measured in red-emitting self-assembled InGaN/GaN quantum dot lasers.²¹

Modulation of the injection current of a semiconductor laser leads to deleterious effects such as linewidth enhancement and chirping, arising from the change in the refractive index of the gain medium. The linewidth enhancement

FIG. 2. (a) Electroluminescence spectra under cw bias above and below threshold; (b) α -parameter as a function of emission wavelength measured by the Hakki-Paoli technique.

factor, expressed as $\alpha = -\frac{4\pi}{\lambda} \left(\frac{\partial n_r}{\partial n} / \frac{\partial g}{\partial n} \right)$, where $\frac{\partial g}{\partial n}$ —the differential gain, was determined from Hakki-Paoli measurements²⁴ on a $10 \mu\text{m} \times 1 \text{ mm}$, and the measured values as a function of emission wavelength are plotted in Fig. 2(b). The trend of the data, with α exhibiting a minimum value of ~ 0.2 at 610 nm is in good agreement with theoretical calculations of Miyake and Asada.²⁵ These authors have shown the existence of a sharp minimum around the peak gain in the wavelength dependence of α for quantum dot lasers. Such minima in the value of α have been measured for InAs/InP QD lasers.^{26,27} The trend of our data therefore suggests the presence of InGaN quantum dots in the gain region. The formation of self-organized islands in the InGaN disk region, which behave as quantum dots, has been confirmed by us by transmission electron microscopy and the observation of single photon emission.²⁸

Measurement of the small-signal modulation response provides a means of determining the differential gain and other dynamic characteristics. These measurements were made on the $4 \mu\text{m} \times 400 \mu\text{m}$ ridge waveguide lasers with the modulation response appropriately calibrated to account for the losses in the cables, connectors, and bias network. The measured response for different injection currents is shown in Fig. 3(a). The differential gain of $3.1 \times 10^{-17} \text{ cm}^2$ is derived from a plot of the resonance frequency f_r versus $(I - I_{th})^{1/2}$, shown in Fig. 3(b), with values of η_r and confinement factor Γ equal to 0.52 and 0.018, respectively. This value compares favorably with the differential gain of red-emitting self-organized quantum dot lasers.²¹

FIG. 3. (a) Measured small-signal modulation response of a $400 \mu\text{m} \times 4 \mu\text{m}$ nanowire ridge waveguide laser for varying DC injection currents; (b) resonance frequency, f_r , versus square root of the injection current; (c) measured chirp as a function of small-signal modulation frequency.

Chirp in a semiconductor laser during small-signal modulation is directly proportional to the α -parameter. To measure chirp, the envelope of the dynamic shift in the wavelength was recorded as a function of small-signal modulation frequency. The measured difference between the half-width of the observed envelopes with and without modulation is plotted in Fig. 3(c). The chirp is fairly constant at a low value of $\sim 0.8 \text{ Å}$ up to 6 GHz. The low value of chirp is very encouraging in the context of optical communication in plastic fibers. Chirp is usually small in lasers with quantum confined gain media. Furthermore, in GaN and related materials, the change in refractive index with carrier injection is small.

In conclusion, we have fabricated edge-emitting red ($\lambda = 610$ nm) lasers with GaN-based InGaN/GaN disk-in-nanowire heterostructures grown on (001) Si substrates and have measured their dynamic characteristics under small-signal modulation. The lasers are characterized by a differential gain of 3.1×10^{-17} cm² and very low chirp and line-width enhancement factor, α . The variation of α with wavelength exhibits a sharp minimum at ~ 610 nm, suggesting the formation of InGaN quantum dots in the disk regions of the nanowires. The results indicate that silicon-based nanowire visible lasers may prove to be a very viable and important technology for a number of applications.

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¹See Denso Global News Release available at <http://www.globaldenso.com/en/newsreleases/121019-01.html> for description of heads-up display application.

²Y. Miyamoto, D. Nishikiori, F. Hagino, M. Wakita, I. Tanabe, and M. Toida, *Laser Therapy* **20**, 135 (2011).

³H. Ohta, S. DenBaars, and S. Nakamura, *J. Opt. Soc. Am. B* **27**, B45 (2010).

⁴K. Itaya, H. Sugawara, and G. Hatakoshi, *J. Crystal Growth* **138**, 768 (1994).

⁵T. Frost, S. Jahangir, E. Stark, S. Deshpande, A. Hazari, C. Zhao, B. S. Ooi, and P. Bhattacharya, *Nano Lett.* **14**, 4535 (2014).

⁶S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, *Appl. Phys. Lett.* **69**, 4056 (1996).

- ⁷A. Avramescu, T. Lerner, J. Müller, S. Tautz, D. Queren, S. Lutgen, and U. Strauß, *Appl. Phys. Lett.* **95**, 071103 (2009).
- ⁸C. Y. Huang, M. T. Hardy, K. Fujito, D. F. Feezell, J. S. Speck, S. P. DenBaars, and S. Nakamura, *Appl. Phys. Lett.* **99**, 241115 (2011).
- ⁹A. Kikuchi, M. Kawai, M. Tada, and K. Kishino, *Jpn. J. Appl. Phys.* **43**, L1524 (2004).
- ¹⁰H. P. T. Nguyen, K. Cui, S. Zhang, S. Fatholouloumi, and Z. Mi, *Nanotechnology* **22**, 445202 (2011).
- ¹¹S. Jahangir, T. Schimpke, M. Strassburg, K. A. Grossklaus, J. M. Millunchick, and P. Bhattacharya, *IEEE J. Quantum Electron.* **50**, 530 (2014).
- ¹²L. Cerutti, J. Ristic, S. F. Garrido, E. Calleja, A. Trampert, K. H. Ploog, S. Lazic, and J. M. Calleja, *Appl. Phys. Lett.* **88**, 213114 (2006).
- ¹³S. F. Garrido, J. Grandal, E. Calleja, M. A. S. Garcia, and D. L. Romero, *J. Appl. Phys.* **106**, 126102 (2009).
- ¹⁴C. Chêze, L. Geelhaar, O. Brandt, W. Weber, H. Riechert, S. Munch, R. Rothmund, S. Reitzenstein, A. Forchel, T. Kehagias, P. Komninou, G. Dimitrakopoulos, and T. Karakostas, *Nano Res.* **3**, 528 (2010).
- ¹⁵X. Duan and C. M. Lieber, *J. Am. Chem. Soc.* **122**, 188 (2000).
- ¹⁶W. Guo, M. Zhang, A. Banerjee, and P. Bhattacharya, *Nano Lett.* **10**, 3355 (2010).
- ¹⁷J. B. Schlager, K. A. Bertness, P. T. Blanchard, L. H. Robins, A. Roshko, and N. A. Sanford, *J. Appl. Phys.* **103**, 124309 (2008).
- ¹⁸W. Guo, M. Zhang, P. Bhattacharya, and J. Heo, *Nano Lett.* **11**, 1434 (2011).
- ¹⁹M. Zhang, A. Banerjee, C. S. Lee, J. M. Hinckley, and P. Bhattacharya, *Appl. Phys. Lett.* **98**, 221104 (2011).
- ²⁰A. Banerjee, T. Frost, E. Stark, and P. Bhattacharya, *Appl. Phys. Lett.* **101**, 041108 (2012).
- ²¹T. Frost, A. Banerjee, K. Sun, S. L. Chuang, and P. Bhattacharya, *IEEE J. Quantum Electron.* **49**, 923 (2013).
- ²²T. Frost, A. Banerjee, S. Jahangir, and P. Bhattacharya, *Appl. Phys. Lett.* **104**, 081121 (2014).
- ²³S. Jahangir, M. Mandl, M. Strassburg, and P. Bhattacharya, *Appl. Phys. Lett.* **102**, 071101 (2013).
- ²⁴B. Hakki and T. Paoli, *J. Appl. Phys.* **46**, 1299 (1975).
- ²⁵Y. Miyake and M. Asada, *Jpn. J. Appl. Phys.* **28**, 1280 (1989).
- ²⁶S. Bhowmick, M. Z. Baten, T. Frost, B. S. Ooi, and P. Bhattacharya, *IEEE J. Quant. Elec.* **50**, 7 (2014).
- ²⁷A. Ukanov, A. Stintz, P. Eliseev, and K. Malloy, *Appl. Phys. Lett.* **84**, 1058 (2004).
- ²⁸S. Deshpande, J. Heo, A. Das, and P. Bhattacharya, *Nat. Commun.* **4**, 1675 (2013).