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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 1.2μm 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 In0.85Ga0.15N 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 ~3×1010 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 d g/dn in these devices are 1.24 kA/cm^2, 242 K, and 5.6×10^-17 cm^2, respectively. The peak emission is observed at ~1.2 μm.

Silicon photonics is an important application area for an optical communication system, and both on-chip and interchip optical communications are envisaged in the future. 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. 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. 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 ~1 mW, respectively. More recently, lasers with direct bandgap GeSn alloys are being reported, 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. 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/InGaN nanowire edge-emitting lasers grown directly on (001)Si substrates. In0.85Ga0.15N disks inserted in the In0.2Ga0.8N nanowires form the gain media, and the peak emission wavelength of the lasers is ~1.2 μm.

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 In0.2Ga0.8N in 10 equal steps (composition and thickness). Eight pairs of undoped In0.85Ga0.15N (3 nm) disks/In0.2Ga0.8N (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 1.17×10^-7 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 1.1×10^-7 Torr and at 4.03×10^-8 Torr, respectively. The InGaN disks were grown at 442 °C with In flux of 6.04×10^-8 Torr and Ga flux of 2×10^-8 Torr. The InGaN barriers were grown at the same substrate temperature as that of the disks, but with In and Ga fluxes of 3.01×10^-8 Torr and 1.1×10^-7 Torr, respectively. The p-GaN region of the heterostructure was grown at a substrate temperature of 800 °C with a Ga flux of 9.63×10^-8 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 ~3×10^10 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.
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 In$_x$Ga$_{1-x}$N ($x = 0–0.4$ in 10 equal steps) and then by 120 nm In$_x$Ga$_{1-x}$N having the same composition ($x = 0.85$) 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 In$_{0.85}$Ga$_{0.15}$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 μm). The variation of the PL emission peak energy with temperature, shown in Fig. 2(b), can be analyzed by the Varshni equation$^{18}$ with the parameters $\alpha = 0.42$ meV/K and $\beta = 615$ 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 $E_1 = 23.6$ meV and $E_2 = 173.0$ meV. The value of $E_1$ is in
an excellent agreement with the $X_A$ exciton binding energy, and the quenching of luminescence represents the deactivation of the free exciton.\textsuperscript{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.\textsuperscript{11} From the ratio of the PL intensity at room and cryogenic temperatures at an excitation level of 150 kW/cm$^2$, an approximate value of the internal quantum efficiency ($\eta_i$) 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, $\tau_r$ and $\tau_{nr}$, as a function of temperature are determined from the measured recombination lifetime $\tau$ and $\eta_i$. These are shown in Fig. 2(d). The measured transient PL at room temperature is shown in the inset. Values of $\tau$, $\tau_r$, and $\tau_{nr}$ at room temperature are 0.3 ns, 1.84 ns, and 0.36 ns, respectively. The low values of $\eta_i$ 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 epitaxy,\textsuperscript{21} 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.\textsuperscript{11} Defects can also be created due to the $\approx$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\%.\textsuperscript{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 processes have been published elsewhere.\textsuperscript{9} Two-step mesa etching was used to define the laser width of 50 $\mu$m 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 MgF$_2$/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 $\Omega$ 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$_{0.35}$Ga$_{0.65}$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 $\mu$m 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.\textsuperscript{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 $\mu$m x 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 $J_{th} = 1.24$ kA/cm$^2$, taking into account the fill factor of 0.85 of the nanowire ensemble. From these characteristics, a differential efficiency $\eta_d = 0.13$ 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.\textsuperscript{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 (1.13$J_{th}$) is shown in the inset of Fig. 4(a), and the emission peak is at 1.17 $\mu$m. The blue shift of this peak from that of the photoluminescence peak at 1.46 $\mu$m 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 $\AA$. 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. 4(b), was analyzed with the relation: \( J_{th}(T) = J_{th0} \exp(T/T_0) \) from which a value of \( T_0 = 242 \text{ K} \) was derived. This value is significantly higher than those measured for GaAs-based \( \sim 1.0 \mu m \) quantum well lasers\(^{26}\) 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. Figures 4(c) and 4(d) depict the variation of \( \eta_{ld}^{-1} \) 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 quantum efficiency as a function of cavity length, and (d) measured variation of threshold current density as a function of inverse cavity length.

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 \( \mu m \) 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 \( \mu m \) 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.

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