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Electrically injected ultra-low threshold room temperature InGaN/GaN-based lateral triangular nanowire laser

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We have demonstrated an electrically injected ultra-low threshold (8.9 nA) room temperature InGaN/GaN based lateral nanowire laser. The nanowires are triangular in shape and survived naturally after etching using boiling phosphoric acid. A polymethyl methacrylate (PMMA) and air dielectric distributed mirror provide an optical feedback, which together with one-dimensional density of states cause ultra-low threshold lasing. Finite difference eigen-mode (FDE) simulation shows that triangular nanowire cavity supports single dominant mode similar to TE01 that of a corresponding rectangular cavity with a confinement factor of 0.18. © 2015 AIP Publishing LLC.

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The field of semiconductor nanowire research and specifically nanowire lasers is attractive for various reasons including the possibility of ultra-low threshold current, potential to be integrated in on-chip optical communication systems and sensor applications.1–3 The high optical gains attainable at low carrier injection levels in spatially confined structures due to higher density of states at the band edge translate to low threshold currents during laser operation.2 The quantum wires have the advantage of possessing the highest density of states at the lowest energy of each successive excited state, thus making it easier to achieve population inversion. The lateral nanowires offer larger volume for the gain medium in comparison to that of vertical nanowires and therefore should show superior performance. They also have the potential to make optical integrated circuits viable.1,4 Additionally, they have greater mechanical stability as compared to the vertical ones. The tight spatial confinement in quantum wires leads to an increased binding energy of the electron-hole pairs and the possibility of excitonic lasing.8,9 Demonstrations of single nanowire lasing generally employ optical pumping;4,6–8 however, electrical injection is the ultimate aim for device applications.10

Generally, epitaxial growth of nanowires results in a forest of vertical nanowires, either site controlled or self-organized, which are drop-cast onto suitable substrates to obtain lateral nanowires for device applications. There have been reports of lasing in nanowires of GaN and ZnO, where either single nanowires or a forest of vertical nanowires3,6,10–12 have been used for optical and electrical pumping. Although individual nanowires itself can support lasing, adding distributed mirrors (DM) accommodates more allowances for device losses thus potentially enhancing lasing performance of quantum wires at a lower threshold. Quantum wire lasers based on large band-gap materials provide a mean to study the impact of excitonic and free carrier transitions on material properties like gain spectrum and the resultant threshold conditions.4,8,9 Defects and dislocations adversely affect the performance of the lasers leading to a higher threshold current even in the presence of the efficient radiative transitions engendered by excitons. The detrimental effect of the threading dislocations can be greatly reduced by using the lateral nanowires formed by wet chemical etching where further the excitonic transitions and tight confinement in the fabricated quantum wire light emitting diode lead to superluminescent light emission.13

This letter reports the observation of ultra-low threshold lasing in individual lateral nanowires coupled to lateral circular PMMA-air dielectric gratings. The nanowires have been obtained by controlled high temperature wet chemical etching of an InGaN-based LED heterostructure as described elsewhere13 when the screw dislocations are selectively removed leaving behind nearly merged hexagonal etch pits. Simulations of the chosen triangular nanowire waveguide predict a power confinement of ~18% for the design wavelength of 436.5 nm with the mode peak intensity lying within the nanowire waveguide. The experimentally observed peak lies at 433.8 nm and a threshold current density of 28.6 A/cm2 is realized for room temperature operation of the fabricated nanowire laser under pulsed-bias (frequency 100 kHz, 0.5 duty cycle) condition. The physical dimension of the thinnest nanowire in the device is ~20 nm and ~3 μm long while it starts lasing at a bias current of 8.95 nA.

Metalorganic chemical vapour deposition (MOCVD) technique is used to grow the heterostructure, shown in Fig. 1(a), on c-plane sapphire substrate. The growth of the 25 nm GaN buffer layer is followed by the 1.5 μm thick undoped GaN and the 2 μm thick Mg doped p-type GaN layers on a sapphire substrate. An electron blocking layer of 10 nm thickness and then 70 nm of undoped GaN are grown beneath the active region which comprises six 3 nm InxGa1−xN (x = 0.1)/10 nm InxGa1−yN (y = 0.01) unintentionally doped uncoupled quantum wells (see supplementary document14). While the thick undoped GaN layer prevents out diffusion of Mg into the active region during subsequent...
growth of other layers, it also increases the turn-on voltage of the diode. The equilibrium energy-band diagram as determined from the self-consistent simulation of Schrödinger and Poisson equations is shown in Fig. 1(b). The thick top n-layer ensures that sufficient thickness of the material remains after the wet etching process in order to facilitate the formation of the n-contact to the diode. The thickness of the n-layer along with etching duration provides tuning parameters for the nanowire lateral dimension. The nanowire itself can act as a Fabry-Perot cavity with the end facets being the mirrors such that it can support longitudinal lasing. The end-facet and side-wall leakage could be high if they are not optically flat. In order to compensate for these possible losses in the device, an external arrangement of dielectric mirrors (DM) has been incorporated into the design for feedback. The lateral stacks of PMMA (refractive index ~1.5 (Ref. 16)) alternating with the air dielectric was designed for the central wavelength of 436.5 nm, the primary peak position of the room temperature electroluminescence (EL) spectrum of the single nanowire LED device (see supplementary material). A schematic of the device with the DM is shown in Fig. 2(a). Figure 2(b) shows the device with both n- and p-contacts. The SEM images of a typical nanowire after primary mesa formation before and after their integration with the DM are shown in Figs. 2(c), inset to 2(d) and 2(d), respectively. The nanowires were formed by using wet chemical etching process using boiling H$_3$PO$_4$. The vertical and sidewall etch rates are found to be 10 nm/min and 0.55 μm/min, respectively. The Miller indices of the side-wall of the nanowire are (hkl) $(3013) \ and \ (1013)$. The individual nanowires were identified and a primary mesa was formed by inductively coupled plasma reactive ion etching (ICP-RIE) in Ar:Cl$_2$ (10:20 sccm) environment at 0.67 Pa pressure, ICP power 500 W and RF power 60 W to reduce current leakage through the top contact. An n-Ohmic stack of Ti/Al/Ni/Au (30 nm/100 nm/30 nm/100 nm) was deposited and lifted off at perpendicular to the length of the nanowire. This metallic contact was utilized as the mask during dry etching (secondary mesa) of the heterostructure in order to expose the bottom p-layer. The width of the metallic contact was designed to determine the length of the nanowire (3 μm). Rapid thermal processing (RTP) at 850°C for 30 s was performed in N$_2$ environment after the ICP-RIE at 0.5 Pa pressure, 550 W ICP power and 200 W RF power using BCl$_3$:Cl$_2$:N$_2$ (32:10:5 sccm). The Ohmic metal stack of Ni/Au (20 nm/20 nm) was deposited on the p-region subsequent to its electron beam lithography (EBL) patterning and lifted off in acetone. Rapid thermal annealing in O$_2$ ambient at 500°C for 1 min completed the p-Ohmic contact formation. A wet chemical treatment using H$_3$PO$_4$, H$_2$O$_2$, and H$_2$O was carried out to smoothen the surface and facets. The final step for creating the lateral dielectric mirror stack involved patterning and developing the PMMA e-beam photo-resist. The first layer in contact with the nanowire is chosen to be PMMA for efficient optical feedback. The measurements are carried out in an electromagnetic interference (EMI) shielded probe station where the optical characterizations are done by fibre optics based spectrometer to ensure maximum coupling to the edge emission from the device. The current versus voltage characteristics of the laser diode is shown in the inset of Fig. 1(b). The devices show higher turn voltage owing to the thick undoped GaN layer and long transport length between the p-contact and nanowire. The threshold current is experimentally determined to be 8.9 nA as observed from the output light intensity versus bias current density (L-I) plot shown in Fig. 3(a). The threshold current density ($J_{th}$) is estimated to be ~28.6 A/cm$^2$. It may be noted that the lateral well width increases as we go away from the surface due to triangular nature of the nanowire. The estimated current density is a pessimistic estimation assuming smallest lateral well width of 20 nm. The light output from a nanowire LED does not show the sharp turn on in its L-I characteristics unlike that of a nanowire laser. The non-linear super-luminescence behaviour of the LED is explained elsewhere. It is also observed that the electroluminescence (EL) spectrum undergoes a line-
width collapse during lasing as shown in the inset of Fig. 3(a). The inset shows the laser line of width 5 Å at a current density of 35 A/cm². The variation of line-width as a function of bias is shown in Fig. 3(b). The simulated field patterns for the nanowire of triangular cross-section are shown in Fig. 4, where the dark lines denote the vertical cross-section of the simulated structure. The dimensions of the simulated triangular waveguide structure closely resemble the atomic force microscope (AFM) image of the nanowire (see supplementary material). The positions of the quantum-wells in the AFM cross-section of the nanowire are determined with respect to the top surface as the reference. The lowest mode is predominantly like the TE₀₁ mode of the corresponding rectangular waveguide. The significant field components Eₓ, Hᵧ, and ᴴ in the electric (E) and magnetic fields (H) are shown in Figs. 4(a)–4(c), respectively. It may be noted that the peak intensity of the mode is within the triangular nanowire waveguide as seen from Figs. 4(d) and 4(e). Figure 5 shows the relative position of the lasing peak with respect to the reflectivity and the nanowire LED EL spectra, respectively. The central window of the reflectivity spectrum of the distributed mirror element overlaps the dominant peak of the EL spectrum of the nanowire LED device. Normal incidence on all points of the semi-circular stack can be assumed by approximating the light escaping from the end facets as point sources. The LED EL spectrum around the lasing wavelength of 433.8 nm is shown in the inset of Fig. 5. It may be noted that although the peak position is within the bandwidth of the reflectivity spectrum, the wavelength of the lasing peak is less than the designed wavelength. This may potentially be happening due to non-ideality in the mirrors which can lead to narrower window for near 100% reflectivity.

FIG. 3. (b) The light output versus bias current density and absolute bias current characteristics shows a threshold current density of 28.6 A/cm² (an absolute current of 8.9 nA). Inset shows the electroluminescence spectrum of the nanowire laser has a line width of 5 Å at the bias current density of 35 A/cm²; (b) linewidth as a function of bias for both nanowire LED and laser.

FIG. 4. (a) Eigen-mode simulated relative magnitude of the electric field components Eₓ, (b) magnetic field components Hᵧ, and (c) ᴴ in the cross-section of the device; (d) energy density distribution in the cross section of the device; and (e) 1-D energy density distribution along the vertical axis. It may be noted that the peak intensity of the mode is within the triangular cross sectional region. The effective group index is estimated to be 3.15 (see supplementary document).

FIG. 5. The central window of the reflectivity spectrum matches with the primary peak of the electroluminescence (EL) spectrum of the single nanowire LED device. The EL spectrum of the laser device lies within the maximum reflectivity band of the mirrors. On closer inspection, it is observed that the LED EL spectrum has a mode at the lasing wavelength of 433.8 nm.
In summary, we have demonstrated an electrically injected nanowire laser light with an ultra-low threshold current of 8.9 nA (threshold current density 28.6 A/cm²) and a line width of 5 Å. The nanowires are obtained by controlled wet chemical etching of an InGaN/GaN light emitting diode heterostructure in hot phosphoric acid. Using the relatively high refractive index difference between air and PMMA, a distributed mirror is coupled to the nanowire to achieve lasing. The method provides an elegant route for using the benefits of quantum confinement in the performance enhancement of optoelectronic devices.

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14See supplementary material at http://dx.doi.org/10.1063/1.4930825 for wave function confinement, eigenmode simulation for higher order mode on AFM cross-section, mirror reflectivity simulation and nanofabrication details.
16Nano PMMA and Copolymer datasheet, Micro Chem.