365 nm operation of *n*-nanowire/*p*-gallium nitride homojunction light emitting diodes

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The authors report gallium nitride (GaN) nanoscale light emitting diodes utilizing *n*-GaN nanowire/*p*-GaN substrate homojunctions. Utilizing electric field assisted alignment, *n*-type gallium nitride nanowires were placed on the surface of a *p*-doped GaN thin film. Electroluminescence with 365 nm peak wavelength and 25 nm full width half maximum was observed from these *p*-*n* junctions. These nanowire/epilayer *p*-*n* junction diodes were passivated with a thin layer of SiO_2 and did not exhibit any parasitic emission related to the bulk or surface defects. The present fabrication scheme, utilizing only batch fabrication techniques, yields reliable, electrically injected nanoscale ultraviolet light sources. © *2007 American Institute of Physics*.
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Multifunctional integrated photonic systems for biological/chemical detection and optical communication require nanoscale photonic building blocks such as light emitting diodes (LEDs), lasers, detectors, and waveguides. Electrically excited nanoscale deep ultraviolet (UV) lasers and LEDs operating in the 350–370 nm range are particularly important for data storage technology and biological applications including UV light induced autofluorescence technique for detecting airborne pathogens. Direct band gap group III-nitride (Al/Ga/In–N) semiconducting nanowires with their unique properties[1] (band gap spanning the whole electromagnetic spectrum, existence of ternary and quaternary alloys, and high thermal stability) are emerging as the most promising candidates for realizing these types of devices.

Gallium nitride (GaN) based nanowire LEDs have so far been realized by crossing *n*-GaN and *p*-GaN nanowires,[2] crossing *n*-GaN and *n*-Si nanowires,[3] *n*-GaN core and InGaN/Gan/*p*-AlGaN/*p*-GaN multishell structures,[4] and *p*-*n* junctions on the same nanowire.[5] Although these structures exhibit electroluminescence (EL), they are realized using tedious individual nanowire registration and manipulation along with serial fabrication techniques such as electron-beam lithography and focused ion beam etching, which make them unsuitable for commercial realization.

We have demonstrated electrically excited 365 nm emission from *n*-GaN nanowires and *p*-GaN substrate homojunction LEDs, which were assembled utilizing dielectrophoresis and fabricated using batch fabrication processes such as photolithography, wet etching, and metal deposition. The uniqueness of the proposed method is its simplicity, self-alignment (not requiring individual nanowire registration and contact formation), and compatibility with any nanowire and substrate material system, including nitrides requiring high processing temperatures (750 °C). The nanowires with diameters ranging from 50 to 300 nm and lengths up to 200 μm were grown by direct reaction of gallium vapor with flowing ammonia at 850–900 °C in a horizontal tube furnace.[6] Electron backscattered diffraction confirmed that the growth direction of the nanowires was along the *a* axis of the wurtzite structure.[7] As-grown, unintentionally doped nanowires are *n*-type with carrier concentration in the range of 2×10^{18} cm^{-3} measured utilizing field effect transistors.[8]

The *p*-GaN epilayer used for this study was 4 μm thick, grown by hydride vapor phase epitaxy on a *c*-plane sapphire substrate with Mg as the *p*-type dopant (hole concentration $=2.5\times10^{18}$ cm^{-3}). A 65 nm thick SiO_2 layer was deposited using plasma enhanced chemical vapor deposition (PECVD) on the *p*-GaN epilayer. This was followed by the deposition of Ti/Al/Ti (30 nm/100 nm/30 nm) layer using electron-beam evaporation [Fig. 1(a)]. Utilizing photolithography and

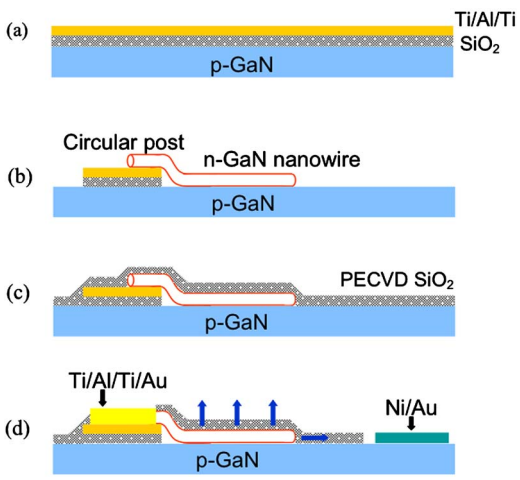

FIG. 1. (Color online) Schematic representation of the process of aligning and fabricating *n*-GaN nanowire/*p*-GaN epilayer LED.

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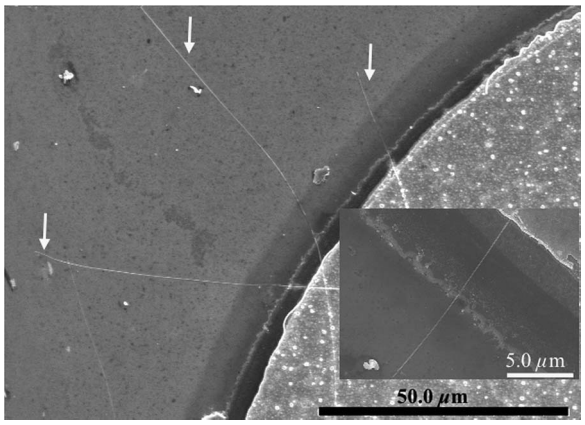

FIG. 2. SEM image of nanowires (indicated with the white arrows) aligned from a post. (Inset) SEM image of a nanowire cantilevered from a post touching the *n*-GaN substrate. Sidewall of the post is visible in the image. The PECVD SiO_2 is removed for the SEM imaging.

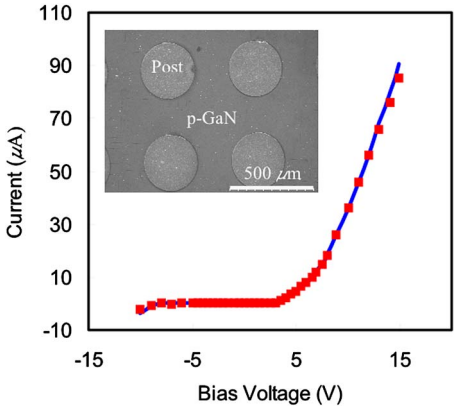

FIG. 3. (Color online) Current vs voltage characteristics of a single GaN nanowire/substrate junction LED at room temperature. Blue curve represents the characteristics of the device after annealing at 500 °C for 30 s in argon, and red squares represent the characteristics of the same device after a second annealing at 750 °C for 30 s. (Inset) SEM image of the posts on the sample. Contacts to the *p*-GaN are placed at the four corners of the samples (not shown here).

wet etching, 300 μm diameter circular, insulated metal contact pads with 500 μm pitch were obtained on the surface of the *p*-GaN epilayer. A suspension of the GaN nanowires in isopropanol, formed by sonicating the growth matrix, was dispersed onto the substrate with the insulated metal contact pads. In order to align the nanowires dielectrophoretically, a 10 V peak to peak, 1 kHz sinusoidal voltage was applied on one post while grounding the adjacent post. Nanowires aligned themselves in a diverging pattern from the biased post towards the grounded post (Fig. 2). The majority of the aligned nanowires had only 10% of their total length lying on top of the pads and the rest was in contact with the *p*-GaN layer forming the *p-n* junction [Fig. 1(b)]. Next, 40 nm of SiO_2 was deposited using PECVD, covering the entire sample [Fig. 1(c)]. A second photolithography and etching resulted in 250 μm diameter circular contacts on top of the first level contacts. Ti/Al/Ti/Au (30 nm/100 nm/30 nm/30 nm) was deposited followed by a lift-off to form the top contact to the nanowire. Having both top and bottom contacts reduce the contact resistances of these nanowire devices. The smaller diameter of the top contact relative to the bottom one would ensure that even with photolithographic alignment tolerance, the top metal contact would not come in contact with the *p* layer, thus eliminating the possibility of parasitic Schottky contact emission. For contact to the *p*-GaN layer, Ni/Au (30 nm/30 nm) layer was then deposited [Fig. 1(d)] at the four corners of the sample by a shadow mask.

A scanning electron microscope (SEM) image of the posts is shown in the inset of Fig. 3. Over 40 contact pads with nanowire junctions were tested, and the as-fabricated devices showed very low current levels with no detectable emission between 10 and 12 V. This is expected since forming low resistance Ohmic contacts to the nitrides require annealing at temperatures as high as 750 °C. These devices showed significant increase in the forward current after annealing in argon for 500 °C for 30 s (Fig. 3). Sharp onset of forward conduction started at 3.5 V, which is consistent with the band gap of GaN. Detectable emission was observed from the annealed nanowire junctions at 8 V forward bias with 18 μA current. Room temperature electroluminescence for different forward bias current levels is shown in Fig. 4(a) from a single *n*-GaN nanowire/*p*-GaN substrate junction device annealed at 500 °C (200 nm diameter nanowire). Peak emission occured at 365 nm with 25 nm full width half maximum (FWHM) at 50 μA. This is consistent with the band edge emission from high quality *n*-GaN epilayer (3.46 eV) grown using metal organic chemical vapor deposition technique,[9] and also with the photoluminescence measurements performed on these nanowires.[10] At higher injection levels (65 μA), a 385 nm emission was also observed in these devices, which could be due to GaN-oxide interface related recombinations. The absence of a 415 nm emission peak (associated with the recombination via Mg related deep levels in *p*-GaN) indicates that the emission was dominated by recombinations in the nanowire.[2] Low energy emissions such as yellow or red bands in the EL, which are often attributed to the presence of dislocations in nitrides, were not observed in these nanowire devices. This indicates that the defects in these nanowires (grain boundaries, stacking faults, etc.) do not act as efficient recombination centers. Over 40 nanowire LED devices have been tested, and all of them showed very similar emission properties. Under forward bias, the emission from the nanowire occurred along its length, consistent with the injection in the nanowire-epilayer junction along the length of the nanowire in contact with the *p* layer, with occasional brighter regions [Fig. 4(b) inset]. The brighter regions could be due to the local injection or light escaping through local defects such as grain boundaries[11] in the nanowire.

In order to investigate the reliability of these nanowire LEDs, approximately 30 operating devices were subjected to a second annealing at 750 °C for 30 s in argon. No deterioration was observed in the electrical properties of these devices after the annealing (Fig. 3). Marginal decrease in the EL intensity at high injection currents (65–75 μA) was observed after the second annealing [Fig. 4(b)]. For higher injection currents a marginal increase in the emission at the 385 nm was also observed. This indicates that the 385 nm emission might be due to surface related effects originating at the oxide-nanowire interface, as annealing would deteriorate the oxide-nanowire interface. Peak emission intensities of these nanowire devices were approximately linear with the current, which is crucial for modulation purposes (Fig. 5). Light intensity and the FWHM did not deteriorate signifi-

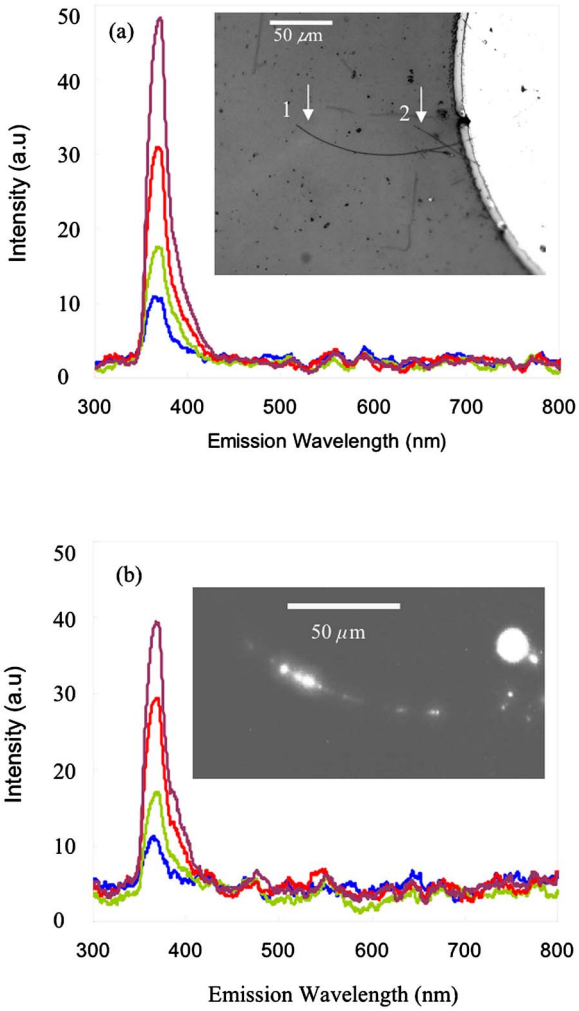

FIG. 4. (Color online) (a) EL of a single nanowire LED after annealing at 500 °C for 30 s in argon. The blue, green, red, and violet curves represent emission recorded with injection currents of 35, 55, 65, and 75 μA, respectively. (Inset) Gray scale optical image of a complete nanowire device with the end contact. A shorter nanowire is visible crossing the longer wire (ends of the two wires are numbered and indicated with white arrows). (b) EL of the same device after a second annealing at 750 °C for 30 s, showing only marginal deterioration in the characteristics. (Inset) Optical image of the same device under forward bias with 75 μA injection current. Wire 1 and wire 2 had 200 and 160 nm diameters, respectively.

cantly after annealing the devices at 750 °C, which demonstrates the robustness of the present device structures. The devices showed no signs of degradation even after significant length of operation (more than 2 h) at room temperature. Excellent thermal stability of the nanowire devices can be attributed to the top and bottom contact pads along with the oxide layer covering the nanowire. The oxide provided mechanical strength to the device structure and also passivated the nanowire surface, which resulted in reliable operation. Improved light extraction from the nanowire LEDs was achieved using the oxide layer instead of the bare wire as the

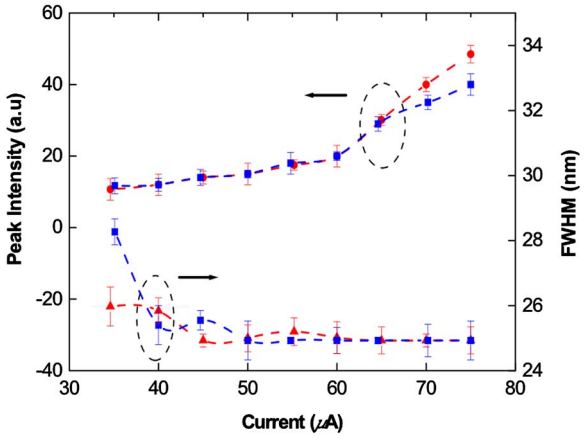

FIG. 5. (Color online) Peak emission intensity and FWHM of nanowire devices under forward injection condition. The red curve indicates the characteristics of the devices after 500 °C annealing and the blue curve indicates the trend after a second 750 °C annealing. The error bars represent the standard deviations of the data over 30 nanowire devices with diameters in the range of 180–220 nm.

critical angle θ_c for the nanowire-oxide interface is larger than that of the nanowire-air interface $[\theta_c = \sin^{-1}(n_1/n_2)$, where n_1 and n_2 represent the dielectric constants of the oxide/air and semiconductor, respectively].[12] Using passivations such as AlN with higher dielectric constant promises to improve the extraction efficiencies.

We have demonstrated the operation of GaN nanowire/bulk UV light emitting diodes, utilizing dielectrophoretic alignment, and simple fabrication techniques. The devices are stable with reliable operation at 365 nm wavelength. The present technique can be applied to other nanowire systems, and is suitable for applications requiring large area nanoscale light sources.

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