Electronic Supplementary Material (ESI) for Nanoscale.

Supplementary Material

Optically and electrically invariant multi-color single InGaN/GaN nanowire light-emitting diodes on a silicon substrate under mechanical compression

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1. PL Characterization of Single InGaN/GaN Nanowires (NWs)

(1) Epitaxial Growth of InGaN/GaN NWs

Single InGaN/GaN NWs with diameters from 220 nm to 280 nm were grown on the same Si substrate by selective area epitaxy (SAE) using radio frequency plasma-assisted molecular beam epitaxy (PA-MBE). The epitaxy took place on an arsenic doped *n*-type Si substrate with a 10 nm thin Ti layer being employed as the growth mask. Openings with sizes in the range of ~160 nm to ~220 nm were created on the Ti mask using e-beam lithography (EBL) and reactive ion etching. The NW diameter was mainly determined by the opening size. The color tunable property of single InGaN/GaN NWs with different diameters on the same Si substrate depends on the growth parameters.

As schematically shown in Figure S1(a), each NW consists of ~0.45 μm *n*-type Si-doped GaN segment, six InGaN/GaN (4 nm/4 nm) layers and ~0.15 μm *p*-type Mg-doped GaN segment. These NWs were grown using a Veeco GENxplor MBE system. Figure S1 (b) shows the field-emission SEM image (45° tilt view) of the single NW structures grown with diameter of 251 nm. The NWs exhibit hexagonal morphology and possess Ga-polarity based on the terminating facets.

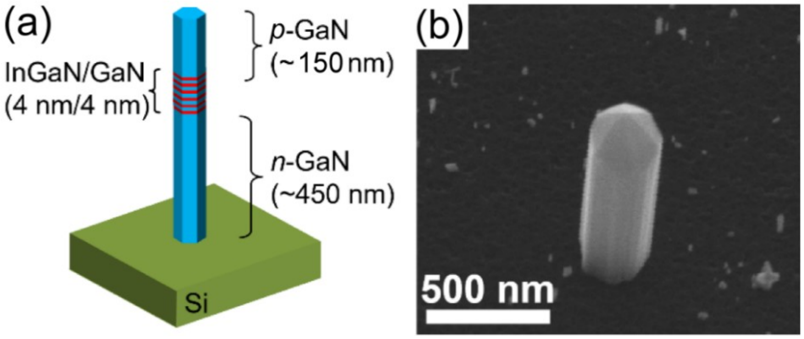

Figure S1: Sample for PL test. (a) Schematic of an InGaN/GaN NW structure selective-area grown on Si substrate. (b) 45° tilt SEM image of an InGaN/GaN NW with diameter of 251 nm.

(2) PL Characterization Results

Figure S2(a) shows the SEM photograph of the two micro-fibers pointing to a single InGaN/GaN NW for PL measurement at room temperature. The illumination microfiber was connected with a 405 nm laser source, and the detection microfiber connected with a spectrometer was employed for detecting luminescence and was positioned to the proximity of the NW top surface. The intersection angle between illumination and detection microfibers and the relative position between the detection microfiber and the NW both remained consistent during all PL measurements. As shown in the inset of Figure S2(a), an InGaN/GaN NW was grown between two straight slot-shaped markers on the Si substrate, and the markers facilitated the alignment of the two microfibers with the NW. The large gap between two adjacent NWs ensured the PL measurement from a single NW and avoids any optical crosstalk between NWs.

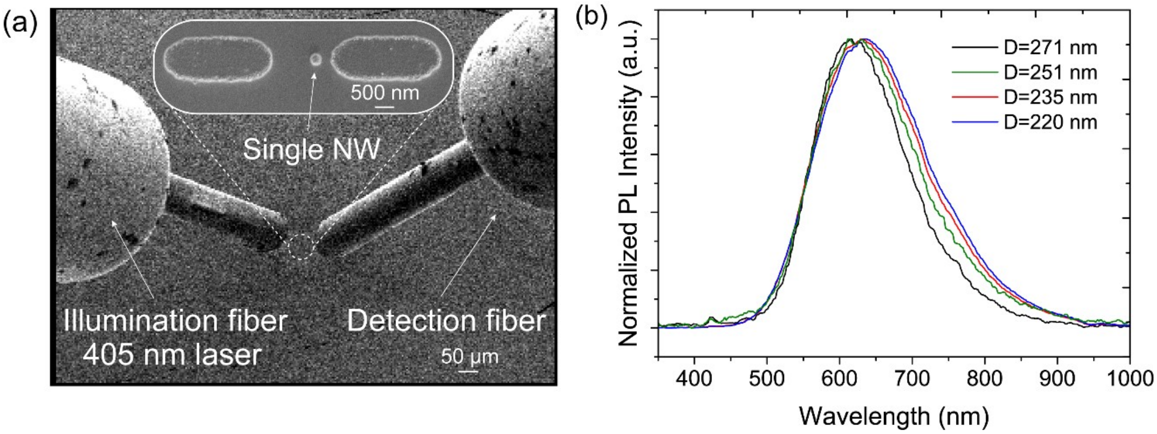

Figure S2: PL characterization of single InGaN/GaN NWs. (a) SEM picture of the PL characterization experimental setup. Top inset: A magnified view of an InGaN/GaN NW grown between two straight-slot-shaped markers. (b) PL emission spectra as a function of the NW diameter.

The PL emission spectra for four NWs with different diameters are shown in Figure S2(b). The four NWs were grown on the same Si substrate with identical epitaxy conditions, except that their lateral sizes (also referred to as diameters in the subsequent text) varied in the range of 220 nm to 280 nm. It is seen that the optical emission shows a consistent blueshift with the increase in NW diameter under, the emission wavelength continuously changes from 645 nm to 627 nm at the NW diameters of 220 nm to 271 nm. This phenomenon of size-dependent optical emission from single NWs can be explained by a previously reported deposition mechanism of size-dependent indium incorporation.[1] It was found that the indium incorporation from diffusion decreased with the increased NW diameter, leading to shorter emission wavelength.

2. Strain Simulation Results on Multi-diameter Single InGaN/GaN NWs

To facilitate the calculation of the reduction of piezoelectric polarization (Δ_{pz}), COMSOL strain simulations were performed for NWs with diameters of 325 nm, 470 nm, and 645 nm. In the simulation, an external compressive force of 5 μN was applied along the growth direction of each Ga-polar NW to induce mechanical strains. We extracted the specific strain in the middle quantum dots layer (48 nm in thickness), as the strain in this layer mainly affects the EL emission (thus the external compressive force of 5 μN could be safely assumed to apply uniformly on the top surface of a NW). Finally, the strain values were derived to be 0.1158%, 0.2005% and 0.3715% for single NWs with diameter of 645 nm, 470 nm, 325 nm, respectively.

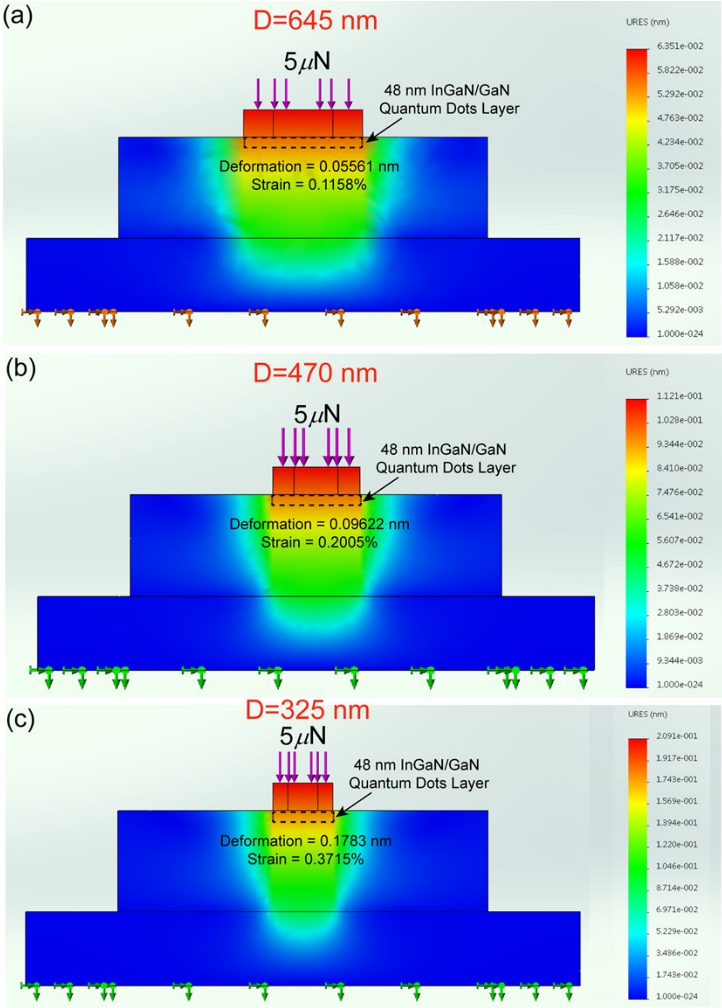

Figure S3: Strain simulation results of InGaN/GaN NWs from induced external stress (D refers to the NW diameter).

3. Sheet Charge Density Calculation

By using the Poisson equation, the 2D sheet charge density (σ) at the interfaces were calculated with/without external compressive stress, as shown in the Table S1. The sheet charge density (σ) was calculated by using the following equation:

$$\sigma = P_{top} - P_{bot} \tag{1}$$

where P_{top} is the total polarization in the top layer, and P_{bot} is the total polarization in the bottom layer. The charge density at the topmost/bottom interfaces of NW active region are changed due to the applied compressive stress.

Table S1. Calculated sheet charge density at the interfaces of nanowires with/without external compressive stress.

NW diameter (nm)	**Sheet charge density σ (C/m^2) without induced strain**		**Sheet charge density σ (C/m^2) with induced strain**	
	At the interface p-GaN/InGaN	At the interface InGaN/n-GaN	At the interface p-GaN/InGaN	At the interface InGaN/n-GaN
645	-0.00271	0.00271	0.01755	-0.01755
470	-0.00373	0.00373	0.02418	-0.02418
325	-0.00566	0.00566	0.03927	-0.03927

References

[1] Y.-H. Ra, R. Wang, S. Y. Woo, M. Djavid, S. M. Sadaf, J. Lee, G. A. Botton, and Z. Mi, “Full-color single nanowire pixels for projection displays,” *Nano Letters*, vol. 16(7), no. 7, pp. 4608–4615, 2016.