Electrically driven single-photon emission from site-controlled InGaNGaN quantum dots

Lei Zhang ¹, Chu-Hsiang Teng ², Pei-Cheng Ku ³, and Hui Deng ¹

¹Department of Physics, University of Michigan, Ann Arbor, MI 48109
²Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109
³peiheng@umich.edu, ‡dengh@umich.edu

Abstract: We report single-photon emission from electrically driven site-controlled InGaNGaN dot-in-nanowires, fabricated from a planar single InGaNGaN quantum well LED using a top-down approach. Each dot-in-nanowire’s formation site, diameter, height and material compositions were precisely controlled.

OCIS codes: (250.5590) Quantum-well, -wire and -dot devices; (160.4236) Nanomaterials.

1. Introduction

Quantum dots (QDs) based on III-N semiconductors are the most promising candidates for achieving scalable electrically driven single-photon sources at high operating-temperatures. High-temperature single-photon sources have only been demonstrated for QDs made of wide-bandgap semiconductors [1, 2] or non-semiconductor materials [3–6]. Among them, electrical-injection and site-control, which are two critical requirements for scalable device applications, have only been separately demonstrated for III-N QDs [2, 7, 8]. Here we demonstrate for the first time electrically driven single-photon sources based on site-controlled InGaNGaN QDs.

2. Sample structure and fabrication processes

The QD sample used in this work consisted of arrays of InGaNGaN dot-in-nanowires (DINs), with each DIN’s material compositions, forming site, diameter and height precisely controlled through the MOCVD growth, electron-beam lithography (EBL) and reactive-ion etching (RIE). Fig. 1(a) shows an array of DINs of 38 nm in diameter and 230 nm in height. Each DIN, as shown in the inset, contains a 3 nm thick InGaNGaN QD sandwiched by a 120 nm thick p-GaN (Mg: 3×10¹⁷ cm⁻²) and 12 nm thick unintentionally doped GaN (uid-GaN) layer at the top, and a 12 nm thick uid-GaN and 83 nm thick n-GaN (Si: 1×10¹⁸ cm⁻³) layer at the bottom. Fig. 1(b) shows the structure of the electrically driven devices, containing a p-contact made of ITO/Ti/Au (200/25/500 nm) layers, an n-contact made of Ti/Au (25/500 nm) layers and an insulating layer made of 200 nm thick spin-on-glass (SOG).

The fabrication flow, illustrated in Fig. 1(c), can be divided into three parts. First, we fabricated the cone-shape DINs from a planar single InGaNGaN quantum-well (QW) LED using EBL and RIE (step 1–3), as in [8]. Second, we cleaved the sidewall slope of the cone-shape DIN using KOH anisotropic wet-etching [9] (step 4), which enabled
simultaneously a thick p-GaN cap-layer for applying electrical contact and a small InGaN dot diameter for quantum confinement. Third, we planarized the sample using SOG, patterned and etched back the SOG, and applied the contacts (step 5-8).

Compared to all other existing III-N QD site-control methods [2,10], our DINs are particularly optimized for efficient current-injection, since the current-pathway fully overlaps with the QD active region.

3. Electroluminescence and single-photon emission

We characterized the electroluminescence (EL) properties of single QDs at 10 K using the setup illustrated in Fig. 1(d). The sample was mounted in a He-flow cryostat connected with a temperature controller and a source meter unit (SMU). The EL of a single QD propagated through the semi-transparent ITO contact and was collected and isolated using a confocal microscope setup, composed of three lenses (L1, L2 and L3) and a pinhole spatial filter, as in [8]. The real-space EL was monitored using a CCD camera. The EL spectrum was analyzed with a spectrometer with 0.1 nm wavelength resolution at ~400 nm. The second-order correlation (g(2)(t)) function was measured using a Hanbury Brown-Twiss (HBT) interferometer with an overall time resolution of ~200 ps.

The real-space EL image of a single QD at 9.5 V applied voltage is shown in Fig. 2(a). It was isolated by a pinhole (Fig. 1(d)) from an array of QDs with a 4 µm inter-dot separation. The EL spectra of the QD at different applied voltages are shown in Fig. 2(b). Each of the spectra was composed of a dominant exciton peak at 3.07 eV with a ~15 meV linewidth, and an optical-phonon peak at 2.98 eV, which was similar to the photoluminescence (PL) spectrum of similar devices [8]. The EL intensity vs. voltage data in Fig. 2(c) suggested that the QD had a turn-on voltage of ~6.5 V. The g(2)(t) data of the QD EL taken at 9.5 V (Fig. 2(d)) showed a g(2)(0) value of 0.45 without background subtraction, or 0.31 with background subtraction, demonstrating the single-photon nature of the QD EL.

![Fig. 2. Single QD EL at 10 K. (a) Real-space EL image of a single QD at 9.5 V DC voltage. The spot-size is limited by the optical resolution of our setup. (b) The integrated EL intensities of the QD vs. applied voltages. (c) The EL spectra of the QD at various applied voltages. (d) The g(2)(t) (blue curve) taken at 9.5 V shows g(2)(0) = 0.45 without background subtraction (red curve) and 0.31 with background subtraction.](JTh5B.6.pdf)

4. Conclusions

In conclusion, we have demonstrated electrically driven single-photon emission from site- and structure-controlled InGaN/GaN dot-in-nanowire QDs. These single-photon-emitting diodes were fabricated in a scalable fashion from planar single InGaN-QW LED sample using electron-beam lithography, reactive-ion etching and anisotropic wet-etching techniques.

[1] S. Bounouar, et al., “Ultrafast room temperature single-photon source from nanowire-quantum Dots,” Nano Lett. 12, 2977–2981 (2012).
[2] M. J. Holmes, et al., “Room-temperature triggered single photon emission from a III-nitride site-controlled nanowire quantum dot.,” Nano Lett. 14(2), 982–986 (2014).
[3] B. Lounis and W. E. Moerner, “Single photons on demand from a single molecule at room temperature.,” Nature 407, 491–493 (2000).
[4] A. J. Morfa, et al., “Single-photon emission and quantum characterization of zinc oxide defects.,” Nano Lett. 12, 949–954 (2012).
[5] N. Mizuochoi, et al., “Electrically driven single-photon source at room temperature in diamond,” Nat. Photonics, 1–5 (2012).
[6] S. Castelletto, et al., “A silicon carbide room-temperature single-photon source,” Nat. Mater. 12, 1–6 (2013).
[7] S. Deshpande, et al., “Electrically driven polarized single-photon emission from an InGaN quantum dot in a GaN nanowire,” Nat. Commun. 4, 1675 (2013).
[8] L. Zhang, et al., “Single photon emission from site-controlled InGaN/GaN quantum dots,” Appl. Phys. Lett. 103, 192114 (2013).
[9] D. Zhuang and J. H. Edgar, “Wet etching of GaN, AlN, and SiC: a review,” Mater. Sci. Eng. R Reports 48, 1–46 (2005).
[10] P. R. Edwards, el al., “Quantum dot emission from site-controlled InGaN/GaN micropyramid arrays,” Appl. Phys. Lett. 85, 4281 (2004).