# Lasing oscillation in multi-stacked InGaAs/GaAs quantum dots with a single GaAs nanowire cavity

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# Abstract

We report a demonstration of infrared lasing oscillation in multi-stacked  $In_{0.22}Ga_{0.78}As/GaAs$  quantum dots (QDs) with a single GaAs nanowire (NW) Fabry-Pèrot cavity. Micro photoluminescence spectra at 6 K of the NW cavity containing 50 stacked QDs exhibits lasing behavior at a peak wavelength of 864 nm with a threshold pump power density of 5.35 kW/cm<sup>2</sup>, which originates from the higher-order subband of the multi-stacked QDs. This is the first demonstration of lasing oscillation in a QD-NW cavity system.

# 1. Introduction

Semiconductor nanowire (NW) lasers have been intensively exploited as a component for applications in ultrasmall, highly efficient coherent light sources coupling to highly integrated nanophotonic components and optical circuits. In particular, NW lasers based on compound III-V materials, specifically GaAs, are most promising in terms of their compatibility with existing, well established growth/fabrication technology for integration of III-V-based photonic devices on Si platform. So far there have been several reports on the demonstration of GaAs-based NW lasers utilizing AlGaAs(or InGaP)/GaAs core-shell structures.[1-3] It would be advantageous if quantum dots (QDs) could be incorporated into NW cavities for the realization of ultrahigh-performance NW lasers, due to their discrete sets of density-of-states.[4] However, despite several reports on the formation/optical properties of nanowire-quantum-dots (NWODs) with various material combinations, no groups have realized NW lasers utilizing QDs as an active media because of difficulty in realizing highly-uniform, multistacked QD gain.

Our group has so far reported the demonstration of sitecontrolled InAs/GaAs NWQDs with a clear evidence of fully-quantized energy states in the NWQD[5,6], and realized high-quality, highly-uniform, multi-stacked In-GaAs/GaAs NWQDs (up to 200 individual QDs stacked in a single NW) without degradation of photoluminescence (PL) intensity, which has been difficult to attain with conventional Stranski-Krastanow QD growth technology.[7] Such structures can be realized by carefully tuning the growth conditions of each QD in single NWs (to tailor the emission energies) and also the locations of each QD. Here, we report on the first demonstration of infrared lasing oscillation in multi-stacked  $In_{0.22}Ga_{0.78}As/GaAs$  NWQDs within a single GaAs NW cavity. Micro-photoluminescence ( $\mu$ -PL) characterization is performed at 6 K to corroborate the lasing behavior of the single Fabry-Perot NW cavity containing 50 stacked NWQDs.

## 2. Experiments

Sample Preparation and optical characterization

All samples are grown by low-pressure metalorganic chemical vapor deposition at a total pressure of 76 Torr on patterned semi-insulating GaAs(111)B substrates. Trimethylgallium, trimethylindium, trimethylaluminium and tertiarybutylarsine are used as Ga, In, Al and As precursors, respectively. A 10 nm thick layer of  $SiO_2$  is patterned with an array of apertures with an average opening diameter of 44.8±1.3 nm and a pitch of 500 nm using electron beam lithography and reactive ion etching to be used as a growth mask. After surface cleaning with sulfuric acid for 2 minutes to remove carbon-related residue, wafers are loaded immediately into the reactor. First, the 50 nm thick GaAs core is formed at a growth temperature of 750°C on the patterned substrate. Next, 50-stack In<sub>0.22</sub>Ga<sub>0.78</sub>As heterostructures are formed at 750°C on the GaAs core which is followed by the growth of a GaAs spacer. (Figure 1(a)) The growth duration of each insertion is tuned in order to tailor



Fig. 1(a) Schematic, SEM and cross-sectional transmission electron microscope images of as-grown multi-stacked In-GaAs/GaAs NWQDs on patterned GaAs(111)B substrates. (b) SEM images of multi-stacked InGaAs/GaAs NWQDs transferred on SiO<sub>2</sub>/Si substrates. (c)  $\mu$ -PL spectrum at 6K of the scattered light from the end of a single GaAs NW embedding 50stack InGaAs/GaAs QDs with a pump power density of 4.2 W/cm<sup>2</sup>.



Fig. 2 (a) PL spectra of a single GaAs NW embedding 50-stack InGaAs/GaAs QDs with a pump power density ranging from 29.7 W/cm<sup>2</sup> to  $5.94 \text{ kW/cm}^2$  and (b) its integrated intensity at 864 nm and full-width at half-maximum versus pump power density.

the emission energies in a single GaAs NW for realization of uniform multi-stacked In<sub>0.22</sub>Ga<sub>0.78</sub>As/GaAs highly NWQDs.[7] Then, the In<sub>0.22</sub>Ga<sub>0.78</sub>As/GaAs heterostructures are completely covered with a GaAs shell at 570°C and a 10-nm-thick Al<sub>0.1</sub>Ga<sub>0.9</sub>As layer at 750°C which acts as in situ epitaxial passivation to mitigate the effect of surface Finally, a very thin GaAs cap layer is grown at states. 750°C to prevent the oxidation of  $Al_{0.1}Ga_{0.9}As$  layer. Detailed growth conditions are described in Refs [5-7]. The scanning electron microscope (SEM) image of typical In<sub>0.22</sub>Ga<sub>0.78</sub>As/GaAs NWQDs in Figure 1(a) displays the formation of a highly uniform, site-controlled hexagonal GaAs NW array with average diameter and height of 328±32 nm and 2.10±0.14 µm. Optical characterization of individual structures is carried out using confocal µ-PL spectroscopy under an excitation by pulsed Ti:sapphire laser (770 nm) with a repetition rate of 80 MHz and pulse width of >200 femtoseconds. Insertion of an f=50 cm cylindrical lens into the pump laser beam produces an elliptical focus with major and minor axes of approximately 15 and 2 µm, respectively. In order to detect the signal from a single NW using the confocal µ-PL setup, NWs are removed from their substrate by ultrasonication in isopropyl alcohol and transferred onto heated SiO<sub>2</sub>/Si substrates. The NWs transferred on SiO<sub>2</sub>/Si substrates are sparse enough that the signal from a single NW device with multi-stacked QDs is detectable by conventional  $\mu$ -PL setup, as shown in Figure 1(c).

#### Results and discussion

Figure 1(c) shows the  $\mu$ -PL spectrum at 6 K of the scattered light from the end of a single GaAs NW containing 50 InGaAs/GaAs QDs when excited with a pump power density of 4.2 W/cm<sup>2</sup>. Under a very low pump power density, only a single peak from the ground state of NWQDs is observed at 1.35 eV (925 nm) with a full-width at half-maximum (FWHM) of 54.5 meV, which is comparable to the wire-towire size distribution of single-stack InGaAs/GaAs NWQD ensembles, as we have previously reported.[5,6] We also observe a periodic modulation of the spontaneous emission caused by longitudinal Fabry-Pèrot resonances with a mode spacing of ~40 meV. Upon increasing the pump power density, the PL intensity of the ground state of NWQDs saturates and instead another peak emerges at shorter wavelength. A sudden increase in the emission intensity is observed at the emission peak wavelength of 864 nm and the PL intensity immediately becomes one order stronger than the background spontaneous emission. Figure 2(b) shows the integrated intensity at 864 nm and the respective peak versus pump power density which exhibits clear "s-like" dependence characteristics of transition from spontaneous to amplified spontaneous emission, and finally to lasing. We also observe a narrowing of the FWHM from >8 nm to <1 nm with pump power densities. From these results, we believe that the observed lasing behavior originates from the higher-order subband of multi-stacked NWQDs.

## 3. Conclusions

We report the demonstration of infrared lasing oscillation at 6 K in 50-stack  $In_{0.22}Ga_{0.78}As/GaAs$  QDs with a single GaAs NW cavity. Single Fabry-Pèrot NW cavities containing multi-stacked QDs are realized by removing asgrown NWs by ultrasonication and transferred on SiO<sub>2</sub>/Si substrates.  $\mu$ -PL spectra of the NW cavity containing the QDs at 6 K exhibits lasing behavior at 864 nm with a threshold pump power density of 5.35 kW/cm<sup>2</sup>, which originates from higher-order subband of multi-stacked QDs. To the best of our knowledge, this is the first demonstration of lasing oscillation from QD-NW cavity system.

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