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Growth and Characterization of Vertical Nanocavity Using Core-multishell Nanowires

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Abstract

We have fabricated vertical cavity structures utilizing GaAs/InGaAs core-multishell nanowires (NWs) by selective-area metalorganic vapor phase epitaxy (SA-MOVPE). The low-temperature PL exhibited quasi-equi-distant peaks under cw excitation, which were confirmed to be originated from the cavity mode in NWs. Under pulsed excitation, new peaks appeared superlinearly with excitation power, which is suggestive of stimulated emission or lasing in vertical NWs.

1. Introduction

Semiconductor nanowires (NWs) are attracting interest for applications in various kind of nanoscale devices, such as field-effect transistors (FETs), light-emitting devices, solar cells, and so on, due to their unique electrical and optical properties. From the application point of view, small footprints of the NWs are important for the high-density integration of NW-based devices. In contrast to the significant progress in the vertical surrounding gate NW FETs, less attempts have been made for vertical light-emitting devices, particularly, NW-based lasers. This is partly because of the difficulty in realizing high reflectivity at the NW/substrate interface in vertical NWs and achieving large Q-factors, while lateral, laid down NWs can utilize their both edge to realize Fabry-Perot cavity structures with sufficient reasonable Q-factors [2]. The presence of large Q-factors is demonstrated in thick nanoneedle structures in the vertical configuration, and compensates the small refractive index difference between NWs and the substrates [1]. In the previous study [3], we reported on the modal structure in relatively thick (diameter d larger than λ/n_r, where λ is the wavelength and n_r the refractive index of an NW) NWs and method of their realization by utilizing two-step growth [4] of NWs in selective-area metalorganic vapor phase epitaxy (SA-MOVPE). Here, we report on the growth of GaAs/InGaAs core-multishell NWs for vetical NW cavity structures and their characterization.

2. Experimental Procedure

The InGaAs/GaAs core-multishell NWs having this diameter was grown by SA-MOVPE. The starting substrate partially covered with SiO_2 mask for SA-MOVPE was prepared by electron-beam lithography and wet etching. The diameter d_0 of the mask hole was 100 nm, and the pitch a of the array was 3 μm. We first grew GaAs NWs under high growth temperature T_G and low AsH_3 partial pressure [AsH_3], namely, T_G =720°C and [AsH_3] =2.5×10^{-4} atm. The growth time was 25 min. Then, T_G was lowered to 570°C and GaAs, InGaAs and GaAs were successively grown under [AsH_3]=1.0×10^{-3} atm, for 15, 1, and 5 min, respectively. The partial pressure of TMGa [TMGa] and TMIn [TMIn] was 2.7×10^{-6} and 2.6×10^{-7} atm, respectively. After the growth, size of the NWs was measured by secondary electron microscopy (SEM), and photoluminescence (PL) measurement on single NWs was conducted from 4 K to 100K using HeNe laser or Ti:sapphire laser for cw and pulsed excitation, respectively.

3. Results and Discussions

Figure 1 shows an SEM image of the grown NWs. We can see uniform array of NWs. The diameter d of the NWs is about 800 nm. The length L of the NWs were 6.45 μm.

Figure 2 shows PL spectra of individual NWs at 4.2K under cw excitation. Although the size of the NWs are very similar each other (as shown in Fig. 1), the emission spectra considerably differs from NWs to NWs. This is presumably because of the difference of microstructure in InGaAs layers. That is, alloy content may differ from NWs to NWs. Furthermore, it is likely that there are large alloy fluctuations in InGaAs layer within a single NW. It is noted that nearly periodic, multiple peaks were observed in most of the NWs investigated here.

To investigate the origin of these peaks, temperature-dependent measurement of PL was carried out. The PL spectra of NW #1 are shown in Fig. 3(a). As shown in Fig

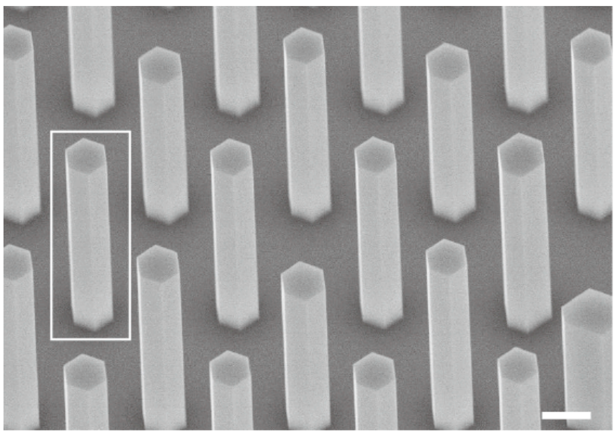

Fig. 1 SEM image of the core-multishell NWs. An NW enclosed by a white box indicates the NW investigated in detail (NW #1). Scale bar, 1 μm.

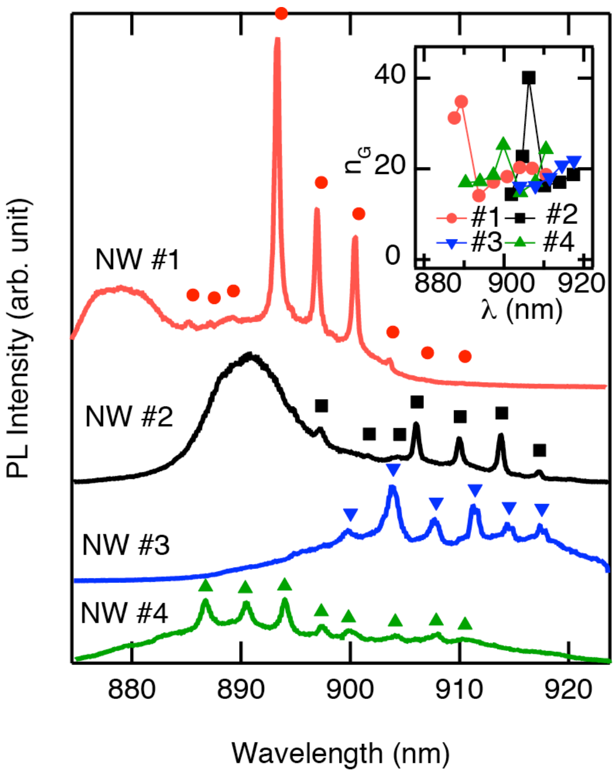

Fig. 2 Low-temperature PL spectrum of individual NWs. Inset shows the group index of calculated based on the peak spacing in each spectrum.

3(a), these peaks were clearly observed up to T=100K, and showed redshift as T increased. Figure 3(b) shows the positions of the peaks, plotted as a function of T. The results of NW #2 are also plotted. The dashed line in the figure represents the wavelength shift of GaAs band gap energy, and one can see the observed shift of the peaks was much smaller than the shift associated with the bandgap shrinkage of GaAs/InGaAs. This concludes that the observed peaks are originated from the cavity mode in the vertical NWs. The cavity Q-factors are in the order of 2000.

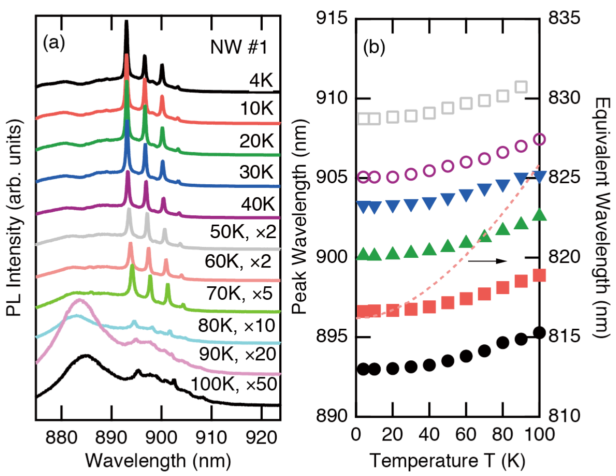

Fig. 3 (a) Temperature dependence of PL spectra of NW #1. (b) PL peak position, plotted as a function of temperature for NW #1 (closed symbols) and NW #2 (open symbols).

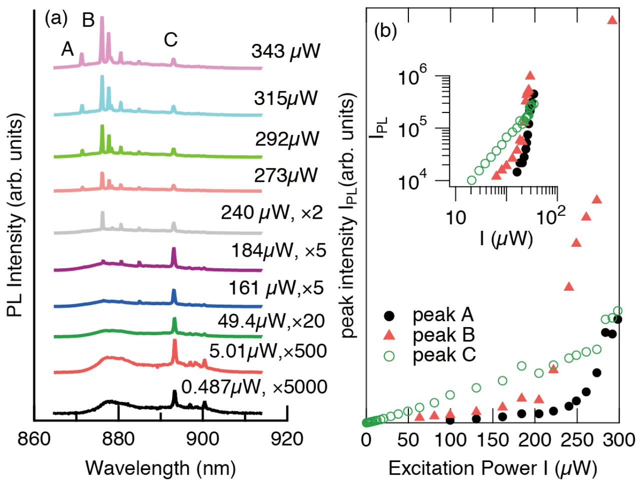

Fig. 4 (a) Excitation intensity dependence of PL under pulse excitation. (b) PL peak intensity, plotted as a function of excitation

The group index n_G of the NW cavity is calculated by using formula

$$n_G = \lambda^2 / 2L\Delta\lambda \qquad (1)$$

and is plotted in the inset of Fig. 2, where $\Delta\lambda$ is the peak spacing. The calculated group index was order of 20. This value is much larger than the expected group index in NWs from the dispersion relationship of propagation constant of the NW waveguide [3]. Numerical simulation using Meep [5] revealed that the there were a variety of cavity modes in the present wavelength range, and the assignment of the modes requires further investigation.

PL under pulsed excitation was conducted for NW#1 and results are summarized in Fig. 4. The intensity of cavity peaks (for example, peak C in Fig. 4(a)), which were observed under cw excitation, increased linearly with excitation power I for three decades. In addition, at intense excitation, new peaks (for examples, peaks A and B in Fig. 4(a)) appeared around 880nm, which grew superlinearly with I (see Fig. 4(b)). This suggests the stimulated emission or lasing in vertical NWs.

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