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# Fabrication and Characterization of InP Nanowire Light Emitting Diodes

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## 1. Introduction

Semiconductor nanowires (NWs) are attracting recent interest as a promising candidate as the building blocks for nanoelectronics and nanophotonics. Especially, InP-based NWs [1-4] are promising for the application of photonic devices as well as electron devices, because they have direct band gap compatible with optical fiber telecommunication bands. Various kinds of heterostructures have also been realized based on InP NWs, such as quantum dots (QDs) [5-7] or core-shell structures [9].

Light-emitting diodes (LEDs) are one of the important device applications of NWs[5,10]. One of the advantages of NW-based LEDs is that, because of their small footprints, NWs can be grown epitaxially without constraints of lattice matching issues [11]. This allows more selections of materials and expansion of wavelength range. More importantly, it enables us to grow dislocation-free III-V or nitride-based materials directly on Si or other heterogeneous substrates. Tomioma *et al*. [12] and Kikuchi *et al*. [13] have already demonstrated GaAs-based and GaN-based NW LEDs on Si, respectively. Free-standing NWs are also advantageous for LEDs because they are isolated from high-index materials and thus, have large light extraction efficiency. Furthermore, making contacts for individual NWs are straightforward. The latter two points are particularly important for QD-based single photon sources and offer possibilities over conventional structures, where QDs are embedded in high-index materials and complicated post growth fabrication process is required [14] as well as density and position control of QDs.

We here report on the fabrication and characterization of LEDs using InP NW arrays formed by selective-area metalorganic vapor phase epitaxy (SA-MOVPE). We will show a feasibility of our SA-MOVPE grown NWs to optically access single NW-LEDs, which is suitable for single photon sources.

## 2. Experimental Procedures

Figure 1 shows a schematic cross section of a NW-LED. First, InP NW array with p-n junction in the axial direction were grown by SA-MOVPE. Starting substrate of the growth was p-type InP (111)A, on which $SiO_2$ mask pattern consisting of triangular lattice of circular holes was defined. Mask patterns for NW array were defined within 100 $\mu$m by 100 $\mu$m regions, and each region had different diameter $d_0$ and pitch $a$ of mask opening. $d_0$ was changed from 50 nm to 100nm, and $a$ was from 600 nm to 3 $\mu$m. Then, SA-MOVPE growth was carried out with horizontal low-pressure system operating at 76 Torr. Trimethylindium (TMIn) and tertiarybutylphosphine (TBP) were used for source materials, and $SiH_4$ and diethylzinc (DEZn) were use for n- and p-type dopant sources, respectively. V/III ratio was 18.4 and growth temperature was 640°C, which expected to result in the formation of wurtztite (WZ) InP [2,4].

Fabrication process of LEDs is as follows. After the growth, the space between NWs was filled with polymer-resin (benzocyclobutene, BCB) as a transparent electrical insulator by spin coating. The overlaid excess resin was removed by reactive ion etching. Next, a transparent indium tin oxide (ITO) film electrode was first sputtered onto NWs array and patterned by using photolithography and wet etching by HCl. Finally, the backside electrode on the substrate was formed by alloyed Au-Zn.

For characterization, current-voltage (I-V) and electroluminescence (EL) measurement was carried out at room temperature with standard setup. Micro-photoluminescence ($\mu$-PL) measurement was also carried out at room temperature with excitation and detection spot of about 2 $\mu$m. We studied two NW-LED chips (#1 and #2) fabricated in different growth and process runs.

## 3. Results and Discussions

Figure 2 shows a typical SEM image of InP NW array with p-n junction for $a$=1 $\mu$m. We can see NWs with height $h$=2.0 $\mu$m and with hexagonal cross sections are formed. The NWs were slightly tapered and the side of the hexagon was parallel to the [110]-direction. This indicates that the NW had WZ crystal structure as expected [4]. Formation of WZ was also confirmed by $\mu$-PL, which exhibited blueshifted peak at 1.43 eV with respect to zincblende InP. The diameter $d$ of the NWs was 180 nm at its base, and was larger than the opening diameter $d_0$ (~100nm), indicating some lateral growth. The tapering and lateral growth are presumably due to lower growth temperature as compared

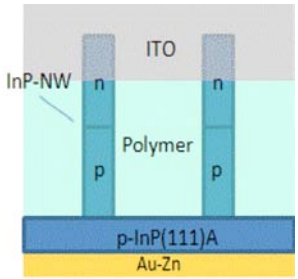


Fig. 1: Schematic cross-sectional illustration of a NW-LED.

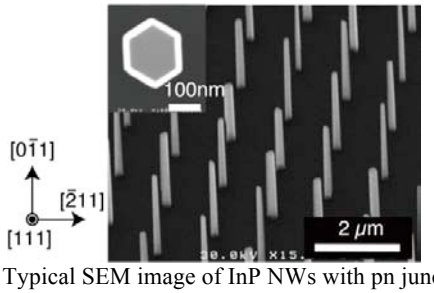

Fig. 2: Typical SEM image of InP NWs with pn junction.

to the conditions for ideal WZ reported in Ref. [4]. Similar NW arrays were formed for other pattern pitch $a$ and opening size $d_0$.

We observed clear rectifying characteristics with negligible forward bias leakage in current-voltage (I-V) characteristics reasonably uniform EL from 100 $\mu$m by 100 $\mu$m regions, where NW array was defined, in most of the fabricated LEDs. One of the typical results is shown in Figs. 3(a) and (b) for a device with $d$=120nm, $h$=2.45$\mu$m, and $a$=600nm in LED #1. The turn-on voltage was about 1.4 V, which is consistent with the band gap of WZ-InP, EL peak was located at 857 nm (~1.45eV), and the peak position shows no shift up to I~20mA. Furthermore, current-light output (I-L) is fairly linear. Detailed analysis of I-V characteristics of this device showed ideality factor $n$ of the diode was about 7.3, which is higher than compound III-V semiconductor planar LEDs [14], and a series resistance of about 61 Ω.

Figure 4 shows an emission image of NW-LED for a sample with $a$=3$\mu$m in LED #2. The emission is not completely uniform and the current leakage seems to be larger than other samples with shorter $a$. Nevertheless, we can clearly see emission from individual NW-LEDs. This indicates that it is possible to optically access single NW-LED. Because the pitch of the array is 3 $\mu$m and can be controlled by mask pattern, electrical contact with single NWs will also be feasible. We have recently reported single photon emission from a InAsP QD in a single InP NW [15]. Thus, our results are promising for realizing single photon sources using NWs.

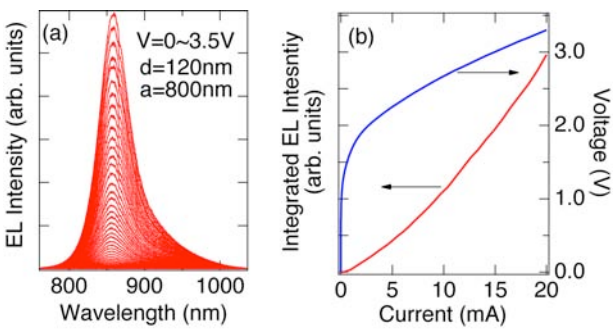

Fig. 3: (a) EL spectra of a NW-LED. (b) I-L and I-L characteristics.

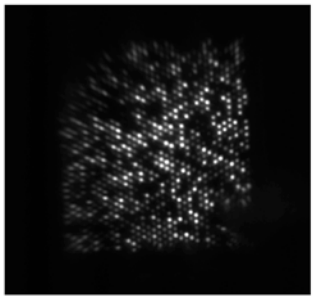
Fig. 4: Emission image of a NW-LED array with pattern pitch $a$=3$\mu$m.

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