Invited Paper

Radial InP/InAsP/InP Nanowire Heterostructures and Controlling Their Position for Near-infrared Nanowire-arrayed Optical Devices

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Semiconductor nanowires (NWs) that have a vertically elongated shape are attractive as building blocks for arrayed nano-devices because of their small footprints. InP NWs, on which heterostructures can be formed by introducing In(Ga)AsP alloy materials, are suitable for application to near-infrared optical devices. Especially, heterostructures formed in the radial direction of NWs are expected to have an advantage in terms of device performance, since the radial heterostructures create a larger active region in each NW owing to their high aspect ratio. In this work, radial InP/InAsP/InP quantum well (QW) structures were fabricated on the sidewall of InP NWs. In consideration that these NW heterostructures are to be applied to array-type devices, position-controlled growth of InP NWs on patterned substrates was also demonstrated.

The InP NWs were fabricated by vapor-liquid-solid (VLS) growth with the assistance of Au catalysts. On InP(111)B substrates, Au colloidal particles with a diameter of 100 nm were randomly deposited. The crystal growth was performed using metal-organic vapor-phase epitaxy. 3-µm-long InP NWs with wurtzite (WZ) crystal phase were grown at 400°C using $(CH_3)_3In$ and PH_3 as precursors. Sulphur doping with H_2S was used to enhance the formation of WZ crystal phase in the NWs [1]. After the Au particles were removed by wet chemical etching, which suppressed the axial growth of the NWs during the radial growth process, single InP/InAsP/InP QWs were radially grown on the sidewall of the InP NWs at 530°C. AsH_3 was used as an As source. In the position-controlled VLS growth of the InP NWs, patterned substrates with regularly-aligned Au catalysts at SiO_2-mask openings were used. The patterned substrates were prepared by depositing a 50-nm-thick SiO_2 film on an InP substrate, forming a two-dimensional array of 100-nm-diameter openings on the film, and depositing 40-nm-thick Au films in the openings. Pattern with a pitch range of 10 – 100 µm, which gives sufficient space for fabricating individually addressable devices, was intensively studied.

Scanning-electron-microscope (SEM) images of InP NW cores grown using random Au particles and InP NWs with a radial $InAs_{0.4}P_{0.6}$/InP QW are shown in Figs. 1(a) and (b), respectively. As for the radial QW sample (Fig. 1(b)), it is clear that radial growth increased the lateral size of the NWs while axial growth was well suppressed. As a result, straight and smooth NWs with a radial QW were obtained.

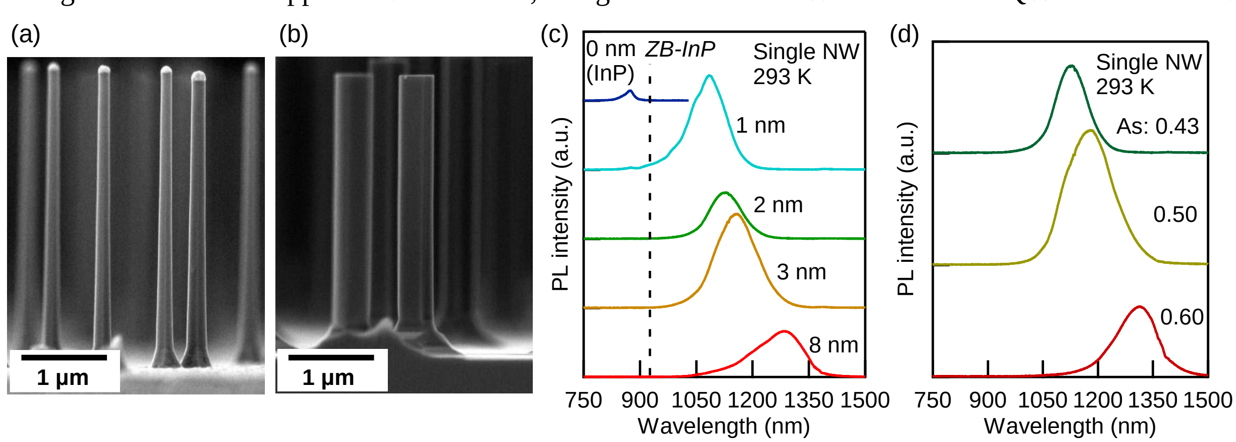

Fig. 1. SEM images of (a) InP NW cores and (b) InP NWs with radial $InAs_{0.4}P_{0.6}$/InP QW. Room-temperature PL spectra of single NWs with varying (c) $InAs_{0.4}P_{0.6}$ QW widths and (d) As content of 2-nm-thick InAsP QW.

Transmission-electron-microscope (TEM) observations and X-ray diffraction measurements show that the radial QWs grew epitaxially on the sidewall of the NW cores and have high-quality WZ crystal phase [2].

Photoluminescence (PL) properties of single NWs (dispersed on Si substrates) with varying InAsP QW thickness and As content were evaluated at room temperature. As shown in Fig. 1(c), an InP NW core with an InP shell (0-nm InAsP) shows PL emission at around 870 nm, which is 60-nm shorter than the wavelength of zinc-blende (ZB) InP, indicating the WZ crystal structure. As InAsP QW thickness increases, PL wavelength redshifs due to the change in the quantum confinements. As shown in Fig. 1(d), as As content of the InAsP QW layer increases, PL wavelength redshifts due to the reduction of InAsP bandgap energy. PL wavelength of the radial QWs on the sidewall of the NWs can thus be controlled in the same manner as a conventional film grown on planar substrates with ZB crystal. Moreover, the PL wavelength covers the 1.3-μm region, suggesting the possibility of data-communication applications.

In regard to the position-controlled growth, the axial growth rate of the InP NWs on the patterned substrates was found to be controllable to the same order as that of NWs grown on InP substrates by conventional VLS growth without SiO_2 masks. However, as shown in Fig. 2(a), in addition to the vertical Au-catalyst NWs, plural NW-like structures were formed in inclined directions from a single opening. This result suggests that excess group-III materials that are not incorporated in Au catalysts easily accumulate in the mask openings possibly via vapor-phase diffusion from the mask regions, which form In droplets and cause self-catalyst NW growth. It was found that introducing HCl gas during the NW growth efficiently removes the excess group-III materials. As shown in Fig. 2(b), straight, vertical InP NWs were successfully formed by controlling the HCl flow rate, while suppressing the anomalous growth.

Using the same fabrication procedure of radial heterostructures as used for the random NWs, InP/InAsP QWs were radially grown on the sidewall of the position-controlled InP NWs. Figure 2(c) shows a PL-intensity mapping image of NW arrays at room temperature. A two-dimensional PL pattern coming from the radial QWs were clearly observed in the 1.3-μm wavelength region.

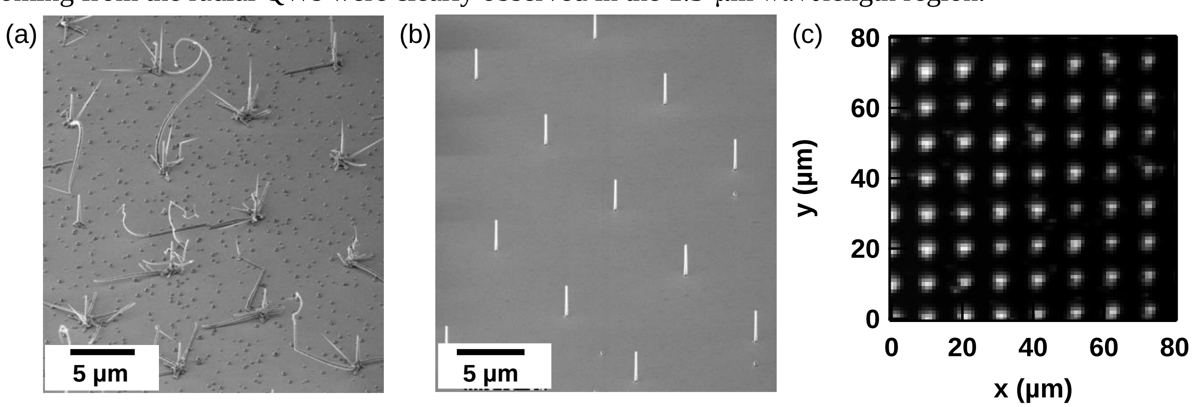

Fig. 2. SEM images of position-controlled InP NWs formed (a) without HCl flow and (b) with HCl flow. (c) PL-intensity mapping image of NW arrays with radial InP/InAsP/InP QWs (λ = 1350 nm).

In summary, we realized high-quality WZ-InP NWs with radial InP/InAsP QWs, and observed the PL from single NWs at a room temperature. We showed that the PL wavelength was controllable by adjusting radial QW thickness and arsenic composition, and demonstrated PL in the 1.3-μm region. Also we successfully grew position-controlled InP NWs using patterned substrates and observed PL of NW arrays with radial QWs. These results demonstrate that high-quality WZ-InP NWs with radial InP/InAsP QWs are promising for application as compact near-infrared light-emitting-device arrays.

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References

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