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Control of Diameter and Pitch of InGaAs Nanowire Arrays in Selective-area Metalorganic Vapor Phase Epitaxy

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1. Introduction

Free-standing semiconductor nanowires (NWs) have generated much research interest lately because of their unique features which is suitable for future electronic/pho–tonic devises, such as field–effect transistors (FETs), single photon sources (SPSs), and so on [1,2]. For realization of such future devises, it is important to control the diameter of NWs. In particular, reduction of diameter is important to avoid introducing misfit dislocations in lattice–mismatched systems [3] as well as to improve the performance of devi–ces. In addition, it is necessary to control the position and spacing of NWs freely depending on the application. To date, we have reported on InGaAs NWs grown by selective -area metalorganic vapor phase epitaxy (SA–MOVPE) [4–6]. However, these reports are still limited to use of over 40 nm–diameter openings. In present study, we investigated the SA growth of InGaAs NWs in smaller diameter (30 nm) openings, and found that their growth behavior and nucleation process are significantly dependent on opening diameter and mask pitch. We will discuss the origin of these growth behaviors and explain the procedures to grow 30nm-diameter InGaAs NWs independent of mask pitch.

2. Experimental Procedures

SA–MOVPE growth of InGaAs NWs was carried out on GaAs(111)B partially covered with SiO_2 mask. The opening diameter, d_0, and mask pitch, *a*, of mask holes were changed from 30 nm to 50 nm, and 750 nm to 5 μm, respectively. The ratio of partial pressures of TMIn, [TMIn], and TMGa, [TMGa], was 13:87. Total group-III supply, [TMIn]+[TMGa], was 2.3×10^{-6} atm, and growth time, *t*, was 30 min unless otherwise specified. The partial pressure of AsH_3, [AsH_3] was ranged from 0.63×10^{-4} to 5.0×10^{-4} atm, giving V/III ratio (V/III) was from 27 to 214. The growth temperature, T_G, was 695°C and kept constant through the experiment, in order to minimize the variation of alloy composition in InGaAs [4–6].

3. Results and discussions

1. Growth of InGaAs NWs by using conventional optimum growth condition

Figures 1(a) and 1(b) show SEM images of the sam–ples after the growth of InGaAs for a = 3 μm. The V/III was 107, which is the optimum value led from our previous reports [4–6] to obtain thinner NWs with sufficient length. We can see highly uniform NWs are formed for d_0 = 50 nm (Fig. 1(a)). The Ga composition of these NWs was 77% estimated by micro–photoluminescence measurements at 4K. Although the NW diameter, *d*, was larger than d_0 and was 110 nm, it can be reduced close to d_0 when an appropr–iate growth time is used [4]. However, there was no growth for d_0 = 30 nm (Fig. 1(b)). The growth was confirmed when a < 1μm for d_0 = 30 nm, as summarized in Fig. 1(c). On the other hand, NW growth was confirmed independent of *a* when d_0 = 50 nm. These results indicate that the nucleation process of InGaAs is clearly dependent on d_0 and *a*.

2. Growth behavior depending on the V/III ratio

To study the effect of nucleation process in more detail, we investigated the V/III dependence of growth behavior for d_0 = 30 nm and a = 3 μm, and the results are summarized in Fig. 2(a)–(d). The growth of InGaAs was confirmed in almost all of mask openings with high uniformity when V/III was lower than 54. In addition, the amount of growth of InGaAs increases as V/III decreases. Similar growth behavior was also confirmed for a = 5 μm.

These results can be explained as follows. Firstly, nucleation of InGaAs in the mask holes is less probable for smaller d_0. Secondly, the nucleation is also influenced by the effective V/III at the mask hole, and lower effective V/III promotes the nucleation due to the reduction of the coverage of As-trimer on GaAs(111)B surface [7]. Thirdly, the amount of effective supply of Ga and In at the mask holes is dependent on *a*. Because the growth temperature was relatively high, group-III supply from the masked areas to the mask openings was reduced due to re-evaporation, and the reduction of group-III supply was more enhanced for lager *a*. Thus, effective V/III increases for larger *a*, resulting in the difficulty of the nucleation.

V/III dependence of NW height, *h*, and *d* for d_0 = 30 and 50 nm are shown in Figs. 2(e) and 2(f). The *d* reduces as V/III ratio decreases. In addition, the axial growth rate was the maximum when V/III was 107, which is thought to be optimum for d_0 > 50 nm. However, the axial growth rate rapidly decreased for V/III of less than 54, and NW length becomes quite short as well as shown in Fig. 2(d). This su–ggests that the desorption of InGaAs from (111)B NW top facet was significantly enhanced with reducing V/III. Con–cequently, it is difficult to obtain sufficient length of NWs with d ~ 30 nm with simple a manipulation of V/III.

3. Two-step growth sequence for obtaining 30nm-diameter InGaAs NWs independent of the mask pitch

Based on aforementioned understanding, we carried out the growth of 30 nm-diameter NWs by adopting two-step growth sequence shown in Fig. 3(a). Here, the V/III for the first growth was set to be 9.1 to enhance the nucleation at the initial stage, and it was 107 for the second growth to enhance the axial growth and minimize the radial growth. The result is shown in Fig. 3(b). We successfully obtained highly uniform NWs without any radial growth for d_0 = 30 nm and a = 3 μm. Similar NWs were also obta–ined for the other a, where radial growth was limited to a few nm as shown in Fig. 3(c). These results will contribute to realize much finer and various high quality axial heterostructure NWs independent of the location of NWs.

References

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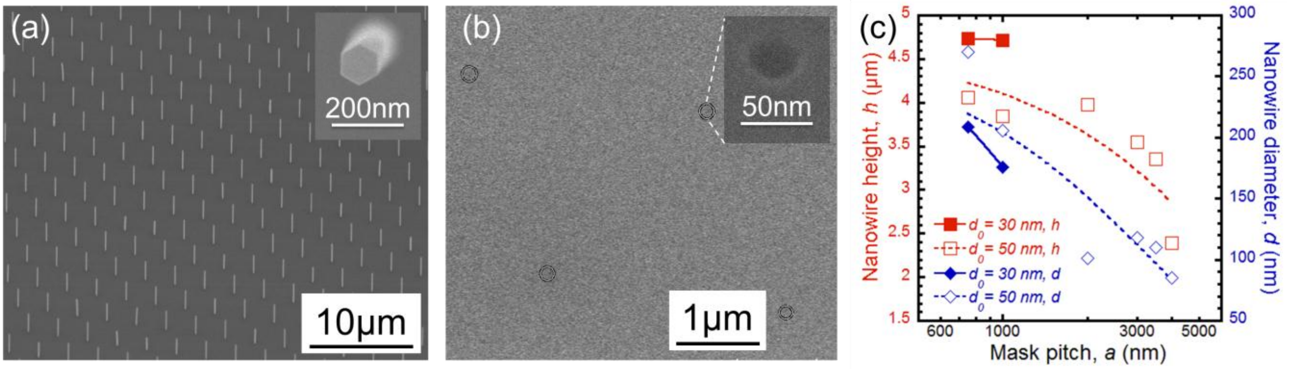

Fig. 1. (a), (b) 30°-tilted SEM images of patterned substrate after the growth of InGaAs. The V/III ratio and t were 107 and 30min, respectively. The d_0 were (a) 50, (b) 30 nm. The circles in (b) represent position of opening holes. (d) Mask pitch dependence of h and d for d_0 = 30 and 50 nm. The V/III ratio and t were 107 and 30min, respectively.

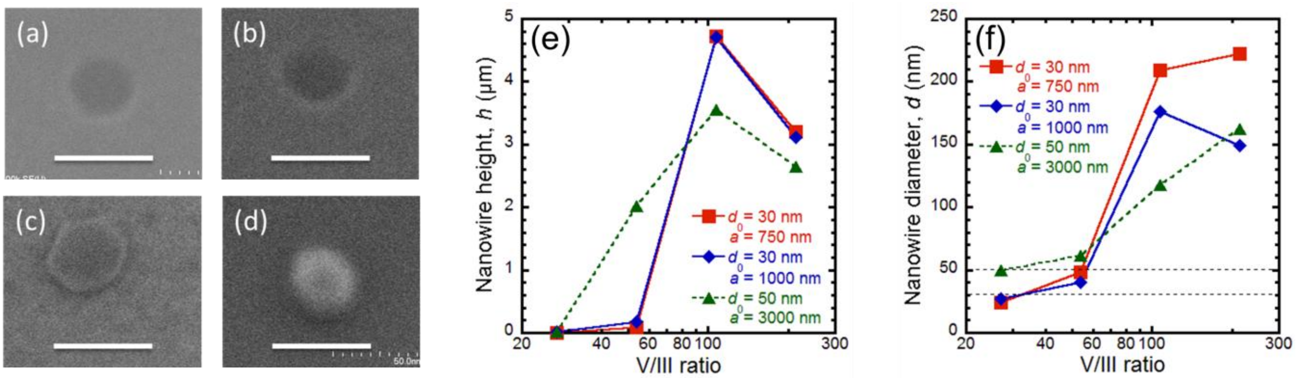

Fig. 2. (a), (b), (c) and (d) show 30°-tilted SEM images of patterned substrate after the growth of InGaAs. The V/III ratios were (a) 214, (b) 107, (c) 54, (d) 27, respectively (d_0 = 30 nm, a = 3μm, t = 30 min). The white scale bar represents 50nm. (e) and (f) show V/III ratio dependence of h and d, respectively, for d_0 = 30 nm, t = 30 min with various a (d_0 = 50 nm, a = 3 μm is shown as a reference.). The upper and lower dashed lines in (f) show d of 50 nm and 30 nm, respectively.

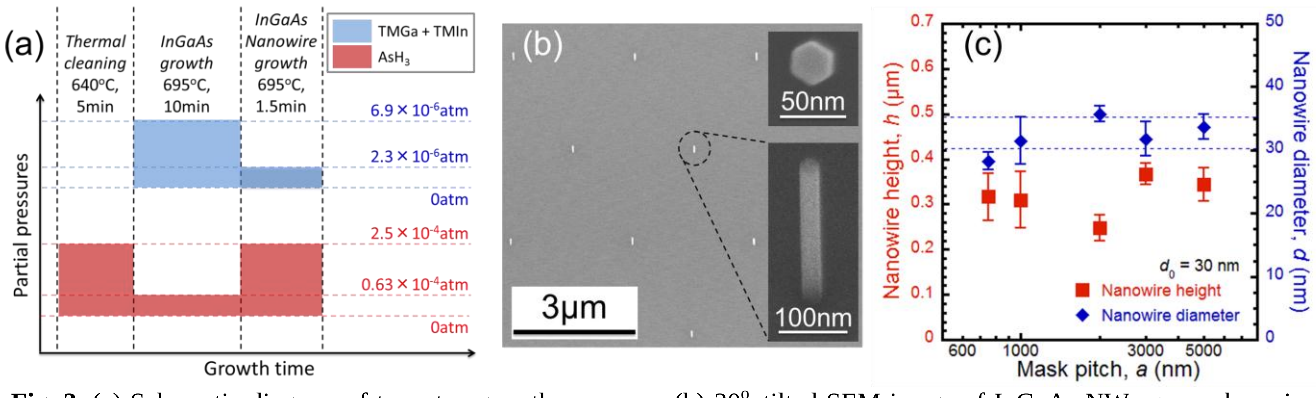

Fig. 3. (a) Schematic diagram of two-step growth sequence. (b) 30°–tilted SEM image of InGaAs NWs grown by using two-step growth sequence (d_0 = 30 nm, a = 3 μm). The upper and lower insets show enlarged view of NW top and 30°–tilted image of NW, respectively. (c) The h and d are plotted as a function of mask pitch, a (d_0 = 30 nm). The error bars show standard deviation of h and d. The upper and lower blue dashed lines show d of 35 nm and 30 nm, respectively.