HOKKAIDO UNIVERSITY

Title	Composition controllability of InGaAs nanowire arrays in selective area growth with controlled pitches on Si platform
Author(s)	Chiba, Kohei; Tomioka, Katsuhiro; Yoshida, Akinobu; Motohisa, Junichi
Citation	AIP Advances, 7(12), 125304 https://doi.org/10.1063/1.4993689
Issue Date	2017-12
Doc URL	http://hdl.handle.net/2115/68223
Rights	https://creativecommons.org/licenses/by/4.0/
Rights(URL)	https://creativecommons.org/licenses/by/4.0/
Type	article
File Information	1.4993689.pdf

Instructions for use

Composition controllability of InGaAs nanowire arrays in selective area growth with controlled pitches on Si platform

Kohei Chiba, Katsuhiro Tomioka, Akinobu Yoshida, and Junichi Motohisa

---

Articles you may be interested in

Composition controllability of InGaAs nanowire arrays in selective area growth with controlled pitches on Si platform

Kohei Chiba,[a] Katsuhiro Tomioka, Akinobu Yoshida, and Junichi Motohisa
Graduate School of Information Science and Technology, and Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University, Kita 13 Nishi 8, Sapporo 060-8628, Japan

Composition controllability of vertical InGaAs nanowires (NWs) on Si integrated by selective area growth was characterized for Si photonics in the optical telecommunication bands. The pitch of pre-patterned holes (NW sites) changed to an In/Ga alloy-composition in the solid phase during the NW growth. The In composition with a nanometer-scaled pitch differed completely from that with a μm-scaled pitch. Accordingly, the growth morphologies of InGaAs NWs show different behavior with respect to the In/Ga ratio. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.4993689

The electrical intra-connection and inter-connection of chips are facing technical limitations in terms of reliability following the miniaturization of Si complementary metal-oxide-semiconductor (Si CMOS) technologies. Optical interconnections using Si photonics,[1,2] in which various optical devices such as light sources, detectors, modulators, and waveguides are integrated on an Si platform, are being advanced as an alternative wiring technology.[3] However, integrating light sources and detectors at a nanometer scale remains a challenge. The difficulty of Si in terms of light source is in the fact that Si is an indirect band gap material and exhibits poor emission efficiency. As such, Raman lasers[4] and nanostructured Si lasers[5] have been demonstrated, but emission intensity is still an issue, especially in chip-to-chip connections. The alternative approach is to integrate non-Si materials such InP and InGaAs on Si.[6] As for photodetectors, Si is transparent in the optical telecommunication bands, so the heterogeneous integration of Ge or InGaAs is required.

Although heterogeneous integration such as with wafer bonding has been reported, a much more favored, straightforward approach is to integrate the material at a nanometer scale. Thus, there is a strong demand for the direct growth of InGaAs-based semiconductors on Si both for light emitters and detectors. Despite this straightforward approach, mismatches in the lattice constant, which generate misfit dislocations, and polarity mismatch resulting in antiphase defects are issues. Nanometer-scaled selective-area epitaxy of III–V semiconductor nanowires (NWs)[7] could resolve these issues; i.e., a small footprint of NWs can accommodate lattice mismatch and its strain,[8] and manipulating an initial Si surface into a (111)B-polar surface can align vertical III–V NWs.[9,10]

It is noted that, in integrating InGaAs NWs on Si, the controllability of NW size parameters, such as diameter d, height h, and NW array pitches a, and In composition gives us a new possibility and requirements for the application. The target In content is around 51% for Si photonics with a wavelength of 1.55 μm. Pitches a or density $(1/a^2)$ of NW array alters emission patterns, and the size and pitch of NWs can be optimized at target wavelength to maximize light absorption in photodetectors.[11] As mentioned, because the optimum NW pitch depends on the target devices, controlling the composition of InGaAs NWs at various scaled pitches is very important. Photonics and optoelectronic applications monolithically integrating InGaAs NWs on a silicon-on-insulator (SOI) platform have been reported,[12] but details of the compositional controllability resulting from

---

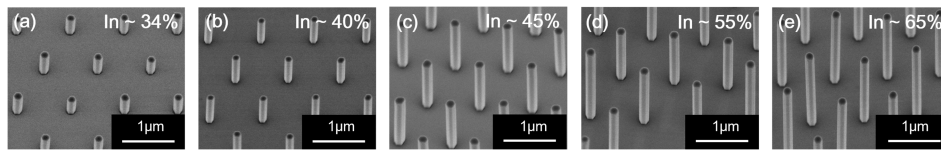[a]k-chiba@rciqe.hokudai.ac.jp

7, 125304-1

FIG. 1. 30°-tilted SEM image view showing growth results of InGaAs NWs on Si with d_0=150 nm and a=1000 nm. The In composition of vapor phase is (a) 34%, (b) 40%, (c) 45%, (d) 55%, and (e) 65%.

the NWs pitches are still lacking, particularly on Si substrates and smaller a. Here, we characterized controllability of In content in InGaAs NWs, which have a bandgap compatible with the optical telecommunication bands.

The growth process for integrating vertical InGaAs NWs was the same as that used previously.[13] Si(111) substrates partially masked with 20-nm-thick SiO$_2$ were prepared by thermal oxidation, electron-beam lithography, and wet chemical etching. The SiO$_2$ mask had a periodic circular opening with diameter d_0, and the openings were arranged in a triangular lattice with pitch a. The a ranged from 350 nm to 2 μm, and the d_0 was 150 nm. The source materials for growth were trimethylgallium (TMGa), trimethylindium (TMIn), and arsine (AsH$_3$). The method for aligning a vertical NW is described elsewhere.[10] The V/III partial pressure ratio was 112. The growth temperature was 670°C. The composition of In in the vapor phase (ratio of TMIn supply over the sum of TMIn and TMGa supply) increased from 34% to 65% and had a lattice mismatch with Si of about 6.6–9%.

Scanning electron microscopy (SEM) images of InGaAs NWs grown for the intended composition of In in the vapor phase from 34% to 65% are shown in Figs. 1(a)–1(e). In this case, the pattern pitch a and the mask opening diameter d_0 were 1 μm and 150 nm, respectively. All of the InGaAs NWs were aligned in the vertical <111> direction, meaning formation of a (111)B–like polarity on Si surface. According to Refs. 10 and 14, In-rich and Ga-rich InGaAs NWs respectively exhibit zincblende crystal structure containing a lot of twins. Thus, it is believed that all the InGaAs NWs discussed in the present study is similarly made into a zincblende structure with twins. The relationship of the pitch a with the NWs height h for each In composition of the vapor phase for d_0 = 150 nm is shown in Fig. 2. The growth temperature and V/III ratio were fixed. At all values of a, h increased with an increase in the In composition of the vapor phase. The NW pitch dependence of h varied with the In composition of the vapor phase. For the In composition of the vapor phase
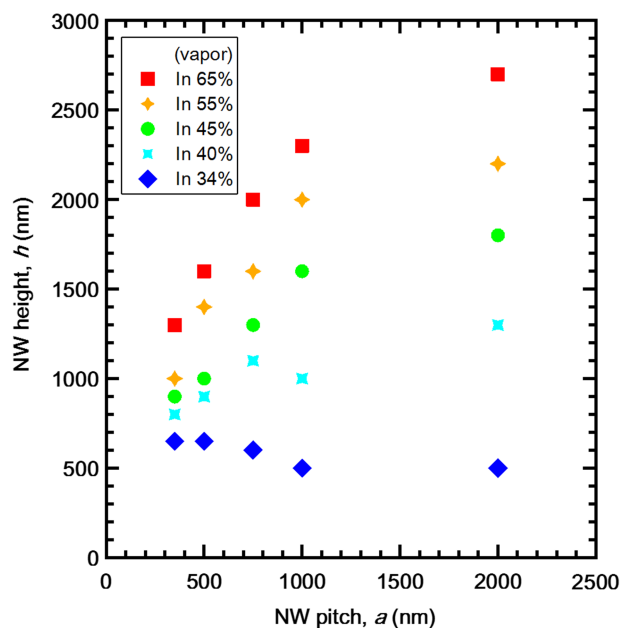

FIG. 2. NWs pitch a dependence of height h of InGaAs NWs with each In composition of vapor phase for d_0 = 150 nm.

at 34%, *h* decreased as *a* was widened. Whereas for the In composition of the vapor phase at over 40%, *h* increased as *a* was widened.

The *h* sublinearly increased with an increase in the In content of the vapor. It was reported that As trimers that formed on GaAs(111)B reduced the growth rate in the (111)B direction[15] and that Ga-rich InGaAs NW growth was affected by the formation of As trimers on (111)B.[16] We consider that as the content of Ga in InGaAs NW increases, the effect of the As trimers becomes stronger; therefore, h decreased with an increase in the Ga composition of the vapor phase. Furthermore, as shown by the NW pitch *a* dependence in Fig. 2, when the In composition of the vapor phase was 34% and 65%, the growth morphology of InGaAs NWs due to *a* was similar to that of GaAs NW[17] and InAs NW,[18] respectively.

The measurement of x-ray diffraction (XRD) in 2θ-ω scan was carried out for InGaAs on Si. The XRD measurement range included the whole pattern obtained by electron beam lithography. Additionally, the In composition of InGaAs NWs grown at all pitches and diameters and InGaAs deposited on Si (111) were measured. Fig. 3(a) exhibits XRD spectra and the intended composition of In in the solid phase including InGaAs NW growth calculated by XRD measurement for vapor-phase In compositions ranging from 34% to 65%. The solid circles and error bars represent the peak positions and their half-widths from the XRD measurement results shown in Fig. 2. In Fig. 3(b), the In content in the solid phase was larger than that in the vapor phase. This is considered to be the main reason that the diffusion length of In atoms was longer than that of Ga atoms on the SiO$_2$ mask surface.[12] Moreover, as the Ga composition in the vapor phase increased, the composition in the solid phase tended to correspond to the composition in the vapor phase. This is because the diffusion of In atoms was inhibited by gallium on the mask, and the actual diffusion length of In atoms was shortened. Note that the In composition of InGaAs NWs is at the point at which the XRD peak position may contain errors due to the signal from planar InGaAs on Si.

Thus, micro-photoluminescence (μ-PL) measurement at 4.2 K was performed to clarify the In composition of InGaAs NWs grown with different pitches. Fig. 4(a) shows the μ-PL spectra of InGaAs NWs grown with In incorporation at 34% in the vapor phase. The observed PL peak wavelength at *a* = 2000 nm shifted to a shorter wavelength with narrowing *a*. This indicates that the In composition of InGaAs NW growth changed with pitch *a*. The In composition of InGaAs NWs at each pitch estimated from the PL peak wavelength position is plotted in Fig. 4(b). The estimated In composition was larger than the In composition at the peak position of XRD, but it was located within the error bar range. This indicates that InGaAs NWs covering the optical telecommunication bands can be adjusted if the In composition in the vapor phase is roughly in the range of 34% to 40%, and composition controllability is different in the case of a nm-scale pitch and a μm-scale pitch. Therefore, as *a* widens, the In composition of InGaAs NWs increased at a nm-scale pitch, whereas that became approximately
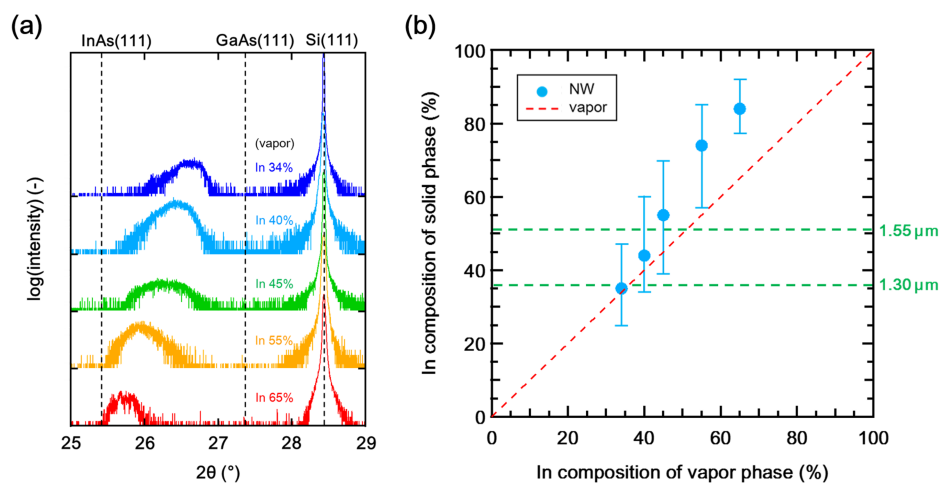

FIG. 3. (a) XRD 2θ-ω peak diffracted from (111) plane of InGaAs crystal with each In composition of vapor phase. (b) In composition of solid phase as function of In composition of vapor phase by XRD measurement.
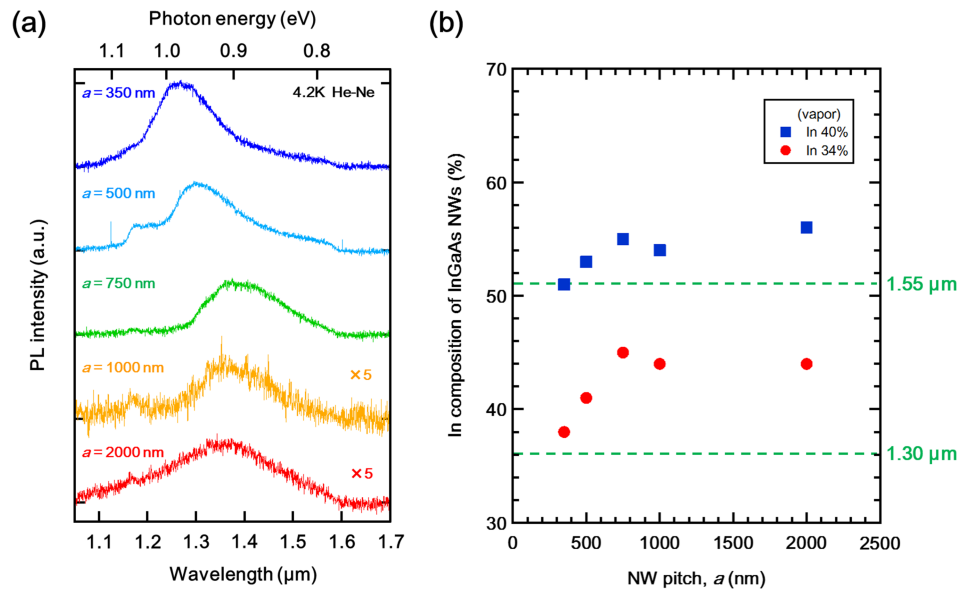
FIG. 4. (a) μ-PL spectra for InGaAs NWs with 34% In composition of vapor phase measured at 4.2 K. Spectra taken for $a = 350 \sim 2000$ nm and $d_0 = 150$ nm. Base of each spectrum is shifted along vertical direction for clarity. (b) NWs pitch a dependence of In composition of InGaAs NWs for 34% and 40% In composition of vapor phase.

constant for a μm-scale pitch. It seems that the incorporation rate of Ga for NW growth decreased as a was widened because of the short diffusion length of Ga.[17] Thus, when forming an InGaAs NW with a certain In content, pitch a is an important factor in precisely controlling the composition.

Comparing the cases in which the In composition of the vapor phase is either 34% or 40%, when the In composition of InGaAs NWs was dominant, h increased as a was widened; conversely, when the Ga composition of InGaAs NWs was dominant, h decreased as a was widened, as seen in Fig. 2. These results indicate that the InGaAs-NW growth morphology in the pitch dependence directly reflects the changes in NW composition. The tendency in InGaAs NW composition in Fig. 3(b) and 4(b) are consistent with previous work results.[19] Here the present results is important that detail dependence on pitches a<1μm was revealed, where the device application is important. We also have reported on the pitch-independent size control for thin (diameter down to 30 nm) InGaAs NWs.[7] The present work, however, have shown that the NW pitch is an important factor to determine the composition of InGaAs NWs. Thus, more careful study is required for simultaneous control of their size and composition when NW size less than 50 nm are required. Fortunately, due to a requirement for the volume of optical gain section, absorption cross section, and wavelength limitation, the target NW size for photonic devices in optical communication bands would not have to be so thin. Precise control of the composition of NWs for Si photonic devices can be achieved by using these insights.

In conclusion, we characterized the composition controllability of the InGaAs NW arrays having different pitches. The In composition of InGaAs NWs was larger than the In content in the vapor phase and increased as the NW pitch was widened. Therefore, when forming an InGaAs NW with a certain In content for Si photonics, pitch is an important factor for controlling the composition. These insights will contribute to precise wavelength matching for optical devices on the Si platform for optical communication applications.

[1] W. Fang, H. Park, O. Cohen, R. Jones, M. J. Paniccia, and J. E. Bowers, Optical Express **14**, 9203 (2006).
[2] A. Biberman and K. Bergman, Rep. Prog. Phys. **75**, 046402 (2012).
[3] D. K. T. Ng, Q. Wang, J. Pu, K. P. Lim, Y. Wei, Y. Wang, Y. Lai, and S. T. Ho, Optics Letters **38**, 5353 (2013).
[4] H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang, and M. J. Paniccia, Nature **433**, 725 (2005).
[5] S. G. Cloutier, P. A. Kossyrev, and J. Xu, Nature Mater **4**, 887 (2005).
[6] Y. Gao, Z. Zhong, S. Feng, Y. Geng, H. Liang, A. W. Poon, and K. M. Lau, IEEE Photonics Technology Letters **24**, 4 (2012).

[7] Y. Kohashi, S. Sakita, S. Hara, and J. Motohisa, Appl. Phys. Express **6**, 025502 (2013).

[8] F. Glas, Phys. Rev B **74**, 121302(R) (2006).

[9] K. Tomioka, J. Motohisa, S. Hara, and T. Fukui, Nano Letters **8**, 3475 (2008).

[10] K. Tomioka, M. Yoshimura, and T. Fukui, Nature **488**, 189 (2012).

[11] J. Motohisa and K. Hiruma, Jpn. J. Appl. Phys. **51**, 11PE07 (2012).

[12] H. Kim, A. C. Farrell, P. Senanayake, W.-J. Lee, and D. L. Huffaker, Nano Lett. **16**, 1836 (2016).

[13] K. Tomioka, T. Tanaka, S. Hara, K. Hiruma, and T. Fukui, IEEE Journal of Selected Topics in Quantum Electronics **17**, 1112 (2011).

[14] M. Yoshimura, K. Tomioka, K. Hiruma, S. Hara, J. Motohisa, and T. Fukui, Journal of Crystal Growth **315**, 148 (2011).

[15] K. Ikejiri, J. Noborisaka, S. Hara, J. Motohisa, and T. Fukui, Journal of Crystal Growth **298**, 616 (2007).

[16] M. Yoshimura, K. Tomioka, K. Hiruma, S. Hara, J. Motohisa, and T. Fukui, Jpn. J. Appl. Phys. **49**, 04DH08 (2010).

[17] J. Noborisaka, J. Motohisa, and T. Fukui, Appl. Phys. Lett. **86**, 213102 (2005).

[18] S. Hertenberger, D. Rudolph, M. Bichler, J. J. Finler, G. Abstreiter, and G. Koblmüller, J. Appl. Phys. **108**, 114316 (2010).

[19] T. Sato, Y. Kobayashi, J. Motohisa, S. Hara, and T. Fukui, Journal of Crystal Growth **310**, 5111 (2008).