



## Selective-area growth of indium nitride nanowires on gold-patterned Si(100) substrates

C. H. Liang, L. C. Chen, J. S. Hwang, K. H. Chen, Y. T. Hung, and Y. F. Chen

Citation: Applied Physics Letters **81**, 22 (2002); doi: 10.1063/1.1490636 View online: http://dx.doi.org/10.1063/1.1490636 View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/81/1?ver=pdfcov Published by the AIP Publishing

Articles you may be interested in

Self-catalyzed GaAs nanowire growth on Si-treated GaAs(100) substrates J. Appl. Phys. **109**, 094306 (2011); 10.1063/1.3579449

Growth of size and density controlled GaAs / In x Ga 1  $\times$  As / GaAs (x = 0.10) nanowires on anodic alumina membrane-assisted etching of nanopatterned GaAs J. Vac. Sci. Technol. B **28**, 1111 (2010); 10.1116/1.3498753

In situ growth of aligned CdS nanowire arrays on Cd foil and their optical and electron field emission properties J. Appl. Phys. **104**, 014312 (2008); 10.1063/1.2952013

Self-catalytic growth of single-phase AlGaN alloy nanowires by chemical vapor deposition Appl. Phys. Lett. **89**, 193105 (2006); 10.1063/1.2364272

Low-temperature growth and properties of ZnO nanowires Appl. Phys. Lett. **84**, 4941 (2004); 10.1063/1.1760594



This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 77.93.19.10 On: Thu, 03 Apr 2014 10:55:13

## Selective-area growth of indium nitride nanowires on gold-patterned Si(100) substrates

C. H. Liang and L. C. Chen<sup>a)</sup> Center for Condensed Matter Sciences, National Taiwan University, Taipei, Taiwan

J. S. Hwang and K. H. Chen Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan

Y. T. Hung and Y. F. Chen

Department of Physics, National Taiwan University, Taipei, Taiwan

(Received 11 February 2002; accepted for publication 5 May 2002)

This letter reports the synthesis of indium nitride (InN) nanowires on gold-patterned silicon substrates in a controlled manner using a method involving thermal evaporation of pure indium. The locations of these InN nanowires were controlled by depositing gold in desired areas on the substrates. Scanning electron microscopy and transmission electron microscopy investigations showed that the InN nanowires are single crystals with diameters ranging from 40 to 80 nm, and lengths up to 5  $\mu$ m. Energy dispersive x-ray spectrometry showed that the ends of the nanowires are composed primarily of Au, and the rest of the nanowires were InN with no detectable Au incorporations. The Raman spectra showed peaks at 445, 489, and 579 cm<sup>-1</sup>, which are attributed to the  $A_1$  (transverse optical),  $E_2$ , and  $A_1$  (longitudinal optical) phonon modes of the wurtzite InN structure, respectively. Photoluminescence spectra of the InN nanowires showed a strong broad emission peak at 1.85 eV. © 2002 American Institute of Physics. [DOI: 10.1063/1.1490636]

Indium nitride (InN) has attracted much attention due to its direct band gap in visible range<sup>1</sup> and large drift velocity at room temperature.<sup>2</sup> This property suggested that InN is likely to be a better choice of material than GaAs and GaN for field effect transistors. InN/Si tandem cells have been proposed for high efficiency solar cells.<sup>3,4</sup> Carrier captured by InN quantum dots has been attributed to the efficient emission of blue-violet commercial InGaN light emitting diode lasers.<sup>5</sup> The mechanism of the luminescence in InGaN/GaN quantum wells arises from the radiative recombination within the selforganized InN quantum dots.<sup>6</sup> The pre-eminent role of the InN quantum dots has led to our interest in the synthesis and characterization of the InN nanostructures. Because of the low dissociation temperature, good quality InN samples are not easily attainable. Also, isolating and manipulating the freestanding tangled nanowires are still very challenging. Therefore, it is of interest to grow InN nanowires on a substrate in a controlled fashion, so that no postgrowth manipulation is needed for the purpose of measurement or device use. In this letter, we demonstrate that InN nanowires with diameters of 40-80 nm can be grown on gold-patterned silicon substrates using a simple thermal evaporation method. In particular, we find the nanowires are grown only within the patterned gold circle on the substrates. This result indicates that the growth of the nanowires on the silicon substrates can be positioned and controlled by gold patterning of the substrates, which can be easily integrated with current semiconductor technology.

P-type silicon (100) substrates were patterned with 10nm-thick gold film by sputtering deposition under 5  $\times 10^{-2}$  Torr through a shadow mask, which contained circle shaped openings of micrometer size. Pure indium foil (ACROS 0.127 mm thick, 99.99%) placed in an alumina boat served the purpose as the indium vapor source upon heating. The boat was covered with a gold-patterned silicon substrate and then loaded into the center of a half-inch quartz tube, which was housed in a conventional tube furnace. The quartz tube was degassed and then purged with ammonia  $NH_3$  (40 sccm) as the atomic nitrogen precursors and nitrogen (20 sccm) as the carrier gas. During the growth process, the furnace was set to 500 °C and held for 8 h.

The morphologies and structure of the as-grown samples were characterized by field emission scanning electron microscopy (SEM, JEOL 6700), and transmission electron microscopy (TEM, Philips CM200 FEG). Energy dispersive x-ray spectrometry (EDS) and electron diffraction analysis were also performed. Raman scattering and photoluminescence (PL) spectra were measured at room temperature by means of a Renishaw 2000 micro-Raman Fourier transform spectrometer using an Ar<sup>+</sup> laser at 514 nm as the excitation source.

Typical field emission SEM images of nanowires grown on Au patterned silicon (100) substrates [Fig. 1(a)] confirm that the InN nanowires grow only in the Au-coated areas. A high-magnification SEM image [Fig. 1(b)] shows that the diameters of these wires range from 40 to 80 nm, which is related to the size of the aggregated Au clusters caused by the heating of substrate during growth. Typical lengths of these nanowires can be up to 5  $\mu$ m.

As can be seen from high-resolution TEM image in Fig. 2, an individual nanowire with a 40 nm diameter exhibits single crystal structure of high quality. The inset of the Fig. 2 shows a selected area electron diffraction pattern of the

<sup>&</sup>lt;sup>a)</sup>Author to whom correspondence should be addressed; electronic mail: chenlc@ccms.ntu.edu.tw



FIG. 1. SEM images of InN nanowires on the silicon substrate. (a) Image taken at low magnification. The bright circles are InN nanowires grown on patterned-gold film. The other area remains blank. The array of gold circles was formed by sputtering through a shadow mask. (b) Top view of the InN nanowires on one gold circle taken at high magnification.

nanowire, which can be indexed to the reflections of hexagonal InN crystal along the  $\langle 001 \rangle$  directions. The corresponding high-resolution TEM image clearly shows the lattice plane of (100) with an interplanar spacing of 0.308 nm. The [110] direction was parallel to the long axis of the wire, indicating that the nanowire preferably grew along the [110] direction. In addition, TEM studies also reveal that almost every InN nanowire was capped with a nearly equiaxial nanoparticle, as shown in Fig. 3. EDS measurements performed on the nanoparticle and the nanowire indicate that the ends of the



FIG. 3. A TEM image of a single InN nanowire terminated with a Au nanoparticle. The corresponding EDS spectra of the nanoparticle and the wire stem are shown in (a) and (b), respectively. Cu signals are generated from microgrid mesh that supports the nanowires.

nanowires are composed primarily of Au as shown in Fig. 3(a), and the rest of the nanowires are InN with no detectable Au incorporations as shown in Fig. 3(b). The presence of Au nanoparticles at the ends of the InN nanowires is consistent with the pseudo-binary Au-InN phase diagram, and provides strong evidence for a vapor-liquid-solid growth mechanism.

The Raman spectrum of the InN nanowires measured at room temperature is shown in Fig. 4(a). The Raman peaks can be easily assigned when compared with the spectrum of an InN thin film<sup>7,8</sup> in Fig. 4(b). In these spectra the first-order modes of the prominent peaks correspond to the  $A_1$  longitudinal optical (LO) phonon and  $E_2$  phonon at around 579 cm<sup>-1</sup> and 489 cm<sup>-1</sup>, respectively, whereas the peak at 445 cm<sup>-1</sup> has been identified as the  $A_1$  (transverse optical) mode. In comparison with the first-order optical phonon peaks of InN film, the corresponding Raman peaks of InN nanowires exhibit broader line width and more asymmetric line shape. It is also intriguing that only the  $A_1$ (LO) peak observably shifted by about 14 cm<sup>-1</sup> toward lower wave numbers. In general consideration for Raman scattering of onedimensional nanometric-sized systems, the downshifts of the





is article is copyrighted as indicated in the article. Reuse of AIP content is subject to FIG. 4. Raman spectra of (a) InN nanowires and (b) InN films. Three promi-FIG. 2. High-resolution TEM image of a typical InN nanowire.



FIG. 5. Room temperature PL spectrum of the InN nanowires using an argon laser at 514 nm as the excitation source.

Raman peaks are mainly attributed to the size-confinement effect. When the crystalline size decreases, momentum conservation will be relaxed and Raman active modes will not be limited to be at the center of the Brillouin zone. The smaller the crystalline grain is, the bigger the frequency shifts and the more asymmetric the line shape. Moreover, the phonons can be confined in space by crystallite boundaries, causing an uncertainty in the wave vector of the phonons, which results in broadening of the Raman features.

Figure 5 shows a typical photoluminescence PL spectrum measured from a large quantity of InN nanowires at room temperature. The strong broad peak at 1.85 eV is in good agreement with the 1.86 eV measured by Tansley and Foley<sup>9</sup> using an optical absorption technique. The broad half width of the PL peak is primarily due to the thermal excitations and the broad size distribution of the nanowires. It should be pointed out that the PL measurement of InN is rarely reported in the literature. Presumably, this is because of the inherent process difficulties caused by the low dissociation temperature of the material; therefore, the InN sample usually contains extremely high defect density. The present process, in contrast, demonstrated a catalytic route to achieve high purity InN growth.

In summary, we report a convenient and robust method to synthesize InN nanowires on selective-area by gold patterning of silicon substrates and subsequent growth via a vapor-liquid-solid mechanism. The capability of direct and patterned nanowire growth allows us to fabricate nanoscale device on the substrate in a controllable fashion. Using current lithography and other integrated circuit technologies, more complicated gold patterns on substrates can be made. In addition, the availability of these high quality InN nanowires provides opportunities not only in testing theories of one dimensional quantum confinement, but also for realizing high-efficiency InN/Si solar cells because of the large surface area/volume ratio. The InN nanowires fabricated in the present study gave a strong PL peak at 1.85 eV and three prominent Raman peaks. Further detailed experiments will be needed to sort out the origin of the luminescence. In addition, the size-dependent optical and electrical properties of InN nanowires are now in progress.

This work was supported by the National Science Council in Taiwan (NSC89-2119-M001-011, NSC89-2112-M002-085, and NSC90-2112-M002-048), Ministry of Education in Taiwan (90-W-FA01-2 4-5) and Academia Sinica, Taiwan.

- <sup>1</sup>T. L. Tansley and C. P. Foley, J. Appl. Phys. 59, 3241 (1986).
- <sup>2</sup>S. K. O'Leary, B. E. Foutz, M. S. Shur, U. V. Bhapkar, and L. F. Eastman, J. Appl. Phys. **83**, 826 (1998).
- <sup>3</sup>E. N. Matthias and B. M. Allen, IEEE Trans. Electron Devices **ED-34**, 257 (1987).
- <sup>4</sup>A. Yamamoto, M. Tsujino, M. Ohkubo, and A. Hashimoto, Sol. Energy Mater. Sol. Cells **35**, 53 (1994).
- <sup>5</sup>K. P. O'Donnell, R. W. Martin, and P. G. Middleton, Phys. Rev. Lett. **82**, 237 (1999).
- <sup>6</sup>H. C. Yang, P. F. Kuo, T. Y. Lin, Y. F. Chen, K. H. Chen, L. C. Chen, and J. I. Chyi, Appl. Phys. Lett. **76**, 3712 (2000).
- <sup>7</sup>J. S. Hwang, C. H. Lee, F. H. Yang, K. H. Chen, L. G. Hwa, Y. J. Yang, and L. C. Chen, Mater. Chem. Phys. **72**, 290 (2001).
- <sup>8</sup>F. H. Yang, J. S. Hwang, K. H. Chen, Y. J. Yang, T. H. Lee, L. G. Hwa, and L. C. Chen, Thin Solid Films **405**, 194 (2002).
- <sup>9</sup>T. L. Tansley and C. P. Foley, Electron. Lett. 20, 1066 (1984).