Kinetic Growth of Self-Formed In$_2$O$_3$ Nanodots via Phase Segregation: Ni/InAs System

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Nanostructures are defined as materials with at least one geometric dimension less than 100 nm. Many fascinating phenomena and unexpected properties, which differ from their bulk counterparts, have been explored as their dimensions shrink down to nano- or sub-nanometer regions. In recent years, a multitude of approaches have been applied to synthesize various nanostructures, including nanobelts, nanowires, and nanodots with tunable optical and electrical properties due to “quantum effects”, such as size-dependent excitation, quantized conductance, single-electron tunneling, and metal-insulator transition. Nanomaterials with these extraordinary properties can be incorporated into optoelectrical devices and system-on-chip (SOC) modules.

Indium oxide (In$_2$O$_3$) is an important transparent material with a wide band gap ($E_g$) of ~3.6 eV and has been used for numerous applications in optical and electrical devices, including solar cells, gas sensors, and light-emitting diode devices. Several methods have been proposed for the growth of In$_2$O$_3$ nanodots, such as template-assisted growth, sol–gel synthesis, and laser ablation. These methods, however, suffer from several problems, such as low yielding rate, impurity contaminations, non-uniform size distribution, and material damage. In this paper, we present a novel approach to synthesize highly compact In$_2$O$_3$ nanodots from an InAs wafer by direct annealing of the Ni/InAs sample at temperatures over 250 °C. From experimental results, the formation mechanism of these In$_2$O$_3$ nanodots is believed to result from a catalyst-assisted growth, which is based on the phase segregation of In and As atoms out of a saturated Ni/InAs underlying layer to form In$_2$O$_3$ nanodots with residual oxygen molecules during annealing, while the As atoms are found to not be involved in the formation of In$_2$O$_3$ nanodots. The size and density of In$_2$O$_3$ nanodots are controllable, depending on different annealing time and ambient conditions. This research also demonstrates the possibility of patterned segregation sites for In$_2$O$_3$ nanodots.

RESULTS AND DISCUSSION

The process of catalyst-assisted growth of highly compact In$_2$O$_3$ nanodots with uniform size is schematically illustrated in Figure 1a. A 50 nm thick Ni layer was deposited onto native oxide-free crystalline InAs(100) substrates by electron-beam evaporation with a deposition rate of ~0.03 nm/s. The samples were then heated by rapid thermal annealing (RTA) at temperatures from 250 to 350 °C in different annealing ambient conditions. Highly compact In$_2$O$_3$ nanodots

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were then formed upon the surface of Ni\textsubscript{x}In\textsubscript{As}/In\textsubscript{As} substrates. It is worthwhile to mention that a Ni\textsubscript{x}In\textsubscript{As} film layer will be formed prior to the formation of In\textsubscript{2}O\textsubscript{3} nanodots. The surface morphology and distribution of In\textsubscript{2}O\textsubscript{3} nanodots were characterized by atomic force microscopy (AFM). Figure 1b shows the statistical size distribution of In\textsubscript{2}O\textsubscript{3} nanodots ranging from 60 to 110 nm with an average size of 80 nm for a Ni (50 nm)/In\textsubscript{As} sample annealed at 250 °C for 150 s. Inset shows the fast Fourier transform diffraction pattern of the In\textsubscript{2}O\textsubscript{3} nanodot with a zone axis of [110].

The structural analysis of In\textsubscript{2}O\textsubscript{3} nanodots was carried out with a transmission electron microscope (TEM). Figure 2b shows a low-magnification cross-section TEM image of Ni/In\textsubscript{As} after annealing at 250 °C for 150 s. (b) Corresponding HAADF image and compositional profiles of nickel, indium, arsenide, and oxygen. (c) High-resolution TEM image of a single In\textsubscript{2}O\textsubscript{3} nanodot taken from region (c) in Figure 2a. Inset shows the fast Fourier transform diffraction pattern of the In\textsubscript{2}O\textsubscript{3} nanodot with a zone axis of [110]. (d) High-resolution TEM image of the Ni\textsubscript{x}In\textsubscript{As}/In\textsubscript{As} interface taken from region (d) in Figure 2a, revealing the sharp interface.

Table 1. Quantitative EDS Data from Selective Regions in Figure 2a

<table>
<thead>
<tr>
<th>position</th>
<th>In (atomic %)</th>
<th>As (atomic %)</th>
<th>Ni (atomic %)</th>
<th>O (atomic %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>43</td>
<td>57</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>b</td>
<td>25</td>
<td>26</td>
<td>49</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>c</td>
<td>21</td>
<td>27</td>
<td>52</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>d</td>
<td>41</td>
<td>&lt;0.1</td>
<td>59</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>e</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>100</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>f</td>
<td>45</td>
<td>55</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>g</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>100</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>h</td>
<td>41</td>
<td>57</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>i</td>
<td>22</td>
<td>27</td>
<td>51</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

There are no In\textsubscript{2}O\textsubscript{3} nanodots if the annealing temperature is below 200 °C, while the diffusion of Ni into In\textsubscript{As} still remains, thereby forming the Ni\textsubscript{x}In\textsubscript{As} alloy.
layer with abrupt interface (Supporting Information, Figure S1). As depicted in Figure 3b,c, uniform and dense In$_2$O$_3$ nanodots were grown at annealing temperatures over 250 °C. At the annealing temperature of 350 °C, the size and density of nanodots increase accordingly. The corresponding statistical evolution of nanodot size in Figure 3d reveals that the size of nanodots increases from ~100 to ~150 nm with annealing temperature increased from 250 to 350 °C. The results indicate that the formation mechanism of In$_2$O$_3$ nanodots follows catalyst-assisted growth, which is based on the phase segregation of In and As atoms out of the underlying Ni$_x$InAs layer once Ni$_x$InAs reaches the saturated state. This phase segregation behavior of In and As atoms out of the Ni$_x$InAs layer is similar to segregation of Si out of the disilicide system at elevated annealing temperature. 22,23 Similar segregation of In has been found in the Ni/InP system.23 Once the In and As atoms are segregated from Ni$_x$InAs layer, In atoms tend to form In$_2$O$_3$ nanodots with residual oxygen molecules during the annealing while As atoms prefer to become vapor rather than be involved in the oxidation reaction. The heat of evaporation energy (5.1 kJ/mol)24 for As is much lower compared to that of In (236.6 kJ/mol)25 and much higher free energy (−259.3 + 0.17 – 2.6 × 10⁻³ T ln T)26,27 with O compared to that with In (−909.4 + 0.37 kJ/mol).27 Therefore, the system prefers to form In$_2$O$_3$ during the oxidation reaction. This result is also consistent with EDS findings for In$_2$O$_3$ nanodots, as illustrated in Table 1, where the concentration of As atoms is almost zero at position d in Figure 2a. To confirm our proposed mechanism, a Ni layer with the same thickness was deposited on the same InAs substrate with an InAsO$_x$ layer as the barrier layer intentionally formed between Ni and InAs via the direct oxidation of InAs wafer, as shown in Figure 4a, in which a distinctly different contrast between Ni and InAs can be observed. Figure 4b shows a high-resolution TEM image of the

Figure 3. AFM images of Ni/InAs sample after annealing at (a) 200 °C, (b) 250 °C, and (c) 350 °C for 150 s. (d) Statistical size distributions of In$_2$O$_3$ nanodots synthesized at different annealing temperatures.

Figure 4. Effect of InAsO$_x$ oxide layer on the formation of In$_2$O$_3$ nanodots. (a) Low-magnification cross-section TEM image of Ni/InAsO$_x$/InAs after annealing at 250 °C for 100 s. (b) High-resolution TEM image of selected region taken from (a). (c) Low-magnification cross-section TEM image of Ni/InAsO$_x$/InAs after annealing at 350 °C for 100 s. (d) Corresponding HAADF image and elemental profiles of nickel, indium, arsenide, and oxygen across Ni/InAsO$_x$/InAs, in which the voids can be clearly distinguished.

Figure 5. Ambient effects on the distribution of size and density. AFM images of Ni/InAs samples annealed at 250 °C for 100 s in (a) vacuum, (b) nitrogen, (c) atmosphere, and (d) ambient oxygen. (e,f) Size and density distributions in different ambient conditions.

InAsO$_x$ layer with a thickness of ~2 nm taken from the rectangular area of Figure 4a, revealing the amorphous feature of InAsO$_x$. The EDS quantitative analysis of data obtained at layers marked e, f, and g is shown in Table 1. Figure 4c shows a TEM image for the sample after annealing at 350 °C for 100 s. Figure 4d shows the corresponding HAADF image with elemental profiles of each layer and quantitative analysis at positions h and i, as shown in Table 1. Note that only Ni atoms can partially diffuse into InAs to form Ni$_x$InAs during annealing, leading to the formation of voids. It indicates that the InAsO$_x$ layer can indeed retard the diffusion of Ni atoms into InAs. No formation of In$_2$O$_3$ nanodots was observed at this annealing condition, revealing that the segregation of In and As atoms out of the Ni$_x$InAs layer does not occur in this case, which further confirms that the compositional saturation of the Ni$_x$InAs is not reached yet because of the existence of the InAsO$_x$ barrier layer. In addition, we find that In$_2$O$_3$
nanodots can only be formed on the InAs system using Ni as a capping layer, while no In$_2$O$_3$ nanodots can be formed using Au or Pt as capping layers.

To shed light on the ambient effect on the formation of the In$_2$O$_3$ nanodots, the Ni(50 nm)/InAs samples were annealed at 250 °C for 150 s in different annealing ambient conditions from vacuum with a base pressure of $1 \times 10^{-3}$ Torr, to nitrogen, atmosphere, and pure oxygen environments. The corresponding AFM results with the same scale bar are shown in Figure 5a–d for comparison. Figure 5e,f shows the results of size distribution and density evolution derived from AFM results. The size of In$_2$O$_3$ nanodots decreases from ~85 to ~65 nm with an increase of oxygen content in the annealing ambient condition, while the density of In$_2$O$_3$ is monotonically increased from $\sim 3 \times 10^9$ to $\sim 9 \times 10^9$ dots/cm$^2$. At the same annealing temperature and time, the amount of segregated In atoms out of Ni$_x$InAs should be the same while the nucleation size of In$_2$O$_3$ nanodots may highly depend on the amount of oxygen content. The higher the concentration of oxygen during formation of the In$_2$O$_3$ nanodot, the smaller the critical size for nucleation of In$_2$O$_3$ nanodots. It is the reason why the density increases with decreasing size at the same annealing condition with higher oxygen concentration (Supporting Information, Table S1). Therefore, we believe the In$_2$O$_3$ nanodots with a few nanometer ranges should be possibly achieved upon precise control of annealing conditions, such as annealing time or ambient conditions. In addition, the difference in thickness of the Ni layer will also influence the solid diffusion of Ni into InAs and phase segregation, thereby affecting the formation of In$_2$O$_3$ nanodots. If the thickness of the Ni layer is increased from 50 to 100 nm, the annealing time for the formation of In$_2$O$_3$ nanodots is also increased at the same annealing temperature (Supporting Information, Figure S2).

Photoluminescence (PL) spectra were measured at room temperature with the excitation wavelength of 325 nm, as shown in Figure 6 for In$_2$O$_3$ nanodot/Ni$_x$InAs/InAs and pure InAs samples. Two distinct peaks located at $\sim 430$ and $\sim 850$ nm, corresponding to 2.9 and 1.5 eV, respectively, for In$_2$O$_3$ nanodot/Ni$_x$InAs/InAs samples can be observed. The energies for two emission peaks are much larger than the band gap transition of InAs, for which InAs has a direct band gap of $\sim 0.35$ eV. Therefore, emitting peaks from the underlying InAs substrate can be ruled out, while the emission from band to band excitation of In$_2$O$_3$ is forbidden due to the indirect band gap nature with a band gap of $\sim 3.6$ eV, corresponding to a wavelength of $\sim 345$ nm. In addition, emission from the Ni$_x$InAs layer is also unlikely due to the metallic property. Accordingly, we can conclude that these two emitting peaks originate from radioactive recombination centers such as oxygen vacancies or indium interstitials inside In$_2$O$_3$ nanodots. Moreover, the smaller In$_2$O$_3$ particles prefer the existence of more oxygen vacancies because of larger surface-to-volume ratio and thereby higher...
intensity of PL emission. A very weak and broad peak located at 430 nm, corresponding to 2.9 eV for the pure InAs wafer, which originated from a native In$_2$O$_3$ oxide, further confirms the interpretation. PL property is further studied by annealing In$_2$O$_3$ nanodots with different annealing times. As the size of In$_2$O$_3$ nanodots increases with annealing time, the PL intensity becomes weaker with a little shift of peak position. The decease of PL intensity for In$_2$O$_3$ nanodots with larger particle size at elongated annealing time can be observed as the reduction of surface ratio and concentration of oxygen vacancies. A similar result is also observed in ZnO nanoparticles.29

A unique advantage of our processes is to precisely control positions of In$_2$O$_3$ nanodots. To demonstrate this concept, a periodic Ni microdisc array with the diameter and interdisc distance of ∼5 and ∼10 μm, respectively, were patterned on the InAs substrate surface by conventional photolithography and lift-off processes. The corresponding optical microscope (OM) and SEM images are shown in Figure 7a,b, respectively. Inset in Figure 7b shows the cross-section view of these periodic Ni microdisc arrays. After annealing at 350 °C for 150 s, the In$_2$O$_3$ nanodots can be found only on patterned region, as can be seen from the AFM image in Figure 7c. This patterning technique can be applied for making systems on an InAs chip to enhance performance of related optoelectrical devices.

**CONCLUSIONS**

In summary, we present a novel approach to synthesize highly uniform In$_2$O$_3$ nanodots by directly annealing a Ni/InAs sample at temperatures over 250 °C. The formation mechanism of In$_2$O$_3$ nanodots is understood in terms of phase segregation and solid diffusions between nickel and InAs via a catalyst-assisted process. The sizes of In$_2$O$_3$ nanodots decrease from ∼85 to ∼65 nm with the increase of oxygen-containing ambient condition, while the density of In$_2$O$_3$ is monotonically increased from ∼3 × 10$^9$ to ∼9 × 10$^{10}$ dots/cm$^2$. Additionally, PL spectra were obtained at room temperature for In$_2$O$_3$ nanodots. Two distinct peaks located at ∼430 and ∼850 nm, corresponding to 2.9 and 1.5 eV, respectively, can be observed, which are originated from some radioactive recombination centers such as oxygen vacancies or indium interstitials inside In$_2$O$_3$ nanodots. The decease of PL intensity for In$_2$O$_3$ nanodots with larger particle size at elongated annealing time can be observed due to the reduction of surface ratio and concentration of oxygen vacancies. The advantage on how to precisely control positions of In$_2$O$_3$ nanodots with a pattern of periodic Ni microdiscs based on our synthesis approach was demonstrated, which has potential applications in precisely locating optoelectronic nanodevices in combination with electronic nanodevices.

**METHODS**

InAs wafers were cleaned by acetone and isopropyl alcohol. Subsequently, wafers were dipped into dilute HF solution (HF/H$_2$O = 1:10 v/v) for 20 s to totally remove the native oxide layer. The Ni layer was deposited by an E-gun evaporation system with deposition rate of ∼0.03 nm/s. The samples were then heated by rapid thermal annealing (RTA) at temperatures from 250 to 350 °C in different annealing ambient conditions. The surface morphologies were examined by atomic force microscopy (AFM, Digital Instrument 3100). Field-emission transmission electron microscope (TEM-3000F, operated at 300 kV with point-to-point resolution of 0.17 nm) equipped with an energy-dispersion spectrometer (EDS) was used to obtain the information of the microstructures and the chemical compositions. Room temperature PL measurements were performed with excited laser wavelength of 290 nm. Optical microscopy (OM) was also applied to examine the surface conditions of the samples. Periodic Ni microdisc arrays with the diameter and interdisc distance of ∼5 and ∼10 μm were patterned on the InAs substrate surface by conventional photolithography and lift-off processes.

**Acknowledgment.** This research was supported by the National Science Council through Grant No. NSC 100-2628-E-007-003-, NSC 98-2112-M-007-025-MY3, and by the General Research Fund of the Research Grants Council of Hong Kong SAR, China, under Project No. CityU 101210.

**Supporting Information Available:** The TEM results at annealing temperature of 200 °C and AFM results of Ni/InAs sample with Ni thickness of 100 nm annealed at 350 °C with different annealing time. This material is available free of charge via the Internet at http://pubs.acs.org.

**REFERENCES AND NOTES**


