Title

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InN nanrods grown on different planes of Al_2O_3

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There has been a large increase in interest in Indium Nitride (InN) for use in optoelectronic devices, such as laser diodes, high frequency/high power electronic devices, and high efficiency solar cells. The growth of high quality epitaxial layers of InN is challenging because it requires a low growth temperature (~600 to 700°C) and high NH_3 partial pressure to avoid nucleation of In droplets. However, the fabrication of potential one-dimensional structures, such as nanowires and nanorods, has proven even more difficult due to the thermodynamic properties of In and N. We report here on the structural quality of InN nanorods grown on sapphire using non-catalytic, template-free hydride metal-organic vapor phase epitaxy (H-MOVPE). TEM was used to study growth polarity, faceting of the nanorod tips and defects formed in the nanorods grown on different planes of Al_2O_3. JEOL 3010 with acceleration voltage of 300 keV and sub-Angstrom CM 300 were used to these studies.

InN nanorods grown on the a-, c-, and r-plane of Al_2O_3 are monocrystalline, but their shape and faceting differ from each other. Many of them are elongated along the wurtzite c-axis but not all nanorods are distributed vertically to the substrate and thus form flower-like or random arrangement along different crystallographic directions. The nanorods grown on the c-plane and a-plane have a hexagonal cross-section. Their diameter is in a range of (100-200 nm) and their length (700-2000 nm). These nanorods were removed from the substrate and placed on holey carbon film for TEM observation. They appear rectangular at the one end and with small facets on the other end. It is therefore, understood that these rectangular shape ends, whose surface is not atomically flat, were earlier attached to the substrate and ends with facets indicate growth direction. Facets and most of the tops of the faceted tips are atomically flat. It also appears that one side along the length of the crystal is atomically flat and the other has a substantial roughness. In some nanocrystals grown on a-plane their diameter is slightly changing along their length and a v-shape grove appears along one elongated side of the crystal (Fig. 1a). CBED patterns (Figs. 1b-d) show two interconnected identical patterns where c-axis of the one part is rotated by about 60° toward the other. This coincides with the $[0\underline{1}11]$ direction, which has the same displacement vector as a prismatic stacking fault (PSF). This suggests that PSFs might be present in these nanorods and give rise to the growth of the crystals at different angle and thus form the "flower-like" arrangement.

If one considers nanorods grown on c-plane of Al_2O_3 their faceting appear at one end indicating growth direction of a particular nanorod (see Fig. 2a). CBED patterns (Figs. 2b-c) taken in several areas of this nanocrystal and compared to calculated patterns, for the same thickness and accelerating voltage as experimental patterns, indicate N growth polarity, which is equivalent to a long bond direction from N to In along c-axis. The uniform contrast was observed along all the length of the nanocrystal suggesting that this crystal was free of structural defects. There were however, other nonorods also grown on c-plane of Al_2O_3 with a long axis parallel to $[10\underline{1}0]$, like that shown on Fig. 2d. In this nanorod faceting was observed on both ends, therefore it was impossible to distinguish which end was earlier attached to the substrate. This crystal also shows contrast uniformity for different diffraction conditions suggesting lack of any structural defects, similarly as those grown along c-axis.

The nanorods grown on r-plane Al_2O_3 (Fig.2e) are semi-round in cross-section tapering to pencil-shaped at the growth front with a small (about 20 nm) plateau on the c-plane at the tip. Many other growth orientations have been observed for these nanorods but the pencil-like shape was observed for all of them. Their diameter and length are in the range of 300-600 nm and 1000-2500, respectively. Their diameter is the largest in comparison with crystals grown on a- and c-planes. Moreover, when studied by high-resolution microscopy one can observe that roughness of tip facets of the same nanocrystal is different and this might be related to growth polarity. Plane bending from the outside area compared to the central part of the tip facets is also observed (Figs 2 f). This bending is not observed along the length of this nanocrystal, however, some corrugation and coverage with an amorphous material is clearly visible.

This study shows that high ratio of surface area to the volume of nanorods prevents structural defect formation, since defects such as dislocations will escape to the surface and will be not present in the volume of nanocrystal. This is very promising for the application of such material in devices.

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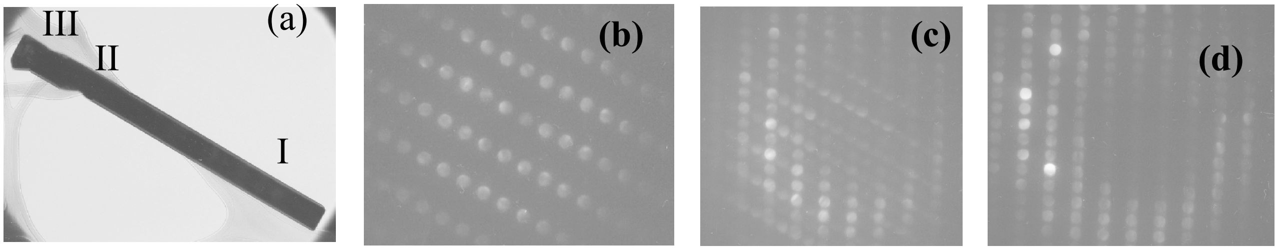

Fig. 1. (a) A nanocrystal grown on the a-plane of Al_2O_3; (b-d) Convergent Beam Electron Diffraction patterns obtained from the areas indicated by numbers: (b) from area (I); (c) from area (II), and (d) from area (III) showing two interconnected crystals rotated 60° toward each other.

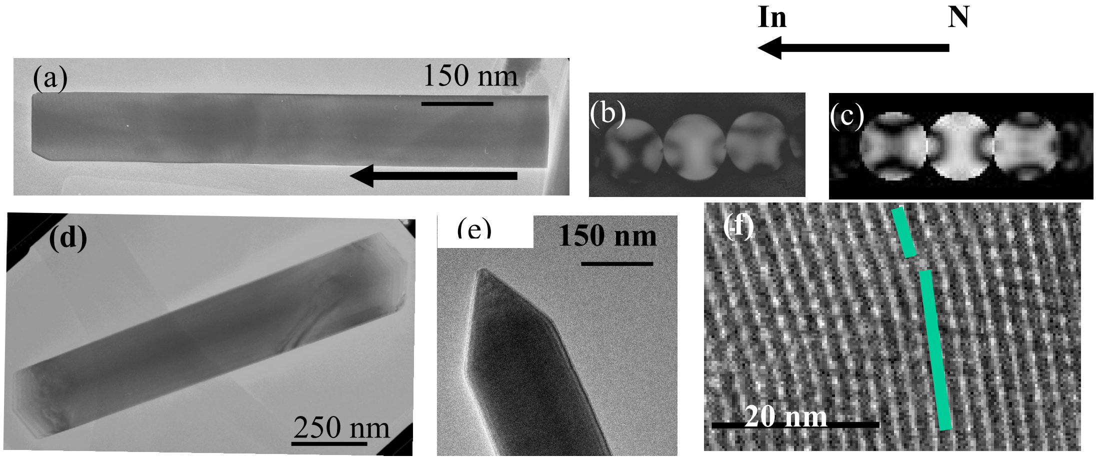

Fig. 2. (a) InN nanorod grown on c-surface of Al_2O_3 along polar [0002] direction. The arrow indicates growth direction; (b) An experimental and (c) calculated CBED pattern indicating N-growth polarity, as shown by the arrow; (d) another nanocrystal grown on c-surface Al_2O_3. This crystal was grown along $[10\underline{1}0]$ direction. Note an uniform diffraction contrast for both crystals indicating a high structural perfection; (e) InN grown on r-surface Al_2O_3 along polar [0002] direction. Note a specific pencil-like shape with slightly different facet length at their tip; (f) Bending of the planes in the subsurface of the facet.