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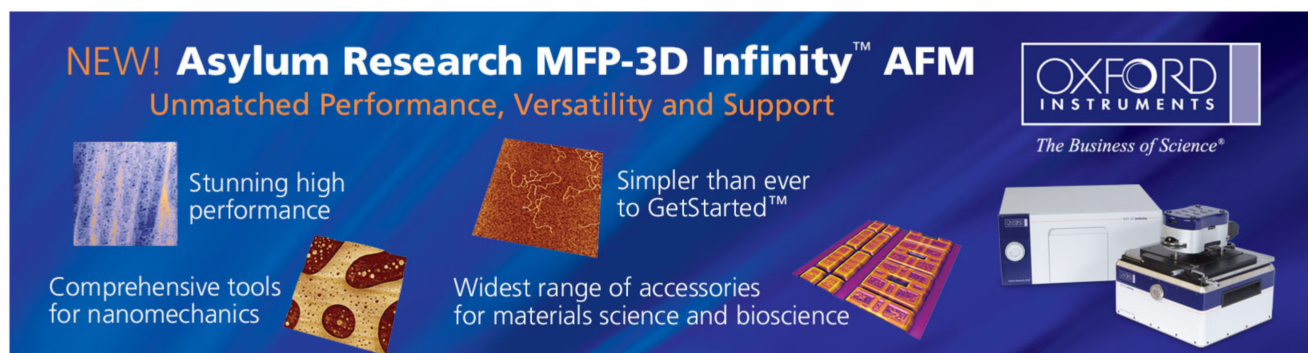


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# InN nanotips as excellent field emitters

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Unidirectional single crystalline InN nanoemitters were fabricated on the silicon (111) substrate via ion etching. These InN nanoemitters showed excellent field emission properties with the threshold field as low as 0.9 V/$\mu$m based on the criterion of 1 $\mu$A/cm$^2$ field emission current density. This superior property is ascribed to the double enhancement of (1) the geometrical factor of the InN nanostructures and (2) the inherently high carrier concentration of the degenerate InN semiconductor with surface electron accumulation layer induced downward band bending effect that significantly reduced the effective electron tunneling barrier even under very low external field.
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Indium nitride (InN) has been studied intensively in recent years because of the unusual characteristics such as small effective mass,[1,2] large electron drift velocities,[3,4] surface electron accumulation layer,[5] and the controversy in its bandgap.[6,7] These unique properties have not only attracted a great deal of scientific interest but also opened up many device application possibilities,[8] for example, in high-speed high-frequency electronics,[9] electron emitters, detectors,[10] solar cells,[11] etc. In particular, its unusual surface properties and inherently heavily doped nature can, in fact, be exploited for vacuum microelectronic devices. Despite the difficulty in sample preparation,[12–15] field emission (FE) of electrons has been observed in single crystalline and polycrystalline nanostructural forms of InN thin films grown on insulating substrates.[13–15]

In this work, we have produced well-aligned and unidirectional single crystalline InN nanotips as a field emitting device fabricated on silicon substrates, which shows excellent FE properties with the threshold field as low as 0.9 V/$\mu$m based on the criterion of an emission current density of 1 $\mu$A/cm$^2$.

The unidirectional InN nanotips were fabricated through etching process on molecular beam epitaxy (MBE) grown InN(0002)/AlN(0002)/Si(111) sample. This multilayered heterostructure consists of 78 nm $\alpha$-AlN (wurtzite phase AlN) and 1 $\mu$m $\alpha$-InN (wurtzite phase InN) on *n*-type Si(111) substrate whose resistivity is 30–50 $\Omega$ cm. The growth temperature of the $\alpha$-AlN and $\alpha$-InN are 830 and 350 °C, respectively. Other details of the growth conditions largely follow a previous report on optimized intermediate AlN layer.[16] Free carrier concentration of the MBE-grown InN based on the Hall measurement using van der Pauw method at room temperature is as high as $1.5\times10^{19}$ cm$^{-3}$ (*n*-type InN) and the resistivity of the epitaxial InN film is $9.7\times10^{-4}$ $\Omega$ cm.

Dry etching process is carried out with an Ar$^+$ plasma system under a constant pressure mode ($6\times10^{-5}$ torr) within a high vacuum environment. The etching area of the InN nanotip-populated sample studied for this report was measured to be 1.512 mm$^2$. Morphology of the InN nanotips which are manufactured on Si(111) substrates is displayed in Fig. 1. Tip density of the InN nanotips is estimated to be $\sim10^7$ cm$^{-2}$ based on the observation using FE scanning electron microscopy (FESEM).

The specimen for transmission electron microscopy (TEM) was prepared using a dual-beam focused ion beam (FIB) facility. Microanalysis by TEM was carried out to closely investigate the InN nanotips. Low and high magnification (inset photo) bright field (BF) TEM pictures of the tip apex and the high resolution compositional line scan under the scanning TEM (STEM) mode are shown in Fig. 2. The apex of the InN nanotip has a spherical shape with a diameter of curvature ~22–30 nm based on the FESEM and

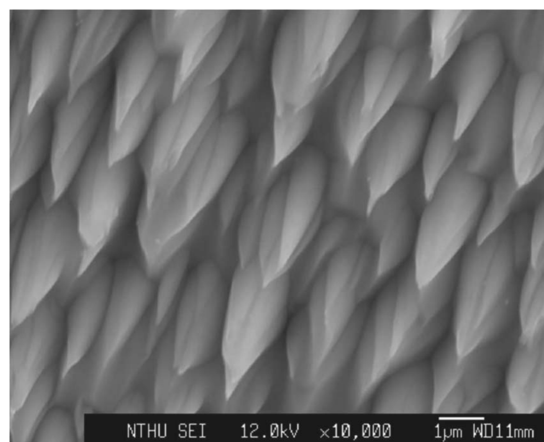


FIG. 1. The surface morphology of the well-aligned and unidirectional InN nanotips is examined using FESEM. The nanotip density is estimated to be $\sim10^7$ cm$^{-2}$.

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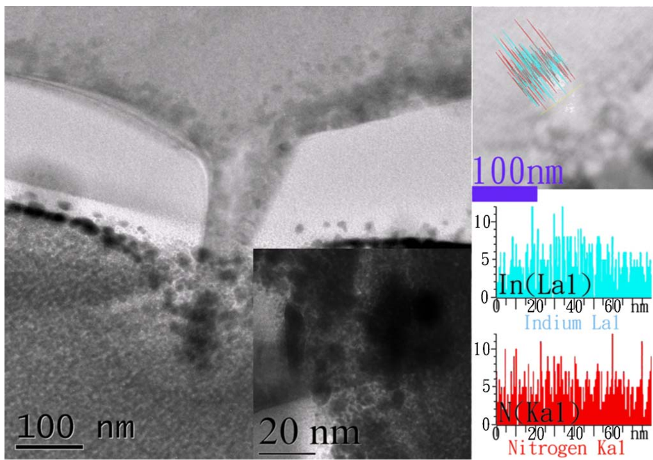


FIG. 2. (Color online) Microanalysis using TEM has given us a close look of the InN nanotips. Low and high magnification (inset) of the BF TEM images, and the high resolution compositional line scan under STEM mode are displayed in this figure.

TEM images. Although great care has been exercised, a small part of the tip was still damaged as a result of the TEM specimen preparations by FIB. The compositional line scan appears to be much broadened probably due to the diffusion during the deposition of the platinum layer by FIB. However, line shape of the tip remains clear.

To assess the performance of InN as a field emitter, the FE properties were measured with a high vacuum level around $10^{-6}$ torr or lower. The measurement was conducted on a standard parallel-plate-electrode configuration where the indium tin oxide glass substrate was used as the anode. The anode was separated from the InN surface by a 95 $\mu$m gap using the $Al_2O_3$ as spacer. Both the anode and the cathode were connected to a computer-controlled Keithley 237 source meter, with the highest output power was 11 W (i.e., 1100 V, 10 mA). Prior to the current-voltage (*I-V*) measurement, the InN nanotips were kept at 200 V (i.e., 2.1 V/$\mu$m) for 3 min. The InN-nanotip sample was measured five times and the data of electron emission characteristics were depicted in Fig. 3. The current density–applied field (*J-E*) and *I-V* curves are both shown in this figure. Meanwhile, the emission current density *J* is exponentially rising with the increase of applied field *E* in the low field region (i.e., 0.5–2 V/$\mu$m).

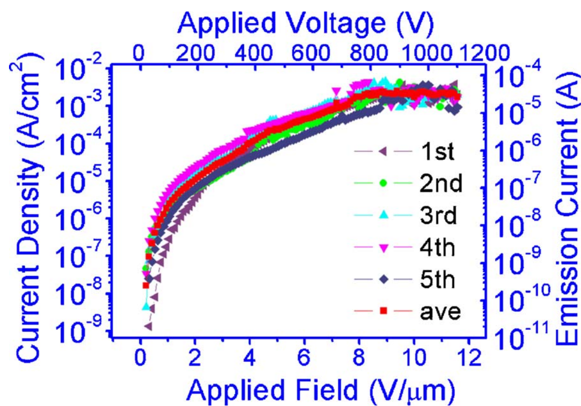


FIG. 3. (Color online) The FE property of the InN nanotips is shown on these *I-E* and *I-V* curves after five scans where the averaged data are also illustrated on this chart.

The average turn-on fields of the InN nanotips based on the 1 $\mu$A/cm$^2$ current density criterion are $0.90 \pm 0.34$ V/$\mu$m. As a low turn-on voltage in effect represents lower energy barrier for electron tunneling, the surface accumulation layer in the InN surface causes a downward band bending near the surface region that eventually helps lowering the electron tunneling barriers.[5] Meanwhile, judged from the very high carrier concentration, the as-grown InN is a degenerate semiconductor, of which the Fermi level is located above the conduction band minimum. This could also have added to the efficiency of tunneling at low electric field. Precautions are taken to keep the specimen free from contaminants although it cannot be excluded completely.

A short-term stability test after the fifth scan was carried out. When the applied field was fixed at 10 V/$\mu$m for 180 s, the current density scattered around $2.03 \pm 0.79$ mA/cm$^2$. That the stability did not perform well might be attributed to several possibilities: (a) the intrinsic material quality of InN nanotip emitters might not be able to sustain the huge applied field, (b) the emitters might be damaged after the five runs of measurement, and (c) the fabrication process might have to amend further. All of these suggest that there is still room for improvement.

To test whether the electron emission is originated from electron tunneling or not, the Fowler–Nordheim (FN) equation is commonly used to examine the tunneling phenomena.[17] Whenever the $\ln(J/E^2)$ versus $1/E$ plot yields a straight line, electrons are considered to emit through tunneling the energy barrier. The simplified equation of the FN theory can be described as[18–22]

$$J = \frac{I}{A} = k_1 \frac{F^2}{\phi t^2(y)} \exp\left(-k_2 \frac{\phi^{3/2} \nu(y)}{F}\right), \quad (1)$$

where *I* is the emission current (amperes), *A* is the effective area of electron emission (cm$^2$), $\phi$ is the work function of the emitting material (eV), $k_1 = 1.54 \times 10^{-6}$ A eV V$^{-2}$, $k_2 = 6.83 \times 10^7$ eV$^{-3/2}$ V cm$^{-1}$, $t^2(y)$ and $\nu(y)$ are the electric-field-dependent elliptical functions, and *y* is the image charge lowering factor related to $\phi$. The $t^2(y)$ and $\nu(y)$ are often taken to be unity because *y* is dependent on *E* which is a very slowly varying function. *F* is the local electric field that is expressed as $F = \beta E = \beta V d^{-1}$, where $\beta$ is the field enhancement factor, *d* is the gap between the two parallel plates, and *V* is the applied voltage. The equation can be further expressed as[18–22]

$$\ln\left(\frac{J}{E^2}\right) = -\left(\frac{k_2 \phi^{3/2}}{\beta}\right)\left(\frac{1}{E}\right) + \ln\left(\frac{k_1 \beta^2}{\phi}\right). \quad (2)$$

Therefore, the slope *S* can be obtained from the FN plot, $\ln(J/E^2)$) versus $(1/E)$, as

$$S = \left(-\frac{k_2 \phi^{3/2}}{\beta}\right). \quad (3)$$

The FN plot of the InN nanotips is presented in Fig. 4. The field enhancement factor $\beta$ and the reliability factor of the least-square fit, $r^2$, are also shown in the figure. When the applied field kept increasing, the FE current of the InN nanotip experienced an unusual kink, which was also seen in other InN nanostructures reported by other groups.[13,14]

The work function of the InN nanotips used in this analysis was 4.1 eV,[23] with which the $\beta$ value was calculated to be ~69 000 (in the field of 0.5–2.0 V/$\mu$m). The field enhancement factor of the InN nanotip is larger than the

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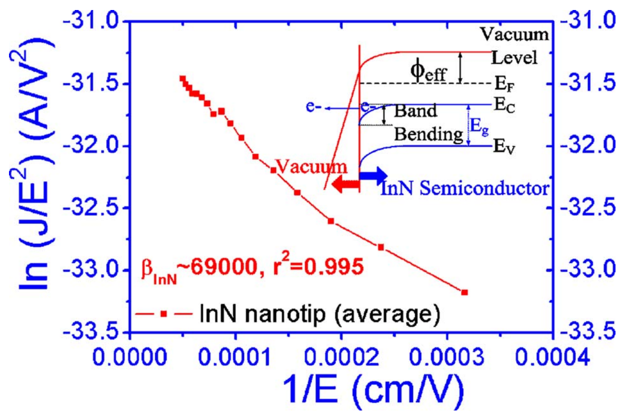


FIG. 4. (Color online) FN plot of the InN nanotips is shown the excellent FE property of the well-aligned and unidirectional InN nanotips where $\beta$ is as high as ~69 000 in the low field regime of 0.5–2.0 V/$\mu$m. The inset shows the surface band diagram of the degenerate InN nanotip.

reported FE materials, such as carbon nanotubes[24] and ZnO.[25] This is believed to be due to the double enhancement of (a) the geometrical factor (i.e., the small size of the spherical nanotips) and (b) the inherently high carrier concentration of the degenerate InN semiconductor with Fermi level lying above the conduction band minimum, hence, significantly reducing the effective electron tunneling barrier.

In conclusion, single crystalline, well-aligned, and unidirectional InN nanotips fabricated on silicon substrates have been shown to be an excellent field emitting material in terms of the turn-on field and the emission current in the low field regime. According to the analyses presented above, a brief summary for the InN nanotips can be drawn as follows: (1) The FE characteristics of the InN nanotips follow the FN equation in the low field region. (2) The field enhancement factor of the InN nanotips is as high as ~69 000 that is possibly being a consequence of geometrical enhancement. (3) The low turn-on field of InN nanotips is ascribed to the surface electron accumulation layer and the inherent degeneracy of the InN semiconductor.

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