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Vacuum field emission from GaN and (Al,Ga)N/GaN nanorods with pyramidal tips has been measured. The turn-on fields, defined at a current density of 0.1 μA/cm^2, were found to be 38.7 and 19.3 V/μm, for unintentionally doped GaN and (Al,Ga)N/GaN nanorods, respectively. The 5 nm (Al,Ga)N layer reduced the electron affinity at the surface, thereby lowering the turn-on field and increasing the current density. The nanostructures exhibit a field enhancement factor of approximately 65 and the work function of the (Al,Ga)N/GaN nanorod heterostructure was estimated to be 2.1 eV. The stability of the emission characteristics and the simple fabrication method suggest that intentionally doped and optimized (Al,Ga)N/GaN nanorod heterostructures may prove suitable for field-emission device.
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One-dimensional semiconductor heterostructures in nanowire or nanorod forms have potential for enhancing the performance and broadening the range of applications of electronic, photonic, optoelectronic, and field-emission devices.[1–4] Besides the capabilities for integration with dissimilar media afforded by the nanoscale dimensions and high-aspect ratio form factors, nanowire and nanorod heterostructures also offer a broader range of lattice-mismatched compositions that may be grown coherently.[5] AlN and its alloys with GaN have been reported to exhibit very low values of electron affinity (0.25 eV for AlN);[6] however, these ternary compounds are difficult to dope and, thus, are not suitable as field emitters.[7] The possibility of integrating a high electron concentration material such as GaN:Si with a pointed tip morphology for field enhancement and a low electron affinity material such as AlN and its alloys with GaN in a one-dimensional heterostructured nanorod motivates the present work.

GaN has an electron affinity of approximately 3.0 eV,[6] lower than the work function of most metals, and this makes GaN a potential contender for field-emission devices such as cold cathode emitters and flat panel displays. GaN also exhibits a high electron concentration even in the unintentionally doped condition due to native nitrogen vacancies (V_N) (typically $\sim 10^{17}$ cm^{-3}). Micron-scale GaN pyramids with pointed tips have been grown by selected area epitaxy, resulting in large field enhancement effects.[8,9] The biggest obstacle in this approach is the limitation of conventional lithography in defining the openings for selective area growth resulting in a low areal density of field emitters (~ 0.01 μm^{-2} in comparison to ~ 10 μm^{-2} emitter areal density in the present work).[8] There have also been some reports of a reduction of the turn-on field and increase in the current density by employing surface roughening and nanotip formation by etching.[10,11] Although these structures exhibit a small radius of curvature at their tips, the tip size distribution is not uniform or controllable over the wafer scale, resulting in nonuniform electron emission over the surface of the wafer. In the present work, field-emission characteristics in one-dimensional nanoscale (Al,Ga)N nanorods with pointed tips are investigated. It is shown that the (Al,Ga)N/GaN nanorod heterostructure exhibits a lower turn-on electric field and higher current density as compared to GaN nanorods.

Four different samples were prepared: (a) GaN nanorod (undoped), (b) (Al,Ga)N/GaN nanorod (undoped), (c) GaN

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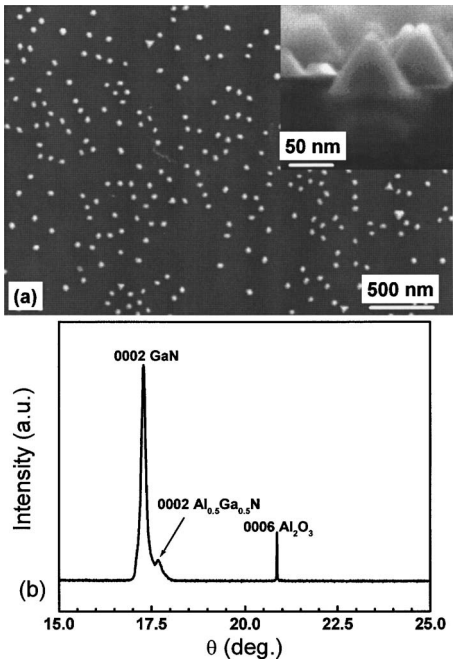

FIG. 1. (a) Field-emission scanning electron microscopy image of GaN nanorods. The inset shows an edge-on view of the (Al,Ga)N/GaN nanorods, and (b) high-resolution x-ray diffraction θ-ω scan from (Al,Ga)N/GaN thin film.

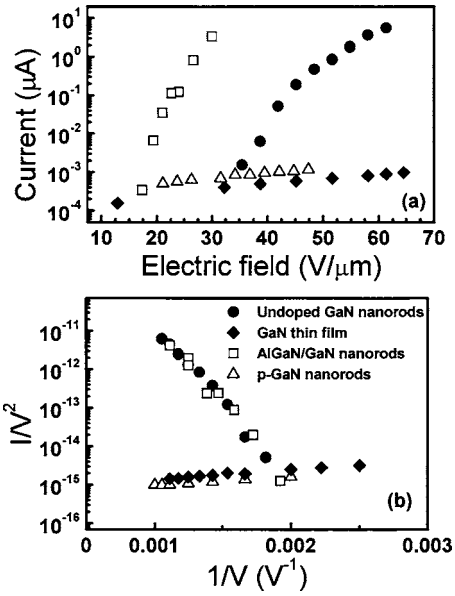

FIG. 2. (a) Emission current as a function of applied electric field characteristics, and (b) Fowler-Nordheim plots of the *I-V* data. The anode area is 7.07 mm^2.

film (undoped), and (d) *p*-GaN nanorod. The GaN nanorods were synthesized using a catalyst-free templated approach that employs a silica mask fabricated using a porous anodic alumina template. The complete fabrication process leading to diameter-controlled GaN nanorods with a pointed tip morphology has been reported in Ref. 12. An optimized growth condition of a low V-III ratio (~1350) and hydrogen as the carrier gas (details in Ref. 12) was used for synthesizing the nanorods. This growth condition resulted in self-limited growth with the nanorod caps exposed above the silicon dioxide template as shown in Fig. 1(a). The nanorods are vertically aligned, have pointed tip morphologies, and are faceted with an average diameter of 50±5 nm and total height of 100 nm. The base of each nanorod consists of six prismatic planes of the $\{1\bar{1}00\}$ type and the pyramidal cap is made up of six $\{1\bar{1}01\}$-type planes. The underlying substrate on which the GaN nanorods were synthesized was an unintentionally doped GaN film on a *c*-plane sapphire substrate. The as-grown GaN nanorods are expected to have the same carrier concentration as that of thin-film GaN grown under the same growth condition. The measured electron concentration for thin-film GaN by capacitance-voltage (*C-V*) measurements was approximately 8×10^{16} cm^{-3}. Surface depletion at the nanorod surface was not so severe as to deplete the entire nanorod.[13]

(Al,Ga)N/GaN heterostructure nanorods were grown with a 5 nm thick (Al,Ga)N layer to enhance the electron tunneling from the underlying GaN nanorod. Figure 1(b) shows the θ-2θ *x*-ray diffraction (XRD) pattern from a thin-film (Al,Ga)N/GaN sample. The AlN mole fraction in the (Al,Ga)N film grown on a GaN substrate as estimated from the XRD pattern, assuming that all of the strain was relieved by introduction of misfit dislocations, was approximately 0.5. The same (Al,Ga)N growth condition was used to synthesize (Al,Ga)N/GaN nanorod heterostructures. Mg-doped *p*-type nanorods were also prepared to demonstrate the effect of carrier type on field-emission properties. The hole concentration in the *p*-GaN nanorod is expected to be approximately 2×10^{17} cm^{-3}, as calculated from *C-V* measurements on *p*-GaN films grown with the same conditions as the *p*-GaN nanorods.

Field-emission experiments were conducted in a vacuum chamber at a pressure of approximately 5×10^{-7} Torr. The anode was a molybdenum rod with a circular shape of 1.5 mm radius (7.07 mm^2 cross-sectional area). The anode-to-cathode distance was varied using a micromechanical translation device having a linear accuracy of approximately 1 μm. The anode-to-cathode distance was varied in the range of 15–30 μm. The exact anode-to-cathode distance was determined by moving the anode towards the sample surface (emitter) after acquiring the field-emission data and observing a short circuit condition when the molybdenum rod touched the emitter.

Figure 2(a) shows the field-emission characteristics from the four samples. The turn-on fields, defined at approximately 0.1 $\mu A/cm^2$ for the both GaN and (Al,Ga)N/GaN nanorods, were calculated to be 38.71 and 19.33 V/μm, respectively. The current density for all experiments is defined as the total emission current divided by the anode area. However, the GaN thin film and the *p*-GaN nanorods did not show any field-emission characteristics until the field reached ~70 V/μm. The field-emission data were analyzed using the Fowler-Nordheim (FN) equation given by[14–17]

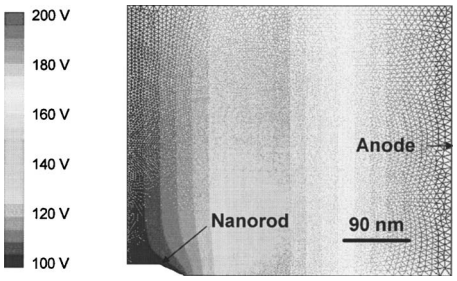

FIG. 3. Color solution of Laplace's equation for a nanorod emitter voltage of 100 V and a flat anode voltage of 200 V. The estimated field enhancement factor is 64.

$$J = (A\beta^2 V^2/\phi d^2)\exp(-B\phi^{3/2} d/\beta V), \quad (1)$$

where J is the current density, β is the field enhancement factor, ϕ is the work function, d is the anode-to-cathode distance, and V is the applied potential. The terms A and B in Eq. (1) are numerical constants with values of 1.56×10^{-10} Δ V^{-2} eV and 6.83×10^9 V $eV^{-3/2}$ m^{-1}, respectively. Figure 2(b) shows the resulting Fowler-Nordheim plots. The negative slope of the FN curves from the GaN and (Al,Ga)N/GaN nanorods indicates that the measured current is a result of field emission. The FN plots from the GaN thin film and the *p*-GaN nanorod samples exhibit a positive slope, which indicates a deviation from Fowler-Nordheim behavior. The *p*-GaN nanorods are devoid of free electrons, and the Fermi level is deep within the band gap, which increases the effective work function.[18]

The energy difference between the conduction band minimum and the Fermi level and the resulting work function for the GaN nanorod emitters were estimated to be approximately 0.1 and 3.3 eV, respectively, assuming an electron concentration of 8×10^{16} cm^3 and an electron affinity of 3.2 eV. In the absence of any field enhancement, as in the case of the GaN thin film, this work function (3.3 eV) is sufficiently large to prevent any observable field emission at moderate fields (<100 V/μm), in agreement with the present work. These results imply that the turn-on field was dramatically reduced due to the pointed tip morphology of the GaN emitters. The field enhancement factor of the nanorod emitters was estimated at 65 by fitting the emission data from the GaN nanorods using the FN approximation and assuming a work function of 3.3 eV.

A two-dimensional finite-volume model using commercial software was employed to solve Laplace's equation for the electric potential in the nanorod emitter-flat anode geometry. This model revealed that a radius of curvature at the nanorod tip of approximately 1 nm produces a field enhancement factor in agreement with the field-emission data (65). The simulated electric field is shown in Fig. 3, which shows that the electric field is greatly enhanced near the emitter tip. The finite-difference model results showed that the field enhancement was independent of the cathode-anode tip distance for vacuum gaps larger than 500 nm; therefore, for greater computational efficiency, the anode-to-cathode distance in the model was set at 600 nm. For calculation of the

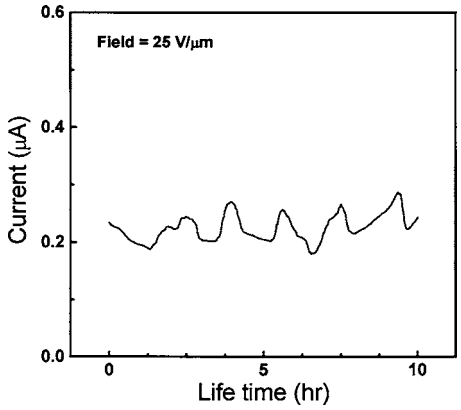

FIG. 4. Emission current stability of (Al,Ga)N/GaN nanorods at a field of 25 V/μm. The vacuum pressure was maintained at approximately 5×10^{-7} Torr.

effective work function of the (Al,Ga)N capped GaN nanorods, the field enhancement factor of 65 as determined from the simulation described earlier was used to fit the obtained data from the vacuum field emission using the Fowler-Nordheim approximation. The fitting resulted in an effective work function value for the (Al,Ga)N/GaN nanorod emitters of 2.1 eV. Thus, the large field enhancement factor due to the sharp nanorod tips combined with the lowering of the surface electron affinity by an (Al,Ga)N capping layer greatly improves the field-emission properties of GaN-based nanorod emitters. It should be noted here that the samples used in the present work were unintentionally doped GaN. Increasing the doping level, the AlN mole fraction in the top (Al,Ga)N layer and the areal density of the nanorod emitters could further reduce the turn-on field and increase the current density.[8,19]

A lifetime study was also conducted for the (Al,Ga)N/GaN nanorod samples to investigate the field-emission stability. As shown in Fig. 4, reasonably uniform electron emission over a period of 10 h was observed with the maximum deviation from the average current value of 8%, which shows the promise of nanorod heterostructures for field-emission applications.

In conclusion, the field-emission characteristics of GaN and (Al,Ga)N/GaN nanorods have been investigated. A 5 nm thick (Al,Ga)N epitaxial film on the GaN nanorod reduced the turn-on field by a factor of 2 compared to GaN nanorods. Such a nanoheterostructure approach for field emitters thus circumvents the necessity of doping the top (Al,Ga)N layer. The experimental data suggest that the increased electron emission from (Al,Ga)N/GaN nanorods is promising for application in field-emission devices.

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