Ultralow-threshold field emission from oriented nanostructured GaN films on Si substrate

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A series of nanostructured GaN films have been prepared on Si substrates. Field emission measurements show that the oriented nanostructured GaN film with a thickness of 40 nm has an ultralow threshold field of 1.2 V/μm at 1 mA/cm² and yields a stable emission current of 40 mA/cm² at 2.8 V/μm, which is comparable to those of carbon nanotubes. A polarization field emission enhancement mechanism with ballistic electron transport is proposed to explain the origin of this ultralow-threshold field emission phenomenon. © 2010 American Institute of Physics. [doi:10.1063/1.3352556]

High-performance electron field emitters are desirable in vacuum microelectronic devices.1 GaN is a one of the good field emission (FE) materials due to its low electron affinity (2.7–3.3 eV), high thermal stability, and high breakdown voltage.2 Furthermore, GaN which has a wide direct band gap of 3.3 eV can induce large band bending which may promote its FE properties,3 and so the FE properties of one-dimensional (1D) GaN structures have been extensively studied.4,5 However, it has been reported that the thermal conductivity in these 1D nanostructures is substantially lower than that in the bulk materials.6,7 For devices operated under high-current and high-power-densities circumstances, ineffective thermal dissipation can result in field emission failure and reduced lifetime. A potential alternative is to use a thin film cathode. Although some theories have recently been proposed to elucidate the FE enhancement by the thin film cathode using quantum structure modulation,8–10 experimental verification is lacking thereby hampering our understanding and commercial applications.11 In this study, GaN films deposited on Si substrates by pulsed laser deposition (PLD) are observed to exhibit ultra-low-threshold field emission and a polarization field emission enhancement model is proposed to explain the excellent emission properties achieved from these orientated nanostructured GaN films.

The GaN films were deposited on (100)-oriented n-type Si substrates by PLD. The PLD target was prepared with GaN powders using pressing and sintering. The target was ablated using a KrF excimer laser with a wavelength of 248 nm, pulse duration of 10 ns, energy density of 3.0 J/cm², and laser frequency of 13 Hz. The ablated species were deposited onto the Si substrate placed at a distance of 80 mm from the target and heated to 850 °C. During deposition, N₂ gas was introduced into the growth chamber to a working pressure of 1 Pa. The GaN films were produced using different deposition time from 1 to 60 min to obtain thicknesses of 30, 40, 50, 120, 300, 500, and 800 nm (designated as samples A–G, respectively).

The orientations of these films were determined by x-ray diffraction (XRD, Bruker AXS D8 Advance) with Cu Kα radiation. Atomic force microscopy (AFM, NT-MDT Solver P47) was employed to investigate the surface morphology and the FE characteristics were measured in the chamber evacuated to 5×10⁻⁷ Pa at room temperature. A Si wafer (0.001 Ω cm) was used as an anode electrode, and the cathode and anode (7×7 mm²) were separated by glass fiber at a distance of 14 μm. The I–V curves were acquired using a Keithley 2410 and to ensure good reproducibility, the FE data were taken many times until the FE current was stable.

The XRD patterns of the GaN films are depicted in Fig. 1(a). The diffraction peak from the (0002) plane of the wurtzite-type hexagonal GaN is observed from samples B–G, indicating that the GaN films are preferentially oriented in the c-axis direction. On the other hand, the hexagonal (0002) diffraction peaks cannot be observed when the film thickness is below 40 nm. It implies that the GaN film with an amorphous phase tends to form only below a certain thickness. Furthermore, according to Fig. 1(b), when the GaN film thickness decreases, the peak of the (0002) plane shifts to smaller angles compared to bulk GaN (JCPDS 50–0792). The slight decrease in the 2θ values suggests increased residual stress in the GaN film,12 which is attributed to the expansion of the interplanar distance along the c-axis.

The J–E characteristics are shown in Fig. 2(a) and the corresponding Fowler–Nordheim (FN) plots are given in Fig. 2(b). The turn-on field E_on and threshold field E_th are defined at an emission current density of 10 μA/cm² and 1 mA/cm², respectively. As shown in Fig. 2(a), no obvious field emission current is observed from the GaN film for samples A (30 nm), D (120 nm), E (300 nm), F (500 nm), and G (800 nm). However, E_th is found to be 1.2 and 0.9 V/μm from samples B (40 nm) and C (50 nm), respectively. These values are lower than that observed from GaN cathodes with a 1D nanostructure,4,5 and even comparable to those of carbon nanotubes.13,14 The FN plots in Fig. 2(b) show a linear relationship in the high-field region for all the samples, suggesting that the emission current should originate from a quantum mechanical tunneling process.
To investigate the electron emission enhancement mechanism of samples B and C, the surface barrier height $\varphi_{\text{sur}}$ and effective emission area $A_{\text{eff}}$ of the samples should be considered carefully because they are key factors affecting field emission from semiconductor films.\textsuperscript{8,11} The $\varphi_{\text{sur}}$ and $A_{\text{eff}}$ can be obtained by linear fitting of the FN curve.\textsuperscript{15} The $\varphi_{\text{sur}}$ can be estimated from the slope of the linearly fitted FN curve $k$ if the field enhancement factor $\beta$ of the emitter can be evaluated. Figure 3 shows the AFM images obtained from samples A–D. Since their surface morphologies are quite similar, the impact of surface morphology (surface defect states) should be negligible. By using the reported $\beta$ value of the film cathode of $1.0 \times 10^3$,\textsuperscript{13} the $\varphi_{\text{sur}}$ values are about 2.4, 3.3, 1.0, 2.4, and 1.7 eV for samples A, D, E, F, and G, respectively, and those of samples B and C are lower at 0.2 and 0.1 eV, respectively. The $\alpha$ value can be calculated from the intercept of the linearly fitted FN curve. Compared to other samples, the effective emission areas of samples B and C are larger by two to three orders of magnitude as shown in Fig. 4. Both $\varphi_{\text{sur}}$ and $\alpha$ have been observed to be enhanced from films with a thickness of 40–50 nm and hexagonal structure. In addition, Figs. 1 and 4 indicate that the thickness of the GaN layer significantly influences the crystallographic characteristics, electron transport characteristics, as well as FE properties. Hence, a polarization FE enhancement mechanism encompassing ballistic electron transport through an oriented nanostructured GaN film is postulated to explain the excellent field emission properties.

As observed from the inset in Fig. 4, the polarization FE enhancement mechanism with ballistic electron transport comprises two effects. The first effect is the polarization effect.\textsuperscript{17} III-V nitrides possess special properties and compared to other III-V compounds, the piezoelectric constants of nitrides are nearly ten times larger and spontaneous polarization is very large.\textsuperscript{18} When the growth direction is along the polar c-axis of the wurtzite structure, piezoelectric, and spontaneous polarization can result in a strong polarization field in the range of a few megalovolt per cm.\textsuperscript{19,20} A polarization field can be formed in samples B and C due to the residual stress along the c-axis as shown in Fig. 1(b). When the polarization field is formed, the conduction band (CB) of...
leads to greatly reduced level. Coupling of the polarization and nanostructure potential difference between the CB level of Si and vacuum of the Si substrate. In this case, GaN near the GaN/vacuum interface but from the CB levels of the substrate. Hence, electrons are emitted not from the CB levels of the GaN layer is less than the mean free path of electrons, electrons tunneling ballistically through the GaN layer. When the thickness of the GaN is dramatically brought down. The second effect arises from the nanostructure.10,11 When the thickness of the GaN layer is less than the mean free path of electrons, electrons are accumulated near the GaN/vacuum interface due to electrons tunneling ballistically through the GaN layer. Hence, electrons are emitted not from the CB levels of the GaN near the GaN/vacuum interface but from the CB levels of the Si substrate. In this case, $\phi_{\text{sur}}$ can be defined as the potential difference between the CB level of Si and vacuum level. Coupling of the polarization and nanostructure effects leads to greatly reduced $\phi_{\text{sur}}$ and consequently, the FE properties are enhanced markedly, as illustrated in Fig. 2.

In summary, ultralow-threshold FE has been observed from oriented nanostructured GaN films deposited on Si substrates. The excellent FE properties originate from polarization FE enhancement with ballistic electron transport. In addition to GaN, several other materials having the hexagonal wurtzite structure and wide band gap, such as AlN, BN, and ZnO, can be used as similar FE cathodes. They are applicable to vacuum microelectronics as it is convenient to integrate these devices into silicon technologies.

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