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Field Emission Characteristics of BN Films with Cubic-BN Phase *

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Boron nitride (BN) thin films with cubic boron nitride (c-BN) phase were prepared on the (100)-oriented surface of n-Si (0.008–0.02 Ωm) by rf magnetron sputtering physical vapor deposition. The c-BN content is determined to be around 50% by using Fourier transform infrared spectroscopy for the BN thin films. The field emission characteristics of BN films were measured in an ultrahigh vacuum system. It is found that the field emission of the BN film with c-BN phase is evidently more excellent than that without c-BN phase. A turn-on field of 5 V/μm and a current of 460 μA/cm² were obtained for the BN film with c-BN phase. The Fowler-Nordheim plots of emission characteristics of BN films indicate a straight line, which suggests the presence of the FN tunneling.

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Much attention has been paid to diamond-based field emitters as an electron source with a highly reliable performance because diamond has superior properties such as negative electron affinity (NEA), chemical inertness and mechanical hardness. Electron emission from diamond films is observed at considerable low electric field.[1,2] Moreover, it was found that the operation of electric field was reduced effectively for Si and Mo field emitters coated with diamond.[3–5] It is known that BN has similar properties to diamond. Moreover, a uniform thin film of BN can be deposited although it is very difficult to deposit, and NEA has been detected on the surface of BN films.[6,7] It was reported that electrons were emitted at a low voltage from S-doped BN film synthesized by plasma-assisted chemical vapor deposition.[8] It was also demonstrated that the threshold electric field increased with the increase of the thickness in the nanometer range for BN thin films.[9]

BN films were prepared on Si (100) by rf magnetic sputtering PVD[9,10] using a 50-mm diameter h-BN (99.99%) target in a mixture of N_2 (10%) and Ar (90%) at a total pressure of 2 Pa. The chamber base pressure was below 5×10^{-4} Pa and the substrate temperature was kept at 500°C before the deposition. The rf power was 200 W, the target-substrate distance was 5 cm and the deposition time is 60 min. The two samples of 1 and 2 were deposited at the substrate bias of 120 V and 160 V, respectively. The Si-substrates was pretreated by using foregoing method.[11] The field emission testing was conducted at high vacuum ($<5\times10^{-7}$ Pa). A film sample ($5\times5\,\mathrm{mm}^2$) acted as the cathode. An indium-tin-oxide-coated glass plate was utilized as the anode. The anode was set to be 100 μm away from the sample surface using two pieces of insulation glass fibre as a spacer. The ohmic contacts Si substrates were provided with Ag epoxy.

Figure 1 shows the Fourier transform infrared (FTIR) spectra of BN films. There are three absorption peaks at about 1379, 1071 and 783 cm^{-1} in the spectra of samples 1 and 2. The peaks at about 1379 and 783 cm^{-1} are coincident to the h-BN structure[9,10] and the peak at about 1071 cm^{-1} is coincident to the c-BN structure.[10] The peak intensity of sample 1 at about 1071 cm^{-1} is very weak, which indicates that sample 1 is almost a pure h-BN structure. Sample 2 is the mixture of the h-BN and c-BN phases and the c-BN content is about 50 %.

The field emission characteristics are analysed by using the current density versus electric field (J–E) curves. The turn-on electric field is defined as the electric field under which a 2-μA/cm² current density appears. The field emission characteristics of BN films are shown in Fig. 2. The turn-on electric field is 5 V/μm and the emission current density is 460 μA/cm² at an electric field of 26 V/μm for the BN film with the c-BN phase. The turn-on electric field is 8 V/μm and the emission current density is 360 μA/cm² at an electric field of 28 V/μm for BN films without the c-BN phase. It is shown that a significant reduction of the turn-on field can be achieved for the BN film with the c-BN phase. Moreover, the emission current the BN film with the c-BN phase is higher than that without the c-BN phase. In addition,

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the steady emission characteristics for the BN film with the c-BN phase were obtained. There appears a difference of the emission current, which is not more than 6 μA within 6 h.

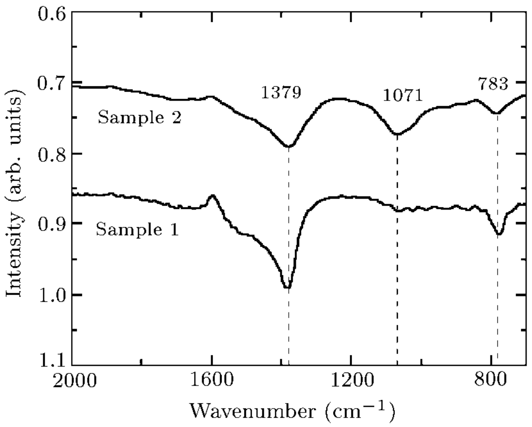

Fig. 1. Fourier transform infrared spectra of BN-coated on Si.

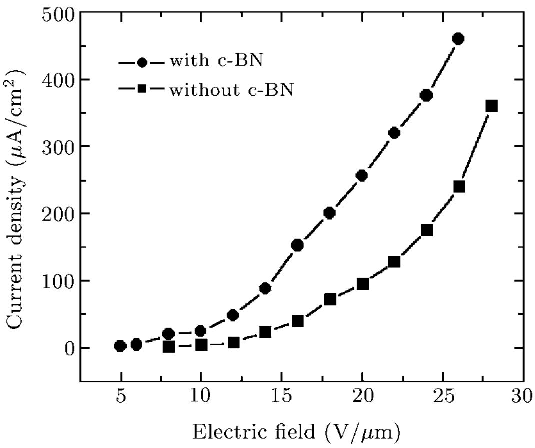

Fig. 2. Current density of BN thin films deposited at various substrate bias as a function of electric field.

The Fowler-Nordheim (FN) plots of BN films are shown in Fig. 3. The straight line suggests that the field emission is consistent with the conventional FN theory. It is shown that electrons were emitted from BN to vacuum by tunneling through the potential barrier at the surface of BN thin films at exterior electric field. The field enhancement factor of the samples can be estimated by the FN theoretical formula $\ln(I/V^2) = \ln a - 6.83 \times 10^7 d\phi^{3/2}/\beta V$, where d is the cathode-to-anode distance in cm, ϕ is the work function in eV, and β is the field enhancement factor.[14] Assuming that $\phi = 2$ eV, the field enhancement factors of BN films with and without the c-BN phase are estimated to be about 1.3×10^3 and 6.1×10^2, respectively, by using the slope of the FN plot in Fig. 3.

The atomic force microscopic (AFM) images of BN samples with and without c-BN phase are shown in Figs. 4(a) and 4(b), respectively. The surface morphology of the two samples is analogous and the surface roughness is estimated to be about 9–11 nm. Thus, the field emission characteristics of two samples are not influenced strongly by surface morphology.

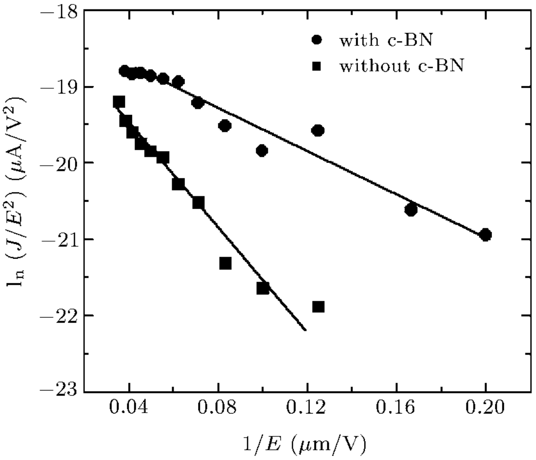

Fig. 3. Fowler-Nordheim plots of BN thin films deposited at various substrate bias voltages.

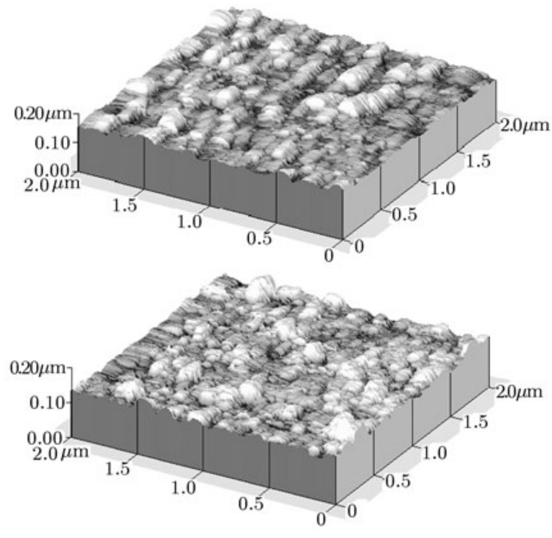

Fig. 4. AFM images of BN films (a) with and (b) without the c-BN phase.

The mechanism of the field emission of BN films is explained by the band bending theory. The maximum value of band bending is nearly linearly proportional to the band gap of wide-band gap semiconductors, and may amount to a few eV.[12] The conduction band minimum closes to the Fermi energy level due to band bending, so enough quantities of electrons are assembled at the conduction band minimum. The electron can be emitted from the conduction to vacuum,[13] and the electron emission mostly originates from the conduction band minimum due to small quantities of electrons taking up the higher energy level. C-BN and h-BN are two typical wide-band gap semiconductors, and the field emission characteristics are affected by band bending. The maximum value of the band bending increases with the increasing band gap for a wide-band gap semiconductor, and enough quantities of electrons are supplied in the conduction band minimum due to band bending. The band gap of c-BN is wider than h-BN, so there is a rise of the quantity of electrons for the BN film with c-BN. Therefore, the turn-on electric field is reduced and the emission current is increased for the BN film with c-BN phase, considering the lower electron affinity property of BN films at the same time.

In summary, the field emission characteristics of the BN film with c-BN phase are better than that without c-BN phase. A turn-on electric field of $5\,\mathrm{V}/\mu\mathrm{m}$ and an emission current density of $460\,\mu\mathrm{A/cm^2}$ were obtained for the BN film with c-BN phase. The FN plot shows that electrons were emitted from BN to vacuum by tunneling through the potential barrier at the surface of BN thin films at exterior electric field.

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