UV photoemission and field emission study of AlGaN/GaN emitters

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Abstract – The electron affinity and the field emission characteristics are studied on $Al_xGa_{1-x}N$/GaN grown by metalorganic vapor phase epitaxy. The clean $Al_xGa_{1-x}N$ surfaces prepared with multiple cycles of nitrogen ion sputtering and annealing were investigated by ultraviolet photoemission spectroscopy (UPS). The electron affinity of $Al_xGa_{1-x}N$ is determined to be 3.6~2.9 eV for x = 0~0.59, which decreases as the increase of AlN molar fraction x. GaN and $Al_{0.1}Ga_{0.9}N$/GaN pyramidal field emitters fabricated by a selective area growth technique are investigated and it is found that the turn-on voltage is reduced by using $Al_{0.1}Ga_{0.9}N$/GaN emitter with lower electron affinity than GaN.

Wide band gap III-nitrides have been attracted much attention as promising materials not only for opto-electronic devices in short wavelengths but also for field emission devices, because III nitrides are expected to have low electron affinities and exhibit high field emission currents. Recently, field emission from arrays of hexagonal GaN pyramids, which obtained by the selective area growth, have been reported by several research groups.[1-3] However, they showed turn-on voltages higher than 150 V. Moreover, the electron affinities of III nitride surfaces remain ambiguous and studies on III nitrides emitters with extraction gate electrode have been scarce. In this study, the electron affinities of the clean $Al_xGa_{1-x}N$ have been investigated by ultraviolet photoemission spectroscopy (UPS) and the field emission characteristics of the gated GaN and $Al_{0.1}Ga_{0.9}N$/GaN pyramidal field emitters are studied.

The samples for UPS measurements are Si-doped $Al_xGa_{1-x}N$/GaN ($0 \le x \le 0.59$) grown by metalorganic vapor phase epitaxy (MOVPE) on *c*-plane sapphire substrates. The thickness of AlGaN and GaN layers are 0.1 and 4 μm, respectively. The *n*-type GaN under-layer with a high electronic conductivity was to minimize the charging effects associated with a low conductivity of AlGaN layer and an insulating substrate. The photoemission spectra were measured on the clean AlGaN surfaces prepared with multiple cycles of nitrogen ion sputtering (1.5 keV, 10 min) and annealing (900°C, 10 min).[4] A resonance line of He I (21.2 eV) was used as the incident light.

Figure 1 shows the UPS spectra of AlGaN surfaces with various AlN molar fractions. Each spectrum has been aligned at the energy of the valence band maximum (E_{VBM}). The width of UPS distribution curve (W) and the excitation photon energy ($h\nu$) yield the ionization energy (I) as $I = h\nu - W$, and the difference of the ionization energy and the electron affinity of semiconductor is equal to the band gap energy (E_g). The electron affinities of AlGaN determined in this manner are shown in Fig.2, which decrease as the AlN molar fraction increases. Negative electron affinity (NEA) was reported on a Al-rich AlGaN.[5] But the present results demonstrate that the electron affinity of AlGaN surface is positive and in good agreement with the recent results on clean GaN and AlN surfaces.[4,6]

In order to confirm the reduction of the affinity in $Al_xGa_{1-x}N$ (x>0), gated GaN and $Al_{0.1}Ga_{0.9}N$/GaN emitters were fabricated using a self-aligned process as shown in Fig. 3. The sharp pyramidal emitters with diameter of 5μm and spacing of 10μm were obtained by a selective area growth technique.[3] SiO_2 and polyimide were used as the insulating layers between the emitters and the gate electrode. Polyimide layer was etched back in O_2 plasma to expose the emitter tip apex. Ni was evaporated on the polyimide layer as the gate electrode. Then, Ni and SiO_2 layer at the tip apex was removed to form a gate opening. The gate-tip spacing and the gate-opening diameter were determined by the thickness of SiO_2 (typically 0.4-0.5μm) and polyimide which is adjusted in the etch-back process. The field emitter array consists of about 200 tips in the area of 120 × 120 μm^2.

The emission currents of the gated GaN and $Al_{0.1}Ga_{0.9}N$/GaN emitters were measured in a vacuum of 10^{-7}Pa. All emitters were baked at 150°C for 6hrs before being tested. A molybdenum plate anode was located 5mm above the emitter tips and was biased at 500V. Figure 4 shows the typical current-voltage characteristics of the GaN and $Al_{0.1}Ga_{0.9}N$/GaN field emitters with the gate-tip spacing of 0.4 or 0.5 μm.

The extraction voltage is as low as 42V. In Fig.4, it is obvious that the gate turn-on voltage is reduced by using $Al_{0.1}Ga_{0.9}N$/GaN instead of GaN. The lower electron affinity of $Al_{0.1}Ga_{0.9}N$ than that of GaN accounts for enhancement of the emission current.

In conclusion, the electron affinity of $Al_xGa_{1-x}N$ measured by UPS was found to be 3.6~2.9 eV for x = 0~0.59, which decreases as the increase of AlN molar fraction x. GaN and $Al_{0.1}Ga_{0.9}N$/GaN gated field emitter arrays with pyramidal sharp tips were obtained by the selective area growth and the self-aligned process. A low turn-on voltage of 42V was achieved by using $Al_{0.1}Ga_{0.9}N$/GaN emitter with the small gate-tip spacing of 0.4μm.

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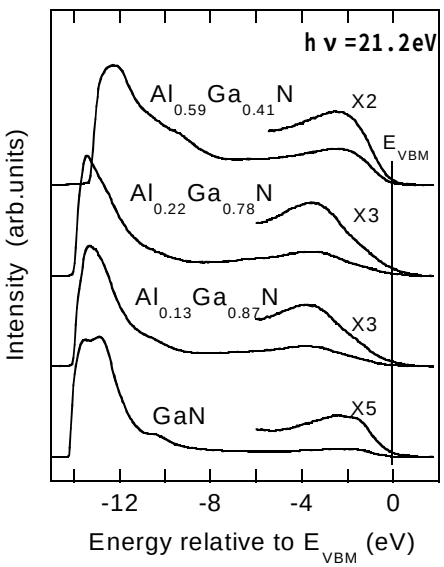

FIG. 1. UPS spectra of AlGaN aligned at the energy of the valence band maxima.

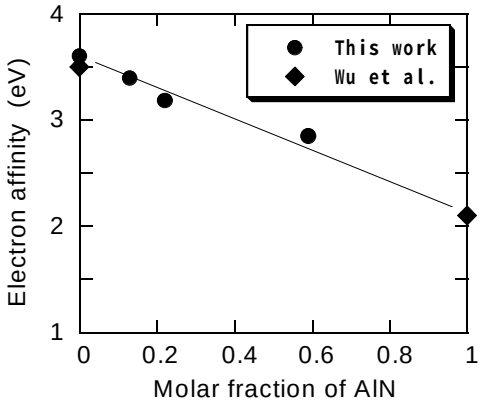

FIG. 2. Electron affinities of AlGaN alloys.

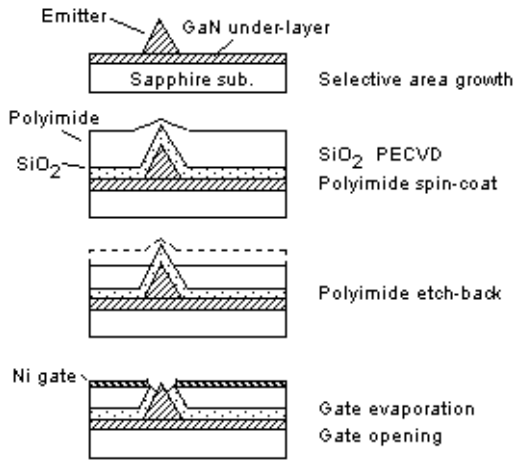

FIG. 3. Fabrication procedure of gated field emitter.

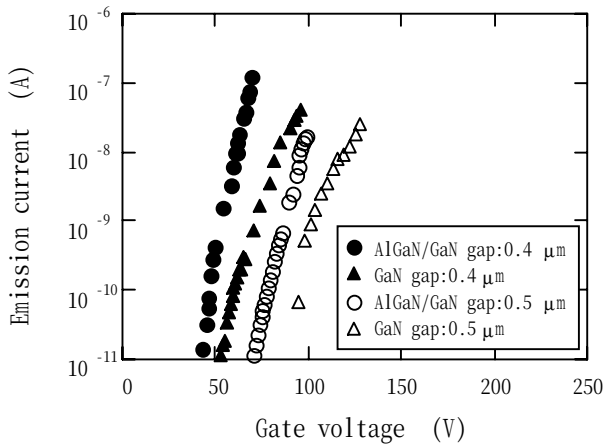

FIG.4. I-V characteristics of gated field emitters.