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An $Al_{0.25}Ga_{0.75}N$/GaN Lateral Field Emission Device with a Nano Void Channel *

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We report an $Al_{0.25}Ga_{0.75}N$/GaN based lateral field emission device with a nanometer scale void channel. A ∼45 nm void channel is obtained by etching out the SiO_2 sacrificial dielectric layer between the semiconductor emitter and the metal collector. Under an atmospheric environment instead of vacuum conditions, the GaN-based field emission device shows a low turn-on voltage of 2.3 V, a high emission current of ∼40 μA (line current density 2.3 mA/cm) at a collector bias $V_C = 3$ V, and a low reverse leakage of 3 nA at $V_C = -3$ V. These characteristics are attributed to the nanometer scale void channel as well as the high density of two-dimensional electron gas in the AlGaN/GaN heterojunction. This type of device may have potential applications in high frequency microelectronics or nanoelectronics.

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During the past several decades, significant advances in complementary metal-oxide-semiconductor technology have contributed considerably to contemporary electronics.[1] The solid-state devices are scalable without loss of performance, consume extremely low power per function, and can be easily integrated into functional circuits enabling large-scale manufacturing. The conventional semiconductor channel suffers from optical and acoustic phonon scattering. In comparison, a vacuum is an excellent electron conveying medium since it enables ballistic transport, and the velocity of electrons in a vacuum can be much higher than that in semiconductors. Field emission devices (FEDs) are widely used in vacuum microelectronics such as ultrahigh speed or high frequency devices and microwave amplifiers. As a core part of FED, various cathode materials have been developed to realize high performance FED, these materials include Mo, diamond, and carbon nanotubes.[2] Among these materials, semiconductor materials as field emission cathodes become an important research topic due to their mature processing techniques in micro and nanometer scales and their good performance from their intrinsic properties of the materials.

Gallium nitride has attracted a great deal of interest because of its remarkable physical and chemical properties, such as a wideband-gap of 3.4 eV, a low electron affinity of 2.7–3.3 eV and a high electron mobility of ∼1000 $cm^2V^{-1}s^{-1}$, which make it a highly promising electron field emission device, e.g., using GaN as a field emission cathode.[3–7] Most of the GaN field emission devices in the previous reports are based on a vertical structure, and the formation of the anode electrode is very complicated. Moreover, the distances between GaN cathode and the metal anode of the vertical structured devices are from several microns to hundreds of microns, which results in high turn-on voltages, and thus the devices must operate in a vacuum environment. However, lateral FED can offer significant advantages for IC-compatible high speed and RF applications from its low input and negligible parasitic capacitance structure, lithography-controlled small inter-electrode gap and versatile emitter geometry.[8,9] As we know, the mean free path of electrons in atmosphere is about 60 nm.[10] If the active geometry of a device is smaller than 60 nm, it will become possible to avoid the vacuum requirement. Compared with bulk GaN, the AlGaN/GaN heterojunction is highly preferred for ultrahigh speed or high frequency field emission devices due to its room temperature mobility of 2000 $cm^2V^{-1}s^{-1}$ with a two-dimensional electron gas (2DEG) sheet density of 1×10^{13} cm^{-2}.[11–13]

In this work, we fabricate an AlGaN/GaN lateral field emission void channel device with a ∼45 nm gap between the emitter and collector, and the device can work in the atmospheric environment. The GaN-based field emission device exhibits a low turn-on voltage of ∼2.3 V, a high emission current of ∼40 μA at collector bias $V_C = 3$ V, and a low reverse leakage of 3 nA.

Figure 1(a) shows the schematic view of the device that consists of AlGaN/GaN emitter and metal collector. The AlGaN/GaN heterostructure epitaxy materials were grown by metal organic chemical vapor deposition (MOCVD) on a 2-inch Si (111) substrate, which

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consists of a 20-nm undoped $Al_{0.25}Ga_{0.75}N$ barrier, a 100-nm GaN channel layer and a 2.5-μm carbon-doped GaN buffer layer (HR GaN). Room-temperature Hall measurements of the structure yield an electron mobility of 1550 $cm^2V^{-1}s^{-1}$ and sheet charge density of 7.5×10^{12} cm^{-2}. For the fabrication of the device, a 25-nm-thick SiN_x dielectric layer was deposited on the surface of $Al_{0.25}Ga_{0.75}N$ by low pressure chemical vapor deposition (LPCVD). The active region of the device was defined by standard photolithography and ion implantation isolation. Ti/Al/Ni/Au (20 nm/130 nm/50 nm/150 nm) multi-layers were subsequently evaporated on the surface of $Al_{0.25}Ga_{0.75}N$ layer after the SiN_x opening was formed by reactive ion etching, and annealed at 890℃ for 30 s in N_2 ambient to form the ohmic contact of the emitter. The mesa terrace was formed by inductive coupled plasma reactive ion etching, and the shape of the emitter was with a planar structure with 170 μm width and 250 nm depth. Then, ∼45 nm SiO_2 was deposited on the wafer by inductive coupled plasma chemical vapor deposition at 75℃, which was used as a sacrificial layer to form a nano void channel between the emitter and collector. Cr/Au (20 nm/300 nm) were then evaporated as the collector. Finally, the SiO_2 sacrificial dielectric layer between the semiconductor emitter and the metal collector was removed by HF etchant. Figure 1(b) shows the SEM image of AlGaN/GaN lateral FED. The gap between the emitter and the collector can be controlled by the thickness of the SiO_2 sacrificial layer.

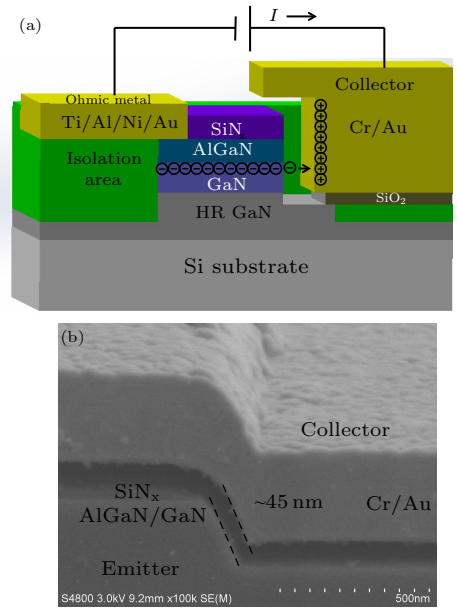

Fig. 1. (a) Schematic view of AlGaN/GaN lateral FED with nano void channel. (b) SEM cross section image of AlGaN/GaN lateral FED.

The measurements for AlGaN/GaN lateral FED were carried out in air ambient at room temperature. The Si substrate and the emitter were grounded to maintain the same potential. Figure 2(a) shows the measured current-voltage (I–V) characteristics, and the collector bias V_C sweeps from −3 to 3 V with the step of 0.05 V. When the forward voltage is above 2.3 V (the electric field between the emitter and the collector was 51 V/μm), the current of the device between nano void channel rises abruptly, and the current is ∼40 μA at collector bias $V_C = 3$ V. The reverse leakage is 3 nA at collector bias $V_C = -3$ V. When a low bias is applied between the nano void channel, the I–V characteristic with a slope of 1.0 in logarithm shown in Fig. 2(b). The barrier is too high for low energy electrons, and the current is detected as the leakage current which may be caused by surface states or the transmission through HR-GaN. The current between the semiconductor emitter and the metal collector was measured before the SiO_2 layer was etched out, and it was 5 nA at the bias of 3 V (as shown in Fig. 2(a)), which was far smaller than the current with nano void channel at forward voltage. It can be clearly seen that electrons were emitted through the nano void channel after the SiO_2 was removed, and the SiO_2 sacrificial layer could block the emitting process.

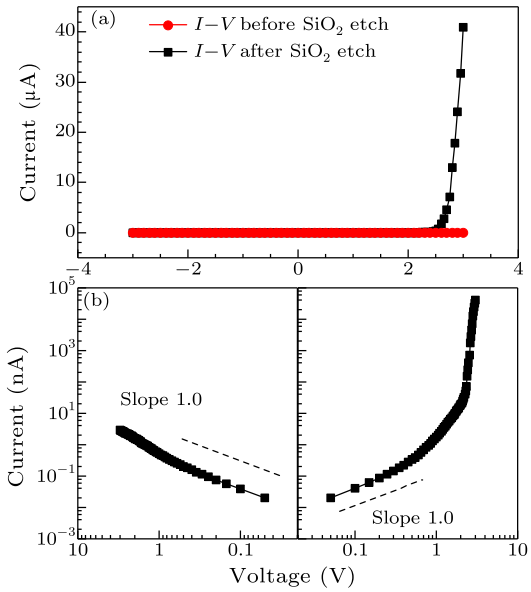

Fig. 2. (a) The I–V characteristics of the devices in linear scale before and after SiO_2 etching. (b) The log-log I–V characteristics of the devices measured from −3 V to 3 V.

It can be seen that the mechanism of carrier transport of the devices changed when the applied voltage was above the turn-on voltage. According to the Fowler–Nordheim (F-N) model,[14] the emission current is expressed as

$$\ln\left(\frac{I}{V^2}\right) = -\frac{Bd\Phi^{3/2}}{\beta}\frac{1}{V} + \ln\left(\frac{A\alpha\beta^2}{d^2\Phi}\right),$$

where A and B are constants, $A = 1.54 \times 10^{-6}$ A·eV·V^{-2}, $B = 6.83 \times 10^7$ V·cm^{-1}·$eV^{-3/2}$, Φ, d,

V and α are the work function of the emitter, the distance between the emitter and the collector and the applied voltage to the samples and effective emission area, and β is the field enhancement factor. A device showing linearity in the $\ln(I/V^2)$ versus $1/V$ plot signifies that the F-N tunneling is the dominant carrier transport mechanism. Figure 3 shows the F-N plots converted from the I–V characteristics of devices with a calculated β of 37.

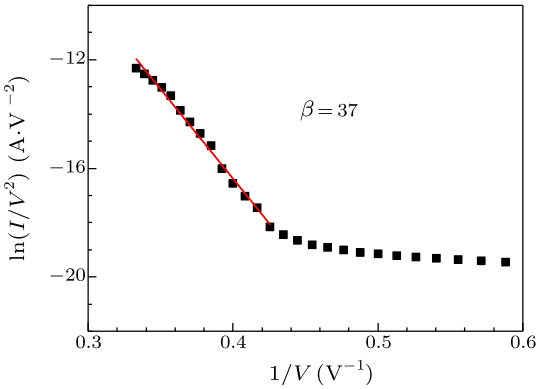

Fig. 3. The Fowler–Nordheim (F-N) plot converted from the I–V characteristics of the devices.

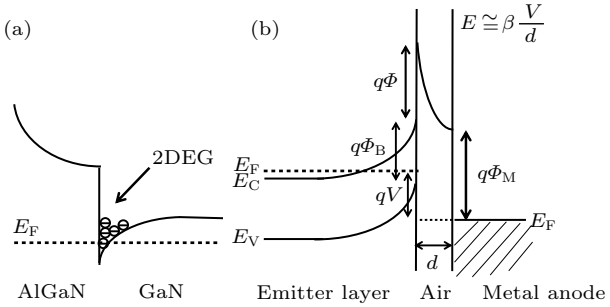

Fig. 4. (a) Energy band diagram of AlGaN/GaN. (b) Energy band diagram of the lateral FED with nano void channel at forward bias.

As mentioned previously, there is a 2DEG in the sample, and the 2DEG in the AlGaN/GaN heterojunction acted as an electron storage layer, which is shown in Fig. 4(a). The field enhancement factor β is related not only to net accumulation charges in the AlGaN/GaN structure but also to the emitter surface roughness. It has been reported that the field enhancement factor β increases linearly with the decrease of the emitter-collector distance, and a blunt tip can be deployed if the space is sufficiently scaled down.[13] It is demonstrated that when the spacing of the void channel becomes less than the mean free path of electrons in air, the free ballistic transport of electrons across the channel can be achieved, and the turn-on voltage of field emission is reduced.[10,15,16] The properties of the device at high voltage (>2.3 V) are attributed to the emitter-collector nanometer scale channel, as well as the high density of 2DEG layer in the AlGaN/GaN structure.

The energy band diagram of the device under forward bias is shown in Fig. 4(b). There is upward band bending on the surface of the emitter layer due to the surface states.[17–19] Higashiwaki *et al.* have experimentally proved that the surface barrier height ($q\Phi_B$) ranges from 1.0 to 3.0 eV, which depends on the thickness of the AlGaN barrier layer and the AlGaN surface treatment.[17] The electrons flow over the surface barrier height to the surface by the gradient of carrier concentration in the emitter layer. The net current density J_1 in the emitter layer can be expressed as $J_1 = qnuE_1 + qD\frac{d_n}{d_x}$, where D is the diffusion coefficient for the electron in the 2DEG, n is the number of electrons per unit volume, q is the charge of one electron, μ is the electron mobility of 2DEG, and E_1 is the electric field applied on the emitter layer. When a low bias is applied across the nano void channel, electrons transport on the surface of HR-GaN or through the HR-GaN, and the emission current is mainly dominated by the leakage current. When a forward voltage larger than turn-on voltage is applied to the device, it makes electrons emit through the triangular barrier into the air with an initial velocity, and transported ballistically to the side of collector Cr/Au. This transport of electrons in the AlGaN/GaN lateral field emission nano void channel device is governed by the F-N tunneling emission mechanism at high voltages ($V_C > 2.3$ V).

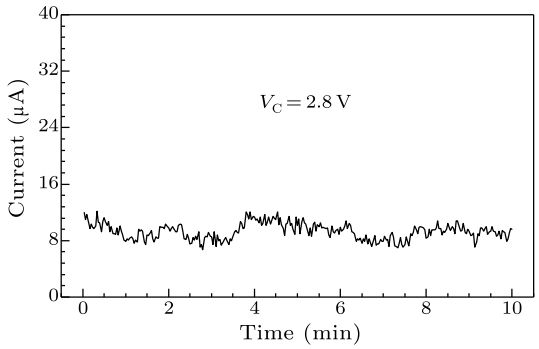

Fig. 5. Current-time plot of the AlGaN/GaN FED with nano void channel at constant collector voltage.

The field emission stability of the device was measured under a bias of 2.8 V during 10 min in air. The emission behavior of the AlGaN/GaN lateral FED is shown in Fig. 5. The current keeps almost the same but with fluctuations, which can be improved in the future by reducing the length of the void channel, the morphology of emitter, or using the vacuum package.

In conclusion, we have demonstrated an AlGaN/GaN lateral field emission nano void channel device for the first time. This device can operate in air, the turn-on voltage of field emission is as low as 2.3 V, and the emission current is as high as about 40 μA at a collector voltage of 3 V. The dominant mechanism of the emission current is identified to be the F-N emission in the high electric field ($V_C > 2.3$ V). The prop-

erties of this device are attributed to the nano void gap between the emitter and collector, and the 2DEG layer in the AlGaN/GaN structure.

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