KM-4-4

Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1310-1311

Low voltage operable field emission triodes with high transconductance based on laterally grown ZnO nanowires

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1. Introduction

Renewed interest in vacuum field emission (FE) devices has emerged recently [1-3]. Among them, triode-type emitters have attracted considerable attention in the application of Field emission displays (FEDs) [4-5]. However, one major adverse characteristic of conventional FE triodes which employed diamondlike carbon (DLC) films, vertically aligned nanostructure materials such as nanotubes, nanowires, nanobelts, or nanotetrapods, etc., is that they require a large range of operation voltages to handle the device. Essentially, an aggressive reduction of the operation voltage is vital to simplify circuit design and make integration of FE devices more straightforward. In this work, Low voltage (≤5 V) operable FE-triodes based on laterally grown ZnO nanowires was demonstrated. A simple two electrode pattern with a bi-layer using chromium (Cr, acting as a barrier layer) and an under-cut ZnO film (ZnO, acting as a seeding layer) for the laterally grown ZnO nanowires (ZnO NWs) on top of a Si/SiO_2 substrate using hydrothermal growth (HTG) method. The proposed bi-layer structure allows the inter-emitter spacing of ZnO NWs to be precisely controlled through the HTG process, and a thin SiO_2 layer is formed as a dielectric layer for bottom gate (BG) structure, which makes it possible for low voltage operation of ZnO NWs based FE-triode with high FE currents and high transconductance (g_m). The electrical performance of the prepared ZnO NWs based FE-Triodes was investigated and transconductance (g_m) as high as of 299 µS (@ V_a=5 V and V_g=-5 V) has been obtained.

2. Experiments

Fig. 1 shows the key fabrication processes of the ZnO NWs based FE triodes. First, a 60-nm-thick SiO_2 was formed as a dielectric layer on p-type Si substrate (Fig. 1(a)). The active region of the FE-triode which has two neighboring vertical sidewalls with 500 µm in width (W) and 8 µm spacing (L_M) between two electrodes were defined by a photolithography process. Then, a 200-nm-thick ZnO film served as seeding layer for the growth of ZnO NWs was deposited by sputter, and a 100-nm-thick e-gun evaporated Cr film was deposited as an electrodes and a barrier layer to suppress the vertical growth of ZnO NWs. Wet etching on the two neighboring ZnO side walls using dilute phosphors acid (H_3PO_4) was conducted (Fig. 1(c)). Note that both ends of the Cr barrier layer overhung the under-cut region of the ZnO seeding layer, which is crucial for suppressing the vertical growth of ZnO NWs. The sample were then placed in a mixed solution of 7.7 mM $Zn(NO_3)_2 \cdot 6H_2O$ and 19 mM $C_6H_{12}N_4$ at 85°C for 2 hr for the laterally grown ZnO NWs (Fig. 1(d)).

3. Results and discussion

Fig. 2(a) shows a typical SEM image of the as prepared sample. The sample shown in the figure has a 200-nm-thick ZnO seeding layer which was subjected to an etching of around 30 nm to the side-wall of the ZnO layer. Laterally grown ZnO NWs with about 3.5-3.9 µm in length, 150-250 nm in diameter, and 5~7 μm^{-1} in line density were successfully obtained. It is seen that the proposed bi-layer structure effectively suppresses the vertical growth of ZnO NWs as expected. The emitter-to-emitter spacing (L_G) was measured to be about 0.1 µm based on the SEM image shown in Fig. 2(c).

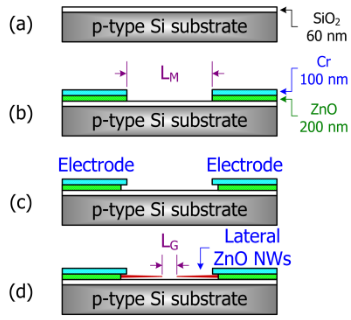

Fig. 1 The key fabrication processes flow of the ZnO NWs based FE triode.

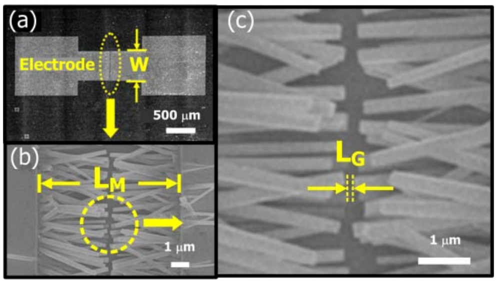

Fig. 2. SEM images of laterally grown ZnO NWs prepared with HTG.

Fig. 3 shows a typical XRD pattern and a TEM image of the synthesized ZnO NWs for the FE-triode. The strong diffraction peak of 34.42° reveals that the ZnO NWs are essentially with a wurtzite hexagonal structure and a preferred orientation along the (002) direction according to JCPDS Card No. 36-1451. Based on TEM image, the inter plane distance of d-space was determined to be 0.26 nm, confirming again that the ZnO-NWs obtained from HTG process have a well wurtzite single-crystalline structure.

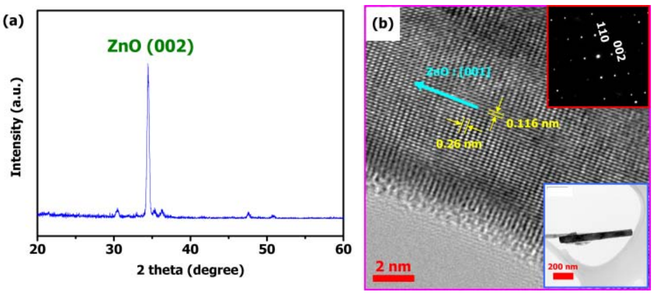

Fig. 3 A typical XRD pattern (a) and TEM image (b) of a laterally grown ZnO NW.

Fig. 4 shows the schematic diagram of the system used for field emission measurement. The FE properties of the BG-structure ZnO NWs based FE-triodes were examined in a vacuum chamber with a base pressure of 5×10^{-6} torr at room temperature. Keithley 236 and 237 source-measure unit (SMU) were used for field emission I-V characteristics measurement.

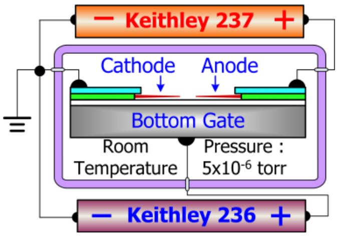

Fig. 4 The schematic diagram of the system used for f ield emission I-V characteristics measurement.

Fig. 5 shows the measured current-voltage (I-V) curves of the prepared FE-triodes under gate bias voltages (V_g) ranging from -1 to 5 V. It is seen that the FE performance of the FE-triode can be significantly enhanced with positive V_g via an MOS-like field effect. Especially noteworthy is that the proposed devices can be operated at low gate and anode voltages (≤5 V), which is attributed to the fact that the laterally aligned ZnO NWs exhibit a low turn-on voltage of around 0.6 V at 10 μA and a short L_G of around 0.1 μm. A fairly good gate controllability in the rage of -1~5 V is also evident by the figure. With the gate biased in the range of -1~5 V, the ZnO NW-based FE-triode shows a low turn on voltage (V_a) of 0.70~0.15 V at 10 μA, a high FE current of 2.17~3.02 mA @ V_a=5 V. Based on the corresponding Fowler–Nordheim (F–N) plots shown in the inset, it reveals that the FN tunneling should govern the carrier transport of the FE-triodes at voltage ≥2 V.

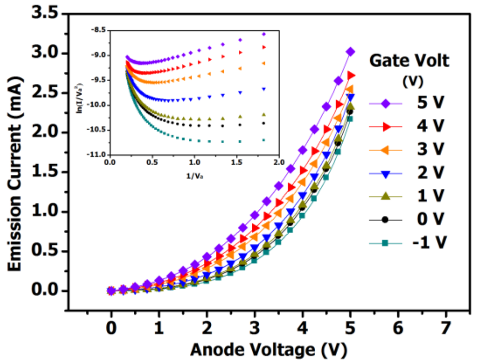

Fig. 5 I-V characteristics of ZnO-NW based FE-triode under different gate biases. The inset shows the corresponding FN plot (($\ln(I/V_a^2)$ vs. $1/V_a$) curves).

Assuming that the work function of ZnO NWs is 5.37 eV, then the corresponding field enhancement factor (β) were estimated to be as high as 1055~4840 under a gate bias ranging from -1 to 5 V. Note that β increases with increasing the gate bias is ascribed to the fact that local electric field strength (positive in magnitude) at the edges of the cathode emitters has been strongly enhanced by the increased positive gate bias. On the contrary, a negative gate bias turns the local electric filed strength toward a negative magnitude at the edges of the cathode emitter; as a c onsequence, electron emission from the emitters is suppressed.

Fig.6 shows the relationships between g_m and V_g for the ZnO NW based FE-triode with the anode voltage as a parameter. Note that g_m of the ZnO-NW FE-triode can be significantly enhanced with positive V_g and depressed by negative V_g via an MOS-like field effect. With V_g ranging from -1 to 5 V, it is interesting to observe that quite high values of g_m ranging from 96 to 299 μS at V_a=5 V were obtained. Note that the irregularity behavior of the g_m-V_g curves for V_a=3, 4, and 5 V m ight be caused by the fluctuations in the FE current which could be strongly related to the thermal issue at high FE currents.

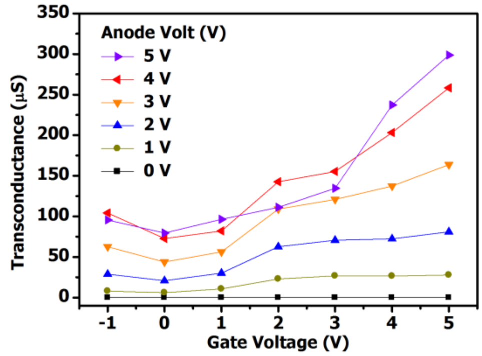

Fig. 6 Transconductance versus gate bias characteristics for the ZnO-NW based FE-triode.

4. Conclusion

In summary, a simple Cr/ZnO bi-layer structure with an under-cutting to the side-wall of the ZnO layer on both ends of two electrodes was proposed for the HTG of laterally grown ZnO NWs. We have fabricated bottom-gate structured low voltage (≤2 V) operable FE-triodes using laterally grown ZnO NWs as electron emission sources and characterized their field emission properties with and without gate bias. The prepared triodes have demonstrated to have a high g_m of 299 μS which is attributed to a low turn-on voltage (~0.6 V at 10 μA), a short L_G of around 0.1 μm and a good gate controllability. It is expected that with BG adopted ZnO-NW FE triode would provide a promising and facile route for future vacuum microelectronics applications.

Acknowledgements

This work was supported by the National Science Council (NSC) of Taiwan, Republic of China, under Contract No. NSC 99-2221-E-006-150, NSC 100-3113-E-006-015, and by the Landmark Project Grant for NCKU's Top-University Project.

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