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Structure and surface effect of field emission from gallium nitride nanowires

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ABSTRACT

Gallium nitride nanowires (GaN NWs) were synthesized by plasma-enhanced hot filament chemical vapor deposition under different ratios of nitrogen to hydrogen, which the GaN powder and nitrogen gas were used as the Ga and N sources. The characterization results indicate that the GaN NWs are grown in wurtzite crystalline structure with different length, diameters and surface adsorption. The field emission of GaN NWs was measured in the high vacuum condition of $\sim 10^{-6}$ Pa, which the results show that the turn-on field of GaN NWs changes from 0.86 to 2.8 V/μm depending on their structures and the current density can reach up to 830 μA/cm^2 at the field of 6 V/μm. Combined the characterization results with the work function theory related to field emission, the origin of the field emission enhancement was analyzed, which associates with their surface potential and geometric structure. These results can enrich our knowledge on the field emission of GaN NWs and are highly related to the development of the next-generation of GaN nano-electronic devices.

1. Introduction

Gallium nitride (GaN) is a direct band-gap (3.4 eV) semiconductor material, which has extensive applications in the areas of microelectronic and optoelectronic devices such as light emitting diodes and field-effect-transistors [1–3]. Thus, the GaN nanowires (NWs), one-dimensional structure of GaN, have attracted much attention in recent years due to their unique structures, properties and great potential applications in the field of nanoscale solid devices [1–4]. To date, the GaN NWs with different structures were catalytically synthesized using various methods and the field emission (FE) properties of synthesized GaN NWs were studied. For example, when the current density was 10 μA/cm^2, the turn-on field of bending GaN NWs synthesized by pulsed laser ablation was 8.4 V/μm, while it was 3.96 V/μm for the triangular-shaped GaN NWs grown by chemical vapor deposition [5,6]. The above examples indicate that the FE properties of GaN NWs strongly depend on their structures. For different preparation methods, there are great differences in the structures of GaN NWs, thus the FE properties of them are further studied for their applications in the nanoscale solid devices. In addition, few of researches focused on the effect of surface adsorption on FE from GaN NWs for different process parameters [7].

In this work, we prepared the GaN NWs with tips in plasma-enhanced hot filament chemical vapor deposition (PEHFCVD) system under different ratios of nitrogen to hydrogen using GaN powder and nitrogen gas as the Ga and N sources. To improve the ionization of nitrogen, the plasma was employed [8]. In hydrogen environment, GaN has a low decomposition temperature [9] and oxidation of Ga can be restrained, thus hydrogen was used in the growth process of GaN NWs. The FE properties of GaN NWs were measured. It was found that the short GaN NWs revealed better FE characteristic than the long GaN NWs. Combined the structures of GaN NWs with the theory related to field emission, the FE properties of GaN NWs were studied. In this paper, we report the research results on FE properties of GaN NWs with different structures and surface adsorption.

2. Experimental detail

Before the synthesis of GaN NWs, a 20 nm gold film was deposited on (100)-oriented n-type Si substrate in a SBC-12 micro-ion-sputtering system. Here, gold was chosen to be used as the catalyst. The silicon wafer deposited with gold film was used as the substrate of growing the GaN NWs.

The GaN NWs was grown in nitrogen and hydrogen environment by PEHFCVD described in detail in previous work [10]. Briefly, there is a heating system constructed with three coiled tungsten filaments in the PEHFCVD chamber, which they were heated about 1800 °C for the heating of the substrate and the decomposition of

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Table 1
The growth parameters including the flow rate of gas, bias current I_b, corresponding bias U_b, growth time t, and ratio of nitrogen to hydrogen.

Specimen	N2 (sccm)	H2 (sccm)	*Ib* (mA)	*Ub* (V)	*t* (min)	Ratio
A	50	0	120	680–700	20	
B	40	10	120	680–700	20	4/1
C	30	20	120	680–700	20	3/2

the reaction gases and the GaN powder. To avoid drawing of the GaN powder from the chamber, the GaN powder was pressed into sheet and placed below the filaments. The distances from the substrate and GaN sheets were about 8 and 2 mm, respectively. The short distances make the substrate heated about 900 °C and GaN decomposed into Ga and N atoms during the growth of GaN NWs. After the chamber was evacuated to the base pressure lower than 2 Pa, nitrogen and hydrogen were inlet into the chamber. When the pressure in the chamber was increased to about 1.5×10^3 Pa, the filaments were heated by an AC power supply till the substrate was heated to about 900 °C, and then the DC power supply was turned on to generate the plasma. The bias current was set to 120 mA to grow the GaN NWs for 20 min. In this work, the three specimens A–C were prepared by change the ratio of nitrogen to hydrogen and their growth conditions were summarized in Table 1.

The structures and components of GaN NWs were investigated by Hitachi S-4800 field emission scanning electron microscopy (FESEM), Bruker AXS D8 Advance X-ray diffractometer (XRD) and ESCALAB 250 X-ray photoelectron spectroscopy (XPS), respectively. When the structures of GaN NWs were analyzed, the FESEM microscopy was operated at 15 kV. During the XRD analysis, Cu *Kα* radiation was employed. In the XPS spectroscopy, the Al *Kα* X-ray source was used to measure the components of GaN NWs. In addition, the work function of specimens was measured by low energy XPS. During the analysis of the work function, a negative bias of 5 V was applied to the specimens to discriminate the signals from the analyzer and the second electron cut-offs.

The FE characteristics of GaN NWs were measured in a high vacuum system of $\sim 10^{-6}$ Pa using a diode configuration. In the configuration, the GaN NW film was used as a cathode and a mirror-polished silicon wafer was used as an anode, which they were spaced by glass fibers with a diameter of 125 μm.

3. Results

Fig. 1 is the FESEM images of specimens A–C. From Fig. 1, one can see that the NWs and NWs with tips are formed, but the NWs with tips are gradually reduced for the specimens A–C. The formation of NWs and NWs with tips was studied in prior work, which the tip formation resulted from the formation of new growth surfaces by strong ion bombardment [10]. According to the typical NWs in Fig. 1, the diameters are about 35–110, 30–160 and 38–115 nm, and the lengths are 1.8–6.2, 2.4–9.5, 1.3–4.6 μm for specimens A–C, respectively. In addition, there are less gold particles on the top of GaN NWs of specimens A–C in Fig. 1. The disappearance of gold particles is relate to the ion bombardment. The high flow rate of nitrogen results in the production of a number of ions including nitrogen such as NH^+, NH_2^+, NH_3^+, etc. [11]. These ions have large mass so that they strongly bombard with the GaN NWs. As a result, the gold particles on the tops of GaN NWs may be removed [10].

Fig. 2 shows the XRD patterns of specimens A–C. As shown in Fig. 2, every spectrum has the diffraction peaks at about 32.41°, 34.54°, 36.83° and 57.76°. These peaks are indexed to GaN crystal with wurtzite structure (JCPDS 65-3410). In addition, the spectrum

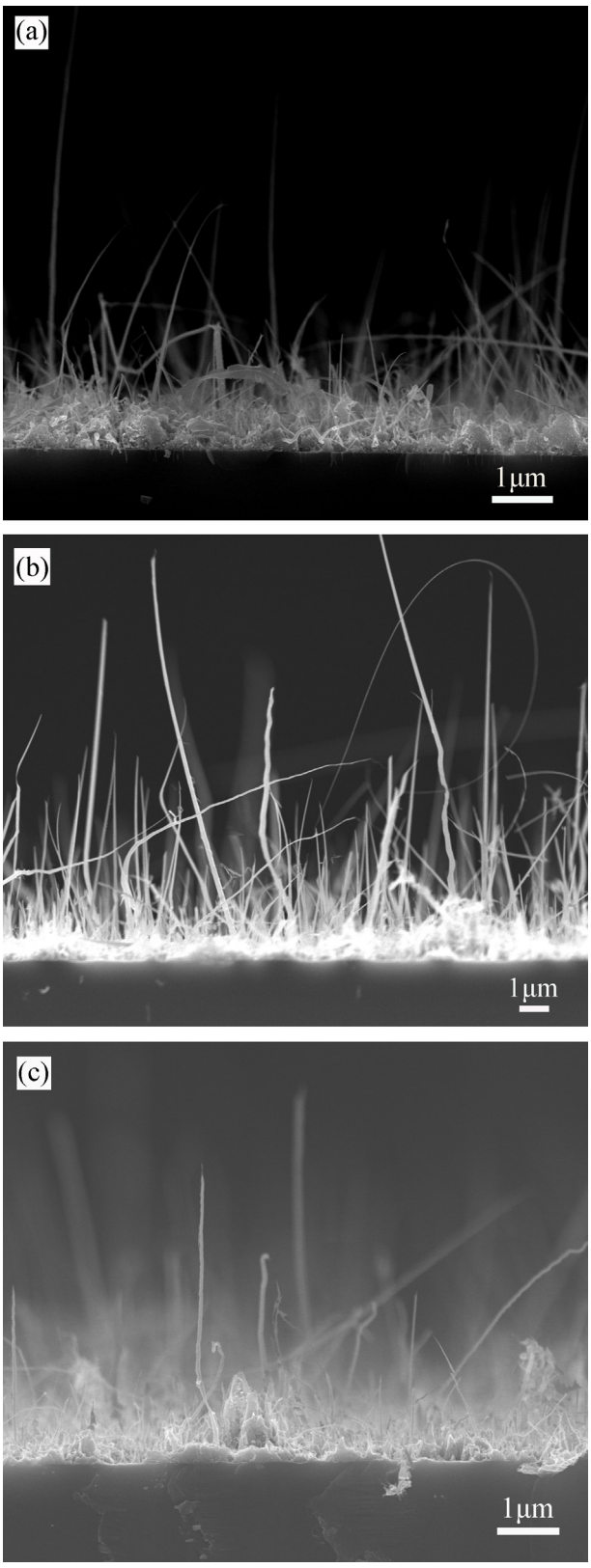

Fig. 1. FESEM images of specimens (a) A, (b) B and (c) C.

(a) shows two other peaks at about 38.57° and 40.37°, which result from diffraction of Ga_2O_3 (JCPDS 43-1012, 06-0503). For the spectra (b) and (c), the disappearance of diffraction peaks of Ga_2O_3 is related to the use of hydrogen in the reaction gases. Due to the existence of hydrogen in the reaction gases, it reacts to oxygen so

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