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Electron field emission from semiconducting nanowires

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Abstract

In this paper we report on investigations of field emission (FE) properties of semiconducting (SiC, ZnO) one-dimensional (1D) nanostructures – nanowire/nanorod arrays, and fabrication of low-voltage field emission display (FED) devices based on these 1D nanomaterials. SiC nanowires were grown on Ni-coated Si substrates using a thermal metal-organic chemical vapor deposition (MOCVD) technique, and ZnO nanostructures were grown on gold-coated Si substrates by a thermal CVD method. Electron field emission properties of SiC and ZnO nanostructures were examined in plane geometry using a flat phosphor screen. The interrelation between the FE characteristics (emission thresholds, current density, surface uniformity, etc.) and microstructure and surface morphology of the produced 1D nanostructures was established. Diode-type FED devices (flat vacuum lamps) with SiC-nanowire-based cathodes were developed and fabricated. The FEDs are characterized by low threshold and operating electric fields – lower 2 V/μm and 5 V/μm, respectively, high current density and brightness, and stable performance of the nanowire-based cathodes.

Keywords: Electron field emission; Semiconducting nanowires; FED

1. Introduction

Recently, growth and characterization of semiconducting one-dimensional (1D) nanostructures – arrays of nanowires, nanorods, and nanosheets, have been extensively studied due to their importance in fundamental research and large potential in fabrication of nanoscale electronic, optoelectronic, and sensor devices [1,2]. The 1D nanostructures of wide-band-gap semiconductors (ZnO, SiC, AlN) were reported to be highly promising candidates for field emission (FE) applications [3–9] as they are characterized by high aspect ratio in combination with high thermal and chemical stability—the factors which are equally important for the performance of field emission cathodes. Other points to be also very important are related to the characteristic features of the 1D-nanostructure growth (especially of ZnO), including (i) reproducible fabrication of highly aligned nanostructures by controlling the synthesis conditions, (ii) simple patterned growth, and (iii) low-temperature (<100 °C) growth of nanowire/nanorod arrays, as was reported in recent papers on the synthesis of various intriguing nanostructures in ZnO [2,5,6,10–12]. This implies that for the fabrication of efficient FE cathodes based on semiconducting 1D nanostructures the detailed study of field electron emission from a variety of the arrayed nanostructures is required, aimed at finding the interrelation between the growth conditions, geometric, electrical and field emission properties of the produced nanostructures.

In the paper we report on the investigations of field emission properties of semiconducting (SiC and ZnO) 1D nanostructures – nanowire/nanorod arrays in dependence on different growth morphologies, and fabrication of low-voltage diode-type field emission display (FED) devices based on these 1D nanomaterials.

2. Experimental details

The 1D nanostructures of wide-band-gap semiconductors (SiC and ZnO) were grown on *n*-type Si substrates of 5 mm × 5 mm

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size under different CVD conditions to obtain different surface morphologies of SiC and ZnO nanostructures.

SiC nanowires (NWs) were grown on Ni-coated Si substrates using a thermal metal-organic chemical vapor deposition (MOCVD) technique [13]. The deposition temperature was 1150 °C, and other parameters (gas flow rates, deposition time) were varied to change the density of nanowires on the sample surface. The typical SEM image and XRD pattern of the synthesized SiC nanowires (high density of nanowires) are shown in Fig. 1. The diameter of SiC nanowires was in the range of 10 nm to ~100 nm and their length was several tens of micrometers. The X-ray diffraction and transmission electron microscopy analysis confirmed that the SiC nanowires were single crystals with hexagonal structure.

ZnO nanostructures were grown on gold-coated Si substrates by a thermal CVD method as described elsewhere [2,10,11]. Two growth regimes (called hereafter as the regimes 1 and 2) were used to produce different surface morphologies of ZnO nanostructures, shown in Fig. 2. The regime 1 was characterized by a higher deposition temperature (900 °C) than for the regime 2 (500 °C), that resulted in a pronounced difference in size (diameter, length), alignment and spacing of the nanostructure arrays.

Field emission measurements of SiC- and ZnO-nanowire-based cathodes were performed in plane geometry using a flat phosphor screen. The FE measurements were carried out in high vacuum of 10^{-7}–10^{-6} Torr; the anode–cathode distance was in the range of 500 μm–800 μm, and the emission area (i.e. the sample size) was 0.25 cm^2. The FE measurement procedure included training (conditioning) of the cathode under emission currents of 30–50 μA for 1 h followed by repeated measurements of I–V (current–voltage) characteristics, and so on. Simultaneously, phosphor screen images (field emission images) resulted from field electron emission of nanowire-based cathodes were captured using a CCD video camera at given values of the emission current/applied voltage to study the surface uniformity of the emission properties of the cathodes.

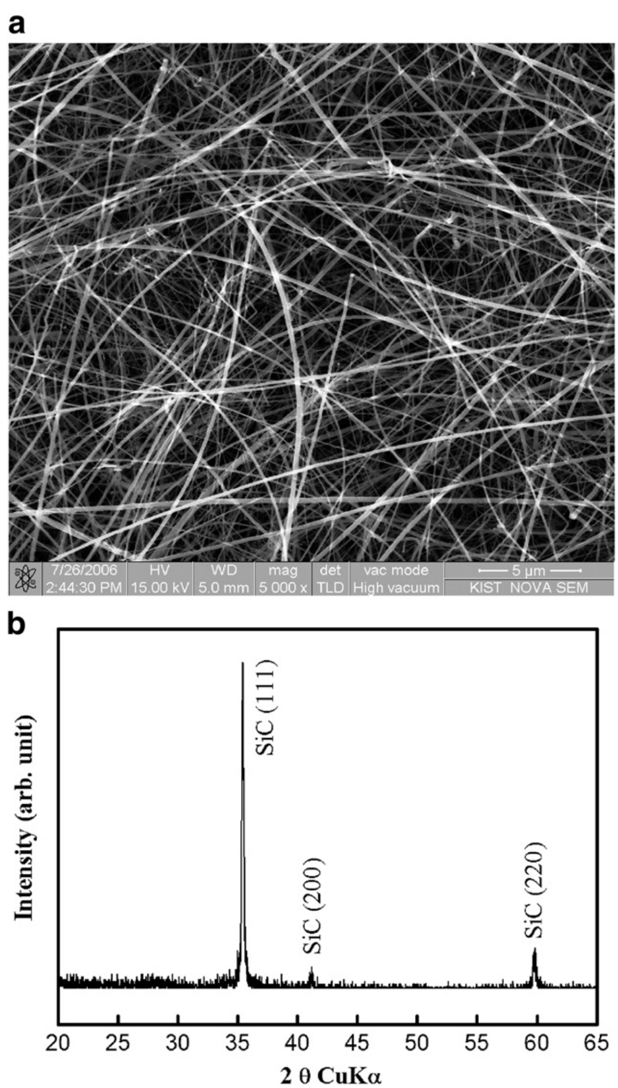

Fig. 1. SEM image (a) and XRD pattern (b) of SiC nanowires (high density NWs) grown on Si substrates by a MOCVD method.

3. Results and discussion

3.1. Field emission of ZnO nanowires/nanorods

Among the ZnO samples tested, the ZnO-1 samples, grown at the regime 1 (see Fig. 2a,b), were found to exhibit excellent FE properties as compared to ZnO nanorod samples synthesized at the regime 2 (Fig. 2c,d). The results of field emission measurements for the samples ZnO-1 are shown in Fig. 3a. It is seen that after training at the current I = 50 μA the field emission behavior is improved, leading to reducing the threshold emission fields (E_{th}) of the cathode (from about E_{th} = 3.5 to E_{th} = 3 V/μm corresponding to the emission current I_{th} = 1 μA). From the inset in Fig. 3a, showing a FE image captured with a CCD video camera at the emission current 50 μA, it follows that the distribution of emission sites is nearly uniform over the sample surface.

The results of FE measurements for the ZnO-2 sample are shown in Fig. 3b: open circles is an I–V curve of the as grown sample; open squares is a repeated I–V curve after 1 h conditioning at the applied voltage 2.5 kV ($E \approx 5$ V/μm); the I–V curve #3 from Fig. 3a is also plotted for comparison. It is seen that the ZnO-2 samples exhibit poor FE properties, pronounced in a weak emission at $E > 8$ V/μm (observed on a phosphor screen as an appearance of a few emission spots), current jumps (not shown) due to micro-arcing and typical hysteresis behaviour, the FE phenomena being previously reported for diamond and related thin-film materials (e.g. [14]). It should be noted that preliminary examination of electrical properties showed similar conductivity values for both the ZnO-1 and ZnO-2 samples.

The analysis of the I–E characteristics of the ZnO-1 samples was performed using a special program, as described elsewhere [15]. Each I–E curve is transformed into a Fowler–Nordheim (FN) plot $\log(I/E^2) = A + B/E$, which was approximated with two line segments using a least-squares method. In the analysis, the following expression of Fowler–Nordheim dependence is