Microelectronics Journal 39 (2008) 763–767

Microelectronics Journal

www.elsevier.com/locate/mejo

Study on the vacuum breakdown in field emission of a nest array of multi-walled carbon nanotube/silicon nanoporous pillar array

Wei Fen Jiang[a,*], Long Yu Li[b], Shun Hua Xiao[b], Yong Fen Dong[b], Xin Jian Li[b]

[a]*Department of Mathematics and Information Science, North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou 450011, China*
[b]*Department of Physics and Laboratory of Materials Physics, Zhengzhou University, Zhengzhou 450052, China*

Received 1 October 2007; accepted 15 December 2007
Available online 20 February 2008

Abstract

A composite structure, a nest array of multi-walled carbon nanotubes/silicon nanoporous pillar array (NACNT/Si-NPA), with good field emission properties, was synthesized through growing CNT on Si-NPA by thermal chemical vapor deposition. In order to make full use of its good field emission properties, the vacuum breakdown behavior accompanied with field emission from NACNT/Si-NPA was investigated. The results revealed that a positive feedback of field emission and resulted Joule heat ignited a small portion of protruding emitters, which caused spark discharge, destroyed the anode and generated a large amount of heat. The thermal runaway ultimately resulted in the destruction of substrate and vacuum breakdown.

Keywords: A nest array of multi-walled carbon nanotube; Silicon nanoporous pillar array; Field emission; Vacuum breakdown

1. Introduction

There have been great interests in the development of field emission electron sources based on carbon nanotube (CNT) due to its peculiar properties [1–6]. Although the turn-on field and the emission current density of CNT-based films are better than those of arrayed Si and metal microtip [7–10], these properties are far from theory computation mainly owing to field screening [11,12]. Recently, many patterned CNT emitters have been fabricated in order to weaken field screening and have shown good field emission properties [13–16]. In the papers published previously [17,18], we prepared a novel silicon hierarchical structure, a silicon nanoporous pillar array (Si-NPA), by hydrothermal etching and based on which a large scale, regular nest array of multi-walled CNTs was synthesized. The nest array of multi-walled CNTs/silicon nanoporous pillar array (NACNT/Si-NPA) had good field emission properties because the pillar array structure also could weaken field screening effectively [19]. In order to optimize and make full use of the field emission properties of NACNT/Si-NPA, the vacuum breakdown behavior has to be understood. At the same time, with the advance of controlled growth, more technological aspects of field emission such as lifetime, emission degradation [20–23], emission stability [24], light emission [25], and electrical breakdown [26] become more and more important. The reason for this might be the fact that these properties are not general intrinsic properties of CNT emitters, but depend on the technological configuration and environment in which the emitter is operated. In this paper, the vacuum breakdown behavior accompanied with field emission from NACNT/Si-NPA was investigated and the cause was analyzed.

2. Experiment

The initial silicon wafers used in the present experiments were heavily boron-doped, (1 1 1)-oriented single-crystal silicon wafers with an electrical resistivity of 0.015 Ω cm. The hydrothermal preparation of the Si-NPA template was described in detail previously [17,18]. As-prepared Si-NPA templates were placed in a quartz tube furnace to grow CNTs by thermal chemical vapor deposition (CVD).

*Corresponding author. Tel./fax: +86 371 65790758.
E-mail address: gingerwfj@yahoo.com.cn (W.F. Jiang).

0026-2692/$ - see front matter
doi:10.1016/j.mejo.2007.12.019

First, the furnace was heated up to 820 °C under the protection of pure H_2 flow. Then, while maintaining the temperature, the flow gas was changed to a mixture of hydrogen and nitrogen (V_{H2}:V_{N2} = 3:7), with a feed solution of ferrocene dissolved in xylene (ferrocene concentration: 0.015 g ml^{-1}). The flow rate of the feed solution was 0.2 ml min^{-1}. This process lasted for 15 min. Then the flow gas was changed to pure N_2 and the furnace temperature was naturally cooled down to room temperature. The NACNT/Si-NPA sample obtained was ready for the related measurements.

3. Results and discussion

Si-NPA has been proved to be a micro/nanometer composite structure, i.e., the regular array of micron-sized silicon pillars, the high-density nanopores distributed all over the pillars, and the silicon nanocrystallites composing the pore walls. Here, Fig. 1(a) shows a typical scanning electron microscope (SEM) image of the sample surface after the CVD process, where many nest-like structures can be observed. It can be seen more clearly from the cross-sectional image (Fig. 1(b)), numerous entangled, random-orientated CNTs form a nest-shaped assemblages on each pillar and finally the regularly patterned NACNT/Si-NPA is formed.

Vacuum breakdown associated with field emission of NACNT/Si-NPA was performed with a diode structure in a windowed vacuum chamber at a base pressure of 6×10^{-5} Torr maintained by a turbomolecular pump. The distance between the NACNT/Si-NPA (as cathode) and ZnO/indium tin oxide (ITO)-coated glass was 270 μm, and the actual emission area in this experiment was 0.6×0.67 cm^2. DC voltage was employed in the examination of the emission process.

For a typical NACNT/Si-NPA, threshold fields of 3.9 and 5.2 V μm^{-1} were required to produce spark discharge and vacuum breakdown, respectively, while a turn-on field of about 1.5 V μm^{-1} was required to produce a microampere of field emission current (after several 0–3.7 V μm^{-1} voltage sweepings). Fig. 2 gives the relation of emission current density (I) and applied electric field (E). Obviously, current density increased monotonically with applied field prior to the onset of spark discharge. In the vicinity of the onset of spark, the emissions showed fluctuation in the I–E plot (a and b points in Fig. 2). Meanwhile, the spark discharges were accompanied by the variation in the number and density of emitting sites, which was the result of cathode erosion. Fig. 3(a) was taken at the point of 5 V μm^{-1}, with an emission current density of 3270 μA cm^{-2}, which was just prior to the point of vacuum breakdown. When field strength reached 5.2 V μm^{-1}, the emission current density suddenly increased to 7270 μA cm^{-2}, the spark discharge became so strong that all light spots merged into a continuous incandescence state (Fig. 3(b)) and soon resulted in short circuit. The field emission activities were stopped immediately. The location of the breakdown can be easily identified as that point is different from the other part because of the appearance of discharge.

Fig. 4 shows the SEM images of typical morphological features of the sample after vacuum breakdown. It can be observed from Fig. 4(a) that there are no nest-like structures left, only some CNTs covered by a layer of unknown substance. In order to identify the elements of the surface, electron energy spectra (EDS) were taken at four different sites, as shown in Fig. 4(b). A relatively high ratio of zinc and oxygen elements can be found at every chosen site. It is clearly indicated that the anode material, i.e. zinc oxide, was attracted to cathode due to the electrical forces during the course of spark discharge.

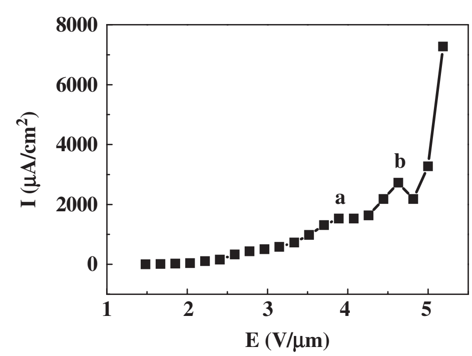

Fig. 2. Plot of the field emission current density versus applied electric field of NACNT/Si-NPA.

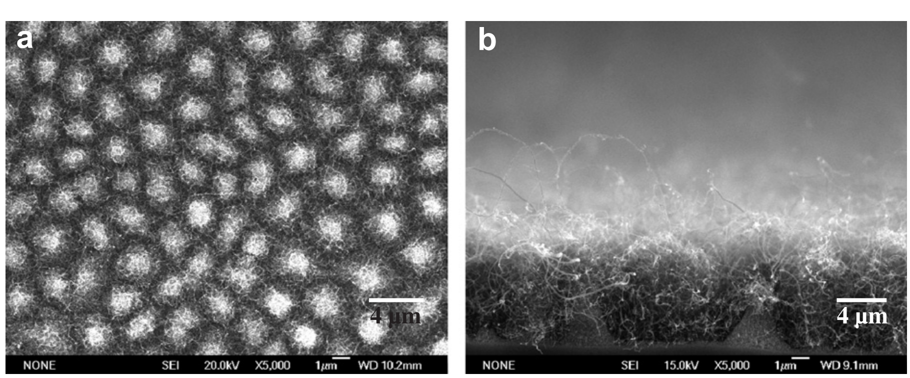

Fig. 1. SEM images of as-synthesized NACNT/Si-NPA (a) top view image, (b) cross-sectional image.