Thin Solid Films 517 (2009) 2012–2015

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Effects of welding head on the carbon nanotube field emission in ultrasonic nanowelding

Bo Zhao *, Changxin Chen, Boluo Yadian, Ping Liu, Zijiong Li, Dong Xu, Yafei Zhang *

National Key Laboratory of Nano/Micro Fabrication Technology, Key Laboratory for Thin Film and Microfabrication of the Ministry of Education, Research Institute of Micro/Nanometer Science & Technology, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 14 November 2007
Received in revised form 4 July 2008
Accepted 24 September 2008
Available online 7 October 2008

Keywords:
Carbon nanotube
Electrical properties and measurements
Field emission
Scanning electron microscopy
Ultrasonic nanowelding

ABSTRACT

Ultrasonic nanowelding technique was used to improve the field emission properties of carbon nanotube (CNT) cathodes. Two kinds of welding heads were used and the effects of the head on the emission properties were studied. The results show that cathodes welded by Al_2O_3 flat head demonstrate excellent field emission properties with high emission current density and good current stability. The improved field emission performance is attributed to the reliable and low resistance contact between CNTs and metal substrates. Cathodes welded by steel matrix head show a lower turn-on electric field due to the protruding CNTs at the edge of the welded pits.

1. Introduction

Building reliable interconnections between one-dimensional nanomaterials and the external electrical circuits is one of the most important issues in nanoelectronics. Many physical and chemical processes have been explored to address this need. It had been shown that metal-carbon nanotube (CNT) contact resistance could be reduced by exposing the contact area to focused electron beam [1] or ion beam [2]. However, these methods are not easy to realize in real situation due to the limited access to a focused beam. High-temperature annealing method was demonstrated to be able to improve the metal–CNT contacts [3,4]. However, high temperature used in this method will produce many unexpected side effects on the devices. Joule-heating-induced nanospot welding of CNTs [5,6] involves complicated transmission electron microscope operation and low yield, which significantly limits their applications. In addition, chemical modification of the electrodes was used to enhance the adsorption between CNT and electrodes [7,8]; however, a stronger bonding instead of a weak chemical adsorption is mandatory for constructing reliable nanodevices.

Ultrasonic nanowelding is a promising technique to create reliable contact between one-dimensional nanomaterials and electrodes [9,10]. The contacts formed by this simple method have demonstrated low contact resistance, good long-term stability and mechanical strength. CNTs are promising candidates for cold cathode field emitters [11,12]. However, the realization of CNT field emission devices has been limited due to the absence of a stable emitter fabrication process. Many approaches have been tried as possible fabrication techniques such as direct growth [13], screen-printing [14], spraying [15] and electrophoretic deposition [16]. Most of them have some disadvantages, such as high complexity and high cost of the technological process for the direct growth, or the producing of reactionless conducting chemicals for printing technologies. Spraying and electrophoretic deposition are simple methods and can be used to fabricate a large area of cold cathode. However, poor adhesion of CNTs to the substrate is a drawback. In this paper, Ultrasonic nanowelding was used to obtain stable CNT field emitting cathodes and the effects of the welding head on the carbon nanotube field emission were studied.

2. Experimental details

The CNT cathodes were fabricated by electrophoretic deposition method. The multiwall carbon nanotubes produced by chemical vapor deposition have a specific diameter 10–30 nm and the purity is higher than 95%. The pristine CNTs were first treated at temperature of 1500 °C under vacuum of 10^{-4} Pa. The high-temperature vacuum process efficiently removed residual metal catalysts and enhanced the graphitization of the CNTs [17]. Then, the CNTs were treated with mixed acid (HNO_3:H_2SO_4 = 3:1) at 90 °C for 70 min. 7 mg of the treated CNTs were dispersed in 700 ml of acetone solution that contained 3.5 mg of dissolved $Mg(NO_3)_2$. The CNT electrophoresis suspension was ultrasonically dispersed for about 3 h. The Ti-coated glass wafer as a cathode and a stainless steel plate as an anode were immersed into the CNT electrophoresis suspension at room temperature. The two electrodes were kept at a constant gap of 2 cm for 10 min under the

* Corresponding authors. Tel./fax: +86 21 6293 2017.
E-mail addresses: phyzhaobo@sjtu.edu.cn (B. Zhao), yfzhang@sjtu.edu.cn (Y. Zhang).

0040-6090/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.tsf.2008.09.092

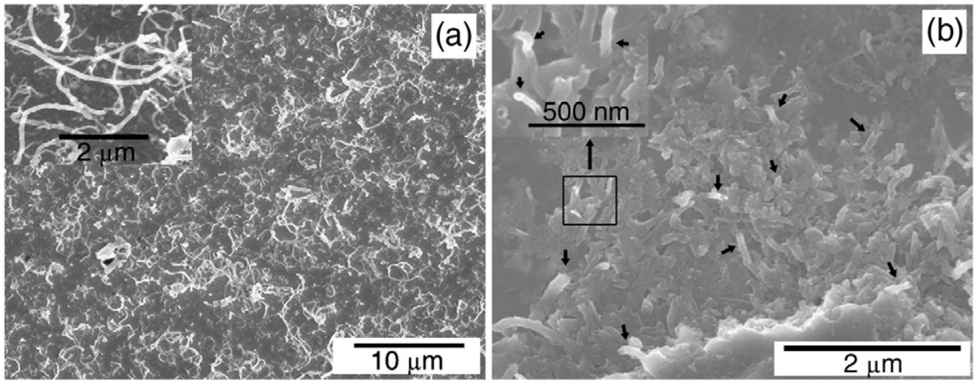

Fig. 1. SEM images of the samples non-welded (a) and welded by Al_2O_3 flat welding head (b). The arrows in (b) show that the sidewall and the short end of the CNT exposed on the welded substrate. The insets are magnified images.

voltage of 20 V. Finally, the glass wafer was cut into 1×1 cm^2 for the subsequent nanowelding and field emission measurement.

Ultrasonic nanowelding was carried out in a BRANSON 2000d ultrasonic welder. Two kinds of welding heads were used to investigate the effects of the heads on the emission property: one is Al_2O_3 single crystal with a 1×1 cm^2 pressing surface and a root mean square roughness of 0.5 nm, the other is steel matrix head with protruding array on the 1×1 cm^2 surface and per protruding area is 30×40 μm^2. A welding force of 70 N was applied to press the welding head against the nanotube and substrates. At the same time an ultrasonic vibration with a frequency of 60 kHz was applied to the welding head through an ultrasonic transducer. The ultrasonic energy was transferred to the bonding interface through the ultrasonic welding head. Thus the CNTs and substrate were welded together under the combined action of the ultrasonic energy and a clamping force.

The field emission properties of the samples were measured by a diode configuration in a vacuum chamber with the pressure below 3×10^{-4} Pa. The anode was a copper plate, and the distance between the CNT cathode and the anode was 100 µm. *The field emitting area was 1 cm^2 for each of the sample.* The macroscopic electric field was estimated by dividing the applied voltage by the cathode-anode separation. The emission current density was calculated from the quotient of the obtained emission current divided by the emission area (1 cm^2). The morphology of the CNT cathodes was observed by scanning electron microscopy (SEM, FEI SIRION 200) at an operating voltage of 5 kV.

3. Results and discussion

Fig. 1 shows typical SEM images of the sample non-welded and welded by Al_2O_3 flat welding head. In the non-welded sample, the CNTs uniformly disperse and loosely stay on the surface of the metal substrate (Fig. 1(a)). While welded by Al_2O_3 flat head, the CNTs and metal substrate are compacted and bonded together to form a fresh

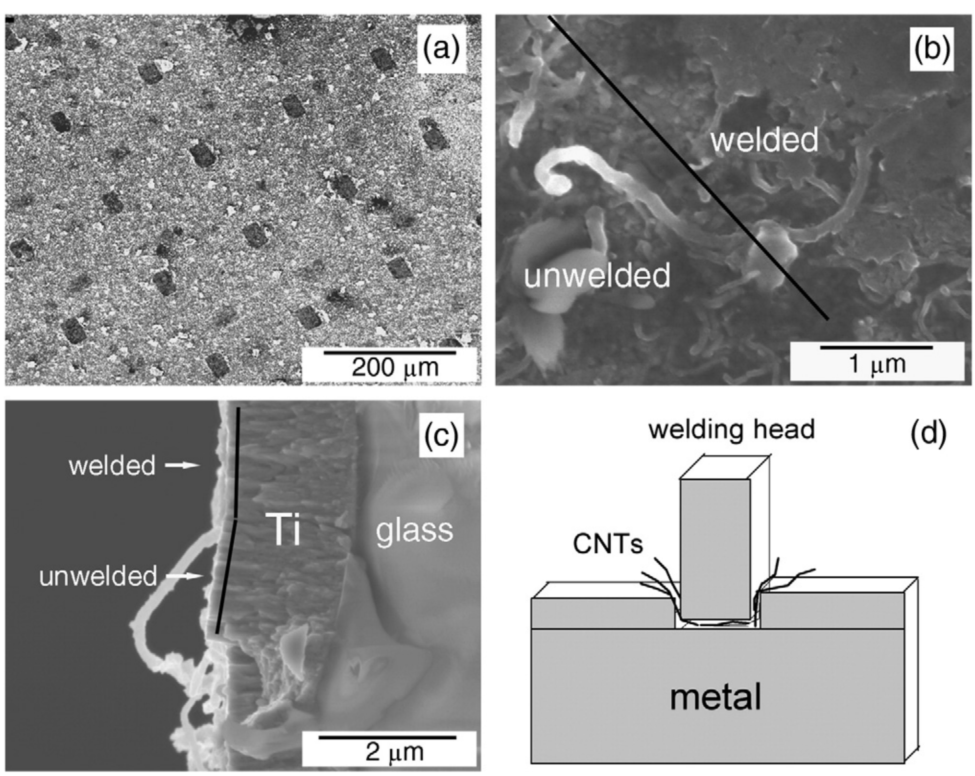

Fig. 2. (a) Low-magnification SEM image of the sample welded by steel matrix welding head. (b) Planar and (c) cross-sectional images at the edge of the welding pit. (d) Schematic diagram of the protruding CNTs.