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Fabrication and Model Simulation of the Triode-Type Carbon Nanotube Emitter Arrays

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The goal of field emission study is to obtain the highest current density at the lowest applied electric field. The high aspect ratio of the carbon nanotube (CNT) enables the enhancement of the local electric field close to the nanotube cap [1]. A triode-type configuration, in which an integrated gate electrode is added between the anode and cathode, has been proposed as means to lower the anode voltage required to generate emission and exert significant control over the field emission process [2]. We report here an effective method to fabricate triode-type CNTs emitter arrays by combining the dual-beam focused ion beam (DB-FIB) technology and plasma enhanced chemical vapor deposition (PECVD) process. The computer simulations were also carried out to investigate the effect of gate settings on the changes of local electric field in triode-type CNT emitter arrays. To construct the substrate, a multilayer silicon wafer with an embedded catalyst layer was fabricated. The wafer consisted of an ITO adhesion (15 nm), Ni catalyst (10 nm), SiO2 insulation (1 μm), second ITO adhesion (15 nm) and finally Pt electrode (120 nm) layers deposited, in that order, on the Si wafer. An FEI DB-FIB was then used to mill arrays of holes to expose the Ni catalyst for the CNT growth. Substrates were heated to 750 °C and exposed to 50 SCCM of C2H2 and 200 SCCM of NH3 for 10-30 min. Under these conditions vertical aligned CNTs were synthesized in each DB-FIB milled cavity by PECVD [2]. A schematic diagram of the triode-type CNT emitter is shown in Fig. 1. Fig. 2 shows a 5 × 5 triodetype CNT emitter arrays fabricated by this method. The diameter of these CNTs is from 30 to 60 nm. A high resolution TEM image of a typical CNT-based triode-type emitter is shown in Fig. 3. The Ni catalyst is located at the tip of the CNTs. The tip-growth mechanism is favored because the plasma electrostatic force detaches the Ni from the ITO diffusion barrier. The internal structures of the PECVD tubes display bamboo-like fringes characterized by periodic curving graphitic bands normal to the tube axis. The height of CNTs in relation to the gate layer can be controlled by adjusting the plasma exposure time during PECVD growth. We considered three different settings for the gate: top gate (gate higher than CNT emitters), standard gate (almost the same height of gate and CNT emitters) and side gate (gate lower than CNT emitters) [Fig. 4]. In order to simulate the effect of different gate settings, we solved Laplace's equation to determine the variation in electrostatic potential energy and plotted the electric field equipotential lines, represented as a color spectrum in Fig. 4. It is significant to note that the potential drop concentrated mostly at the tip region, indicating that the strongest electric field points along the CNT center axis. The local electric field intensity at the CNT tips increased from 3.1 to 4.7 to 5.8 V/nm when the gate settings were changed from top gate (high shielding) to standard gate to side gate, respectively. In general, the larger the local electric field, the easier it is to start field emission. In summary, combining the DB-FIB technique and the PECVD process enables us to effectively synthesize triode-type CNT emitter arrays. By adjusting the CNT growth time in PECVD, we can get top gate, standard gate or side gate triode-type CNT emitters. Model simulations demonstrate the equipotential lines and local electric field at the CNT tips are strongly affected by different gate settings, which are determined by the relative heights between CNT emitters and gate layer. It is expected that the simulation results introduced here will provide useful guidance for the design and fabrication of triodetype CNT based field emission device applications.

References: [1] W. I. Milne et al., J. Mater. Chem., 14 (2004) 933. [2] J. Wu et al., _ano Letters., 9(2) (2009) 595.

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Fig. 1

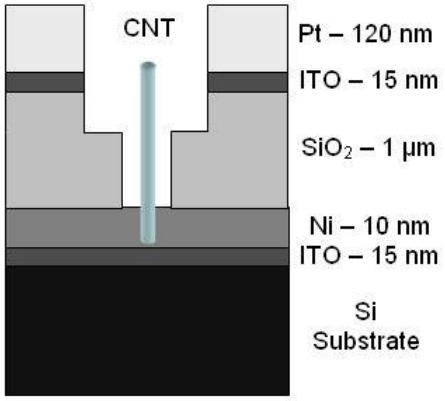

Fig. 2

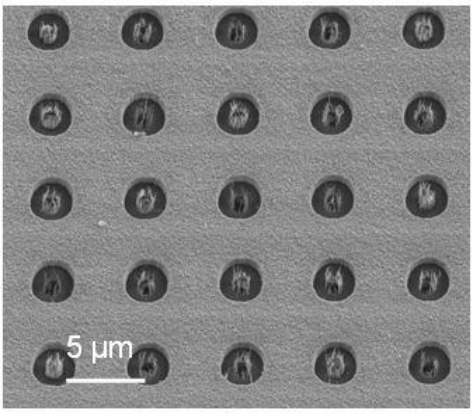

Fig. 3

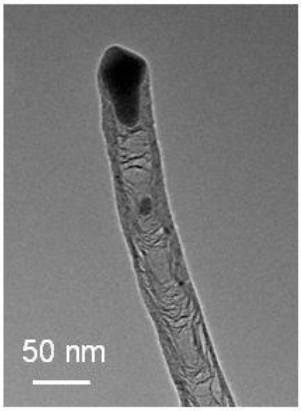

Fig. 4

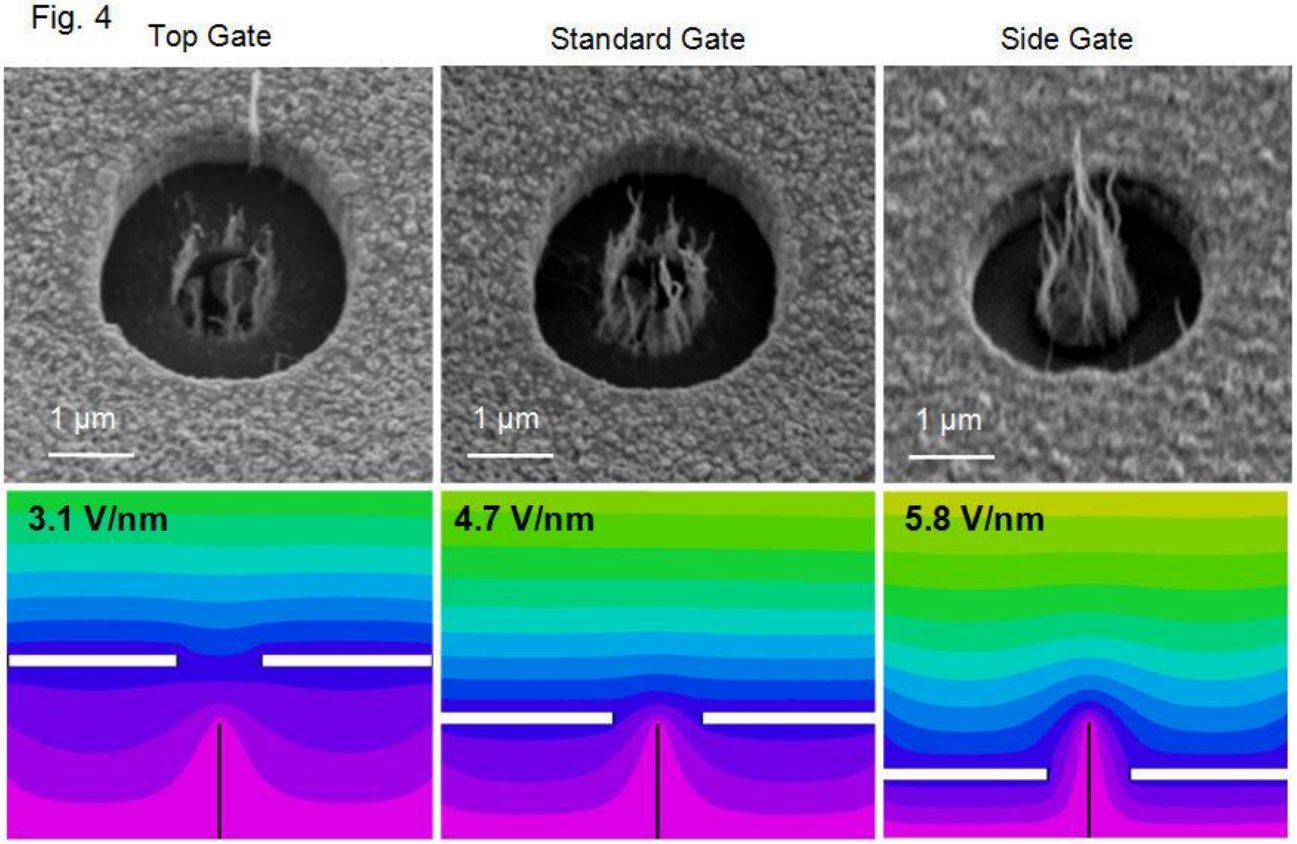

Fig.1 Schematic of the multilayer substrate with embedded Ni catalyst. DB-FIB was used to mill microgated holes and expose the catalyst layer, followed by PECVD to fabricate triode-type CNTs emitter arrays. Fig.2 A 5 × 5 triode-type CNT emitter arrays fabricated by a combination of DB-FIB and PECVD techniques. Fig.3 TEM image of one of CNTs grown by the PECVD process. The Ni catalyst is located at the tip of each nanotube while bamboo-type fringes form inside of nanotubes.
Fig.4 SEM images of three kinds of gate settings: top gate; standard gate; and side gate. The model simulation equipotential lines are also plotted in each gate settings.

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