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Fabrication and electrical characteristics of carbon nanotube field emission microcathodes with an integrated gate electrode

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Abstract
We report on the fabrication of field emission microcathodes which use carbon nanotubes as the field emission source. The devices incorporated an integrated gate electrode in order to achieve truly low-voltage field emission. A single-mask, self-aligned technique was used to pattern the gate, insulator and catalyst for nanotube growth. Vertically-aligned carbon nanotubes were then grown inside the gated structure by plasma-enhanced chemical vapour deposition. Our self-aligned fabrication process ensured that the nanotubes were always centred with respect to the gate apertures (2 μm diameter) over the entire device. In order to obtain reproducible emission characteristics and to avoid degradation of the device, it was necessary to operate the gate in a pulsed voltage mode with a low duty cycle. The field emission device exhibited an initial turn-on voltage of 9 V. After the first measurements, the turn-on voltage shifted to 15 V, and a peak current density of 0.6 mA cm^{-2} at 40 V was achieved, using a duty cycle of 0.5%.

1. Introduction

The remarkable field emission properties of carbon nanotubes (CNTs) have generated considerable interest for their application in vacuum microelectronic devices [1–5]. Due to their small diameters (below 50 nm) and relatively long lengths (a few micrometres), nanotubes have a high aspect ratio and can generate a large electric field enhancement in order to obtain electron emission at low apparent electric fields.The ability to preferentially deposit vertically-aligned multi-wall CNTs onto patterned catalyst substrates has been demonstrated using plasma enhanced chemical vapour deposition (PECVD) [6, 7]. For device applications using field emission, these vertically-aligned nanotubes must be equipped with some kind of integrated gate electrode, in order to produce a truly low-voltage triode-type field emission microcathode. Although the realization of triode-type microstructures integrating CNTs has recently been shown [8], the fabrication process, as reported, requires a rigorous alignment between the gate apertures and the CNTs which are separately patterned. Moreover, to the best of our knowledge, field emission from such a device has not yet been reported.

In this paper, we demonstrate the fabrication of a field emission microcathode using a single mask, self-aligned process [9] which ensures that the CNTs are aligned and centred with respect to the gate aperture. We have also obtained peak emission current densities of 0.6 mA cm^{-2} from this device when applying 40 V to the gate. We believe that this is the first report of field emission measurements from a carbon nanotube device with an integrated gate electrode.

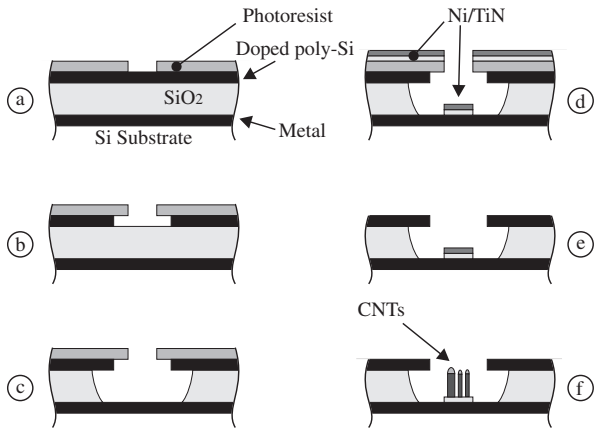

Figure 1. Self-aligned fabrication process for microcathodes with vertically-aligned CNTs as the emission source.

2. Fabrication process

Our fabrication process (figure 1) began with the deposition of a sandwich structure on a doped silicon substrate comprising of 150 nm of doped polysilicon (gate) on 500 nm of silicon dioxide (insulator) on a base metal electrode. An array of 150×150 holes of 1 μm diameter at a pitch of 4 μm was then patterned using optical lithography (figure 1(*a*)). A reactive ion etching (RIE) step using SF_6 gas at 2×10^{-2} mbar was then used to isotropically etch the polysilicon gate (figure 1(*b*)). Wet chemical etching in buffered hydrofluoric acid was used to isotropically etch the silicon dioxide insulator, in order to form an array of microcavities (figure 1(*c*)). Both the gate and insulator were deliberately overetched to produce an undercut. A 20 nm thick TiN layer was then deposited by sputtering. This was followed by the evaporation of 3 nm of nickel which is the catalyst for CNT growth (figure 1(*d*)). The role of the TiN layer [10] is to prevent nickel diffusion into the back metal electrode during the CNT growth which occurs at 700 °C. The unwanted TiN and nickel over the gate were then removed by dissolving the photoresist in acetone (lift-off process, figure 1(*e*)). The vertically aligned CNTs were deposited using PECVD with acetylene and ammonia gases at 700 °C as described in [7]. This process produced vertically-aligned CNTs which were catalytically nucleated on the nickel particles inside the gated device structure (figure 1(*f*)).

The scanning electron micrograph (SEM) images in figure 2 show selectively grown CNTs inside each gate aperture. The isotropic etching of the polysilicon has been performed to enlarge the gate aperture diameter to $\sim$2 μm. The silicon dioxide cavity was further undercut beneath the gate aperture in order to prevent the silicon dioxide from being charged during field emission. The CNTs are well defined within a 1 μm area in the centre of the gate aperture. Thus, possible short circuits between the CNTs after growth and the gate were avoided. The CNTs had diameters between 10–50 nm. The growth time was chosen to obtain CNTs up to $\sim$0.4 μ m heights—this is approximately equal to the base electrode to gate distance. This configuration has been shown to be optimal for Spindt-type cathodes [11] and should improve the field emission characteristics of our microcathodes.

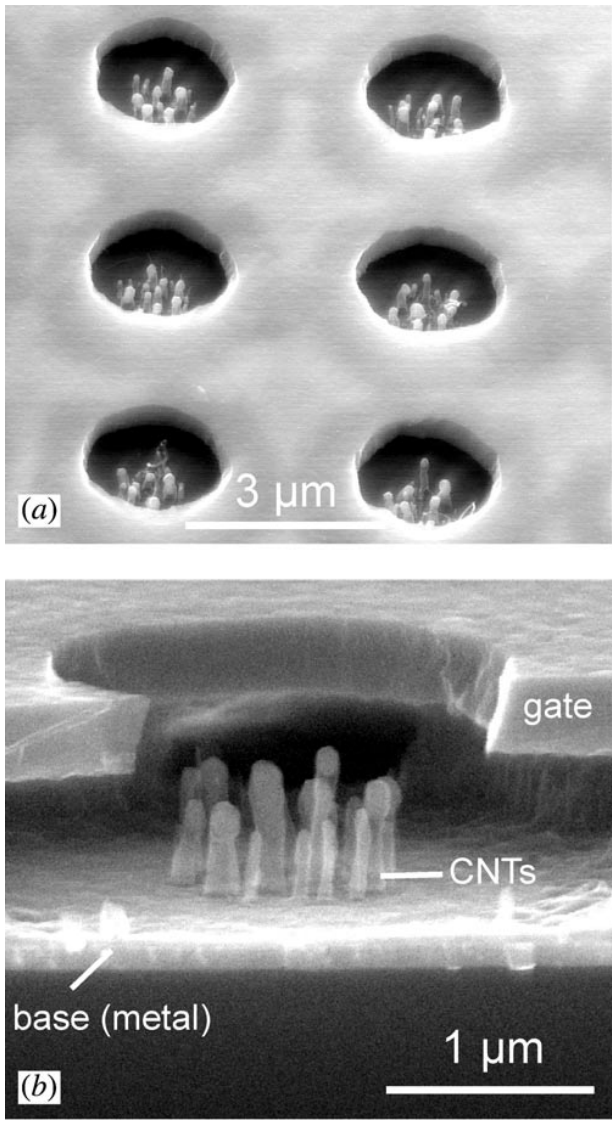

Figure 2. Tilted (45 °) top (*a*) and cross-sectional (*b*) SEM images of a microcathode.

3. Results and discussion

After deposition, the device was tested in a field emission measurement system evacuated to a base pressure of 10^{-8} mbar. Figure 3 shows the test configuration used during field emission characterization. Either a negative dc voltage or square-wave voltage pulses with a low duty cycle were applied to the base electrode (CNTs) relative to the grounded gate electrode, in order to extract electrons from the CNT emitters. A pulsed mode operation allows high peak emission currents to be extracted whilst limiting the overall power which prevents the degradation of the device. The field emitted electrons were then filtered through two grids which were biased so as to repel the low-energy secondary electrons generated by field emitted electrons bombarding the gate. A positively biased phosphor anode was used to collect and measure the average field emission current by means of a picoammeter. The field emission measurements were performed automatically via PC-controlled voltage sources and ammeters. The turn-on voltage is defined as the voltage required to produce detectable field

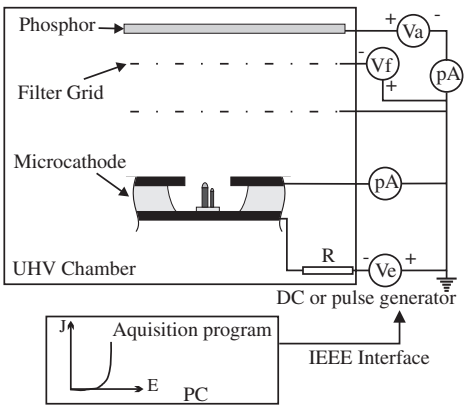

Figure 3. Schematic view of the field emission measurement system used to test the microcathodes.

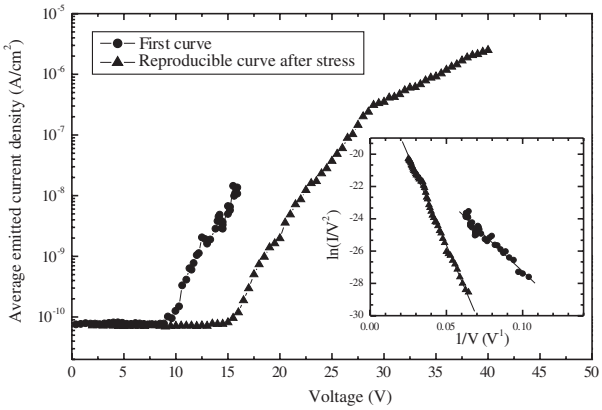

Figure 4. Field emission I–V measurements obtained in pulsed mode with a duty cycle of 0.5%. The inset shows the data plotted in Fowler–Nordheim coordinates.

emission from our device (in our case, an average emitted current density of $\sim 10^{-10}$ A cm^{-2}).

The field emission measurement results performed with a duty cycle of 0.5% and a frequency of 100 Hz are shown in figure 4. The initial turn-on voltage was 9 V. However, after recurrent measurements by cycling the gate voltage, the turn-on voltage was observed to shift to 15 V, after which stable and reproducible field emission characteristics were obtained. The shift in emission characteristics was probably due to the destruction of some of the nanotubes during the initial turn-on phase, as reported in [12]. The average current density, measured at a voltage of 40 V using a duty cycle of 0.5%, was 3.0 μA cm^{-2} which corresponds to a peak emission current density of 0.6 mA cm^{-2}.

The emission characteristics exhibit a Fowler–Nordheim (FN) type behaviour, as shown in the inset of figure 4. Thus, we are able to fit our results to the simplified FN equation

$$J = aV^2 \mathrm{e}^{(-b/V)} \tag{1}$$

where J is the emitter current density (A), V is the applied voltage (V), and a and b are the FN parameters. At this point it is worth pointing out that the parameter b from figure 4 (around 100 V) is one order of magnitude lower than that obtained with Spindt-type Mo cathodes (about 1000 V) [11, 13]. As the field enhancement factor, β, to an approximation, is inversely proportional to b for emitters of similar work function ($\phi_{\mathrm{Mo}} \sim 4.5$–4.95 eV, $\phi_{\mathrm{CNT}} \sim 5$ eV) [11], we surmise that CNT emitters must have a higher β compared with Spindt Mo tips. From figure 4, we find that the FN parameter b increased from 89 V for the initial emission to 221 V for the reproducible emission. This probably indicates that the high-β nanotubes which produced the initial emission (turn-on voltage at 9 V) were the first to be destroyed by over-currents, leaving the lower-β CNTs which produced the stable, reproducible emission characteristics afterwards. Further work is currently being performed to investigate the observed change in emission characteristics.

4. Conclusion

In summary, this work has demonstrated the fabrication and performance of a field emission microcathode with an integrated gate using vertically-aligned CNTs as the emission source. Such a device exhibits an initial field emission turn-on voltage as low as 9 V. A stable and reproducible behaviour is achieved with a peak current density of 0.6 mA cm^{-2} at 40 V, using a duty cycle of 0.5%. Our self-aligned process can be developed further to produce devices with one CNT per gate aperture by simply reducing the diameter of the holes in our lithographic pattern down to $\sim$100 nm. A single CNT per gate avoids electric field screening amongst the nanotubes. The screening effect is observed when many CNTs are in close proximity, thus lowering the effectiveness of the applied field [14]. The emitter density in the cathode can be increased by reducing the spacing between the gate apertures. Active circuit control or an integrated ballast resistor can be used to limit the current during operation, in order to prevent the degradation of CNTs during field emission.

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