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21.4: Gated Carbon Nanotube Pillar Arrays for High Current Applications

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Carbon nanotubes (CNTs) are attractive electron sources because of their mechanical stability, high electrical conductivity, and low turn-on fields. These properties make CNTs attractive candidates for a number of possible applications, in particular, those requiring high current densities such as travelling wave tube amplifiers and electric propulsion systems. In addition to high emission current density, a generally desirable operational parameter of cathodes is low electron extraction voltage. This is achievable with an array of emitters in which each of the emitters is fabricated with its own extracting electrode at a close distance, as illustrated in Fig. 1a.

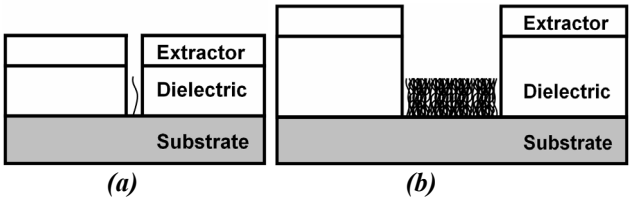

Figure 1*. A schematic representation of gated CNT cathodes for: a) individual CNT and b) CNT pillar.*

This concept has been previously developed for microfabricated Si cathodes [1]. Similar cathode structures have been investigated for carbon nanostructure emitters, however, a number of challenges have been insurmountable, namely the inability to fabricate an individual CNT array in a controlled manner. This limitation has hindered the success of such cathode structures. To address this issue, in this work, we will introduce an integrated gated array of controlled CNT cathodes based on our previously demonstrated, highly stable carbon nanotube pillar array as shown in Fig. 1b. A detailed fabrication process for this cathode structure will also be presented.

SEM images of a CNT pillar array (CPA) fabricated in our lab is shown in Fig 2a. The CNT pillar structures, shown in Fig 2b, may be fabricated by patterning metal catalysts or by directly growing the CNTs on patterned metal alloy substrate [2]. Through the use of conventional photolithography, CNT arrays with varying pillar diameters and inter-pillar spacing may be fabricated, depending on applications and the desirable emission current. We have fabricated pillars as small as 10 μm diameter, while still maintaining large-scale uniformity and most importantly vertical alignment.

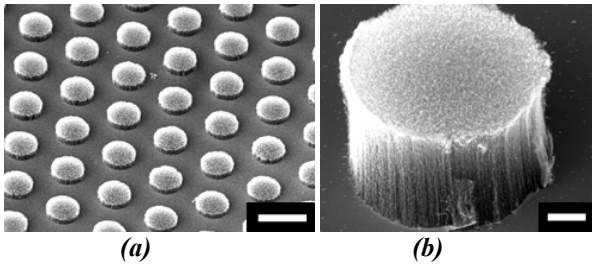

Figure 2*. SEM images of a) a CPA (scale bar is 20 μm) and b) a highly ordered and vertically aligned bundle of CNTs (scale bar is 2 μm).*

In addition to the inherently simple and highly reproducible fabrication technique, we have demonstrated that CPA emitter structures are capable of achieving turn-on fields as low as 0.9 V/μm, as is evident in the I-V characteristic of Fig. 3. The turn-on fields are comparable to those previously reported for individual CNT emitters, yet these structures show significantly more stability. This is attributable to the van der Waals forces responsible for the formation of the bundles. This bundled configuration results in an increased current carrying capacity and enhanced thermal dissipation characteristics.

Consequently, stable current densities of 10 mA/cm^2 have been demonstrated with 30 μm diameter pillar arrays with 20 μm inter-pillar spacing. Preliminary experiments have indicated that significantly higher current densities are possible with 10 μm diameter pillar array at a spacing of 15 μm.

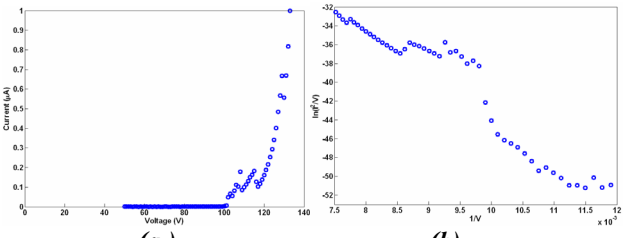

Figure 3*. a) A typical I-V characteristic and b) corresponding Fowler-Nordheim plot for an array of CNT pillars in a diode configuration with an anode cathode separation of 100 μm.*

For measurements conducted in a diode configuration, CPAs show current densities comparable to those of commercially available field emitter arrays on metal substrates [3]. The performance of the CPAs will be improved by integration of a gate electrode. The fabrication of this gated cathode begins by depositing a layer of conformal oxide on a CPA. The structure resulting from this deposition is shown in Fig. 4. This oxide layer serves as a protective layer during processing and also forms part of the dielectric stack in the final device.

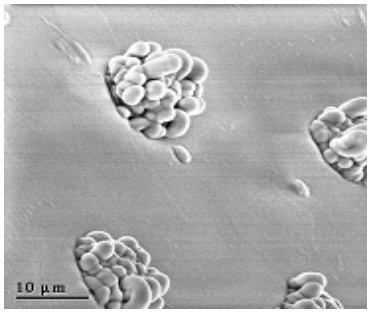

***Figure 4**. SEM image showing a CPA after being coated conformal oxide layer.*

With the protective oxide in place, this structure is then coated with a layer of polyimide followed by a patterned Mo gate, as shown in Fig. 5. The gate electrode is subsequently used as a mask during the dielectric etching process used to expose the CNT pillars, yielding the final structure schematically shown in Fig. 1b.

This fabrication technique adds a high degree of flexibility in the positioning of the final gate electrode with respect to the emitter structure and will allow for optimal gate placement. The dimensions of the emitter-gate spacing, inter-pillar spacing, pillar aspect ratio, etc., will depend on the current density requirements. Optimization of these parameters will increase emission uniformity, emitter stability, and lifetime. For a 10 µm diameter CNT pillar structure the voltage required to induce emission will be less than 100 V. This is a direct result of placing the comparably sized gate holes in close proximity to the emitters. In contrast, a 2 mm diameter CNT pillar array cathode with a 2 mm monolithic gate electrode would require extraction voltages on the order of 10's of kV.

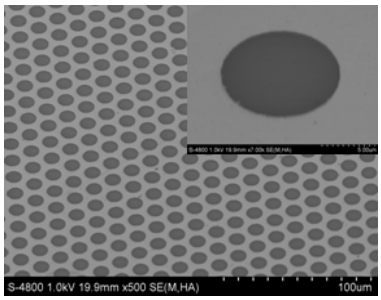

***Figure 5**. SEM of an array of gates after patterning on top of dielectric layer.*

In this paper we outline a process for the integration of gated CPAs. The process employed to fabricate this gated cathode is highly scaleable and promises the realization of stable high current cold cathodes with low turn-on voltages for many potential applications. In addition, we will present data detailing the field emission performance and reliability of gated carbon nanotube pillar arrays.

1. Spindt, C. A., Holland, C. E., Rosengreen, A., Brodie, I.,Trans. Electron Dev., Vol. 38, 10, pp. 2355-2363, 1991.
2. Killian, J. L., Zuckerman, N., Niemann, D. L., Ribaya, B. P., Rahman, M., Espinosa, R., Meyyappan, M., Nguyen, C. V.," *accepted J. Appl. Phys., in press, 2008.*
3. Kirk, E., Soichiro, T., Sehr, H., Vogel, T., Gobrecht, J., Ganter, R., Wrulich, A., Proc. IVEC07, pp. 321-322, 2007.