Carbon Nanotube Field Emission Devices with Integrated Gate for High Current Applications

Darrell L. Niemann,[1,2] Jeremy Silan,[1,2] Jessica L. Killian,[3,4] Kevin R. Schwanfelder,[3]
Mahmudur Rahman,[2] M. Meyyappan[1], and Cattien V. Nguyen[3,#]
[1]NASA Ames Research Center, Moffett Field, CA 94035
[2]Electron Devices Laboratory, EE Dept., Santa Clara University, Santa Clara, CA 95053
[3]ELORET Corp. NASA Ames Research Center, M/S 229-1, Moffett Field, CA 94035
[4]Department of Chemistry, San Jose State University, One Washington Sq., San Jose, CA 95192
[#]email: cattien.v.nguyen@nasa.gov

Abstract- **We present a fabrication technique for the integration of a gate electrode with an array of carbon nanotube (CNT) emitters. These gated cathode structures have high emission current density and may be utilized in X-ray tubes, traveling wave tubes, and ion propulsion systems. The CNT emitters are grown directly on polished bulk metal substrates and are comprised of CNT bundles that are vertically aligned and can be uniformly produced over a large substrate area. These arrays present many advantages including the capacity to sustain current densities greater than 60 mA/cm^2 and turn-on fields as low as 0.9 V/μm. We also present a detailed integration scheme utilizing these arrays of CNT emitters for the fabrication of gated cathode structures. Relative to other CNT emitters these gated structures have low operating voltages at higher emission current densities. Finite element analysis is used to investigate the electrostatic properties of both gated and ungated pillar structures. These results demonstrate that the benefits afforded by CPAs can be further enhanced by the addition of an integrated gate electrode.**

I. INTRODUCTION

Carbon nanotubes (CNTs) have attracted a great deal of attention for use as electron sources in recent years. The advantages of CNT emitters are primarily mechanical stability, low turn-on fields, and high emission current density. These properties lead to a number of proposed high current density applications, such as X-ray tubes, traveling-wave tubes, and electric propulsion systems. In theory, arrays of individually separated CNT emitters should have the highest emission current density. This ideal CNT structure has not been achievable due to insufficient fabrication control. The nonuniform CNT array results in an uneven emission pattern leading to unstable hot spots. Recently, CNT pillar arrays (CPAs) have emerged as a promising solution due to their ease of fabrication and inherent resilience [1, 2].

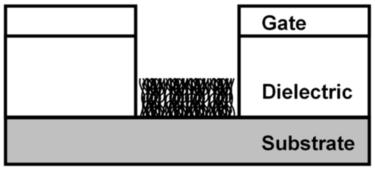


Fig. 1. *A schematic representation of the cross-section for a gated CNT cathode incorporating a single CNT pillar. A patterned Molybdenum layer acts as the extracting gate electrode. The dielectric stack is comprised of Polyimide and Oxide and the substrate acts as the Cathode in this system. This structure may be repeated to produce large arrays of emitters.*

It is highly desirable to provide a completed cathode device with an integrated extractor to reduce turn-on voltage and provide easy system level integration. As illustrated in Fig. 1, each of the individual CNT pillars is integrated with its own extracting gate electrode separated from the substrate by a distance on the order of a few microns. This idea has been extensively explored previously using microfabricated Si cathodes, commonly know as Spindt Cathodes [3, 4].

A number of research groups have investigated similar structures using CNT emitters, however, serious challenges have prevented the realization of gated CNT devices. The primary factor limiting progress has been the inability to fabricate arrays of individual CNTs in a highly controllable and reproducible manner. In order to overcome these challenges we have selected the CPA as the underlying CNT emitter structure. Due to the relatively simple fabrication process and high reproducibility of CPAs, we are able to utilize these structures for the integration of the gate electrode.

II. CARBON NANOTUBE PILLAR ARRAYS

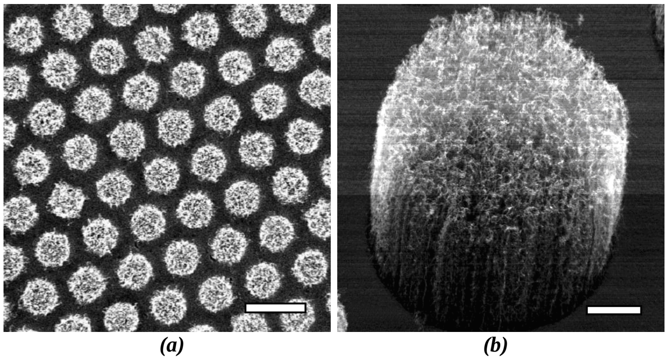

(a) ***(b)***

Fig. 2. *(a) A top down SEM image of a typical CPA (scale bar is 20 μm) and (b) A side view SEM image of a highly ordered and vertically aligned bundle of CNTs (scale bar is 2 μm).*

CPAs can be grown from patterned catalysts on substrates like Si or directly on bulk metallic alloy substrates that have been patterned with metal film layers that inhibit CNT growth [5, 6]. Both of these fabrication methods yield CNT emitter structures that exhibit low turn-on fields and also excellent structural stability. The alignment of CNTs in pillars is a result of the van der Waals interaction between adjacent

978-1-4244-2104-6/08/$25.00

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Carbon Nanotube Field Emission Devices With Integrated Gate for High Current Applications**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NASA Ames Research Center,Moffett Field,CA,94035**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002137. Proceedings of the 2008 IEEE International Conference on Nanotechnology (8th) Held in Arlington, TX on August 18-21, 2008. U.S. Government or Federal Rights License

14. ABSTRACT

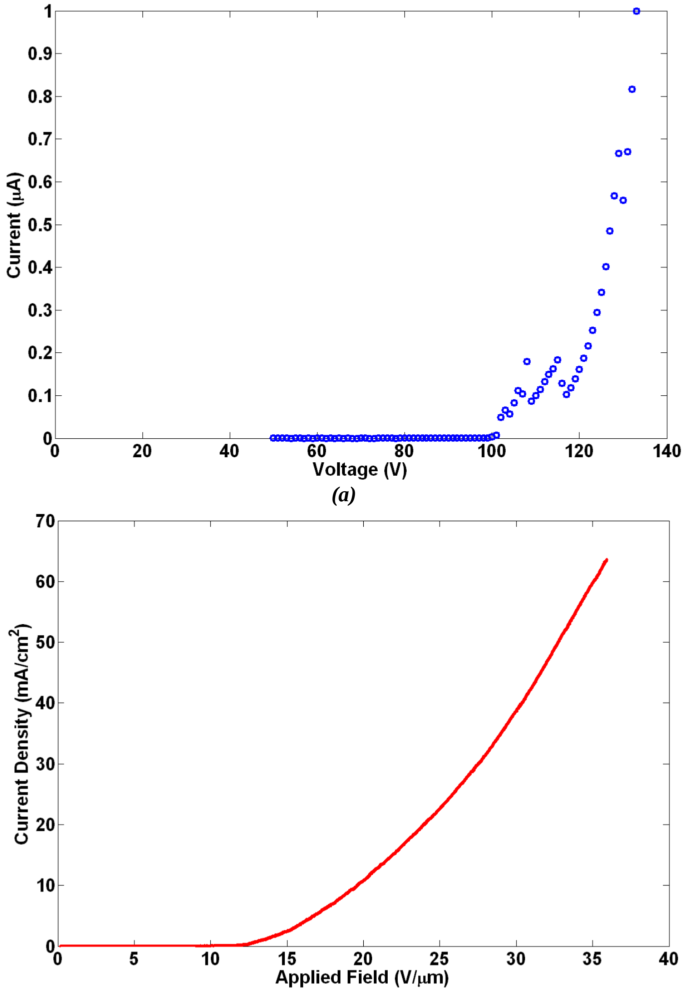
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

CNTs, as seen in Fig. 2. Coupling the vertically aligned structure of CPAs with a robust substrate/CNT junction, an increase in structural stability is obtained while still retaining the desirable electrical properties of CNT emitters.

In this paper we outline a methodology for fabricating patterned CPAs directly on metallic substrates. The process is based on commercially available Kanthal (74/24/2 wt% of Fe/Cr/Al) substrates that have been polished to an ultra smooth surface with RMS roughness of less than 5 nm. The Kanthal substrate is then patterned by a photolithography process and subsequently coated with a 10 nm layer of Chromium and a 15 nm layer of Molybdenum film in order to inhibit CNT growth in the coated areas. The growth of the CPA is carried out by thermal chemical vapor deposition (CVD) at 750ºC with 200 SCCM Hydrogen and 800 SCCM Ethylene flowing into the growth chamber [6]. Fig. 2a shows a highly uniform array of 10 μm diameter pillars obtained by direct growth of MWNTs directly on the patterned Kanthal surface.



(a)

(b)

***Fig. 3**. (a) A typical I-V characteristic demonstrating a turn on voltage of approximately 100 V and (b) A plot of current density as a function of applied field for a 15 μm pitch CPA composed of 10 um diameter pillars. Measurements were conducted in a diode configuration with an anode cathode separation of 100 μm.*

Arrays of varying pillar diameters and inter-pillar spacing can be easily achieved with photolithography, thus allowing the design of cathodes with application specific emission current and operating field. Figure 3a shows the field emission I-V characteristics of a CPA with a turn-on voltage of 0.9 V/μm. This low turn-on field of CPAs is comparable to values typically reported for individual CNT emitters [7, 8].

For measurements conducted in a diode configuration, our CPAs have proven to be capable of high current and are promising for many commercial applications [9]. Preliminary testing indicates that these structures show a high degree of current stability under continuous operation for hundreds of hours. As shown in Fig. 3b, current densities as high as 60 mA/cm^2 are possible with an array of 10 μm diameter pillars at a center-to-center spacing of 15 μm.

III. GATED AND UNGATED CPA FIELD ENHANCEMENT

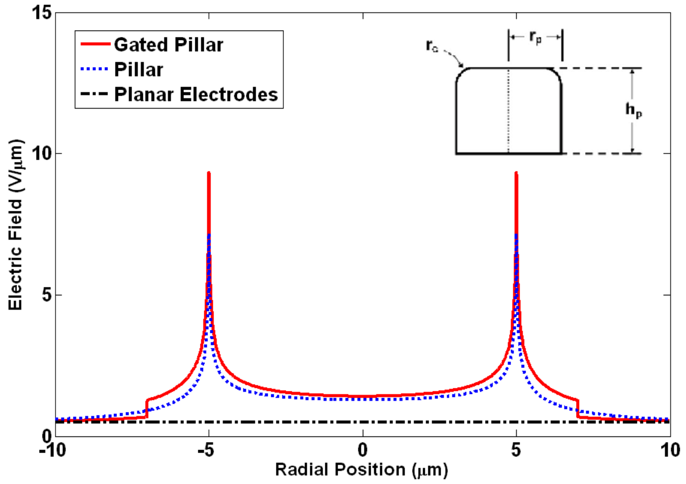


***Fig. 4**.* Simulated electric field as a function of radial position for a gated CNT pillar, CNT pillar with no gate, and for the case where the pillar is replaced by a planar surface. The structures are constructed with an anode-cathode separation of 10 μm, pillar height, h_p, of 10 μm, and a pillar radius, r_p, of 5 μm. The model of the pillar structure is constructed with a corner radius, r_c, of 1 nm. A schematic of the pillar model is shown as an inset.

In order to further elucidate the performance of these pillars the electrostatic properties of these deices have been investigated using finite element analysis. The modeled structure is defined to be a perfectly conducting cylinder with a corner radius joining the top surface to the sides. A schematic representation of this structure is shown as an inset in Fig. 4. Joining this structure to a planar electrode completes the model of the cathode structure. Figure 4 shows three different anode and cathode configurations all with a fixed separation between the two structures. In the first case, the cathode structure is opposed by a planar anode, a diode configuration. The increase in electric field at the edge of the pillar has been associated with the performance improvement observed for CPAs when compared to other CNT structures [5, 6].

In the second case, the new model is constructed using an identical cathode, while the anode structure is replaced by a gate electrode. This is constructed with an aperture radius of 5.5 μm. The hole in the dielectric polyimide layer has a radius of 7 µm. The electric field applied between the gate electrode and the cathode is kept the same as the first case. As shown in Fig. 4 it is clear that the gated structure also exhibits an edge effect and in fact, shows a slight enhancement. A baseline structure, consisting of two parallel plates with the same applied field and separation as the previous cathodes models has also been simulated for comparison.

This series of simulations demonstrates that there is a significant field enhancement. The data show that a gate with an aperture leads to a further increase in the field enhancement at edge of the pillar. These enhancements should decrease the turn-on voltage for the CPAs when in comparison to unpatterned CNT films. Thus, the gated extraction electrode structure should have an additional advantage of lowering operating voltage.

IV. INTEGRATED GATED CPAS

In light of these results a process is developed to fabricate high aspect ratio CPAs with integrated gate electrodes. As discussed in the previous section integration of a gate electrode with the CPA emitter will further enhance the performance of these CNT emitters. This gate electrode, in close proximity to each pillar, will ensure that each pillar across the array experiences a more uniform applied field. This is very difficult to achieve using a diode configuration or a macroscopic monolithic gate. As a consequence of improved field uniformity turn-on voltage, power consumption, stability, and emission uniformity will all improve.

In order to begin fabricating the gated cathode the CPA structure described in section II is first coated with an oxide layer. This is accomplished by standard SiO_2 CVD using TEOS. SEM images of the pillars before and after being coated with oxide are shown in Fig. 5. In addition to becoming a part of the final dielectric stack, this oxide layer protects the CNTs during processing. After the deposition of the oxide layer the CPA cathodes are then coated with polyimide. The polyimide layer is deposed via spin coating. This layer is subsequently fully cured at 400 ºC in a tube furnace under Ar. Polyimide has been selected as the dielectric because it is well suited for coating the high aspect ratio CNT pillars and for its high break down field of about one kV/µm [10]. This fabrication technique adds a high degree of flexibility in the positioning of the final gate electrode with respect to the emitter structure.

After preparation of the dielectric layers a Molybdenum gate electrode is deposited using an ion beam sputtering system. Figure 6 shows the structure after the Mo gate electrode patterning. The patterned Mo layer also functions as a mask for the dielectric etching process in the subsequent steps.

In order to demonstrate the ability of this oxide layer to sufficiently protect the CNTs during the processing an investigation of the pillars after etching is carried out. The image shown in Fig. 7 shows a 45^o view of a pillar after etching. It is clear from this image that the pillar has maintained its cylindrical shape as well as its orientation perpendicular to the substrate surface. This image also verifies the existence of CNTs over the outer surface of the pillar. There is also no appreciable change in the density of the pillar as a result of the processing.

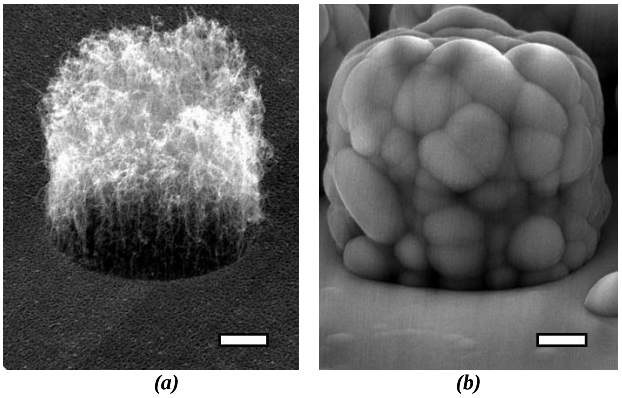

(a) (b)

Fig. 5. *SEM images collected with a sample tilt of 45º showing a typical 10 µm CNT pillar (a) before and (b) after being coated with an oxide layer. The scale bars are both 2 µm.*

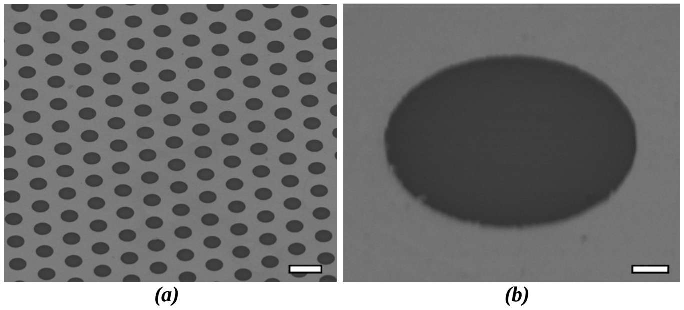

(a) (b)

Fig. 6. *SEM images collected with a sample tilt of 45º showing (a) an array of gates (scale bar is 20 µm) and (b) a single gate after patterning on top of the dielectrics (scale bar is 2 µm).*

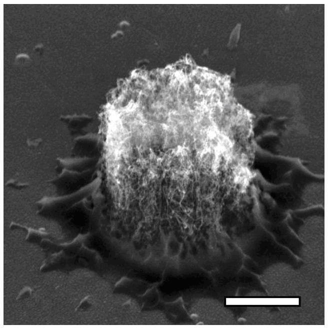


Fig. 7. *SEM images of a typical 10 µm CNT pillar after etching the dielectric layers showing a view at a sample tilt of 45º (scale bar is 5 µm).*

The combination of all the optimization parameters will enable significant performance gains. As indicated from the simulated electrostatics the addition of the gate electrode will not reduce the edge effect for the CNT pillars. As a result of this it is expected that the voltage required to induce emission will be less than 100 V for individually gated, 10 µm diameter CNT pillar structures. This is a direct result of placing the comparably sized gate holes in close proximity to the emitters. In contrast, a wide area monolithic gate electrode for a 2 mm diameter CPA cathode would require a higher extraction voltage for the same performance due to an inhomogeneous electric field.

V. CONCLUSION

We report a process for creating CPAs directly on metal alloy substrates and present field emission data demonstrating their superior performance. A highly scalable fabrication process for the production of gated CPAs is also presented. This cathode with integrated gate based on CPAs promises the realization of stable high current cold cathodes with low turn-on voltages which are ideal for many potential applications.

REFERENCES

[1] Wong, Y. M., Kang, W. P., Davidson, J. L., Choi, B. K., Hofmeister, W., Huang, J. H., "Array geometry, size and spacing effects on field emission characteristics of aligned carbon nantobues", Diamond & Rel. Mat., 14, 2078, 2005.

[2] Manohara, H. M., Bronikowski, M. J., Hoenk, M., Hunt, B. D., Siegel, P. H., "High-current-density field emitters based on arrays of carbon nanotube bundles", J. Vac. Sci. Technol. B, 23, 1, 2005.

[3] Spindt, C. A., Holland, C. E., Rosengreen, A., Brodie, I., "Field-emitter arrays for vacuum microelectronics," *Trans. Electron Dev.*, Vol. 38, 10, pp. 2355-2363, 1991.

[4] Trujillo, J. T., Hunt, C. E., "Fabrication of gated silicon field-emission cathodes for vacuum microelectronics and electron-beam applications", J. Vac. Sci. Technol. B, 11, 2, 1993.

[5] S. Fujii, S. Honda, H. Machida, H. Kawai, K. Ishida, M. Katayama, H. Furuta, T. Hirao, K. Oura,"Efficient field emission from an individual aligned carbon nanotube bundle enhanced by edge effect", *Appl. Phys. Lett.*, 90, 153108, 2007.

[6] Killian, J. L., Zuckerman, N., Niemann, D. L., Ribaya, B. P., Rahman, M., Espinosa, R., Meyyappan, M., Nguyen, C. V.,"Field emission properties of carbon nanotube pillar arrays," *J. Appl. Phys., 103, 064312, 2008.*

[7] Hii, K., R. R. Vallance, S. B. Chikkamaranahalli, M. P. Menguc, A. M. Rao,"Characterizing field emission from individual carbon nanotubes at small distances," J. Vac. Sci. Technol. B, 24, 3, 2006.

[8] Niemann, D. L., Ribaya, B. P., Gunther, N., Rahman, M., Leung, J., Nguyen, C. V., "Effects of cathode structure on the field emission properties of individual multi-walled carbon nanotube emitters", Nanotechnology, 18, 485702, 2007.

[9] Kirk, E., Soichiro, T., Sehr, H., Vogel, T., Gobrecht, J., Ganter, R., Wrulich, A.,"Development of All-metal Field Emitter Arrays for high Current Applications," *Proc. IVEC07*, pp. 321-322, 2007.

[10] Muramoto, Y., Goto, H., Mitsumoto, S., Fukuma, M., Hozumi, N., Nagao, M., "Breakdown and space charge distribution in polyimide film", Annual Report Conference on Electrical Insulation and Dielectric Phenomena**,** pp. 570- 573, 2002.