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Self-aligned gated field emission devices using single carbon nanofiber cathodes

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We report on the fabrication and operation of integrated gated field emission devices using single vertically aligned carbon nanofiber (VACNF) cathodes where the gate aperture has been formed using a self-aligned technique based on chemical mechanical polishing. We find that this method for producing gated cathode devices easily achieves structures with gate apertures on the order of 2 μm that show good concentric alignment to the VACNF emitter. The operation of these devices was explored and field emission characteristics that fit well to the Fowler–Nordheim model of emission was demonstrated. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1517718]

The integration of nanostructured carbon based materials into microfabricated field emission (FE) device structures is currently being investigated by a number of groups.[1–9] In particular, the use of carbon nanotubes[1–4] and nanofibers[6–9] as FE cathodes in integrated devices of various designs has received attention from a number of researches in the past four years. These materials offer great promise in numerous applications of microfabricated FE devices because they possess a number of properties that may lead to significant advances in FE device performance. These properties include low threshold field for the initiation of electron emission,[10] the ability to operate for extended periods of time in moderate vacuum,[11,12] and high emission current density,[13] among others. Vertically aligned carbon nanofibers (VACNF) offer some advantages over other materials in this class as their synthesis is completely deterministic[13,14] and they can be integrated into standard device fabrication processes that are scalable to wafer-level production.[8,9,15] Previous work by this group has shown that individual VACNFs can be incorporated into operational integrated gated cathode structures[8,9] and used as a cold cathode. The presence of a deterministically placed single VACNF within the device offers an unprecedented amount of control over the location of the emission site from a nanostructured graphitic carbon cathode. This feature is critical for electron sources suitable for electron beam lithography or electron microscopy, for which generation of a highly collimated emitted beam is essential. The presence of numerous emission sites or a single site poorly aligned to the electrode apertures of the device significantly complicates or even precludes the production of a highly focused beam from a microfabricated structure.

In our previous work the fabrication process used to produce the VACNF-based FE devices depended upon lithographic alignment of the gate electrode aperture to the VACNF emitter.[6,8,9] While the level of misalignment between the two can be negligible, this requirement necessitates the use of lithography equipment with sophisticated alignment capabilities.[16] A method for producing device structures where the gate aperture and a single VACNF emitter are aligned as a consequence of nonlithographic processing (i.e., self-aligned) would increase the range of applications for VACNF-based FE devices and significantly lower the cost of production.

Pirio *et al.*[7] demonstrated a process described as being self-aligned for producing integrated gated cathode structures using randomly distributed arrays of VACNFs for the emission cathode. While this work represents a simple way to fabricate VACNF-based gated cathode structures, this method lacks control over the location or density of the emission sites, and is therefore unsuitable for applications with more stringent requirements on the placement of the VACNF inside the device structure as described earlier.

For over a decade it has been known that chemical mechanical polishing (CMP) can be used to produce self-aligned gated cathode structures using oxide-sharpened Si tips as cathodes.[17–19] This process exploits the mound formed by the deposition of conformal passivating layers onto high aspect ratio Si features. Typically, a dielectric layer of SiO_2 is deposited using some form of chemical vapor deposition followed by a conductive layer that is impervious to wet chemical etchants for SiO_2, usually *n*-type polycrystalline Si. By planarizing these layers, the mound is removed forming a circular ring in the conductive layer that is automatically concentrically aligned to the apex of the emitter tip. This layer is then used as a mask for the removal of the SiO_2 dielectric layer.

In earlier work by this group, it was shown that the CMP process is compatible with substrates containing VACNF material.[8,9] In this letter we show that CMP can be used to produce operational integrated gated FE devices using single

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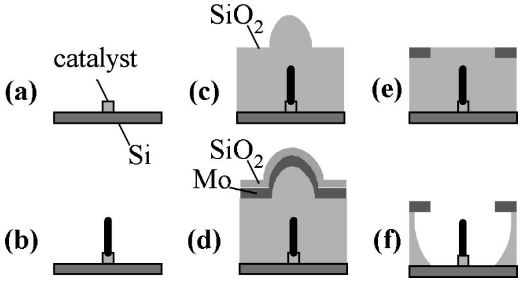

FIG. 1. Summary of the VACNF-based self-aligned gated cathode fabrication process.

VACNF cathodes with self-aligned gate electrode apertures. This work demonstrates that the VACNF can be used as a replacement for single Si field emitter tips in similar CMP-based self-aligned fabrication processes.

In the present work, whole, 3 in., low resistivity Si *n*-type wafers were used as substrates. Electron beam lithography and physical vapor deposition (PVD) were used to realize the catalyst sites for VACNF growth and alignment marks for subsequent lithographic patterning[14] [Fig. 1(a)]. DC plasma enhanced chemical vapor deposition (PECVD) of VACNF material was performed at 700 °C as described in previous work[8,9] [Fig. 1(b)]. This process produced VACNF that were 1 μm tall, on average, with tip diameters of less than 30 nm. A 1.2-μm-thick layer of SiO_2 was deposited onto the substrates using a silane-based rf PECVD process, and resulted in the formation of conformal mounds surrounding the VACNF emitters [Fig. 1(c)]. The gate electrode was defined using photolithography, omitting any lithographic definition of apertures aligned to the VACNF emitters. The gate pattern was metallized with 2000 Å of Mo deposited by electron gun PVD. Before performing CMP, an additional layer of SiO_2 was deposited onto the substrate to provide better control over the CMP process [Fig. 1(d)]. CMP was then performed to remove the mounds created during the PECVD SiO_2 deposition, and resulted in the creation of self-aligned gate electrode apertures [Fig. 1(e)]. A diluted solution of hydrofluoric acid was used to release the buried VACNF emitters [Fig. 1(f)]. The structures were thoroughly rinsed in DI water and blown dry with N_2.

Scanning electron microscope (SEM) micrographs of completed devices are shown in Fig. 2. The images on the right side of the figure were taken at normal incidence to the substrate and show reasonably good concentric alignment between the gate aperture and the VACNF emitter. Corresponding oblique angle images are shown on the left side of the figure taken at 45° from normal incidence. These images show the quality of the VACNF in the well, demonstrating that the processing used to create these devices leaves the emitter free of gross macroscopic damage.

The position and shape of the gate electrode aperture of each device was found to be slightly different due to the variations in VACNF morphology including height, cone angle, and degree of orthogonality with respect to the substrate. In Figs. 2(a) and 2(b), the VACNFs are relatively straight and sharp, with small cone angles. As a result, the aperture formed in these devices is round, fairly smooth, and within 100 nm of concentric alignment with the VACNF emitter [refer to Figs. 2(d) and 2(e)]. The diameter of the aperture is a function of the amount of SiO_2 placed on the emitter and how conformal that material covers the VACNF. In this work electrodes with diameters ranging from 2 to 2.4 μm were produced. This variation was attributed to the uniformity of the SiO_2 deposition process layer coupled with the intrinsic variation of the VACNF emitter geometry.

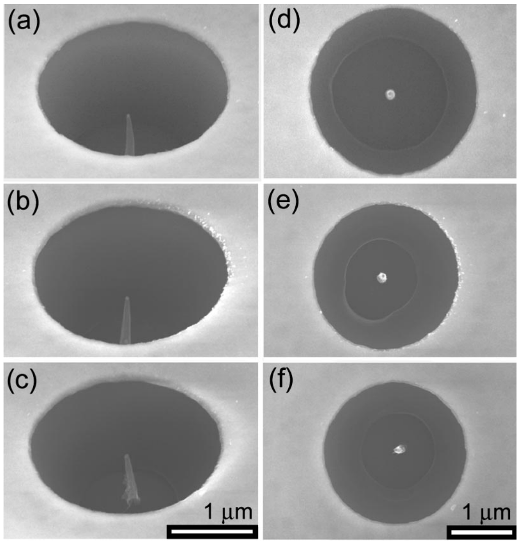

FIG. 2. SEM micrographs of devices following the CMP and wet chemical etching processes. (a)–(c) Oblique angle micrographs taken at 45° of the corresponding devices shown in (c)–(f) taken at normal incidence.

SiO_2 deposition processes can be designed to produce perfectly conformal films that have excellent uniformity across an entire substrate. Unfortunately, variations in the VACNF growth are not nearly as easy to control. This point is exemplified in Fig. 2(c). The VACNF shown in this image is slightly tilted, resulting in the formation of an aperture that is greater than 100 nm misaligned with the emitter tip. Although this aperture is round with smooth edges, it is clear that the direction of the misalignment is a direct result of the geometry of the VACNF [refer to Fig. 2(f)]. Alignment of the VACNF is understood to be a function of the interaction of the catalyst particle with the electric field present in the plasma sheath during the growth process.[20] However, unexpected relatively small variations from the ideal model can clearly occur.

FE measurements were conducted in a vacuum chamber operated at a pressure of 10^{-7} Torr. Data were collected by placing a flat Cu anode roughly 1 mm away from the surface of the VACNF FE devices. Keithley Instruments model 2410 dc source-measure units were connected to the cathode, gate, and anode to provide simultaneous and independent control of the potentials at each node while recording the corresponding currents. The data presented in this work were obtained with the gate at ground potential, and a 100 V positive bias on the anode. Anode and gate currents were measured as the cathode potential was varied between ground and -100 V.

Devices were conditioned by sourcing 20 nA of current through the emitter for periods of 1 h continuously. FE current versus voltage ($I-V$) curves were taken following the initial conditioning period. An example curve is shown in Fig. 3 and displays a threshold voltage of 50 V, defined here as the gate-to-cathode, V_{gc}, bias required to source 1 nA of

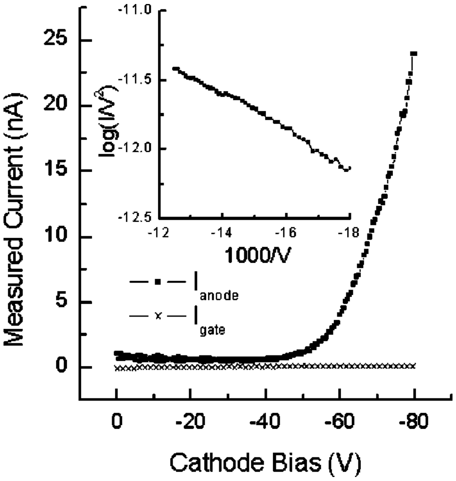

FIG. 3. FE $I-V$ curve of a single gated cathode device following emitter conditioning for 1 h Inset: the measured anode current plotted in FN coordinates.

current to the anode. However, this value is a strong function of the aspect ratio of the VACNF as observed in previous work.[13] During all tests performed on these devices, the amount of current measured at the gate was negligible and never increased beyond the noise level of the measurement system, while the current measured at the anode varied less than 1% from the current sourced through the VACNF emitter. This represents a slight increase in emission efficiency[21] over devices fabricated using strictly lithographically aligned processing.[8] However, this difference was typically less than 3% and indicates that the emitted beam from the VACNF tip was reasonably well collimated in both types of device structures preventing emitted electrons from intercepting the gate electrode.

The measured anode current I_A, plotted in Fowler–Nordheim (FN) coordinates is shown as an inset to Fig. 3. The linear nature of this plot indicates that FE is occurring by a tunneling mechanism in the tested range of cathode bias in accordance with the FN model of FE. Consequently, I_A can be assumed to obey the FN equation, $I_A = A \times V_{gc}^2 \exp(-B/V_{gc})$, where $A = 1.42\times 10^{-6} \times \alpha(\beta^2/\phi)\exp(10.4/\phi^{1/2})$, $B = 6.44\times 10^7 \times \phi^{3/2}/\beta$, α is the emission site area in units of cm^2, β is the field enhancement factor defined as the applied field at the VACNF tip, E, divided by V_{gc}, given in units of cm^{-1}, and ϕ is the work function in units of eV. B was determined for nine devices with similar geometry VACNF and gate apertures using the slope of their respective FN plots and found to be between 152 and 123. Taking ϕ to be equal to the work function of graphite, 4.6 eV, values for β were found in the range of 3.4×10^6 to 4.2×10^6 cm^{-1}. Using a simple electrostatic argument,[19] the tip radius r can be approximated as $r = 1/\beta$. This gives values of r on the order of 2 nm possibly indicating that emission is occurring from high aspect ratio nanostructured features on the tip of the VACNF and not the entire tip area. These results are consistent with results observed for similar geometry lithographically aligned structures reported previously.[8,9]

In this letter we have shown that it is possible to produce functional gated cathode devices using single VACNF emitters via a self-aligned process. While some misalignment is present between the position of the VACNF and the center of the gate aperture, this figure is typically less than 100 nm; the morphology of the VACNF and its geometric relation to the substrate play a large role in determining the severity of this misalignment. Refinement of the thin film deposition and CMP removal processes can be used to fabricate more complex structures with smaller apertures, as demonstrated for Si-based devices.[18,19] Incorporation of the VACNF into triode sources using these techniques is currently under investigation.

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[21] Defined as the percentage of the total emitted current collected by the anode relative to the amount of current collected by the gate electrode.