High-current, low-cost field emission triode using a reticulated vitreous carbon cathode

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A simple, macroscale field-emission triode was assembled using a single 3.8 mm diameter Ar^+-ion irradiated reticulated vitreous carbon (RVC) cathode. The irradiation process results in random carbon nanostructures on the surface of the RVC, providing effective, low-field emission sites. The use of RVC results in a self-ballasting cathode. The grid electrode further increases local field enhancement on the cathode surface, increasing the extracted current over what is produced in diode mode. The anode electric field required to produce 0.1 $\mu A/cm^2$ was measured to decrease from 0.9 to 0.65 $V/\mu m$ with 300 V applied to the grid electrode. With 2.1 $V/\mu m$, and 300 V applied to the grid, the limits of our power supply were reached, and a current density of 16.0 mA/cm^2 and a current of 1.82 mA from a single cathode were measured. Semiconductorlike emission properties, showing three regions of operation, were observed. In region III the cathode emits from a large number of sites, producing a total beam that is readily focused to a small spot size with ordinary electron optics. This low-cost, robust configuration, machined without microfabrication processes or lithography, makes very-high total current in single field-emission triodes possible. © *2010 American Vacuum Society.* [DOI: 10.1116/1.3305455]

I. INTRODUCTION

A high-brightness, high-current field-emission source is potentially beneficial in rf amplifiers, lighting, and other applications, including x-ray lamps for phase-contrast imaging (the target application of this research), which need to be a point x-ray source with high flux.[1] X-ray tubes using thermionic cathodes are able to achieve high current densities (~ 0.5 A/cm^2) (Ref. 2) and high flux; however, the space-charge-limited flow and corresponding lower brightness, as well as the greater energy spread of electrons coming from this type of source, limit the final spot size on the target to a value larger than is useful for phase-contrast imaging. Field emission electron sources, with their high brightness and smaller energy spread, have been somewhat limited by the lower total current. A high current (such as >5 mA) field-emission electron source would be desirable for x-ray phase contrast imaging. Recent improvements in materials and fabrication processes have shown promise for high-current field-emission cathodes. Among the most promising materials is carbon,[3–5] often showing high geometric field enhancement factor, low extraction fields, along with reasonable resistivity. The objective in this work is to give proof of concept of a macroscopic, low-cost, high-current field-emission electron source, which can be used in the stated applications. This source can be combined with electron optics and acceleration to give greater beam energy and potentially very small beam spot size.

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II. BACKGROUND

Previous work using reticulated vitreous carbon (RVC) as a field emission material, combined with Ar^+-ion irradiation,[6–8] has suggested this is a useful cathode material in a simple, large-area triode. RVC is an open-pore carbon foam, made from pyrolized fumed phenolic, resulting in a network of interconnected pores with small struts between each pore. RVC is robust and inexpensive to manufacture. When RVC is irradiated with Ar^+-ion flood bombardment, a self-assembly process produces carbon nanowires, nanotubes, and random amorphous and fullerene structures on the surface of the RVC.[7] This collection of carbon structures, such as seen in Fig. 1, creates effective, low-field emission sites. Typical nanowires extend far beyond the surface of the RVC and have a diameter of <50 nm.

III. EXPERIMENT

The cathode, made from 100 pores/in. RVC, was shaped using hand tools, resulting in a 3.8 mm diameter cylinder. The cylinder was made 5 mm long to allow the RVC to self-ballast the cathode. The surface of the cathode was rounded to approximately hemispherical to suppress extraction from the edges of the cathode. The cathode was then cleaned, and subsequently irradiated in a commercial ion-beam etching tool. An ion acceleration voltage of 1200 V, with a beam current of 200 mA, was used for 30 min at 2.4×10^{-4} Torr, after a base pressure of $<3\times10^{-6}$ Torr was maintained. The long carbon nanostructures seen in Fig. 1 are produced by a self-assembly process during this irradiation.[8] A triode-configuration assembly, seen in Fig. 2, was machined using stainless steel electrodes. Insulating standoffs were attached using commercial vacuum-safe ep-

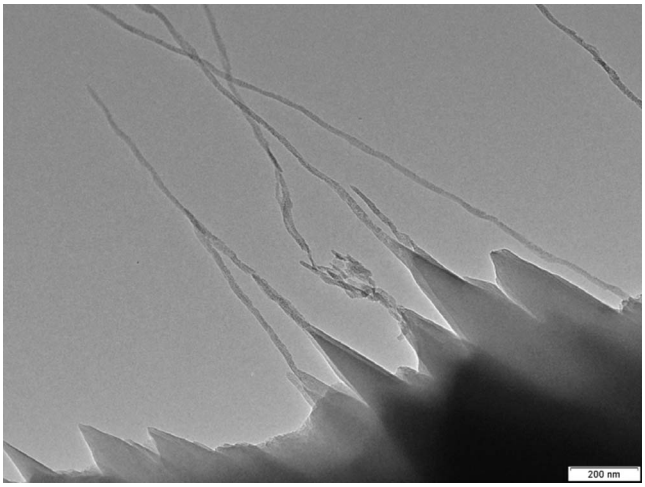

FIG. 1. Transmission electron micrograph of carbon nanostructures grown on RVC using the Ar^+-ion bombardment process.

oxy. The grid electrode was 1 mm in diameter larger than the cathode, having a 20° bevel and a sharp inner edge. The RVC cathode was attached to the stainless steel back plate using silver paste two-part epoxy. A stainless steel, mirror-polished anode was used for electrical characterization, whereas a phosphor-coated indium tin oxide anode was used for beam imaging. All experimental tests were conducted in a stainless-steel vacuum chamber equipped with a turbopump at pressures of $<5\times10^{-7}$ Torr. Electrostatic simulations (using ANSOFT MAXWELL) examined the field modifications caused by a voltages applied to the anode and grid electrodes.

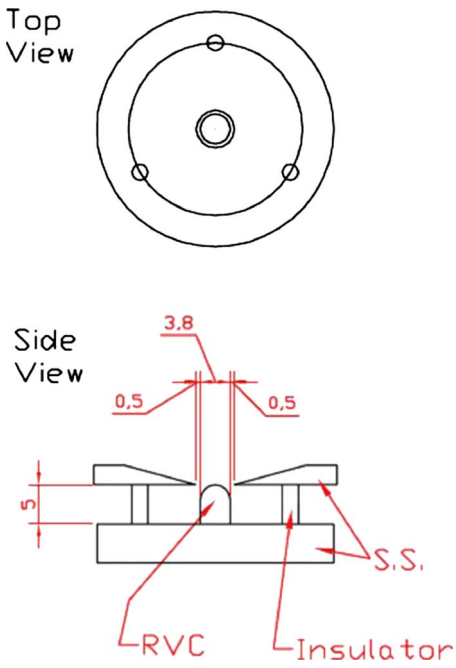

FIG. 2. (Color online) Triode design using the RVC cathode. Dimensions are given in millimeters.

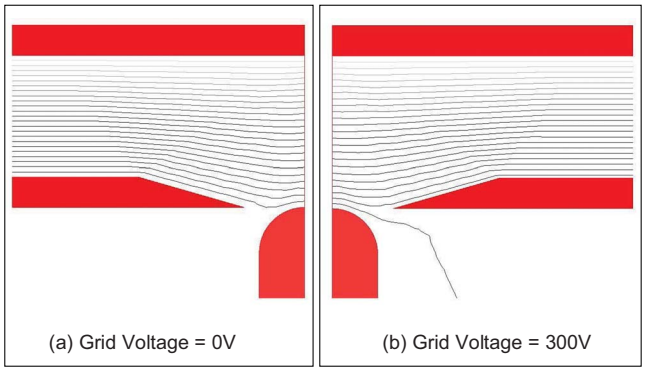

FIG. 3. (Color online) Electrostatic simulations showing anode voltage set to 5 kV and cathode grounded. (a) Grid voltage set to 0. (b) Grid voltage set to 300 V.

Experiments were carried out by setting the grid electrode to a fixed value and varying the anode voltage. The currents flowing through the cathode and the grid, and the voltages on the grid and anode were simultaneously measured and recorded using LABVIEW 7 software.

IV. RESULTS

Figure 3 shows the simulation observations. Isopotentials in the left image, (a), show zero volts applied to the grid electrode, whereas on the right image, (b), with 300 V applied, a notable shaping of the electric field results. In both simulations the anode potential was held constant. The electric field is greatest in the area closest to the anode, as expected. In addition, however, the nonzero grid potential increases the electric field in other areas of the cathode, notably the areas further away from the anode, resulting in greater overall emission from the shaped cathode, as desired.

Figure 4 shows the current density versus electric field for various grid voltages. It is clear that increasing the grid voltage not only increases current density, but it also decreases the field needed to initiate emission. Grid current was measured and, at operational current densities, it was $\leq1\%$ of the total current flowing through the cathode. During the measurements, hysteresis was observed. Upon initially increasing the anode voltage, the extracted current would reach a given value but would decrease after a few seconds of settling. The opposite effect is observed when the anode voltage is decreased. The cause of this hysteresis is currently being studied. However, to stabilize the data for this investigation, a 6 second settling period was always used.

The beam pattern was examined using the phosphor screen, as shown by example in Fig. 5. It is clear that only parts of the surface were emitting due to the large RVC pore size used (as large as 0.3 mm in diameter). Judging from the observed beam pattern, and taking into account blooming in the phosphor screen, approximately 30% of the surface was emitting.

The cathode exhibits emissive properties characteristic of carrier-limited materials, such as *p*-type or intrinsic semicon-

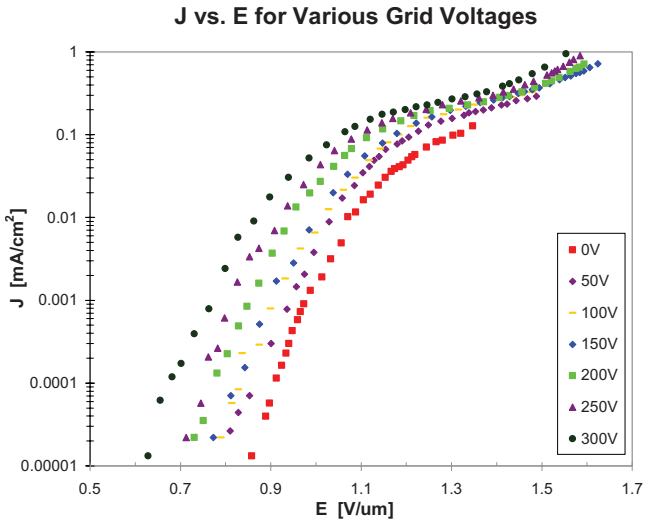

FIG. 4. (Color online) Field emission current density vs electric-field plot from the RVC triode with grid voltage varied from 0 to 300 V in 50 V increments. The area used to evaluate field is the total cathode area rather than the actual emission area.

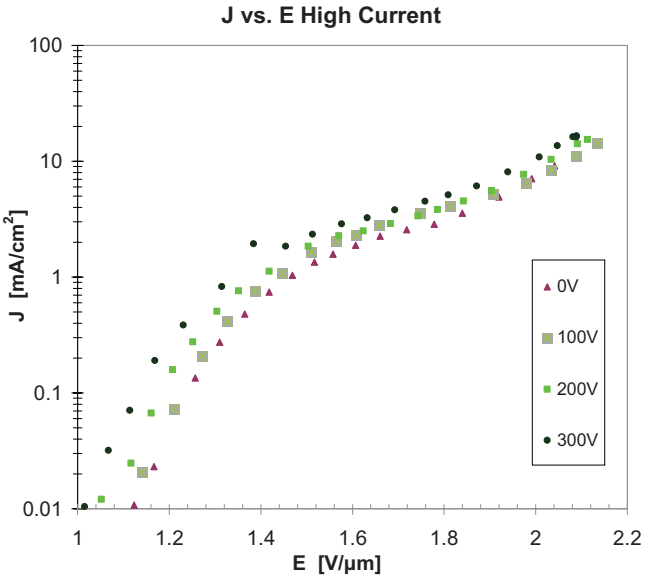

FIG. 6. (Color online) Field emission current density vs electric field plot from the RVC triode at higher current densities, with grid voltage varied from 0 to 300 V. Regions I, II, and III of operation are clearly seen.

ductors, those typically used in field-emission photocathodes. The characteristic region I (field limited), region II (supply limited), and region III (impact ionization)[9] are clearly seen in Figs. 6 and 7, when a bias necessary for higher currents is applied. Because Ar^+-ion irradiated RVC has been demonstrated to have a random combination of single-wall, and multiwall carbon nanotubes, as well as totally amorphous carbon whiskers,[7,8] it is demonstrated here that simultaneous emission proceeds from a combination of metal, semimetal, and semiconducting nanostructures that have been formed on the treated RVC surface. In these measurements, with an applied grid voltage of 300 V, a peak current of 1.8 mA was obtained, corresponding to a current density of 16.0 mA/cm^2 (total cathode area and not emission area) with an applied field of 2.1 $V/\mu m$. This value was limited by the power supply used, and not the cathode. Because a relatively small portion of the cathode is emitting electrons, this current can (using electron optics) be focused to a much smaller ultimate beam spot size.

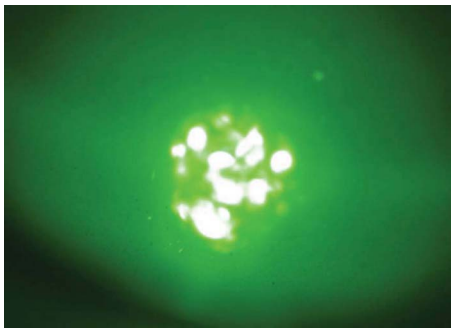

FIG. 5. (Color online) Image of the current on a phosphor screen, showing the RVC triode beam pattern, demonstrating that not all areas of the cathode are emitting in this measurement.

V. CONCLUSION

A simple, macroscopic field-emission triode was built using Ar^+-ion irradiated RVC as a cathode material. This device performed as simulated, and demonstrated higher maximum current than might be extracted from comparably sized Si or metal microtip technologies. The device required no microfabrication or lithography. The beam pattern showed that the cathode was only partly emitting; the peak-current measurements were limited by the power supply used. Further refinements of the shape of the cathode's surface, using finer porosity RVC, along with using a high-power supply and beam optics, are being investigated in order to optimize the current output, as well as to discover the cathode's emission and spot-size limits. The measurements presented here suggest that given such enhancements, it is likely that total

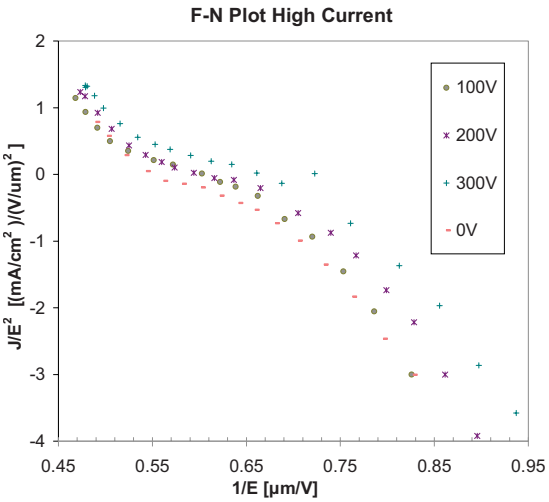

FIG. 7. (Color online) Fowler–Nordheim plot with grid voltage varied from 0 to 300 V showing regions I, II, and III of operation.

current values appropriate for phase-contrast x-ray sources, and other applications requiring high brightness and high total current, can be obtained.

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