UNIFORMITY CONDITIONING OF DIAMOND FIELD-EMITTER ARRAYS

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Abstract

We present results in the conditioning of diamond field-emitter arrays towards uniform emission. Post-fabrication conditioning procedures consisting of thermal annealing, gas exposure, and high field/emission operation have been examined. A high degree of emission uniformity was successfully achieved by thermal-assisted field evaporation of the diamond nanotips. This uniform emission was stable up to currents of 15 µA/tip, at which point the phosphor anode began to degrade from the high input power density.

INTRODUCTION

Recent experiments have demonstrated the potential of diamond field-emitter arrays as cathodes for free-electron lasers [1, 2]. One of the greatest challenges in the development of field-emitter arrays (FEAs) has been reliable scalability and the ability to condition them for uniform emission. A self-limiting conditioning process that discriminates based on electric field and emission current is essential for the development of successful FEAs. Experiments with SRI Spindt FEAs have shown that high-current-pulsed conditioning can reform its individual molybdenum emitters in a self-limiting fashion [3]. The combination of field stress, surface tension, and self joule heating by emission has resulted in emitters that possess almost identical emission properties. Despite this success, Spindt cathodes have not proved scalable to areas larger than 1mm^2 and tip numbers higher than 50,000. Non-uniform emission from an FEA is the result of morphological, compositional, and contamination differences between individual emitters. In the following work we examine various conditioning procedures that affect one or more of these sources of emission non-uniformity.

CONDITIONING METHODS

In this work we consider three main conditioning schemes for enhancing uniformity of diamond FEAs. The first is a thermal annealing of the cathode while it is emitting, called vacuum thermal electric conditioning (VTEC). The second is the selective exposure of the cathode to various gaseous backgrounds. During gas exposure, we have tested the effects of low and high field and emission operation, as well as the application of heat. The final conditioning technique we have considered is prolonged operation of the cathode at moderate to high current levels. All testing thus far has been performed in a DC mode. Pulsed conditioning techniques will be examined in the coming months.

EXPERIMENTAL CONFIGURATION

A schematic of the experimental configuration for these conditioning procedures is shown in Figure 1.

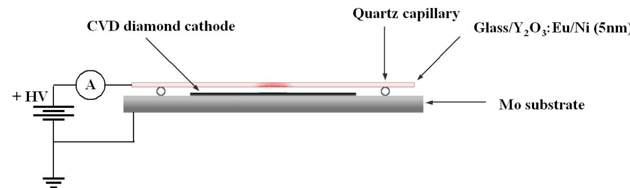

Figure 1. Uniformity apparatus schematic.

An ungated diamond field-emitter array is placed in a close-diode configuration with a phosphor anode. The anode-cathode gap is set using precision quartz capillaries allowing the application of known electric fields up to ~30 V/µm. The conditioning test stand has a base pressure of ~10^{-8} Torr and allows a variety of gaseous environments (~10^{-3}-10^{-8} Torr) to be achieved using a fine leak valve. The cathode can be heated as high as 350 °C by a tungsten filament under its base.

CONDITIONING RESULTS

VTEC

Experimental observations show emission dominated by weakly bound adsorbates for low and moderate current operation of unconditioned cathodes (Figure 2). VTEC appears to drive off these weakly attached adsorbates while activating tightly bound species, allowing them to migrate to the region of highest field. These adsorbates enhance the emission by a dipole lowering of the local-surface-energy barrier, resonant tunneling, or other effects. Following VTEC treatments of ~200-300 °C, emission uniformity is greatly improved, turn-on field is decreased, and current fluctuation due to adsorbate diffusion is dramatically reduced.

In Figure 3, a VTEC treatment has increased the fraction of active tips from ~30% to ~60%, while enhancing stability, and total current at the same field markedly. The right side of the array is preferentially brighter because asymmetry in the electrostatic force tilted the anode.

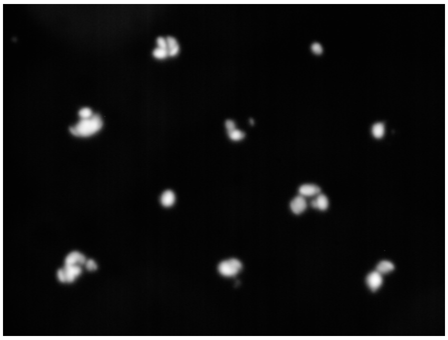

Figure 2. Beamlets from individual adsorbates on diamond nanotips (centroid spacing ~300μm).

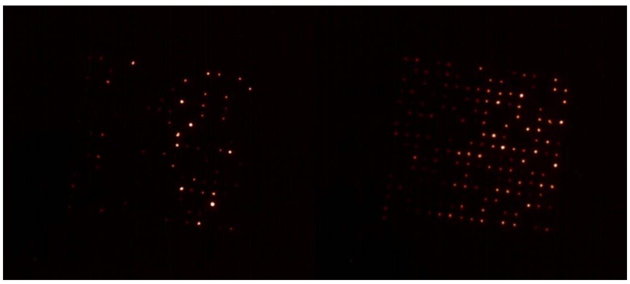

Figure 3. (left) Before VTEC ~30% of tips active, (right) after VTEC ~60% of tips active.

Emission images from another cathode before and after a VTEC treatment are presented in Figure 4. Typical emission current data from such a treatment are shown in Figure 5.

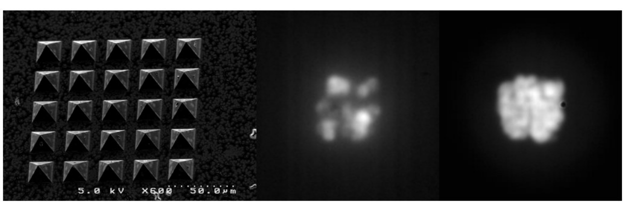

Figure 4. Electron beam from a 5x5 diamond FEA before and after VTEC.

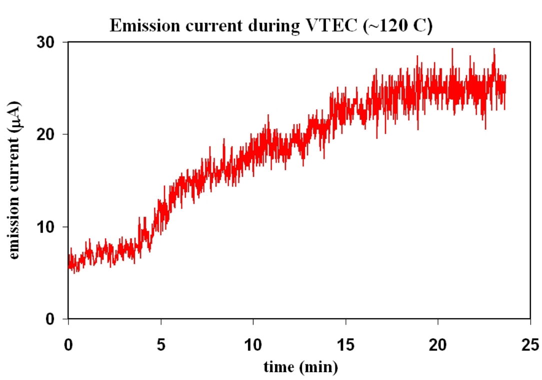

Figure 5. Typical emission current data during a low temperature VTEC treatment.

Selective gas exposure

Thus far, exposure to a background gas at 10^{-5}-10^{-3} Torr, while emitting at any level, has resulted in an increased turn-on field for every tip. Lower pressures have produced no significant effect. Following high-pressure-gas exposure, VTEC has improved emission somewhat, however the damage is mostly irreversible. An apparatus is under development for heating the cathode to high temperatures (~800 °C) in the presence of atomic hydrogen. This hydrogen termination and the negative electron affinity surface it produces may enhance the emission properties substantially.

Moderate/High current operation

Operation at high currents has resulted in the highest degree of uniformity of any conditioning method investigated. The mechanism of conditioning is believed to be thermal-assisted field evaporation of the diamond nanotips to a uniform effective radius. At high emission current, it is expected that the temperature of the emitting surface rises significantly, many hundreds of °C. Combined with the high electric field at the emitter sites, negatively charged carbon clusters can be evaporated into the vacuum. Because this process is extremely sensitive to electric field and current, the best emitters are selectively targeted leading to uniform tip geometry across the entire array. The self-limiting nature of the conditioning mechanism makes it difficult to determine the time required for termination of conditioning at a certain field. Microsecond-high-current pulsing will help to refine this technique while minimizing anode sputtering. This is especially important for high-density arrays, where current densities are prohibitively high for close-diode-DC operation.

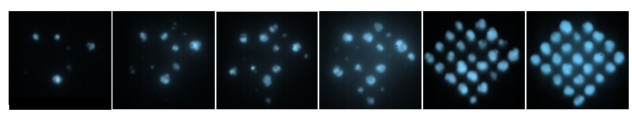

Figure 6. High-current conditioning of a 5x5 DFEA.

The beam from a 5x5 array undergoing conditioning is shown in Figure 6. The array current/field were progressively increased over approximately two hours of operation (left to right). The final current in the right-most frame was ~15 μA/tip. Figure 7 presents SEM micrographs of four tips in this array before and after high-current conditioning.

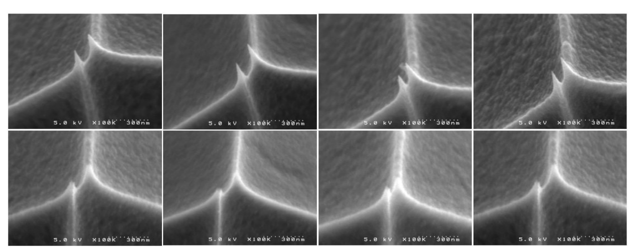

Figure 7. Emitters before (top) and after (bottom) high-current conditioning.

A controlled study of this conditioning process was performed on a 3x24 FEA by applying progressively higher average current levels for a set amount of time. Between each current level, all 72 tips were characterized in detail in the electron microscope, and emission uniformity at low current levels was checked with a phosphor anode. A 200 °C VTEC treatment was performed after the conclusion of high current operation to enhance uniformity. Figure 8 demonstrates the conditioning progression while Figure 9 shows typical conditioning of a tip's morphology.

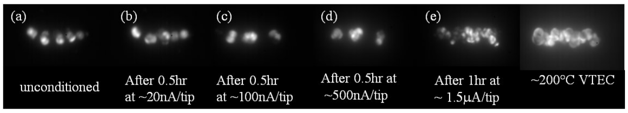

Figure 8. Conditioning progression for 3x24 FEA.

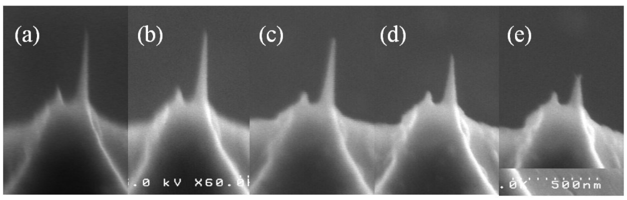

Figure 9. Evaporation progression of a single nanotip.

In addition to uniformity conditioning by evaporation, we observe field-induced-self-healing effects, which serve to correct certain fabrication or processing defects. This includes the straightening of bent tips and the separation of double tips that are stuck together. Approximately 15% of all emitters in the 3x24 array possessed these defects, and they were all corrected without exception.

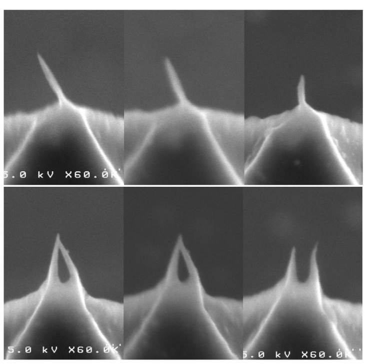

Figure 10. Examples of self-healing behavior of nanotips.

CONCLUSIONS

We have presented preliminary results in the exploration of various uniformity-conditioning strategies for diamond FEAs. Annealing while the cathode is at emission-level fields has been shown to increase uniformity and stability markedly, while lowering the required field for emission. Successful conditioning techniques utilizing selective gas exposure at different pressures, temperatures, and electric fields have not yet been discovered. The most successful uniformity conditioning thus far has been high current operation. The proposed thermal-assisted-field evaporation is self-limiting and leads to highly uniform emission over the entire array. Additionally, we observe field-induced reshaping of damaged nanotips into well aligned emitters. Diamond FEAs have proven their capability in an extremely harsh low-vacuum close-diode experimental arrangement. We expect that RF-pulsed operation in a higher vacuum environment will unlock new levels of performance for these devices. Toward that end, microsecond-pulsed-DC experiments are underway to optimize conditioning procedures.

ACKNOWLEDGEMENTS

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