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Title: Current Experimental Work with Diamond Field-Emitter Array Cathodes

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CURRENT EXPERIMENTAL WORK WITH DIAMOND FIELD-EMITTER ARRAY CATHODES

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Abstract

Diamond Field-Emitter Array (DFEA) cathodes are arrays of micron-scale diamond pyramids with nanometer-scale tips, thereby providing high emission currents with small emittance and energy spread. To date they have been demonstrated in a "close-diode" configuration, spaced only a few hundred microns from a solid anode, and have shown very promising results in terms of emittance, energy spread, and per-tip emission currents. We present recent results investigating DFEA performance in a large-gap configuration, such that the cathodes are a few millimeters from a solid anode, and show that performance is the same or better as the close-diode geometry previously studied. However, array performance is still limited by anode damage. We are redesigning our cathode test stand to overcome the inherent limitations of a solid anode, allow for transport of the emitted beam, and further explore real-world DFEA performance.

INTRODUCTION

Diamond Field-Emission Array (DFEA) cathodes are arrays of exquisitely sharp diamond pyramids [1]. They are a promising cathode option for a wide range of applications. DFEAs are particularly relevant to FELs because they can produce high-current, low emittance beams. LANL is currently investigating using DFEAs as the cathode for a dielectric laser accelerator (DLA), which can achieve acceleration gradients of GV/m in a structure where the transverse and longitudinal dimensions of the accelerating field are on the order of the laser wavelength [2]. The promise of DLAs is that they can be orders of magnitude more compact than conventional linacs driven by RF sources. We are currently working to characterize DFEA emission in order to understand how to gate, focus, and collimate beams from a single or few tips. The experimental work presented here is supported by a theoretical modelling effort [3].

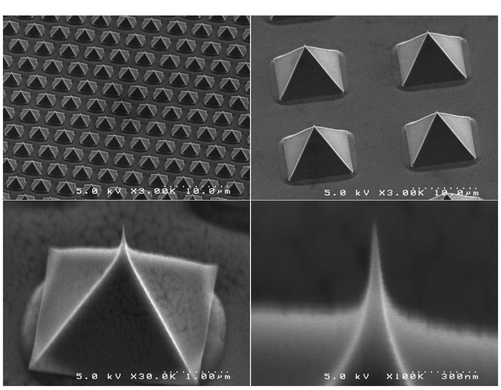

Figure 1: DFEA pyramids at four magnifications, showing the exquisitely sharp tip. (Vanderbilt University)

DFEAs emit in high or low vacuum, can be transported in air, and have good thermal conductivity that allows for very high per tip current emission without failure. We fabricate DFEAs using standard silicon wafer fabrication processes, so that they can be fabricated in any array configuration. Individual pyramid base sizes range from 25 micrometers to 2 micrometers.

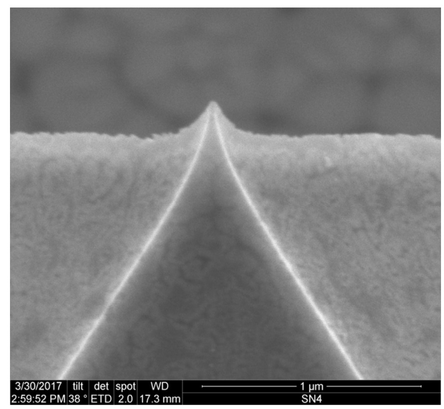

Figure 2: An SEM image of a recent DFEA tip. It has a diameter of around 50 nm.

DFEAs were first fabricated at Vanderbilt University, but are now used at a number of institutions. Originally (see Fig. 1), the diamond was highly conductive and yielded exquisitely sharp tips, however more recent DFEAs consist of less conductive diamond and exhibit the more blunt tips shown in Figure 2. The overall emission properties of the two types of diamond appear similar. We hope to investigate these differences more in the future.

EXPERIMENTAL SETUP

Our cathode characterization experiments are conducted in a vacuum test stand that is equipped with a number of diagnostics and shown in Figure 3. The test chamber has an ion gauge mounted adjacent to the cathode and anode. The chamber is also equipped with an RGA to analyse constituent gasses. The high-voltage is supplied by a negative 60 kV supply connected to the cathode mount. Experiments are typically conducted at 40 kV, allowing us to operate the DFEAs with an anode-cathode spacing of a few millimeters. The cathode is mounted on a fine linear actuator. This actuator is used to precisely adjust the field applied to the cathode. The anode-cathode gap can be adjusted from zero to 25 mm. We use either a AZO ($ZnO:Al_2O_3$) coated sapphire or diamond substrate or a stainless-steel plate with a mesh welded across a 0.4 inch hole as the anode. With a mesh anode we either im-

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age the beam on the AZO coated substrate (screen), or dump the beam onto a flat stainless steel plate that acts as a Faraday cup. Both the anode and screen or Faraday cup are connected to ground through current-viewing resistors. Typically, we operate the experiment as follows: with a large anode-cathode gap we turn up the voltage to 40 kV, then slowly bring the cathode closer to the anode. After taking measurements of emission current and pictures of the spot if using a screen at various gap distances, we bring the cathode away from the anode, continuing to record data.

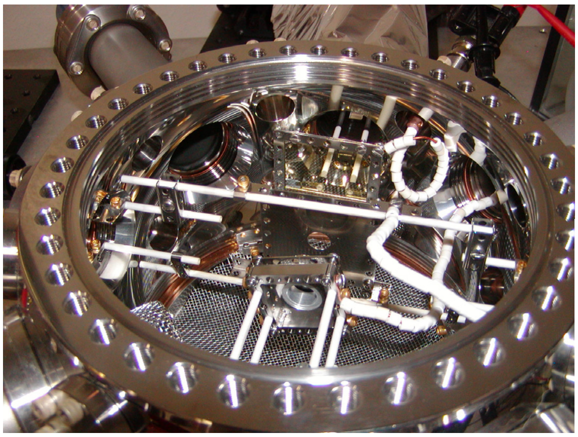

Figure 4: Image from the top of the small experiment chamber. The cathode holder, mesh anode, and phosphor are in line from close to far in this image.

We are in the process of commissioning a new experiment chamber that will include all the measurement features of the small chamber. The main feature of the new chamber is that it is large enough to contain electron focusing and collimating optics and diagnostics.

EMISSION FROM A DENSE ARRAY

Even operating at a relatively large anode-cathode gap of about 4 mm, we still damage the AZO screen. Any anode damage inevitably leads to cathode damage through ion back-bombardment. Recently we were able to operate a dense cathode, observing very nice conditioning data, and also extensive AZO screen anode damage from the process.

Figure 4 shows the image of a dense array (5 mm x 5 mm square, 20 μm base, 30 μm pitch) both initially (left), and after about 2 hours of conditioning at 11 MV/m and 250 μA total current (right).

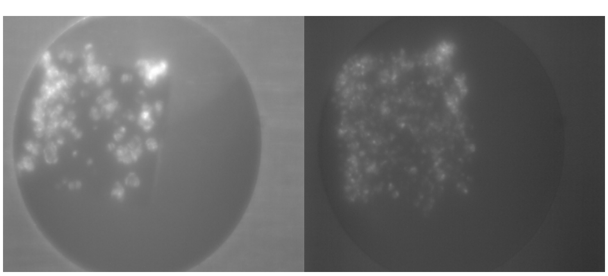

Figure 5: Emission imaged on an AZO screen from a dense array (5 mm x 5 mm, 20 μm base, 30 μm pitch) after about 30 minutes of conditioning (left) and after about 2 hours of conditioning at about 11 MV/m field and 250 μA total current (right). Figure 5 shows the image of

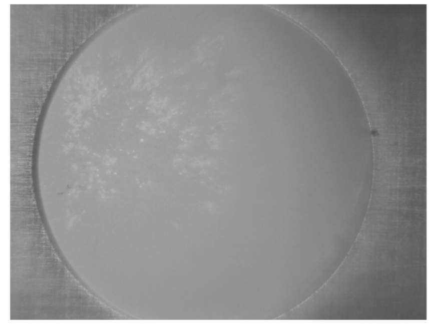

Figure 3: Image of the dense array above in the AZO coating. We suspect in this case the insulating diamond substrate charged and damaged the coating during discharge.

the dense array burned into the AZO coating material. We suspect in this case that the insulating diamond substrate charged during operation and damaged the AZO on discharge. Potentially we could get around this by using a conductive diamond substrate, however we have observed burn marks in the AZO coating from moderate current beams so it is not clear that increased substrate conductivity would help much.

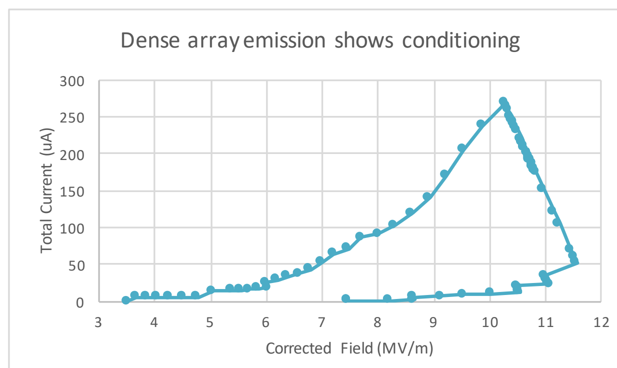

Figure 6: Emission from the dense array shown above.

Figure 6 shows the emission from the dense array shown above. The corrected field is the voltage/gap minus the voltage drop across the 20 MΩ ballast resistor. In this run the array turned on around 7.5 MV/m, we turned the field up to about 11.5 MV/m, the array conditioned (increasing current at constant voltage), then we opened the gap slowly, dropping the field to 3.5 MV/m at which point the array turned off. The behavior of the turn-on field lowering after conditioning seems to be characteristic of the lower conductivity diamond arrays and we would like to explore this behavior further.

CHARACTERIZING THE EFFECT OF A MESH ANODE

The advantage of using an imaging screen to view the beam is that, for sparse arrays, we can see how many tips are emitting and measure their spot size in order to find the inherent divergence of the beams. The significant disadvantages are that we cannot do anything else with the beam, and that even at moderate per-tip currents we can burn the AZO coating. In order to address both these issues we are characterizing the effect that a mesh anode has on beam divergence. Figure 7 shows images of an emission spot on an AZO screen under three conditions.

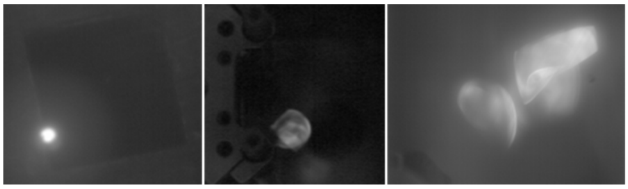

Figure 7: Emission shown on an AZO screen without (left) and with (middle, right) a mesh anode.

In the left image, the screen is acting as the anode spaced about 4 mm from the cathode. In the middle image the anode is a 50 line/inch mesh with a 0.49 mm square aperture welded across a 0.4 inch diameter hole in a stainless-steel plate, and the screen is placed about 19 mm back from the anode. In the right image the set-up is the same as the middle image, but the camera magnification is increased to show the spot structure. It is possible that this structure is due to a few closely spaced emitting tips, or from a few emission sites on one tip. We need a proper single-tip cathode in order to fully understand what we are seeing.

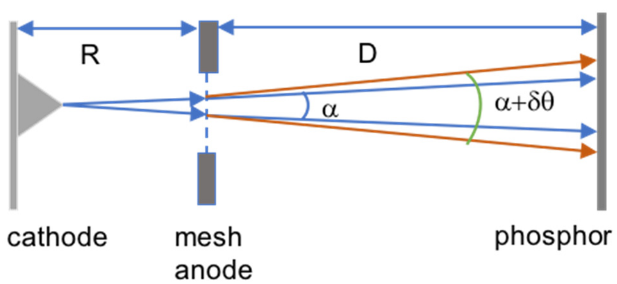

Figure 8: Diagram showing inherent beam divergence (blue) and the contribution of divergence from the mesh anode (orange).

Table 1: Summary of estimated and measured beam divergence and resulting spot sizes.

Quantity	Estimated	Measured
A-K gap		4 mm
Beam divergence	7 degrees	
Mesh contribution	0.7 degrees	
Spot on screen anode		0.5 mm
Spot on screen at 19.7 mm from anode	3.3 mm	2.9 mm
Spot on screen at 29.8 mm from anode	4.6 mm	4.6 mm

The spot sizes we see on an AZO screen anode, at a distance of about 4 mm, are about 0.5 mm. This suggests a divergence angle of about 7 degrees. Theory suggests that the mesh contribution to electron beam divergence should be $\delta\theta \sim h/(8R)$ where h is the mesh aperture and R is the anode-cathode spacing [4]. For our mesh, we estimate that this quantity is about 0.7 degrees. Figure 8 shows a rough diagram of beam divergence (blue) and mesh contribution (orange).

We are now measuring the spot sizes at a range of D (anode-screen distance) in order to determine α and $\delta\theta$. Table 1 shows a rough first look at a comparison of estimated and measured spot sizes for two anode-screen distances. A significant difference between what we are attempting now and prior work is that previously the emittance was measured for an entire array [5]. Here we are interested in divergence of a single beamlet.

Although we have not attempted to estimate the error bars on this data yet because of many complicating factors including differing emission current levels and possibly multiple closely spaced emitting tips, it is encouraging that there is a rough agreement between our measurements and estimates.

SUMMARY AND PATH FORWARD

We continue working towards using a DFEA as the cathode for a DLA. One step in this project is to understand how to focus and guide the beam from a single or few tips. Working at a relatively large gap, we still observe AZO coating damage at moderate tip currents. We expect to have a new batch of cathodes, both sparse arrays and single tips, for testing in the next month. These cathodes will help us make reliable measurements of inherent beam divergence and mesh contribution to beam divergence. Reliable measurements also require that we take data at similar current levels for various anode-screen distances. Current can be hard to control day-to-day, but will hopefully be easier if we can condition the cathode using a mesh anode and metal Faraday cup in place of the AZO screen.

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