ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-THYD5

DEVELOPMENT OF NANOPATTERNED STRONG FIELD EMISSION CATHODES

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Abstract

Increasing brightness at the cathode is highly desirable for a diverse suite of applications in the electron accelerator community. These applications range from free electron lasers to ultrafast electron diffraction. Many options for higher brightness cathodes are under investigation notably semiconductor cathodes. We consider here the possibility for an alternative paradigm whereby the cathode surface is controlled to reduce the effective area of illumination and emission. We fabricated nanoblade metallic coated cathodes using common nanofabrication techniques. We have demonstrated that a beam can be successfully extracted with a low emittance and we have reconstructed a portion of the energy spectrum. As a result of our particular geometry, our beam possesses a notably high aspect ratio in its transverse plane. We can now begin to consider modifications for the production of intentionally patterned beams such as higher aspect ratios and hollow beams.

INTRODUCTION

One of the main goals of the National Science Foundation Center for Bright Beams is to increase electron beam brightness for many applications including free electron lasers, ultrafast electron diffraction, etc. Many concepts are currently being considered to increase beam brightness at the cathode. High brightness semiconductor cathodes are very promising due to the low MTE of produced beams but are challenging to work with for several reasons including their sensitivity to vacuum conditions [1]. As an alternative, we consider here custom nanofabricated surfaces. By creating nanostructured surfaces we can produce high field enhancement in smaller areas thus reducing the effective spot size illuminated by the emission producing laser. One of the simplest geometries we use as our proof of principle study is inspired by nanotips used for electron microscopy where incident laser fields along with geometry-based field enhancement lead to electron emission via tunneling [2–4].

The physics responsible for the emission is complex and under continued theoretical investigation. It is, for example, dependent on re-scattering effects in the intense laser field which multiply the energy of the emitted electrons significantly. This work is more thoroughly covered in related publications [5, 6]. Instead we limit our discussion here to the implications to future cathode development given our previous observations of transverse structure, emittance, and emission energies [7, 8].

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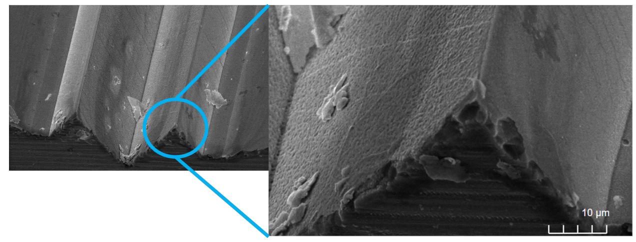

Figure 1: SEM image of nanoblades at the 10-μm scale.

NANOBLADE FABRICATION

It is useful to first go through the nanofabrication process used successfully thus far and explain some of its advantages and limitations. The blades are made through two chemical wet-etches into a silicon wafer. The challenge of the process is precisely controlling the position and dimensions of each etch. The first etch creates the two grooves, the second etch cuts in between them to create the two blades. The multi step process uses well-established methods and at this point is fairly repeatable.

A 2-D design is made using L-edit software to make the photolithography masks. The primary pattern that we have used are multiple long thin rectangles used to etch the groves as well as shapes (crosshairs etc) that are used to align with the second mask later on. Another 2-D design is made in L-edit to make the second mask. The long thin patterns (later, etches) to be made are between the ones in the first mask pattern. There are the same crosshairs to align to the pattern of the first mask.

We then use plasma enhanced chemical vapor deposition (PECVD), to deposit a layer of nitride on the silicon wafer followed immediately after by a thin layer of photoresist (PR) which is spun onto the silicon wafer. A machine designed for precision alignment is then used to place the mask on top of the wafer such that photolithography can be used to form the mask pattern on the photoresist. The nitride layer that is not covered by photoresist is then etched away using oxide etching. The photoresist can then be removed and the structures in silicon can be anisotropically etched away with a KOH solution. After this the remaining nitride is removed and the process is repeated to form additional features including, for the case of the cathodes like those in Fig. 1, the double blade geometry. A 10-20-nm metallic coating is then sputtered into the blades. One wafer is then diced into 40 usable cathode samples.

It is then necessary to address the nature of the nanoblade cathode reproducibility. In previous iterations of our man-

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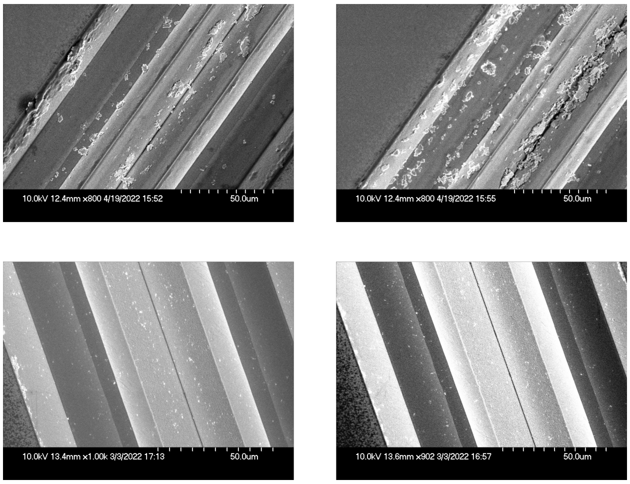

Figure 2: SEM images of two different blades (above and below) at two different locations each (left and right).

ufacturing process low pressure chemical vapor deposition (LPCVD) was used instead of the newer PECVD. In this older procedure we would often run into an issue during the KOH acid etch known as lift-off. During the bath, pieces of nitride seemingly pull off the silicon substrate causing the entire surface of the silicon wafer to be etched. On rare occasions this can render the entire sample unusable. The most likely explanation is a non uniform or thin nitride coating, thus motivating our change to the PECVD.

We show two nanoblade samples' SEM images in Fig. 2. The lower images show a sample prepared with relatively minimal visible residue on the blade structure and the upper image shows the extant of maximal residue which still produces an electron signal.

Robustness

Additional discussion is reserved here for the laser intensity damage threshold. Figure 3 show one such example of presumed laser damage. We refer to this as presumed since electron yield did not noticeably decrease during measurements with this sample and post-illumination SEM imaging was necessary to find the damage. Furthermore the damage is sufficiently isolated and may in fact come from an uneven sputter coat at the edge of the sample exposing silicon to incident laser and melting. This would seem consistent as no damage can be seen further along the blade towards the center of the sample.

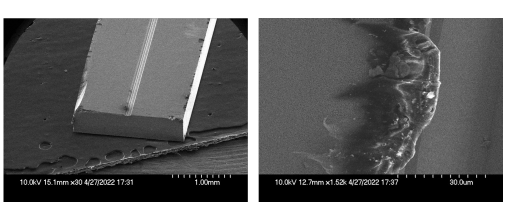

Figure 3: SEM image of small dark spot on sample where slight laser damage can be seen (left). Closeup of the spot showing what is likely melted silicon (right).

EMISSION CHARACTERIZATION

Emittance and preliminary yield measurements were presented previously [8, 9]. Due to the asymmetry of the cathode pattern it is important to further characterise our cathodes' angular emission dependence. In Fig. 4 we can see our rectangular sample (15 mm × 3 mm) along which our nanoblade is indicated. The laser is incident at 5 degrees and the electrons are emitted along the blade in a high aspect ratio parallel to the surface normal vector in the $\hat{z}$ direction.

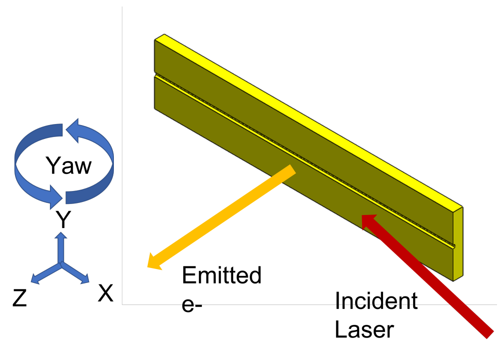

Figure 4: Schematic diagram of coordinate axes of sample as it is illuminated by the laser at an inclination of approximately 5 degrees.

We examine the three rotational degrees of freedom within small angles (under 10 degrees in either direction). We find that pitch and roll, rotation about the x and z coordinates, have minimal impact on measured signal. Yaw, the rotation about the y axis, does affect yield. In each case, sample bias ramps were performed at different angular displacement. The results are shown in Fig. 5. The labels p−100, p−50, and p50 refer to the displacements of the picomotors in the measurement setup. Data is compared to a ramping bias simulation for angles between 0 and 7.5 degrees.

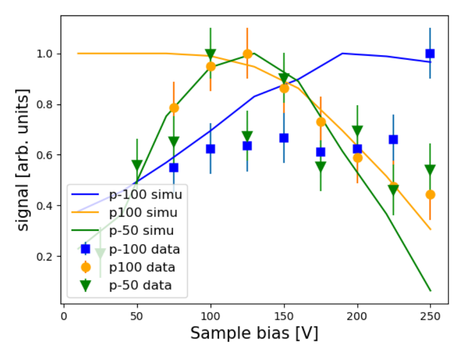

Figure 5: Sample cathode bias sweeps for 3 different angular displacements of the yaw axis between 0 and 7.5 degrees (further explained in Fig. 4). Data in points is compared to particle tracking simulations.

The simulation differs from measurement, however they do seem to agree in the general trend in each bias ramp. The discrepancy is likely due to the slight coupling of yaw and pitch due to the use of an in-vacuum optics mount for the picomotors.

ADDITIONAL GEOMETRIES

Due to our observation of a beam which demonstrates the transverse patterning of our nanoblade cathode we now can consider patterning cathodes for specific desirable transverse structure. The first to consider is the high aspect ratio beam we have already produced. Future versions of our cathode with a simplified single blade may be useful for certain wakefield accelerator applications [10]. Another desirable transverse shape that can be considered are hollow beams or rings [11]. As a result of our exploration with focused ion beams (FIB), we have created a proof of concept for a bullseye type pattern shown in Fig. 6. It is nowhere near the atomically sharp blade produced with our anisotropic wet etch but does open the possibility for future work.

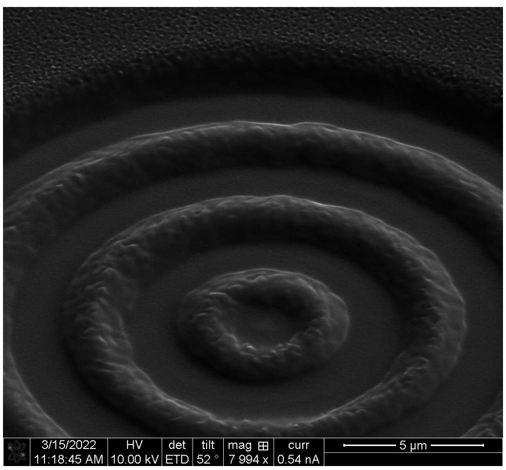

Figure 6: Proof-of-concept bullseye pattern made with FIB which could be used in future plasmonic cathode studies.

CONCLUSIONS

We have presented here our continued development of a new class of nanofabricated cathodes where we have control of the nanostructure and consequently the produced beam shape. Our process has been refined to usefully repeatable levels with room for improvement. Uniformity of emission from sample to sample is the next step. Alternative geometries that could potentially harness plasmonic effects to increase field enhancement are under consideration and various beam patterns can be studied.

ACKNOWLEDGEMENTS

This work was supported by the Center for Bright Beams, National Science Foundation Grant No. PHY-1549132 and DOE HEP Grant DE-SC0009914.

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