EXPERIMENTAL INVESTIGATION OF FIELD-EMISSION FROM SILICON NANO-CONE CATHODES

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Abstract

Field emission cathodes are capable of forming electron beam with extreme brightness via strong-field excitation applying electrostatic, or electromagnetic (radiofrequency and laser) fields. Our group, in collaboration with the Argonne Center for Nanoscale Materials, has recently developed nanocone field-emission cathodes. These cathodes can be configured as a single-cone emitter or as large arrays of tightly-packed emitter. The present paper reports on the experimental setup developed to investigate the performances. The tests carried in a diode setup are capable of measuring $I-V$ characteristic curves and transverse beam distributions.

INTRODUCTION

Field emission cathodes are a key to the development of ultra-fast electron diffraction and novel compact light-sources. This type of electron source are foreseen to enable the generation of high-brightness electron beam with phase-space volume approaching the quantum limit.

In quantum mechanics, the smallest six-dimensional phase-space volume allowing a single particle to occupy is limited and dictates the lowest possible emittance for electron beam called the quantum-limited emittance. As the degeneracy parameter $\mathcal{D}$ is defined as a ratio between the quantum-limited emittance and beam emittance with $0 < \mathcal{D} < 1$, typical solid-state photocathodes have the degeneracy parameter $\mathcal{D} \sim 10^{-11}$ which means the phase space is largely occupied.

The development of electron sources for higher degeneracy has become active over the past few years. Cold-atom-based electron sources were proposed [1, 2] and foreseen to reach the quantum-degeneracy limit ($\mathcal{D} \sim 1$). In parallel, field-emission sources have been actively explored [3, 4] to produce continuous and pulsed (few fs duration) electron beams. The field-emission process also becomes a promising candidate toward the realization of cold electron sources with typical degeneracy close to $\mathcal{D} \sim 10^{-4}$.

Field emission is the escape of electrons from an emitting surface, due to electric field generating deduction of the potential barrier from the linear potential. The theory of the field emission is well established in [5, 6], and the instantaneous field-emitted electron-beam current density at a location $\boldsymbol{x}$ on the emitter surface follows the Fowler-Nordheim's (F-N) law [5]

$$\boldsymbol{j}(\boldsymbol{x},t) = A(\Phi)E(\boldsymbol{x},t)^2 \exp\left(-\frac{B(\Phi)}{E(\boldsymbol{x},t)}\right)\hat{\boldsymbol{n}}(\boldsymbol{x}), \qquad (1)$$

where $E(\boldsymbol{x},t)$ is the *local* field at $\boldsymbol{x}$, $A(\Phi)$ and $B(\Phi)$ are constants that depend on the material work function Φ, and $\hat{\boldsymbol{n}}(\boldsymbol{x})$ is the local unit vector normal to the emitting surface.

A single-tip field-emitter (FE) cathode emits electrons from a very small area of a sharp tip edge and also produces low transverse emittance beams [7]. Large arrays of FEs, field-emission-array (FEA) cathodes gives more beam currents [4], while sacrificing emittance with FEA macroscopic radius as a beam size. Nanocone cathodes configured as both FEs and tightly-packed FEAs have recently been developed by our group in collaboration with the Argonne Center for Nanoscale Materials.

This paper presents the experimental setup develop to investigate the performance of field-emission cathodes. The experiments are performed in a closed-diode setup and will enable the measurement $I-V$ characteristic curves along with the beam transverse distributions. The setup will be employed to systematically investigate the properties of silicon nanocode field-emitter cathode being developed by our group in collaboration with the Argonne Center for Nanoscale Materials.

CATHODE-ANODE SETUP

The cathode-anode was designed and set up at Northern Illinois University and make use of parts borrowed from Vanderbilt University used for studies of early field emission from diamond FEAs [8]. A schematics of the system is illustrated in Fig. 1.

The system employs a diode configuration. A 5-kV high voltage (HV) is applied between the anode and cathode. The cathode is grounded while the anode is maintained at +5 kV. The cathode is epoxied on a stainless-steal support using conductive UHV-compatible epoxy (from Accu-Glass Products, Inc.). Electron emitted from the cathode drive toward the anode. The anode is made of a Cerium-doped Lutetium-yttrium oxyorthosilicate, (LYSO:Ce) scintillator disk of 25-mm diameter and 0.5-mm thick with both sides polished [9]. The screen surface facing the cathode was

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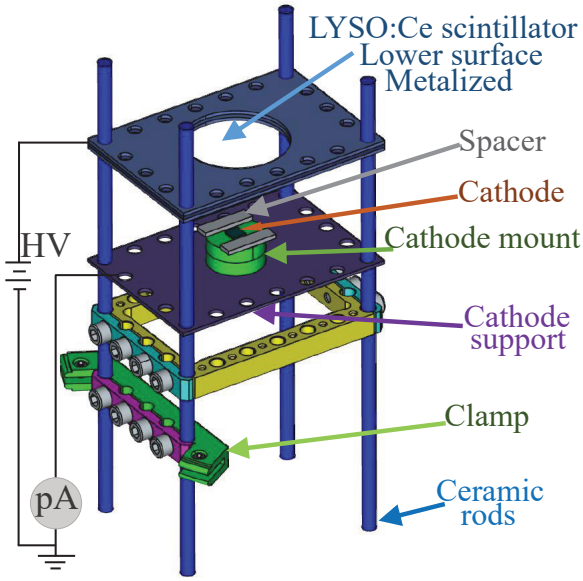

Figure 1: Schematic (exploded view) of the cathode-anode setup with associated electrical setup. The system is housed in s ultra-high-vacuum chamber shown in Fig. 2.

metalized by depositing a ~ 5-nm-thick Nickel layer. This conductive layer ensures the screen surface is at a +5 kV potential and is chosen to be thinner than the penetration depth (about 160 nm) associated to the 5-keV electrons so that they can penetrate the LYSO:Ce bulk and scintillate. In the present version of the setup the anode-cathode gap is fixed by ceramic spacers (hallow miniature borosilicate tubes from VitroCom) placed between the LYSO:Ce screen's inner surface and the cathode surface. The gap is currently ~ 300 μm but can be reduced down to 50 μm. The cathode is housed in a 3-way cross retrofitted with a "groove-grabbers" assembly (from Kimball Physics) to allow for fast swaps between different cathodes. Several of the assemblies shown in Fig. 1 can be prepared. Photographs of the constructed system appear in Fig. 2. The test stand is under ultra-high-vacuum (typically 10^{-9} Tor) maintained with a 20-l.s^{-1} ion pump. The system was baked and can in principle reach lower pressures of ~ 10^{-10} Tor. Given the low volume it takes a few hours to change cathode and pump back the system to 10^{-8} Tor.

In order to measure the characteristic curve associated to different cathode, a pico-ammeter placed between the cathode and ground measures the current flowing across the gap. In addition a CCD camera (model Blackfly 2.3 MP from FLIR) images the LYSO:Ce screen and can record the transverse beam distribution. Both instruments along with the HV power supply are interfaced to a linux-based PC computer and the $I-V$-curve measurement can be automated using the python scripting language.

Performances, such as I-V curves and current stability over days of operation, will be tested for different cathodes (e.g. emitters geometry, material and doping concentration, vacuum level, etc). For some of these tests the LYSO:Ce

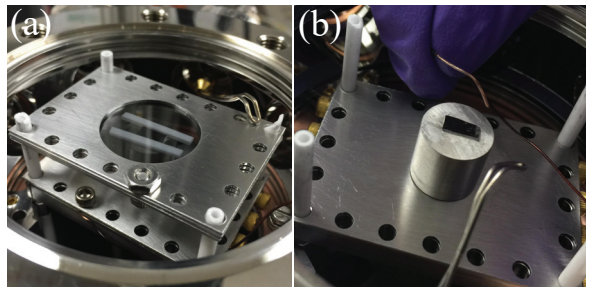

Figure 2: Close-up photograph of the cathode assembly (b) and cathode-anode setup (a) after installation of the LYSO:Ce screen. The vacuum chamber is then sealed using a 4+1/2-CF flange optical port [flange visible in (a)].

screen will most likely have to be replaced by a metallic plate: one of the limitation of the current setup is the close proximity of the LYSO:Ce scintillator to the cathode which leads to the screen degradation of the screen over time (due to heating). A future improvement will consist in replacing the screen with a bored anode and locating the screen further away from the anode to allow for the beam spot to increase further thereby reducing the beam's peak density on the LYSO:Ce scintillator.

NANOCONE CATHODE

The patterned nanoscale structures are made of doped silicon and their fabrication approach involves nanosphere lithography (NSL) and reactive ion etching (RIE) techniques. So far the work, conducted at the Center for Nanoscale Materials in Argonne National Laboratory has focused on optimizing approaches to obtain large area coverage of ordered monolayers of nanospheres which would subsequently act as etch masks for the RIE etching of the underlying silicon to obtain the desired electrode geometries. Towards this end,

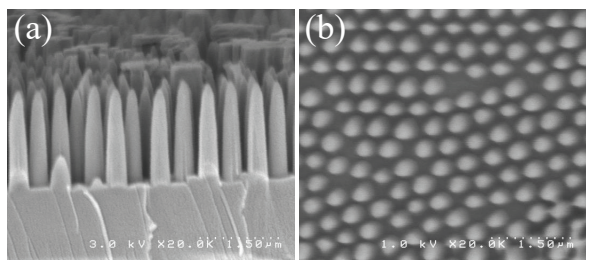

Figure 3: Scanning-electron-microscope micrograph of side view (a) and top view (b) of close-packed nanocones.

the work has focused on optimizing the different recipes of etching so that structures with the desired geometries in terms of the height, aspect ratio, separation distance between the tips and tip radius could be accurately and independently controlled. Optimization of the nanosphere deposition techniques is also currently underway and our preliminary investigation pointed to a new technique of directed assembly of the nanospheres which would significantly improve the surface coverage and repeatability while reducing process-

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ing complexity. Optimization of NSL deposition parameters allowed for a sufficient monolayer coverage to begin testing of the reactive ion etching procedures. Recipes tested and verified include a highly anisotropic Si-selective cryogenic etch based on SF_6/O_2 chemistry, an anisotropic and SiO_2-selective etch base on CHF_3/O_2 chemistry, as well as a semi-selective Cl_2:HBr/O_2 two-stage method that shows promise for nanopillar tapering effects. Upon determining the etch characteristics of each recipe, consideration has been given to the final processing approaches needed in achieving the desired field emission array devices. An example of cathode geometry is shown in Fig. 3, the developed techniques allow for the realization of single tips or ordered (e.g. hexagonally-packed) arrays of tips.

FIRST RESULTS & PLANS

In May 2017, the setup was commissioned and some first beam was detected on LYSO:Ce scintillator; see Fig. 4. The turn on-voltage was approximately 4 kV and several emission sites were observed. These emission sites were mainly

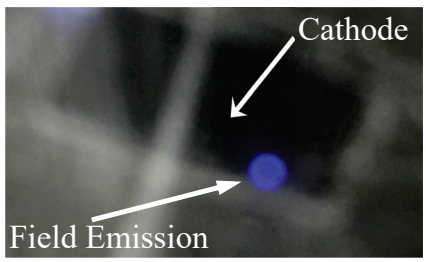

Figure 4: Photograph of the field emitted electron beam detected by LYSO:Ce screen. The black rectangle correspond to the cathode array and blue spot is the field emitted electron beam impinging the transparent LYSO:Ce screen.

located on the edge of the cathode emitting area and are believed to be originating from some sharp features produced when cutting the substrate to fit our setup. Some near-term improvements (including quality control of the cathode-preparation procedure, the use of thinner spacer cathode-anode spacer, and the commissioning of the CCD-based imaging system) will be forthcoming and we expect to start characterizing cathode samples during the summer 2017. In a second phase the chamber will be modified to allow for the injection of an ultra-short laser pulse to investigate optically-assisted pulsed field-emission. In parallel to these investigations a second chamber with long cathode-anode to scintillator-screen separation is being designed and will be dedicated to the measurement of transverse emittances associated to the field-emitted beams.

CONCLUSION

A closed-diode setup was developed and commissioned at Northern Illinois University. The setup will be used to characterize various field-emission cathode currently being fabricated by our group at the Argonne Center for Nanoscale Materials. In addition the simple setup developed will also provide an excellent platform to involve undergraduate students in this experimental program. In the longer term the tested cathodes will be installed in an L-band radiofequency gun available at Fermilab for further testing.

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