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Generation and application of channeling X-rays using a novel, low-emittance electron beam—Status and plans

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ABSTRACT

We plan to use very small emittance electron beams created from our novel, single tip cathodes to make a channeling-radiation X-ray source for X-ray imaging, especially phase contrast imaging. We calculate that we can preserve the electron emittance from the source to the crystal, and focus to a 40 nm spot on the crystal face for 40 MeV electrons. This yields an X-ray source with good coherence properties. We discuss our plan for experiments at Fermilab with 4.5 MeV electrons at the High Brightness Electron Source Laboratory, and with 40 MeV electrons at the Advanced Superconducting Test Accelerator. We also present the state of our art with cathode construction and testing. Electrons come from the cathodes by field-emission, with the electric field enhanced by geometric properties of a very small, robust diamond tip. This can create an electron beam with very small emittance. We estimate that the normalized emittance of such a beam at the cathode is 3 nm rad. We currently test the cathodes in DC, high-voltage test stands. We will begin experiments placing the cathodes in RF guns in early 2013.

1. Introduction

We would like an X-ray device that is more compact than a synchrotron, but still able to have the proper coherence properties for enhanced imaging techniques, like phase contrast imaging [1,2]. Our group has experience with laser back-scattered X-ray sources both on an infrared free-electron laser and on a dedicated Compton back-scattered source [3]. The dedicated Compton source showed some degree of transverse, spatial coherence in the X-ray beam and phase contrast studies were done. This was due to the small X-ray source size coming from the overlap of the focused electron beam and the focused 1 μm wavelength laser.

It has been known for some time that electrons confined to axial or planar channels in a crystal lattice can generate radiation in a narrow spectral line, and with the correct electron energy that radiation is in the X-ray region [4–10]. The electrons are bound in the transverse direction around the sheet of positive ions, and they make transitions between the quantum states defined by that potential. In the electron rest frame, the strength of that positive sheet of charge depends on the Lorentz contraction of the ion charge due to the electron motion; it is stronger when the electrons are more relativistic. For the right energy, 10–50 MeV, the number of transverse quantum states is a few, so the lines coming from electron transitions in those states is a few, and in the X-ray region. For example, for electron channeling between the diamond (110) planes, the 1-to-0 state transition is 161 keV for a 54 MeV electron, while the 4-to-3 state transition is 60 keV [9, page 252].

Using the lessons learned in conventional X-ray imaging and in the Compton back-scattered X-ray source, we are exploring the creation of X-rays generated from electron beams focused to a small spot on the crystal. This requires an electron beam with a very small emittance. We have been studying high brightness electron beams based on field emission from needle structures with a radius of curvature approximately 5 nm. At the source, the electron beam normalized emittance can be of the order 1 nm rad. We have carried out simulations of transport for such a small emittance beam from the cathode, through an RF gun and two accelerating cavities, and find that the emittance is preserved well enough to focus the majority of the electrons to a 40 nm spot with energy of 40 MeV [11].

We are proposing a useful X-ray source using electron channeling in crystals where the electrons are focused to a very small spot size, giving an X-ray source size that is similarly small. This gives the X-ray beam good coherence properties. There will still be an

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incoherent X-ray background, but there are ideas in the literature to filter it [12].

2. Cathodes

Historically, the highest brightness beams have come from RF photoinjectors. These suffer several short-comings, they require a large laser driver, and the cathodes are often short-lived or difficult to maintain. Field-emission cathodes offer a possible alternative that is rugged and eliminates the need for a laser driver.

The process of field emission is the tunneling of the electron through the effective potential defined by the work function potential and the potential imposed by the high electric field on the surface. Nordheim in 1928 calculated the electron currents for a given voltage from field-emission [13], which was later improved by himself and Fowler [14]. In Fig. 1, we show the relationship between current and anode voltage; the anode voltage is related to the surface electric field by the geometry of the needle and the gap between the cathode and the anode. Emitted current is a strong function of the applied electric field at the surface.

We use a single needle emitter for the creation of small emittance electron beams. The needle can source only so much current, and we find we can source about 10 μA for a diamond needle with radius of curvature approximately 5 nm and applied anode voltages of a few thousand volts DC with a gap of 140 μm. The average electric field, supposing there were no needles is then on the order of 15 MV/m. That corresponds to Giga-volt electric fields on the surface of the needle.

In our lab, we have been exploring the fabrication of, and electron field emission from, novel, sharp tips for many years. Our cathode work has progressed from sharpened tungsten needles [15], to our current efforts with sharp diamond tips on pyramid bases [16], either standing alone or with a gate electrode above the needle. We have also tested carbon nanotubes mounted on a tungsten needle tip as a possible high-brightness source. In Fig. 2 you see an example of an ungated cathode, and in Fig. 3 a close-up on the tip of one of the pyramids. We make use of the pyramids to space the small tips, so we can control the separation of the needles. If the needles are too close together there is a certain amount of field shielding—a tip crowded by many neighboring tips may not see the full effect of the geometric enhancement due to its small radius of curvature.

We fabricate the cathodes in the Vanderbilt Institute for Nanoscale Science and Engineering completely from design to final package [17].

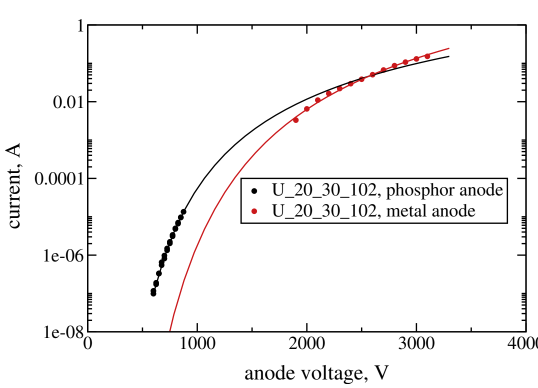

Fig. 1. Current versus voltage for an ungated cathode with corresponding Fowler–Nordheim curves. The red points have been conditioned at high current leading to greater uniformity in the emission and a greater turn-on voltage. Current is the cathode to anode current and the voltage is the cathode to anode voltage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

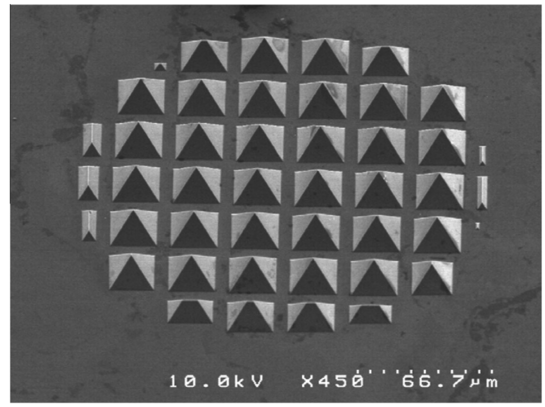

Fig. 2. Small array of ungated pyramids, 30 μm spacing, diamond needles are grown at each pyramid vertex.

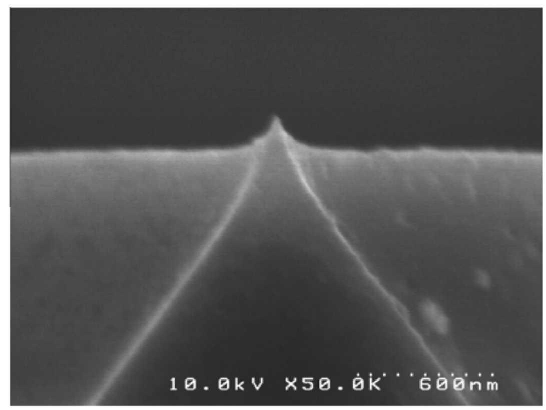

Fig. 3. Close up of the top of a diamond pyramid showing three of the four sides and the tip/vertex.

2.1. Ungated arrays

We produce the ungated arrays by an inverse mold process [18]. We create reverse pyramidal molds in silicon wafers after they have been oxidized, patterned, and etched anisotropically in KOH. We sharpen these molds by thermal oxidation. We pretreat the mold with nanocrystalline diamond by ultrasonification. We use microwave plasma enhanced chemical-vapor deposition to increase the density of these nanocrystalline nucleation sites. Next, we grow nanocrystalline diamond in a nitrogen and methane atmosphere using 700 W of microwave power. We do this to allow the nano-diamond to penetrate the small corners of the mold, to conformally fill the mold, especially the sharpened apex of the inverse pyramid. We maintain the substrate temperature at 700 °C during this process. Then we fill the pyramid with microcrystalline diamond, or other material such as the braze. The mechanical and thermal properties of microcrystalline diamond are superior to nanocrystalline diamond, thus preserving the robustness of the cathode in operation.

We braze the whole onto a polished molybdenum disk with a TiCuSil braze using a vacuum hotplate. The braze temperature and the pressure on the cathode need to be optimized, to mitigate the thermal stresses involved. After the brazing, we remove the silicon mold with a KOH etch, and we remove the sharpening oxide with a buffered oxide etch. We finally clean the cathode with usual techniques. The cathode is ready for testing.

Fig. 2 shows an ungated array with a few pyramids. We have made pyramid arrays with more than 300 by 300 pyramids, and