A Compact X-ray Generator Using a Nanostructured Field Emission Cathode and a Microstructured Transmission Anode

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Abstract. We report the design, fabrication, and preliminary characterization of a compact X-ray generator for improved X-ray absorption imaging that uses a nanostructured field emission cathode (FEC) as the electron source and a microstructured transmission anode as the X-ray generating element. FECs consume less power, respond faster, and tolerate lower vacuum than thermionic cathodes used in conventional X-ray generators. The use of a transmission anode, instead of a conventional reflection anode, allows filtering of the background radiation (bremsstrahlung) while allowing efficient generation of X-rays at lower voltages by exciting atomic shell transitions, resulting in emission of X-rays with narrow spectral linewidth for sharper imaging of biological tissue. The fabricated FEC contains arrays of self-aligned, gated field emitters that turn on at bias voltages under 30 V and transmit 99.5% of the electrons to the anode. The FEC emits a maximum current of 1.2 μA per field emitter (588 μA total array current) at a bias voltage of 85 V. A facility is built and tested to generate X-rays with an FEC and a transmission anode. Using the facility, we obtained an X-ray absorption image of an ex-vivo sample that clearly shows soft tissue and fine bone structures.

1. Introduction

A conventional X-ray generator consists of a thermionic cathode and a reflection anode inside of a vacuum chamber that has an X-ray transmission window. The cathode generates a beam of electrons that is accelerated towards the anode, which is biased at tens of kilovolts above the cathode voltage. Some of the electrons collide with the anode and convert their kinetic energy into radiation, a fraction of which escapes the vacuum chamber through a transmission window made of a suitable material, such as beryllium. The X-ray emission is a mix of bremsstrahlung radiation (broad, continuous spectrum) and fluorescence (emission at specific peaks corresponding to atomic shell transitions). Conventional X-ray technology requires high vacuum to operate, does not efficiently produce X-rays, and has overall low power efficiency [1].

In a thermionic cathode, electrons are “boiled” off the surface of a hot filament (heated to a temperature greater than 1100 K) when the internal energy of the electrons is sufficient to overcome the potential barrier holding the electrons within the material. Thermionic cathodes have a number of issues including low power efficiency due to the filament heating, low brightness, and quick degradation of the filament when exposed to residual gasses. Field emission cathodes (FECs) are an attractive alternative to thermionic cathodes in X-ray systems because FECs consume less power, respond faster, and tolerate lower vacuum than thermionic cathodes [2]. FECs use high surface electric fields (> 3×10^7 V/cm) to decrease and narrow the potential barrier that traps electrons within the emitting material, causing electrons to tunnel to vacuum. FECs use sharp emitters to generate high electric fields on the surface of the emitter tips. To generate high electric fields at low voltage, a gate electrode with an aperture is built in proximity to a nanometer-sharp tip, and a bias voltage is applied between the gate and the emitter so that the gate is positive with respect to the emitter. Arrays of field emitters can be implemented to increase the total emission current, emission uniformity, and reliability of the cathode.

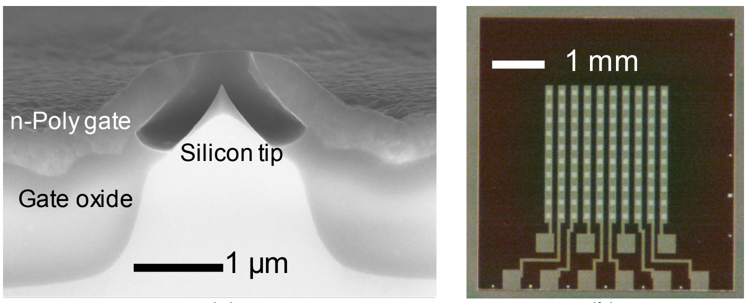
Carbon nanotube (CNT)-based FECs have been recently used in X-ray generators [3-5]. The cathodes are composed of a substrate with a CNT forest and an electrode gate bonded to the substrate. It is relatively simple to fabricate CNT forests; however, the CNTs are tightly packed, the location of the CNTs is random, the height and diameter of the CNTs vary with a wide distribution, and a cluster of CNTs share the same gate aperture, resulting in high operating voltages (> 1000 V) and non-uniform current emission across the CNT forest. Metal tips can also be used in FECs. Cathodes composed of arrays of batch-microfabricated gated metal emitters are possible thanks to the Spindt technology [6], where metal tips are formed by evaporating metal at an angle onto a rotating substrate with pre-fabricated gate apertures. A cone structure can be made because of the shadowing effect of the aperture. Low-voltage operation (< 100 V) is possible because of the small gate-to-tip distance and the small tip diameter; in addition, the Spindt technology produces self-aligned gate apertures so that the electron sources have low emittance. Metal field emitters have lifetime issues as they quickly degrade when exposed to even low partial pressures of oxygen (~5×10^{-7} Torr) [7].

This paper reports efficient generation of X-rays using a batch-microfabricated field emission cathode composed of arrays of self-aligned, gated, and nanometer-sharp n-silicon tips, and a microstructured transmission anode. The nanostructured silicon FEC operates at low voltage and reliably achieves high-current emission with high transmission. The transmission anode efficiently generates X-rays while reducing the background radiation, resulting in emission of X-rays with narrow spectral linewidth for sharp imaging of biological tissue.

2. Device design and fabrication

2.1. Cathode design and fabrication

Figure 1(a) shows a scanning electron microscope (SEM) image of the cross section of a gated field emitter. The emitter consists of an n-silicon tip 2.5 μm tall with a 5 nm tip radius, a 1.5 μm thick gate oxide layer, and a 500 nm thick n-doped polysilicon gate with a 0.6 μm diameter aperture. The separation between the gate aperture and the tip is about 0.5 μm. Figure 1(b) shows an optical microscope image of the whole FEC chip. The chip consists of a 10×10 array of electron guns with square packing and a pitch of 300 μm. Each electron gun contains a 7×7 array of field emitters arranged in square packing with a 10 μm pitch. Each column of 10 electron guns can be independently turned on, such that activation of a column results in the operation of 490 field emitters at once.



(a) (b)

Figure 1. (a) Cross section of a field emitter, (b) picture of a full FEC chip.

Figure 2 illustrates the process flow to fabricate the FEC chip. The process starts with a 6” n-type silicon wafer (100 Ω-cm resistivity) with a film stack consisting of a 100 nm-thick thermal oxide film, a 100 nm-thick silicon-rich silicon nitride film and a 500 nm-thick chemical vapour deposition (CVD) oxide film. The film stack is dry etched to form 2.2 µm diameter discs (Figure 2(a)). Each disc functions as the etch mask for one emitter tip. The silicon is etched using an isotropic dry etch to undercut the discs and form tips with 200-300 nm radii, and a second anisotropic dry etch further etches the exposed silicon to increase the height of the emitters (Figure 2(b)). The wafer is oxidized to sharpen the tips, resulting in 5 nm tip radii (Figure 2(c)). The nitride and oxide films are then striped using diluted hydrofluoric acid (Figure 2(d)), completing the fabrication of the emitter tips. The next step is to add the gate. First, 4 µm of CVD oxide is deposited (Figure 2(e)). This oxide layer is planarized using chemical mechanical polishing (CMP) (Figure 2(f)). A buffered oxide etch (BOE) is used to etch back the oxide layer just until the tips are exposed (Figure 2(g)), and then the emitters are coated with 0.5 µm-thick CVD oxide layer. The different oxide thicknesses over the different areas of the emitters are chosen to achieve both high breakdown voltage as well as low turn-on voltage. Next, a 500 nm-thick n-doped polysilicon film (Figure 2(h)) is deposited, and the substrate is polished using CMP to expose the gate oxide (Figure 2(i)). The polysilicon film is patterned to form the gate arrays, contact pads and to electrically isolate emitters that are not part of the same column. Finally, a BOE dip is performed to etch the oxide immediately surrounding the emitter tips (Figure 2(j)).

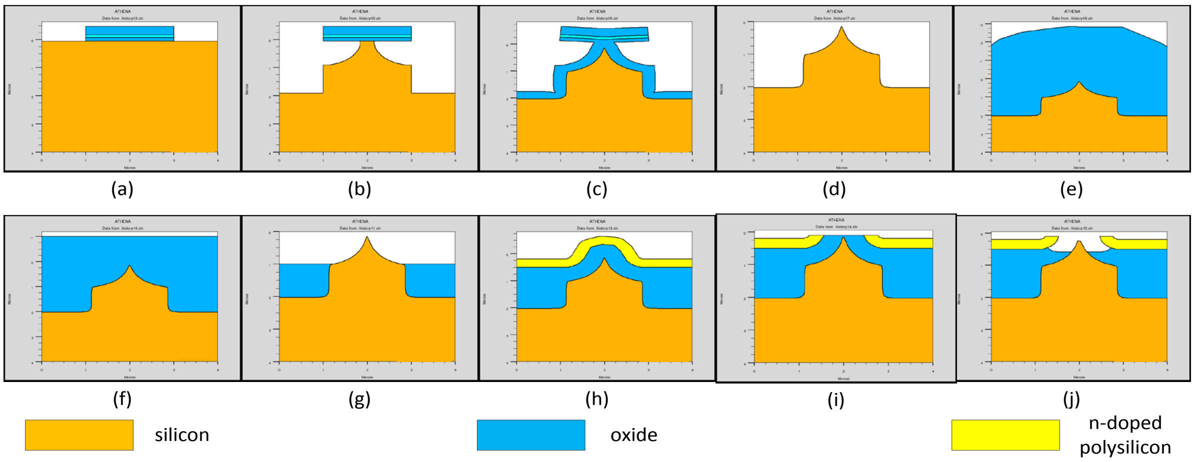


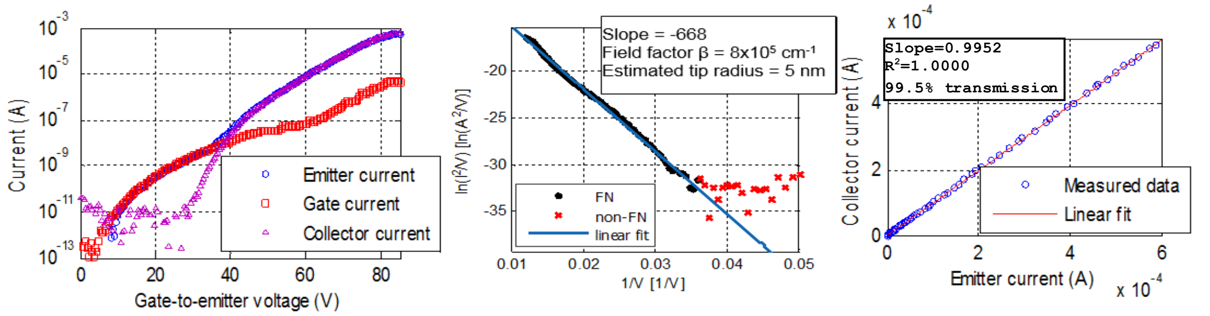
Figure 2. (a)-(j) Silvaco simulation results of the fabrication process flow of the gated field emitters.

2.2. Anode design and fabrication

The anode is a 1” diameter 300 µm-thick beryllium wafer that has a 2.5 µm-thick evaporated gold film on one side. In a transmission anode, electrons impact an X-ray-generating film that is thick enough to absorb most of the electrons, but thin enough to avoid reabsorbing the majority of the X-rays produced (transmission anodes are designed for a particular anode voltage). A transmission anode helps reduce the background radiation and also improves the clarity of the images [1]. If the anode voltage is close to the first ionization potential of the atomic shell transitions of the X-ray generating material, the radiation spectra will be mainly composed of the atomic shell transition peak that is also the high-energy part of the spectra, resulting in emission of X-rays with narrow spectral linewidth for sharper imaging of low-Z materials.

3. Device characterization

Current-voltage (I-V) characterization of the FECs is conducted inside an ultra-high vacuum chamber at a pressure of less than 5×10^{-10} Torr. The field emitters are negatively biased with a Keithley 237 source measurement unit (SMU) by making contact to the backside of the chip. Probes are used to make contact to the polysilicon contact pads that are connected to the gate electrode of each column; the gate electrode is grounded using a picoammeter Keithley 6485 that also measures the gate leakage current. A phosphor screen is mounted 2 cm above the wafer surface, serving as a collector and an electron spot imager. The phosphor screen is positively biased at 1100 V with a second Keithley 237 SMU. During the I-V characterization, the emitter voltage is swept between 0 V and -85 V while measuring the emitter current, the collector current and the gate leakage current. A typical I-V curve (Figure 3(a)) shows that the FEC turns on at ~30 V, and that almost all the current emitted from the tips is transmitted to the collector. Figure 3(b) shows the Fowler-Nordheim (F-N) plot; from its slope, a field factor, β, equal to 8×10^5 cm^{-1}, is estimated. We estimate that the emitter tip radius is 5 nm, which is in agreement with measurements of the tip radii using SEM imaging, verifying that the current is field emitted. The linearity between the emitter and collector currents (Figure 5(c)) further indicates that the currents are field emitted, and the slope of the plot demonstrates that over 99.5% of the electrons are transmitted to the collector.



(a) (b) (c)

Figure 3. Results of field emission tests on a column of field emitters: (a) current-voltage characteristics, (b) Fowler-Nordheim plot, and (c) collector current plotted as a function of the emitted current indicating that the transmission is greater than 99.5%

The compact X-ray source is shown in Figure 4. The system consists of an 8" cubic vacuum chamber that contains the FEC and the transmission anode. The chamber is maintained at a pressure of 2×10^{-8} Torr using a turbomolecular pump and a diaphragm pump. The cathode voltage is applied using a flange with a plurality of SHV-5 feedthroughs for individual addressability of the FEC columns. The cathode holder is mounted onto the same flange, which is connected to a linear positioning stage that is used to adjust the axial position of the cathode. The chamber has a high voltage feedthrough that allows a maximum voltage of 60 kV to be applied to the anode. A beryllium window is located behind the anode holder to achieve a maximum amount of X-ray transmission. Using an FEC and a microstructured transmission anode biased at 30 kV, we have obtained a high-quality X-ray absorption image of an ex-vivo human wrist that clearly shows soft tissue and fine bone structures (Figure 5(a)). This image exhibits superior quality compared to the images from miniaturized FEC reflection anode X-ray sources previously reported [5]. The spectrum of the X-ray emission (measured using an Amptek X-123 X-ray spectrometer) (Figure 5(b)) shows a relatively small level of background radiation and emission peaks that correspond to the first two L-shell transitions of gold.

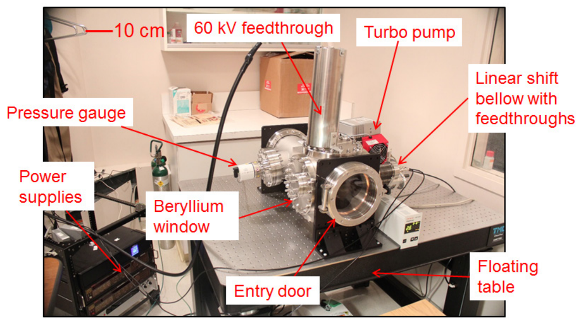
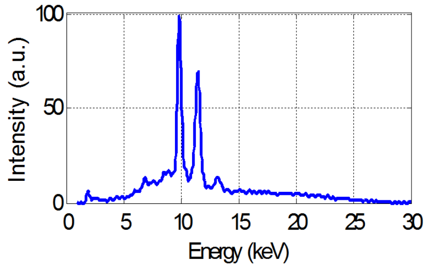


Figure 4. Picture of the x-ray source

(a)



(b)

Figure 5. (a) X-ray image of a human wrist clearly showing soft tissue and fine bone structures. (b) Energy spectrum of the X-ray emission with a small amount of background radiation and emission peaks that correspond to the first two L-shell transitions of gold.

4. Conclusions

A nanostructured silicon-tip field emission cathode capable of low-voltage operation and high current emission with high gate transmission has been demonstrated. A compact X-ray source has been built with the field emission cathode and a microstructured transmission anode. The X-ray source generates radiation that allows clear imaging of low-Z materials, in particular biological samples.

Acknowledgments

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