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High current density electron beam generation from field emission tip cathodes

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Electron beams with current up to 1.2 A and current density over 10^7 A/cm^2 have been generated from a pulsed field emission tip cathode etched from commercial grade tungsten wire. Electron beams with current up to 0.8 A have also been generated from a molybdenum tip. Tip radius was 0.1–1 μm. Applied tip voltage was up to 50 kV with pulse duration of 0.3–1.2 μs. Depending on brightness, these types of electron beams could be suitable for channeling radiation x-ray lasers and might considerably decrease the operating wavelength of free-electron lasers at moderate beam energies.

This work was initiated by the study of channeling radiation x-ray lasers. The idea of channeling radiation x-ray lasers is based on a relativistic electron beam propagating through axial or planar crystal channels and populating transverse bound states.[1] Transitions between these discrete states yield narrow width, strongly forward peaked and tunable x-ray radiation.[2] Besides channeling radiation x-ray lasers, high current density and high brightness electron beams have many other useful applications, including free electron lasers, Cherenkov radiation, parametric x-ray generation, and high brightness x-ray production using Compton scattering.

The channel radiation gain is mainly determined by the properties of the electron beam. It has been shown theoretically[3] that stimulated emission can occur for channeled electrons if the current density $j \approx 10^6$ A/cm^2, total current $I \geqslant 5$ mA, electron energy $W > 5$ MeV, and perpendicular energy $W_\perp < 10$ eV so that electrons remain in a channel. For the x-ray laser application considered, the best electron source is the field emission tip used in the scanning electron microscope (SEM),[4] which typically has high j ($\geqslant 10^6$ A/cm^2) and very small $W_\perp$ (<0.5 eV). The only problem is that the beam currents in typical SEMs are too low (~ 10 nA), for such application. Previous work[5] suggested that high brightness high current density electron beams can be generated from pulsed field emission tip cathodes. In this communication, we report the experiment of a pulsed field emission electron source with a beam current of about 1A.

The system setup is shown in Fig. 1. The vacuum chamber is constructed from standard Del Seal vacuum fittings and can be baked up to 400 °C. The tip cathode is installed into the chamber via a feedthrough. The anode is made of metal screen with the tip-anode distance variable from 1.5 to 5 mm. Both copper and tungsten screens were used during the experiment. Their wire thickness are 50 and 25 μm and transparencies are 45% and 90%, respectively. The purpose is to check the secondary particle emissions of different screens when hit by beam electrons. A current monitor is located about 25 mm behind the screen. The front surface of the monitor is made of conductive glass coated with phosphor. The emission current can be directly measured by the collector. The emission pattern on the phosphor plate can be monitored through the view window II.

Commercial grade tungsten and molybdenum wires were used as tip materials. The tips were fabricated by using the techniques similar to those outlined by Dyke *et al.*[6] A piece of 0.125-mm-diam wire (tungsten or molybdenum) is spot welded onto a V-shaped tungsten filament. The tip is etched by immersing it in a NaOH solution and by applying ac voltage between the tip and a remote electron is the solution. The sharpness of the tip depends on the amplitude of the applied voltage and the concentration of the solution. SEM measurements show that the tip radius can be varied from 0.1 to >1 μm. The filament is mounted on a cathode shank and installed into the chamber. After installation the tip surface is heated before emission. During heating the tip temperature is measured by an optical pyrometer. The purpose of heating the tip is to smooth the tip surface and to achieve a desired tip radius. This procedure is usually done in a vacuum of $<10^{-7}$ Torr.

The working background pressure inside the vacuum chamber was below 3×10^{-9} Torr which is the minimum measurable pressure of our vacuum gauge. The evacuation consists of two steps. First, the chamber is baked at about 200 °C and evacuated to 10^{-6}–10^{-7} Torr by a cryopump. Second, the chamber is isolated from the cryopump by closing a gate valve, and an ion pump is used for final evacuation. No further baking was performed during the second step.

Voltage is applied to the tip cathode from a pulse forming line, consisting of a length of RG-8 coaxial cable and a 4:1 step up transformer. Depending on the cable's length, the pulse duration was variable from 0.3 to 1.2 μs. The voltage was up to 50 kV and it was measured using a Tektronix high voltage probe and monitored by a digital storage oscilloscope.

Emission electron currents up to 1.24 A were achieved using tungsten tip cathodes. According to the tip radius measured by SEM, the current density near the tip surface was over 10^7 A/cm^2. Electron currents up to 0.82 A were generated from the molybdenum tip cathodes. Figure 2 shows the typical voltage-current traces of the field emission. Typical V-I plots for a tungsten tip and a molybdenum tip are shown in Figs. 3 and 4, respectively. The amplitudes of the emission currents were roughly the same when different anode screens were used, given the same tip and the same voltage. The emission pattern measured on the phosphor surface of the

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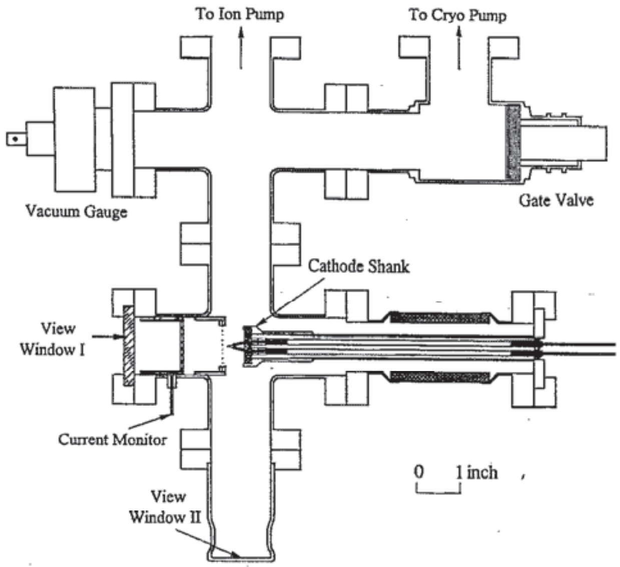

FIG. 1. System setup.

current monitor indicate the emission half-angle is 12°–30° for tungsten tip cathodes and 14°–30° for molybdenum tip cathodes.

Cold field emission was used during the experiment, i.e., the tip was not heated during emission. At high current emission, it was found that "flashing" the tip after each shot could reduce the chance of vacuum arc, sustaining the tip longer and reducing the fluctuation of emission current. Here flashing means heating the tip briefly without applying voltage. It desorbs the layer of contaminants which causes emission irregularities and serves to smooth the tip of pitting caused by ion bombardment during emission.

Figures 3 and 4 show that $\log I$ and $1/V$ has a linear relationship except at high voltage regions where the growth rate of the emission current slows down. According to the

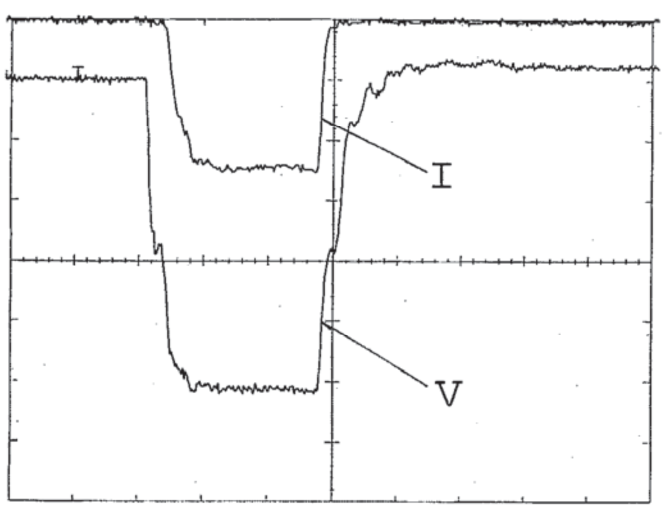

FIG. 2. Typical *V-I* traces for pulsed field emission. Upper trace: emission current (0.27 A/div.), lower trace: tip-anode voltage (8.7 kV/div.); time scale: 500 ns/div.

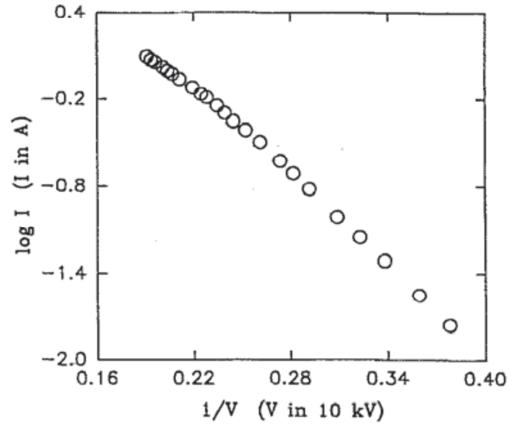

FIG. 3. *V-I* plot for tungsten tip 17.

explanations of Dyke *et al.*,[5] this is mainly due to the effect of space charge. On the tip, the work function for different crystal planes varies. As the tip voltage is increased, the current density at some areas grows high enough that a space-charge effect becomes evident. This retards further current density increases at these areas, while current density continues to increase with increasing voltage at the areas of low emission. At even higher voltage the field emission will initiate a vacuum arc that destroys the tip. Another cause for the slower growth of emission current at high voltage region was that the tip became duller after being run at high emission currents. After a tip was operated at high voltages, the voltage was lowered to the linear region of $\log I$ vs $1/V$ and the emission current was remeasured. However, the decrease of the current was typically less than 15%, indicating that the effect of tip dulling was less significant than the space-charge effect. It is also found that the space-charge effect became insignificant when the emission currents were <100 mA, or current density $<3\times10^6$ A/cm^2.

Usually a tip was damaged by a vacuum arc that was initiated when the applied voltage was raised to such a limit that the emission current density was too high. However, the lifetime of a tip could be quite long should the applied volt-

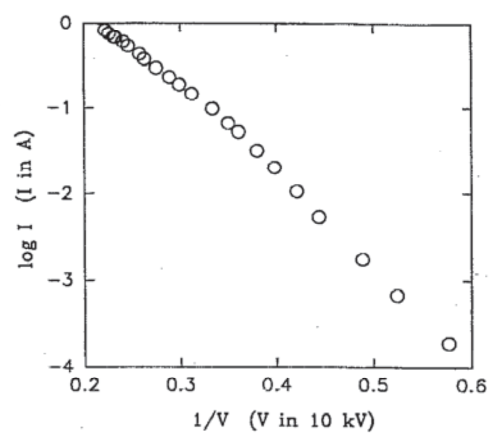

FIG. 4. *V-I* plot for molybdenum tip 7.

age be kept below the maximum. In one test, a tungsten tip emitter survived several hundreds of shots at the same voltage with the fluctuation of emission current from shot to shot of less than 10%. The tip was finally destroyed by raising the voltage less than 5%. It is likely that the tip could have lasted much longer if the voltage were kept 5%–10% below its critical value.

The maximum emission currents in the experiment were mainly limited by the dimension and configuration of the system, electrostatic breakdown between the cathode feedthrough and ground prevented us from applying higher tip-anode voltages. Given our experience, it is likely that higher emission currents can be achieved by doing the following: (1) using a better tip materials, e.g., single crystal wire for which the low work function crystal planes yield high current density at relatively low voltage; (2) using a tip cathode with larger radius, however this would require a higher tip-anode voltage; (3) shorter pulse duration for the tip-anode voltage, this would reduce the resistive heating of the tip during emission that initiates the vacuum arc.[7]

The beam emittance of a field emission electron source $\epsilon = r\theta$, where θ is the half-angle of emission from the tip and r the apparent radius of the source;[4] $r \approx R(V_\perp/V)^{1/2}$, with R the true geometric tip radius, $V_\perp$ the spread in transverse energy of emitted electrons, and V the applied voltage.[8] Typically $V_\perp$ is very small for dc field emission electron sources (0.2–0.5 eV).[4] Whether it increases significantly for pulsed field emission sources operating at high currents (>100 mA) needs to be determined. However, according to the calculation in Ref. 8, the emitted electrons gain $V_\perp$ in a short distance is very close to the emitter surface ($<1\ \mu$m). Since emission current density depends on the field strength at the emitter surface,[5] it is likely that even for pulsed high current emission $V_\perp$ will not increase significantly as long as the current density is not too high. As an example, let us estimate the emittance of tungsten tip 17 ($R \approx 1\ \mu$m) operated at $V = 32$ kV. At this voltage, the emission current $I \approx 100$ mA. Assume $V_\perp = 1$ eV and $\theta = 30°$, we have $\epsilon < 1 \times 10^{-3}\ \pi$ mm mrad. Because the beam emittance of a field emission source is usually extremely small, direct measurement is very difficult and it will be the subject of future research.

The main problems of a field emission electron source are that the performance of the tip is not stable and it gets destroyed easily at high current emission.[9] This experiment shows that they can be solved by : (1) keeping the emission current density from being too high, say $<3 \times 10^6$ A/cm^2, and (2) flashing the tip after each shot, this method can reduce the fluctuation of emission current significantly, even at much higher current density. It has been found that there are several benefits of operating the tip at relatively low current density: (1) the lifetime of the tip is long, (2) the effects of space charge and tip dullness are negligible, and (3) the fluctuation of emission current and beam emittance are small. For a tip of 1 μm radius and operated at 3×10^6 A/cm^2, the total emission current is ~100 mA which is sufficiently large for channeling radiation. An even higher current may be obtained by using a tip of a larger radius applied with a higher voltage.

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