# FIELD EMITTER ARRAYS FOR A FREE ELECTRON LASER APPLICATION

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*Abstract*

The development of a new electron gun with the lowest possible emittance would help reduce the total length and cost of a free electron laser. Recent progress in vacuum microelectronics makes field emitter arrays (FEAs) an attractive technology to explore for high brightness electron sources. Indeed, several thousands of microscopic tips can be deposited on a one millimeter diameter area. Electrons are then extracted by a first grid layer close to the tip apex and focused by a second grid layer one micrometer above the tip apex. In order to be a good candidate for a low emittance gun, field emission cathodes must provide at least the peak current, stability and homogeneity of current state of the art electron sources. Smaller initial divergence should then be achieved by the focusing grid and the intrinsic properties of the field emission process.

## MOTIVATIONS

In a free electron laser undulator, the required normalized transverse electron beam emittance $\varepsilon_n$ must satisfy the following condition:

$$4\pi\varepsilon_n < \lambda\gamma \tag{1}$$

where λ is the radiated wavelength and γ the relativistic factor. Small normalized beam emittance would considerably reduce the required beam energy and thus the cost and size of the accelerator facility. On the other hand a smaller emittance would also reduce the required minimum peak current to efficiently drive a free electron laser. Ultimately the emittance is limited by its initial value at the cathode which can be expressed as follows:

$$\varepsilon_n = \gamma \frac{r_c}{2}\sqrt{\frac{E_{r,kin}}{m_0 c^2}} \tag{2}$$

where $r_c$ is the cathode radius and $E_{r,kin}$ the mean transverse kinetic energy just after emission. To lower the emittance one can reduce the size of the electron source ($r_c$) and/or the mean transverse energy of emitted electrons (roughly the initial divergence).

## FIELD EMISSION CATHODES

Current accelerator guns use photocathodes or thermionic cathodes [1]. In both cases, the mean transverse energy of the extracted electrons is several hundred meV either due to the difference between photon energy and cathode work function or due to the cathode temperature. This already limits the minimum achievable initial transverse kinetic energy of the produced electron beam. In addition, the diameter of these cathodes is usually larger than a few millimeters. One alternative process is field emission where electrons are emitted with energies around the Fermi level and the mean transverse energy is mainly determined by the geometry of the electric field lines [2]. The achievable current density by field emission is also much higher than with other type of cathodes so that the emitting area could be smaller. Field emission cathodes are usually made with tips, either single tip or array of tips with an integrated gate layer (ie. field emitter arrays FEAs). These FEAs consist of thousands of conductive tips in the micrometer size range separated from a conductive gate layer by a one micrometer thick dielectric layer (see Fig. 3 and 4). By applying a voltage between the tips and the gate layer ($V_{ge}$) electrons are emitted from the tip's apexes. In order to shape electron trajectories, FEAs can integrate two grid layers. The first grid is used for extracting the electrons while the second grid provides focusing of the electrons.

### *Field Emitters Characteristics*

To be a good candidate for free electron laser application, field emitters must achieve higher peak currents than in usual applications like flat panel displays or scanning electron microscopes. In addition we must be able to focus the field emitted beam thanks to a focusing layer deposited a few micrometers above the tips. Finally the emission must have a good uniformity and stability in time.

In a first approach we focused our work on the maximum achievable emitted current. Typically a

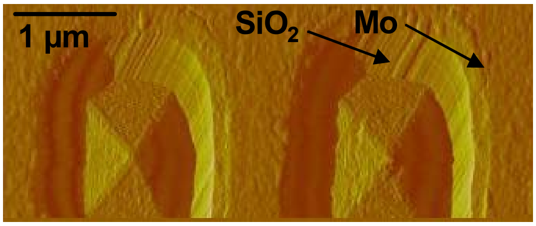


Figure 1: Top view (Atomic force microscope) of two pyramidal diamond tips (height 1 µm) from XDI Inc. Tips are separated by $SiO_2$ dielectric material (1 µm thick). $SiO_2$ is covered by a conductive Mo layer: the gate layer

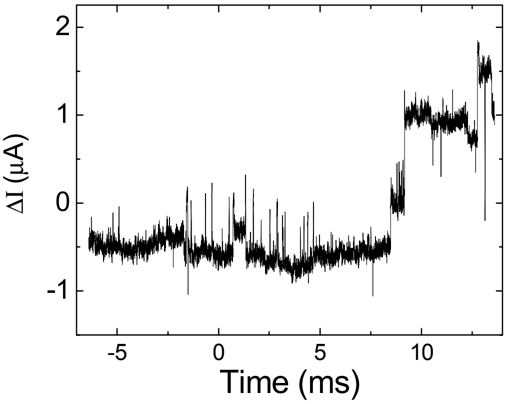


Figure 2: Fluctuations of the field emitted current versus time due to thermally induced surface changes. The DC component (200 μA) of the field emitted current has been removed.

standard gated molybdenum tip is capable of emitting a few microamperes in DC operation [3]. Above this level, the risk of overheating the tip and generate a destructive arc increases. One way to obtain higher current is to use a matrix with thousands of tips (FEAs).

For these preliminary tests, we used cathodes available on the market. The SEM pictures in Fig. 3 and 4 represent diamond tips from the company XDI Inc [4] and molybdenum tips from SRI Inc [5] respectively. XDI's cathode has around 3,000 tips distributed on a 170 μm diameter disc area. These diamond tips have a pyramidal shape due to the molding technique used for their elaboration (Fig. 1). The tip material is a mixing of diamond and graphite which is electrically conductive. Tips are surrounded by a dielectric material ($SiO_2$) which isolated them from the molybdenum gate layer. The typical height and base size of each tip as well as the gate aperture diameter is about one micrometer.

The FEAs from SRI support around 50,000 molybdenum tips on a 1 mm diameter disc area. The dimensions of these conical tips are close to XDI's pyramidal tips but the growing method is different. SRI Inc. has developed the so called Spindt method [3] to grow molybdenum tips in a gated structure with nanometer tolerances. In order to test the emission of these gated structures we used a triode configuration. Field emitted current is measured on a collector positively biased in respect to the gate and tip voltages. If too much electrons are directly collected on the gate, the risk of overheating the gate is too high.

In addition to gated structure, we also investigated the emission from single tips in Zr covered by a ZrC layer from the company APTech Inc. [6]. These tips are inserted in a Vogel mounting without any extracting gate layer (Fig. 6). We tested these single tips in a simple diode configuration.

## *Field Emission Current Instabilities*

As already mentioned, the limiting factor for high current emission in DC operation is the excessive heating of the tip and the surrounding materials (gate, anode, etc.). This leads to a series of thermally induced surface changes like desorption of contaminants or surface migration. When ionized, these desorbed contaminants can also back bombard the tips. Eventually, local pressure rise can initiate destructive arcs.

These well known environmental problems are also responsible for current emission fluctuations by changing either the surface work function or the tip geometry [5]. Fig. 2 represents such typical current fluctuations observed on the emission of one XDI field emitter array. Only the variations of the current are represented, the DC component (~ 200 μA) of the signal has been removed. The amplitude of these fluctuations corresponds to a few

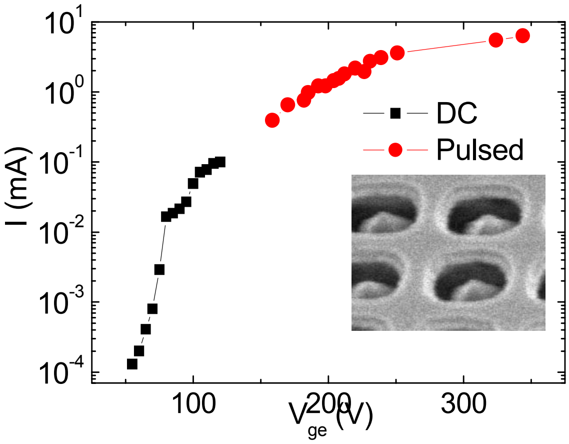


Figure 3: Current voltage characteristic in DC and pulsed regime for a FEA from the company XDI Inc (~3,000 diamond tips, ø = 170 μm). Insert: SEM picture of diamond tips.

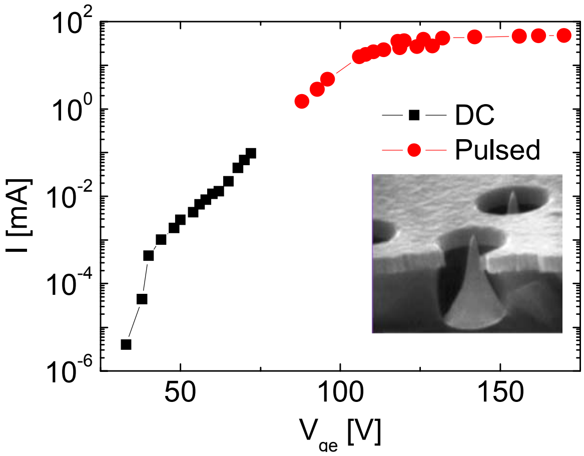


Figure 4: Current voltage characteristic in DC and pulsed regime for a FEA from the company SRI Inc (50,000 Mo Tips, ø = 1000 μm). Insert: SEM picture of conical Mo tips from SRI website [5].

percents of the total emitted current. The “steplike” behaviour of the fluctuations corresponds to instantaneous changes in the surface state due to successive adsorption, desorption and migration processes [8].

Because of the strong dependence of field emitted current on the geometry of the tip (field enhancement factor β) and his surface composition (work function Φ), even small surface changes lead to strong variations in the current intensity. This can be illustrated by Fowler-Nordheim’s equation which describes the dependence of the field emitted current density on these parameters:

$$J = \frac{A}{\Phi}.(\beta.V)^2.\exp\left(\frac{-B.\Phi^{3/2}}{\beta.V}\right)$$

where A, B are constant values, V represents the applied voltage between electrodes, Φ is the work function in eV and β is the enhancement factor of the electric field due to geometrical effect.

One way to increase the total emitted current without overheating is to use a large number of tips. However the strong dependence of the field emitted current on tip geometry and surface composition makes the uniformity between tips very important. After fabrication, it is usual to observe that only a few percent of the total number of tips contributes significantly to the total emission [9]. Field emission will occur preferably from the sharpest tips. Variation of the geometry of the tip apexes at a nanometric scale can lead to non uniformity of emission between tips. Fig. 1 represents atomic force microscope measurements of two neighbouring tips from an XDI array. The nanometric roughness of the tip surface can be seen on Fig. 1. These nanoprotrusions contribute to the overall field enhancement factor and can introduce non uniformity that are not easily controlled during fabrication. Several conditioning processes have been developed in order to improve the uniformity of the emission and promising results have been achieved by scientist from SRI Inc. [7]. In fact, they found that self-heating of tips by drawing large current during short pulses, tends to smoothen and clean tips without destruction. The uniformity of electron emission could be improved by this method. This is in favour of a free electron laser application which does not require DC but only pulsed emission.

## *Pulse Mode of Operation*

By operating the FEA with short voltage pulses at low frequency it is possible to considerably reduce the heat brought to the tips and therefore to eliminate most of the thermally induced problems. Consequently the emitted current can be increased with less risk of deterioration.

Fig. 3 represents the emitted current versus the applied tip to gate voltage for an array of about 3,000 diamond tips distributed on a 200 micrometers diameter disc area. The maximum current measured in continuous mode was about 800 μA but emission was subject to fluctuations and monotonic decay with time was observed as in [7]. However in the 50 Hz pulsed regime, with 100 ns voltage pulses it was possible to reach up to 6 mA peak current. In this mode of operation, emission was very stable and no decrease of the emitted current was observed after one day of operation. The maximum current performance was limited by the internal resistance of the field emitter array (~ 25 kΩ). This internal resistance originates from the silicon wafer on which tips are deposited. In DC applications it is preferable to have a highly resistive silicon wafer in order to protect tips from brutal current rises. In a pulsed mode, a smaller resistivity could be tolerated. This internal resistance also limits the minimum pulse length that can be applied between gate and tips by introducing a large charging time constant. Fig. 4 represents a similar current voltage characteristic but for a

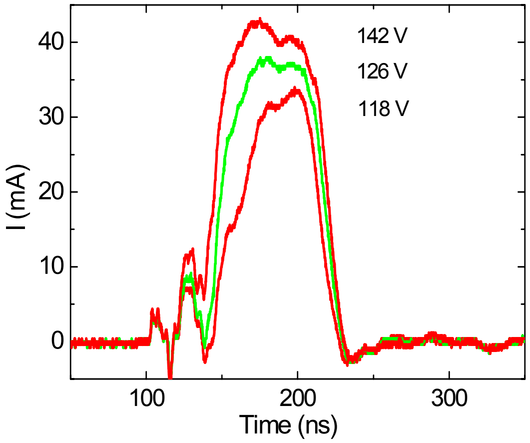


Figure 5: Current pulses emitted by a FEA with 50,000 Mo tips from the company SRI Inc. when applying square voltage pulses with amplitude of 118, 126 and 142V.

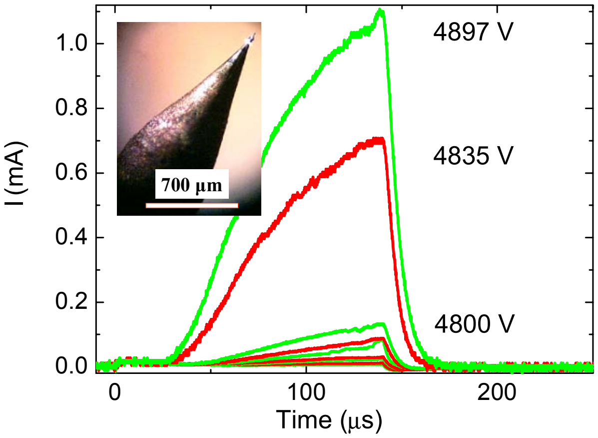


Figure 6: Current pulses emitted by a single ZrC tip from the company APTech Inc. for different square voltage amplitudes of 100 microseconds.

standard FEA from the company SRI Inc. This FEA consists of 50,000 Mo tips grown by the so called Spindt method [3] on a one millimeter diameter disc area. Again, the sensitivity to environmental conditions was much less important in the pulsed regime than in DC. The maximum current performance was limited by the silicon wafer resistance to values around 50 mA. Fig. 5 shows typical 100 ns current pulses collected from a 50,000 Mo tips FEA.

We have also tested the maximum peak current that can be emitted by a single tip in zirconium carbide (ZrC) (see Fig. 6). Since this tip does not have any gate layer a copper anode has been placed five millimeter away from the tip and large voltage pulses (kilovolts) were applied. To protect the tip from too high current values, a 10 kΩ resistor was placed in series with the tip. The effect of the resistor is the slow charging ramp on the current pulses seen in Fig. 6. More than 3 mA peak current have been measured out of such a single tip. Only the apex of the ZrC tip emits and the tip apex radius is less than one micrometer (specifications give values between 20 and 100 nm). If we assumed an emission area of one square micrometer, the corresponding current densities is as high as $10^5$ A/cm$^2$.

## CONCLUSION

Preliminary tests on commercial field emitter samples showed that higher peak current and more stable emission can be achieved when using short square voltage pulses at low frequency. For a free electron laser application such peak current values are still too small [10], but with the help of even shorter pulses and smaller internal FEA resistance we hope to reach the required current.

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