HIGH ASPECT RATIO SILICON FIELD EMITTER ARRAYS (FEAS) AS MINIATURIZED STABLE ELECTRON SOURCE FOR CATHETER-BASED RADIOTHERAPY

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ABSTRACT

This paper presents a miniaturized electron source based on high aspect ratio silicon (Si) field emitter arrays (FEAs) intended for generating x-rays in a catheter-based radiotherapy application. The fabricated Si FEAs demonstrate stable emission currents of approximately 10 μA at an acceleration voltage of 21.7 kV for more than 15 minutes under moderate vacuum requirements. The current stability was enhanced by the introduction of a field compensation frame design for the electric field distribution and a tip conditioning procedure of the Si FEAs. The experimental results are in line with the requirement of delivering relevant doses for cancer radiotherapy.

INTRODUCTION

To realize the vision of catheter-based radiotherapy to achieve minimally invasive treatment of cancers/tumors inside the human body (electronic brachytherapy), a miniaturized high-energy electron source is required for generating x-rays with effective radiation doses. Field emission electron sources have been proposed for this application made of various materials, such as metals [1-2], silicon [1], diamond [1, 3], and carbon nanotubes (CNTs) [4-5]. Compared to the other suggested materials, Si field emitter arrays (FEAs) are easier to manufacture due to the precise geometric control offered by Si microfabrication technology. Furthermore, the monolithic Si-based fabrication process allows various wafer-level vacuum packaging technologies to achieve vacuum encapsulation of the fabricated Si FEAs. These merits enable significant device miniaturization of Si-based electron sources for catheter-based radiotherapy applications.

In order to generate a therapeutically sufficient dose, high acceleration voltages of tens of kV and emission currents on the order of μA over a duration of around 10 minutes are necessary [1]. Previously reported Si FEAs typically work in near ultra-high vacuum environments (~$1x10^{-9}$ - ~$1x10^{-7}$ mbar) and exhibit permanent degradation under pressures above $1x10^{-5}$ mbar [6]. However, Si has also been reported to yield unstable currents even under very high vacuum environments (better than $1x10^{-6}$ mbar), and thus deemed unsuited for radiotherapeutic applications [1]. Nevertheless, lowering the vacuum requirements for the operation of the FEAs is desirable since it is difficult to maintain high vacuum in small sealed MEMS devices (high surface/volume ratio). Addressing these challenges could pave the way for brachytherapeutic applications of Si FEAs. In this paper, we demonstrate that carefully designed and fabricated high aspect ratio Si FEAs could be used as sufficiently stable electron sources for brachytherapeutic applications with lower requirements on vacuum.

DESIGN AND FABRICATION

Two different chip designs of Si FEAs are proposed and illustrated in Figure 1. The first design only consists of Si emitters protruding out from the substrate surface, whereas the other design contains an enclosing frame around the emitter array area. In both designs, the overall emission area of the 10x10 Si FEA is designed to be 400 x 400 μm^2. All the Si emitters are designed to be 50 μm high and have the same high aspect ratio of approximately 15:1. The interval spacing of the emitters is 40 μm.

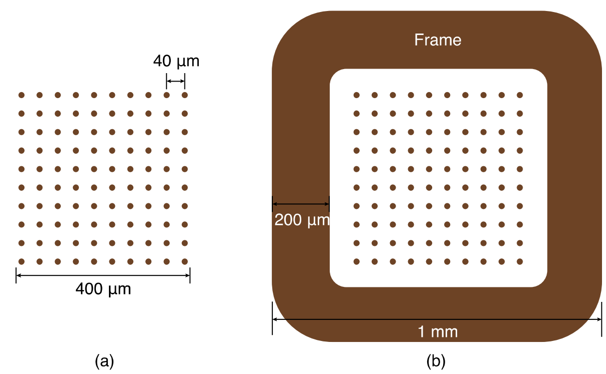

Figure 1: Top view of the two different chip designs of the Si FEA. (a) Si FEA without an enclosing frame. (b) Si FEA with an enclosing frame.

The reason of incorporating a frame around the Si FEA is to investigate its compensation effects on the non-uniform distribution of the induced local electric fields at the tips of the emitters. According to the electric field simulation (*Comsol Multiphysics*) results (assuming a tip radius of 10 nm) shown in Figure 2 and Table 1, the presence of an enclosing frame has a significant influence on the peak field uniformity among the Si emitters. When there is a frame around Si FEA, the relative increase in the peak field of the outmost emitter (i.e. emitter E compared to emitter A) is reduced from 31.7% to 19.6%, and most importantly, the field deviation among the inner emitters (emitter A, B, C, and D) is within 3.5%, which is less than half of the corresponding value of the design without a frame. This indicates that incorporating a frame around the Si emitters will improve the uniformity of the electric field distribution among the tips of all the emitters, especially for the ones inside the outmost emitters.

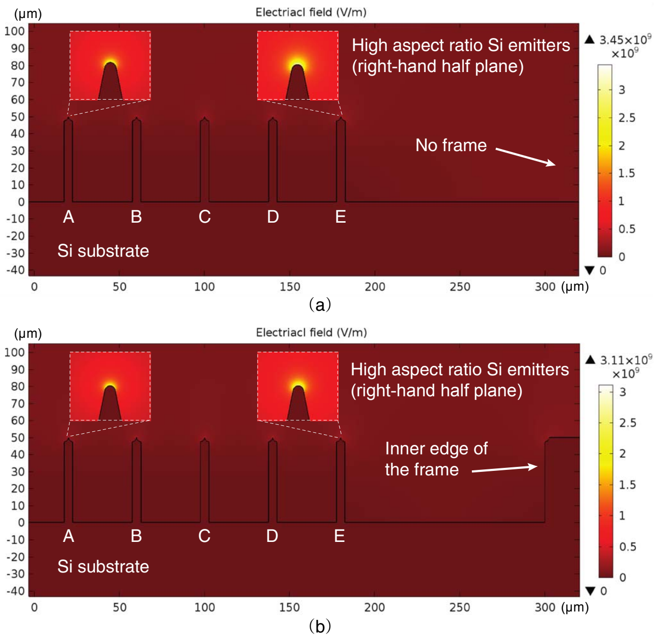

Figure 2: 2D electric field simulation (Comsol) of the right-hand half of the Si field emitters for the two different FEA chip designs. (a) Si FEA without an enclosing frame. (b) Si FEA with an enclosing frame. Emitter A and E represent the center and outmost field emitter in the array, respectively.

Table 1: Simulated peak electric fields of the marked Si field emitters in the two different FEA chip designs shown in Figure 2.

Emitter	Design without a frame		Design with a frame	
	Peak electric field (GV/m)	Relative increase (%)	Peak electric field (GV/m)	Relative increase (%)
A	2.62	0	2.60	0
B	2.64	0.8	2.60	0.0
C	2.69	2.7	2.62	0.8
D	2.83	8.0	2.69	3.5
E	3.45	31.7	3.11	19.6

The fabrication process of the designed high aspect ratio Si emitters is illustrated in Figure 3. A single side polished 500 μm-thick Si wafer with 1 μm-thick thermal oxide was prepared. The oxide mask for the Si emitters was firstly patterned by photoresist and oxide reactive ion etching (RIE). Then, an isotropic Si RIE etching was performed to define the top cone shape of the emitter, which was followed by a Si DRIE to a depth of 50 μm to yield the designed high aspect ratio of the emitters. Thereafter, the wafer was thermally oxidized to form sharp tips on the Si emitters [7]. The oxide mask was finally removed in a 50% HF wet etching step.

The fabricated Si FEAs are displayed in Figure 4. The tip radii of the 50 μm-high emitters were measured to be between 10 nm and 20 nm. The diameters of the fabricated Si emitters were measured to be around 3.2 μm, which corresponds well to the designed aspect ratio of 15:1.

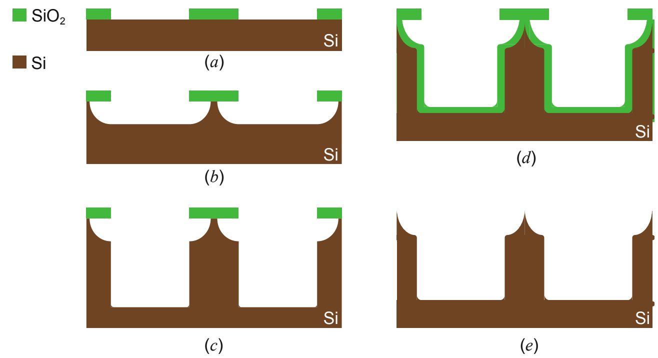

Figure 3: Fabrication sequence of the high aspect ratio Si field emitters. (a) Oxide mask patterning by lithography and RIE etching of SiO_2. (b) Isotropic RIE etching of Si. (c) Anisotropic DRIE of Si. (d) Tip sharpening by thermal oxidation. (e) Oxide removal by 50% HF wet etching.

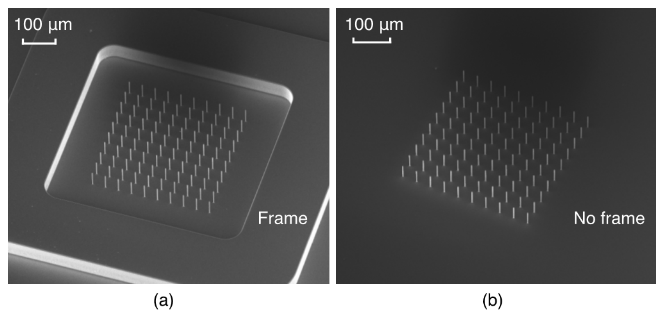

Figure 4: SEM images of the fabricated high aspect ratio Si FEAs from two different chip designs. (a) Si FEA with a frame. (b) Si FEA without a frame.

EXPERIMENTS AND DISCUSSION

The experimental setup is schematically illustrated in Figure 5. The fabricated wafer containing two different designs of Si FEAs was firstly diced into small chips (2 mm x 2 mm) for individual tests. During the experiments, the chips are conductively glued to the cathode electrode and fixed onto a movable stage. The distance between the tungsten anode and the Si FEA cathode was adjusted by a micrometer screw.

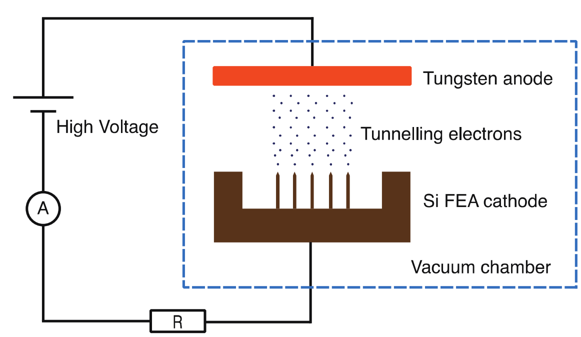

Figure 5: Schematic drawing of the experimental setup.

Tip Conditioning

Ball-shaped emitter tips have been reported to induce larger emission areas than sharp tips [8], which could result in a lower current density at the emission site of each field emitter. This serves our application since degradation due to current induced tip heating could be alleviated in this way.

To produce ball-shaped tips from our fabricated sharp tips, all Si FEAs were firstly conditioned at an inter-electrode distance of 250 μm at a vacuum level of $2.5\text{x}10^{-5}$ mbar. The applied voltage was stepwise ramped up to produce an emission current of approximately 0.2 μA per emitter, which induced a gradual melting of the emitter tips and consequently formed ball-shaped tips. The resulting ball-shaped tips and the corresponding electric field simulation are shown in Figure 6. As indicated in the SEM images, the sharp Si emitter tip with a radius of around 10 nm turned into a ball-shaped tip with a radius of 110 nm after tip conditioning. The simulation shows that ball-shaped tips induce larger emission areas (field > 1 GV/m) and also smaller peak fields under the same experimental conditions, which means that a lower current density at the emission site of each emitter can be expected.

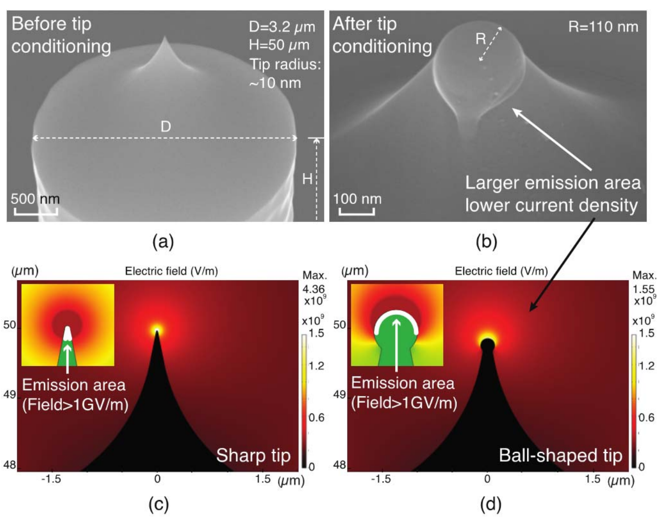

Figure 6: SEM images of a Si field emitter before and after tip conditioning and the corresponding electric field emission simulation (Comsol) under the same experimental conditions. (a) and (c): Sharp Si field emitter before conditioning. (b) and (d): Si field emitter with ball-shaped tip after conditioning.

A typical voltage-current relationship of the fabricated Si FEAs (10x10 array, with frame) after tip conditioning is shown in Figure 7. According to the Fowler-Nordheim (F-N) field emission theory [9], the relationship between the applied electric field and the emission current can be described by the following formula:

$$I = \alpha_{tip} A E_{local}^2 \exp\left(-B/E_{local}\right),$$

$$A = q^3 / \left(8\pi h \Phi\right),$$

$$B = \left(8\pi\sqrt{2m_e\Phi^3}\right) / \left(3qh\right),$$

$$E_{local} = \beta E_{applied} = \beta U_{applied} / d,$$

where α_{tip} is the emission area of the Si emitter, E_{local} is the local electric field at the emission site, q is the electronic charge of the electron, h is the Plank's constant, Φ is the work function of Si, m_e is the electron's effective mass, $U_{applied}$ is the applied voltage and d is the inter-electrode distance. β is the local field enhancement factor, which reflects the amplification effects on the applied electric field at the emission site. Transforming the above formula, a linear relationship between $\ln(I/U^2)$ and $1/U$ can be deduced as:

$$\ln\left(I/U^2\right) = \left(-Bd/\beta\right)\left(1/U\right) + \ln\left(\alpha_{tip} A \beta^2 / d^2\right).$$

The corresponding F-N characteristic plot of the *I-U* data in Figure 7 is shown in the inner diagram. It can be seen that the F-N plot shows good linearity, indicating that the *I-U* data is in line with the F-N model. From the linear F-N plot, a high field enhancement factor of 733 is extracted, although with less sharp ball-shaped tips.

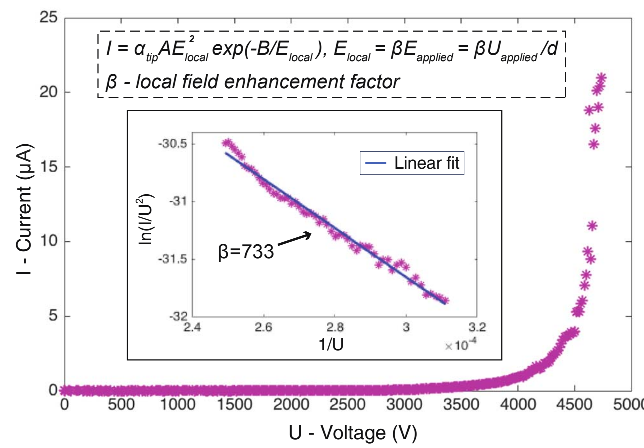

Figure 7: I-V plot and the corresponding Fowler-Nordheim characteristic plot of a typical fabricated Si FEA (10x10 array, with frame) at an inter-electrode distance of 250 μm after tip conditioning procedure.

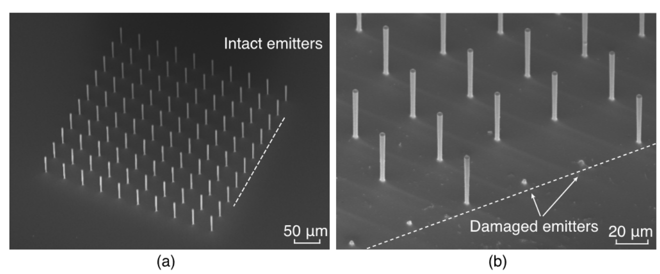

Figure 8: SEM images of a Si FEA (without a frame) before (a) and after tip conditioning (b). The white dashed lines indicate the same position.

As discussed in the previous section, the presence of a frame around the Si emitters will to some extent compensate for the non-uniform distribution of the induced electric fields at the tips of the emitters. An example of the result of this compensation effect is shown in Figure 8. After tip conditioning, the Si field emitters of the FEA design with a frame remained intact (not displayed), whereas the design without a frame showed damaged emitters among the outmost emitters in the array, as displayed in Figure 8b.

Field Emission Stability Test Under High Voltages

After tip conditioning procedure, the Si FEAs were operated under higher voltages and larger inter-electrode gaps for stability test at the same vacuum level of 2.5×10^{-5} mbar. The test result of a Si FEA having a frame is plotted in Figure 9. The test was conducted at an acceleration voltage of 21.7 kV and at an inter-electrode distance of 4 mm. As shown in Figure 9, the emission current stayed at around 10 μA with good stability for more than 15 minutes, which is in the relevant range for application in brachytherapy. The vacuum level here is also below the reported required range for Si field emitters, which may enable more options to achieve miniaturized vacuum encapsulation of the fabricated electron source.

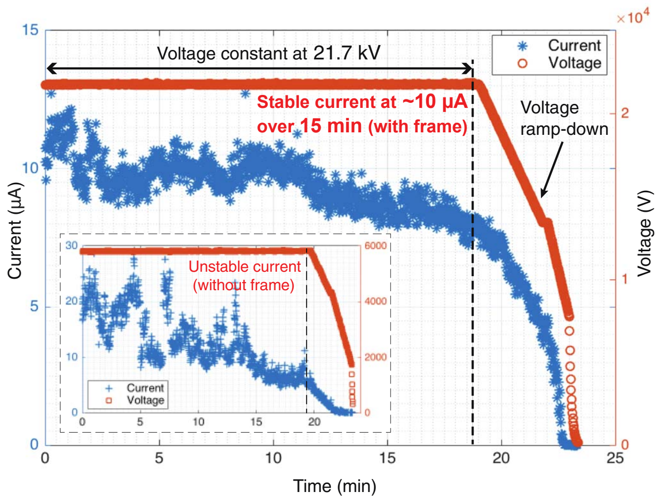

Figure 9: Field emission stability test of a Si FEA (with frame) after tip conditioning at a high voltage of 21.7 kV, at a 4 mm inter-electrode distance and a vacuum level of 2.5×10^{-5} mbar. Dashed-lined inner diagram: stability test of a Si FEA without a frame for comparison (250 μm inter-electrode gap, 2.5×10^{-5} mbar).

For comparison, another test was done using a Si FEA without a frame. The corresponding result is displayed in the smaller dashed-lined inner diagram in Figure 9. It is clear that the emission current exhibits significant fluctuations even for a lower acceleration voltage. These fluctuations could be due to the damaged Si emitters, which relates to the non-uniform distribution of the electric field when there is no frame around the Si emitters. It should be noted that the emission currents can be tuned by varying the inter-electrode distance at a fixed acceleration voltage, which means that the corresponding radiation dose can also be modified.

CONCLUSION

A miniaturized electron source based on high aspect ratio Si field emitter arrays (FEAs) for application in catheter-based radiotherapy has been proposed, fabricated and evaluated. The fabricated Si FEAs exhibit good current emission stability for over 15 minutes at 10 μA under a high acceleration voltage of 21.7 kV and a moderate vacuum level of 2.5×10^{-5} mbar. These values are in the relevant range for generating effective x-ray doses in brachytherapy and within reach of miniaturized vacuum encapsulation technology.

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