Electron beam collimation from an all-metal double-gate 40 000 nanotip array: Improved emission current and beam uniformity upon neon gas conditioning

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In this study, the authors characterized field emission from stacked-double-gate all-metal field emitter arrays (FEAs) consisting of 40 000 nanotips. After careful conditioning of the FEAs under ultrahigh vacuum and in low-pressure neon gas ambient, the authors were able to produce a highly collimated beam with a current of $\sim 50 \mu\text{A}$ which showed an improved beam homogeneity. The beam rms radius reduced by a factor 10 and the transverse energy spread was reduced to well below 1 eV. © 2015 American Vacuum Society. [<http://dx.doi.org/10.1116/1.4916091>]

I. INTRODUCTION

Double-gate all-metal field emitter arrays (FEAs) have been studied extensively as cathodes for applications that require high current and high brightness such as compact free electron lasers (FELs)^{1,2} and THz vacuum electronic devices.^{3–6} Some studies^{7–9} proposed to use submicron-pitch stacked double-gate FEAs^{10–12} excited by near infrared laser pulses at the surface plasmon polariton resonance frequency of the gate electrode. They used detailed modeling of the laser-induced field emission and the beam collimation characteristics of the double-gate structure with large collimation gate apertures to predict that such FEAs have order of magnitude higher beam brightness than a state-of-the-art photocathode that are normally used in the x-ray FEL applications. As recent experiment demonstrated,¹¹ compared to single-gate FEAs, double-gate FEAs can reduce the transverse velocity spread by nearly an order of magnitude. This suggests that these FEAs are highly promising as ultrabright field emission cathodes. However, the emission current of the maximally collimated beam was limited to a few μA .¹¹ In this work, therefore, we explore the beam collimation characteristics of double-gate FEAs at a higher emission current than our previously reported experiments¹¹ by a combination of pulsed switching and neon-gas conditioning.¹⁰

II. EXPERIMENTAL METHODS

A. FEA fabrication

The molybdenum nanotip emitters with a tip apex radius of curvature (R_{tip}) of 5–10 nm and base size of $1.5 \mu\text{m}$ -square were fabricated by a double-oxidation molding process using 4-in. Si (100) wafers as the mold substrates. Details of the molding process are described elsewhere.^{12,13} After removing the mold substrate by etching, an array of nanotips supported on an electroplated nickel substrate was obtained. On

top of the array, the electron extraction gate G_{ext} was fabricated by a self-aligned polymer etch-back process. The collimation gate G_{col} was fabricated on top of G_{ext} by using electron beam lithography. In this way, we achieved stable fabrication of double-gate devices with G_{col} aperture diameters of $\sim 6 \mu\text{m}$ and G_{ext} aperture diameters of $\sim 2 \mu\text{m}$. The gate electrodes were 500-nm-thick molybdenum. The G_{ext} and the emitter layer were separated by a $1.2\text{-}\mu\text{m}$ -thick SiO_2 layer. The G_{col} and G_{ext} layers were separated by a $1.2\text{-}\mu\text{m}$ -thick low-stress SiON layer. In Fig. 1, we show the optical micrograph [Fig. 1(a)] and the SEM image [Fig. 1(b)] of a double-gate FEA with $10 \mu\text{m}$ -pitch and 40 000 tips. The emitters were arranged within a circle of diameter 2.26 mm. Figure 1(c) shows a magnified SEM image of a single double-gate nanotip device. A magnified image of the tip can be seen in the inset.

B. Field emission experiment

Field emission experiments were conducted using a field emission microscope chamber consisting of a 35 mm-diameter P43 phosphor screen and a retractable Faraday cup. To generate a collimated electron beam, an electron extraction potential V_{ge} in the range of 0–100 V was applied between G_{ext} and the emitters, and a beam collimation potential V_{col} in the range of 0 to –100 V was applied between G_{col} and G_{ext} . Both potentials were applied in DC or single-shot pulsed mode. In DC measurements, we connected G_{ext} to ground and applied $-V_{\text{ge}}$ to the emitter and applied V_{col} to G_{col} using two remotely controlled source measure units (SMU, Keithley 2400). We measured the emission current I using the Faraday cup connected to a third SMU (Keithley 2410). The typical DC Faraday cup potential was in the range of 0.5–1 kV. The Faraday cup intercepted the emitted electron beam after ~ 10 mm drift space. In the pulsed measurements, we connected G_{col} to ground and applied a negative pulsed potential V_1 equal to $-(V_{\text{ge}} + V_{\text{col}})$ to the emitter, and applied a positive pulsed potential V_2 equal to $-V_{\text{col}}$ to G_{ext} .

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FIG. 1. (Color online) (a) Optical micrograph of a 40 000-tip stacked double-gate molybdenum nanotip array arranged in a circle with a diameter of 2.26 mm and an array pitch of $10\ \mu\text{m}$. (b) Top-view SEM image of a section of the array. (c) Magnified top-view SEM image of a single emitter and the high-magnification image of the emitter tip (inset). G_{ext} and G_{col} are the electron extraction gate and the beam collimation gate electrodes, respectively. (d) Schematic view of the electron beam collimation experiment. Electron extraction potential V_{ge} (>0) and the beam collimation potential V_{col} (<0) are applied at the same time to generate the collimated field emission beam. The phosphor screen potential V_{an} was 2.5 kV.

The reason to apply the pulsed potentials with respect to the collimation gate is to prepare for a future pulsed field emission experiment of double-gate FEAs in a DC gun test-stand, where an acceleration gradient as high as 5–10 MV/m can be applied.¹² The two pulsed potentials were generated by a custom-built double-pulsar. The pulses' amplitudes and durations were remotely controlled. The used pulses lasted from a few seconds down to $\sim 1\ \mu\text{s}$. For the beam imaging experiments, the Faraday cup was retracted, and the FEA was moved to 50 mm distance from the phosphor screen. We applied a DC accelerating potential V_{an} of 2.5 kV to the screen [schematically shown in Fig. 1(d)] and captured the beam images of the field emission beam produced by single potential pulses by a CCD camera with 16-bit resolution. To avoid the saturation of captured beam image at high emission currents, we adjusted the gate pulse durations. At a given V_{ge} we captured a set of the images for varying collimation potential ratios k_{col} defined as

$$k_{\text{col}} = -V_{\text{col}}/V_{\text{ge}}. \quad (1)$$

The CCD camera was synchronously triggered with the pulsed electron emission using a delay generator (Stanford research systems DG 535).

Assuming that the rms transverse electron velocity u_t is conserved during the propagation of electrons from the FEA to the phosphor screen, the beam size at the screen is larger than the beam radius at the source by u_t multiplied by the propagation time T of electrons from the source to the screen. Therefore, identifying that the source beam size with the array size (rms FEA radius R_0 equal to 0.56 mm. See discussion below), u_t can be evaluated as $\sim (R_s - R_0)/T$, where R_s is the rms beam radius on the screen. Assuming that the initial electron velocity along the beam axis is much smaller than u_{an} defined by the screen potential, $\sqrt{(2\text{ eV}_{\text{an}}/m)}$ equal to $\sim 0.1\ c_0$ (e is the electron charge, m is the electron rest mass, and c_0 is the light velocity in vacuum), as in the case for the maximally beam collimation condition, T is approximately

given by $2L/u_{\text{an}}$ with $L = 50\text{ mm}$ as the FEA-screen distance.¹¹

After loading the FEA into the experimental chamber and evacuating the chamber down to $\sim 1 \times 10^{-8}$ mbar, we first conditioned the FEA by measuring the emission current (I) with the Faraday cup as a function of V_{ge} at zero V_{col} while scanning the V_{ge} between zero and a maximum. The V_{ge} maximum was slowly increased by small steps when the fluctuation of the I - V_{ge} relationship became stable.¹⁰ Typically after several hours and up to a couple of days, a stable I - V_{ge} relationship is observed, with gradual increase in the maximum emission current. In the present experiment, we continued the conditioning in UHV with the maximum V_{ge} equal to 80 V. We subsequently introduced neon gas in the chamber with a pressure of $\sim 2 \times 10^{-4}$ mbar and continued the conditioning procedure (zero V_{col}) with the maximum V_{ge} of 80 V for $\sim 3\text{ h}$ shown in Fig. 2. As a result, we observed a simultaneous increase in the Fowler–Nordheim parameters A_{FN} and B_{FN} . A_{FN} increased by 710%, from 38 to 308 A, and B_{FN} increased by 11%, from 827 to 915 V (Fig. 2), where A_{FN} and B_{FN} are fitting parameters of the I - V_{ge} relationships expressed by

$$I = A_{\text{FN}}(V_{\text{ge}}/B_{\text{FN}})^2 \exp(-B_{\text{FN}}/V_{\text{ge}}). \quad (2)$$

An order of magnitude increase of the A_{FN} suggests that the number of the active emitters has increased.^{10,11} The simultaneous increase of A_{FN} and increase of B_{FN} is difficult to explain solely by the variation of the work function,¹⁰ and probably due to bombardment with Ne ions that can induce the tip blunting and cleaning. This is consistent with the significant improvement of the beam uniformity as can be seen by comparing the images of the uncollimated beam taken before and after the neon gas conditioning shown in Fig. 2.

III. RESULTS AND DISCUSSION

Figure 3 shows the observed beam collimation characteristics for V_{ge} values between 67 and 100 V. The duration of

FIG. 2. (Color online) Relation between the field emission current and V_{ge} before (a) and after (b) neon gas conditioning. In (a), squares and triangles show measurement results obtained by DC and pulsed measurement, respectively. The curves are the Fowler–Nordheim fits of results using Eq. (1). The fitting parameters A_{FN} and B_{FN} and the respective images of the uncollimated beam are shown at the bottom.

the potential pulses were 0.5 ms for $V_{ge} = 67$ V and 20 μ s for higher V_{ge} values. Figure 3(b) shows the rms beam radius R_s extracted from the images that are partly displayed in Fig. 3(a). As the k_{col} value was increased from 0 to 1, the R_s decreased from ~ 5 mm to a value equal to R_0 within ~ 0.1 mm. As shown in Fig. 3(c), there was a concomitant decrease in the emission current as V_{col} decreased the

electric field at the emitter apex. Owing to the large G_{col} aperture, however, the emission current reduction was minimized and the maximally collimated beam current amounted to $\sim 20\%$ of the uncollimated beam at zero k_{col} . At a V_{ge} of 100 V and k_{col} of 0.98, the emission current was equal to ~ 50 μ A. In contrast, the emission currents of double-gate FEAs with smaller G_{col} apertures are highly suppressed even

FIG. 3. (Color online) Collimation properties of the electron beam generated from the FEA. (a) Development of the beam image with the various collimation ratios k_{col} at V_{ge} of 67 and 100 V. (b) rms beam radius as function of k_{col} for $V_{ge} = 67$ V and $V_{ge} = 100$ V. (c) Normalized emission current detected at the Faraday cup as function of k_{col} for V_{ge} of 67 and 100 V. The emission current was evaluated from the integrated beam intensity and normalized by the zero k_{col} value of the respective V_{ge} case. (d) Current density as function of k_{col} at $V_{ge} = 67$ V and $V_{ge} = 100$ V. The current density values were evaluated by dividing the anode current with the rms beam spot size.

FIG. 4. (Color online) Variation of the maximally collimated beam image at $k_{\text{col}} = 0.98$ with an increase in the emission current from 0.2 to 50 μA and an increase of V_{ge} from 67 to 100 V.

at k_{col} values much smaller than 1 and therefore no usable collimation can be observed.¹⁴ As shown in Fig. 3(d), the peak current density on the screen increased nearly an order of magnitude when k_{col} increased from 0 to 1. Furthermore, it increased by two orders of magnitude when V_{ge} was increased from 67 to 100 V.

Figure 4 compares the beam images with V_{ge} of 67, 90, and 100 V at k_{col} equal to 0.98. The emission currents of these beams were ~ 0.2 , ~ 20 , and $\sim 50 \mu\text{A}$, respectively. A gradual increase in the beam size was apparent with an increase in the emission current. A similar observation was also reported recently for a single-emitter double-gate device.¹⁵ We consider that this is caused by the expansion of the beam in the transverse direction at the increased current density due to the Coulomb repulsion between electrons, which normally does not affect the uncollimated or single-gate FEA beam due to large angular beam spread and rapid dilution of the electron density as the electrons propagate along the beam axis.¹⁶

We finally discuss the rms transverse electron velocity u_t of the FEA beam. The u_t value of a photocathode commonly used with the accelerator applications (with the intrinsic emittance of (0.2–0.4) mm-mrad for a 1 mm-diameter cathode) is $(0.8\text{--}1.6) \times 10^{-3} c_0$. In comparison, the u_t values of the FEA beams with k_{col} equal to 0.98 evaluated from the images depicted in Fig. 4 are small: in the range of $(0.32 \pm 0.29) \times 10^{-3} c_0$, where the lower and the upper range of the estimate assumes R_0 equal to 0 (the case when only single emitter is active) or 0.56 mm (active emitters distribute randomly over the entire FEA size). The corresponding transverse beam energies are well below 1 eV, whereas it is typically in the order of V_{ge} in single-gate FEAs due to the large angular divergence ($\sim 30^\circ$) of individual emitters determined by the geometry. Considering that the beam brightness is proportional to the emission current divided by the square of u_t , the beam brightness of the maximally collimated beam was enhanced from the uncollimated case by a factor of $\sim 3 \times 10^2$. For more precise experimental determination of u_t , additional experiments that allows the extraction of the beam parameters (e.g., see Ref. 17) should be conducted,

which is the subject of separate study and out of the scope of the present work.

IV. SUMMARY

In summary, all-metal 40 000-tip double-gate FEAs were successfully fabricated and conditioned. Beam collimation by the FEAs was demonstrated with an order of magnitude enhancement of current density. The emission current of the maximally collimated beam was up to $\sim 50 \mu\text{A}$, with the beam diameter approximately the same as the FEA itself (within ~ 0.1 mm). Although the corresponding maximum current density was equal to $1 \times 10^{-3} \text{ A/cm}^2$ and it is still an order of magnitude smaller than the Child–Langmuir current density ($J_{\text{CL}} = 10^{-2} \text{ A/cm}^2$),¹⁸ we observed systematic increase of the beam size in the maximally collimated condition with the increase of emission current that can be ascribed as the Coulomb expansion of individual in the transverse direction. When this is the case, a higher accelerating gradient can relax the effect. Therefore, a beam collimation experiment at high accelerating gradient F_{acc} , including the transverse beam emittance measurement, is an important next step for this research. A previous study¹⁹ demonstrating stable operation of all-metal single-gate FEAs up to a F_{acc} of 30 MV/m, suggests that the stable generation of a highly collimated field emission beam from our stacked-double-gate FEAs is feasible.

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