Field-emission characteristics of molded molybdenum nano-tip arrays with stacked collimation gate electrodes

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Abstract— Double-gate field-emission characteristics of metallic field-emitter array (FEA) cathodes fabricated by molding with stacked collimation gate electrodes with planar end plane are reported. Collimation of the field emission electron beam with minimal reduction of the emission current was demonstrated when a negative bias was applied to the collimation gate, whereas when the two electrodes were at the same potential, the emission characteristic of the double-gate device was same as that of the single-gate device that shows emission current of ~ 1 mA from 40×40 tip arrays. The results indicate that the device structure of the fabricated double-gate FEAs is promising for high-brilliance cathode applications.

Index Terms— Electron emission, metallic emitters, double-gate field-emitter arrays, collimation, high-brilliance, molding

Fig. 1. (a) Scanning electron microscope image of the double-gate FEA cathode with 40×40 tips. The emitters are aligned with $5 \mu\text{m}$ -pitch. (b) High resolution image of one of the emitters from (a). The apex of the molybdenum emitter can be seen as the bright spot inside the extraction gate aperture.

I. INTRODUCTION

DOUBLE-gate field-emitter-array (FEA) cathodes having a collimation gate electrode G_c stacked on top of the electron extraction gate electrode G_{ex} have been studied in the past for the purpose of eliminating pixel-to-pixel crosstalk in field-emitter displays [1]–[3], for field-ionizer applications [4], and for electron-beam lithography applications [5]–[7]. FEAs have also been studied as the cathode for a compact free electron laser with sub-nanometer wavelength [8]: FEAs can be competitive with the state-of-the-art photocathode [9], [10] when the angular spread $\Delta\theta$ of individual beams is reduced below $\sim 1^\circ$ while keeping the average current density above $\sim 1 \text{ kA cm}^{-2}$ as demonstrated in single-gate devices [11]. $\Delta\theta$ can be reduced in double-gate FEAs by applying a negative bias V_c to G_c with magnitude comparable to the positive electron extraction bias V_{ex} applied between G_{ex} and emitters as reported in the literatures [1–7]. However, since the negative V_c can reduce the electric field F_{apx} at the tip-apex and the emission current, the optimization of the device structure minimizing the influence of V_c on F_{apx} is crucial. For the high-brilliance applications in an acceleration gradient of the order of 100 MV/m , device structures with minimal protrusion are preferred to prevent the parasitic breakdown. Our previous approach [12] based on the molded FEAs having the stacked double-gate electrodes showed successful operation of the device but the emission current decreased substantially by negative V_c . In this Letter, we therefore explore the improved field-emission current-voltage characteristics of double-gate FEAs in a modified gate aperture geometry.

II. SAMPLE AND EXPERIMENT

We fabricated single-gate FEA devices, SG1 and SG2, and a double-gate FEA DG having 40×40 tip array. SG1 was fabricated using a FEA wafer with apex diameter a_{apx} of $\sim 10 \text{ nm}$. SG2 and DG were fabricated using a FEA wafer with a_{apx} of $\sim 20 \text{ nm}$. In addition, a 4×4 tip double-gate FEA was fabricated together with DG. The FEA wafers were fabricated by the molding method [12]–[15] supported by 0.4 mm -thick electro-plated nickel. The emitters have $1.5 \mu\text{m}$ -square base size and $\sim 1.2 \mu\text{m}$ -height, aligned with $5 \mu\text{m}$ -pitch in the arrays. G_{ex} layer was $0.5 \mu\text{m}$ -thick Mo film separated from the arrays by $1.2 \mu\text{m}$ -thick SiO_2 film deposited by plasma-enhanced chemical vapor deposition. For the double-gate FEAs, G_c layer of $0.5 \mu\text{m}$ -thick Mo was added on

Fig. 2. Field-emission characteristics of the double-gate FEA DG with 40×40 emitter tips. (a) Anode current I_a as a function of the bias voltage V_{ge} applied between the extraction gate G_{ex} and the emitter for several collimation gate bias V_c between 60 and -60 V. (b) The variation of I_a , the emitter current I_{em} , and the collimation gate current I_c , when V_c was varied between -70 and 70 V when V_{ge} was fixed at 106 V.

Fig. 3. Schematic diagram of the measurement setup of single-gate FEAs (a) and double-gate FEA (b). The FEAs and the anode (separated by 10 mm) were mounted in the vacuum chamber (background pressure of $\sim 10^{-9}$ mbar), represented by the enclosed area. (c) Anode current I_a vs extraction gate-emitter bias V_{ge} for two single-gate FEAs, SG1, SG2, and the double-gate FEA, DG with the bias V_c at the collimation gate G_c fixed at 0 V. All the devices have 40×40 emitters. SG1 was fabricated using an emitter array with emitter apex diameter of ~ 10 nm. SG2 and DG were fabricated using arrays with emitter apex diameter of ~ 20 nm. SG1 and DG exhibited a reduction of I_a by a factor of 10^3 for V_c of -70 V, had a factor of ~ 3 larger D_{ex}/D_c ratio and γ -value than the present device. This is consistent with the above analysis.

In Fig. 3 (c) we compare the I_a - V_{ge} characteristics of DG with V_c equal to 0 V with two single-gate devices. All three devices have 40×40 emitter arrays. We observed that I_a of the single-gate devices reach ~ 1 mA at V_{ge} of 130-150 V. The maximum I_a of DG was somewhat lower due to the premature failure of the device but its I_a - V_{ge} characteristic is same as that of SG2 within ~ 5 V of V_{ge} . This shows the uniformity of the single- and double-gate fabrication processes over the 40×40 tips.

Finally, to study the effect of V_c on the electron beam collimation, we measured the beam profile in low current regime, Fig. 4, using the double-gate device having 4×4 emitters. Similarly to the large array emitter, the decrease of I_{em} for the 4×4 emitter array was 20% when V_c was decreased from 0 to -70 V, Fig. 4 (d). Fig. 4 (b) shows that when V_{ge} was fixed at 86 V, the beam exhibited the emission angle $\Delta\theta$ of $(20 \pm 3)^\circ$ for V_c larger than -30 V. $\Delta\theta$ was evaluated from the full-width at the half maximum size of the intensity distribution of the phosphor screen image and the screen-FEA distance D . This value is consistent with the previous observation for single-gate Spindt-type FEAs [18], [19]. When V_c was further decreased to -62 V, $\Delta\theta$ was decreased to $(2.3 \pm 0.4)^\circ$ in one direction. The asymmetry and distortion of the collimated beam shape should be improved by careful design of the electrode shape [20] and by elimination of the parasitic field due to the screen assembly, the extraction gate, the electrical

top of the extraction gate separated by 1.2 μm -thick SiON. The diameter of G_{ex} apertures of SG1 and SG2 were equal to 2.3 ± 0.1 μm . The aperture diameters of DG were equal to 1.2 ± 0.1 μm for G_{ex} and 3.5 ± 0.1 μm for G_c , respectively. The details of the fabrication procedure were described elsewhere [12].

The field-emission characteristics were measured in the setups shown in Fig. 3 (a) and (b). The field-emission microscopy experiment was conducted in a separate dedicated system, where the electron beam was amplified by the multi-channel plate and imaged by a phosphor screen, Fig. 4(a). The screen assembly was separated from the devices by 30 mm.

III. RESULTS AND DISCUSSIONS

Fig. 2 (a) shows the I_a - V_{ge} characteristics of DG for V_c between -60 and 60 V measured in the setup shown in Fig. 3(a) and (b). When we increased V_c negatively, the I_a - V_{ge} characteristic shifts towards the larger V_{ge} direction because of the decrease of F_{apx} with negative V_c . However, the sensitivity of I_a to V_c is five orders of magnitude weaker than that to V_{ge} . Fig. 2 (b) shows I_a , the current I_{em} injected to the emitter substrate and the current I_c through G_c . We observe tendencies that I_c increases faster than I_a and I_{em} for positive V_c and a slight increase of I_c with the decrease of V_c for V_c below -20 V. The former can be ascribed to the increased capture of the field emission electrons by G_c while the latter can be ascribed a field emission from the G_{ex} edges to G_c as observed in Ref. [16]. Nevertheless, I_c as well as the difference between I_{em} and I_a are less than 5 % of I_a for V_c below 0 V; the capture of the field-emission electrons by G_{ex} and G_c is minimal and that the gate leak currents are small.

The observed emission current characteristic fits well to the equation, $I_a = AV^n \exp(-B/V)$, with n equal to 2 [17] and with the total effective bias voltage V equal to $(V_{ge} + \gamma V_c)$, where γ is the contribution of V_c to the apex field. From the result of Fig. 2, we evaluated γ to be equal to (0.17 ± 0.014) . The evaluation error represents the bound that the rms spread of the quantity $\ln(I_a/V^2)$ is below 4% when V is equal to 60 V for V_c between -70 and +70 V. The observed value of γ is comparable to the theoretical parameter $\gamma^{(th)}$ given by $(1 + D_c/D_{ex})^{-1}$ equal to 0.18 ± 0.01 obtained from the device geometry, where D_{ex} and D_c are the distances between the emitter apex and G_{ex} and G_c , respectively. Here, $\gamma^{(th)}$ was derived by assuming that F_{apx} is proportional to $[V_{ge}/D_{ex} + (V_c + V_{ge})/D_c]$. We also note that the previously reported double-gate device [12], that was fabricated from the same

contact assembly of the FEA mount, and the aperture shapes in the future experiment. Detailed analysis of the observed collimation characteristic and its comparison with theory will be described elsewhere [21].

In summary, we showed that by engineering the aperture sizes it is possible to collimate the field emission electron beam while minimizing the emission current reduction in double-gate FEAs with stacked G_c with planar end plane. Further optimization of the device structures such as the gate electrode thicknesses [7], the gate insulator thicknesses, and the gate aperture sizes are the next subjects of the research.

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Fig. 4. (a) Schematic diagram of the electron beam imaging experiment setup for the double-gate FEA with 4×4 emitters with fixed V_g of 86 V. (b) and (c) show the result for V_c equal to -10 V and -62 V, respectively, when the distance D between FEA and screen was equal to 30 mm. The bars indicate 10 mm length on the screen. (d) The relation between I_{em} and V_c during the measurement.