DEVELOPMENT OF ALL-METAL STACKED-DOUBLE GATE FIELD EMITTER ARRAY CATHODES FOR X-RAY FREE ELECTRON LASER APPLICATIONS *

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Abstract

Design, fabrication, and characterization of all-metal double-gate field emitter array cathodes at the Paul Scherrer Institute are reported. The beam characterization at low beam energies, combined with the neon gas conditioning for improving the beam uniformity indicated more than an order of magnitude reduction of the emittance. A combination of the proposed double-gate structure with the surface-plasmon-enhanced near infrared laser-induced field emission for ultrafast, high charge bunch generation is discussed.

INTRODUCTION

Realization of a high current and high brightness cathode using field emission has been proposed based on an array of metal nanotip emitters [1,2]. Comparing with conventional etched-wire needle-shaped field emitters, field emitter arrays (FEAs) produced by micro- and nanofabrication methods with an on-chip electron extraction electrode are advantageous for high acceleration gradient operation since the switching of the electron emission can be controlled independently from the acceleration gradient by applying a electron extraction potential in the order of 100 V to the electron extraction gate electrode G_{ex}. Using the all-metal single-gate FEAs developed at PSI, stable operation of FEAs in a combined diode-RF cavity electron gun with gradient up to 30 MV/m [3,4], and electrical pulsing of the FEAs down to ~200 ps [5] were demonstrated. Generation of 5 ps electron bunches was also demonstrated by exciting the FEAs by 50 fs near infrared laser pulses [6]. Although the curved shape of the emitter tip apex leads to a relatively large angular beam spread [7], the transverse emittance of array beam can be reduced by collimating the individual beamlet with a second beam collimation electrode G_{col} fabricated on top of G_{ex} [1,2]. One of the challenges to use double-gate FEAs for practical applications has been the large reduction of the emission current with the application of the beam collimation potential [8]. This was however in part solved with the recently reported double-gate structures with large collimation gate aperture diameters [9,10]. Such double-gate FEAs are promising for advanced accelerator applications including the compact X-ray free-electron lasers (FELs) when an extremely low emittance below 0.1 mm-mrad is required [11] or by utilizing the spatial beam structure combined with the emittance exchange [12]. Double-gate FEAs with low emittance can also be key to realize compact THz vacuum electronic oscillators and amplifiers [13]. Our recent report showed the fabrication of up to 4×10^4 tip stacked-double-gate FEAs and their excellent beam collimation characteristics at low current level [14]. Here we report recent progress of the double-gate FEAs and the numerical study of the emission characteristics for a high density FEAs excited by near infrared laser pulses for X-ray free electron laser applications [15,16].

BEAM CHARACTERISTICS OF SINGLE- AND DOUBLE-GATE FIELD EMITTER ARRAYS

The FEAs used in the experiments consist of pyramidal shaped molybdenum nanotip emitters with the height of ~1 µm and the tip apex radius of curvatures of 5-10 nm. The emitter pitches are equal to 5 µm or 10 µm. The emitters are supported on metal substrates and equipped with G_{ex} and G_{col} electrodes. The gate electrodes and emitters are insulated each other by 1.2 µm-thick SiON layers [14,17,18]. Electron emission characteristics of the all-metal single-gate FEAs have been studied previously [3-6,15,17] including the intrinsic transverse emittance. In Figure 1, we summarize the experimentally observed emittance of *single-gate* FEAs with the FEA diameters between 0.2 and 2.3 mm. The upper boundary of the target emittance with the double-gate FEAs equal to 0.1 mm-mrad with the FEA diameter of 1 mm is also indicated in Figure 1.

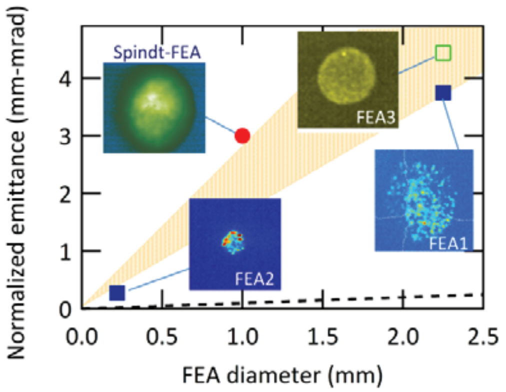

Figure 1: Normalized rms emittance of *single-gate* FEAs. The shaded area corresponds to the rms beam divergence of 20-30°. The broken line is the upper boundary of the target emittance with double-gate FEAs equal to 0.1 mm-mrad with the FEA diameter of 1 mm.

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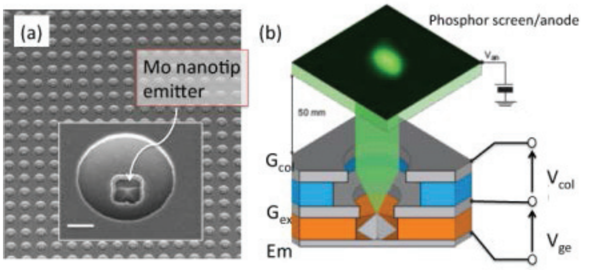

Figure 2: (a) SEM image of all-metal double-gate FEA with 10 µm pitch. The inset is the magnified view of single emitter (the scale bar is 2 µm). (b) Schematic diagram of beam characterization experiment.

The emittance of the single-gate devices FEA1 and 2 was measured using a pulsed diode gun [3] with a beam energy of ~200 keV and an emission current of ~100 µA. The emittance was evaluated from the fitting of the solenoid scan. Other single-gate FEAs, FEA3 and Spindt-FEA, were measured in the dc teststand [5,19] with a beam energy of 50 keV and an emission current of ~1 mA. For these experiments, a FEA holder compatible with the pulsed-diode gun and the dc teststand under high gradient conditions was developed [3-5]. Emittance values in the range of 2-3 mm-mrad for 1 mm diameter FEAs were observed. This corresponds to a rms beam divergence of 20-30° (shaded area in Fig. 1) of the field emission beam at the emitter tip apex [16, 19]. The here observed values are in the same order of magnitude as the emittance of the diamond FEAs without gate electrode [20]. The beam images of FEA1 and 2 are granular due to the emission from the sharpest emitters caused by the non-uniform tip apex radius. The beam uniformity can be significantly improved by applying in-situ neon gas conditioning [5,21] as demonstrated by the uniform beam image of FEA3. Since the emittance values of FEA2 and 3 are approximately the same, the beam non-uniformity appears to be not important in the present experiment [7].

Figure 2 shows the SEM of a double-gate FEA and its schematic operation principle. Application of a positive electron extraction potential V_{ge} to G_{ex} with respect to the emitters (Em) produces a field emission current. When a negative beam collimation potential V_{col} is applied to G_{col} with respect to G_{ex}, the field emission beamlets are individually collimated. Figure 3 (a) shows, the relation between the field emission current and V_{ge} at zero V_{col} after the FEA was in-situ conditioned for 30 min in the neon gas environment with a pressure of 1×10^{-4} mbar [5,21]. The field emission current increases exponentially with V_{ge}, following the Fowler-Nordheim characteristics [22].

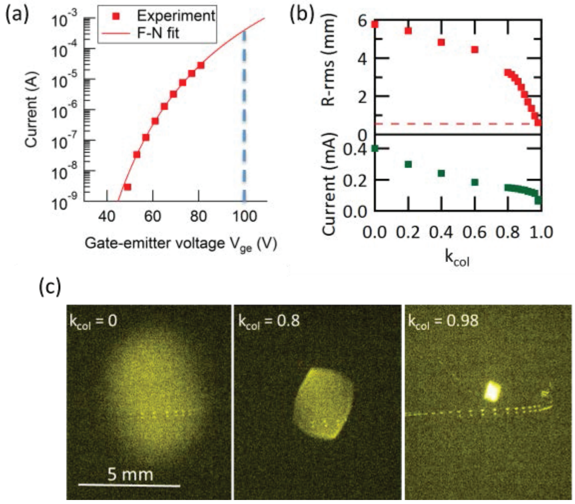

Figure 3: Beam characteristics of a double-gate FEA (a) Field emission current I vs V_{ge} at zero V_{col}. The curve is a fitting by Fowler-Nordheim equation, $I = A\,(V_{ge}/B)^2 \exp(-B/V_{ge})$. (b) Variation of the rms beam radius R-rms and the emission current with k_{col} equal to V_{col}/V_{ge} at V_{ge} of 100 V (marked by the vertical line in (a)). The horizontal broken line indicates the rms FEA radius. (c) Beam image for three k_{col} values with V_{ge} equal to 100 V.

We observed the field emission beam by a phosphor screen at the potential of 2.5 kV separated from the FEA by 50 mm. Figure 3 (c) shows the beam images at three different V_{col} values at V_{ge} equal to 100 V. V_{col} is indicated by the collimation parameter k_{col} equal to $|V_{col}|/V_{ge}$. The reduction of the rms beam radius R_{rms} and the increase of the beam brightness with the increase of k_{col} are visible. At the maximally collimated condition with k_{col} equal to 0.98, R_{rms} approached the rms FEA radius R_0 (equal to 0.56 mm indicated by the broken line in Fig. 3(b) upper panel) and the beam brightness was enhanced by a factor of ~10. At k_{col} equal to 0.98, the emission current was ~60 µA and approximately 20% of the emission current of 0.4 mA at zero k_{col} was retained. Assuming free propagation of the electrons in the transverse direction, we evaluated the rms transverse velocity u_t from ($R_{rms} - R_0$) and found u_t to be equal to $\sim3\times10^{-4}\,c$ (c is the light velocity) at k_{col} equal to 0.98; the estimated emittance is below 0.1 mm-mrad for a 1 mm-diameter FEAs [23]. Recently, the ame beam collimation characteristics was also observed using single-tip double-gate device [24]. The adaptation of the single-gate FEA holder for the double-gate FEAs and the emittance measurement of the double gate FEAs using the dc teststand is under way.

SURFACE-PLASMON POLARITON ENHANCED TIP-LASER INTERACTION

Next we discuss the strategy and design to realize a double-gate FEA compatible for X-FEL applications that can generate short electron pulses with high charge and low emittance. Experiments [6] with 5 µm-pitch single-gate FEA indicated that one can generate short high current pulses by exciting the FEA with the excitation of near infrared laser pulses. The observed electron yield was in the order of 10^{-7}. Therefore to generate high charge electron pulses e.g. 200 pC of the nominal bunch charge of the SwissFEL at the Paul Scherrer Institut, an order of magnitude increase of the electron yield is required. A possible strategy is to reduce the array pitch to sub-micron range by scaling down the double-gate structure

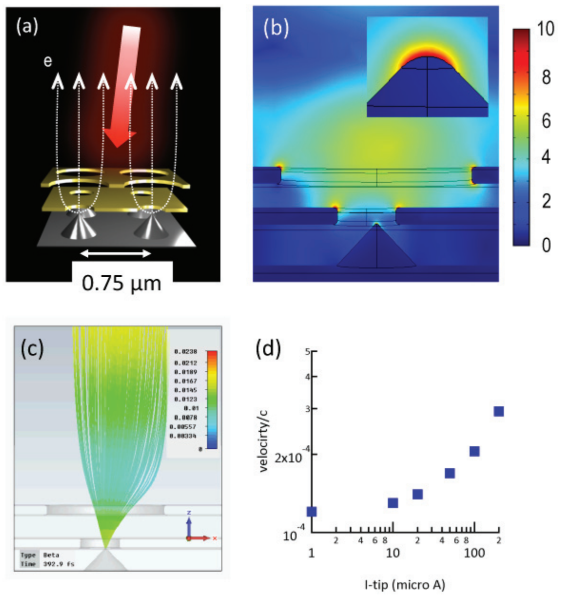

Figure 4: (a) Schematic of sub-micron-pitch double-gate FEAs with Mo emitters and Cu gates excited by near infrared laser pulses at 7° incident angle. (b) Optical electric field distribution calculated for the resonant wavelength equal to 800 nm. (c) Particle tracking simulation of the same structure at 100 MV/m external gradient with V_{ge} equal to 70 V and V_{col} equal to -76 V. (d) Tip current dependence of the rms transverse velocity.

described in the previous section, that can however reduce the tip excitation efficiency because of the concomitant reduction of the gate aperture diameters to sub-wavelength dimension for the excitation of near infrared pulses. We therefore proposed [15,16] to use copper as the gate material and to utilize the surface-plasmon-polariton (SPP) excitation of the gate electrode and the associated extraordinary optical transmission (EOT) of the plasmonic nano-aperture arrays [25]. Figure 4 (b) shows the optical electric field distribution of a 0.75 μm-pitch copper double-gate FEAs calculated by a finite element electromagnetic simulation tool with periodic boundary conditions in the lateral direction at the EOT resonance condition with 1.6 eV incident photon energy. We found that not only the EOT resonance is preserved in the presence of the molybdenum nanotip in the aperture cavity, but the optical electric field at the emitter tip apex is nearly a factor of 10 enhanced when the G_{ex} is shifted from the axis of the emitter tip by 5 nm [15,16]. Interestingly, with the normal incident excitation with the field along the lateral direction, the enhanced tip optical field is in the direction perpendicular to the tip apex surface. To extract electrons, it is however practical to irradiate the laser pulses at an angle slightly tilted from the surface normal direction. Although such oblique incidence angle excites SPP at a difference resonance photon energy [25], we found that when the incident angle is limited within ~10°, see Figure 4 (b), the shift of the resonance photon energy is below ~10 meV, and not relevant for the present application [26].

To evaluate that the impact of the G_{ex} shift on the beam characteristics, we calculated the rms transverse velocity by a particle tracking simulator (CST Particle Studio) with the same double-gate emitter structure as the one used for the electromagnetic simulation in Figure 3. We assumed V_{ge} of 100 V, V_{col} of -76 V, the acceleration gradient of 100 MV/m, and the tip current between 1 and 200 μA. The initial current distribution at the emitter apex was calculated from the optical intensity obtained from Figure 4 (b) and assuming the field emission of the excited electrons that absorbed one photon with the energy of 1.6 eV [16]. The result is shown in Figure 4 (c) and (d). We found that despite the shift of G_{ex}, the field emission beam is well collimated with the rms transverse velocity below 2×10^{-4} c for the tip current below ~100 μA.

These results show the capability a 10^6-tip, 1 mm-diameter sub-micron-pitch double-gate FEA to generate 200 pC, electron pulses with the emittance well below 0.1 mm-mrad by exciting the FEA with 0.1 mJ near infrared laser pulses. The near infrared photon electron yield is increased to ~2×10^{-6} by using the SPP enhanced tip-laser coupling.

Test sub-micron-pitch FEAs fabricated by using the high-through-put electron beam lithography method [17,27] showed that the accuracy of the lithography and the sample uniformity are compatible to the proposed double-gate device, Figure 4 (a). Fabrication of the test device to demonstrate the SPP enhanced field emission is under way.

REFERENCES

[1] C.-M. Tang, A. C. Ting, T. Swyden, "Field-emission arrays — a potentially bright source", Nucl. Instrum. Meth. A **318**, 353 (1992).

[2] M.Dehler, A. Candel, E. Gjonaj, "Full scale simulation of a field-emitter arrays based electron source for free-electron lasers", J. Vac. Sci. Technol B **24**, 892 (2006).

[3] S. Tsujino, M. Paraliev, E. Kirk, T. Vogel, F. Le Pimpec, C. Gough, S. Ivkovic, H.-H. Braun, "Nanosecond pulsed field emission from single-gate metallic field emitter arrays fabricated by molding", J. Vac. Sci. Technol. B**29**, 02B117 (2011).

[4] S. Tsujino, M. Paraliev, E. Kirk, C. Gough, S. Ivkovic, H.-H. Braun, "Sub-nanosecond switching and acceleration to relativistic energies of field emission electron bunches from metallic nano-tips", Phys. Plasmas **18**, 064502 (2011).

[5] S. Tsujino, M. Paraliev, "Picosecond electrical switching of single-gate metal nanotip arrays", J. Vac. Sci. Technol. B **32**, 02B103 (2014).

[6] A. Mustonen, P. Beaud, E. Kirk, T. Feurer, S. Tsujino, "Five picocoulomb electron bunch generation by ultrafast laser-induced field emission from metallic nano-tip arrays", Appl. Phys. Lett. **99**, 103504 (2011).

[7] K. L. Jensen, P. G. O'Shea, D. W. Feldman, J. L. Shaw, "Emittance of a field emission electron source" J. Appl. Phys. **107**, 014903 (2010).

[8] S. Tsujino, P. Helfenstein, E. Kirk, T. Vogel, C. Escher, H.-W. Fink, "Field-emission characteristics of molded molybdenum nanotip arrays with stacked collimation gate electrodes" IEEE Electron Device Letters **31**, 1059 (2010).

[9] Y. Neo, T. Soda, M. Takeda, M. Nagao, T. Yoshida, C. Yasumuro, S. Kanemaru, T. Sakai, K. Hagiwara, N. Saito, T. Aoki, H. Mimura, "Focusing Characteristics of Double-Gated Field-Emitter Arrays with a Lower Height of the Focusing Electrode", Appl. Phys. Express **1**, 053001 (2008).

[10] P. Helfenstein, E. Kirk, K. Jefimovs, T. Vogel, C. Escher, H.-W. Fink, S. Tsujino, "Highly collimated electron beams from double-gate field emitter arrays with large collimation gate apertures" Appl. Phys. Lett. **98**, 061502 (2011).

[11] B. Patterson, R. Abela, H.-H. Braun, U. Flechsig, R. Ganter, Y. Kim, E. Kirk, A. Oppelt, M. Pedrozzi, S. Reiche, L. Rivkin, Th. Schmidt, B. Schmidt, V. N. Strocov, S. Tsujino, A. F. Wrulich, "Coherent science at the SwissFEL X-ray laser", New J. Physics **12**, 035012 (2010).

[12] W. S. Graves, F. X. Kärtner, D. E. Moncton, P. Piot, "Intense superradiant X rays from a compact source using a nanocathode array and emittance exchange", Phys. Rev. Lett. **180**, 263904 (2012).

[13] J. H. Booske, "Plasma physics and related challenges of millimeter-wave-to-terahertz and high power microwave generation", Phys. Plasmas **15**, 055502 (2008).

[14] P. Helfenstein, V. A. Guzenko, H.-W. Fink, S. Tsujino, Electron beam collimation with 40,000 tip metallic double gate field emitter arrays and in-situ control of nanotip sharpness distribution, J. Appl. Phys. **113**, 043306 (2013).

[15] A. Mustonen, P. Beaud, E. Kirk, T. Feurer, and S. Tsujino, "Efficient light coupling for optically excited high-density metallic nanotip arrays", Scientific Reports **2**, 915 (2012).

[16] P. Helfenstein, A. Mustonen, T. Feurer, S. Tsujino, "Collimated Field Emission Beams from Metal Double-Gate Nanotip Arrays Optically Excited via Surface Plasmon Resonance" Appl. Phys. Express, **6**, 114301 (2013).

[17] E. Kirk, S. Tsujino, T. Vogel, K. Jefimovs, J. Gobrecht, A. Wrulich, "Fabrication of all-metal field emitter arrays with controlled apex sizes by molding" J. Vac. Sci. Technol. B **27**, 1813 (2009).

[18] V. A. Guzenko, A. Mustonen, P. Helfenstein, E. Kirk, S. Tsujino, "High-density large-scale field emitter arrays for X-ray free electron laser cathodes", Microelectronic Engineering **111**, 114 (2013).

[19] S. C. Leemann, A. Streun, A. F. Wrulich, "Beam characterization for the field-emitter-array cathode-based low-emittance gun" Phys. Rev. STAB **10**, 071302 (2007).

[20] J. D. Jarvis, B. K. Choi, A. B. Hmelo, B. Ivanov, C. A. Brau, "Emittance measurements of electron beams from diamond field emitter arrays" J. Vac. Sci. Technol. B **30**, 042201 (2012).

[21] S. Tsujino, M. Paraliev, E. Kirk, H.-H. Braun, "Homogeneity improvement of field emission beam from metallic nano-tip array by noble-gas conditioning" Appl. Phys. Lett. **99**, 073101 (2011).

[22] R. G. Forbes, J. H. B. Deane,"Reformulation of the standard theory of Fowler–Nordheim tunnelling and cold field electron emission", Proc. R. Soc. A **463**, 2907–2927 (2007).

[23] P. Das Kanungo, P. Helfenstein, V. A. Guzenko, C. Lee, S. Tsujino, "Pulsed field emission imaging of double-gate metal nanotip arrays: effect of emission current and noble gas conditioning", S3-C6, Technical digest, 27th International Vacuum Nanoelectronics Conference, Engelberg, Switzerland (2014).

[24] C. Lee, P. Das Kanungo, V. Guzenko, P. Helfenstein, S. Tsujino, G. Kassier, A. Casandruc, R. J. D. Miller, "Field emission beam characteristics of a double-gated single emitter", P2-11, Technical digest, 27th International Vacuum Nanoelectronics Conference, Engelberg, Switzerland (2014).

[25] T. W. Ebbessen, H. J. Leec, H. F. Ghaemi, T. Thio, P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays" Nature **391**, 667 (1998).

[26] A. Mustonen, Y. Oh, P. Helfenstein, T. Feurer, S. Tsujino, "Plasmon assisted double-gate field emitter arrays", S1-C1 Technical digest, 27th International Vacuum Nanoelectronics Conference, Engelberg, Switzerland (2014).

[27] A. Mustonen, V. Guzenko, C. Spreu, T. Feurer, S. Tsujino, "High-density metallic nano-emitter arrays and their field emission characteristics", Nanotechnology **25**, 085203 (2014).