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High-density large-scale field emitter arrays for X-ray free electron laser cathodes

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ABSTRACT

High brightness electron sources are of great importance for the operation of the hard X-ray free electron lasers. Field emission cathodes based on the double-gate metallic field emitter arrays (FEAs) can potentially offer higher brightness than the currently used ones.

We report on the successful application of electron beam lithography for fabrication of the large-scale single-gate as well as double-gate FEAs. We demonstrate operational high-density single-gate FEAs with sub-micron pitch and total number of tips up to 10^6 as well as large-scale double-gate FEAs with large collimation gate apertures. The details of design, fabrication procedure and successful measurements of the emission current from the single- and double-gate cathodes are presented.

1. Introduction

Hard-X-ray free electron lasers (FELs) such as the planned SwissFEL X-ray FEL at the Paul Scherrer Institute require high brightness electron sources. Comparing with the state-of-the-art photocathodes [1], field emission cathodes based on double gate metallic field emitter arrays (FEAs) can potentially offer higher brightness by more than a factor of two [2–6]. Therefore, we explore such FEAs as a possible upgrade option for the SwissFEL cathode. Recently, it has been demonstrated that single-gate FEAs operated in the near infrared laser-induced field emission mode [7–9] are capable of generating ultrafast electron bunches, reaching up to 5 pC with 50 fs excitation pulses. Stable operation of these FEAs with the high acceleration electric field up to 30 MV/m was also shown experimentally [10,11]. Additionally, reduction of the field emission beam divergence by a factor of 5–10 with stacked double gate FEAs with minimal current loss was shown [5,6]. The reported results were observed on FEAs fabricated by means of photolithography, which has been a limiting factor for the further improvement of the FEA performance. In particular, it has been difficult to reduce the typical array pitch of 5–10 μm down to the submicron range in order to increase the tip density and thus the total emission current. This could allow us to meet the requirements of SwissFEL for the 200 pC pulse with 10 ps duration while keeping the excitation pulse energy of ~0.1 mJ and nanotip array size about 1 mm in diameter. Up-scaling of the number of emitter tips of the double gate FEAs to 10^4–10^6 has been hard to achieve so far using optical lithography and focused ion beam milling because of the precision and through-put. However, electron beam lithography is likely to provide the solution to circumvent these problems. The flexibility of electron beam lithography for modifying and optimizing exposure designs allows for fabricating large collimation aperture double-gate FEAs [5,6] with thousands to millions of emitters. In addition, combining the vacuum nanoelectronic devices with plasmonic structures can enhance the electron yield of laser-induced field emission by orders of magnitude [12,13], which should boost the FEA performance and make it attractive for SwissFEL as possible upgrade option.

2. Experimental procedure

Fabrication of the gated FEAs requires several technological steps, that are largely divided into the molding technique for array preparation and the gate fabrication processes on top [13–17]. The major improvement in the fabrication procedure is possible by using an e-beam lithography direct writing tool, particularly Vistec EBPG 5000Plus with the Gaussian shape beam, operated at 100 kV acceleration potential.

The process flow starts with an oxidized 100 mm ⟨001⟩ oriented Si wafer coated by a positive tone resist layer. After the first lithography step (optical or e-beam, depending on the target tip size and density) the pattern is transferred into an SiO_2 layer by reactive ion etching (RIE) and then into the Si wafer by anisotropic wet chemical etching in heated 20% KOH solution. This way, the mold for the arrays of inverted pyramids, the sawing lines, and the registration markers for the following e-beam overlay exposures are created. After thermal oxidation of the wafer, the fabrication of the mold is completed. The last oxidation step is done for fine tuning the mold shape especially that of the pits for the emitter arrays. In the case of photolithographically defined 1.5 μm-base arrays, this step consists of repeated oxidation

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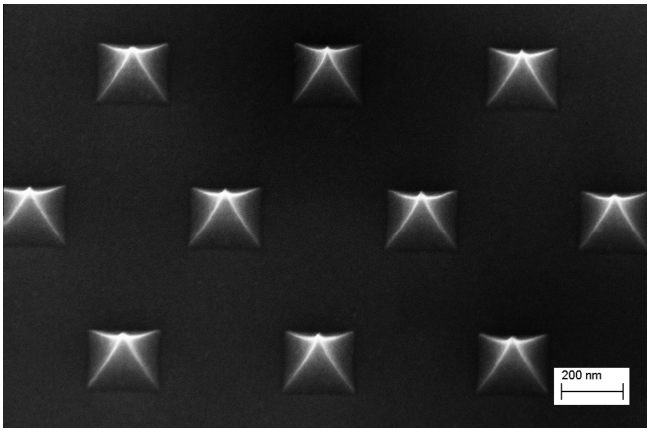

Fig. 1. Scanning electron microscope (SEM) image of several molybdenum tips with the base size of 250 nm, arranged on the hexagonal grid with the period of 640 nm.

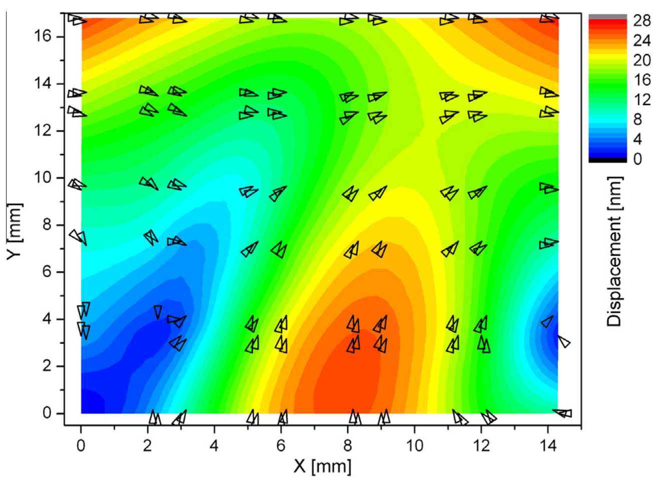

Fig. 2. Color map of the displacements of the registration marker from expected positions as measured on a demonstrator chip with 20 FEA arrays by means of e-beam lithography tool. The arrows indicate the direction of the marker displacement. Compensation for these distortions had to be done during the overlay exposures of the aperture patterns of the gate electrodes.

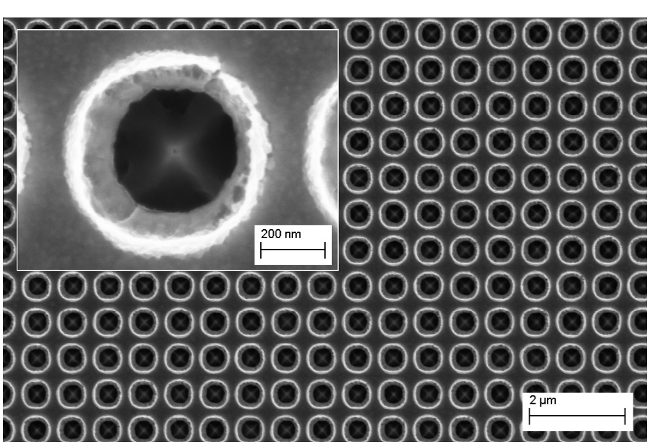

Fig. 3. A part of a 560 µm large single gate FEA with the tip distance of 750 nm and the overlay precision at any location of arrays better than 40 nm. The inset shows more detailed an individual field emitter.

[6,17]. In the case of the high-density FEAs defined by e-beam lithography, we typically apply a single oxidation step with the SiO_2 thickness of 400 nm for the emitter tip sharpening. The SiO_2 layer also servers as a protection layer for emitters during later demolding step. Next, the mold is sputter coated by Mo and then metallized with Cr and Pd by evaporation. The Pd layer acts as the seed layer for the next electroplating of a low stress Ni support layer with thickness of 400 µm. After demolding, i.e. after complete dissolving of the Si wafer in KOH solution, the all metal nano-tip array wafer is ready for dicing. Subsequent fabrication steps are presently performed with individual chips diced into small pieces, but could be optimized for the whole metallic wafer replica in the future process. In order to manufacture the extractor gate electrode, a layer of SiO_2 is deposited by plasma enhanced chemical vapor deposition (PECVD), sufficiently thick to completely cover the tips, followed by a sputtered layer of Mo, required for the fabrication of the gate electrode. For arrays with 5–10 µm pitches, a self-aligned resist etch-back process has been successfully used in order to open the apertures of the Mo extractor gate electrode [5,6,9,17]. However, this technique is limited to a certain minimum size of the tip. The apertures of the high density FEAs can be reliably defined by means of an e-beam overlay exposure and subsequent etching of Mo and SiO_2 layers. The e-beam-based technique is also the key for the fabrication of the second collimation electrode of the double gate FEA with large collimation gate apertures especially with arrays with a large number of tips [6,18].

3. Results and discussion

At this point it is worth focusing on the modified fabrication flow, in particular, on the e-beam lithography steps. As mentioned before, applying the direct write e-beam technique instead of photolithography opens up the possibility to decrease remarkably the tip size and thus, the separation between the neighboring tips. In our experiments, the distance between the tips was selected according to simulations of the electrical field enhancement around the tip apex, while illuminating the FEA by Ti:Sapphire laser light with the central wavelength of 800 nm [12]. For the square tip arrangement, the grid parameter was set to 750 nm and for the hexagonal one to 640 nm, an example of which is shown in Fig. 1. In order to reach the target size of the pyramids in the range of 250 nm, the 50 nm smaller squares were exposed with the dose assignment noticeably higher than the dose-to-clear value. Such "undersize-overdose" technique widens the process latitude of the resist development step and consequently of the

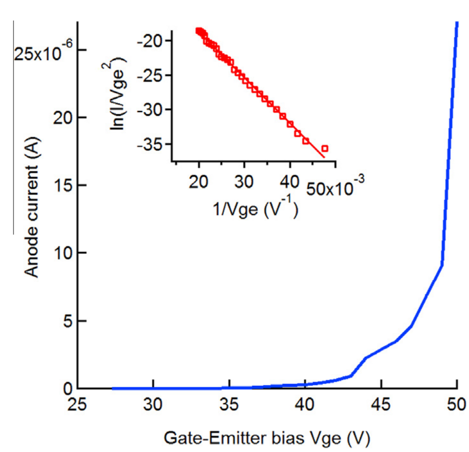

Fig. 4. Emission current vs. gate voltage characteristics of a single gate submicron-pitch FEA with diameter of 560 µm, operated in the DC mode, recorded after several days of operation. The inset shows the corresponding Fowler–Nordheim plot.