PRODUCTION AND INITIAL TESTING OF A NANOSTRUCTURED COPPER PHOTOCATHODE IN AN S-BAND RF GUN*

D. Bazyl†, K. Flöttmann, H. Achour, M. Barthelmess, A. Dangwal Pandey[1], D. Elinjikkal,
M. Hachmann, V. Hennicke, T. F. Keller[1,2], S. Kulkarni[1], M. Lengkeit, L. Lilje, N. Plambeck,
E. Vogel, A. Winiarska-Bialk
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[1] also at Centre for X-ray and Nano Science CXNS,
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[2] also at Department of Physics, University of Hamburg, Hamburg, Germany

Abstract

A copper photocathode based on bulk Cu(100) substrate with a 50 µm-diameter nanostructured region was fabricated and integrated into an S-band radio-frequency gun. We report the procedure for production and preparation of high-quality copper cathodes with nanostructured area compatible with state-of-the-art S-band RF gun. Experimental results indicate absence of increased dark current up to 70 MV/m at the cathode.

INTRODUCTION

The continuous-wave (CW) superconducting radio-frequency (SRF) photoinjector under development at DESY relies on metal photocathodes, predominantly Cu, due to the chemical robustness required for atmospheric handling and subsequent cavity cleaning with the cathode installed. The relatively low quantum efficiency (QE) of Cu limits the achievable bunch charge in CW operation, especially at high repetition rates relevant for CW free-electron laser applications.

Nanoscale surface structuring has been demonstrated as one of the methods for improving QE through increased optical absorption and local laser intensity enhancement [1–3]. One of the questions for nanostructured photocathodes operated in high-gradient RF guns is whether the nanoscale surface features contribute to dark current. In this work, we describe practical experience with fabrication, preparation and initial RF tests of a Cu photocathode incorporating a 50 µm-diameter nanostructured region optimized for 515 nm excitation in a normal-conducting S-band RF gun. The cathode was conditioned to 70 MV/m, with dark current levels comparable to typical values observed during operation with Cs2Te photocathodes. Quantum efficiency was measured at 257 nm on unpatterned regions to evaluate photoemissive characteristics of Cu treated with BPS172 (Cu oxide passivator) [4].

CATHODE FABRICATION AND SURFACE TREATMENT

The pattern was designed using SIMULIA CST Studio® [5] to optimize light absorption at 515 nm and enhance the local laser intensity [6]. The geometry consists of cylindrical holes with radius $r = 188$ nm, pitch $d = 356$ nm, and depth of approximately 200 nm. Angle-resolved reflectivity measurements on similar patterns confirmed excitation of surface cavity modes with characteristic Fano-type signatures arising from plasmon–cavity coupling [7]. The hexagonal pattern was implemented over a circular area of 50 µm diameter matching the typical laser spot size at REGAE facility [8].

Single-crystal Cu(100) was selected as the baseline substrate to provide homogeneous milling response during focused ion beam (FIB) nanopatterning. Initial tests on small-grain polycrystalline Cu produced non-uniform patterns with geometric features clearly separated by grain boundaries, whereas patterns on Cu(100) were clearly homogeneous (see Fig. 1).

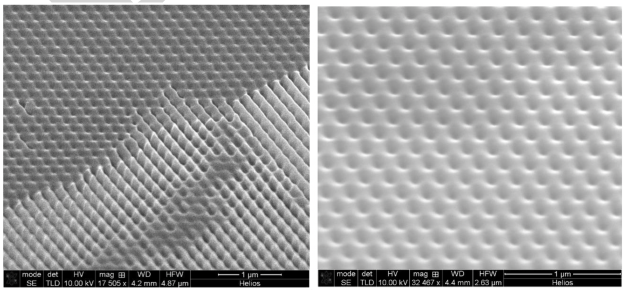

Figure 1: Comparison of nanostructuring on polycrystalline Cu (left) and Cu(100) (right).

A Cu(100) rod of dimensions 20 cm × 2 cm was procured from Surface Preparation Laboratory [9]. Three cathode plugs were fabricated by Edmund Optics son-x GmbH [10] using optical ultra-high-precision diamond turning with an off-center tool trajectory (see Fig. 2). The resulting surfaces had a roughness $S_a < 2$ nm over the emitting area, eliminating the need for polishing. The later is important for cathode geometries with complex mechanical features such as elliptical edges implemented for dark current mitigation. The fabrication sequence is compatible with standard RF guns operated at DESY following adaptions for specific cathode

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† dmitry.bazyl@desy.de

Figure 2: Substrate Cu(100) rod and three cathode heads produced for a cathode plug for the REGAE S-band gun.

plugs, including L-band guns at FLASH, European XFEL, and PITZ (including elliptical cathode edges).

Following fabrication, crystallographic orientation was studied with electron backscatter diffraction (EBSD). EBSD revealed that the near-surface orientation deviates locally from the nominal Cu(100) due to a machining-induced mosaic layer. Typical local orientations were close to (124), (114) and (123). We note that additional controlled polishing procedures could remove the distorted layer and recover baseline Cu(100), which may be of interest for applications requiring homogeneous QE with specific crystallographic orientations without nanoscale structuring. Focused ion beam nanostructuring was performed on one of the cathode plugs at the DESY NanoLab [11] using a dual-beam focused ion beam (FIB) microscope equipped with a gallium ion source (Scios FEI/Thermofisher). An ion beam with an acceleration voltage of 30 kV and a beam current of 0.3 nA was employed to mill an array of 17885 holes each with a nominal diameter of 188 nm, at a pitch of 356 nm to homogeneously cover a circular area of 50 µm diameter in the center of the cathode plug. Milling the nanostructured pattern was optimized by using the stream file option of the FIB, allowing the milling task to be completed within 15 minutes (single-pass, dwell time: 0.05 s for each hole). Despite the near-surface crystallographic distortion, the resulting FIB pattern remained highly homogeneous. Scanning Electron Microscopy (SEM) inspection revealed no visible grain boundaries or surface defects over the region targeted for nanostructuring. Post-fabrication SEM confirmed very good agreement between the dimensions of the fabricated pattern and the target design. Figure 4 (left) shows an overview of the nanostructured pattern on the Cu plug, while Fig. 4 (center) presents a magnified view of the patterned region. Figure 4 (right) shows a cross-sectional view of milled holes fabricated on a different Cu sample using the same milling parameters, but with a slightly different vertical pitch.

Following fabrication and FIB patterning, the cathode was chemically treated with BPS172 solution to form a controlled surface oxide that is resistant to atmospheric contamination. This treatment has been shown to be beneficial for the QE of Cu cathodes [12]. Cathode transfer to the RF gun was performed under inert atmosphere before installation into the load-lock. The cathode was then baked at 120 °C for 60 h under vacuum with heating and cooling ramps of 0.8 °C/min. The pressure initially rose to $\sim 5 \times 10^{-6}$ mbar, decreased to $< 10^{-6}$ mbar within 1 h at nominal temperature, and reached 4×10^{-8} mbar before cooldown. We confirmed by SEM that BPS172 does not alter the nanostructure.

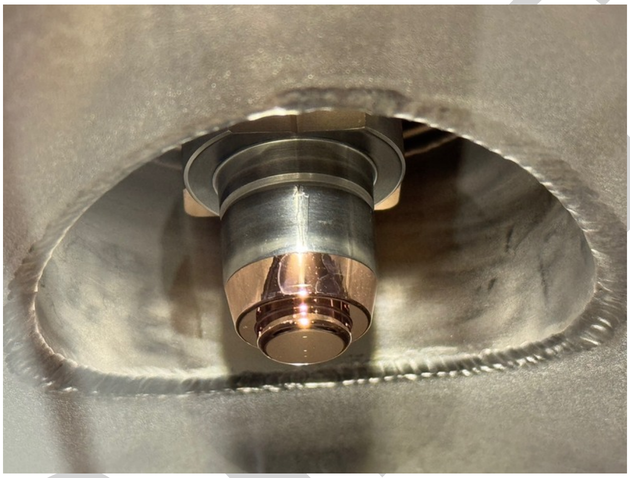

Figure 3: Nanostructured Cu cathode in the load-lock environment. Marks on the emitting top-surface are light reflections.

EXPERIMENTAL SETUP

The nanostructured cathode was integrated into the REGAE normal-conducting S-band RF gun operating at 2.998 GHz with peak surface electric field up to 70 MV/m at the cathode [8]. For dark current characterization, the gun was conditioned by gradually increasing the field up to the maximum value. Dark current was monitored with a Faraday cup downstream of the gun exit using the standard REGAE diagnostics [8,13]. The method provides sensitivity to integrated dark charge in the pC range on a pulse-resolved basis. Photoemission characterization was performed in the same setup using a 257 nm laser. Direct characterization of the 50 µm nanostructured patch was not performed in the present work because the available laser wavelength (257 nm) did not match the pattern periodicity, which had been optimized for excitation at 515 nm. Future work will address this through integration of wavelength-matched (515 nm) laser optics at REGAE and dedicated tests at PITZ.

RESULTS

A transient emitter appeared during conditioning around 45–47 MV/m, but downstream diagnostics indicated that it originated away from the cathode center, outside the 50 µm-diameter nanostructured region. The emitter disappeared

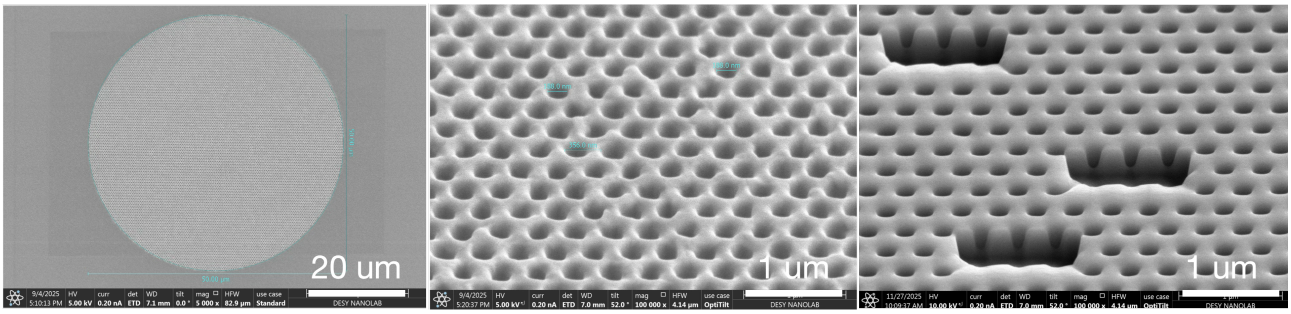

Figure 4: SEM image of the full structured area (left), zoomed in version of the same pattern (center) and cross sections on a different Cu(100) test sample with the same milling parameters but slightly different vertical pitch (right).

after continued RF processing. The dark-charge measurement at a maxiumum peak field of 70 MV/m in this run, taken after about 23 h of conditioning, is shown in Fig. 5. The total integrated dark charge is around 2.4 pC. This performance is comparable to that of a standard CsTe cathode after weeks of conditioning. The QE measured at 257 nm on the flat cathode surface is estimated to be 1.7×10^{-4}. This value was obtained indirectly by scaling low-field QE measurements of a Cs2Te reference cathode by the ratio of photocurrents measured from Cu and Cs2Te under identical conditions in the RF gun.

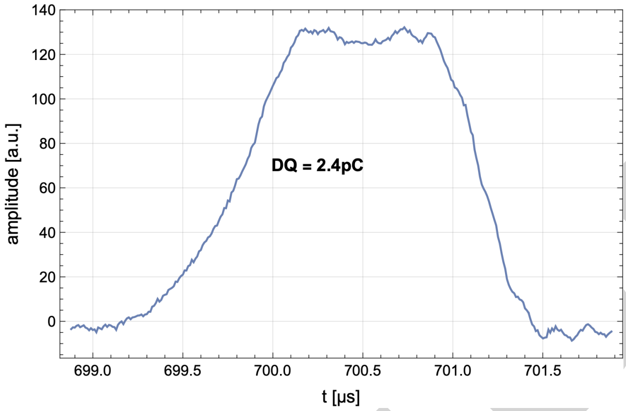

Figure 5: Dark charge measured at 70 MV/m after 23 h of conditioning. The integrated dark charge is 2.4 pC. The y-axis is given in arbitrary units, with 1 a.u. corresponding to approximately 13 nA.

CONCLUSION

A bulk single-crystal Cu(100) photocathode incorporating a 50 µm-diameter nanostructured region optimized for 515 nm excitation was fabricated and operated in a high-gradient S-band RF gun. Dark current after conditioning to 70 MV/m remained comparable to typical Cs2Te photocathode results, indicating that surface modulation of the nanostructure does not the enhance the dark current. The QE at the flat surface at 257 nm is estimated to be 1.7×10^{-4}. In future work we intend to characterize photoemission from the nanostructured area following an optics upgrade which is required for the design wavelength of the nanostructure (515 nm).

Initially driven by demanding surface quality requirements for nanostructuring, the proposed procedure suggests a practical approach for manufacturing high-quality Cu photocathodes with the potential to extend this procedure to operate bulk single-crystal photocathodes. This can enable homogeneous QE and the opportunity to work with favorable crystal orientation.

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