The role of Multiphoton Emission and Plasmon-Photon coupling in the operation High-Gradient Copper Cathodes

Y. Ashkenazi and M. Krief

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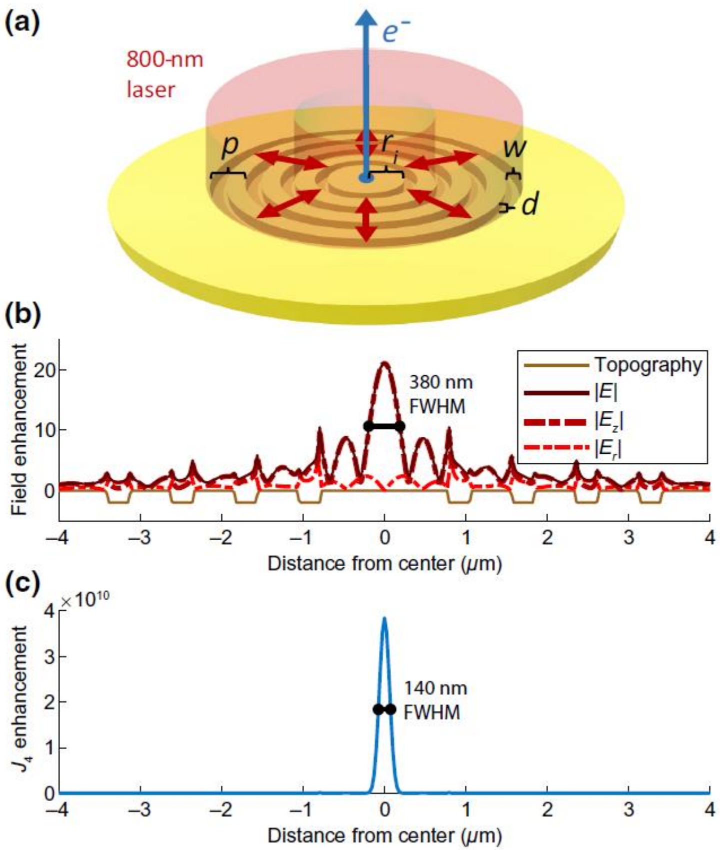
The Racah Institute of Physics, The Hebrew University

Plasmonic Lenses for Tunable Ultrafast Electron Emitters at the Nanoscale

Daniel B. Durham,[1,2] Fabrizio Riminucci,[3,4] Filippo Ciabattini,[5] Andrea Mostacci,[3]
Andrew M. Minor,[1,2] Stefano Cabrini,[5] and Daniele Filippetto[4,*]



lens. The geometry is defined by the five parameters illustrated in Fig. 1(a): the number of rings N, the grating period p, the groove width w, the groove depth d, and the center-plateau radius r_i. Such gratings couple the component of the incident light with the electric field perpendicular to the grooves into surface plasmon polaritons (SPPs). A radially polarized laser at normal incidence is used so that the electric field direction is always perpendicular to the grooves and the launched SPPs are in phase. These SPPs then propagate and interfere to give maximum field enhancement at the structure center.

FIG. 1. The simulated electric field and photoemission profiles during excitation of a Au plasmonic bullseye lens with a radially polarized 800-nm continuous-wave (cw) laser. (a) A schematic of the bullseye geometry. The parameters shown include the grating period p, the groove width w, the groove depth d, and the center-plateau radius r_i. For the simulation results in the following subpanels, $p = 783$ nm, $d = 90$ nm, $w = 270$ nm, and $r_i = 783$ nm. The number of rings $N = 4$. (b) The total ($|E|$) electric field enhancement, shown with its normal ($|E_z|$) and tangential ($|E_r|$) components at the bullseye surface. The field enhancement is defined relative to the peak field in the incident beam. The bullseye topography is superimposed on the plot for reference: the grooves are 90 nm deep. (c) The calculated four-photon photocurrent-density enhancement (J_4) profile at the bullseye surface, using the generalized Fowler-Dubridge equation [19]. FWHM, full width at half maximum.

Two Physical effects leads to a high emitted current

- **Multi**-Photon photoelectric effect
- Plasmon-Enhanced field emission

MultiPhoton Field/Photo emission

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Theory of ultrashort nonlinear multiphoton photoelectric emission from metals

J. P. Girardeau-Montaut* and C. Girardeau-Montaut
Université Claude Bernard-Lyon 1, Laboratoire des Sciences et Ingenierie des Surfaces Interactions Laser-Matériau, 43 boulevard du 11 Novembre 1918, 69622 Villeurbanne Cedex, France
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$$\Gamma=\Phi/\Lambda\ , \tag{1}$$

where Φ is the work function of the material and

$$\Lambda=\frac{e^2E_z^2}{2m\omega^2}\ , \tag{2}$$

where E_Z is the electric field component of the electromagnetic (EM) wave, normal to the surface with frequency ω; e and m are the charge and the mass of the electron, respectively; and Λ is the oscillation (quivering) energy of a free electron in the EM field. The main conclusions were the following.

(i) In the limit when $\Gamma \ll 1$, the current density is the Fowler-Nordeim equation for the dc field emission current.

(ii) In the opposite limit, when $\Gamma \gg 1$, the expression for the current density can be interpreted as the N-photon surface effect photoemission current.

The above conclusions tell us that, for $\hbar\omega$ radiation, when the EM field is weak enough such that the quivering energy Λ of the electron is much less than the work function, multiphoton photoemission results. When the field strength is increased to $\Lambda > \Phi$, the electron can essentially tunnel through the surface barrier during the half period when the electric field is normal to the surface. That is the so-called optical field emission (OFE). However, the triumph of the above treatment in the unification of the phenomena of multiphoton photoemission and field emission can be observed only in diluted media. Because of the recently observed laser damage

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Non-linear electron photoemission from metals with ultrashort pulses

Gabriele Ferrini [a], Francesco Banfi [a], Claudio Giannetti [a], Fulvio Parmigiani [b,*]
[a] Dipartimento di Matematica e Fisica, Università Cattolica del Sacro Cuore, I-25121 Brescia, Italy
[b] Dipartimento di Fisica, Università di Trieste and Sincrotrone Trieste, Strada Statale 14, I-34012 Basovizza, Trieste, Italy

$$\left.\begin{aligned}
\mathbf{J}_n &= \int_{M_n}^{\infty} \mathrm{d}p_z f_n(p_z) \ln\left\{1+\exp\left(\frac{E_F-p_z^2/2m}{k_BT}\right)\right\},\\
f_n(p_z) &= \frac{\sqrt{2}}{\pi^2}\frac{ek_BT}{mch^3}p_z^2\sqrt{p_z^2+2m(n\hbar\omega-\Phi)}|D_n|^2\left(\frac{4\pi^3e^2E_\perp^2}{m\hbar\omega^4}\right)^n\\
M_n &= \begin{cases} 0, & n\hbar\omega-\Phi>0\\ \sqrt{2m(\Phi-n\hbar\omega)}, & n\hbar\omega-\Phi<0\end{cases}
\end{aligned}\right\} \tag{4}$$

where D_n is a function defined in Ref. [40] with a recurrence formula, $E_\perp$ is the component of the electric field normal to the surface, p_z is the component of the electron momentum normal to the surface and Φ is the work function. For $n=0$, the above expression reduces to the Richardson equation for thermionic emission. For $n\neq0$, Eq. (4) shows that each partial current is proportional to the nth power of the intensity associated to the component of the electric field normal to the surface. In this case only a surface effect allows an electron to be photoexcited,

$$J=\sum_{n=0}^{\infty}J_n \tag{6}$$

The expression for each partial current is

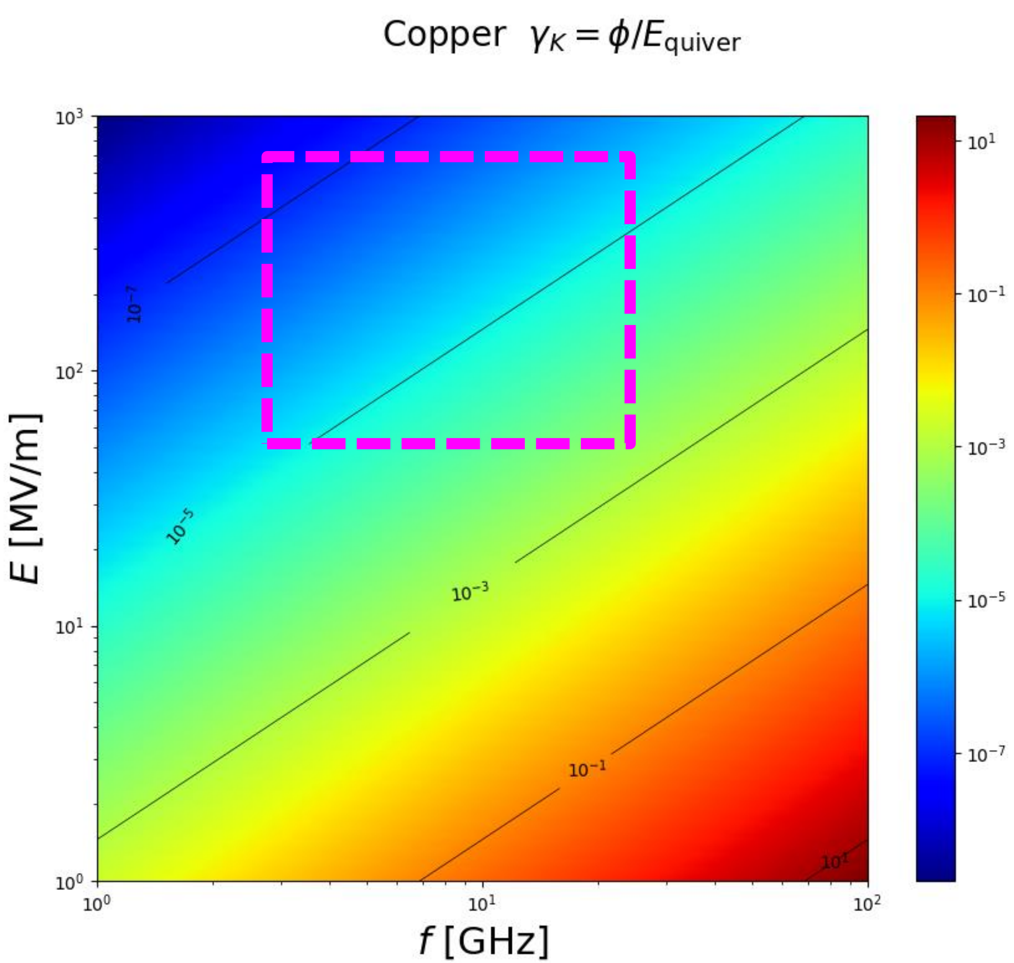
$$J_n = a_n\left[\frac{e}{h\nu}(1-R)I\right]^n AT^2F(X_n)$$

$$F(X_n)=\int_0^{\infty}\mathrm{d}y\ \ln(1+e^{-(y+X_n)})$$

$$X_n=\frac{nh\nu-\Phi}{k_BT}$$

$$F(X_n)=\begin{cases}\displaystyle\sum_{l=1}^{\infty}(-1)^{l+1}\frac{e^{lX_n}}{l^2}, & X_n<0\\[2mm] \displaystyle\frac{\pi^2}{12}, & X_n=0\\[2mm] \displaystyle\frac{\pi^2}{6}+\frac{X_n^2}{2}-\sum_{l=1}^{\infty}(-1)^{l+1}\frac{e^{-lX_n}}{l^2}, & X_n>0\end{cases}$$

Keldysh Parameter for the RF field



$$\gamma_K = \frac{\Phi}{\frac{e^2 E^2}{2m\omega^2}}$$

$$\gamma_K \approx 4.48 \times 10^{-4} \times \phi\,[\text{eV}] \left(\frac{f\,[\text{GHz}]}{E\,[\text{MV/m}]} \right)^2$$

$\gamma_K \ll 1$ Field Emission (Fowler-Nordheim)

$\gamma_K \gg 1$ (Multi)photoelectric effect

Is there a ‘laser equivalent’ in High Gradient Systems?

OTR emission from rf structures and dc spark gap

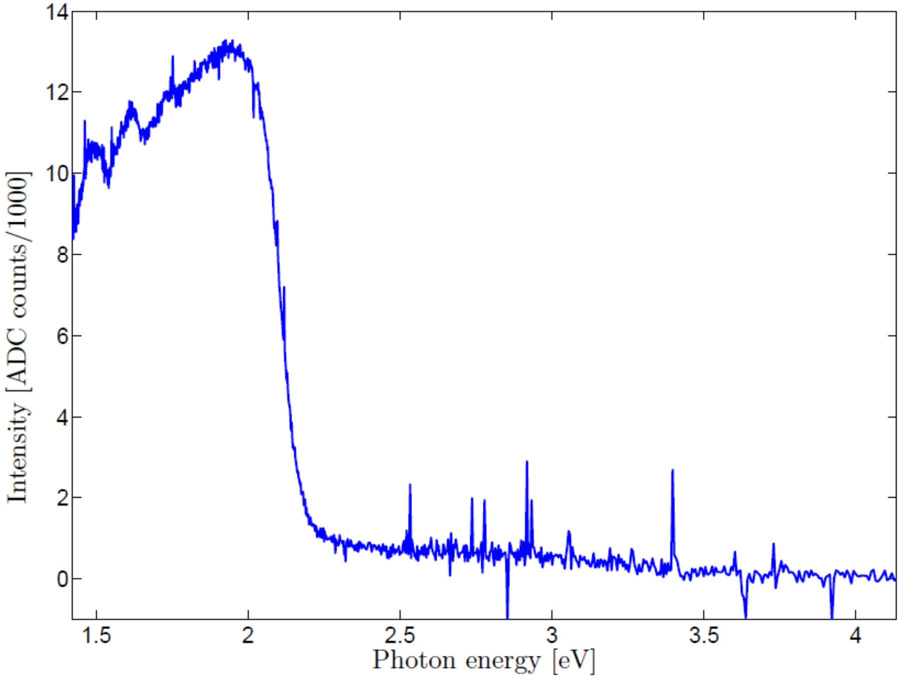


Figure 7.1: OTR light spectrum emitted by a copper spark gap in the dc setup. 20 µm gap, 4.25 kV, 10 accumulated spectra of 60 s integration time, 150 l/mm grating, 250 µm input slit width, CCD QE corrected. Huge grain (cm range) copper.

[Comparative studies of high-gradient RF and DC breakdowns]

JW Kovermann – PhD thesis 2010

Do we have $\gamma_K \geq 1$ for a typical OTR emission spectrum?

Low Field, Optical frequencies ☺

Plasmon-Enhanced field emission For Copper!

Surface-Plasmon Resonance-Enhanced Multiphoton Emission of High-Brightness Electron Beams from a Nanostructured Copper Cathode

R. K. Li,[1] H. To,[1] G. Andonian,[1] J. Feng,[2] A. Polyakov,[2] C. M. Scoby,[1] K. Thompson,[2] W. Wan,[2] H. A. Padmore,[2] and P. Musumeci[1,*]

[1]Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA
[2]Advanced Light Source Division, LBNL, Berkeley, California 94720, USA

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We experimentally investigate surface-plasmon assisted photoemission to enhance the efficiency of metallic photocathodes for high-brightness electron sources. A nanohole array-based copper surface was designed to exhibit a plasmonic response at 800 nm, fabricated using the focused ion beam milling technique, optically characterized and tested as a photocathode in a high power radio frequency photoinjector. Because of the larger absorption and localization of the optical field intensity, the charge yield observed under ultrashort laser pulse illumination is increased by more than 100 times compared to a flat surface. We also present the first beam characterization results (intrinsic emittance and bunch length) from a nanostructured photocathode.

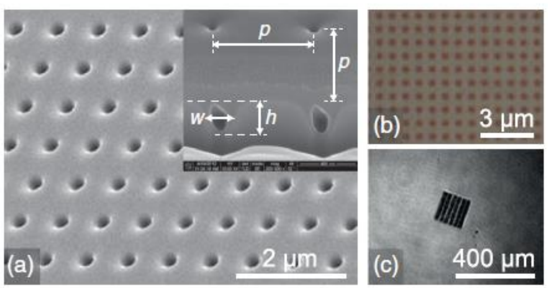

FIG. 1 (color online). (a) Scanning electron microscopy images of the nanohole array. Inset: Zoomed-in cut view of the nanoholes. (b) Nanohole array under an optical microscopy with off-resonance visible light. (c) A nanopattern consisting of 6-by-6 25 μm square patches illuminated at resonant laser wavelength.

(A 3 photon process)

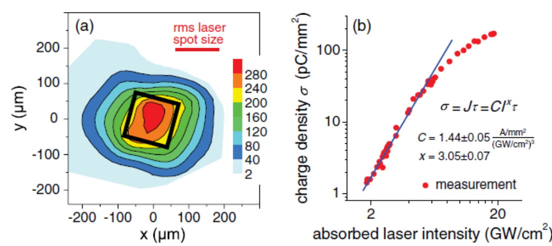

FIG. 3 (color online). (a) Charge yield map of the nanopatterned cathode. The black square indicates the nanopatterned area. The rms laser spot size is illustrated. (b) The charge density σ versus the absorbed laser intensity. σ is obtained by averaging the measured beam charge over the full pattern area. σ can be expressed as $\sigma = J\tau$, where we choose τ to be equal to the pulse duration of the drive IR laser of 150 fs FWHM and J is an equivalent current density. Fitting of the low charge density part yields a slope of 3.05 ± 0.07.

Testing of the nanopatterned cathodes in a high gradient S-band rf gun took place at the UCLA Pegasus Laboratory [7]. The first nanopatterned cathode installed in the gun was fabricated directly on an ordinary cathode made of polycrystalline copper. Because of the larger variations of the nanoholes caused by random grain sizes and orientations of the substrate, the absorption of the 20 nm FWHM bandwidth drive IR laser was 36%. The rf gun was conditioned to the typical operating gradient of 70 MV/m. An initial concern was the possibility of an increased field emission from the nanopattern. However, comparison with the dark current level from a regular cathode shows negligible difference. This can be explained by the relatively small nanopatterned area compared to the total area of the high field surface of the gun body. Moreover, simulation shows that the maximum dc field enhancement is only 12% due to the lack of sharp edges in the nanopattern.

The effectiveness of the nanopattern to enhance the photoemission is clearly seen in the charge yield map [Fig. 3(a)]. IR laser pulses (150 fs FWHM) were focused to 120 μm rms and scanned around the nanopattern at normal incidence ($<1°$) with a piezo-controlled mirror. The position of the laser spot on the cathode was monitored by a virtual cathode screen, and the beam charge was measured by a calibrated high efficiency beam profile camera. The maximum signal, obtained when the laser spot fully covered the nanopattern, is $Y_{exp} > 1.2 \times 10^2$ times larger than when the laser was only hitting the flat surface. The transition between the signal maximum and

It is important to distinguish the multiphoton photoemission regimes from strong optical field emission at nanotips [16–18]. A signature of strong field emitted electrons is a large excess energy spread of a few eV to tens of eV. This is in contrast with the multiphoton regime where the excess energy is typically ≤ 1 eV. The transverse component of the excess energy should be minimized for a low emittance electron source. The Keldysh parameter [19] $\gamma = 73.2\sqrt{\Phi[\mathrm{eV}]/I[\mathrm{GW/cm^2}]}/\lambda[\mu\mathrm{m}]$, where λ is the laser wavelength, Φ is the work function, and I is the laser intensity, is used to evaluate whether the emission is in the strong field regime ($\gamma \ll 1$) or in the multiphoton regime ($\gamma \gg 1$). For our nanopattern and operating laser intensity γ stays >10 after taking into account the intensity localization on the surface, deep in the multiphoton regime.

Plasmon-Enhanced field emission For Gold

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Plasmon-Enhanced Photocathode for High Brightness and High Repetition Rate X-Ray Sources

A. Polyakov,* C. Senft, K. F. Thompson, J. Feng, S. Cabrini, P. J. Schuck, and H. A. Padmore
LBNL, 1 Cyclotron Road, Berkeley, California 94720, USA

S. J. Peppernick and W. P. Hess
PNNL, 902 Batelle Boulevard, Richland, Washington 99352, USA
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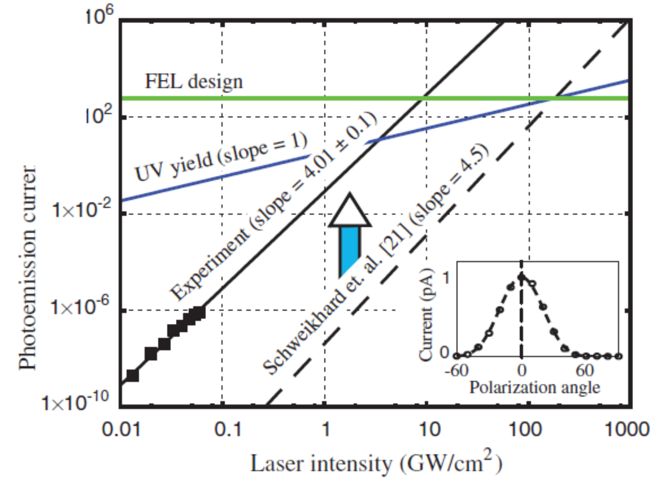
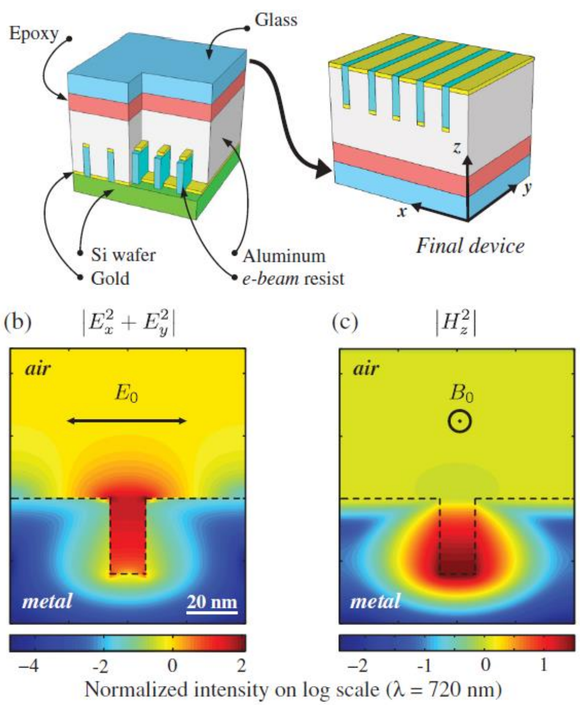
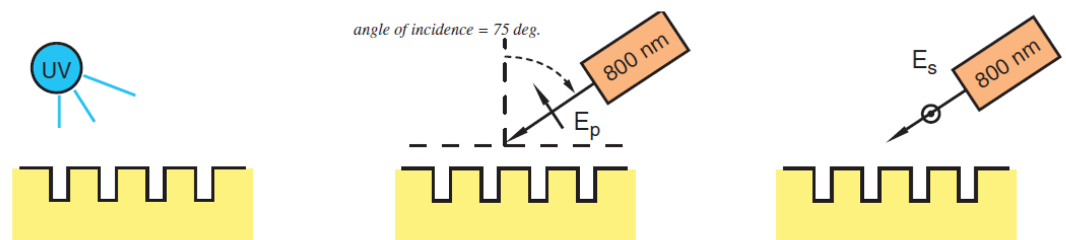
In this Letter, we report on the efficient generation of electrons from metals using multiphoton photoemission by use of nanostructured plasmonic surfaces to trap, localize, and enhance optical fields. The plasmonic surface increases absorption over normal metals by more than an order of magnitude, and due to the localization of fields, this results in over 6 orders of magnitude increase in effective nonlinear quantum yield. We demonstrate that the achieved quantum yield is high enough for use in rf photo-injectors operating as electron sources for MHz repetition rate x-ray free electron lasers.

(A 4 photon process)





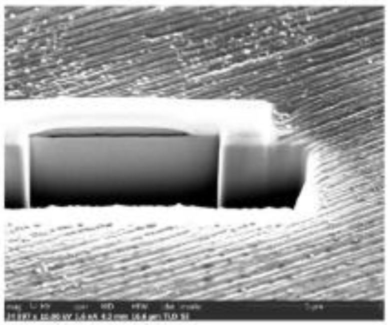


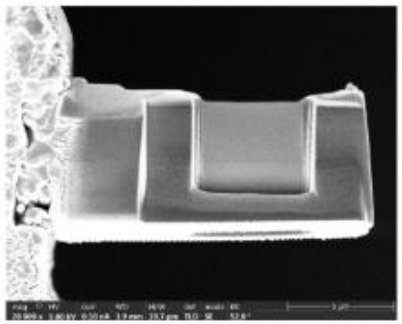
Do we have periodic grating-like structures in High Gradient Cu plates?

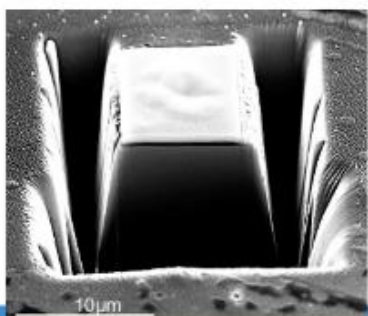
Organized array of dislocations

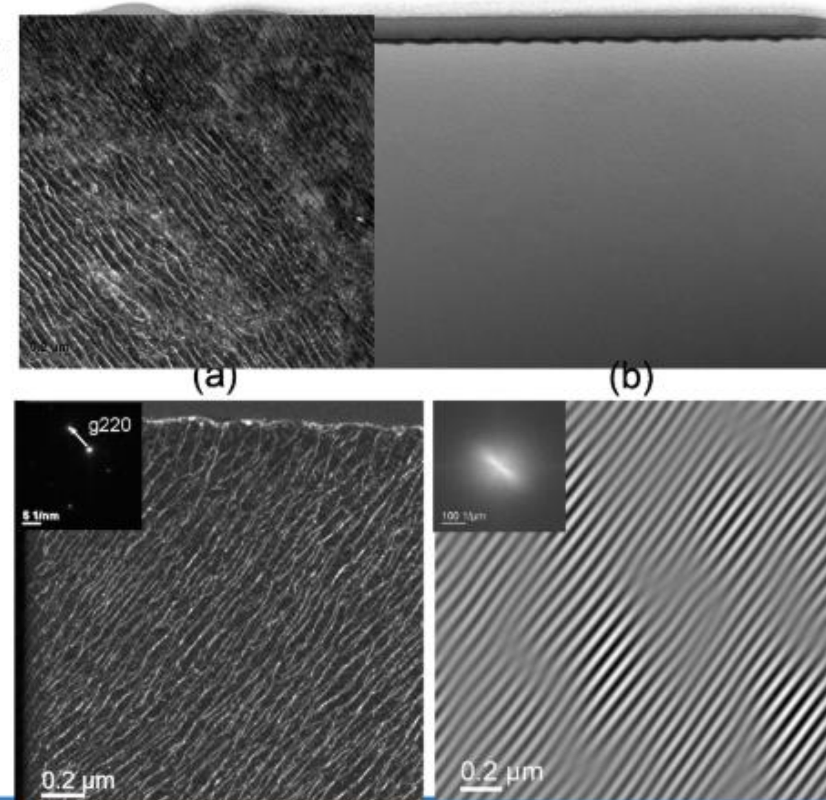
Cut below surface to estimate dislocations structure using SEM

Using Fib –create top or side view lamellas for TEM and STEM









What needs to be done

- Characterize typical **OTR emission** spectra and estimate the importance of various **multi**photon electron emission processes.

- Analyze qualitatively and quantitatively (FDTD simulations) the efficiency of strong SPP-Photon coupling for typical **OTR spectra** and periodic structures found in **Cu plates under high gradient operation**.