Quantum efficiency of flat metallic cathodes under varying electric fields and tunable laser illumination

S. Mingels*, B. Bornmann , D. Lützenkirchen-Hecht and G. Müller

University of Wuppertal, FB C - Physics, Gaußstraße 20, 42119 Wuppertal, Germany, *Contact: s.mingels@uni-wuppertal.de

BERGISCHE UNIVERSITÄT WUPPERTAL

Introduction

Highly brilliant electron sources are crucial for the performance of future free electron lasers [1]. Photo-induced field emission (PFE) might combine the high peak currents of photo cathodes with the low emittance of field emitted electrons. Previous investigations of PFE were performed on tip cathodes and yielded a high brilliance $B \leq 1 \times 10^{13}$ A/m²rad², low emittance $\varepsilon_{x,y} < 7 \cdot 10^{-7}$ m rad but only low currents $I \leq 2.9$ A and parasitic field emission [2]. The systematic investigation of the PFE process requires monochromatic illumination and energy spectroscopy of the emitted electrons. A new UHV analysis system for PFE-spectroscopy (PFES) has been constructed [3].

First results on quantum efficiency (QE, emitted electrons per photon) and different emission regimes of electrons for flat gold and silver crystals are presented.

Basic principles

Field emission (FE)

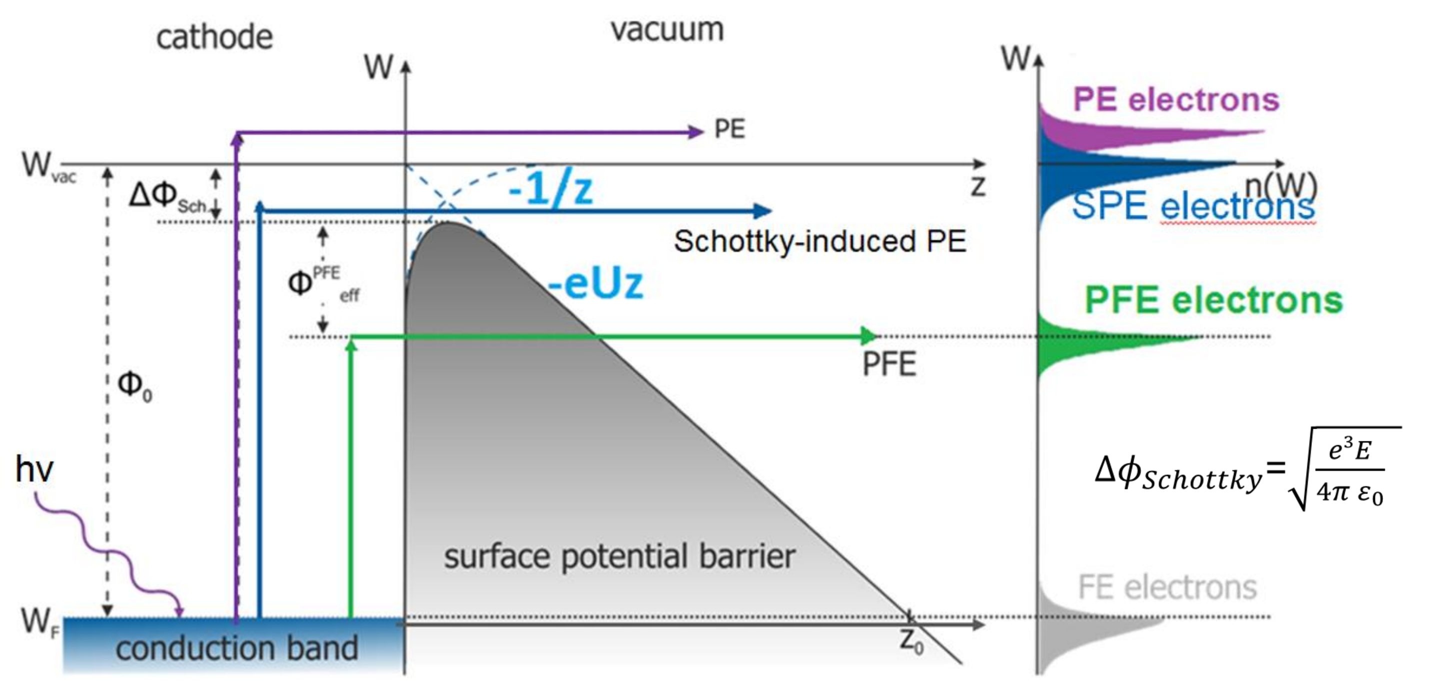
- tunnelling of electrons into vacuum due to an applied electric field
- $I \sim \exp(-B\Phi_0^{3/2}/E)$, B = const.
- low transverse momentum of emitted electrons → low emittance $\varepsilon_{x,y}$
- nanosecond bunches in rf guns
- lifetime ~ O(years)

Photoemssion (PE)

- three-steps-model: (i) absorption of a photon; (ii) transport to surface; (iii) emission
- $W_{kin} = h\nu - \Phi_0 - W_B$
- transverse momentum of electrons is conserved → high emittance $\varepsilon_{x,y}$ ($h\nu - \Phi_0 > 1$ eV usually)
- short pulse length possible (depends on laser pulse)
- lifetime ~ O(month) ($P < 10^{-10}$ mbar)

Photo-induced field emission (PFE)

- photonic illumination of FE cathodes with $h\nu < \Phi_0 - \Delta\Phi_{Schottky}$
- excitation of electrons to energies below $\Phi_0 - \Delta\Phi_{Schottky}$
- higher emission current due to increased tunneling probability at $W = W_F + \Delta\Phi$
- sub-picosecond bunches possible with pulsed illumination [4]

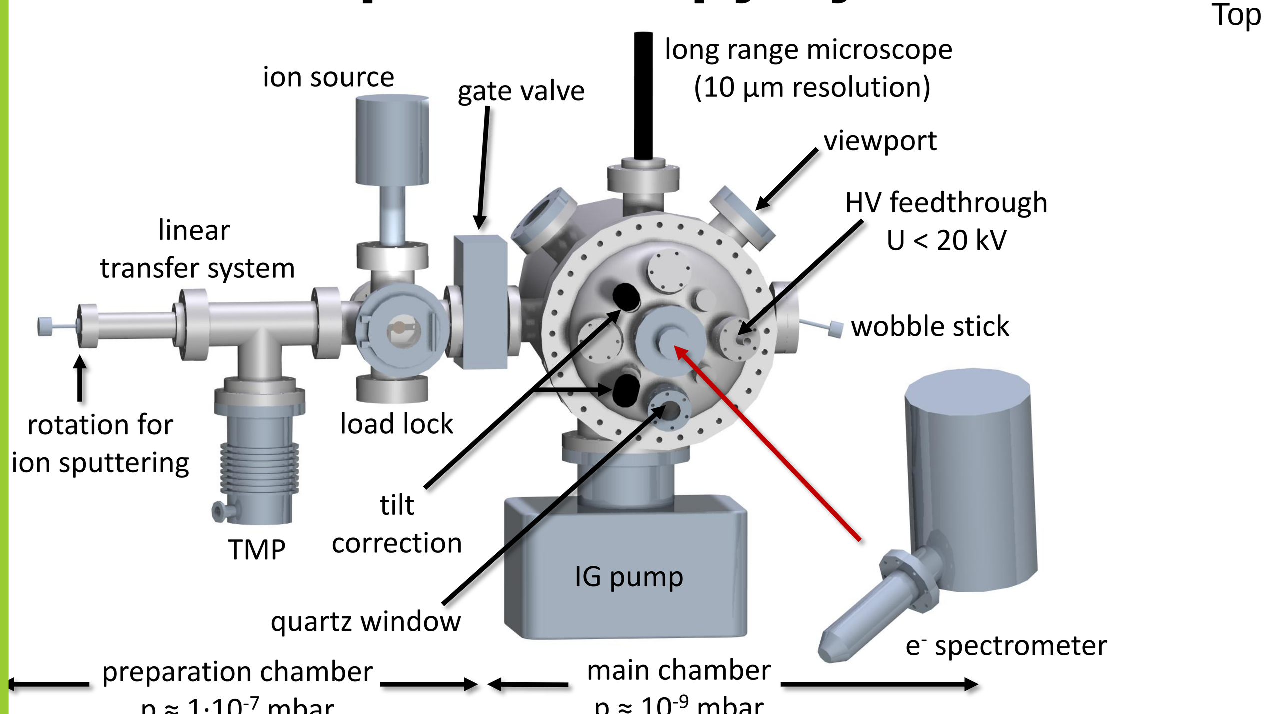


Schematic of the FE, PE, SPE and PFE processes with energy distributions of the emitted electrons.

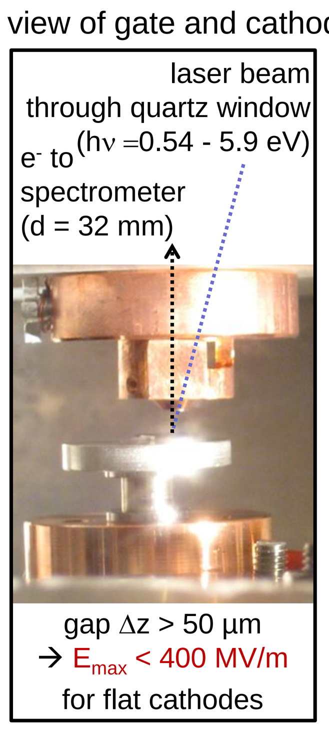
Possible PFE processes

- tunneling of electrons from excited states at $W_F + h\nu$ [5,6]
- relaxation of the photo-excited electrons to states above W_F, resulting in $\Delta\Phi < h\nu$ [7,8]
- immediate tunnelling of excited electrons without existence of electronic states?

PFE spectroscopy system with tuneable laser



Top view of gate and cathode:

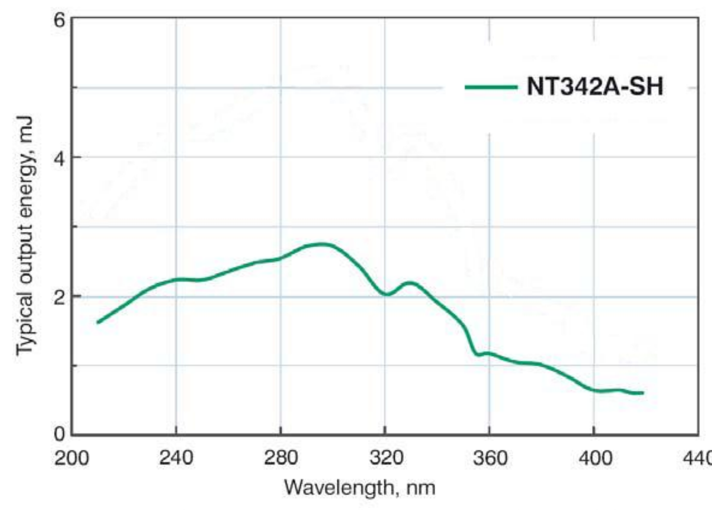


main chamber contains triode configuration:

- adjustable-distance cathode setup
- tiltable gate ($\alpha = \pm 5°$, $\Delta\alpha = 0.003°$)
- $E \leq 400$ MV/m @ $\Delta z = 50$ µm, U = 20 kV
- hemispherical energy analyzer ($\Delta E < 50$ meV).

cathode illumination:

- Nd:YAG Laser (≤ 70 mJ @ 355 nm) pumping tuneable OPO (optical parametric oscillator)
- 210 nm $\leq \lambda \leq$ 2300 nm, gap free
- $t_{pulse} = 3.5$ ns, $f_{rep} = 10$ Hz



Max. laser output for hν = 4,13 – 5,90 eV

Au and Ag crystal sampels

Au sample

- **Au(111)**-bulk
  - mechanically polished to roughness rms ~ 31 nm
  - heated @ 800 °C in the atmosphere (cleaning & recrystallisation)
  - XRD: surface: ~ 60 % Au(111) and ~ 33% Au(100)
  - in situ cleaned with 4 keV Ar⁺-Ions

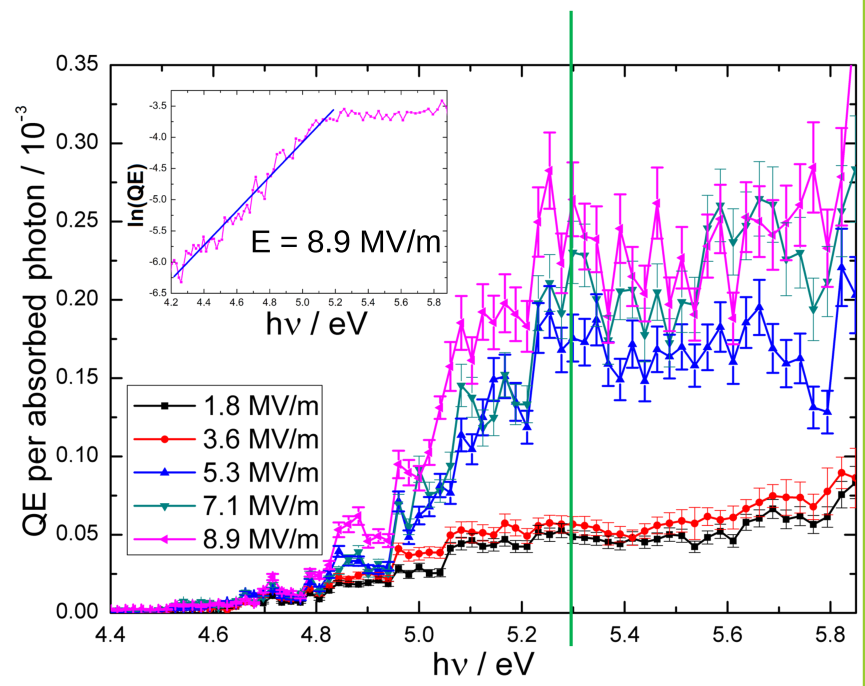
Ag samples

- **Ag(111)**-bulk
  - mechanically polished to roughness rms ~ 15 nm
  - heated @ 780 °C in the atmosphere
  - XRD: surface ~ 84 % Ag(111)
  - UPS: Φ=4,61 ($\Phi_{Lit,111}$=4,74 eV) [9]
- **Ag(110)**-bulk
  - mechanically polished to roughness rms ~ 15 nm
  - heated @ 630 °C and 10^{-7} mbar
  - XRD: surface ~ 52 % Ag(110) and ~ 10 % Ag(311), (331), (420)

Results

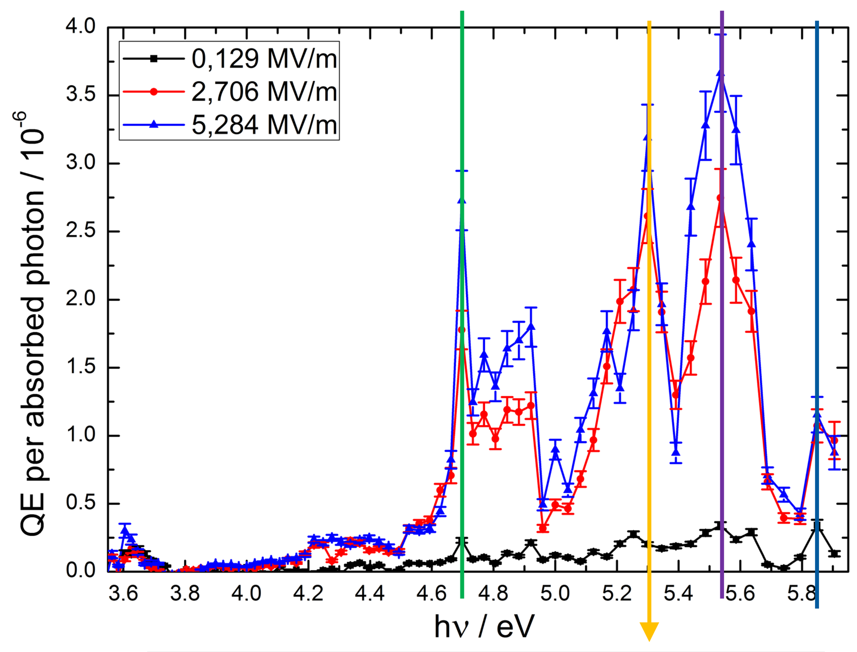
Au(111) sample

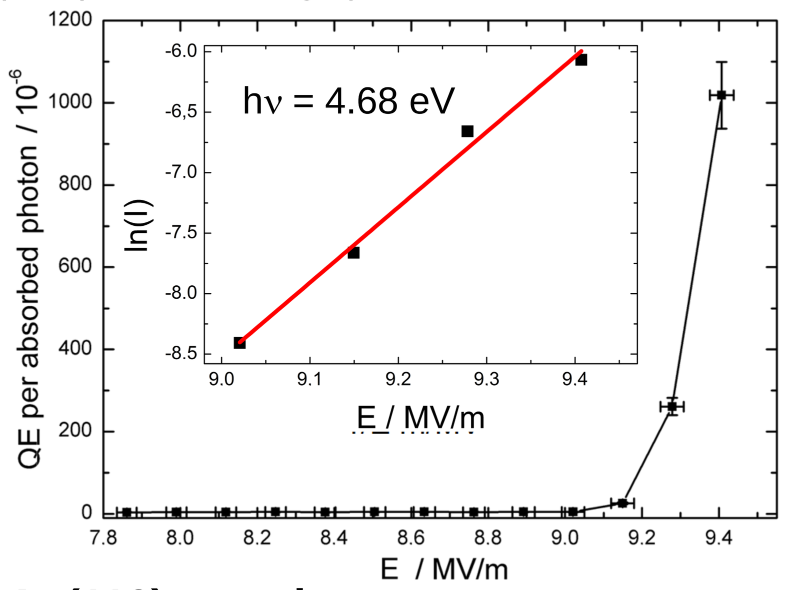
- no FE for E < 8.9 MV/m
- FE measurement for higher E: field enhancement $\beta = 500 \pm 11$, emitting surface S = 106 ± 22 µm²
- laser pulse energy: 50 – 160 µJ
- $E_{eff,\,5.3\,MV/m} = \beta E = 2630$ MV/m → $\Delta\Phi_{Schottky} > 1.9$ eV but no strong decrease of Φ observed → high β due to particles on surface
- pure PE for E = 1.8 MV/m and 3.6 MV/m
- PE: work function Φ = 4,66 ± 0,7 eV (Φ_{Lit} = 5.1 eV for polycrystalline Au) [9] → low Φ due to adsorbats?
- for hν < 5.3 eV hints for resonant optical transitions
- E ≥ 5.3 MV/m → more than 3 times higher QE
- Enhanced PE for E ≥ 5.3 MV/m due to slight lowering of Φ
- hν = 4.7 – 5.3 eV and E ≥ 5.3 MV/m → exponential increase of PFE !? proof: plot of log(QE) vs. hν with linear fit

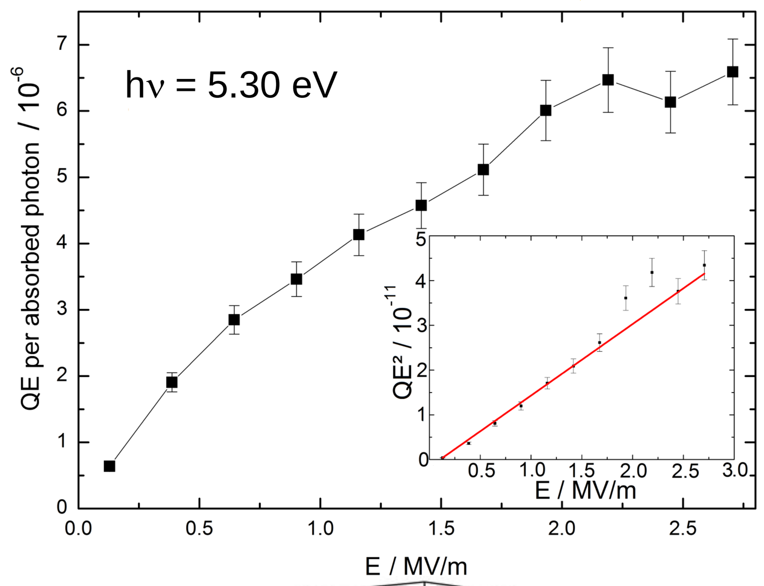


Ag(111) sample

- no pure FE for E < 12 MV/m
- laser pulse energy: 280 – 980 µJ
- clear peaks at 5.30 eV, 5.54 eV and 5.88 eV due to resonant transitions in bandstructure? (see bandstructure below [10])
- further peaks between 4.6 eV and 5.0 eV
- QE measurements at hν = 4.68 eV with varying E show a exponential rise of QE (see plot below) → hint for PFE?
- further measurements with varying E reveal QE ~ $E^{1/2}$ for relatively low fields and pure PE (see plot bottom right)

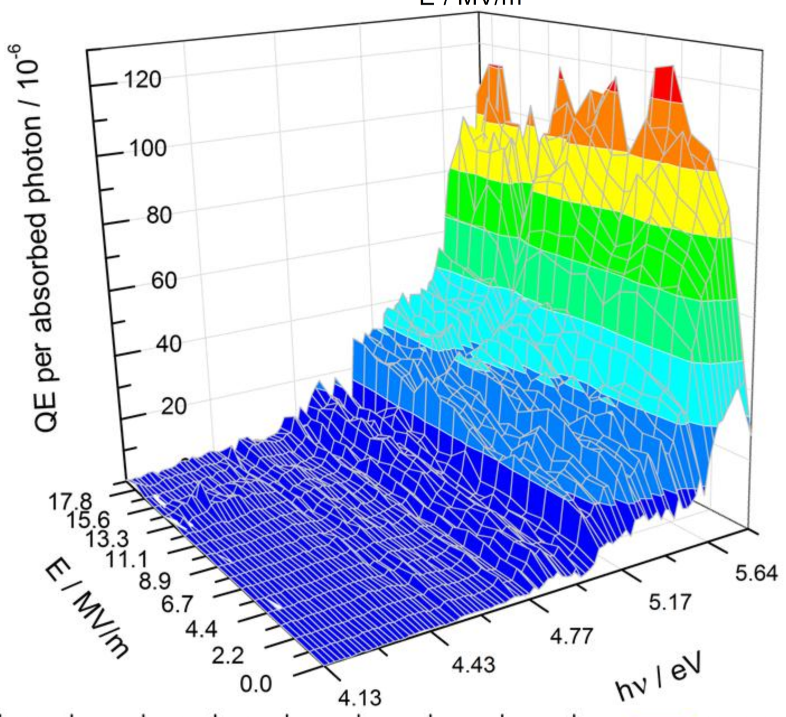


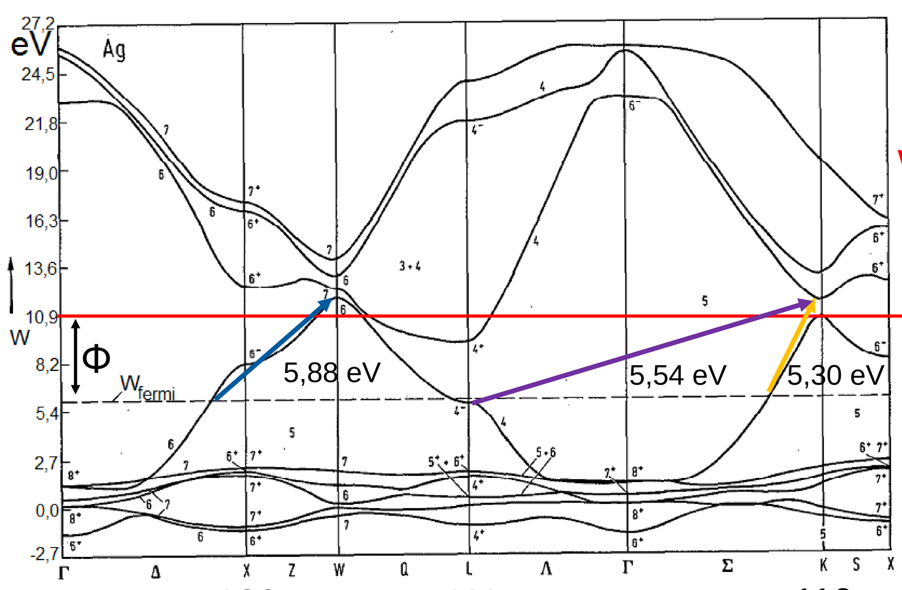


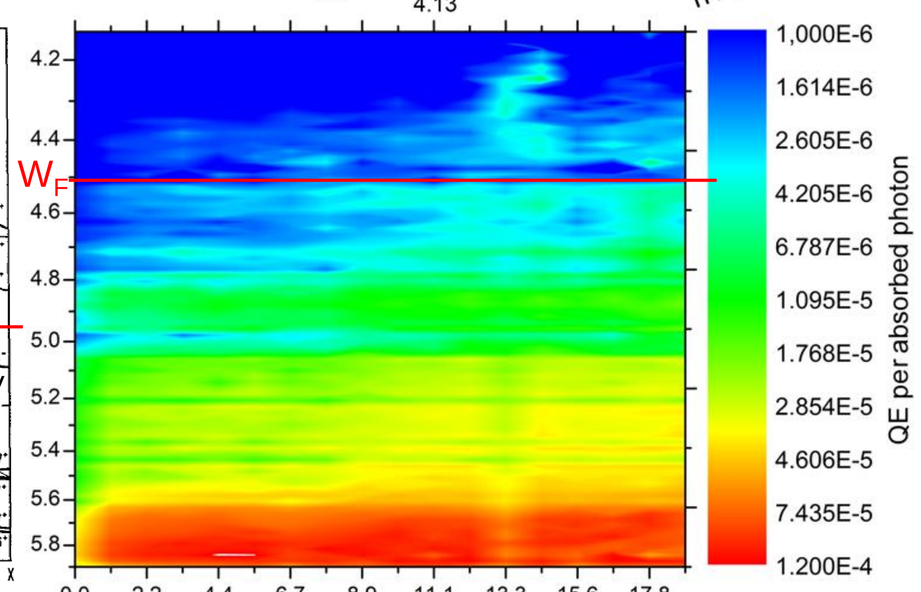


Ag(110) sample

- no FE for E < 19 MV/m
- laser pulse energy: 80 - 200 µJ
- detailed measurements plotted in two different ways (contour plot & 3D surface)
- QE ~ $E^{1/2}$
- increase of QE at 4.52 eV=$\Phi_{110,Lit}$ [9] → fermi-edge
- resonances for hν < 5.6 eV not as clear as the ones revealed for Ag(111)
- dominant peak at ~5.85 eV due to optical transition that leads to preferred emission from Ag(110) (see bandstructure)







Conclusions and Outlook

- QE measurements on Au and Ag crystals showed resonant optical transitions (PE)
- hints for PFE observed for Au(111) and Ag(111) (exponential increase of QE with E and hν)

Future investigations:

- better surface preparation necessary (chem. polishing, in situ heating, cleanroom technology, …)
- spectroscopy of emitted electrons
  - clear distinction between emission regimes
  - certain identification of optical transitions in bandstructure
- further systematic variation of relevant parameters (P_{Laser}, $T_{cathode}$, …)
- test of various materials with different electronic structures (metals, semiconductors, alloys)
- for high QE: test metal oxide crystals!
- emittance measurements of optimized cathode materials (e.g. DESY Zeuthen, FZR Dresden)

References & Acknowledgements

[1] D.H. Dowell et al., Nucl. Instr. And Meth. Phys. A **622**, 685-697 (2010).
[2] R. Ganter et al., Phys. Rev. Lett. **100**, 064801 (2008).
[3] B. Bornmann, et al., Rev. Sci. Instum. **83**, 013302, (2012).
[4] P. Hommelhoff, et al., Phys. Rev. Lett. **96**, 077401 (2006).
[5] M.J.G. Lee, Phys. Rev. Lett. **30**, 1193 (1973).
[6] L. Wu, L.K. Ang, Phys. Rev. B **78**, 224112 (2008).
[7] C. Hernandez-Garcia, C.A. Brau, Nucl. Instr. Meth. Phys. Res. A **429**, 257 (1999).
[8] M. Fhokrul Islam, F. Bary Malik, Solid State Comm. **149**, 1257-1260 (2009).
[9] H.B. Michaelson, J. Appl. Phys. **48**, 4729 (1977)
[10] N.E. Christensen, Phys. stat. sol. (b) **64**, 551 (1972)

In part funded by the German Federal Ministry of Education and Research BMBF, project 05K10PXA.