OSTBAYERISCHE TECHNISCHE HOCHSCHULE REGENSBURG

ALLGEMEINWISSENSCHAFTEN UND MIKROSYSTEMTECHNIK

„Semiconductor Field Emission Electron Source for Application in Sensors and X-ray Sources“

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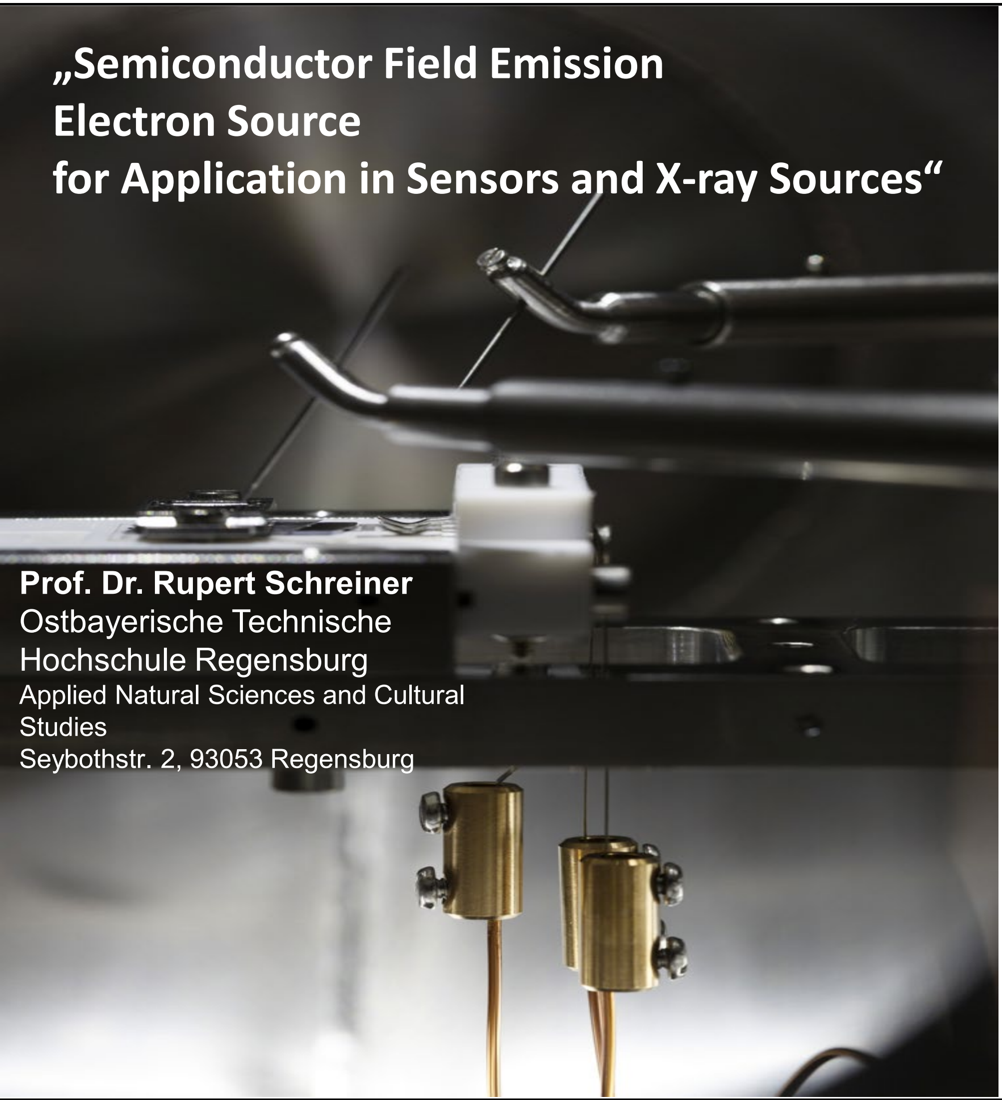

1. Introduction

2. Field emission & field enhancement

3. Si-tip-cathodes: fabrication & characterization

4. FE electron souce

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ALLGEMEINWISSENSCHAFTEN
UND MIKROSYSTEMTECHNIK

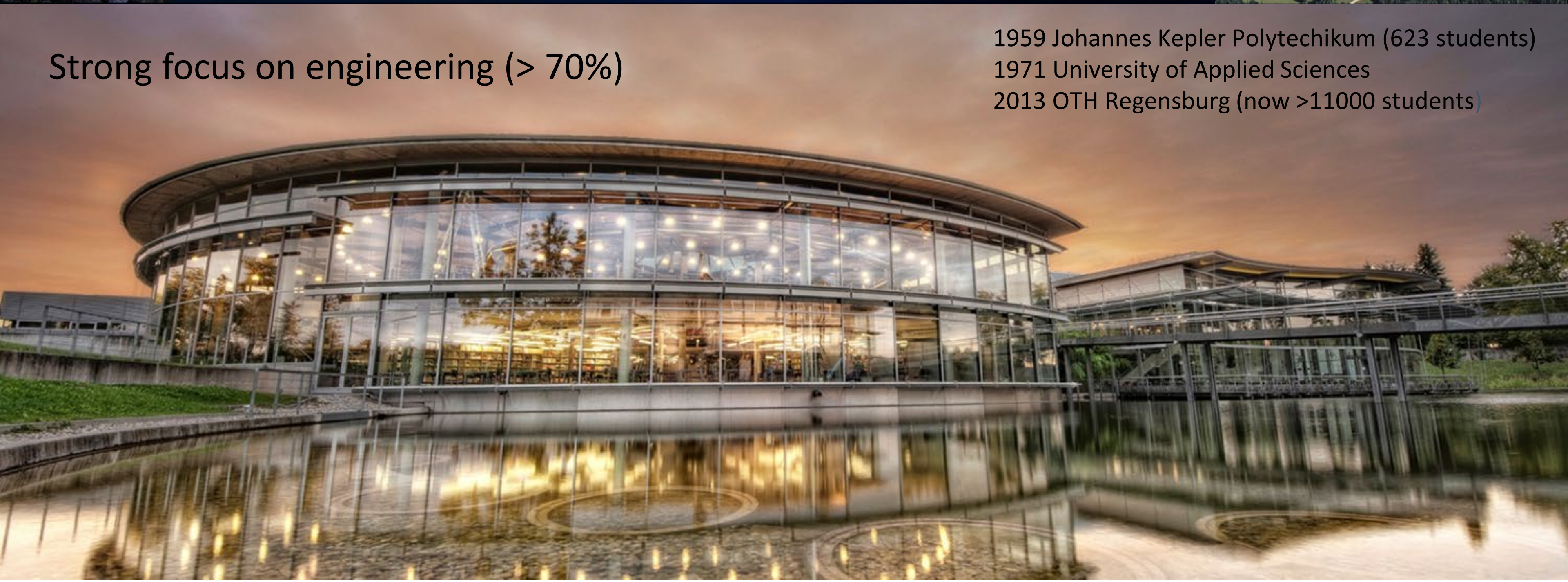
1. Introduction

Ostbayerische Technische Hochschule Regensburg

2 universities – one campus

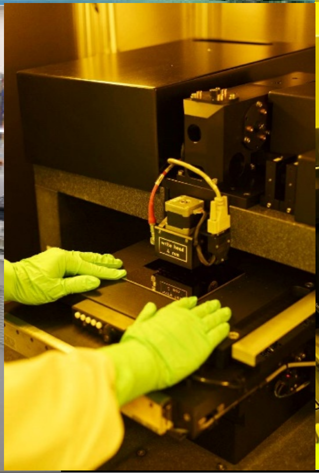
Strong focus on engineering (> 70%)

1959 Johannes Kepler Polytechikum (623 students)
1971 University of Applied Sciences
2013 OTH Regensburg (now >11000 students)

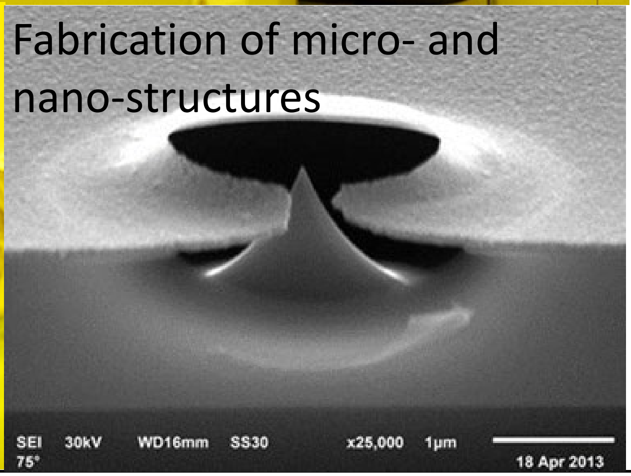


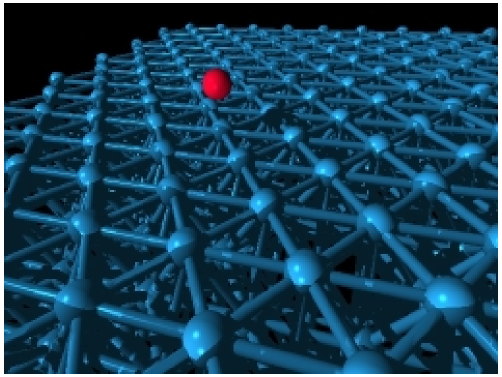
Applied Natural Sciences and Cultural Studies

Microsystems Laboratory



Fabrication of micro- and nano-structures





Nothing is like a vacuum...

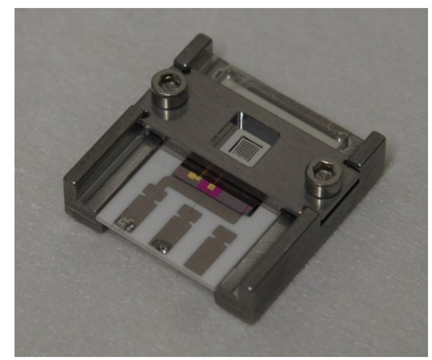
Electrons in a vacuum travel unperturbed from cathode to anode (no scattering, no power-loss, no deceleration)

→ Vacuum tubes can operate at **higher frequencies** and **higher power** than equivalent solid-state semiconductor devices

→ Semiconductor electronics replaced vacuum tubes, not because of their superior technical performance, but because of their reliability, size and cost!

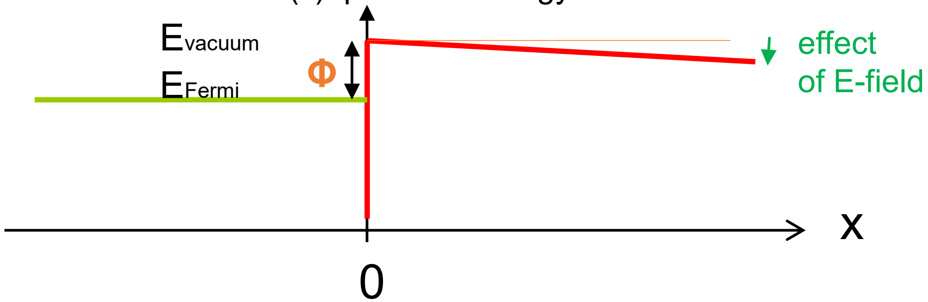
HIFI tube amplifier (Marriola)

Traveling wave tube amplifier for satellite and terrestial communications (Thales, Ulm)



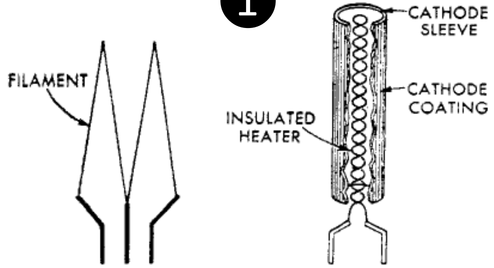
Vacuum nanoelectronics: FE electron source (OTH)

U(x): potential energy of the electrons



How to get the electrons into the vacuum?

1



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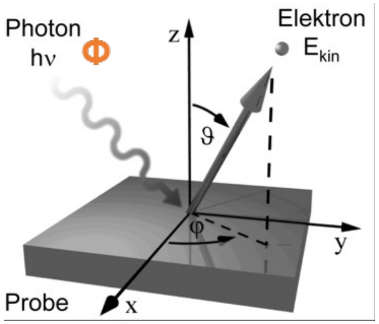

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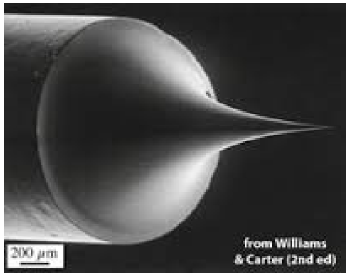
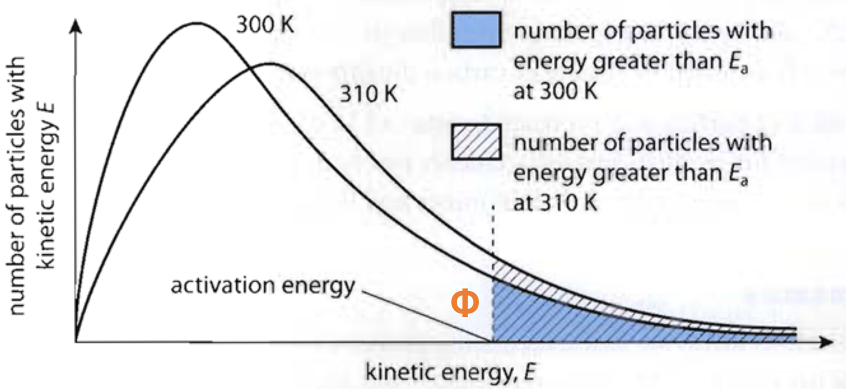
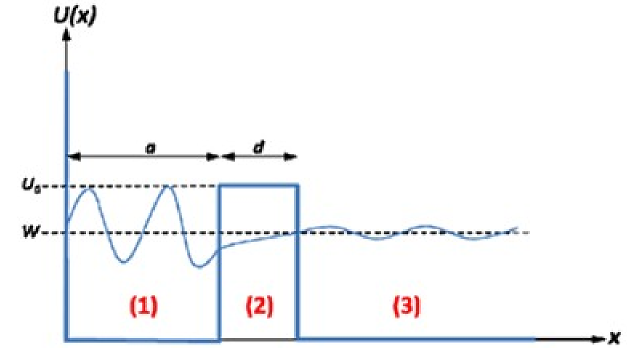
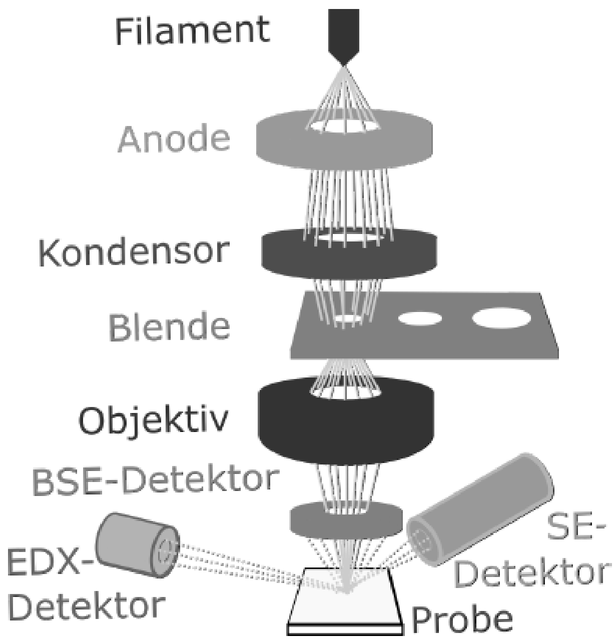




Tunneling through a rectangular barrier:

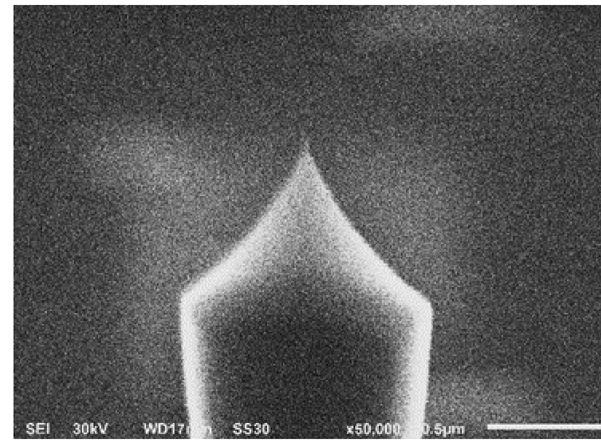


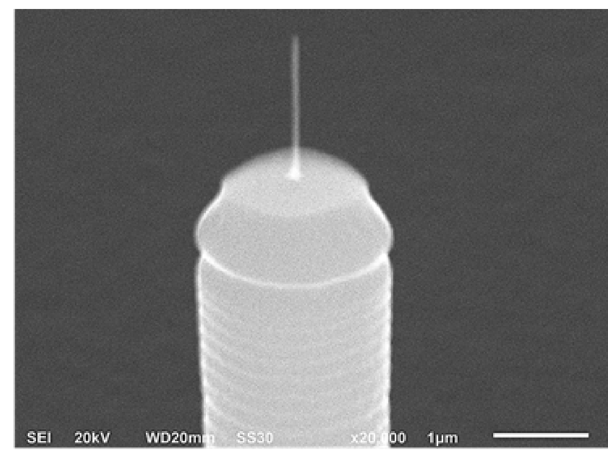
Scanning Electron Microscopy:



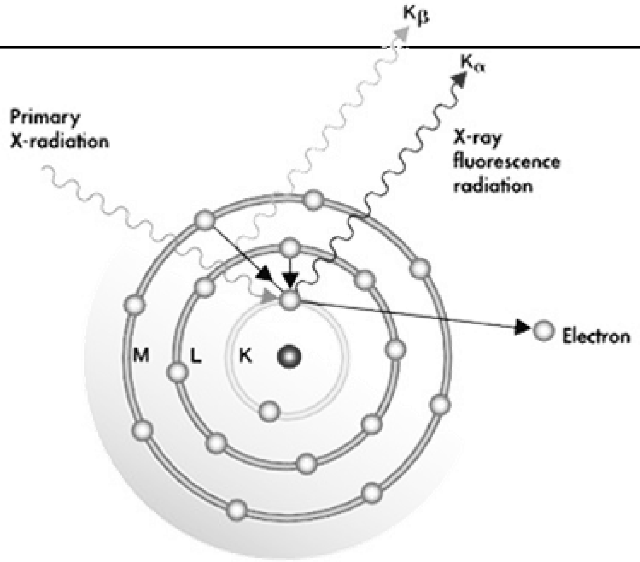
(a)

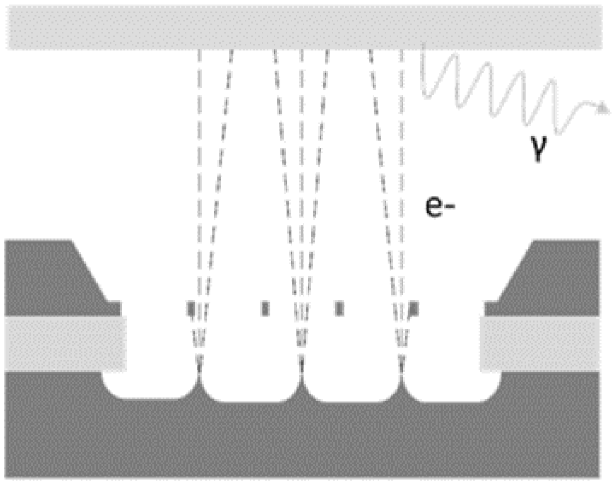
(b)

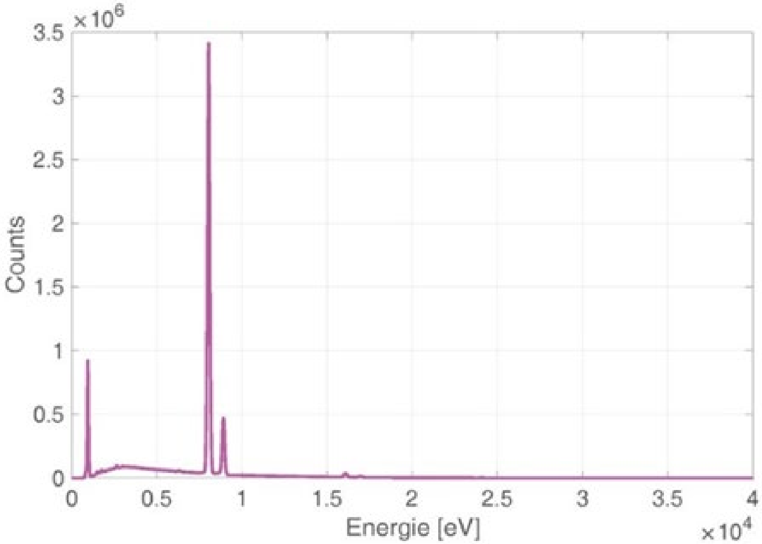




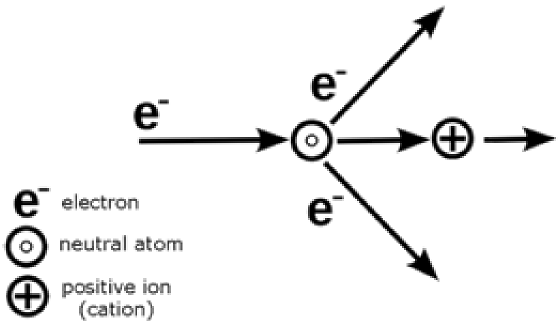
X-ray sources for X-ray fluorescence

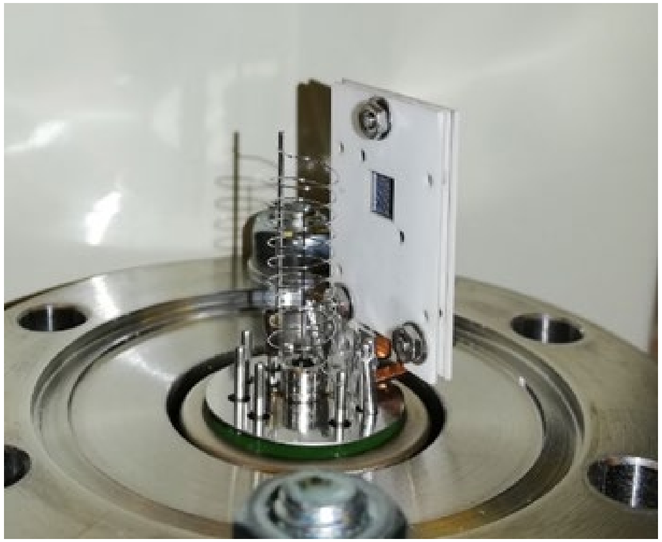


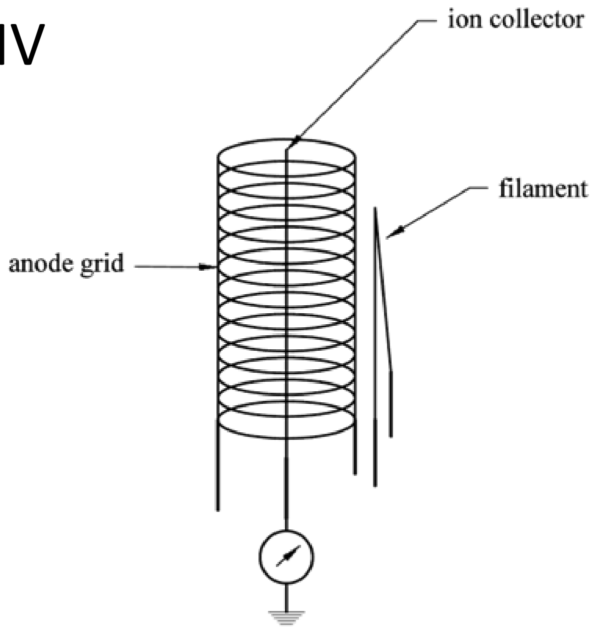


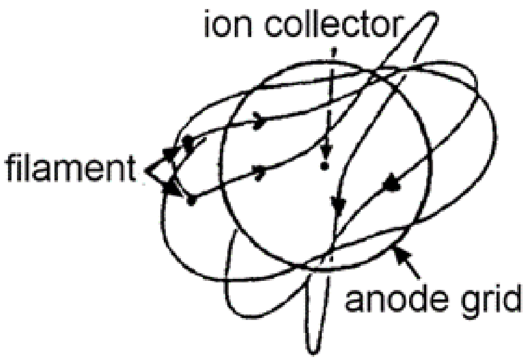


Vacuum measurement in HV, UHV and XHV

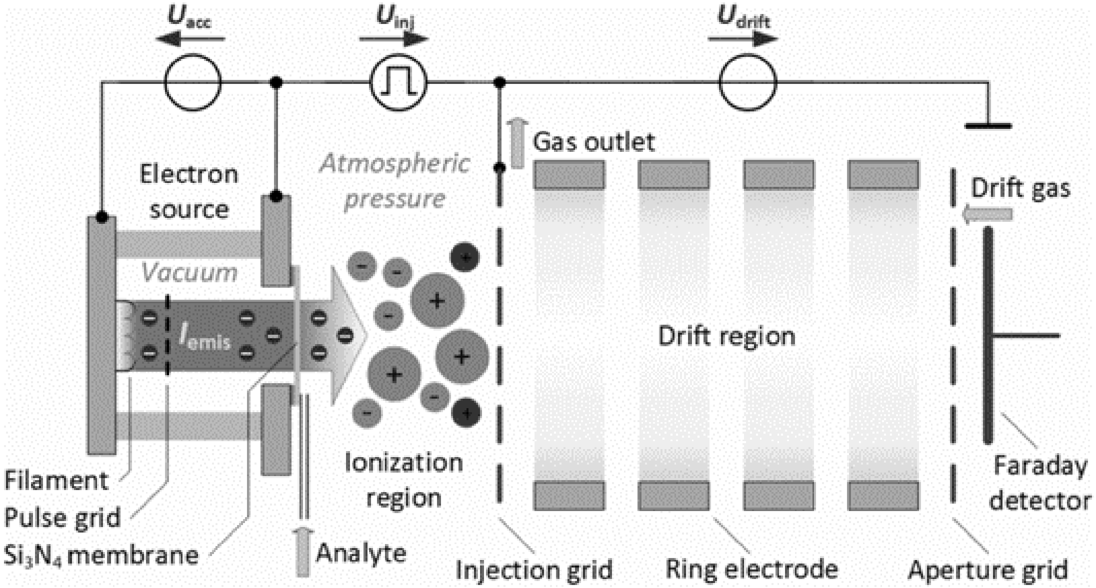


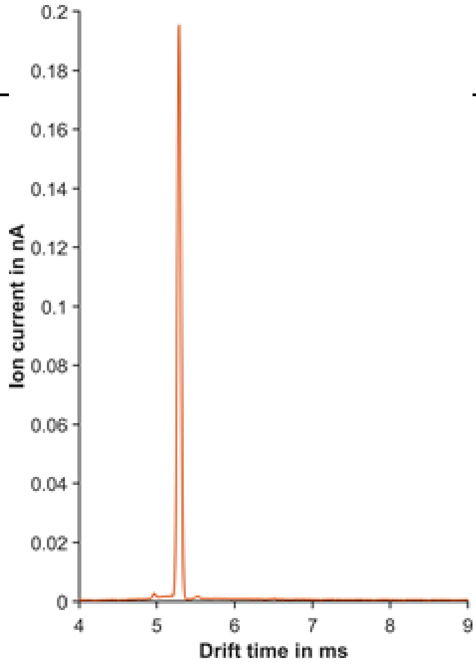


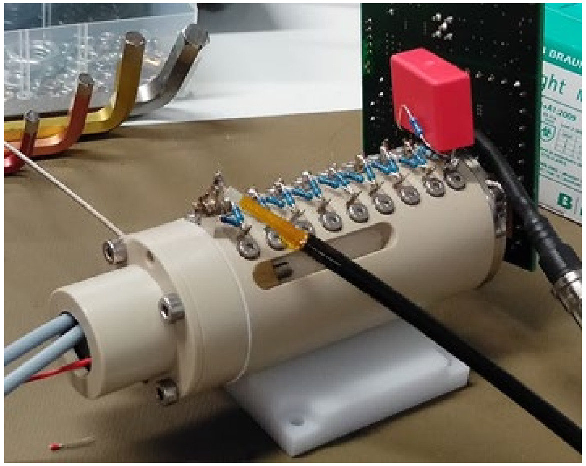




Ion-Mobility Spectrometry





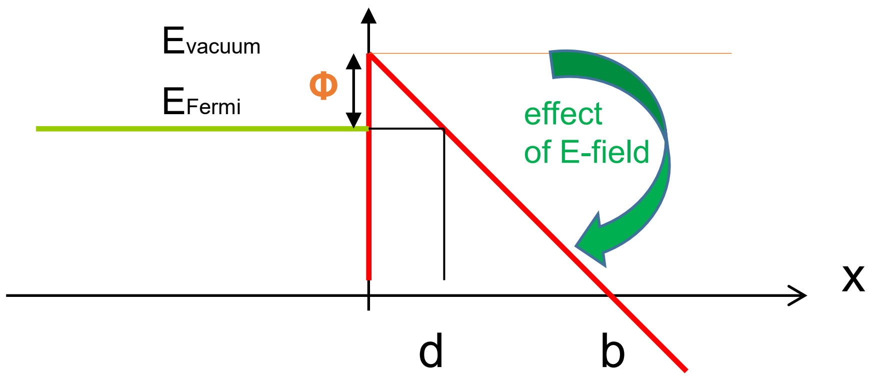


2. Field emission & field enhancement

Field emission: How does it work?

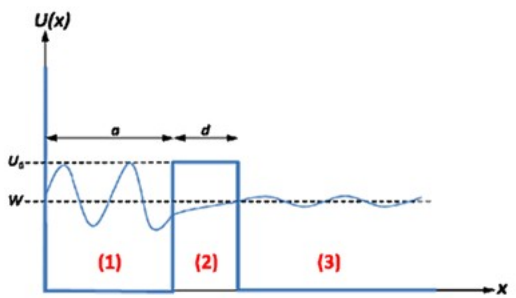
Fowler-Nordheim-tunneling: „planar surface“

U(x): potential energy of the electrons

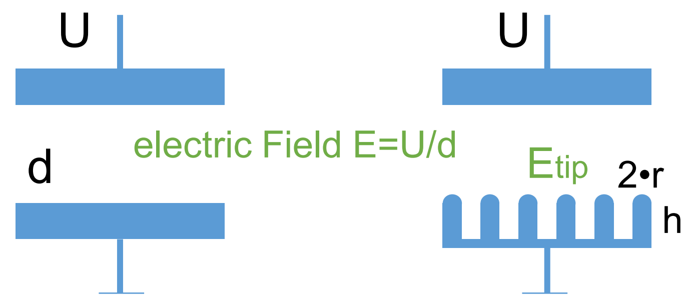


→ **E> 10^8 V/m !**

Tunneling through a rectangular barrier:



Field enhancement : „tips with small curvature“



Etip= βtip • E

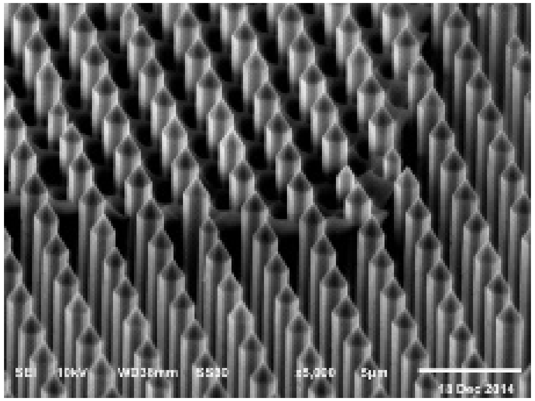
e.g. U=150V, 10µm

βtip ≈ h/r =2,5µm/20nm ≈ **120**

E=15 • 10^6 V/m

Etip ≈ 10^9 V/m

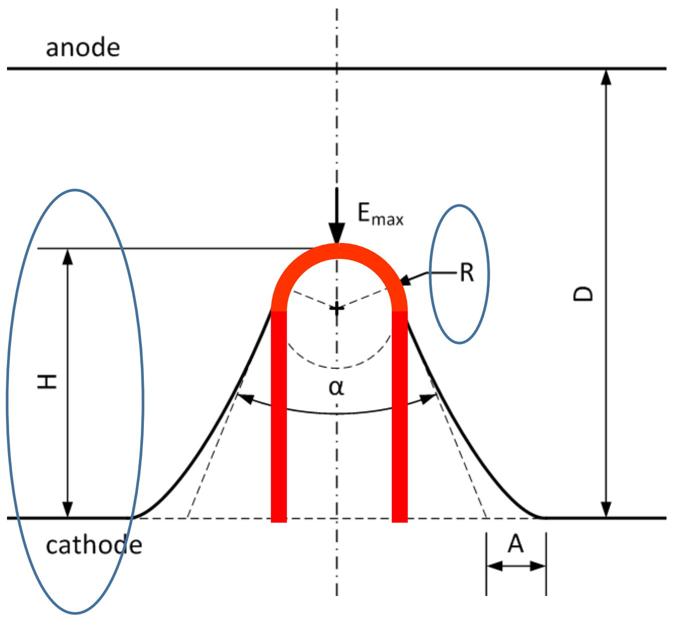
→ Nanostructures

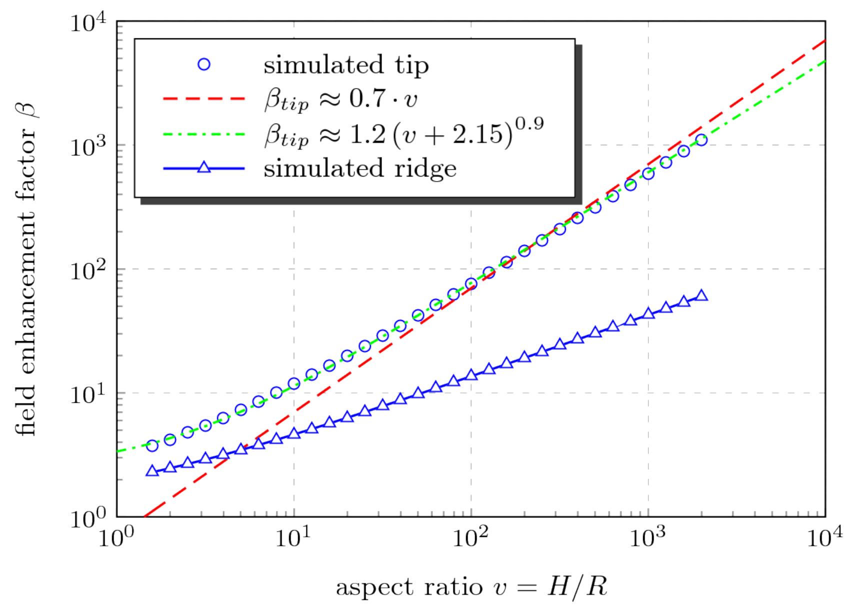


Tip geometry: Simulation

FEM simulations of the field enhancement factor β by Comsol Multiphysics

a) Influence of aspect ratio v=H/R on β: „rounded whisker shape“ (A=0, α=0)





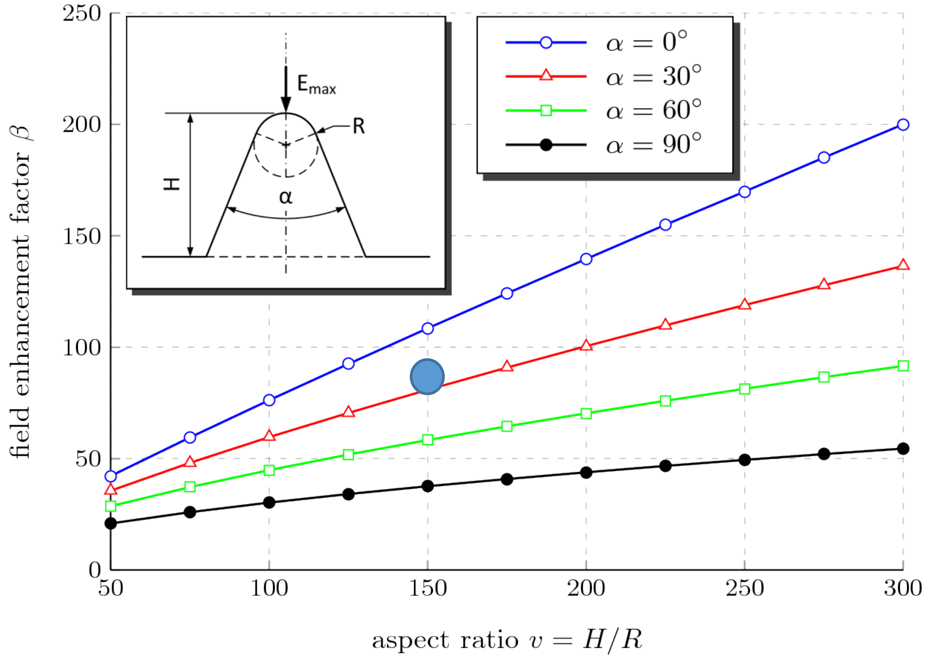
→ in agreement with analytic models

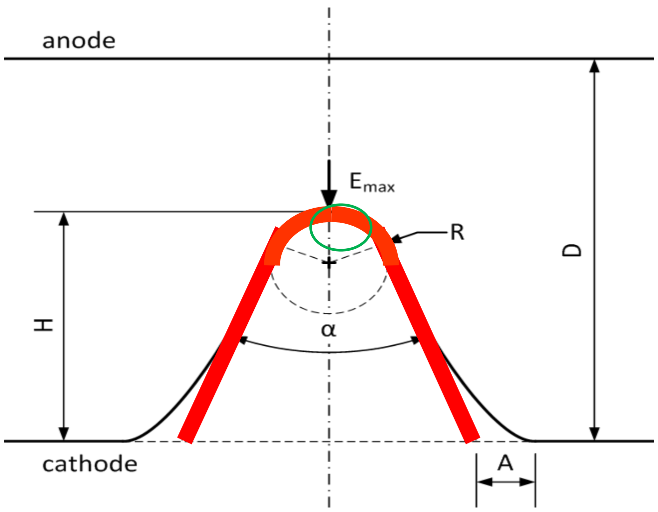
S. Podenok, M. Sveningsson, K. Hansen, E. Campbell, “Electric field enhancement factors around a metallic, end-capped cylinder”, NANO 1 (1), S. 87-93 (2006).

R. Forbes, C.J. Edgcombe, U. Valdrè, “Some comments on models for field enhancement”, Ultramicroscopy 95 (1-4), S. 57-65 (2003).

Tip geometry: Simulation

b) Influence of aperture angle α on β: „rounded cone shape“ (A=0)





v ≈ 150
α ≈ 25°

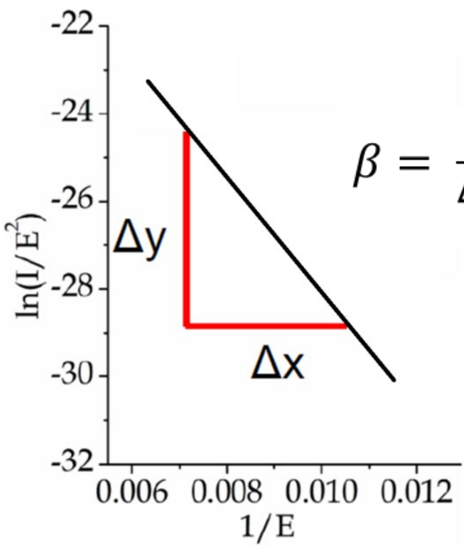
→ β ≈ **80** ≈ 0.5 v

→ Influence of the elliptic curvature can be neglected

→ our Si structures can be described in good approximation by the **rounded cone shape model**

Theory: Fowler-Nordheim-tunneling:

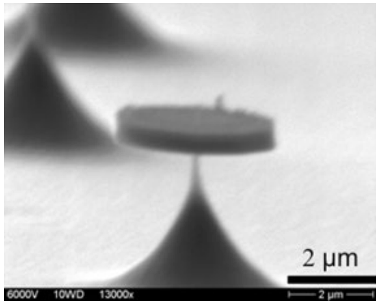
$$j(E) = \frac{A\,E^2}{\Phi} \cdot \exp\left[\frac{B\,\Phi^{\frac{3}{2}}}{E}\right]$$

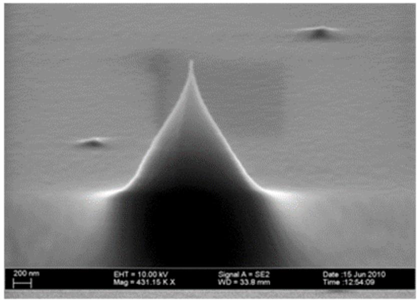


$$\beta = \frac{B\,\Phi^{\frac{3}{2}}}{\Delta y / \Delta x}$$

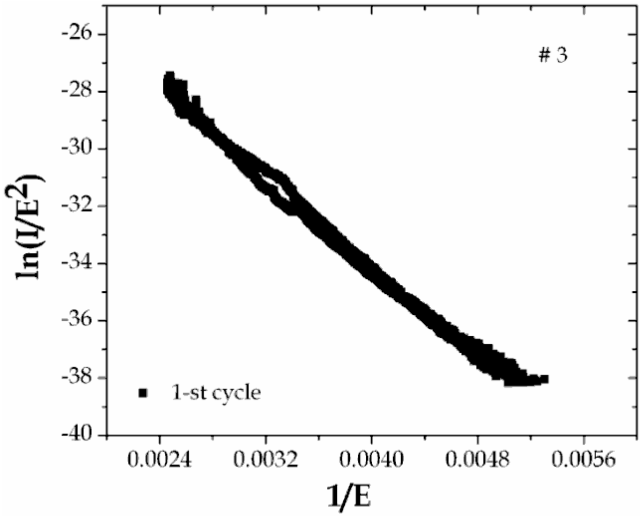
„FN-Plot":

Experiment:





FN-behavior of one conical single Si-tip (n-doped):

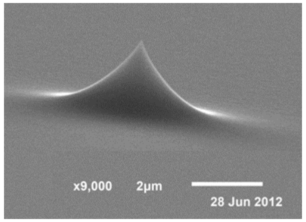


→ β-factors in the order of ~ 100

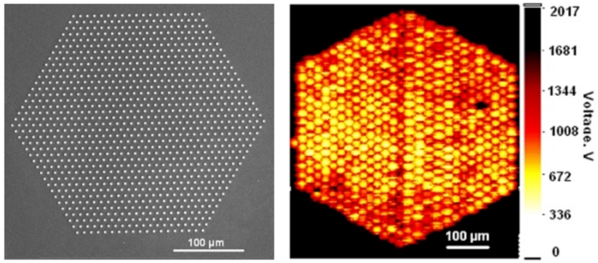
3. Si-tip-cathodes: fabrication & characterization

Experiments

Arrays of conical Si-tips



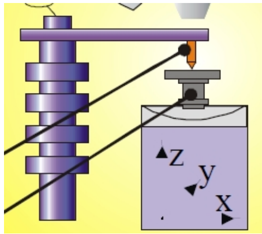
h=1 µm, 1nA, $Z_0 \approx 8$ µm, $Ø_{anode}$= 3 µm



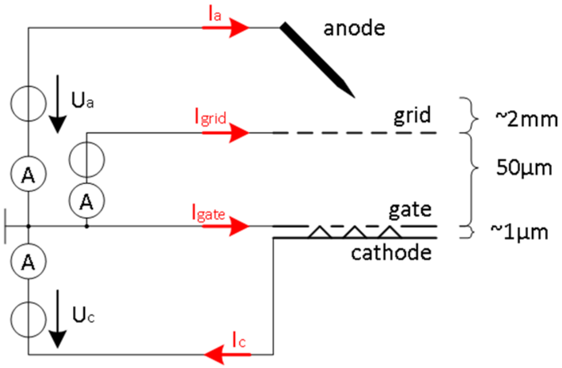
→ homogeneous emission over large areas

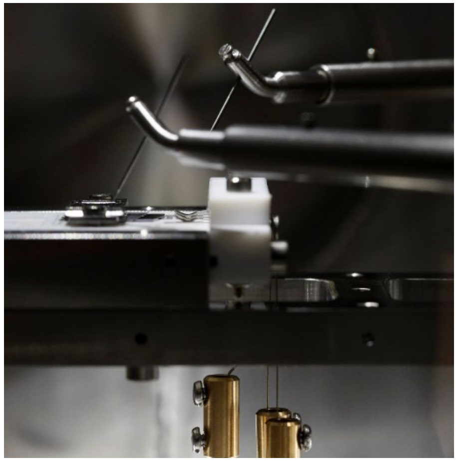
Mo coating (20 nm):
currents up to several µA with only 16 tips

FESM measurements and FE-Electron-Spectroscopy (@ Uni Wuppertal, Prof. Müller)



Integral measurements (@ OTH Regensburg)

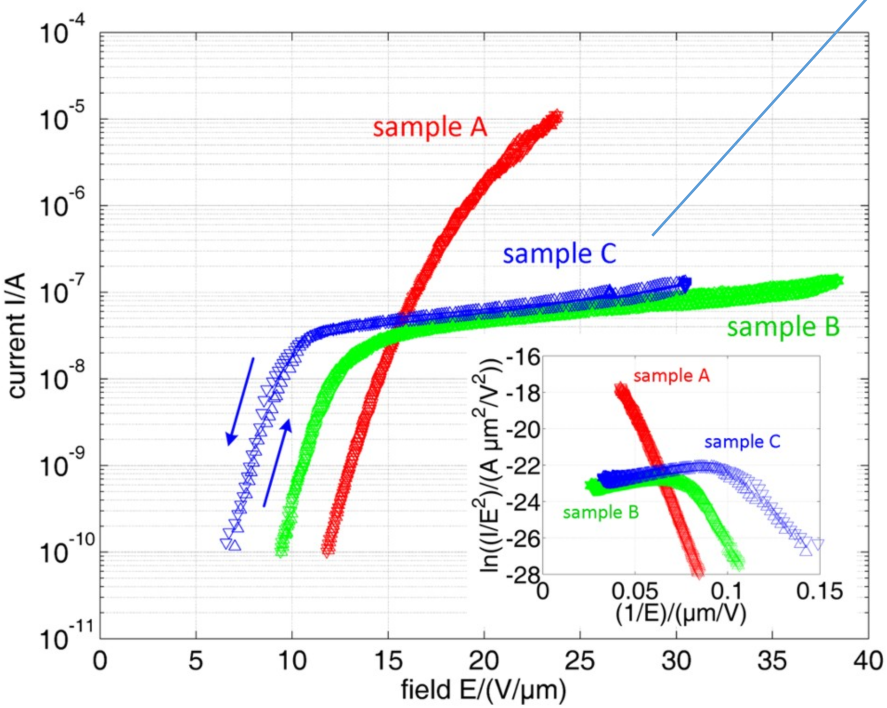


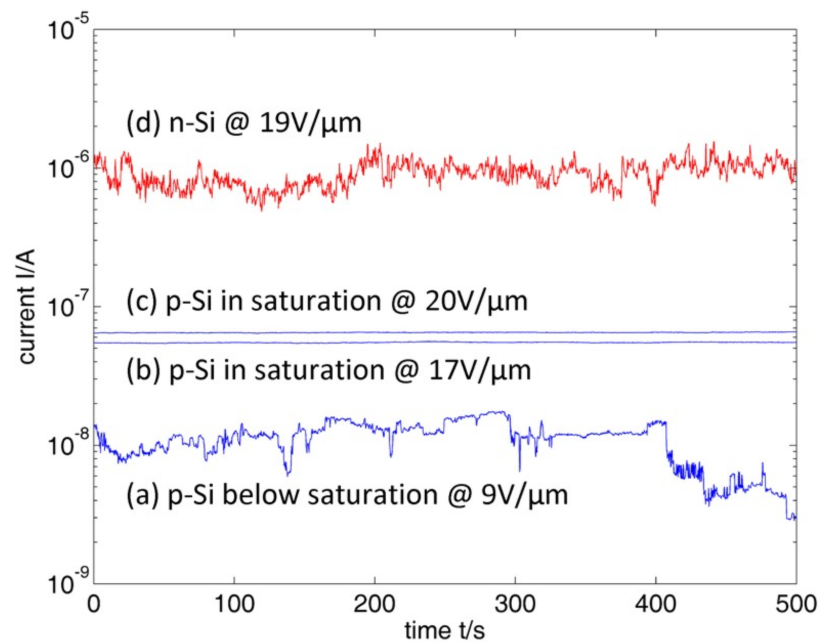


Arrays of 271 Si-tips
Integral Measurements

Sample A: n-doped (< 0:005 Ωcm)
Samples B,C: **p-doped** (1..10 Ωcm)

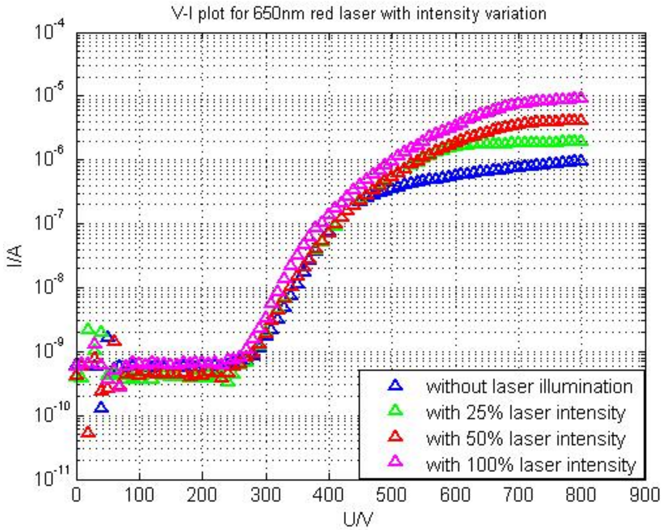
carrier depletion below emitter surface





→ p-Si: FE current saturation and stabilization

3. Si-tip-cathodes: fabrication & characterization



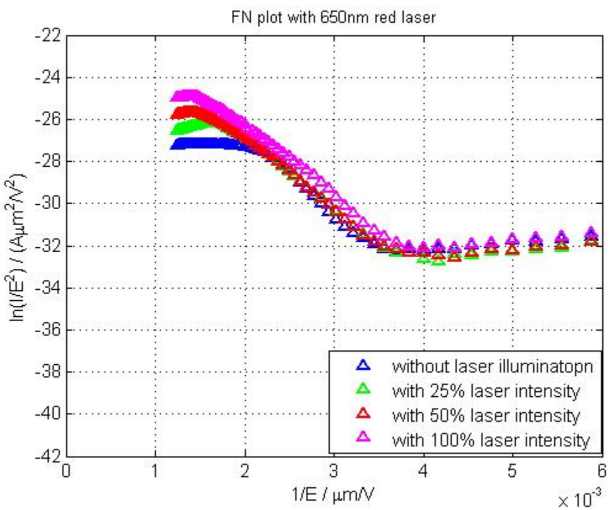
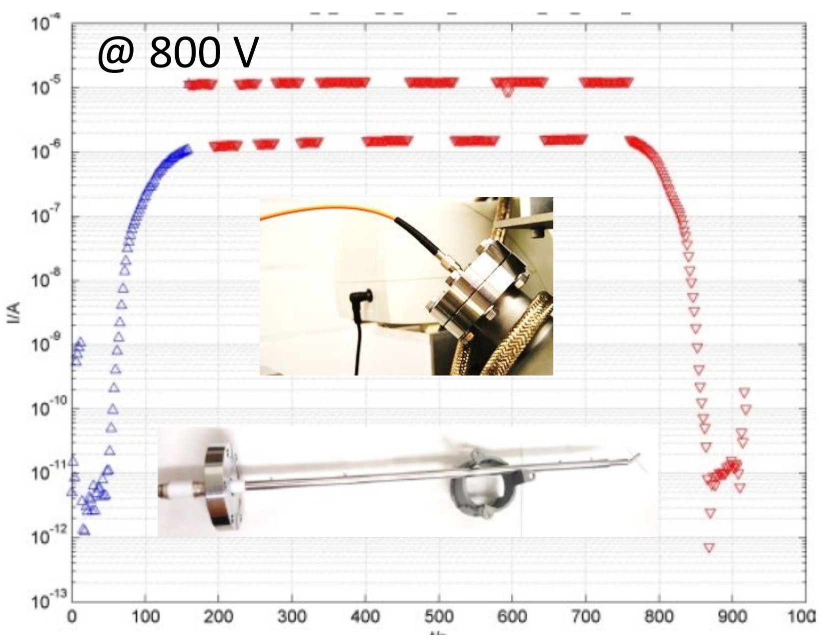


Photo-enhanced field emission

diode laser (650nm, 100mW) coupled into optical fiber

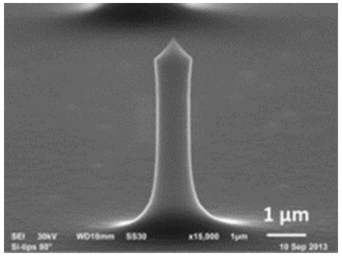
Laser Intensity	PEFE current
Without illumination	1µA
25% laser illumination	2uA
50% laser illumination	5µA
100% laser illumination	10µA



Improved cathode design:

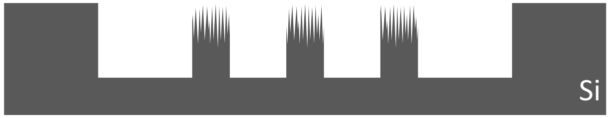
- **Silicon tips with high aspect ratio**

R. Lawrowski et al., in *Vacuum Nanoelectronics Conference (IVNC), 2014 27th International*, 2014, pp. 193–194.
C. Langer et al., in *Vacuum Nanoelectronics Conference (IVNC), 2014 27th International*, 2014, pp. 222–223.

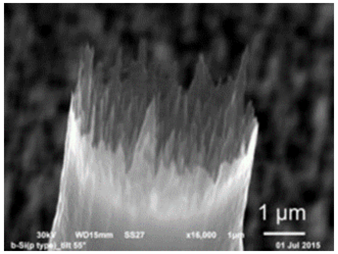


- **Black silicon (on top of pillars)**

C. Langer et al., in *Vacuum Nanoelectronics Conference (IVNC), 2015 28th International*, 2015, pp. 104–105.

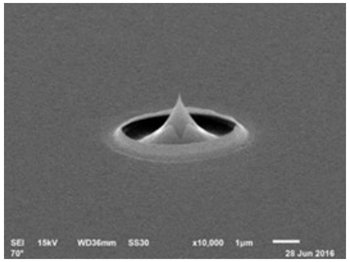


→ low onset fields: 6 V/µm



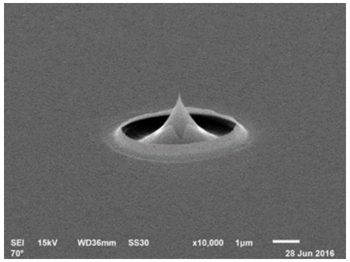
- **Silicon tips with an integrated gate electrode**

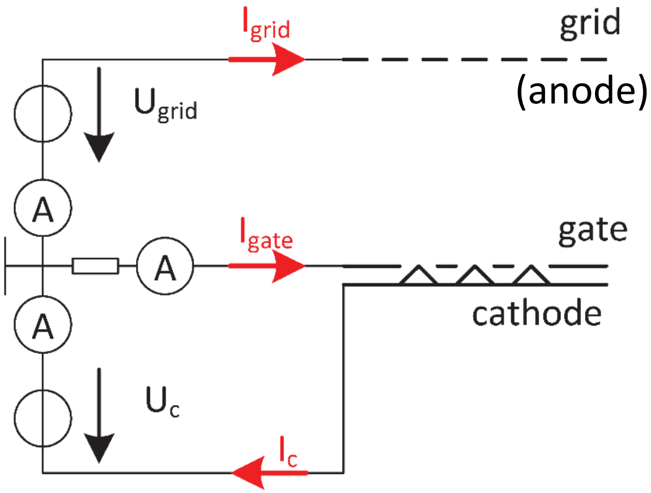
C. Prommesberger et al., in *Vacuum Nanoelectronics Conference (IVNC), 2015 28th International*, 2015, pp. 164–165.

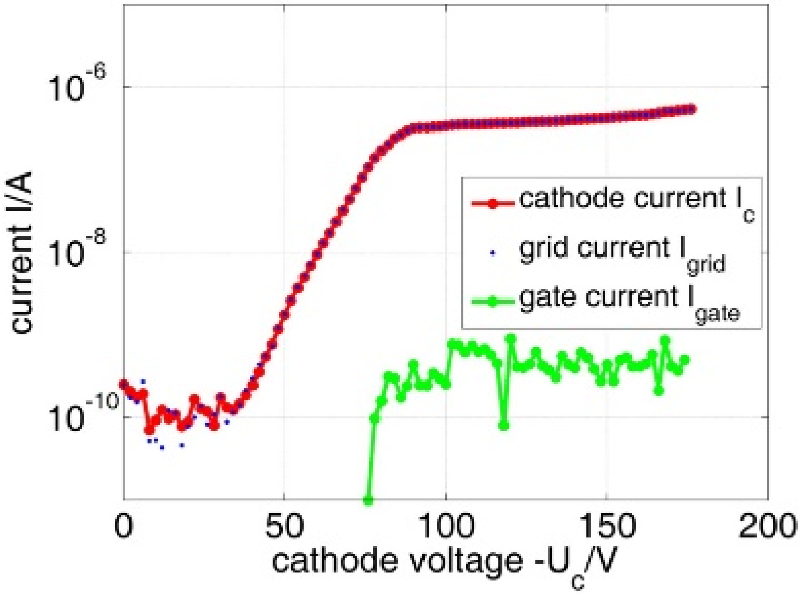


p-Si cathodes with integrated gate structures (Triode configuration)

p-Si: 1..10 Ωcm, Array with 16 tips, Ugrid=400V, Ugate=0V
cathode – anode distance: 50 µm



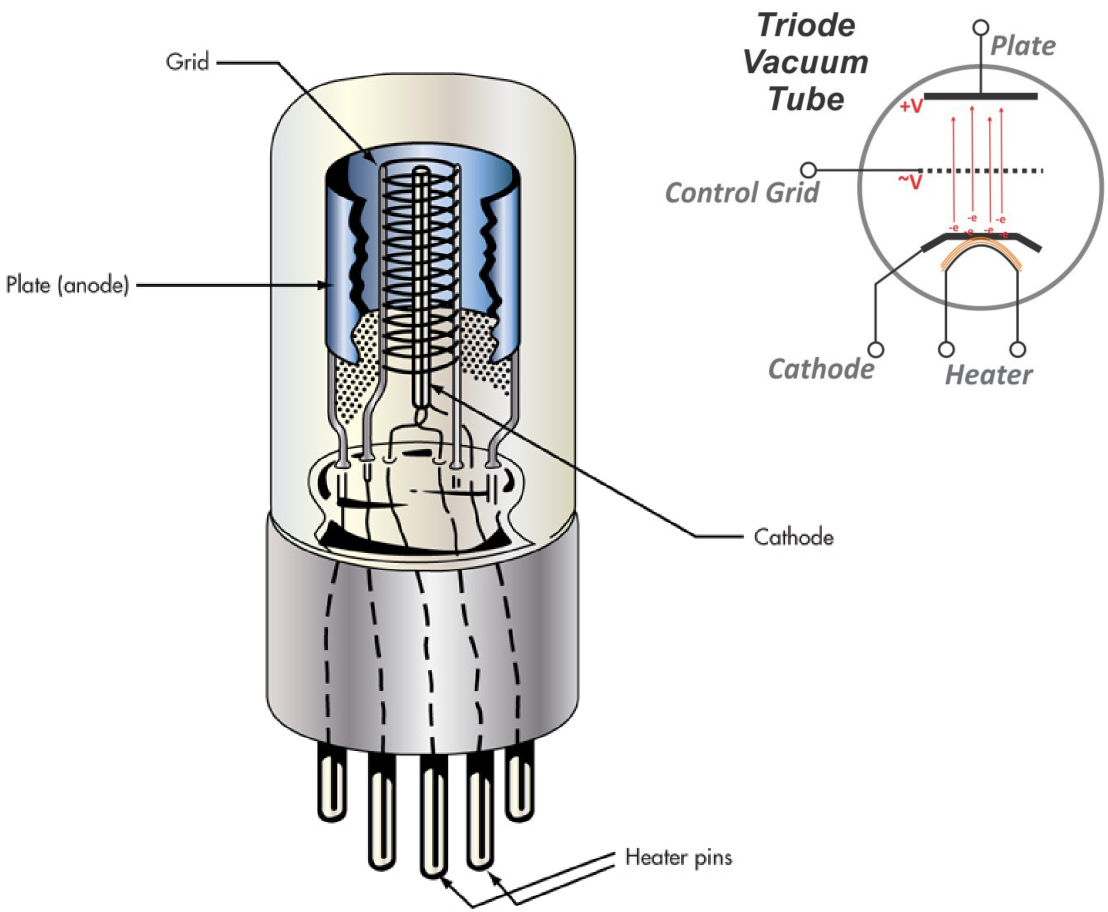


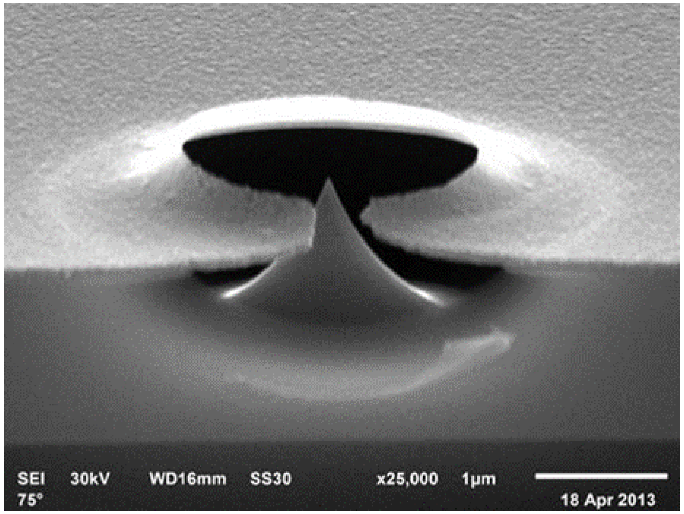


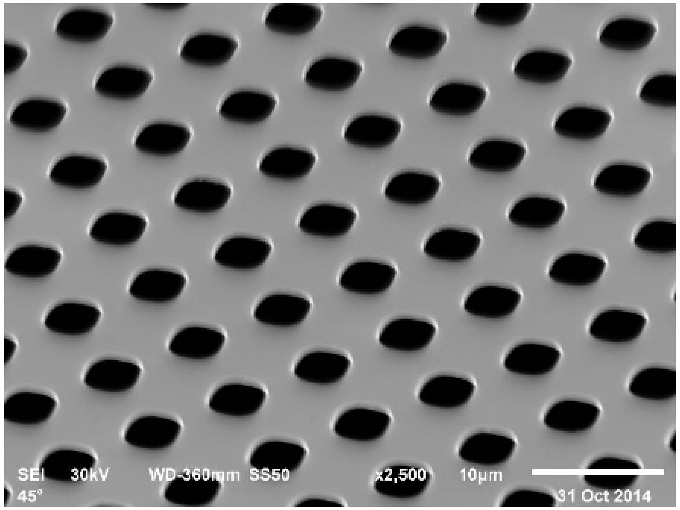
→ I_{gate} can be neglected
→ current fluctuation (for U_c=90…170V) less than 1%

4. FE electron souce

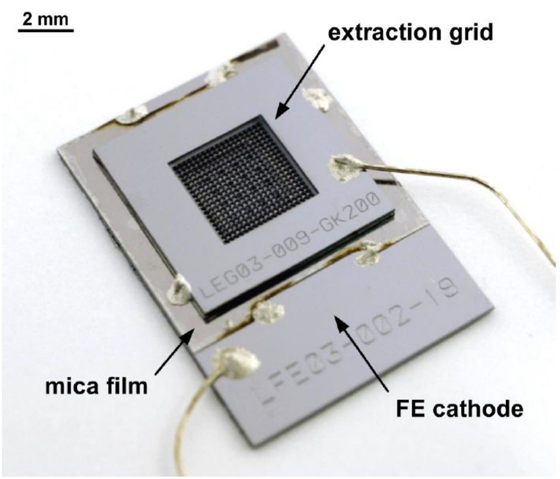
4. FE-Electron-source

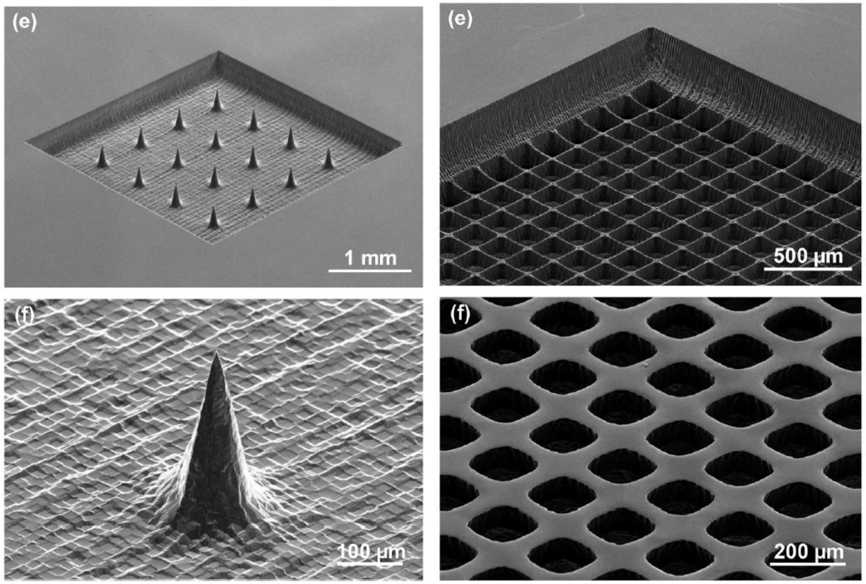




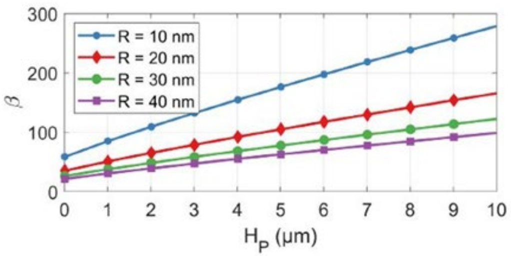


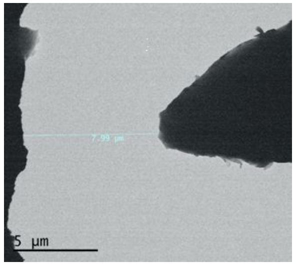
FE electron source on a chip

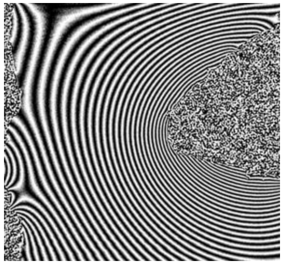




4x4 Array







4. FE-Electron-source

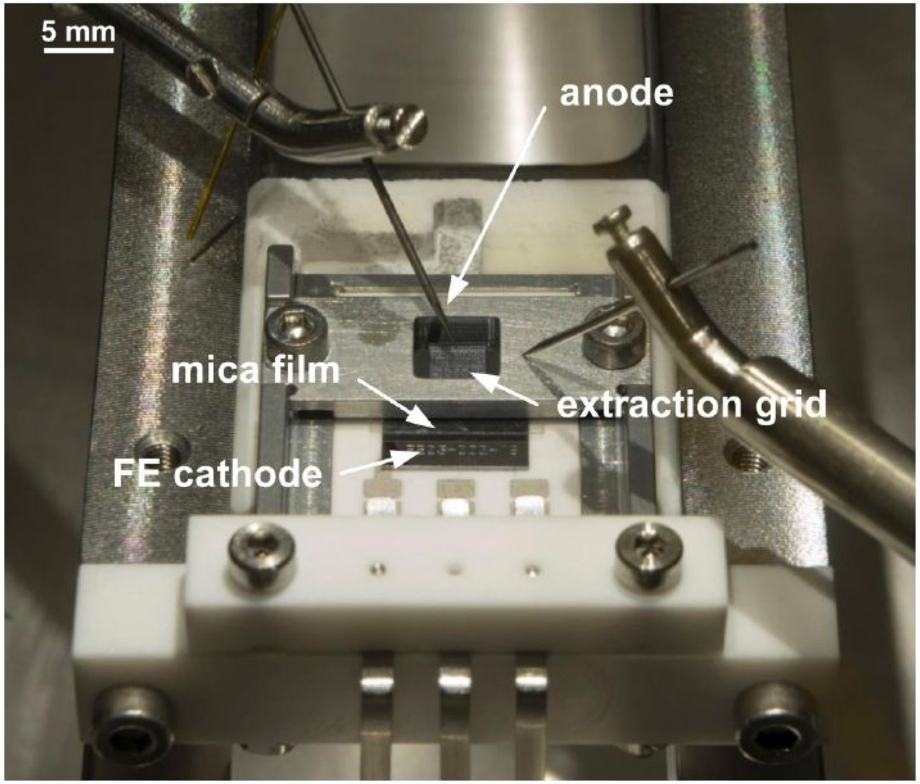


FIG. 5. Modular electron source setup consisting of the FE cathode, the spacer (mica film), and the extraction grid assembled in the aluminum framework inserted in the ultrahigh vacuum system. An optional anode needle is placed above the extraction grid for transmission measurements.

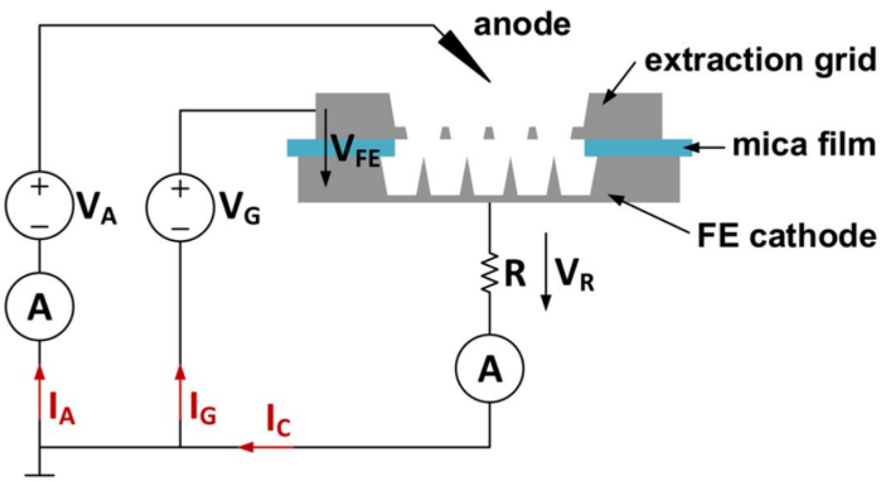


FIG. 7. Schematic drawing of the measurement setup used for characterization of the electron source.

4. FE-Electron-source

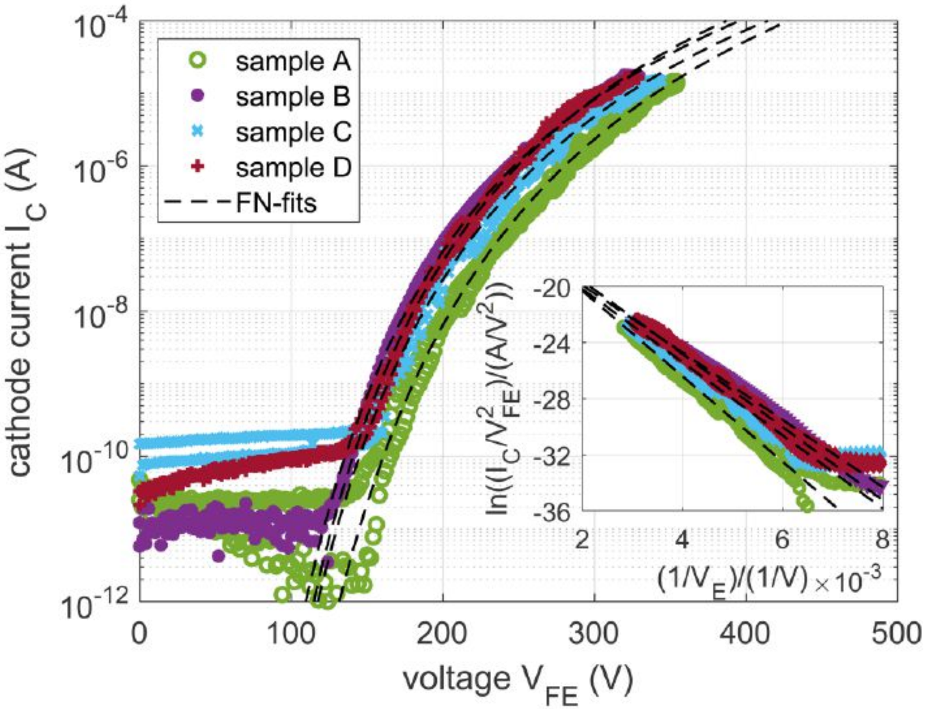
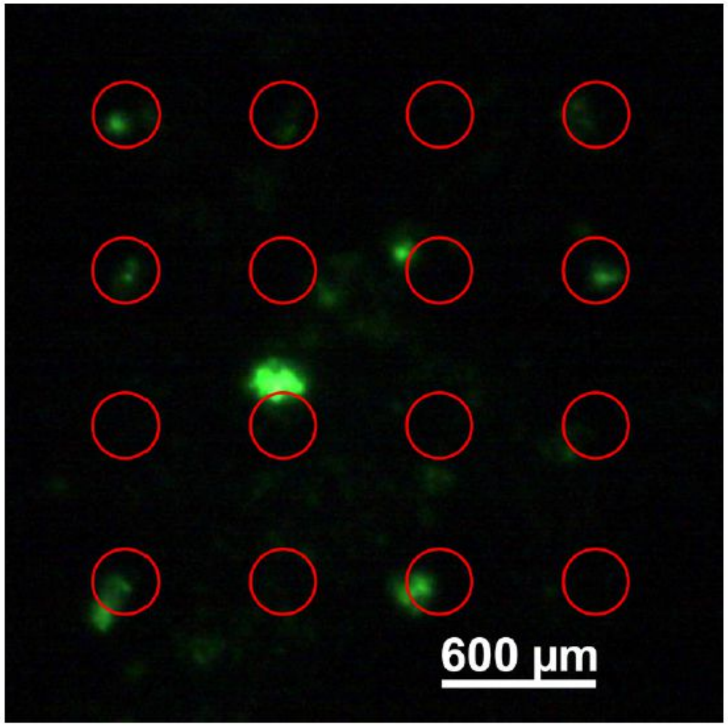
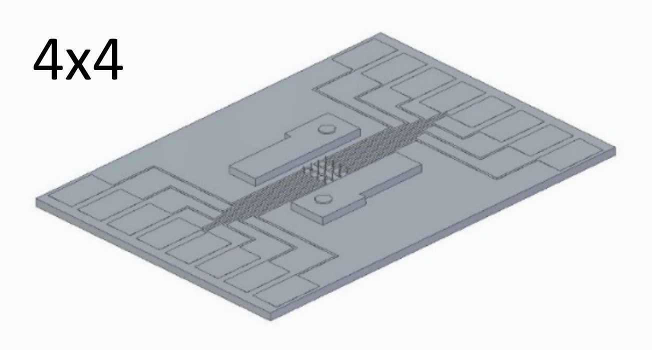


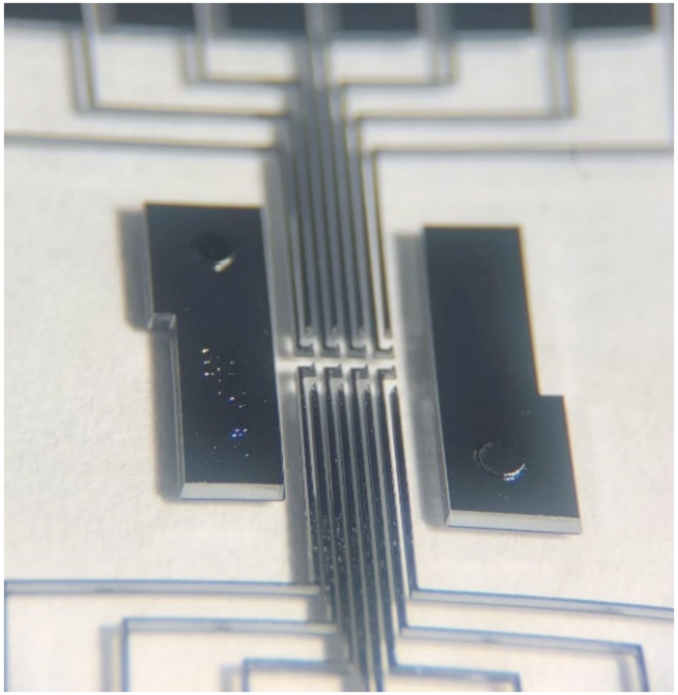
FIG. 9. Representative I–V curves (up- and down-cycle) of the investigated samples and their resulting FN-plots (inset) with the FN-fits: sample A (circles), sample B (asterisks), sample C (x-marks), and sample D (plus-signs).



). Photograph of the emission pattern of sample B using a luminescent The circles indicate the positions of the emitters.

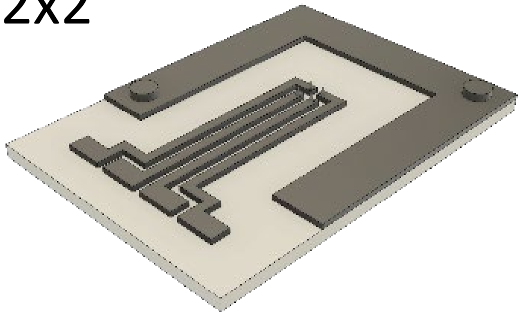
4. FE-Electron-source

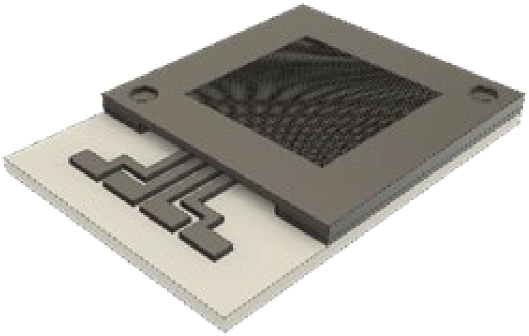


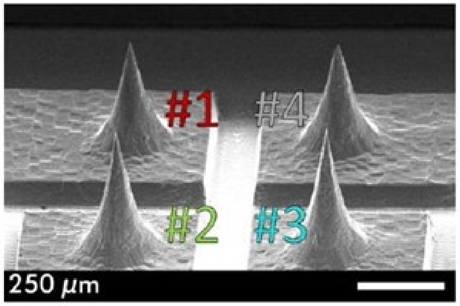


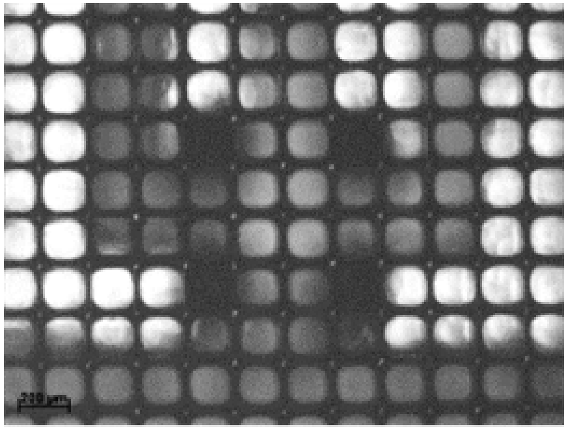
Individual controllable tips

2x2

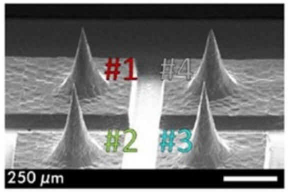








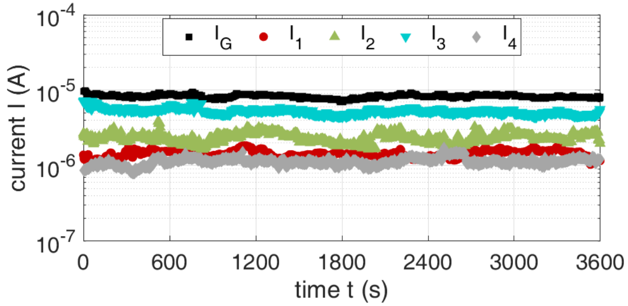
4. FE-Electron-source

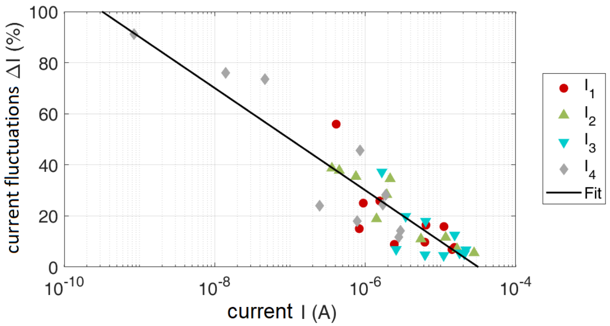


Unregulated operation:

I(t)-plots of the individual emitters (I_1-I_4) and of the total grid current (I_G) of a constant current measurement

(U=1250V, sampling rate 0.5Hz, integration time: 100ms)

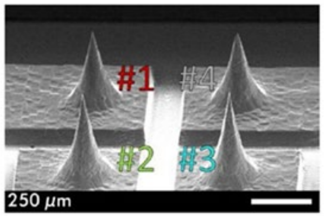


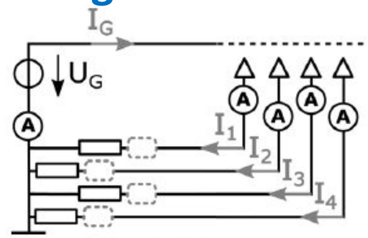


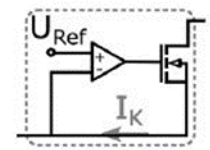
Semi-logarithmic plot of the current fluctuations as a function of the individual currents with a linear fit

(measured for various total emission currents I_G)

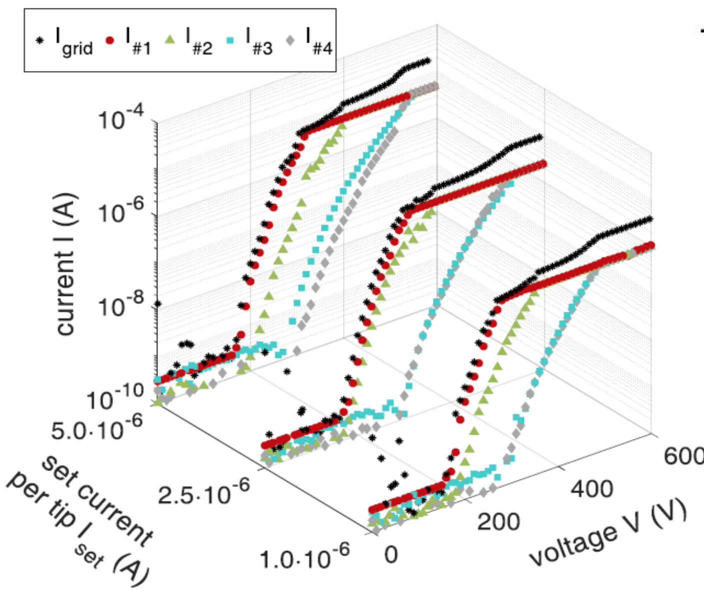
Individual current regulation



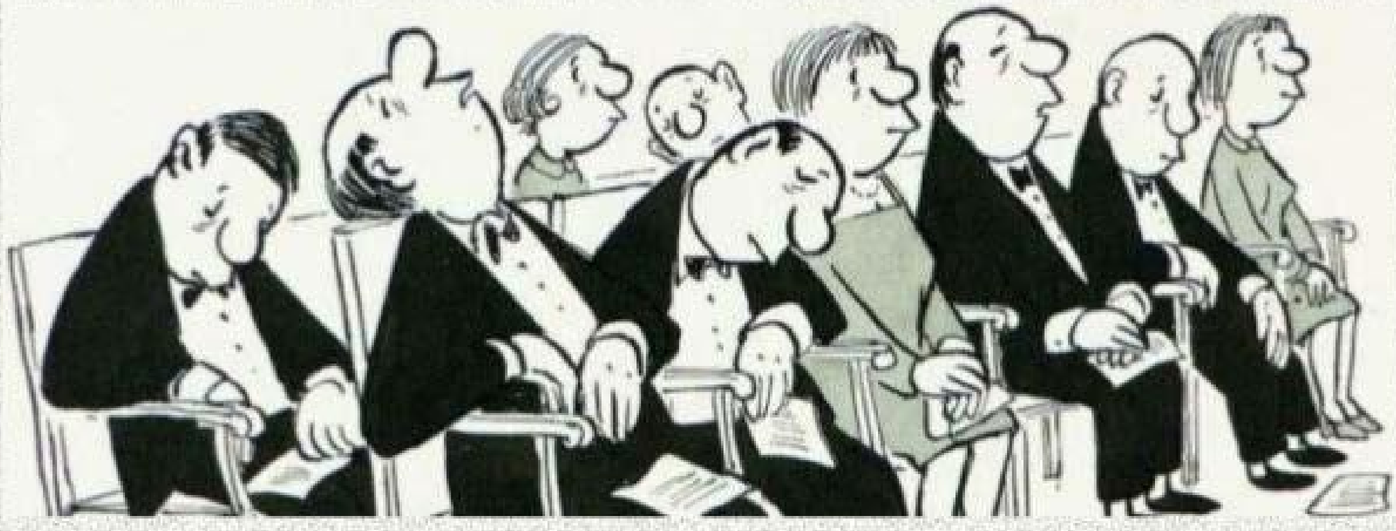




(a)



I-V-plots of the individual emitters (I_1-I_4) and of the grid (I_G) with individual regulated emitter currents (1.0 µA, 2.5 µA, 5.0 µA).



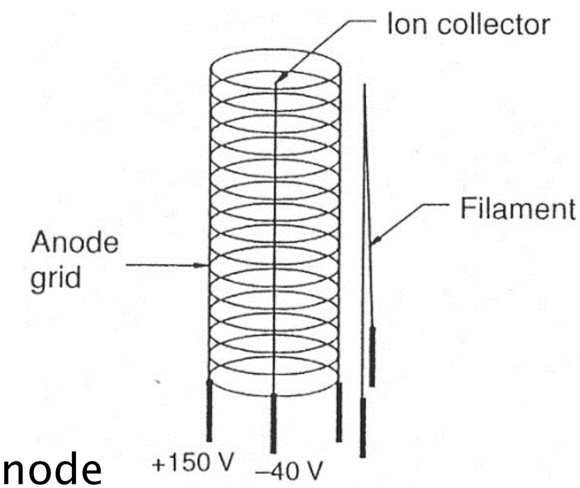
Vielen Dank für Ihre Aufmerksamkeit!

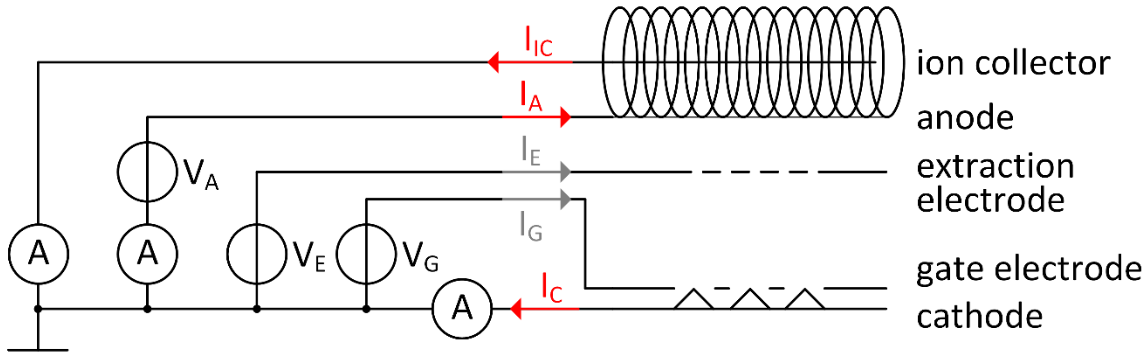
Thank you for your attention!

Seite: 6

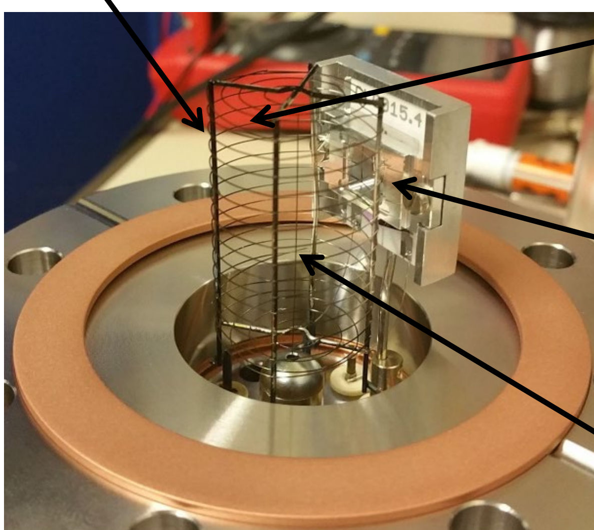
Appendix

Application in an ionisation vacuum gauge





Anode



Ionisation of the residual gas

FE electron source

Ion collector

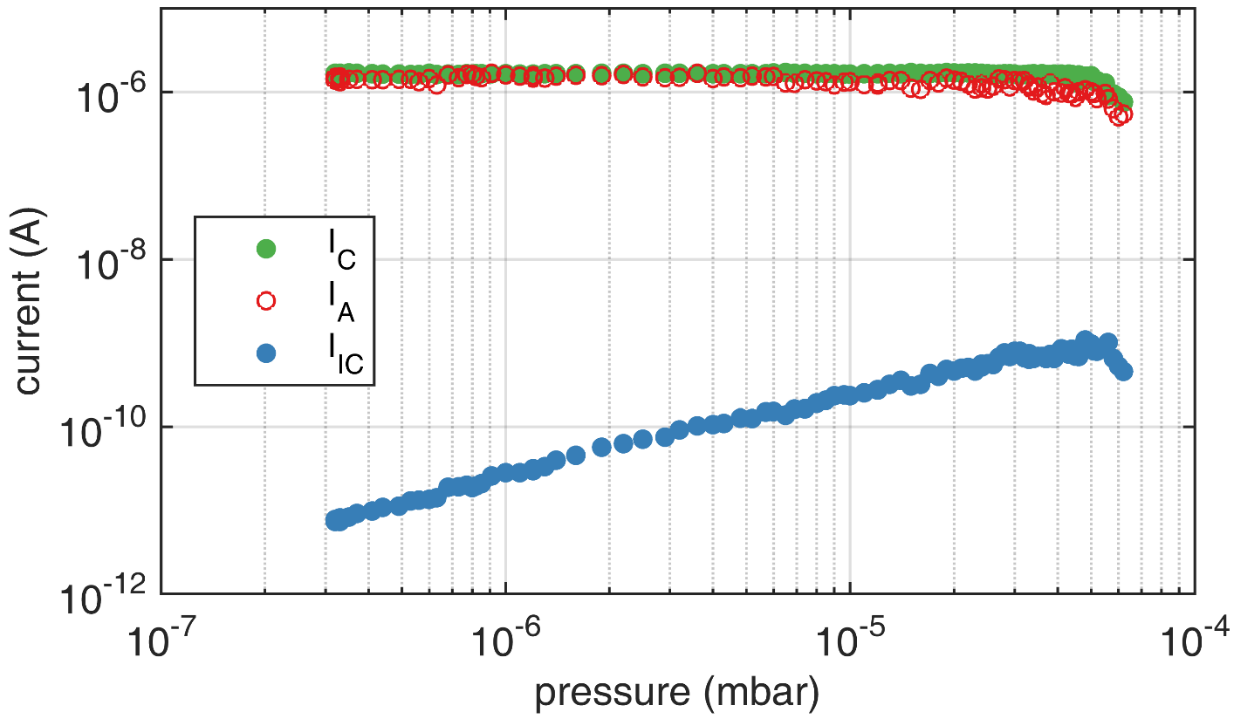
Ion collector = 0 V
Anode voltage = 500 V
Grid voltage = 400 V
Gate voltage = 150 V

FE electron source as a replacement for the hot filament

Application in an ionisation vacuum gauge

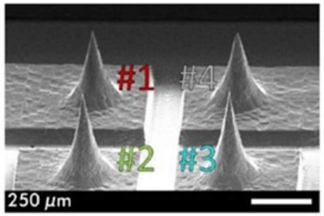
Measurement results

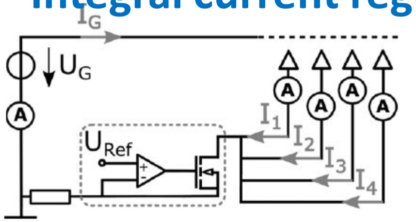
Ion collector current $I_{IC} = I_A * S * p$



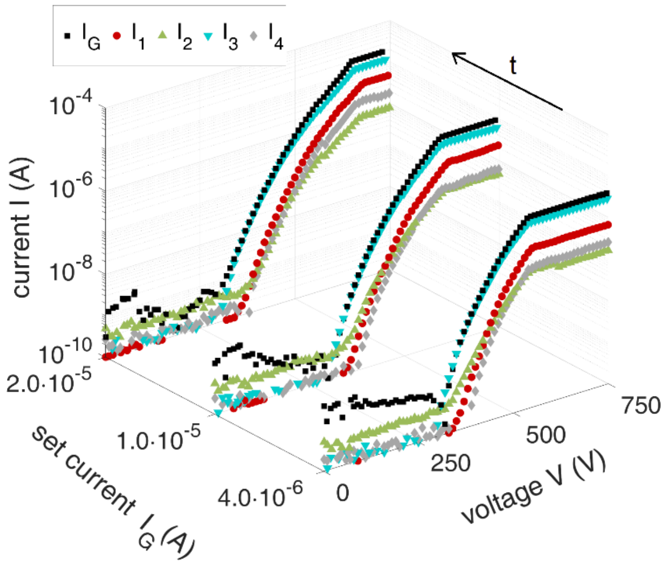
Anode current of 1.3 µA led to an ion current I_{IC} of 7 fA (@ 3 x 10-7) and of 0.8 pA (@ 4 x 10-5 mbar)

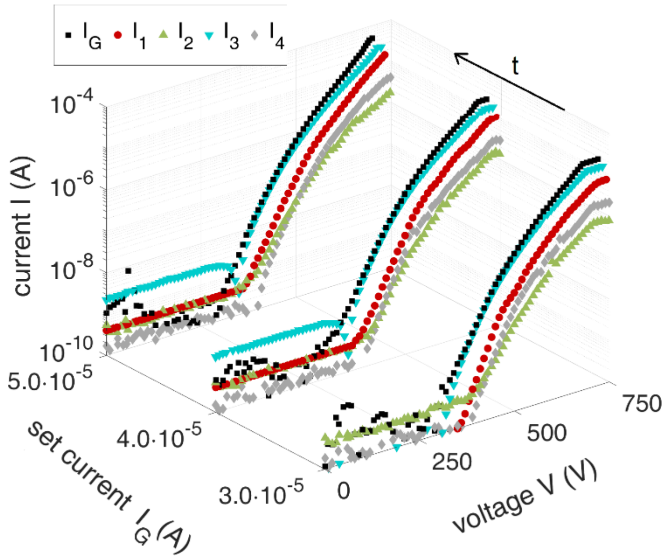
Integral current regulation



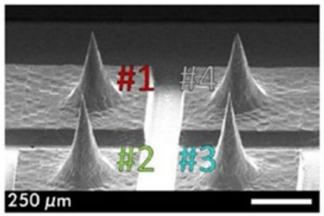


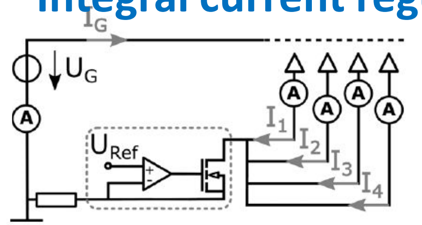
I-V-plots of the individual emitters (I_1-I_4) and of the grid (I_G) with different regulated total emission currents: 4.0 µA, 10 µA, 20 µA (left) and 30 µA, 40 µA, 50 µA (right)





Integral current regulation





I-V-plots of the individual emitters (I_1-I_4) and of the grid (I_G) with different regulated total emission currents: 4.0 µA, 10 µA, 20 µA (left) and 30 µA, 40 µA, 50 µA (right)