Cryogenic Field Emission enhancement in Vertically Aligned Carbon Nanotubes Cold Cathodes through Tip morphology engineering

Dr. Luca Cecchini

IVEW & IVeSC Conference 2026

INFN Sezione di Roma
Sapienza Università di Roma
Titan Lab

August 27°, 2026

TITAN Laboratory

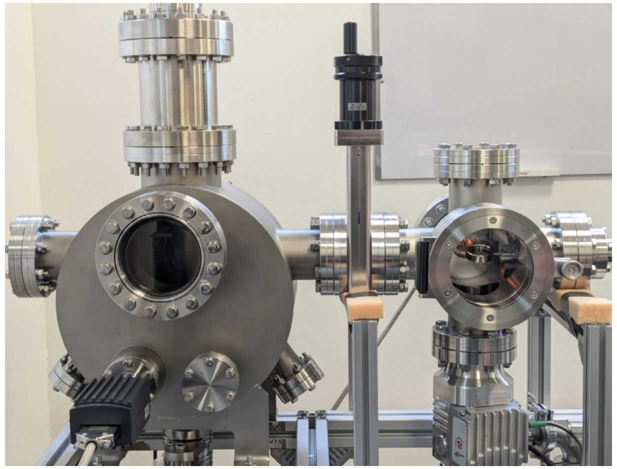
Sapienza University
Department of Physics

People
Prof. Gianluca Cavoto
Dr. Francesco Pandolfi
Dr. Ilaria Rago
Dr. Luca Cecchini
Mrs. Benedetta Corcione

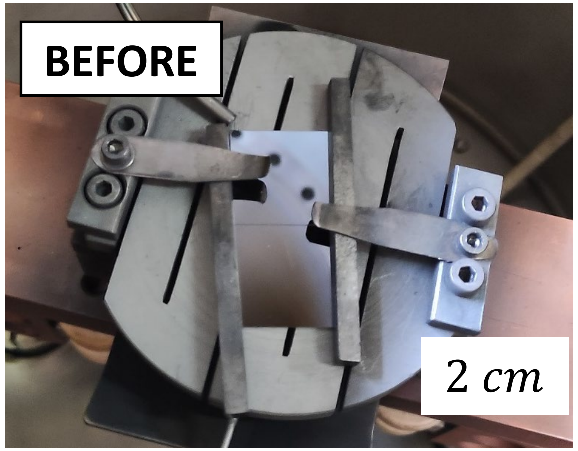
TITAN LAB
TECHNOLOGY INNOVATION THROUGH ADVANCED NANOSTRUCTURES

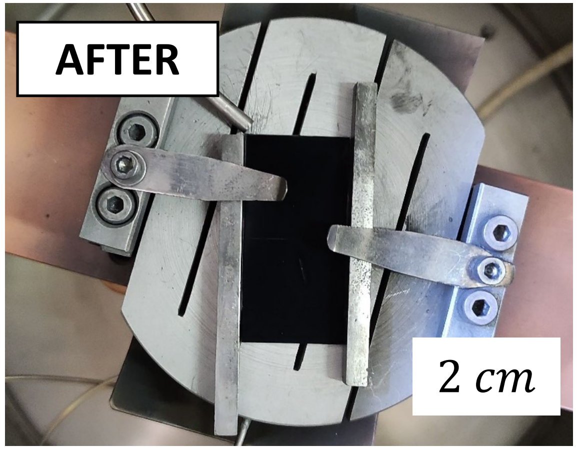
Custom UHV machines
- PECVD
- E-beam Evaporator
- Field emission and Photoemission

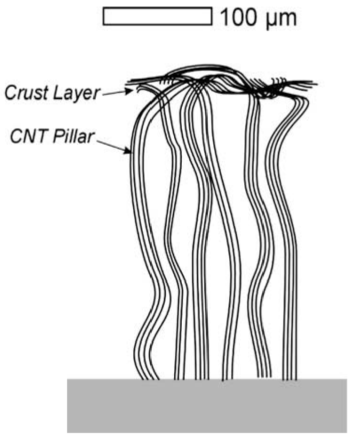
Working Area
- Electron Cold Cathodes
- Target for Dark Matter detection
- Hydrogen & Tritium adsorption
- Composite materials for Additive Manufacturing

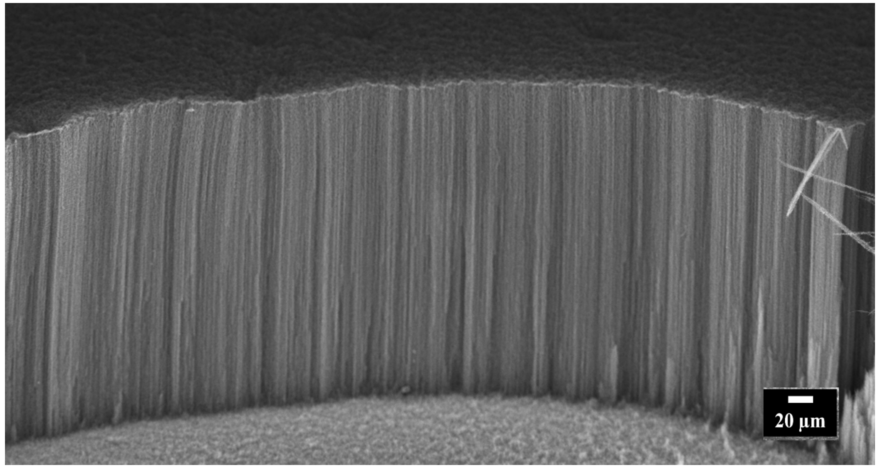


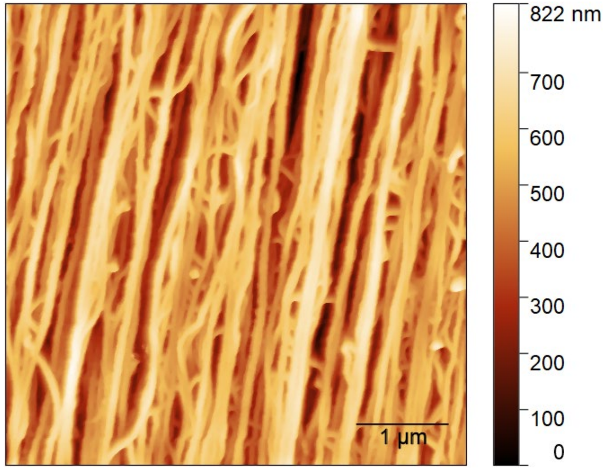
Vertically Aligned Carbon Nanotubes

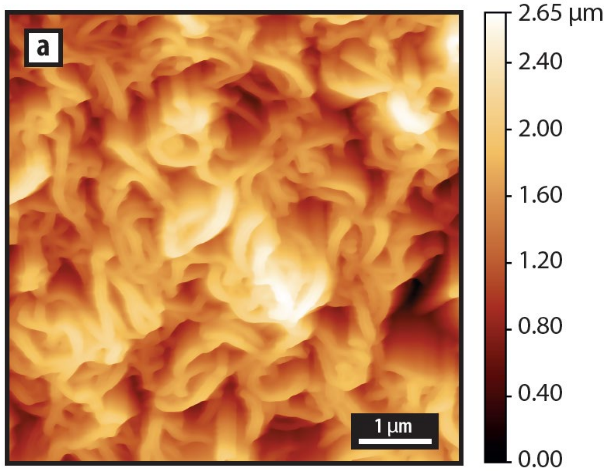












Cryogenic Field Emission

Fowler-Nordheim Equation

Assumptions	Experimental
❑ T = 0K	(T = 2.8K)
❑ In Vacuum	(p = 10^{-7}mbar)
❑ Metal structure	(MWCNTs)

$$J = \frac{a(\beta E)^2}{\phi} \exp\left(-\frac{b\,\phi^{\frac{3}{2}}}{\beta E}\right)$$

❑ Parallel-plate configuration ('MiC')

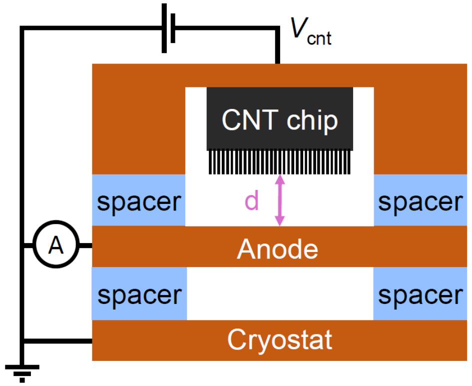
$$\mathrm{I} = \frac{aA(\beta V)^2}{\phi d^2} \exp\left(-\frac{b\,d\,\phi^{\frac{3}{2}}}{\beta V}\right)$$

Field Enhancement Factor

$$\boxed{\beta = b\,\frac{d\,\phi^{\frac{3}{2}}}{s}}$$

Characterization of:

- ❑ ϕ Work function
- ❑ d Effective anode-cathode distance
- ❑ s Slope of FN curve
- ❑ b is a constant

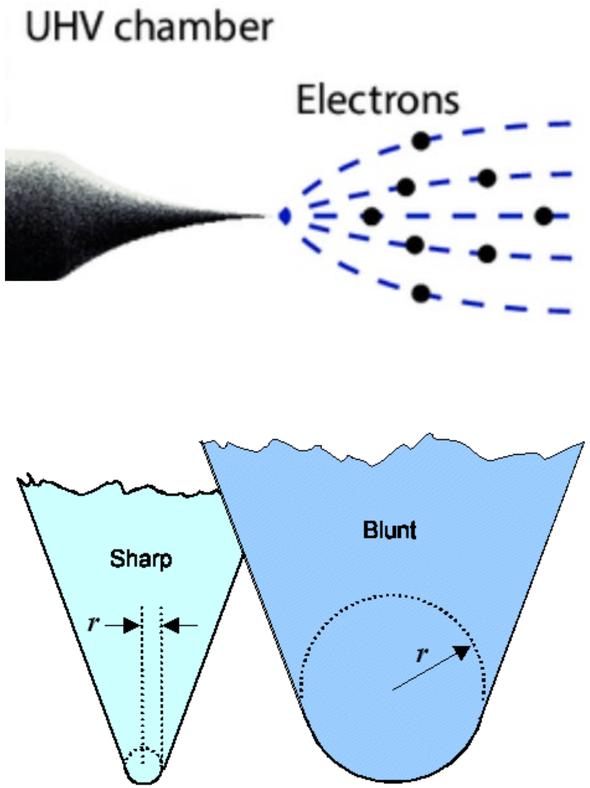


How to enhance performance?

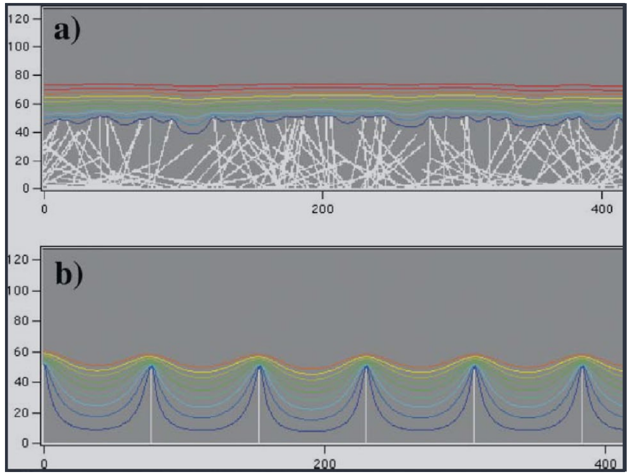
Geometrical dependence

$$\boxed{\beta \simeq \left(\frac{1}{r_c}\right)}$$

Smith, R. C. & Silva, S. R. P. Interpretation of the field enhancement factor for electron emission from carbon nanotubes. *Journal of Applied Physics* **106**, 014314 (2009).

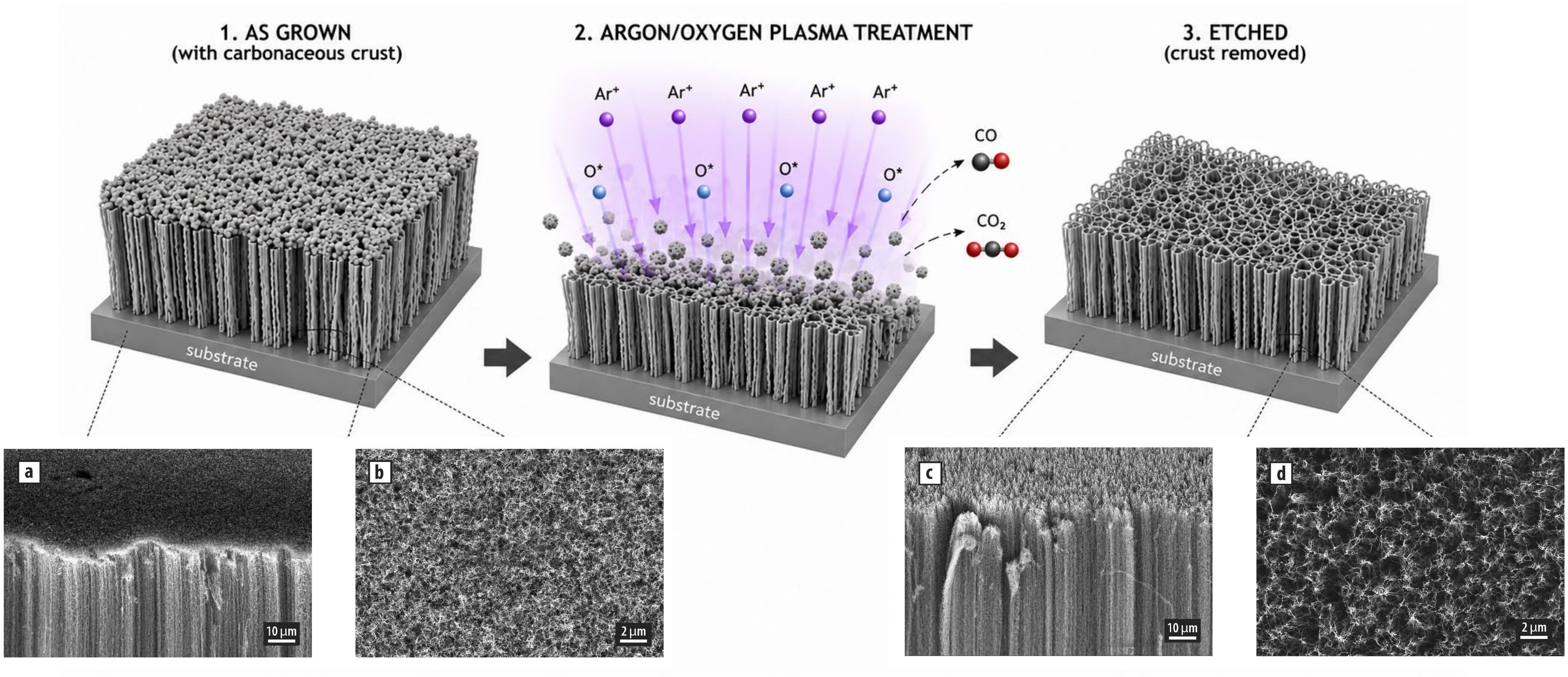


Screening effect:
- Degree of alignment
- Density



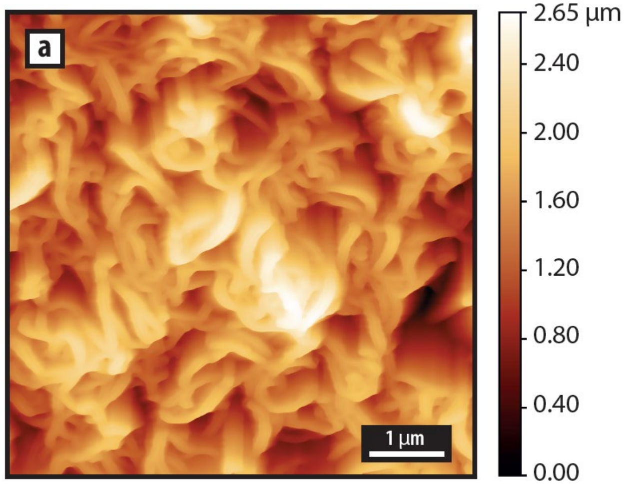
Milne, W. I. *et al.* Carbon nanotubes as field emission sources. *J. Mater. Chem.* **14**, 933 (2004).

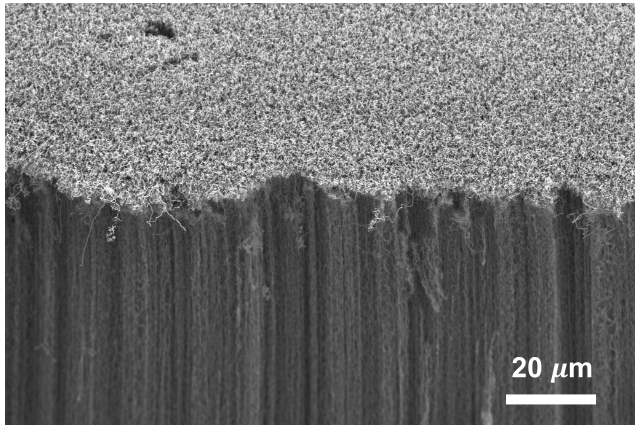
Tip Engineering through Plasma Etching



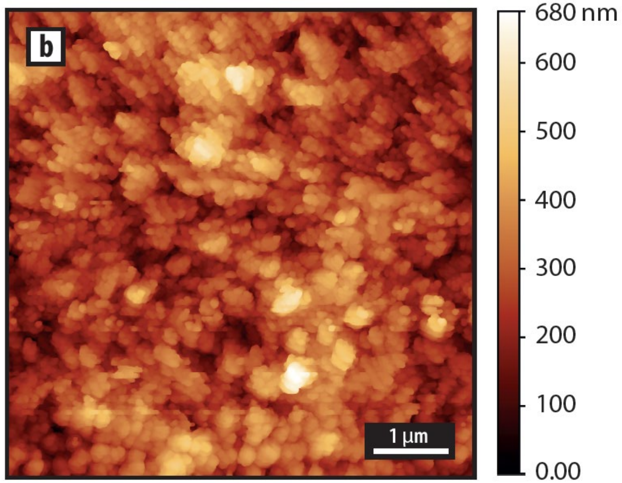
VACNTs Samples

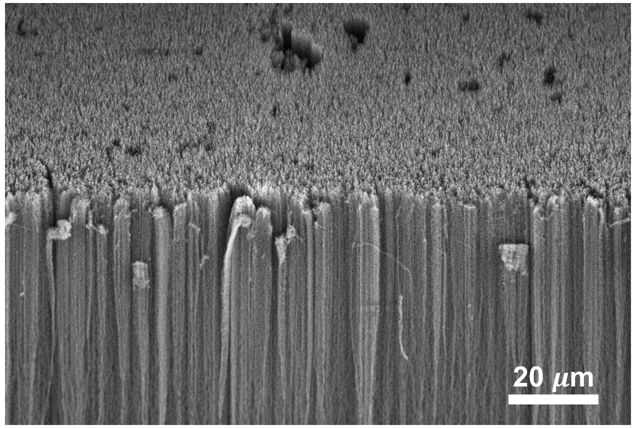
As Grown (Pristine)



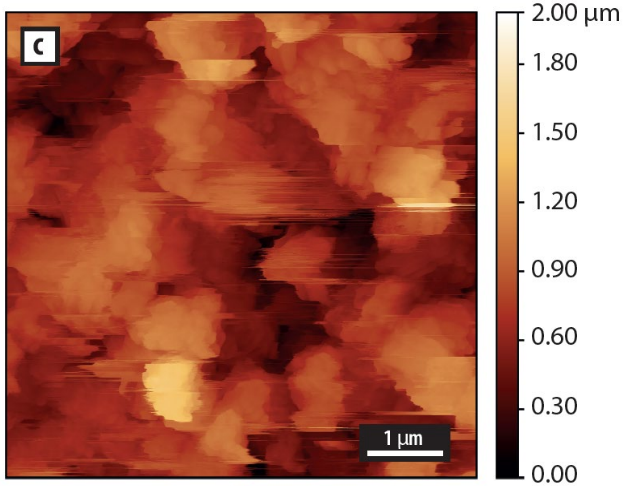


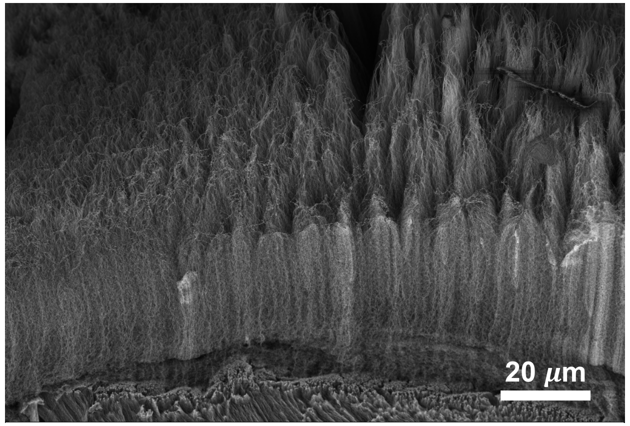
Mild etch (Ar/O_2 plasma)





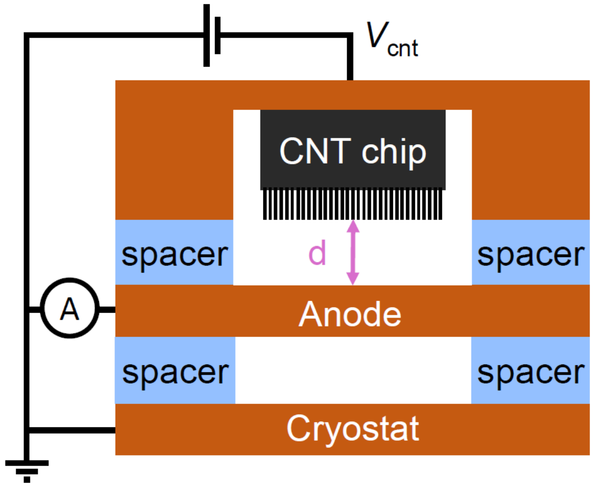
Strong etch (O_2 plasma)

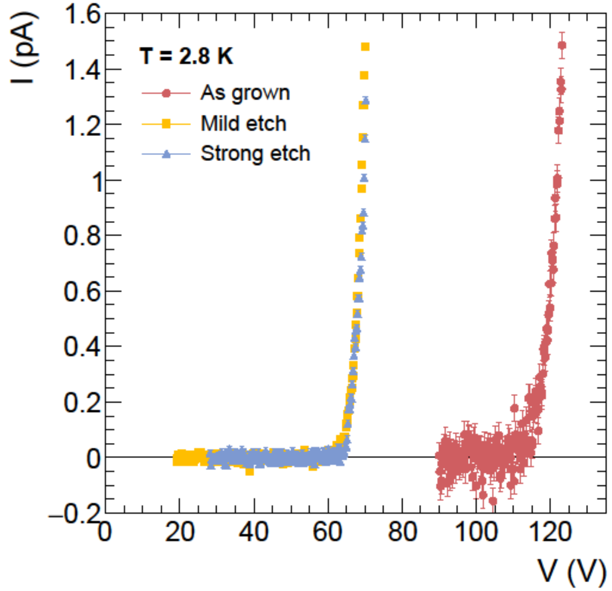


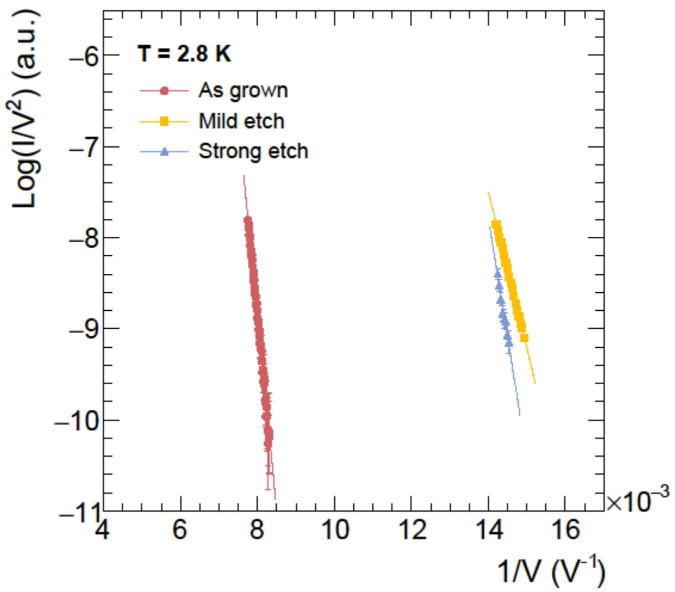


VACNTs as Cold Cathode

$$\beta = b\,\frac{d\,\phi^{\frac{3}{2}}}{s}$$



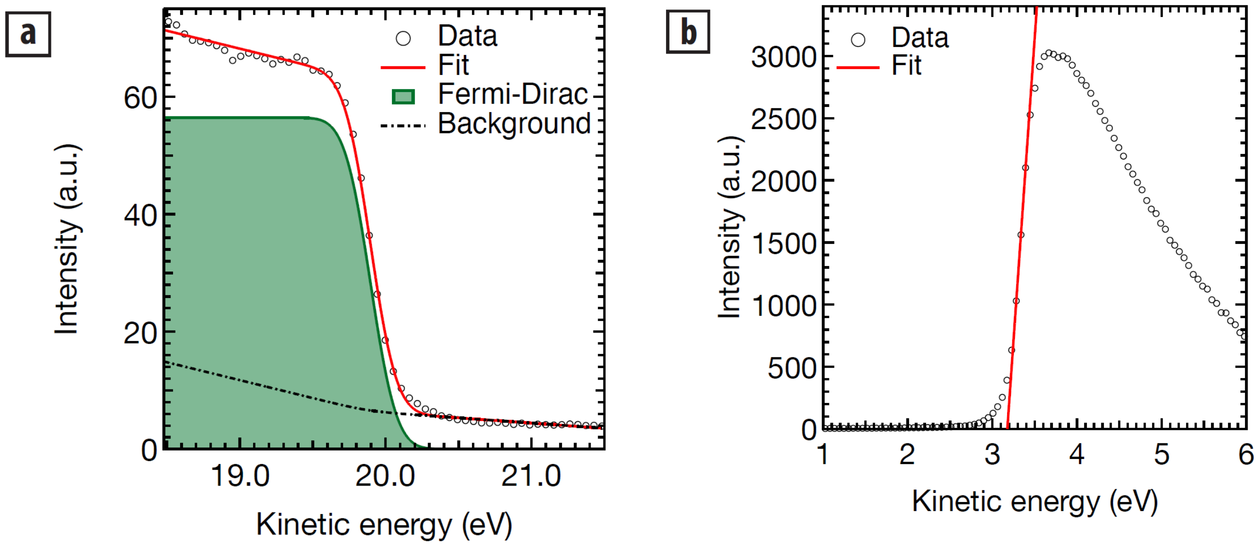




	Turn-On Field @ 0.5 pA [V/µm]	*s* [kV]
As Grown	0.296	-4.28 ± 0.12
Mild etch	0.190	-1.72 ±0.04
Strong Etch	0.112	-2.63 ±0.39

VACNTs Work function

$$\beta = b\,\frac{d\,\phi^{\frac{3}{2}}}{s}$$



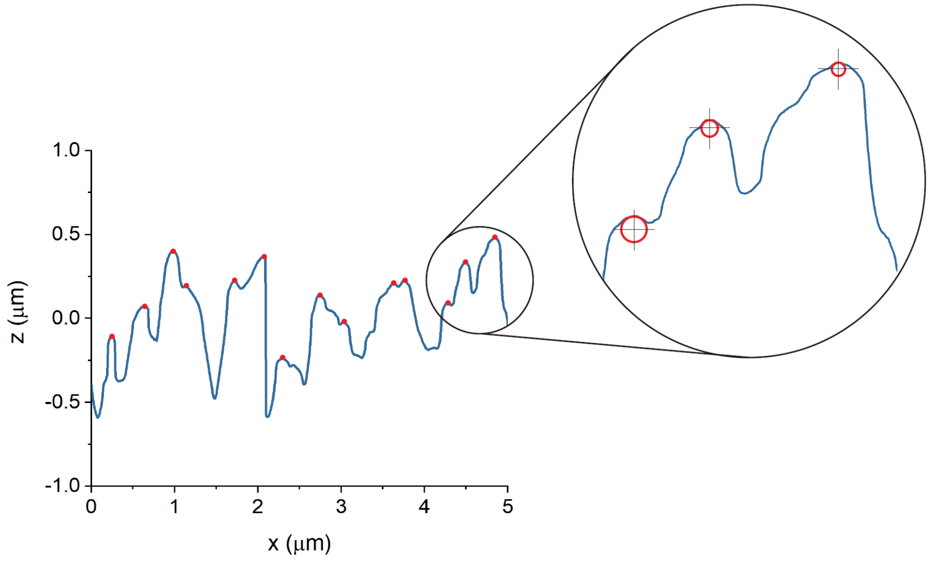
Work Function
Ultraviolet Photoemission Spectroscopy (UPS)
High vacuum 10^{-10} mbar
He discharge lamp photons (hv = 21.22 eV)
$k_B T = 25$ meV

$$\phi = h\nu - (E_f - E_{se})$$

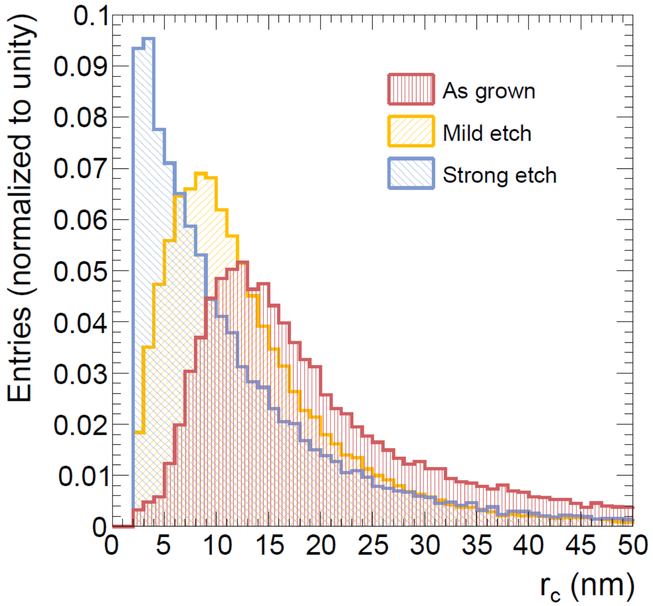
	Work function (eV)	$\beta \times 10^3$ (a.u.)
As Grown	4.26 ± 0.05	5.8 ± 0.7
Mild etch	4.48 ± 0.05	13.5 ± 1.6
Strong Etch	4.53 ± 0.05	15.2 ± 2.5

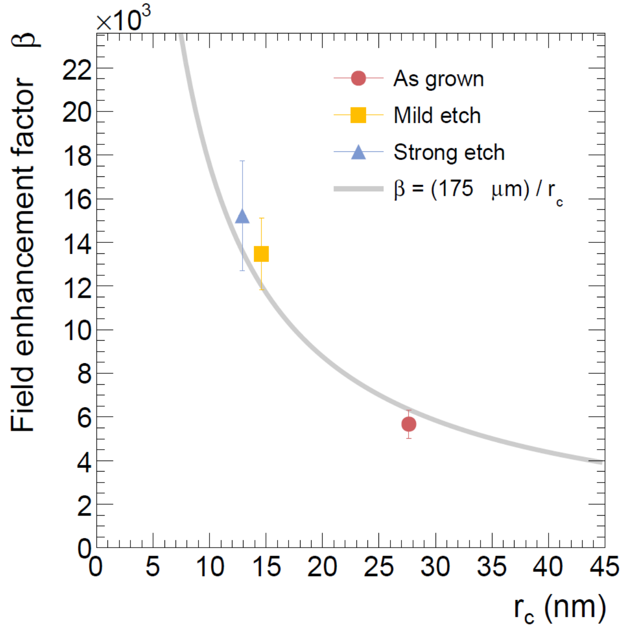
Morphology relation with β

Use AFM profile



$$r_c(x,z) = \frac{\left(1 + z'^2\right)^{\frac{3}{2}}}{z''}$$





	r_c (nm)	$\beta \times 10^3$ (a.u.)
As Grown	28 ± 2	5.8 ± 0.7
Mild etch	14 ± 2	13.5 ± 1.6
Strong Etch	12 ± 2	15.2 ± 2.5

Conclusions

- ✓ Chemical stability in UHV (no degassing or chemical poisoning).
- ✓ Suitable for electron Cathodes for Cryo-Applications.
- ✓ Define a precise method to measure field enhancement factor.
- ✓ Crust removal increase the field enhancement factor from ≃6000 to ≃15000.
- ✓ Define a geometrical experimentally a correlation between β and r_c using high resolution AFM.

- ❑ Current stability in time: ohmic contact and mechanical adhesion.
- ❑ Current density over mA range in Cryo conditions.
- ❑ Emission spatial uniformity.
- ❑ Role of the screening.
- ❑ Role of the aspect ratio.

Thanks for the attention.
Any question?

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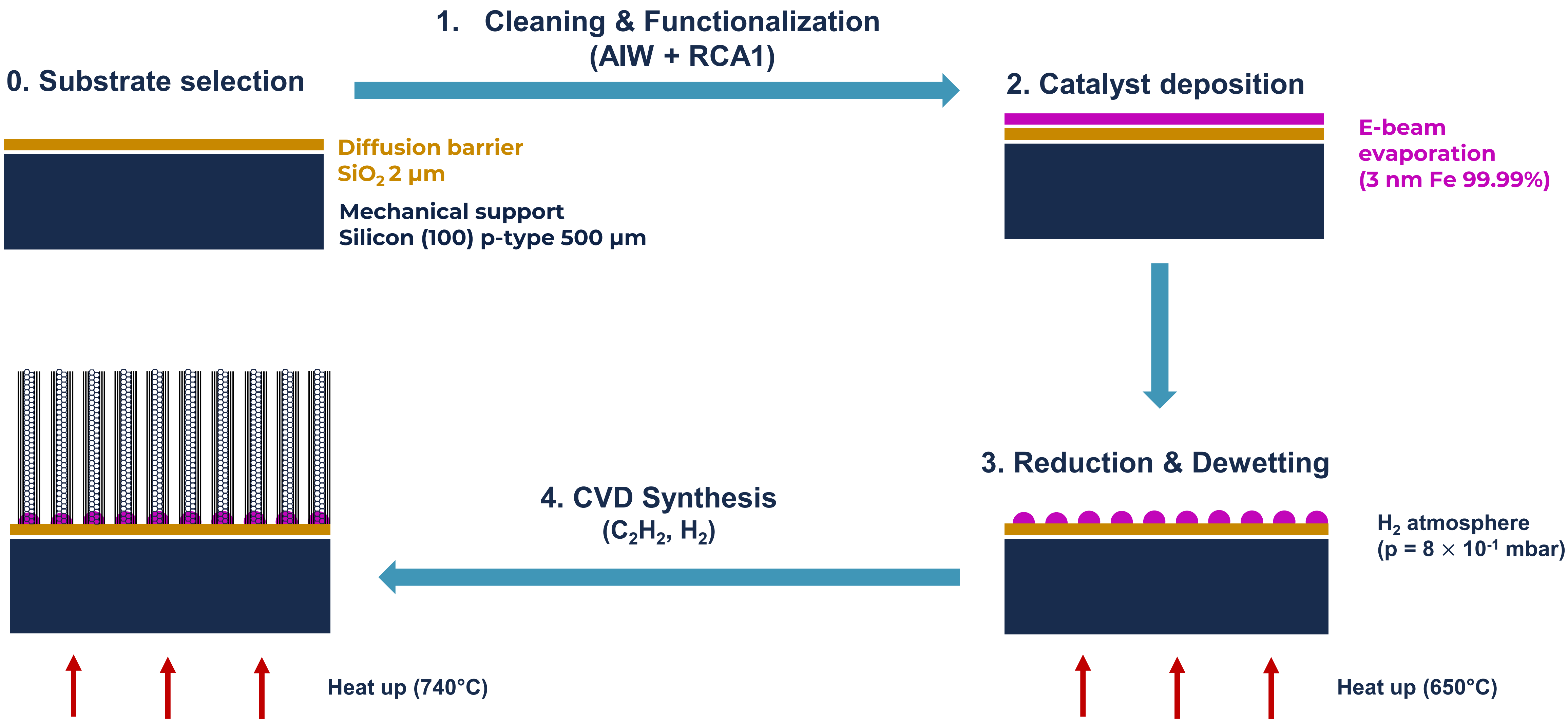
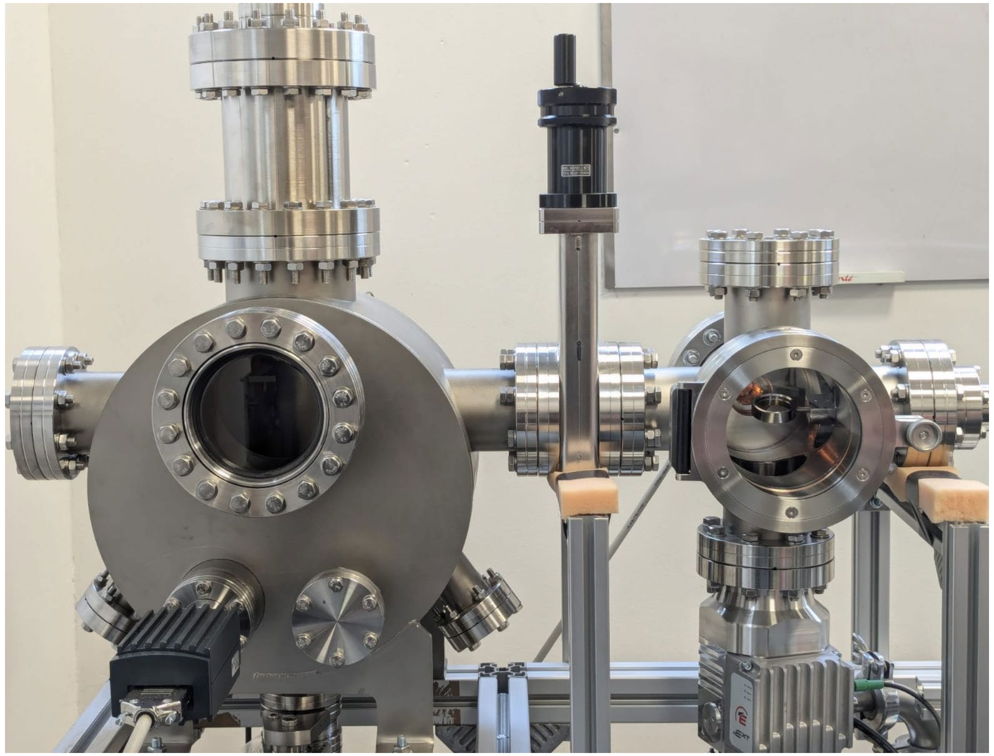
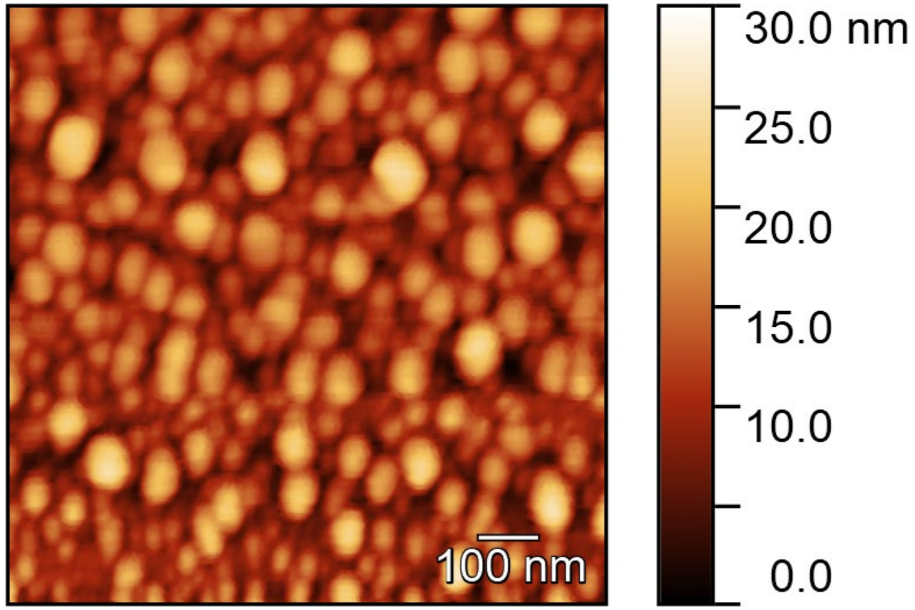
Non-lithographic synthesis of VACNTs



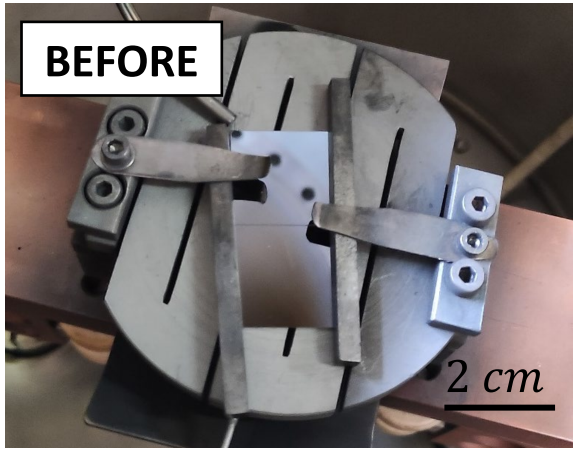
E-beam evaporation

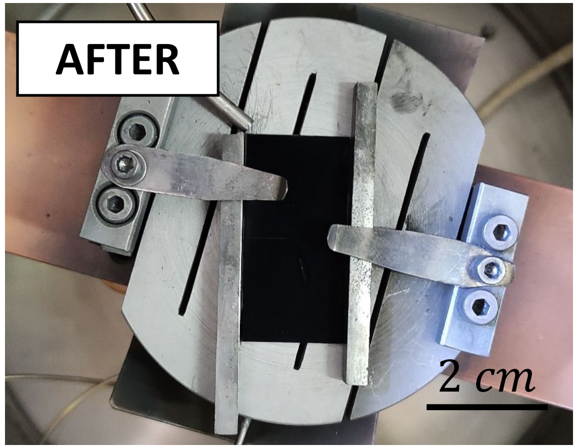




Tip: NCHR-SSS Radius 2 nm
$1 \times 1\ \mu m^2$
512×512 px

Chemical Vapor Deposition





How to determine radius of curvature

Procedure:

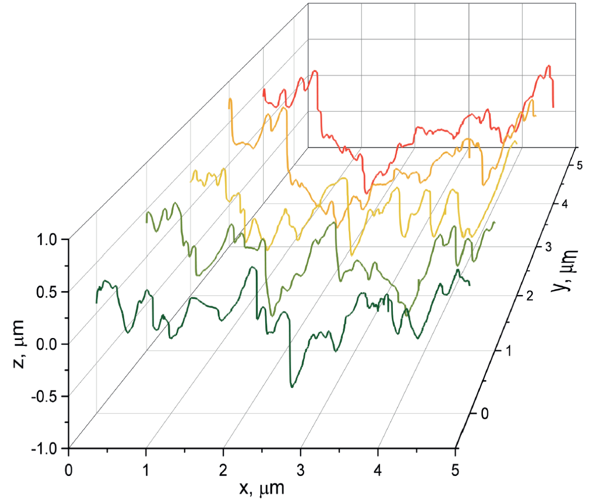
1. Filter 2D image using moving median filter to make comparable noise power.

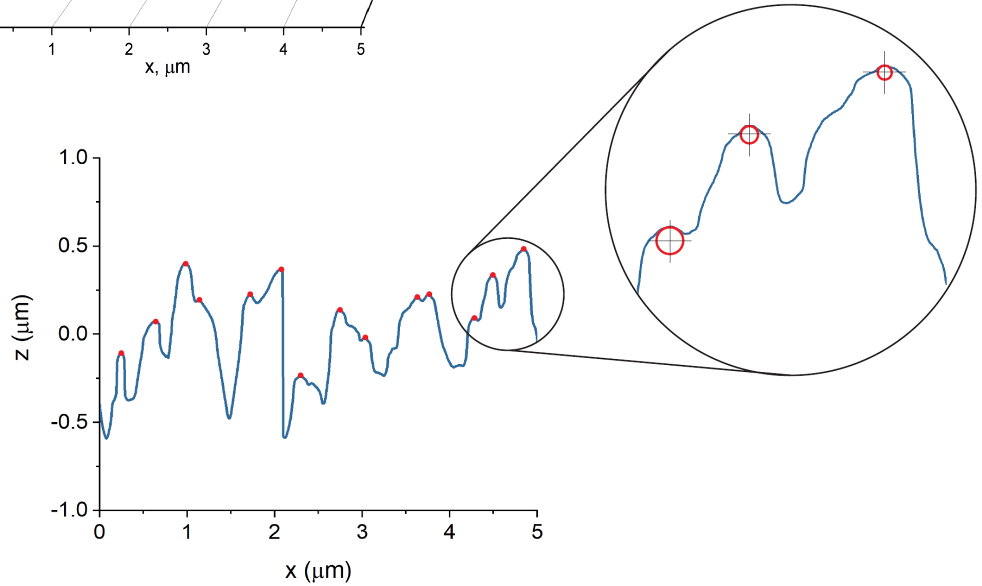
2. Decompose the 2D image in 1D profile.

3. Define “emitting tip” as the local maxima.

4. On the local maxima, evaluate the radius of curvature using:

$$\boxed{r_c(x,z) = \frac{\left(1 + z'^2\right)^{\frac{3}{2}}}{z''}}$$

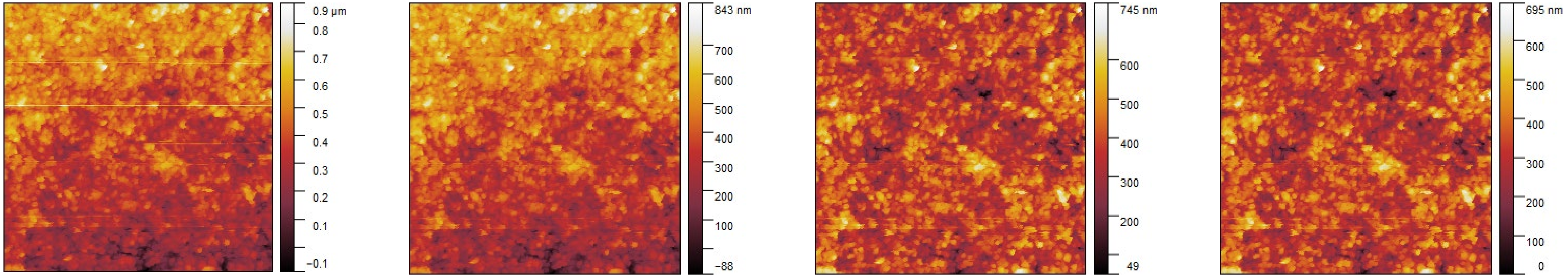




Median Filter

Data level by subtraction of the mean plane

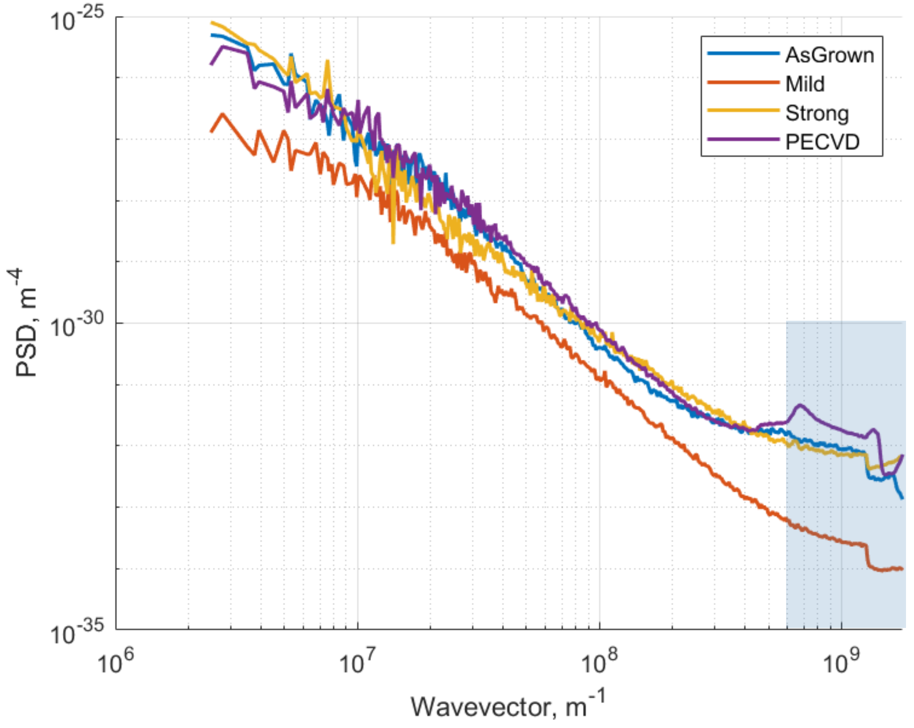
Raw Data

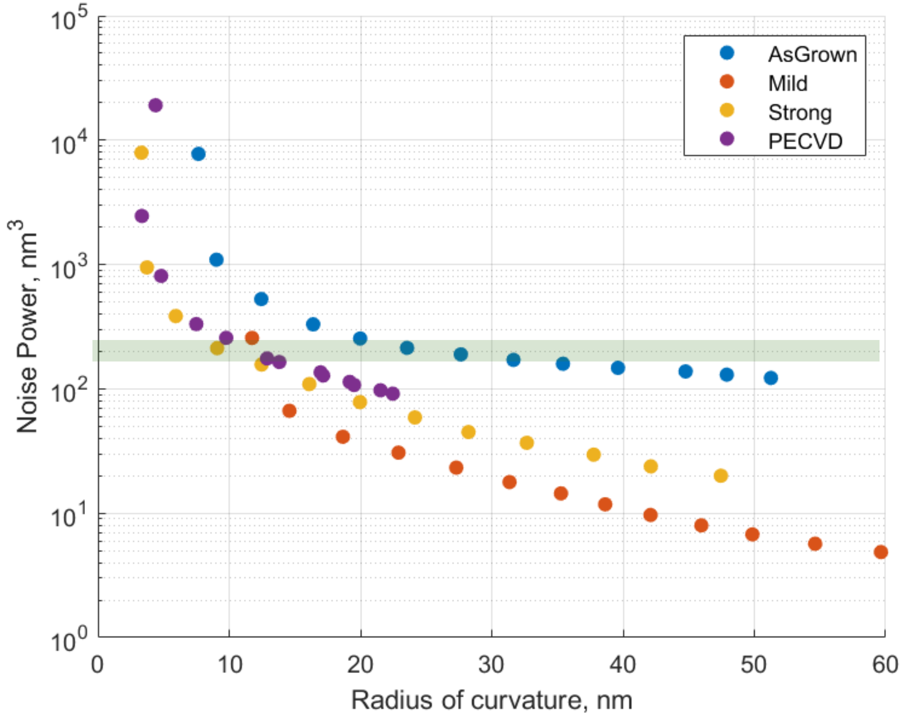


Horizontal damage correction

Median Filter and Fix Zero

Median Filter – Window dimension





Waviness - Cutoff length

Waviness profile

$$w(x) = z(x) * h(x)$$

Gaussian weight function

$$h(t) = \frac{1}{\alpha\lambda_c}\, e^{-\pi\left(\frac{t}{\alpha\lambda_c}\right)^2}$$

- $\alpha = \sqrt{\frac{\ln 2}{\pi}} \simeq 0.4697$
- λ_c cutoff-length

Roughness profile

$$r(x) = z(x) - w(x)$$