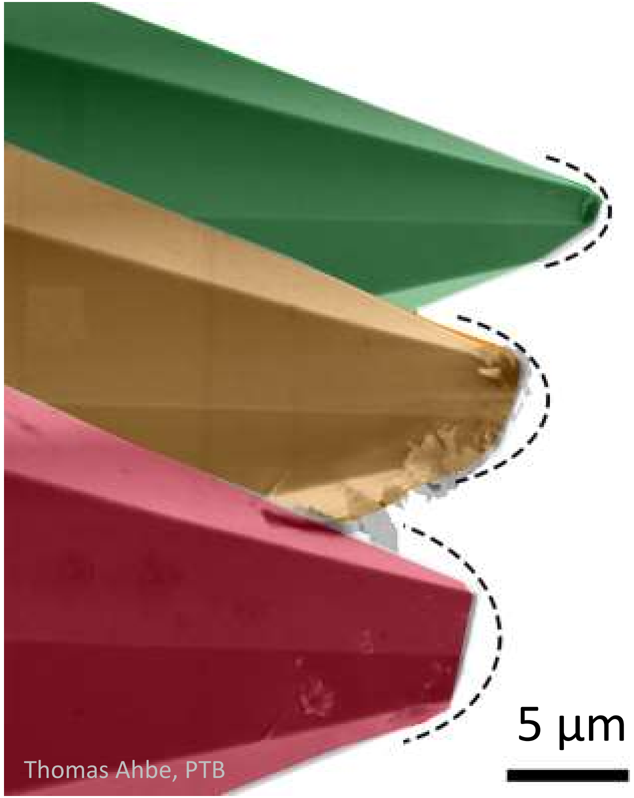
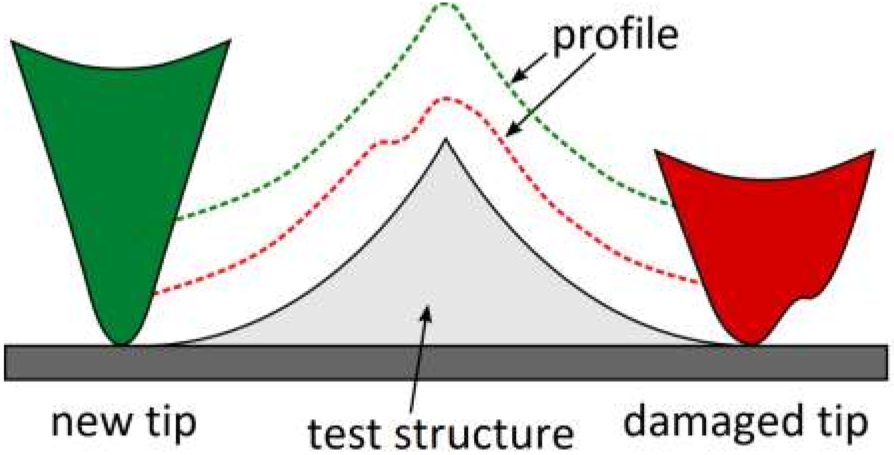
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

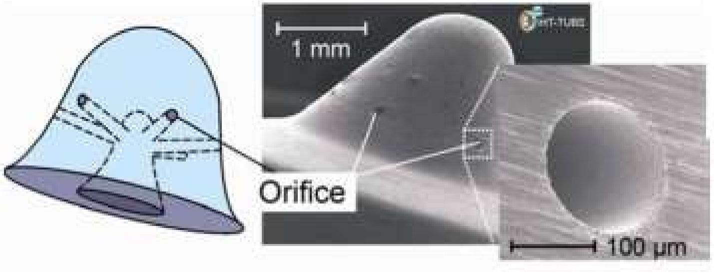
Tip flight and wear for fast roughness measurements

Heinrich Behle, AG 5.11

Motivation


5 µm
Thomas Ahbe, PTB


profile
new tip
test structure
damaged tip


1 mm
Orifice
100 µm

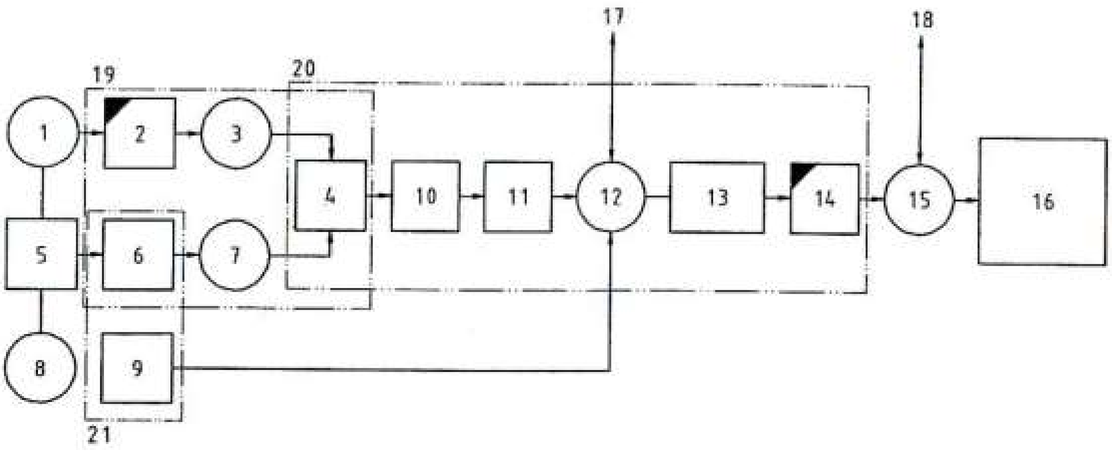
Outline

- Stylus profilometer
- Tip flight in surface profiling
  - Stylus kinematics
  - Morisson limit estimation
- Tip wear in surface profiling
  - Tip characterization
  - Tip breakage as dominating factor
- The PTB Profilescanner

Stylus profilometer: ISO

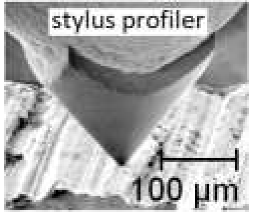
- DIN EN ISO 3274:

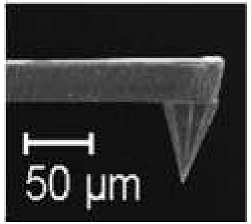
  Surface texture: Profile method - Nominal characteristics of contact (stylus) instruments

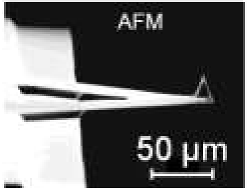


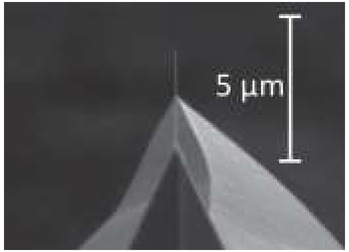
1. Surface
2. Probing tip
3. Felt profile
4. Mechanical-electrical transducer
5. Loop
6. Guidance
7. Reference profile
8. Outer disturbance
9. Infeed
10. Amplifier
11. ADC
12. Total profile
13. Removal of form
14. Profile filter λ_S
15. Primary profile
16. Analysis after ISO 4287
17. Input/Output
18. Input/Output
19. Stylus
20. Vertical profile transfer
21. Infeed

Stylus profilometer: from profiler to AFM









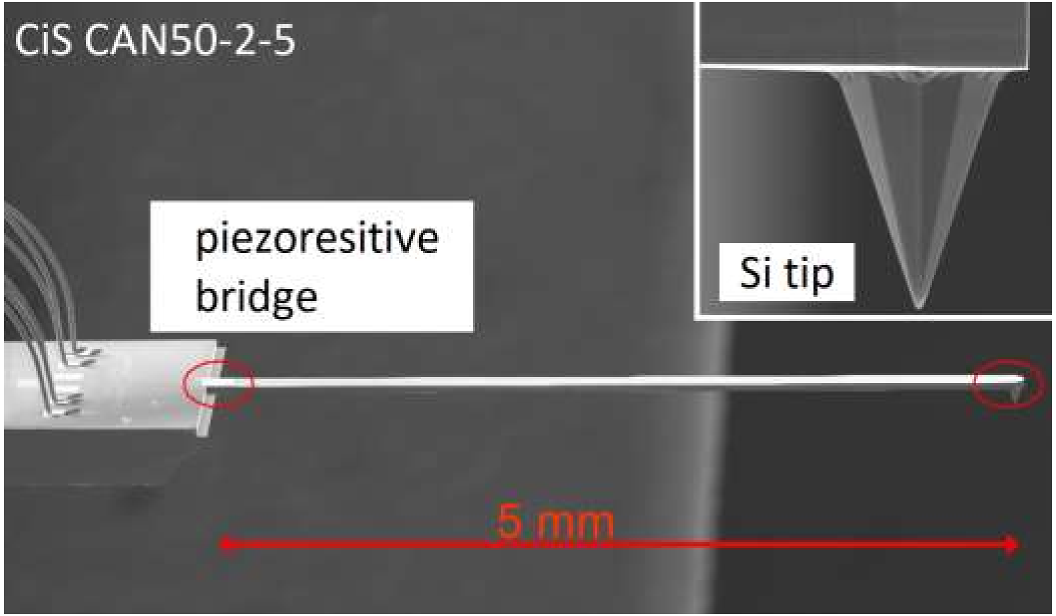
- ISO 3274 ideal tip characteristics:
  - Tip radius r_{tip} = 2 µm, 5 µm, 10 µm
  - Tip opening angle 60°, 90°
  - Static probing force F = 750 µN
- Decreasing tip size and new tip geometries

Stevens, materialstoday **12** (2009)

Stylus profilometer: CiS example

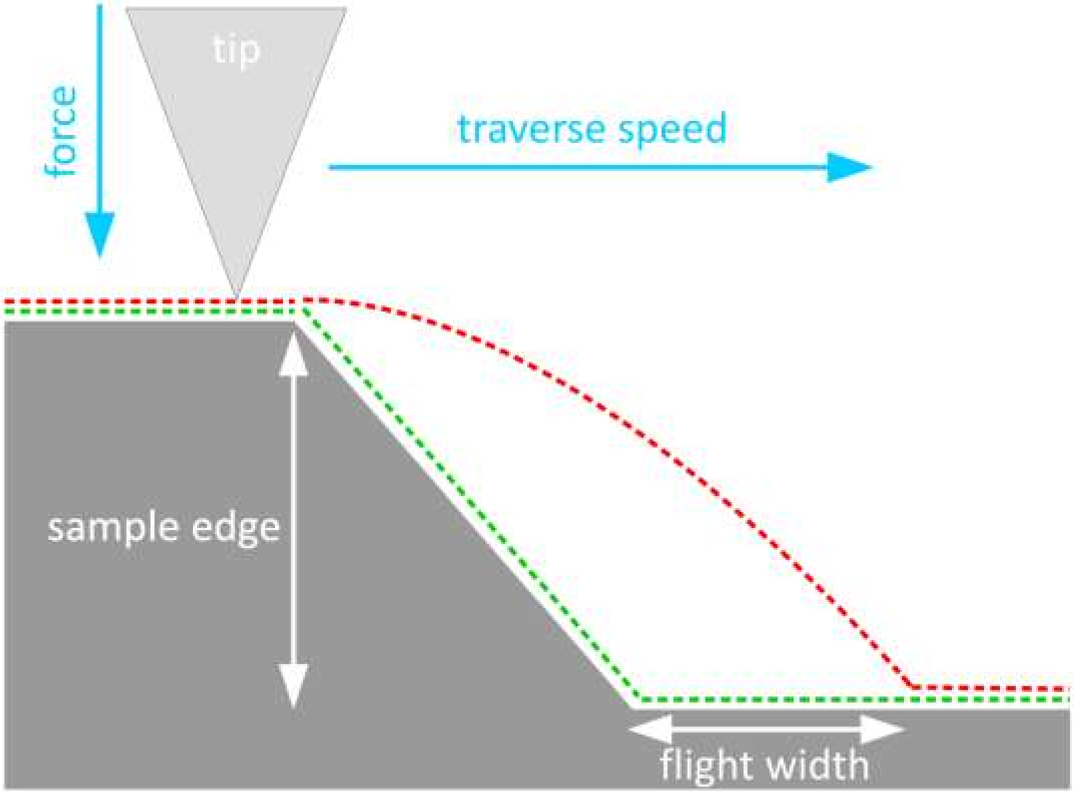
- Singe crystal silicon probe
- Piezoresistive measuring bridge

- Traverse speeds of up to v = 10 mm/s
- Vertical resolution of 11 nm
- Sampling rate of 1600 Hz



CiS Forschungsinstitut für Mikrosensorik und Photovoltaik GmbH, Erfurt, Germany

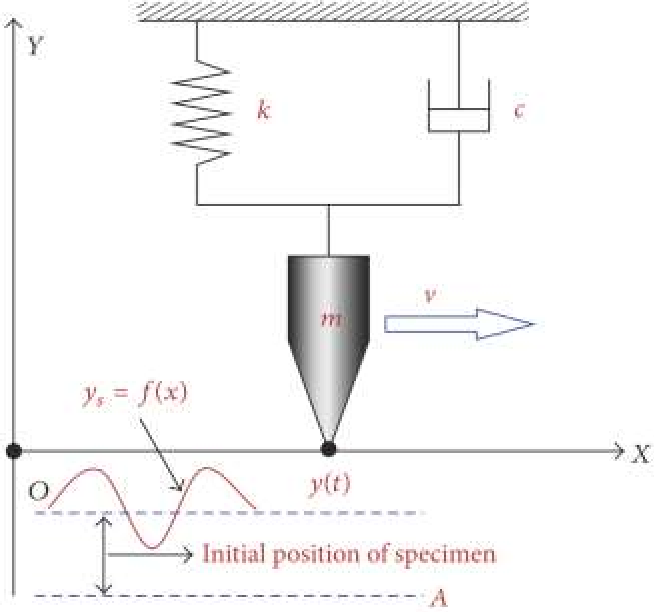
Tip flight in surface profiling



- Error source in stylus tracing analysis due to kinematics
- Failing to maintain contact with surface

- Local surface geometry
- Traverse speed v
- Probing force F
- Spring constant to mass ratio

Stylus kinematics



- Equation of motion

$$-mg - m\ddot{y} - ky - c\dot{y} + F = 0$$

- Assuming measured surface as form $y_s = f(x)$

$$\dot{y} = \dot{x}f'(x)$$

$$\ddot{y} = (\dot{x})^2 f''(x)$$

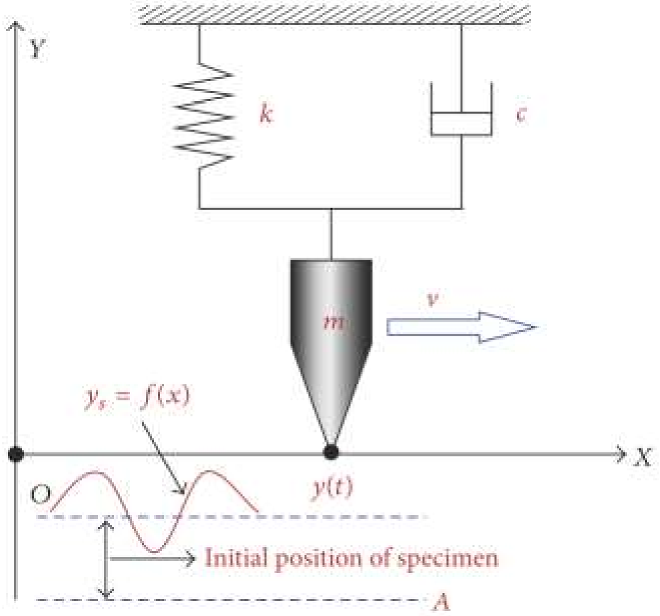
- Rewriting

$$F = mv^2\dot{\rho} + cv\rho + kf(x) + mg$$

with $\dot{\rho}$ variation of surface slope

Fang et al, Journal of Nanomaterials (2016)

Stylus kinematics



- For stylus tip contact with surface

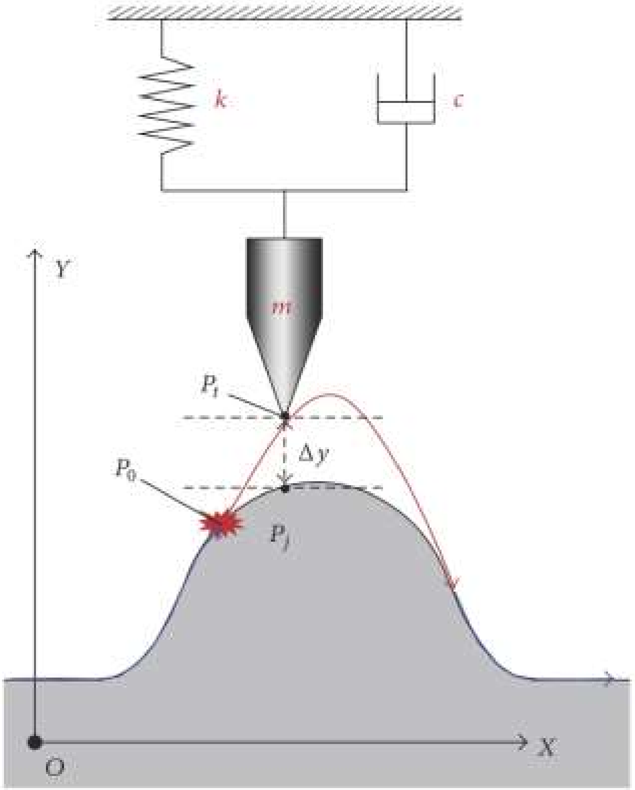
$$F = v^2\dot{\rho} + 2\xi\omega v\rho + \omega f(x) + g > 0$$

with $\xi = c/2\sqrt{km}$ damping ratio and
$\omega = \sqrt{k/m}$ resonant frequency

- For high forces damage of tip or surface may occur, thus parameter tuning is necessary

Fang et al, Journal of Nanomaterials (2016)

Stylus kinematics



- Point of separation for no force $P_0(x_{\_P_0}, y_{\_P_0})$

$$\ddot{y} + \frac{c}{m}\dot{y} + \frac{k}{m}y = -g$$

- Solution for tip flight motion

$$y = e^{-(c/2m)t}\left[\left(\frac{mg}{k} + y_{\_P_0}\right) \times \cos\frac{\sqrt{4km - c^2}}{2m}t + \left(\frac{2mv_{\_P_0} + mgc/k + cy_{\_P_0}}{\sqrt{4km - c^2}}\right)\sin\frac{\sqrt{4km - c^2}}{2m}t\right] - \frac{mg}{k}$$

Fang et al, Journal of Nanomaterials (2016)

Morisson limit estimation

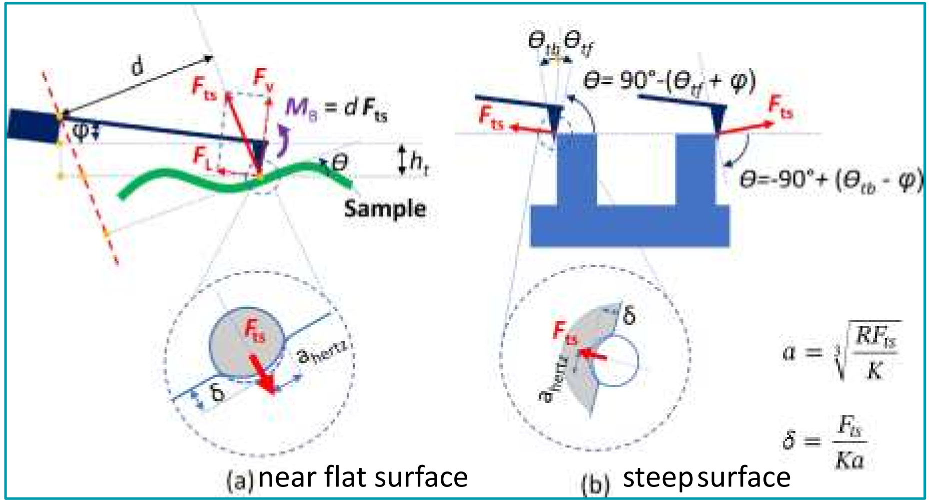
- Flight motion not of interest for measurement quality
- Limit for minimal probing force and maximum traverse speed needed
- Limit estimation after Morrison for sinusoidal surface:

$$\omega^2 A = \frac{3}{m} F_{tip} + \frac{3}{2} g$$

with $\omega = 2\pi v/\lambda$ tip oscillation frequency and A surface amplitude

E Morrison, Nanotechnology **7** (1996)

Tip wear in surface profiling



- ht tip height
- θtb, θtf tip angles
- Fts interaction force
- MB bending moment
- d lever arm

- R tip radius
- δ tip deformation
- a contact radius
- K reduced Young modulus

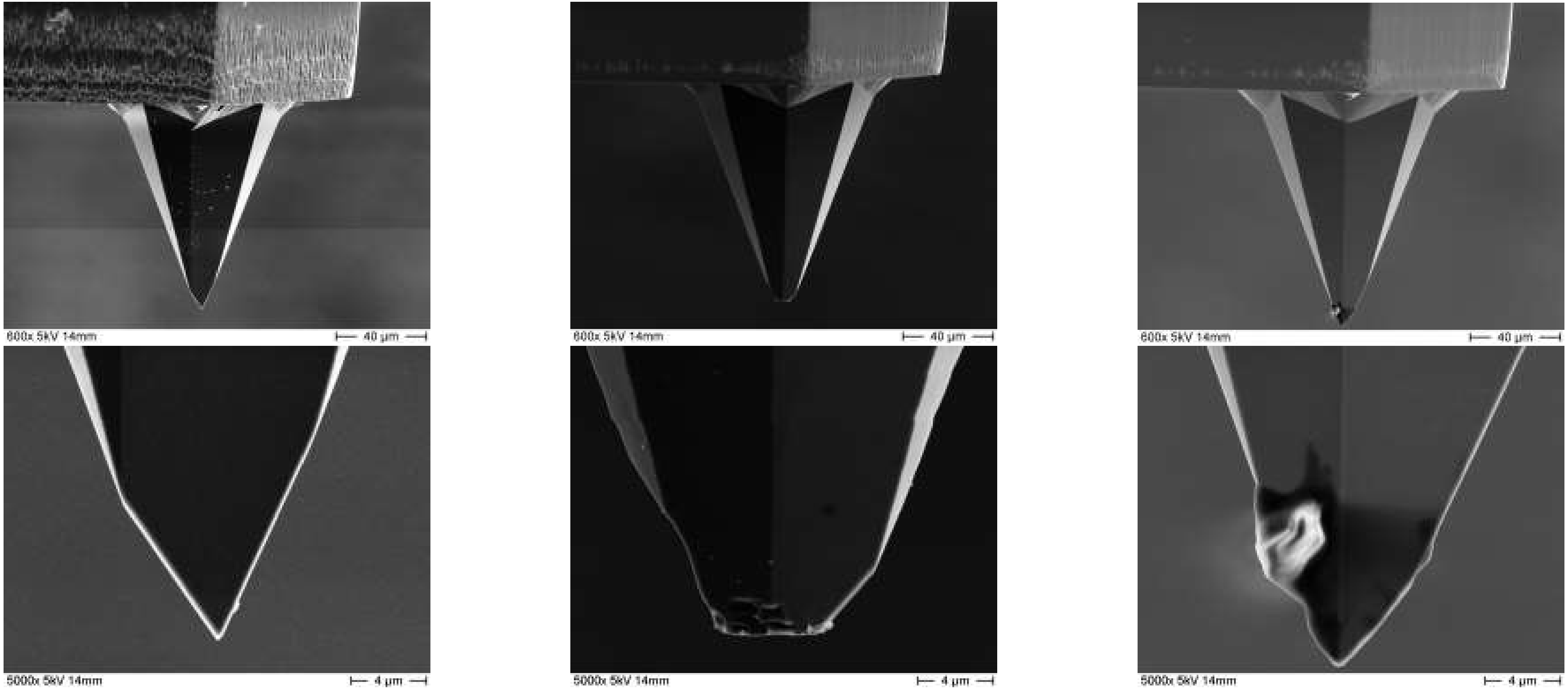
- **Tip breakage dominant over progressive abrasion**

- Tip apex has no contact with surface, instead tip facet for non-flat surface
- Bending moment held constant
- Fv generates compressive stress
- FL tensile and shear stress: main contributor to tip breakage

Strahlendorff et al, Ultramicroscopy **201** (2019)

Tip characterization 1: SEM

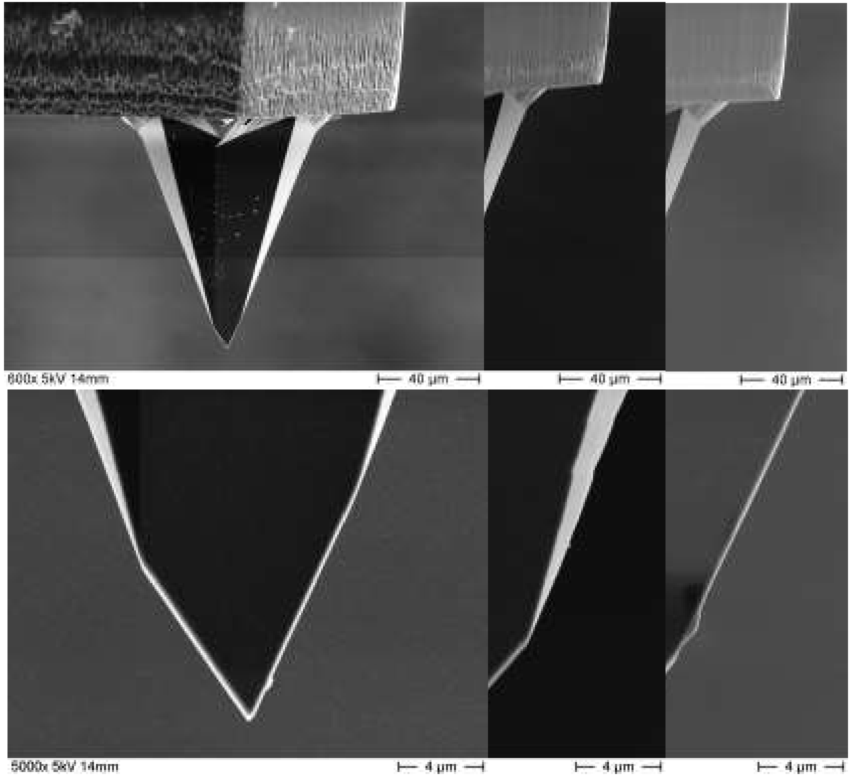
- SEM imaging



Tip characterization 1: SEM

- SEM imaging

- Direct imaging method
- Lateral resolution down to 1 nm
- No in situ measurent possible
- Projected view of tip only
- Charging and contamination

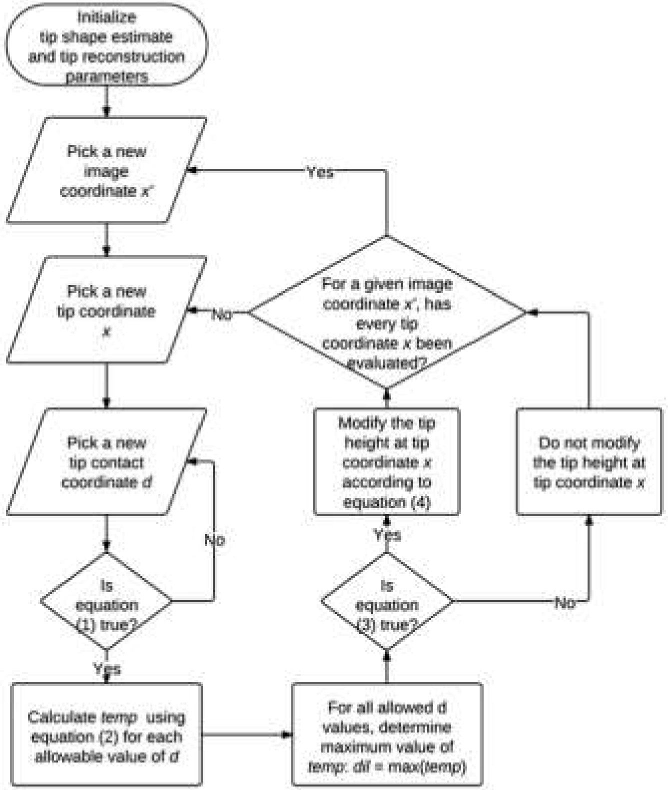


Tip characterization 2: BRT

- Blind tip reconstruction (BRT) technique

- Based on Villarubia algorithm
- Estimates tip shape directly from measurements
- To retrieve shape, erode by known sample geometry

- Able to determine 3D tip shape in situ
- Highly sensitive to measurement noises



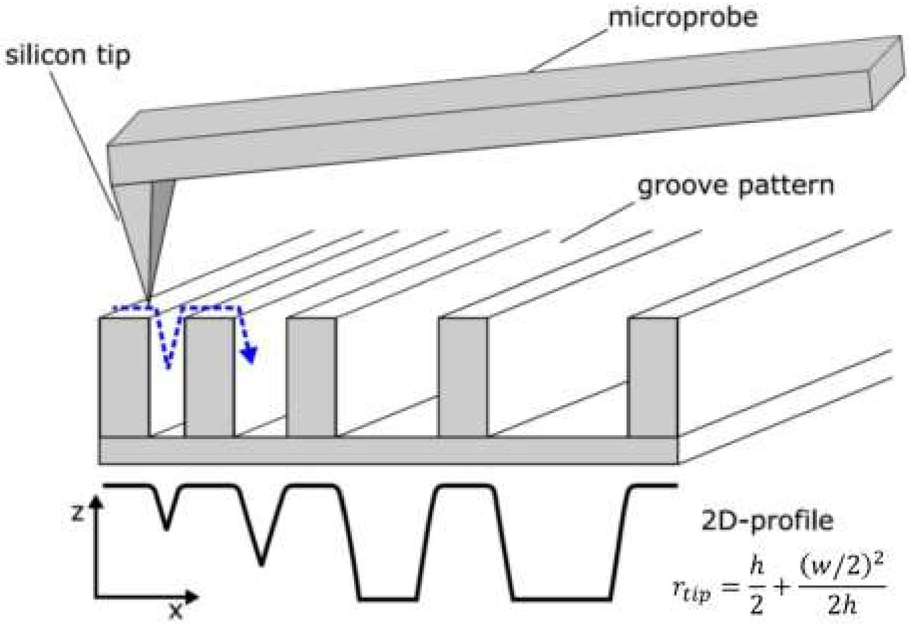
Flater et al, Ultramicroscopy **146** (2014)

Tip characterization 3: reference standard

- Line width reference standard type IVPS100-PTB

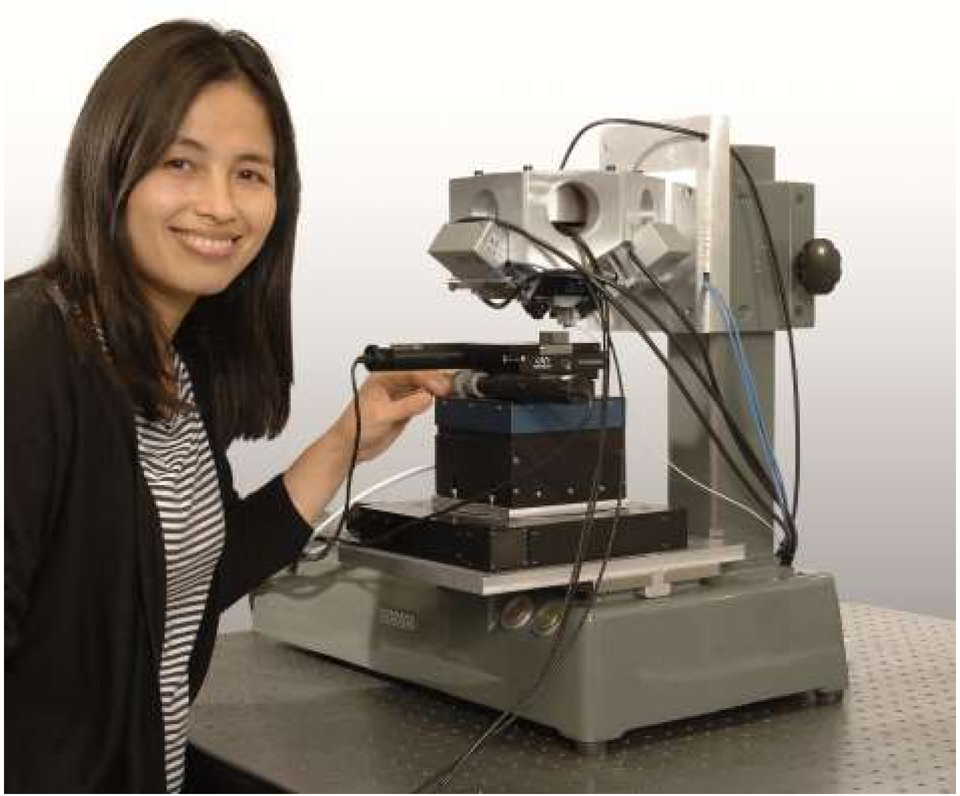
- Vertical sidewalls (90° ± 5°)
- Small top corner rounding (r < 7 nm)
- Tall line features (h > 2 µm)

- Only allows for 2D tip profile characterization



Dai et al, Meas. Sci. Technol. **26** (2015)

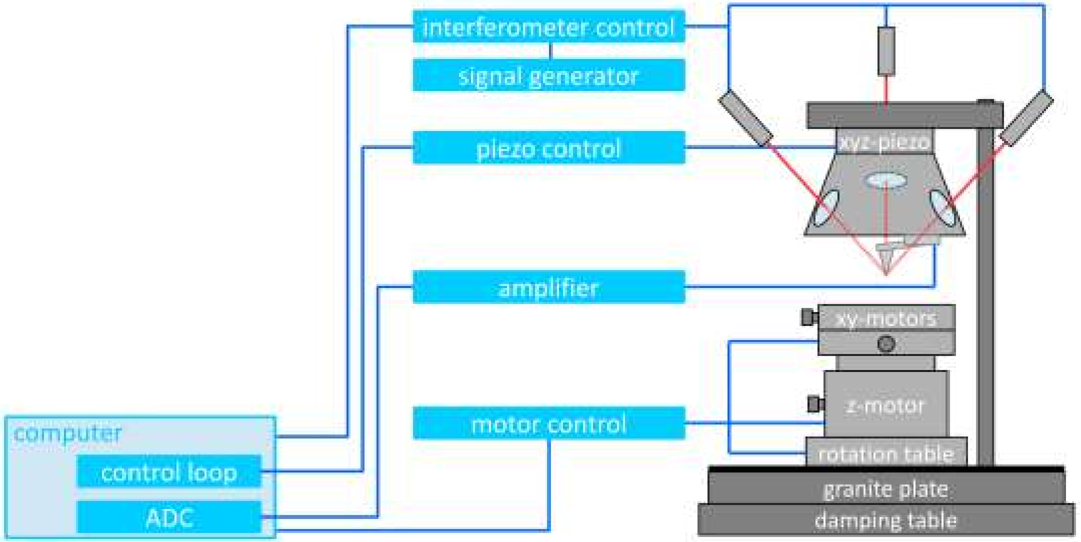
Profilescanner



- Traceable roughness measurements through 1 nm resolution interferometers
- allows for HARMS to be measured
- Free of Abbe-error

Xu et al, Meas. Sci. Technol. **27** (2016)

Profilescanner schematics



- Minimal probing force 1 µN
- Scan range (xyz) 800 µm x 800 µm x 250 µm
- Uncertainty of 10 nm

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