Towards hybrid microfluidic solutions for real-time silica detection in underground coal mines

Silica Exposure and Lung Disease in the Mining Industry Workshop

10/23/2020

Igor Paprotny
University of Illinois at Chicago

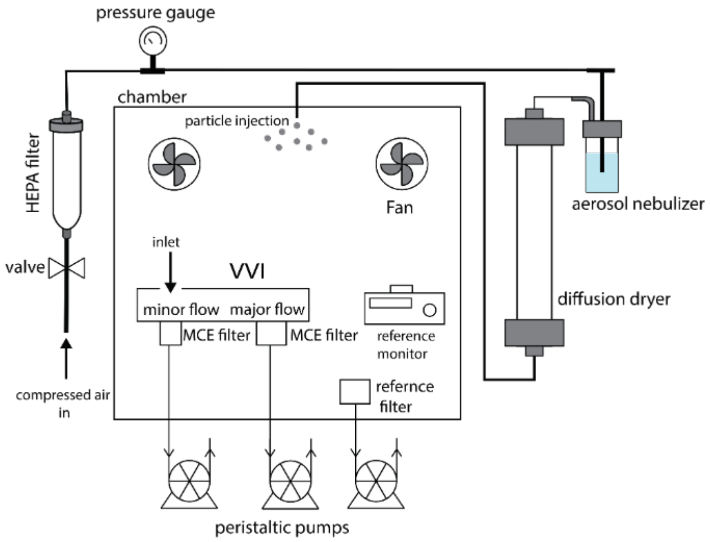
Air-Microfluidics Group (AMFG)

Access to facilities at four (UIC/UCB/ANL) campuses

Marvel Nanofabrication Laboratory, UCB

Nanofabrication Central Facility, UIC

Center for Nanoscale Materials, ANL



Paprotny Lab, UIC

Funding:

U.S. DEPARTMENT OF ENERGY

KANOMAX The Ultimate Measurements

National Institute for Occupational Safety and Health NIOSH

WYND

NSF

PerkinElmer For the Better

NIH National Institute of Environmental Health Sciences

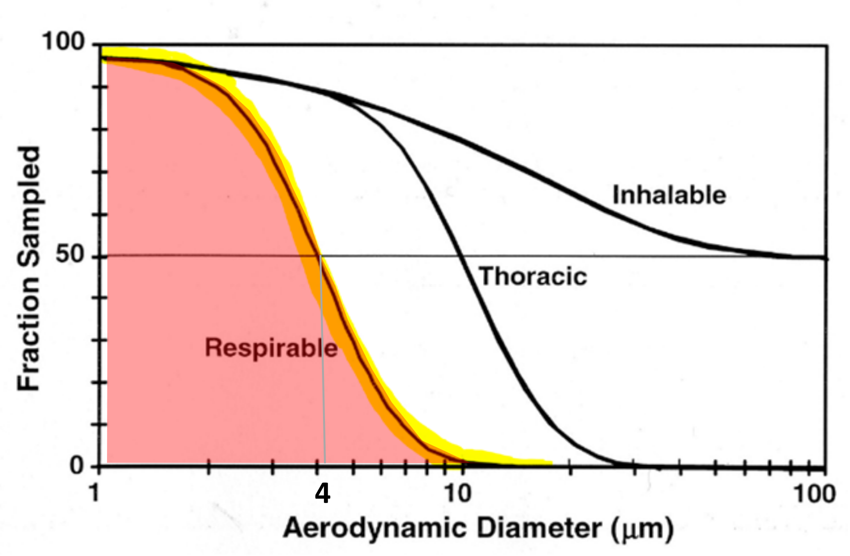
NIH National Institutes of Health

TDK

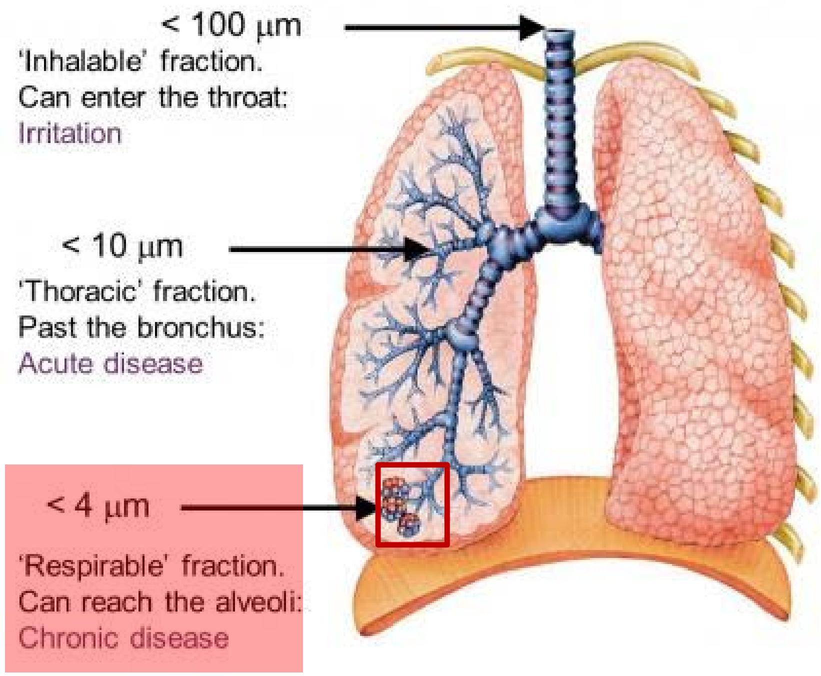
aclima

https://en.wikipedia.org/wiki/Longwall_mining

Respirable Dust Fraction (ISO) – coal/silica dust



ACGIH/ISO sampling criteria for inhalable, thoracic, and respirable fraction



American Conference of Governmental Industrial Hygienists (ACGIH)

30 CFR Sub. B

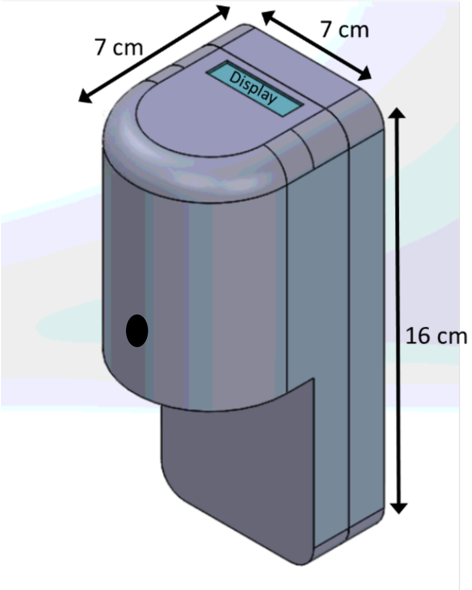
- 1.5 mg/m^3 – underground and surface coal mines
- 0.5 mg/m^3 – air-intakes and part 90 miners
    - LOD –> 100 µg/m^3
- 0.1 mg/m^3 – quartz, or 10%
    - LOD –> 20 µg/m^3

WEARDM (Wearable Respirable Dust Monitor)

In development at Air-Microfluidics Group, University of Illinois at Chicago.

Technical specs:

- Large dynamic range (30 µg/m^3 – 10 mg/m^3)
- Real-time (< 30 min integration at LOD)
- Small
- Low cost (< $1000.00)
- Respirable fraction (4.0 µm 50% cut-point following ISO respirable convention)
- Battery life (250 ml/min flow rate)
- MSHA permissible



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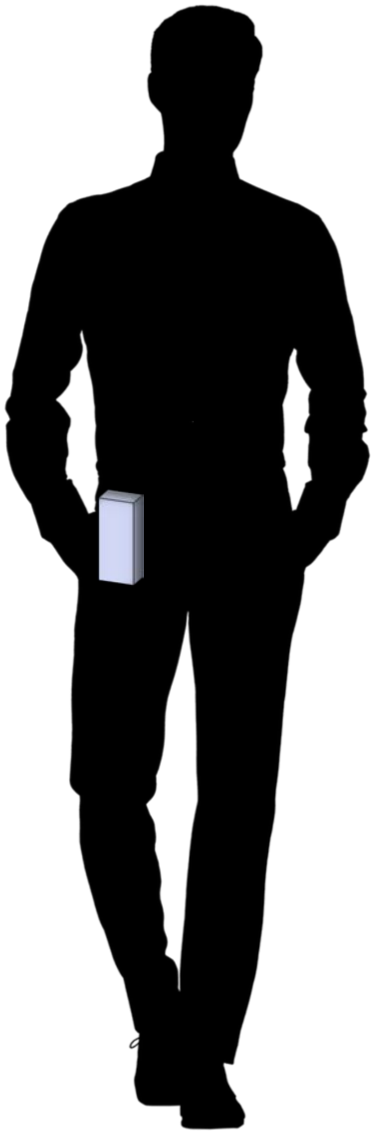
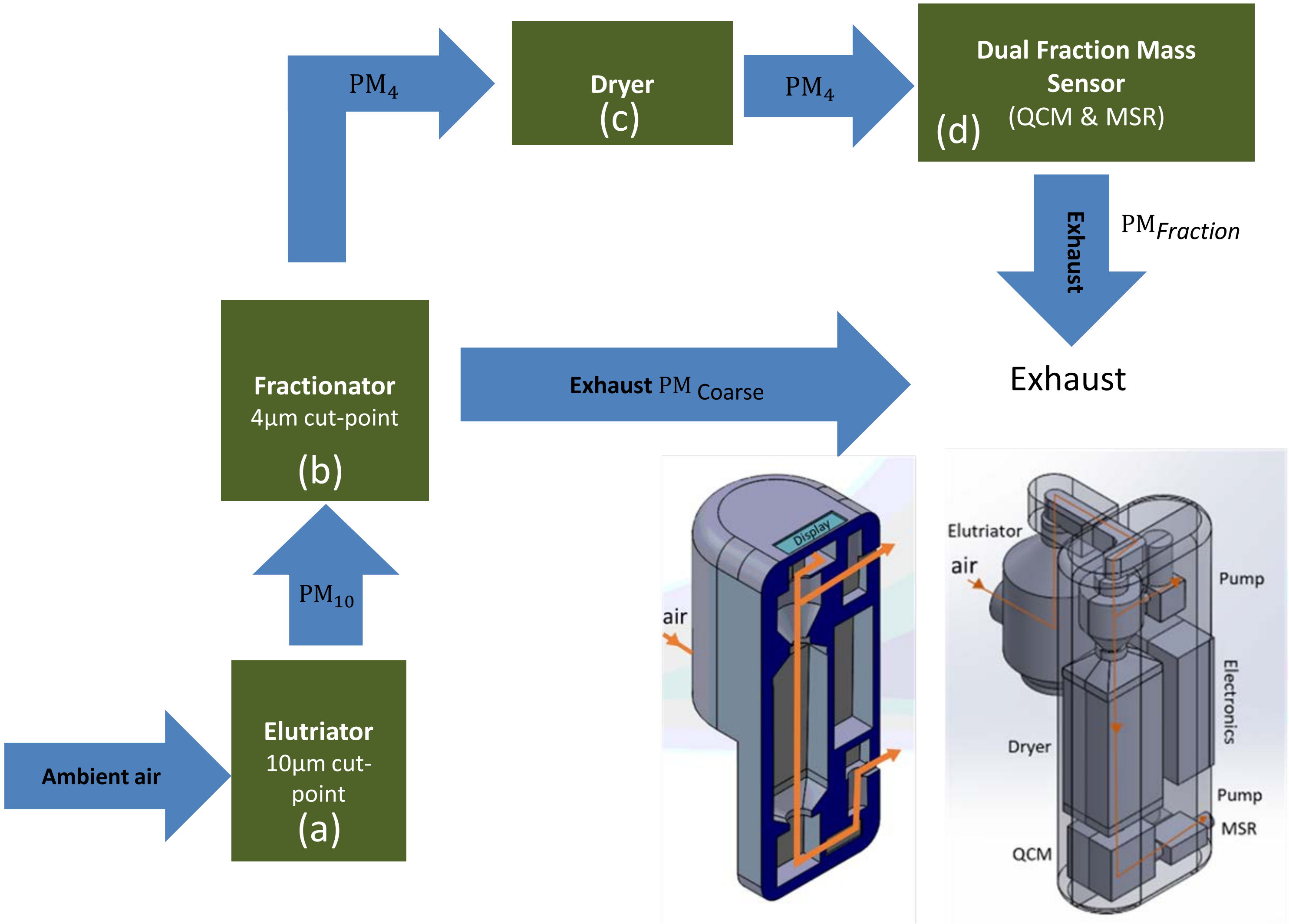
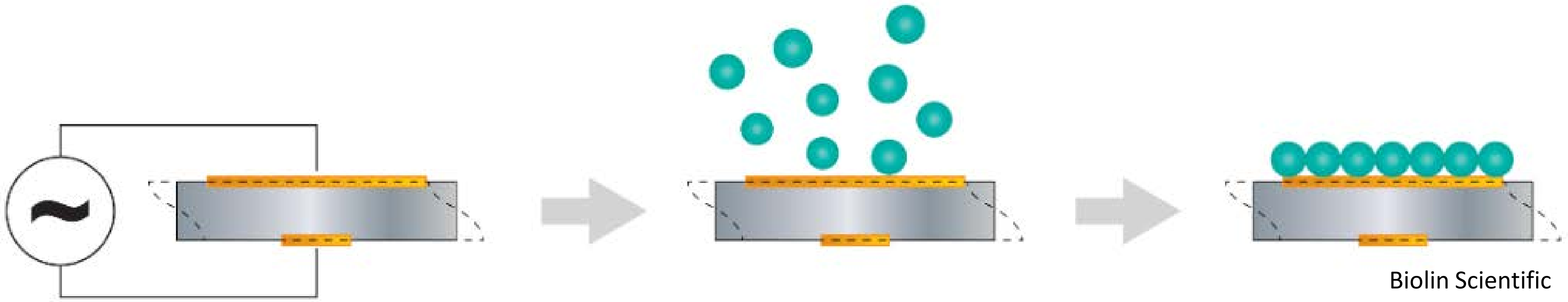


WEARDM (Wearable Respirable Dust Monitor)



Detection principles : Mass-Sensing Resonator (MSR)

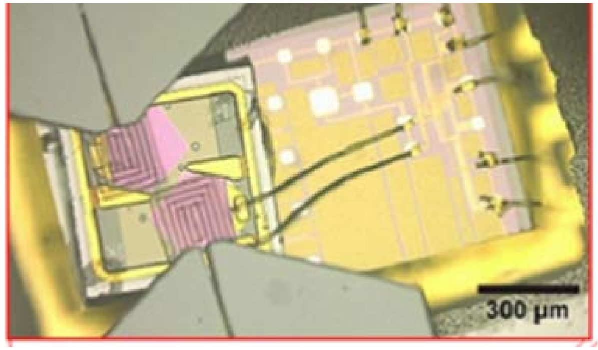


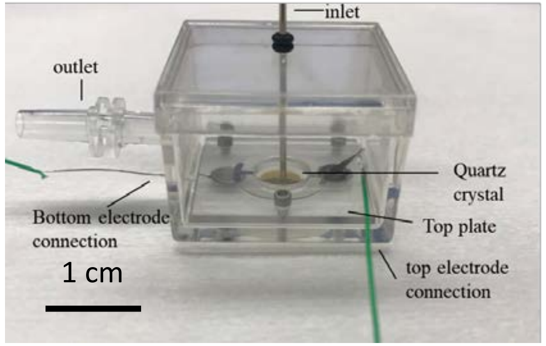
Biolin Scientific

$$Concentration(mg\,.m^{-3}) = \frac{\Delta m\ (mg)}{Flow\ rate(m^3.s^{-1}) \times time(s)}$$

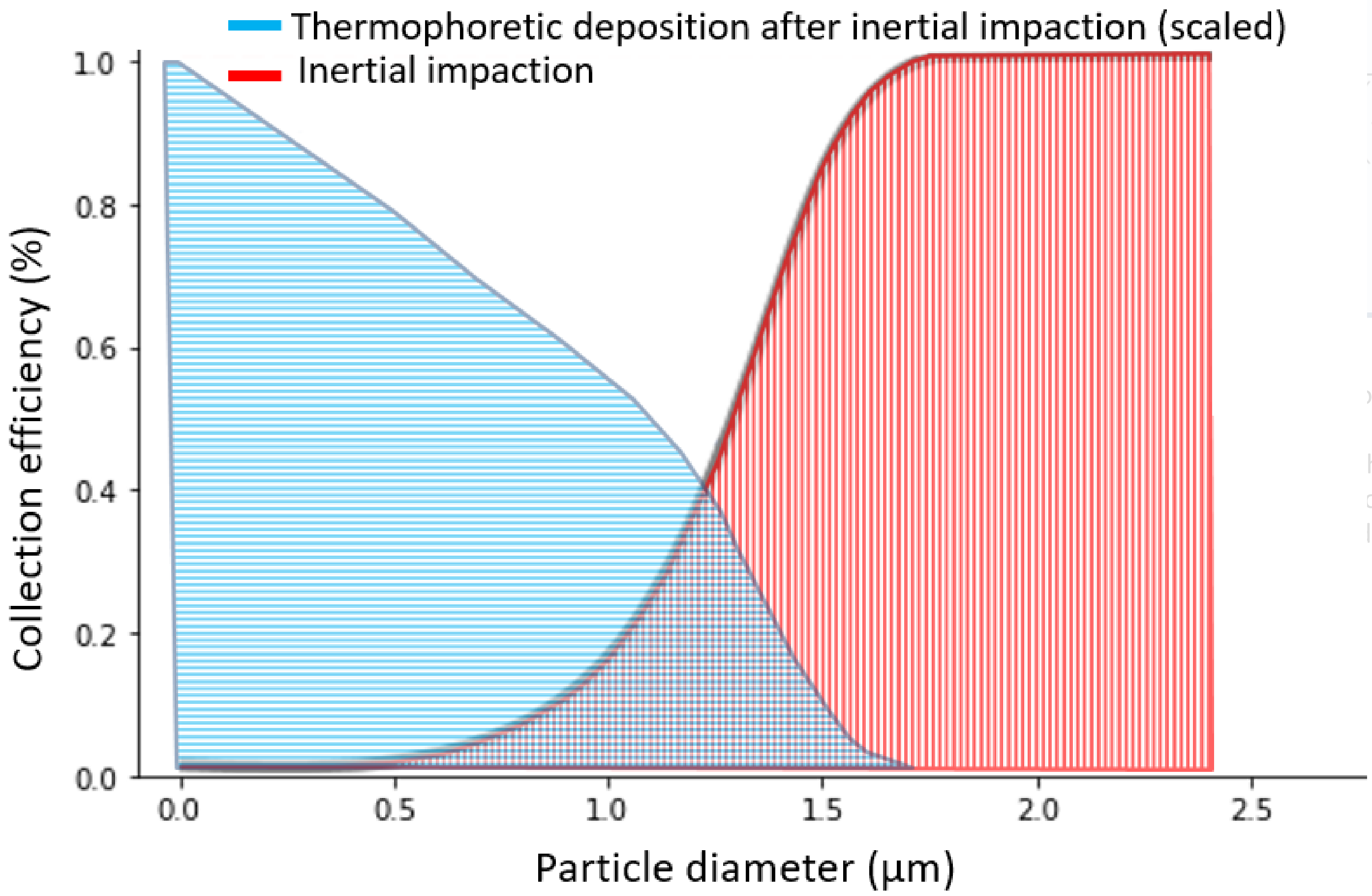
Sauerbrey equation: $$\Delta m = \frac{\Delta f \cdot A\sqrt{\mu_q \rho_q}}{2 f_0^2}$$

Δf : frequency change
A : active sensing area of the crystal
ρ_q : quartz density
μ_q : shear modulus of quartz for AT-cut crystal
f_0 : resonant frequency of the quartz crystal
Δm : mass added to the crystal's surface.

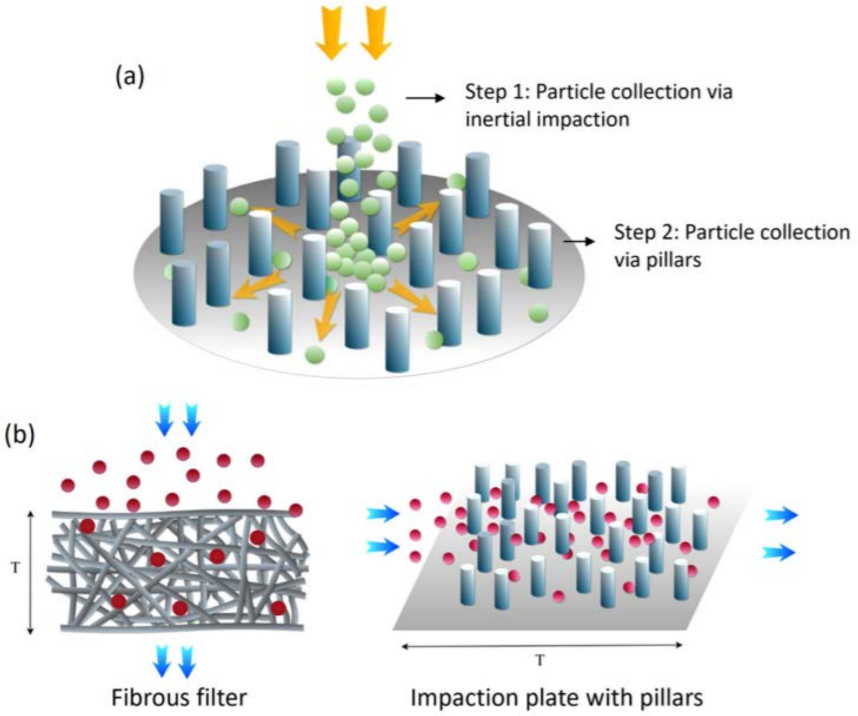


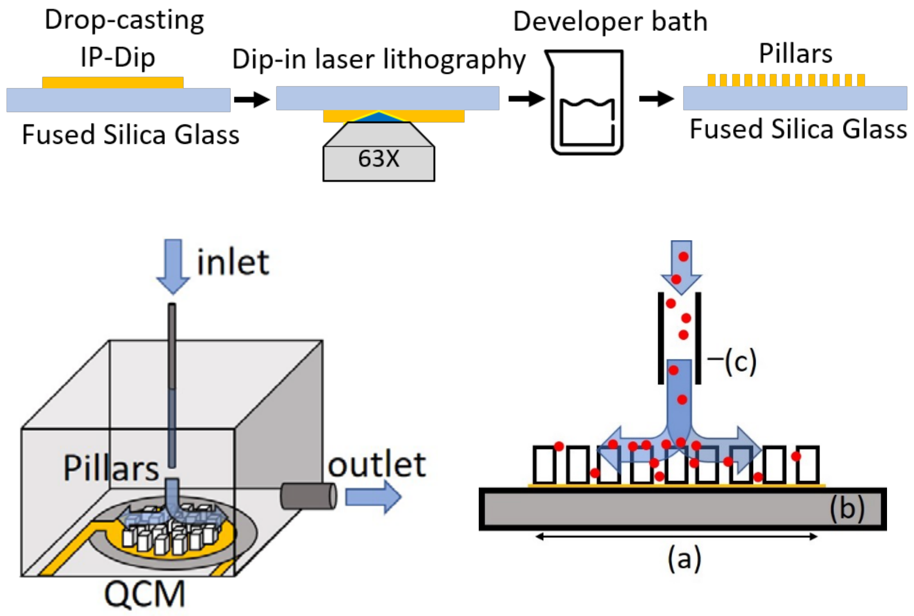


Dual Resonator Mass Sensor (DRMS)



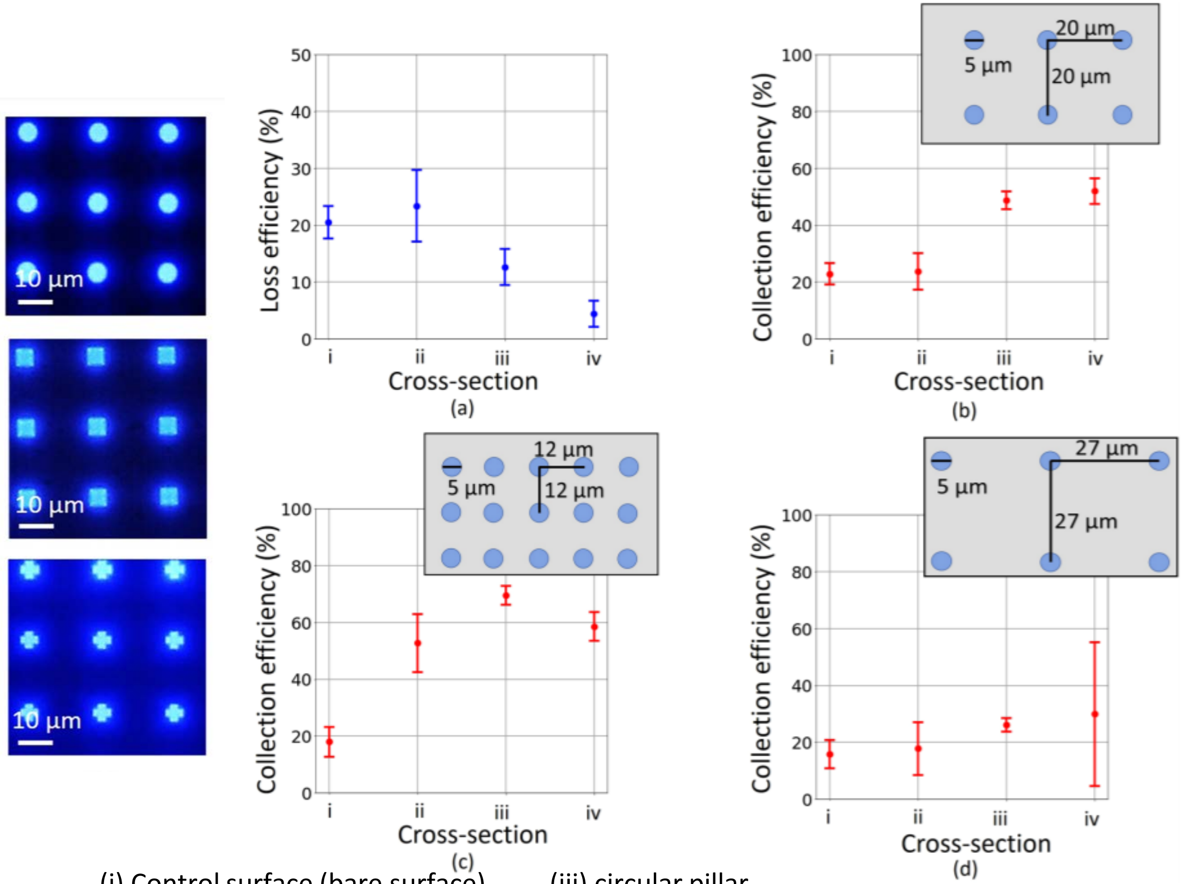
Surface-modification of the MSR: enhanced- inertial impaction



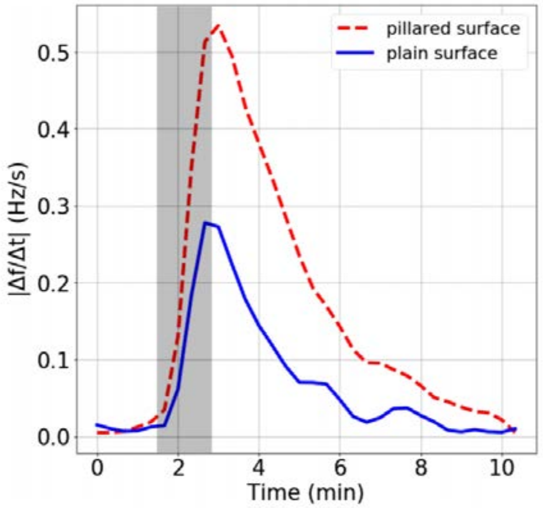


Similarity between the particle capture mechanism of fibrous filter and the pillar enhanced surface

Surface-modification of the MSR: Pillar geometry with 2PP



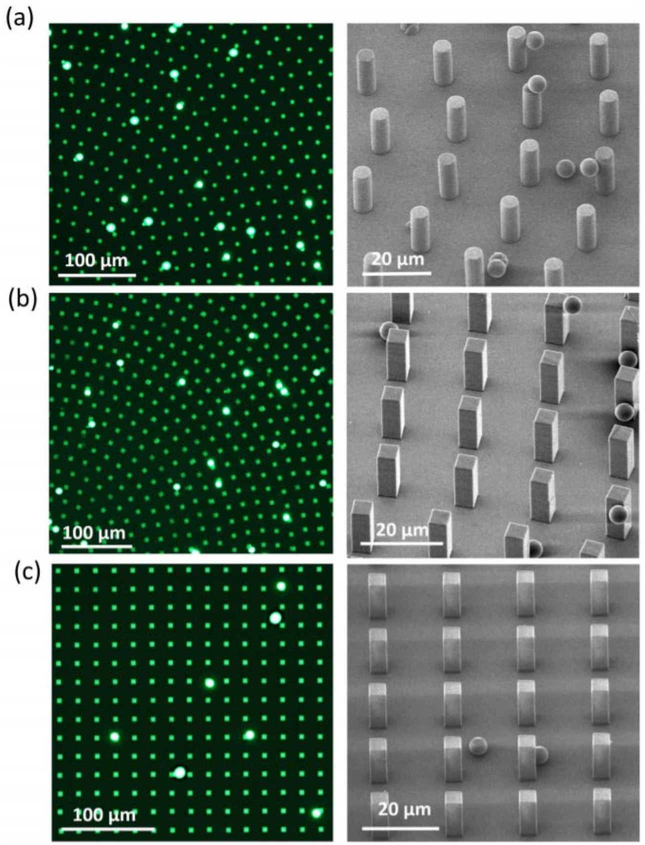
(i) Control surface (bare surface)
(ii) rectangular pillars
(iii) circular pillar,
(iv) cross-shaped pillars.



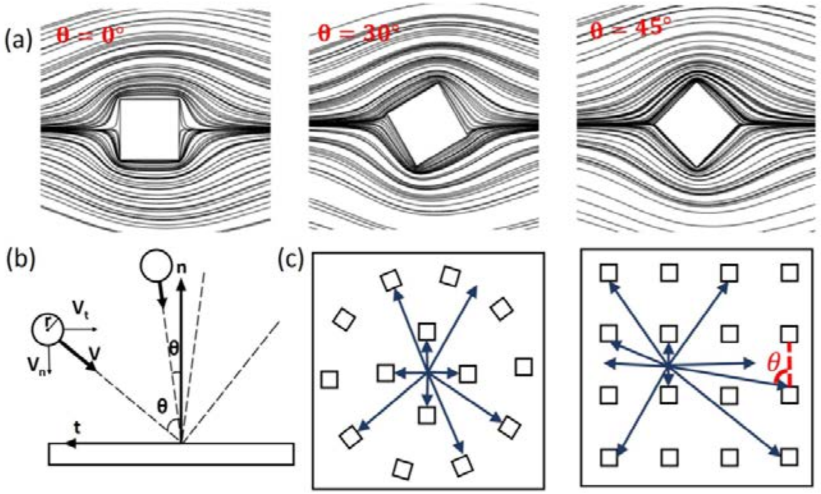
Response of QCM devices with and without optimized pillar geometry to test aerosols (incense smoke).

M. Hajizadehmotlagh, I. Paprotny, "Effect of micropillars with varying geometry and density on the efficiency of impaction-based quartz crystal microbalance aerosol sensors" , ***J. Appl. Phys***. 127, 184903 (2020)

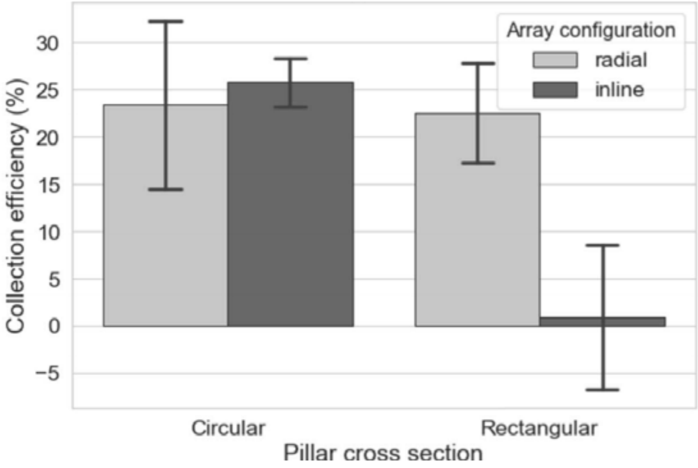
Surface-modification of the MSR: Pillar distribution



(a) radially staggered array of circular pillars.
(b) radially staggered array of rectangular pillars.
(c) inline array of rectangular pillars.



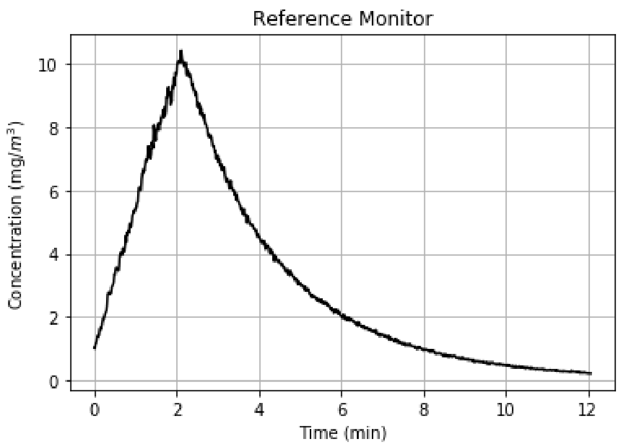
(a) Flow field around rectangular fibers. (b) Tangential and normal components of the particle velocity in oblique impaction



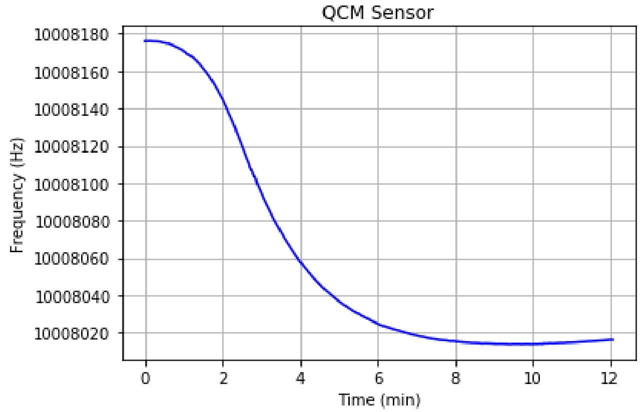
M. Hajizadehmotlagh, A. Singhal, I. Paprotny, "Enhanced Capture of Aerosol Particles on Resonator-Based PM Mass Sensors Using Staggered Arrays of Micro-Pillars", ***JMEMS***, 2020.

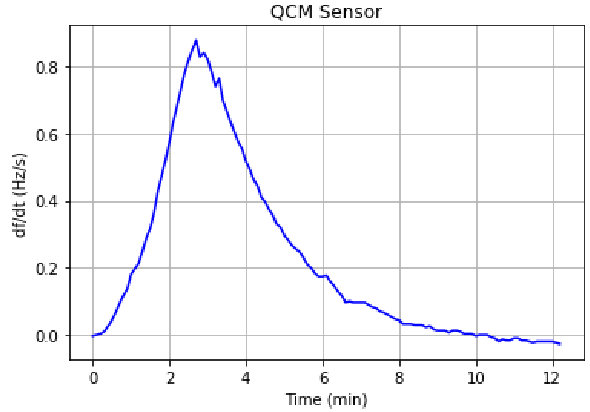
Initial Results

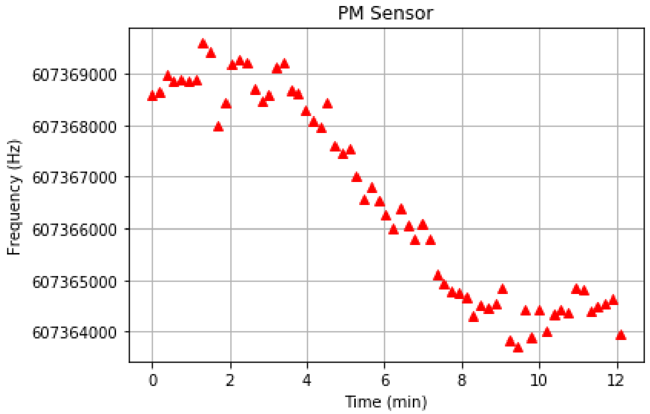
Test aerosol (incense)

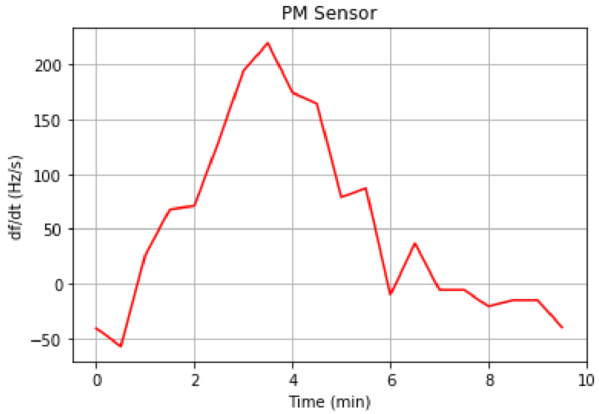


Reference monitor
(Kanomax 3442)





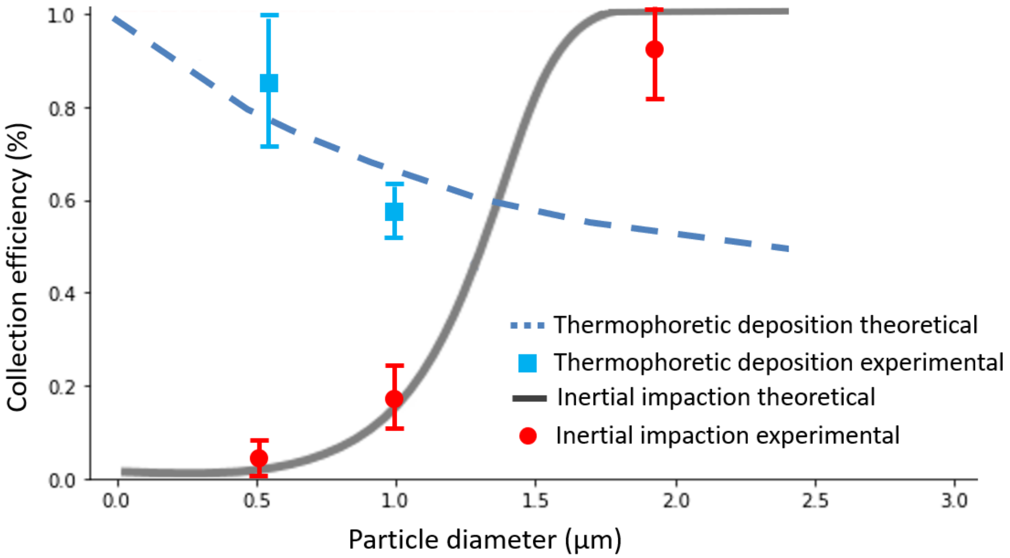


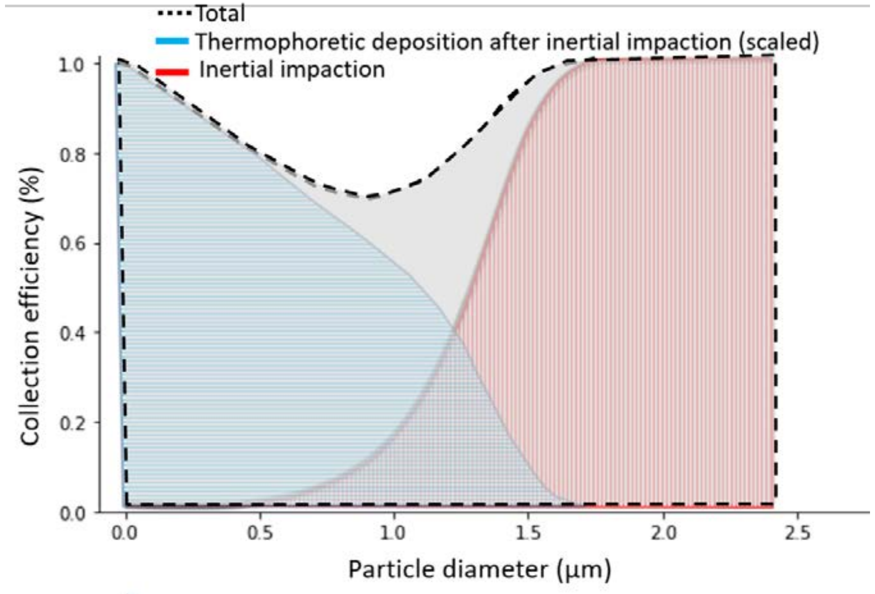


M. Hajizadehmotlagh, et al., ***SNA A***, in preparation.

Initial Results

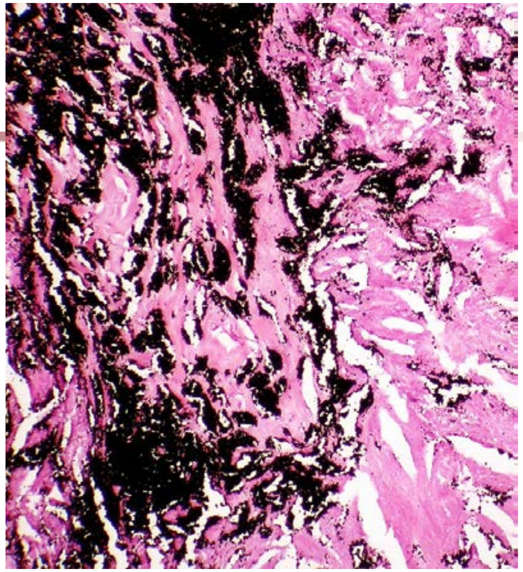
Cut-point test results with PSL particles.



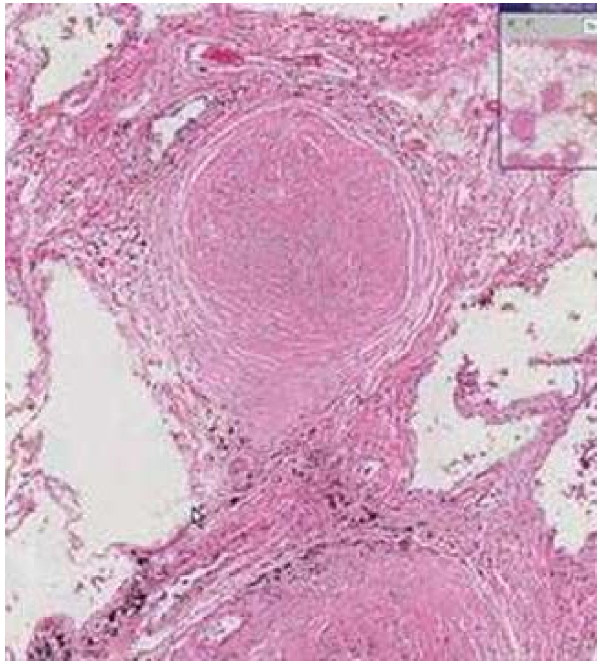


M. Hajizadehmotlagh, et al., ***SNA A***, in preparation.

Histopathology



Coal macule.



Silicotic nodule.

Silica Speciation

- Beer-Lambert Law

Measure of absorbance ↑ transmittance ↑

$$A = -\log T = \log \frac{I}{I_0}$$

I → Final light intensity

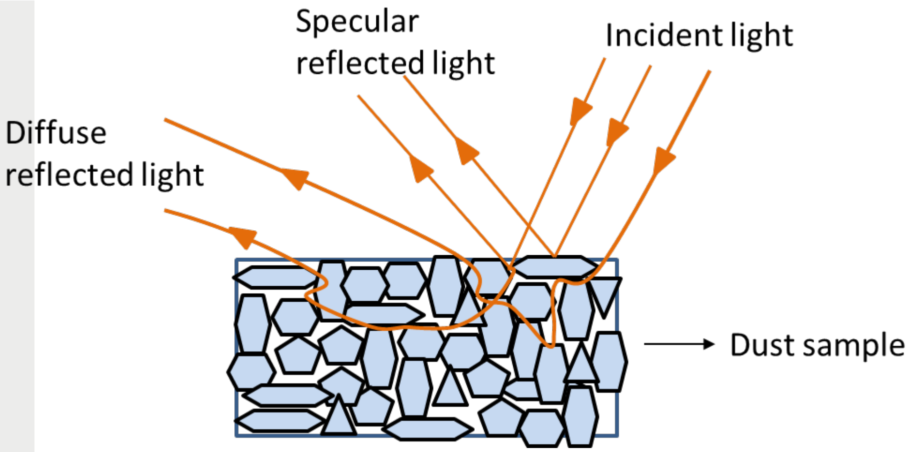
I_0 → initial light intensity

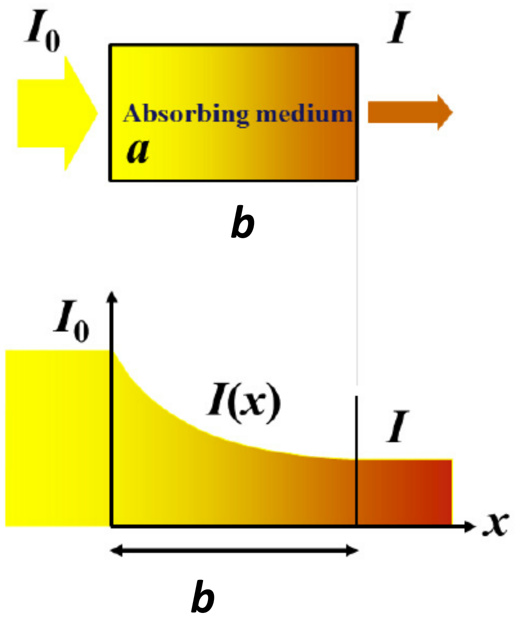
Absorptivity ↑ Path length ↑

$$A = a(\lambda)\, b\, C$$

C → Concentration

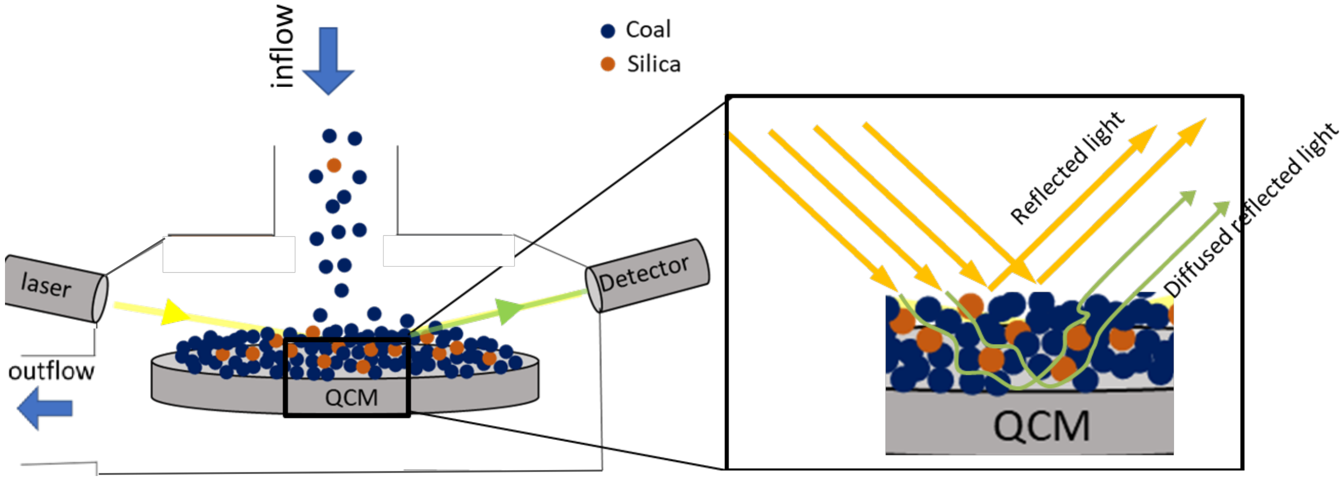
$$A_{total} = \sum_i a_i(\lambda)\, b\, C_i$$





Silica Speciation – Optical/Mass Sensor

- Optical sensor is based on diffuse reflectance spectroscopy and beer-Lambert law.



Optical sensor

(2) $a_{Si}(\lambda)\, b\, C_{Si} + a_{Co}(\lambda)\, b\, C_{Co} + a_b(\lambda)\, b\, C_b = \log \frac{I}{I_0}$

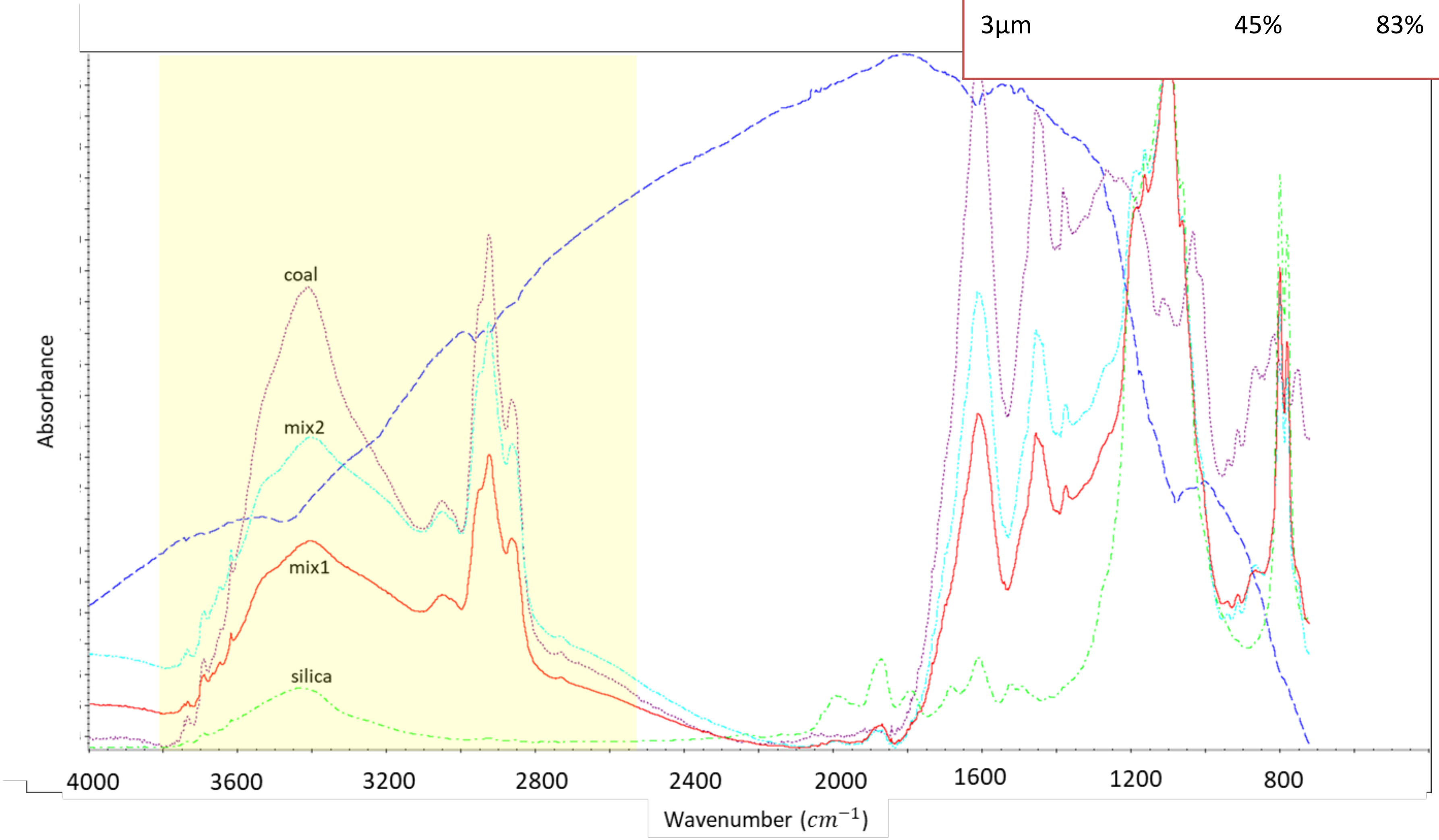
(3) $a_{Si}(\lambda')\, b\, C_{Si} + a_{Co}(\lambda')\, b\, C_{Co} + +a_b(\lambda')\, b\, C_b = \log \frac{I'}{I'_0}$

Mass sensor ← (1) $\rho_{Si} C_{Si} + \rho_{Co} C_{CO} + \rho_b C_b = M_{QCM}$

→ C_{Si}, C_{Co}, C_b

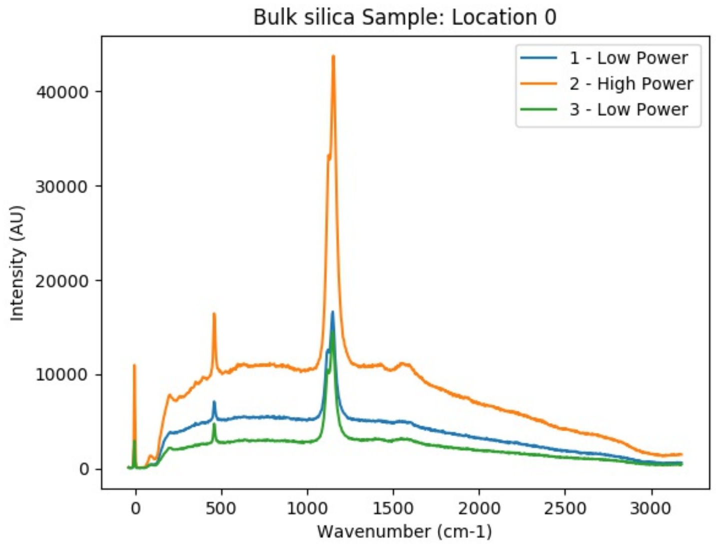
FTIR Results

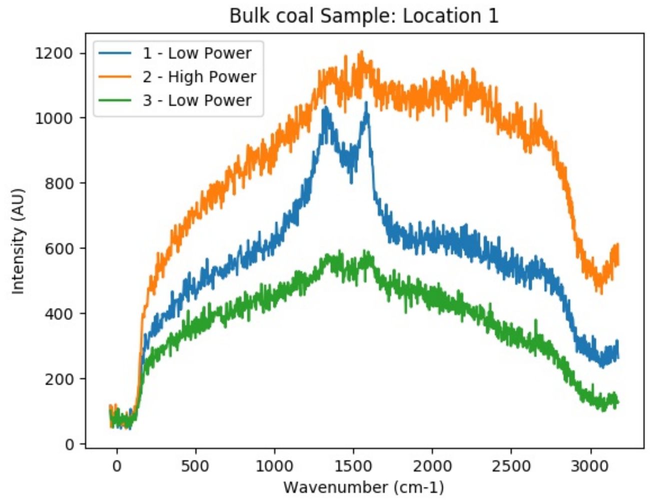
Wavelength	Coal	Silica
2.5 µm	70%	81%
3µm	45%	83%

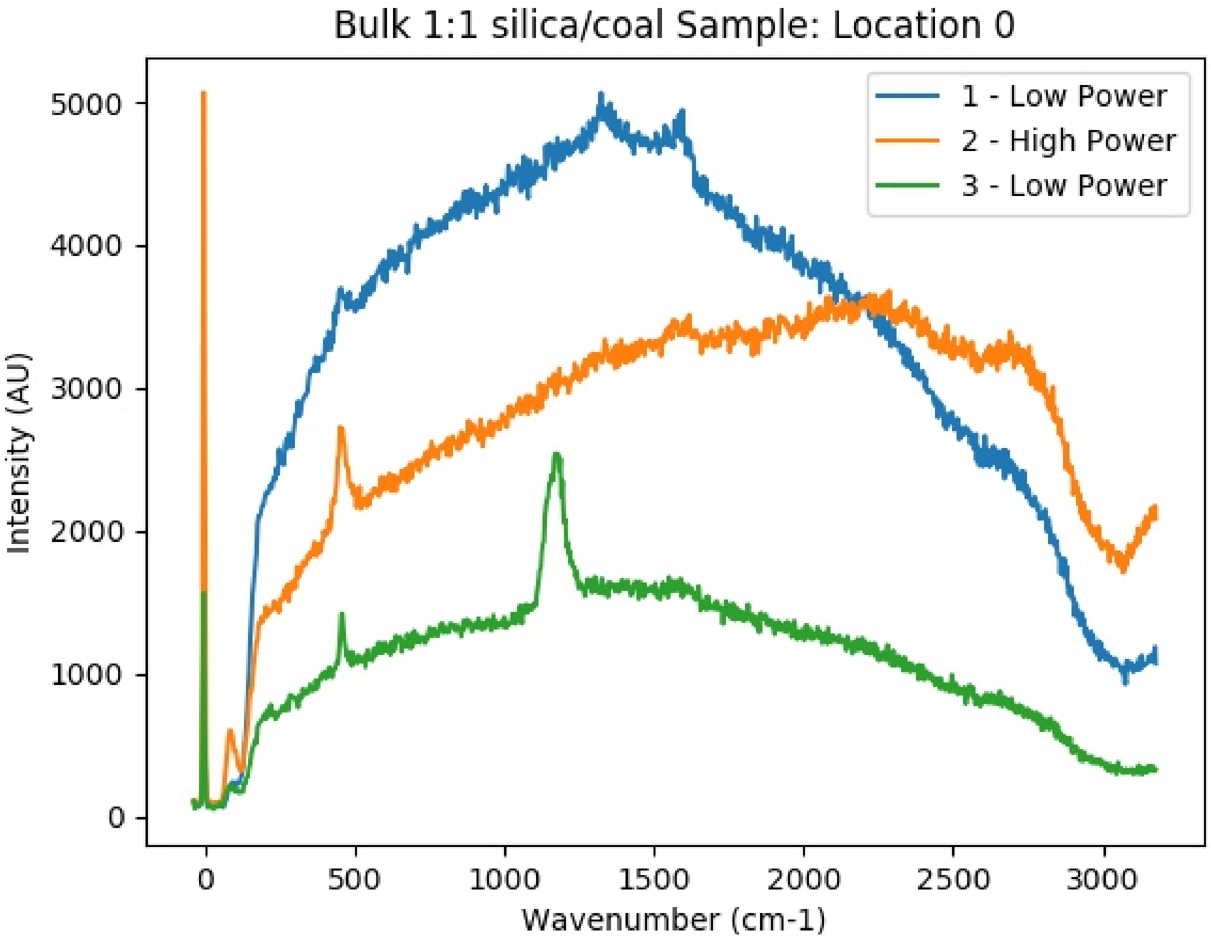


Mix1 - 1:3 silica to coal Mix2 - 1:4 silica to coal

RAMAN spectroscopy







Shortcomings of optical methods w. WEARDM

- **WEARDM sampling at 250 mL/min**
  - Low signal-to-noise at silica LOD
  - Long integration time

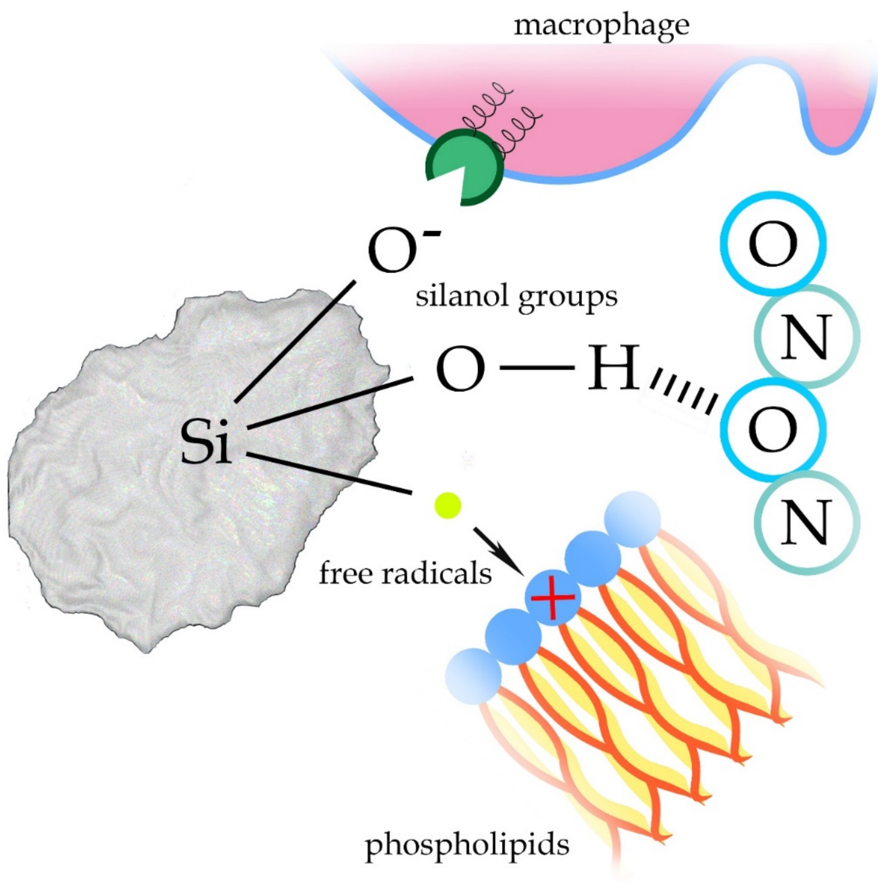
- **Confounding signal**
  - Water peak at 2900 nm
  - Kaolin
  - Silica vs. silicates

Liquid microfluidic platform -> chemical detection of cellular toxicity

Silica-inducing cellular damage

- **Silanol groups**
  - Activation of macrophages producing reactive oxygen species
  - Disruption of biological membranes

- **Free radicals**
  - Lipid peroxidation
  - DNA damage



Silica-inducing cellular damage

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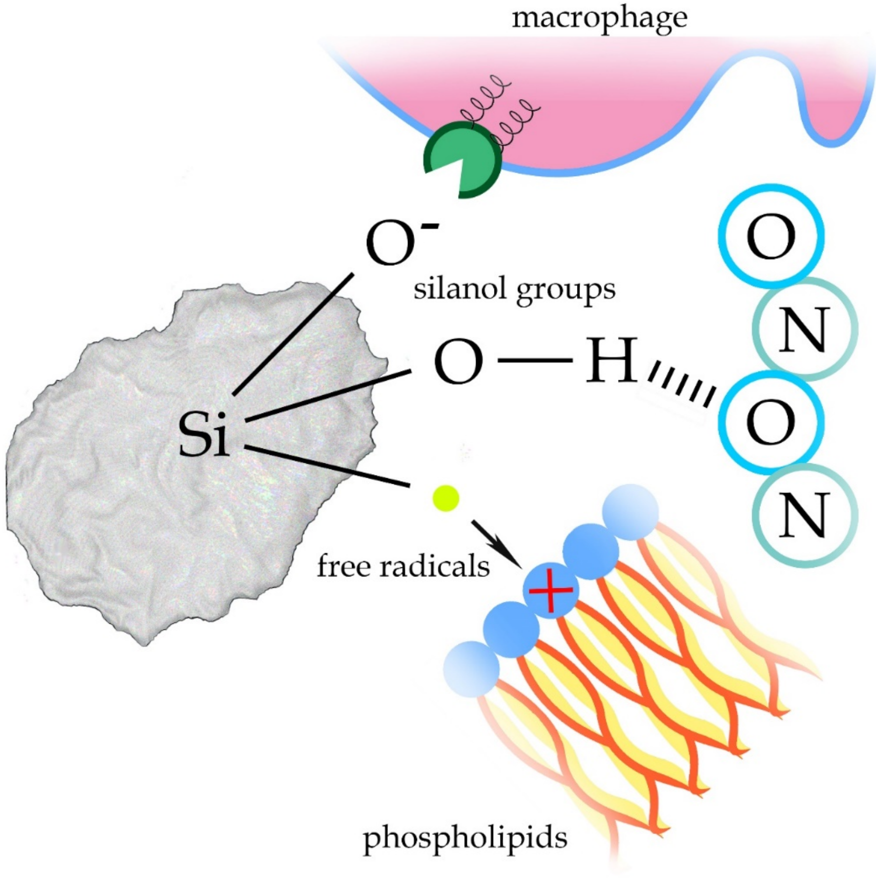
  - Activation of macrophages producing reactive oxygen species
  - Disruption of biological membranes
- **Free radicals**
  - Lipid peroxidation
  - DNA damage

Colorometric detection



Free radicals – first steps

J Toxicol Environ Health. 1990;29(3):307-16.

Role of free radicals in the mechanisms of hemolysis and lipid peroxidation by silica: comparative ESR and cytotoxicity studies.

Dalal NS[1], Shi XL, Vallyathan V.

Author information

1 Department of Chemistry, West Virginia University, Morgantown 26506.

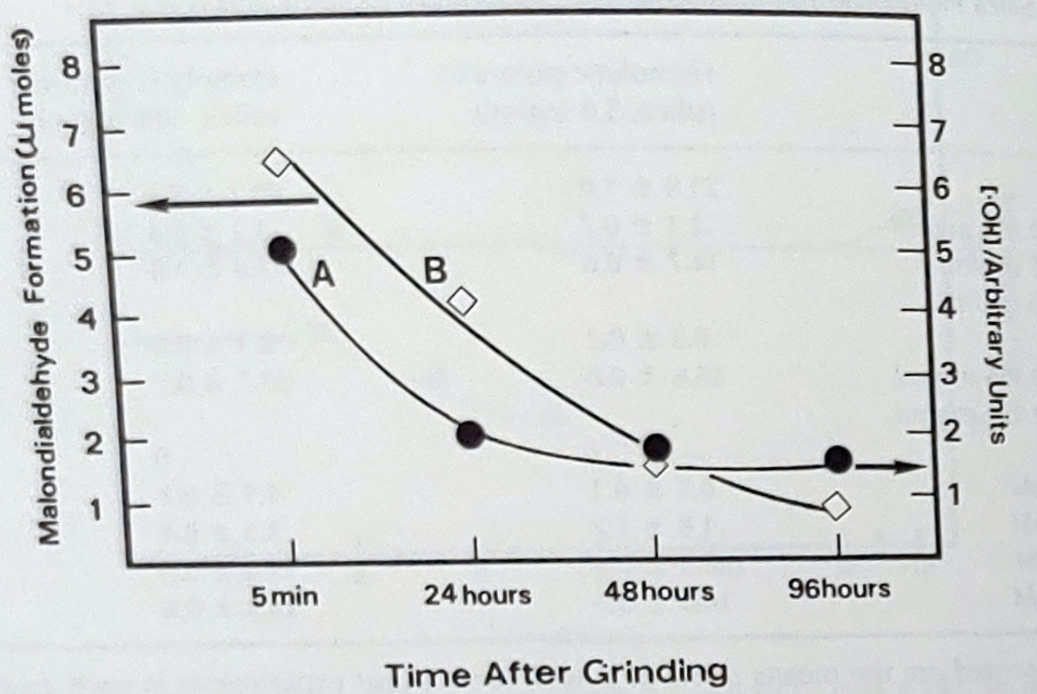
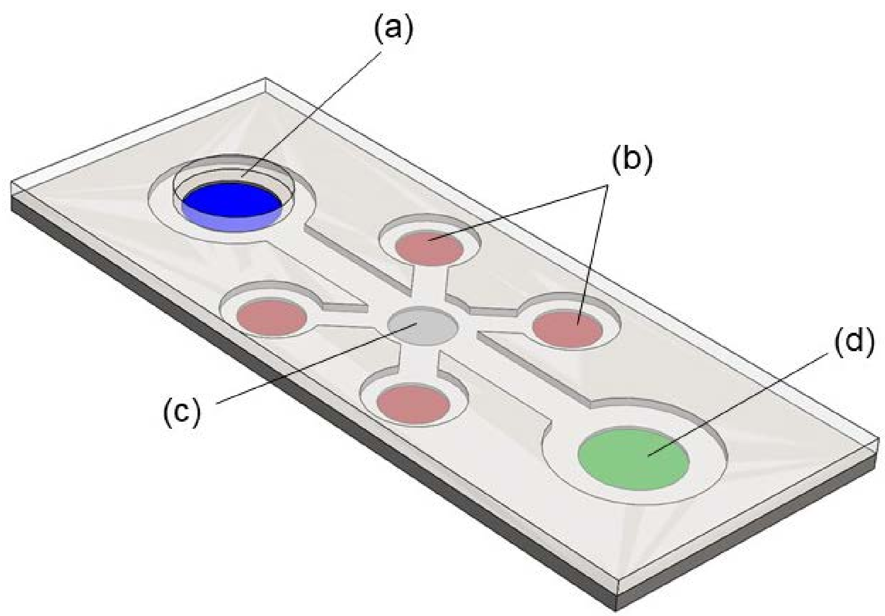
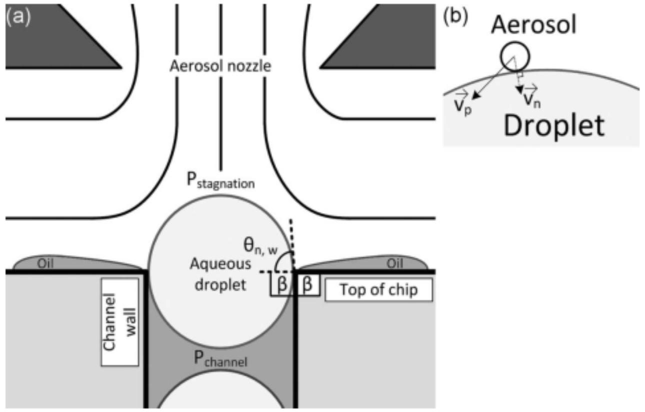


FIGURE 3. Effect of "aging" on the silica's ability to generate hydroxyl radicals, plot A (●) and effect of "aging" of the same sample on the rate of peroxidation of linoleic acid, plot B (◊).

Hybrid (air / liquid) microfluidics



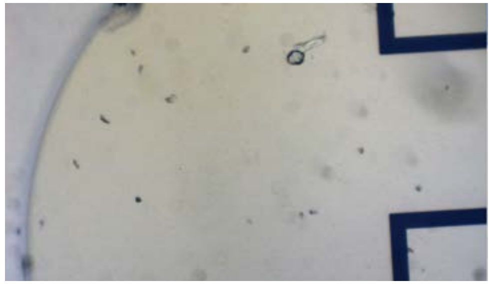
a) deposition/concentration site
b) reagents, media
c) Mixing/detection site (optical)
d) exhaust



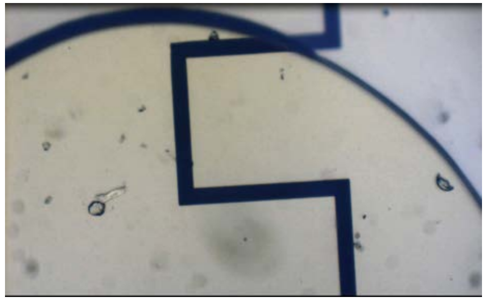
Damit, Brian. "Droplet-based microfluidics detector for bioaerosol detection." *Aerosol Science and Technology* 51.4 (2017): 488-500.

- **Air microfluidics**
  - Initial fractionation (respirable)
  - Pre-concentration
- **Liquid microfluidics**
  - Separation concentration
  - Transport
  - Chemical reaction / detection

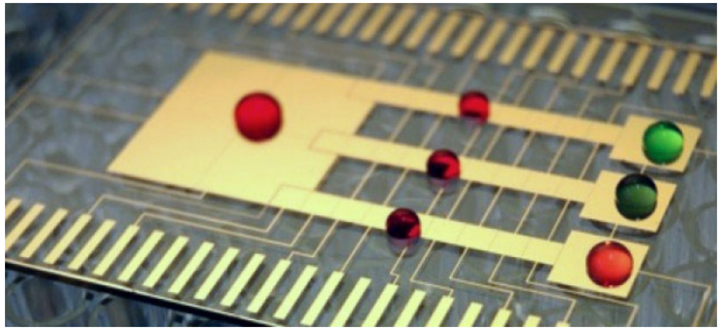
Seemless transport : digital microfluidics

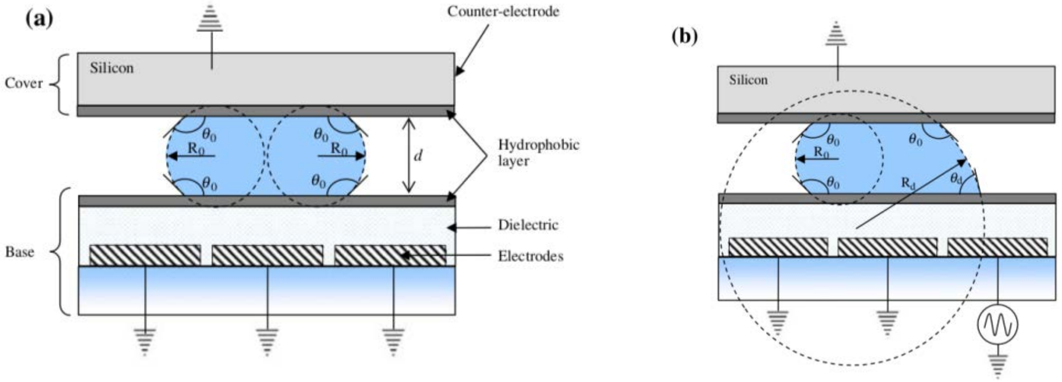


No voltage - No droplet movement



Droplet movement driven by voltage





$$R_0 = -\frac{d}{2\cos\theta_0}$$

$$R_d = -\frac{d}{\cos\theta_0 + \cos\theta_d}$$

We found:

$$\Delta P = \gamma \frac{\cos\theta_d - \cos\theta_0}{d}$$

Design features that improve pumping

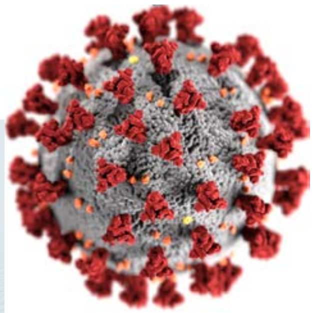
Superhydrophobic surfaces

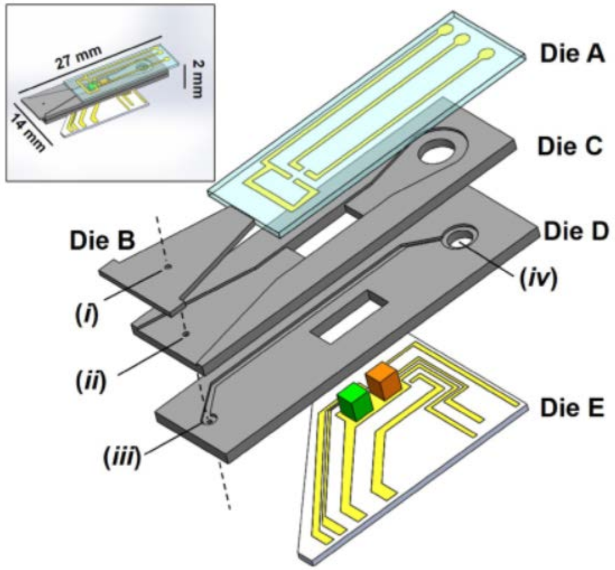
Dielectric thickness

Height of top plate

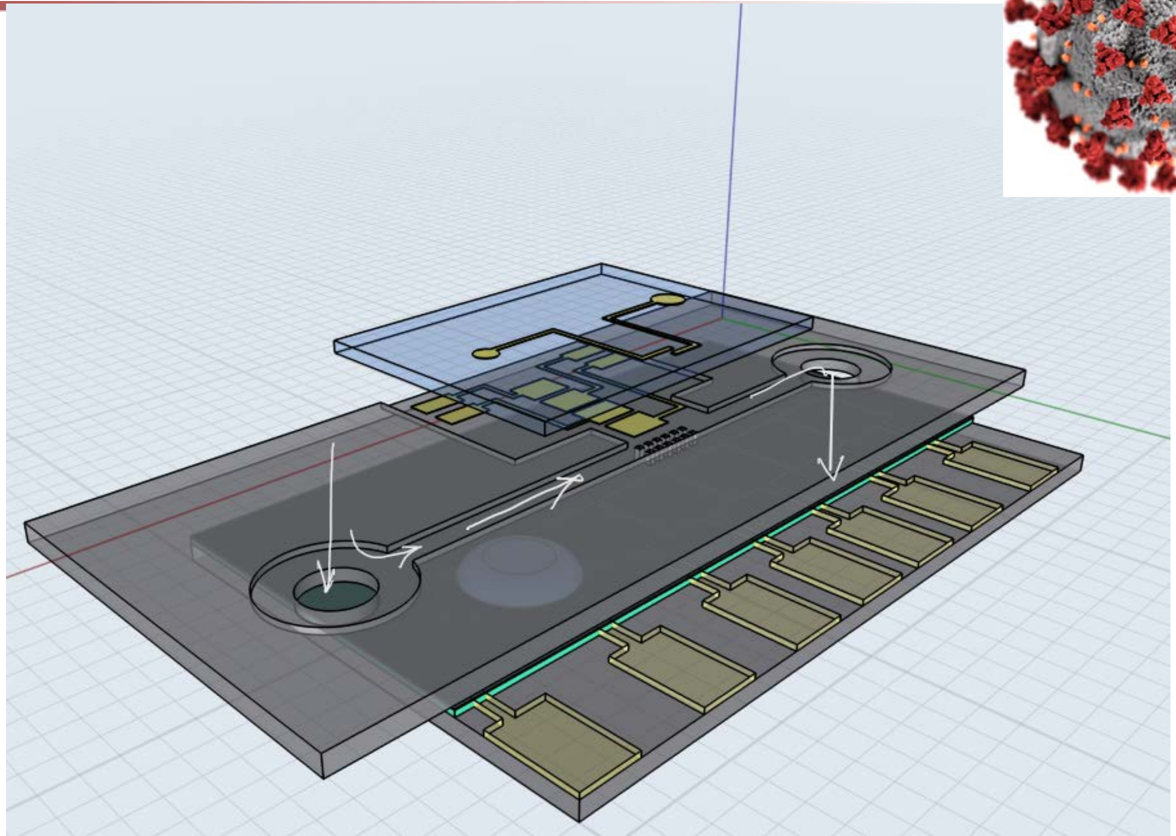
Material properties/conc.of solution

Bio-Aerosol Detector (Concept drawing)





Legacy PM2.5 sensor design



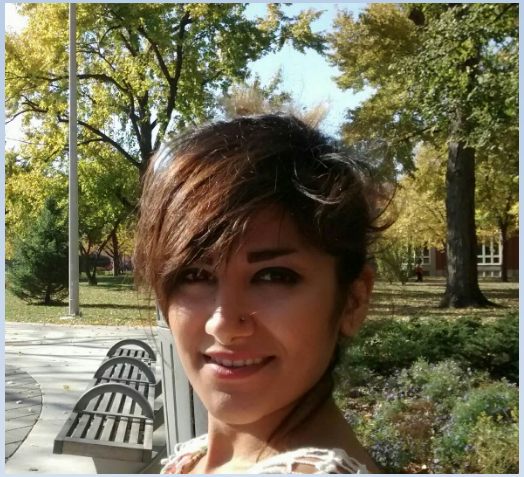
Adaptation of PM 2.5 design for EWOD pumping based aerosol sampler;

Fahimi, Dorsa, et al. "Vertically-stacked MEMS pm2. 5 sensor for wearable applications." *Sensors and Actuators A: Physical* 299 (2019): 111569.

Conclusion

- Difficult to detect silica in real-time (< 30 min integration time) with a wearable footprint using air microfluidics and opto-gravimetric methods
- Established methods exists to detect cellular damaging silica dust in laboratory settings
- Hybrid microfluidic platforms allow for enhanced concentration and chemical detection using legacy methods
- Can be made very low cost:
  - Small footprint
  - Inexpensive materials (i.e. paper)

Acknowledgements



Mandana Hajizadehmotlagh

Nitin Jayakumar

NIOSH #200-2016-91153

Thank you!

paprotny@uic.edu