NEMS - From devices to systems

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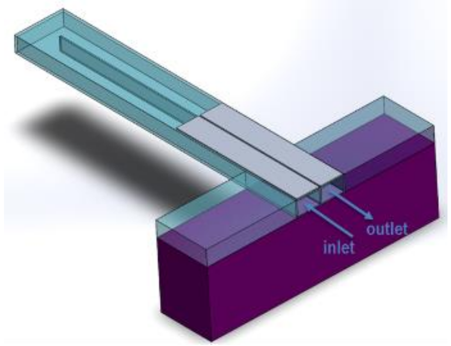
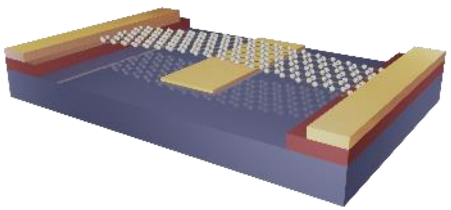
Outline

- **Motivation**
- **(Some) Research Activities**
  - Hollow Resonators
    - A.k.a. Improving Q in liquid



  - Multi-physical gas detection
    - A.k.a. addressing selectivity (what really matters)



- **Take home message**

Sensor Networks around the Globe

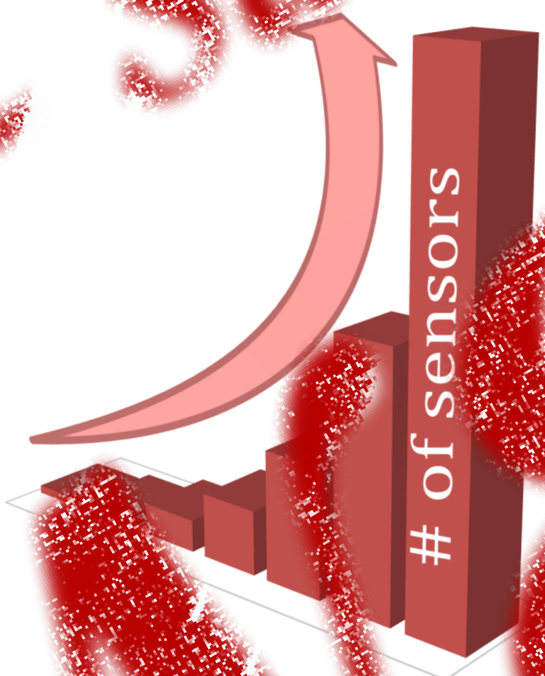
Traffic

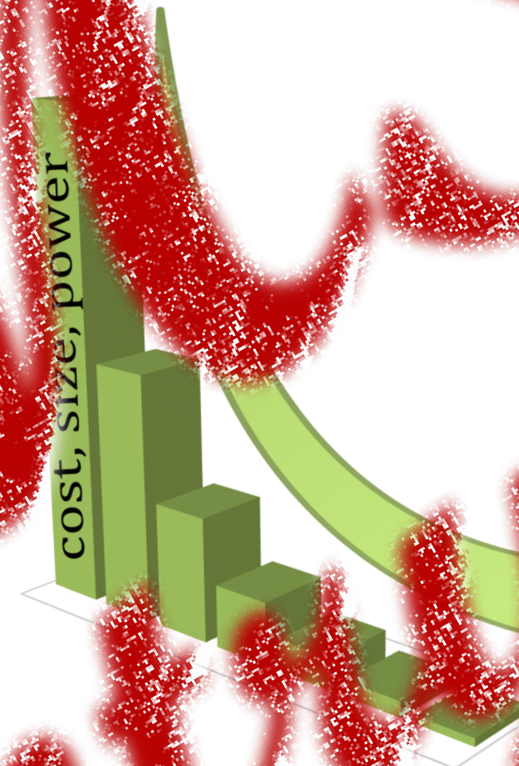
Personal health

Floods

Seismic activities

Sensor Networks around the Globe

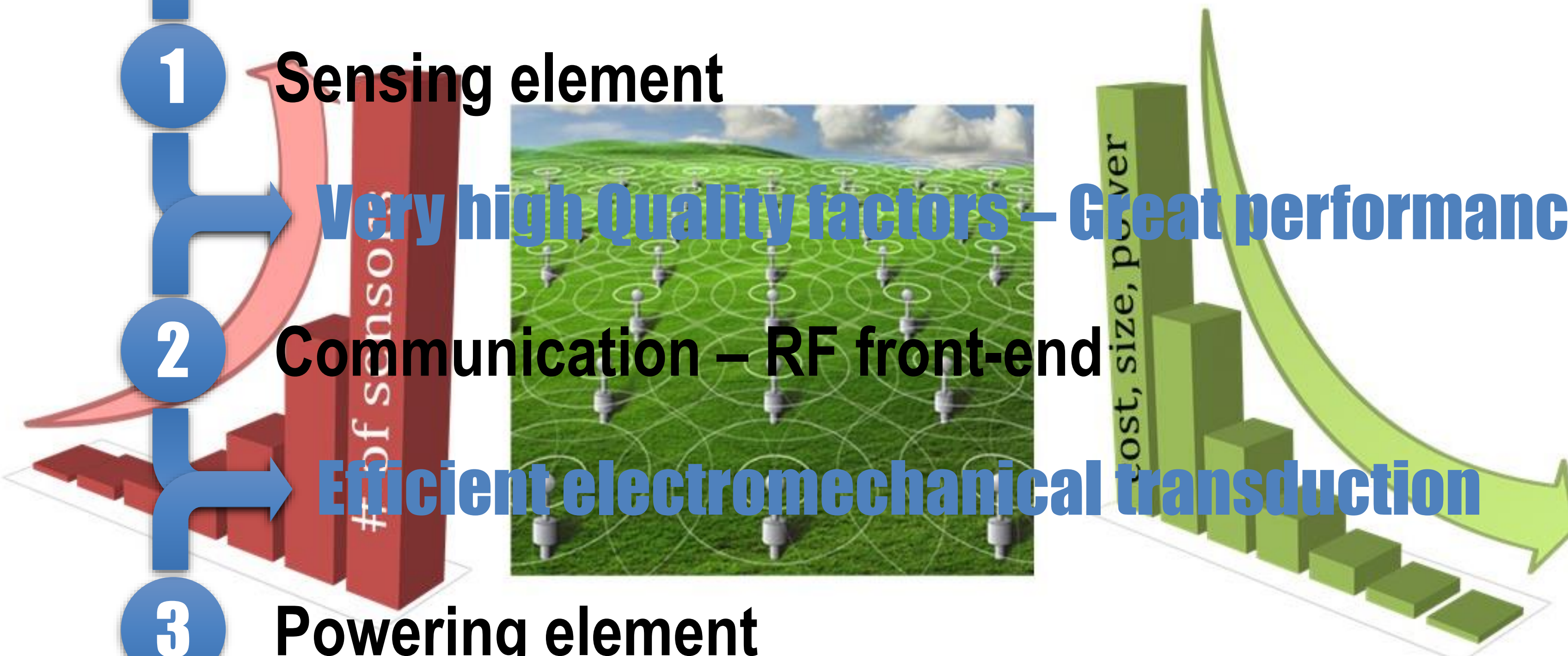




Why mechanical devices?

Access to manifold magnitudes

1. Sensing element



Very high Quality factors – Great performance

2. Communication – RF front-end

Efficient electromechanical transduction

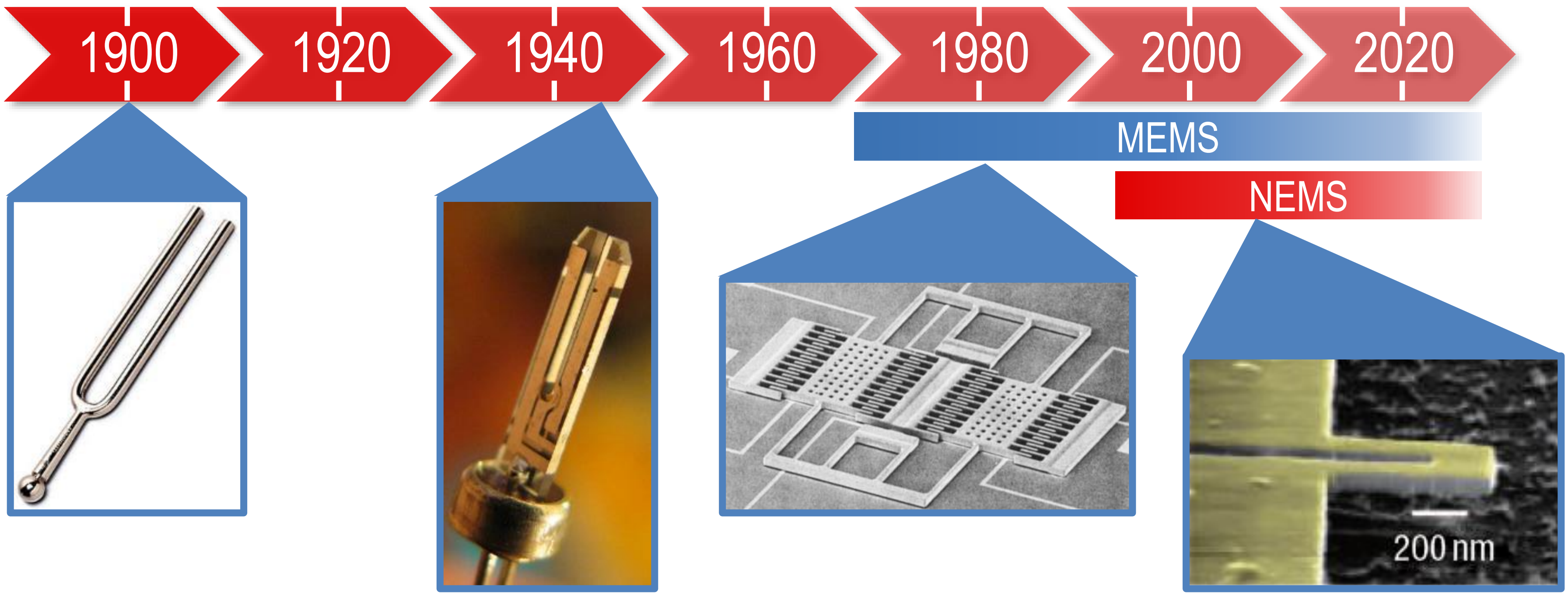
3. Powering element

Movement/Vibrations harvesting

Why small devices?

- Advances in mechanical devices have paralleled civilization development
  - E.g. Timekeeping

Miniaturization brings improvements



Size ↘

Cost ↘

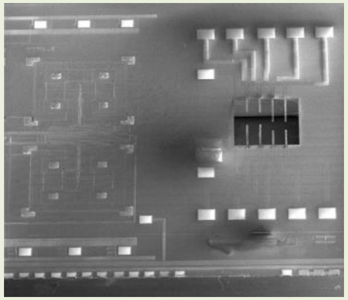
Power ↘

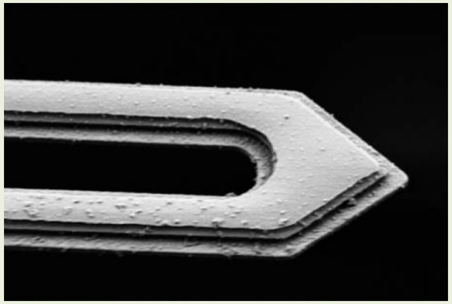
Sensing performance ↗

Research track

2002-2006 – UAB

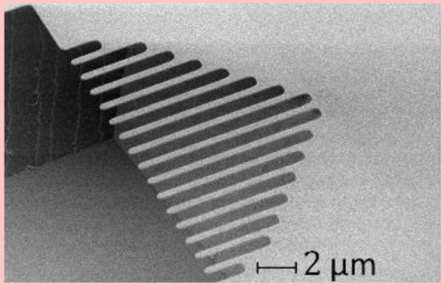
- DC Force sensors
- CMOS integration

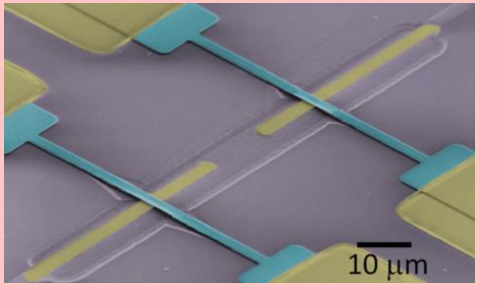




2007-2009 – EPFL

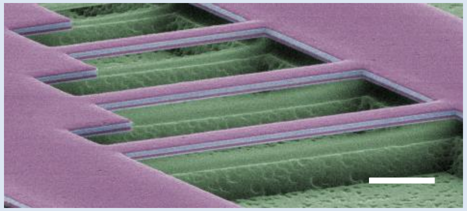
- Nanofabrication
- Hydrogen sensors

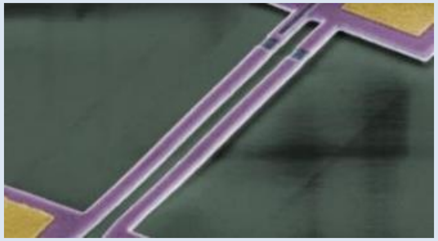




2009-2012 – Caltech

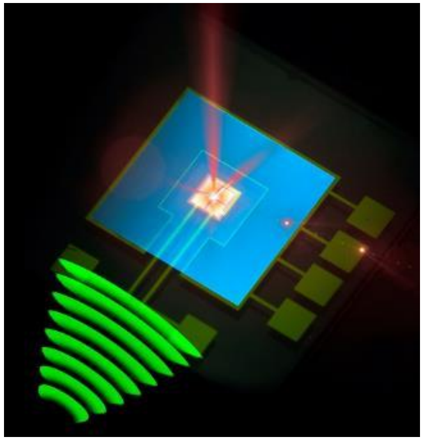
- Resonant NEMS
- NL dynamics





2012-2013 – DTU

- Back-action
- Optomechanics



Since July 2013

- **Advanced NEMS Group Leader @ EPFL**

Annalisa

Zohreh

Alberto

Kaitlin

Andrea

Tom

Faizan

Marco

FNSNF

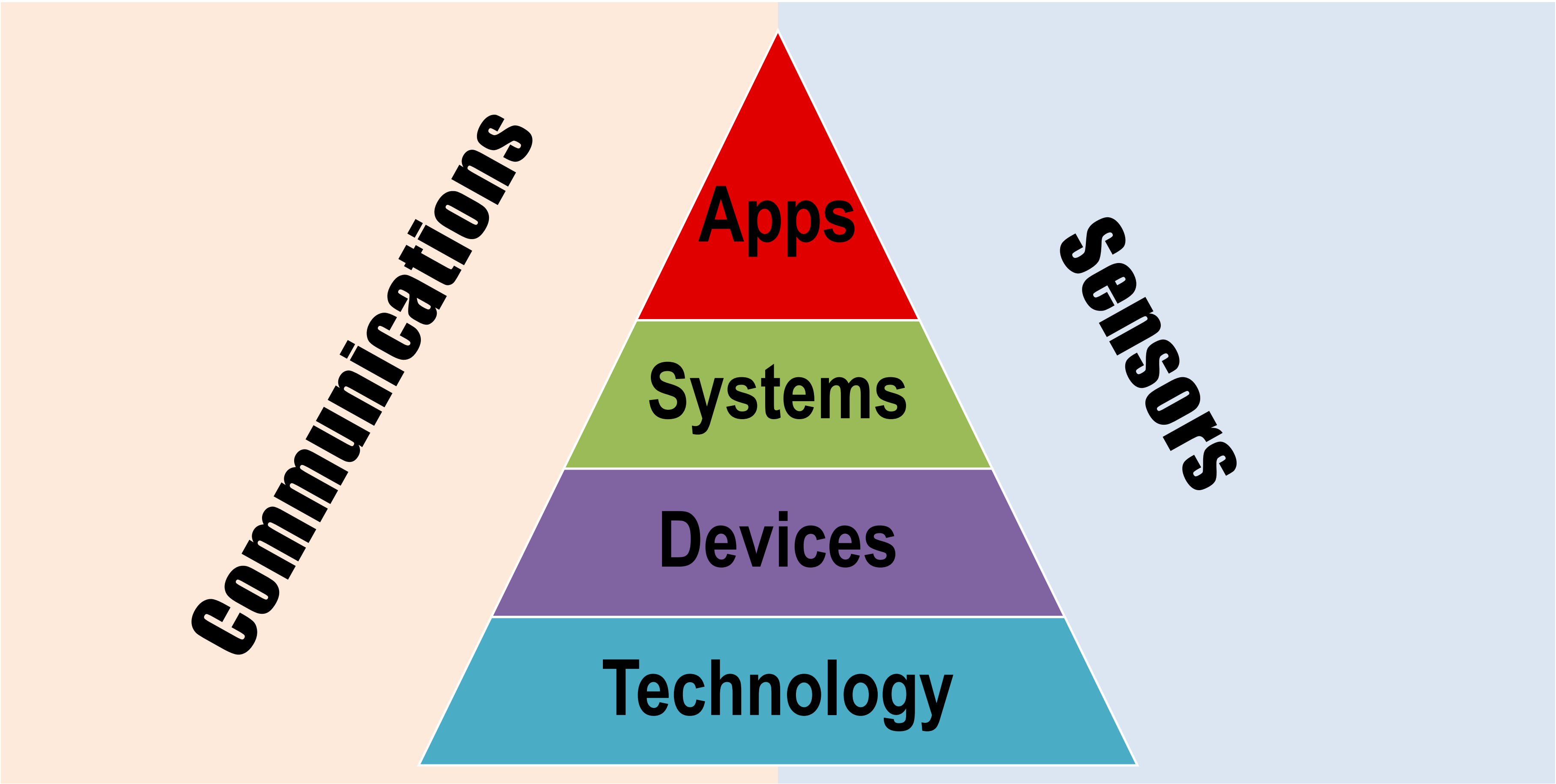
MARIE CURIE ACTIONS

TEXAS INSTRUMENTS

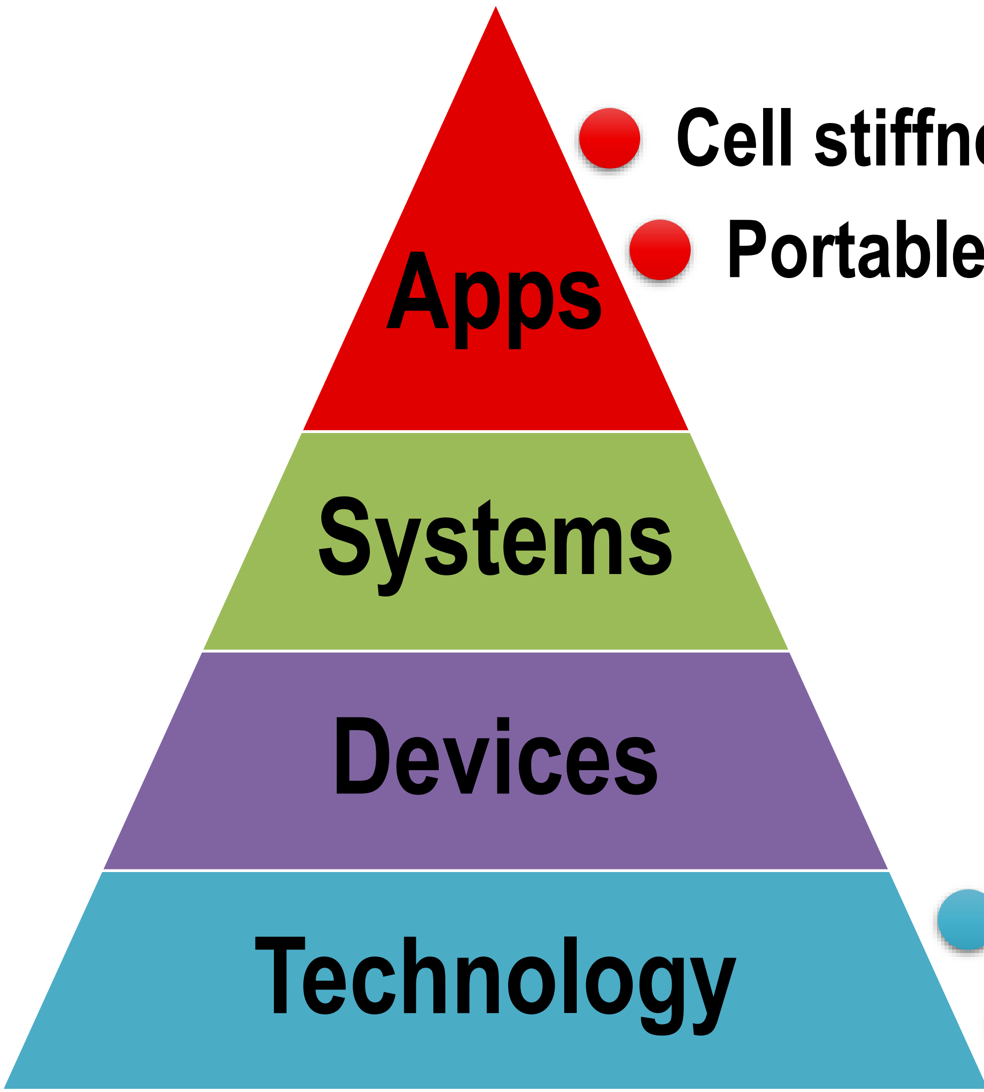
GEBERT RÜF STIFTUNG
WISSENSCHAFT.BEWEGEN

Advanced NEMS – Research overview

- Introducing new application fields for NEMS
- Fundamental studies on performance and noise at the nanoscale



Advanced NEMS – Research overview

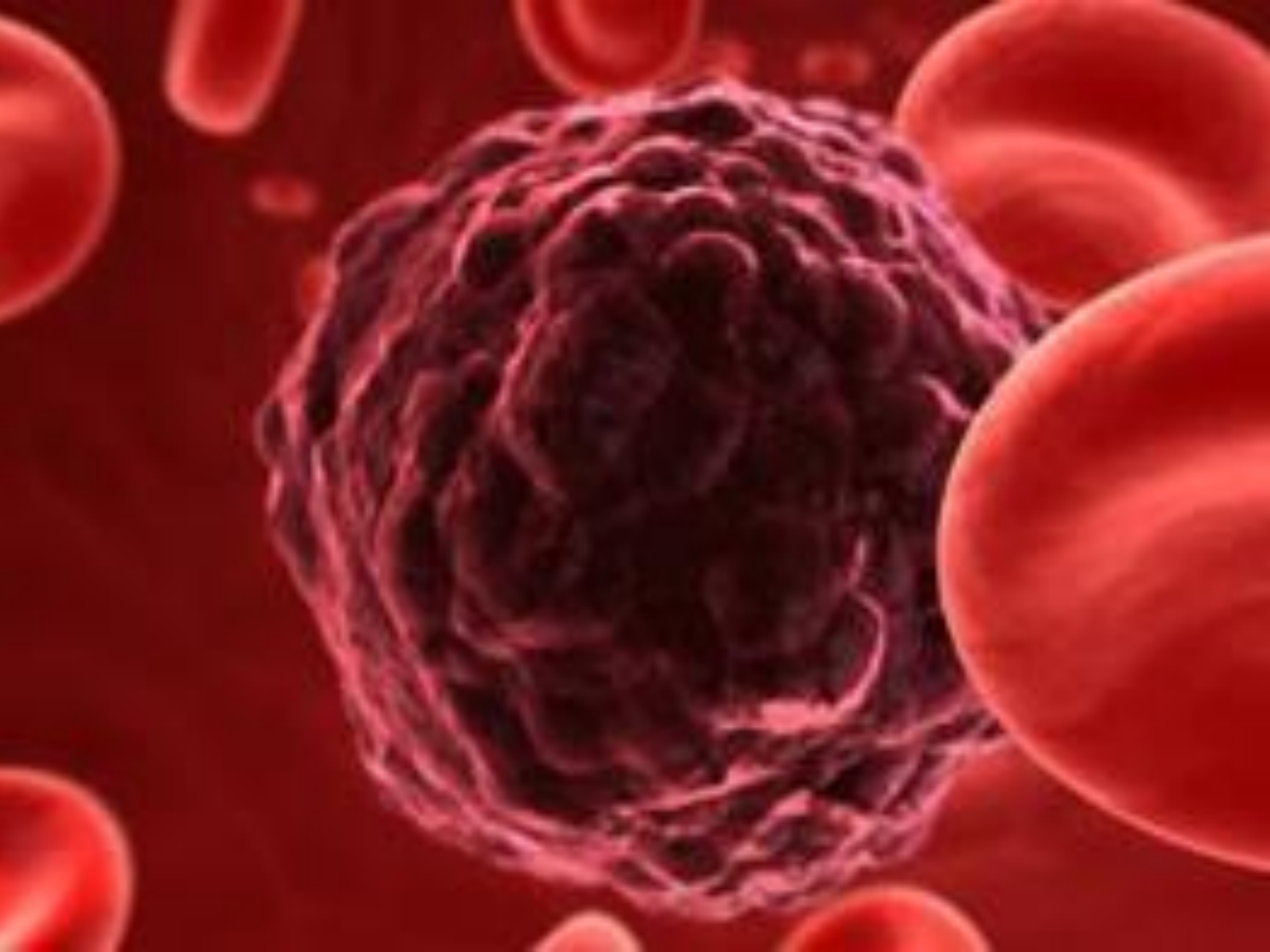


- Cell stiffness detection
- Portable gas analyzer

- Hollow N-MEMS
- 2D NEMS

Hollow resonators

a.k.a. How to improve Q in liquid

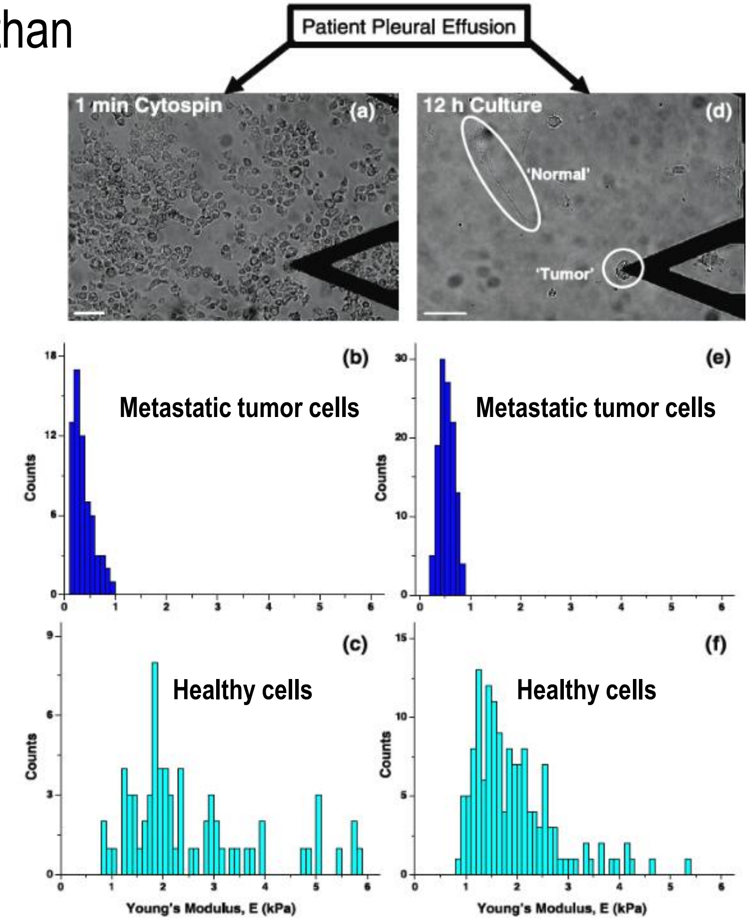


Cancer cells softer than benign cells

- Cross et. Al: AFM ex vivo (body fluids) sampling
  - They found that pleural fluid cancer cells are more than 70% softer than benign cells

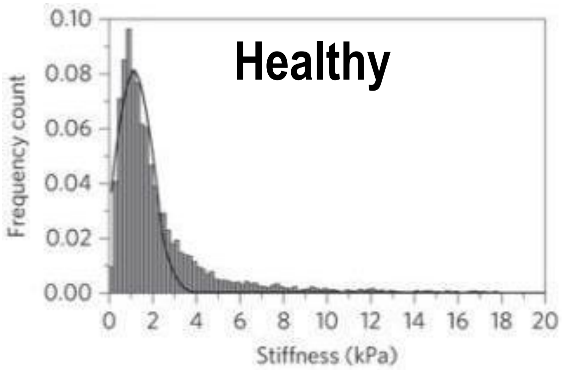
	Cytospin	12 h culture
Tumor cells	0.38±0.20 kPa	0.53±0.10 kPa
Benign Cells	2.53±1.30 kPa	1.97±0.70 kPa

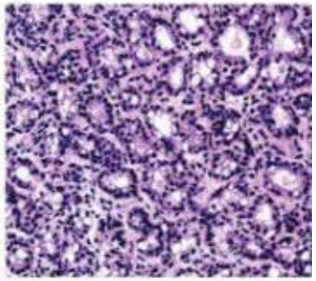
The mechanical analysis can distinguish cancerous cells from normal ones, even when they show similar shapes.

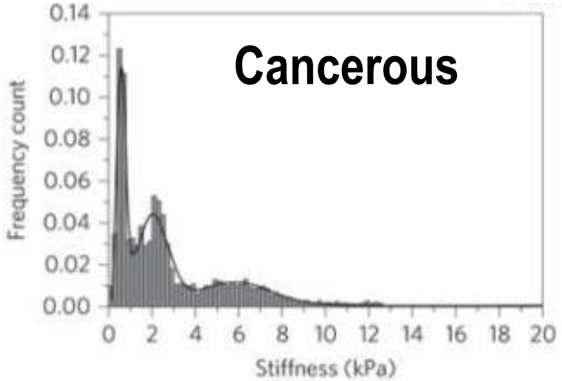


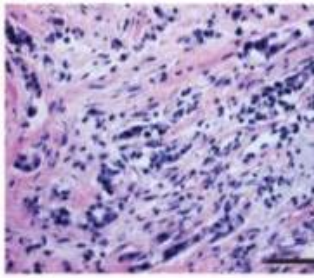
Cross, S.E., et al., Nanomechanical analysis of cells from cancer patients. Nature Nanotechnology, 2007, 2(12), 780- 783.)

Cell stiffness is a good mechanical biomarker







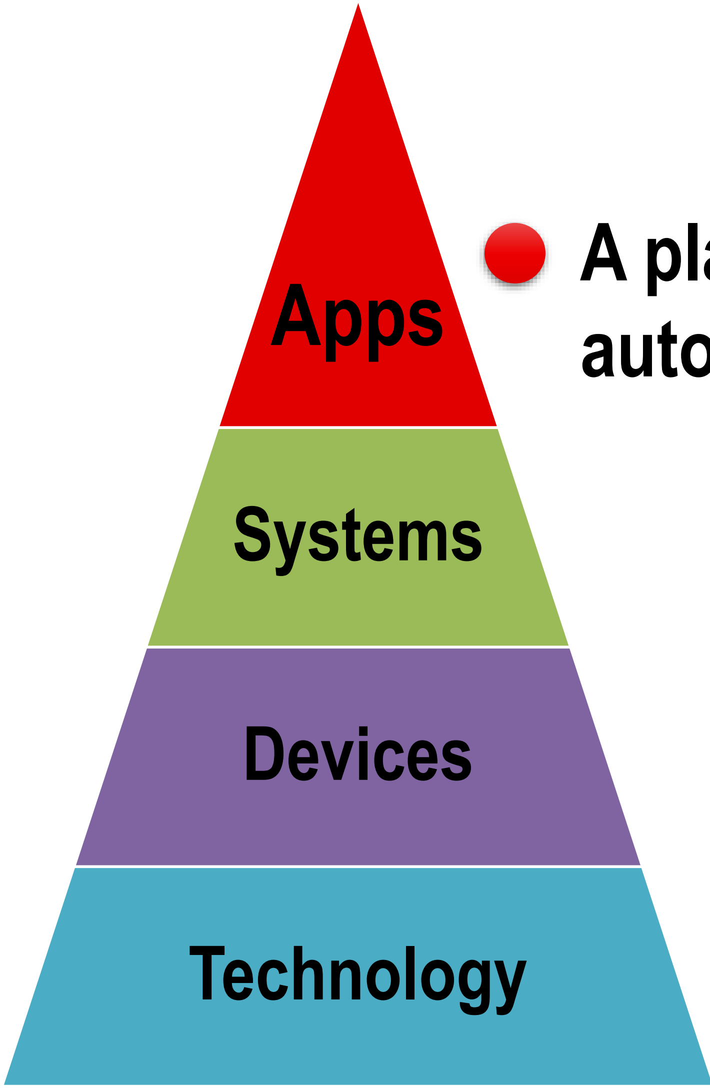


M. Plodinec, *Nature Nano*, 7, 757–765 (2012)

At cellular level typically probed using Atomic Force Microscope

At tissue level, probed with NMR

Research Objective #1



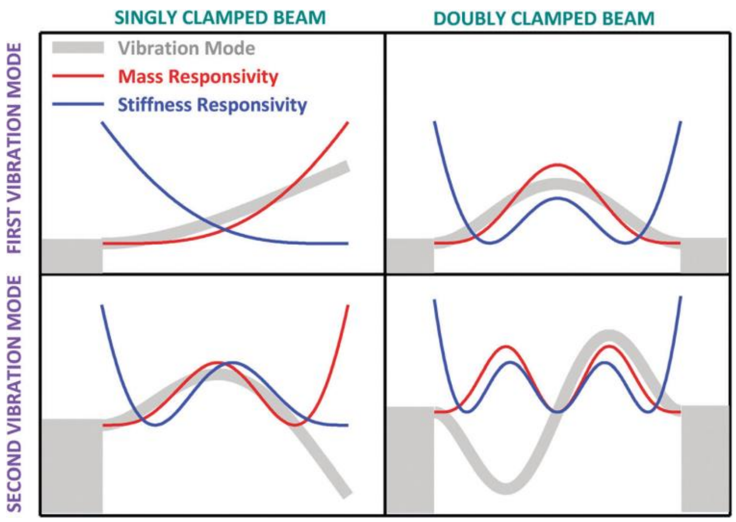
- A platform that allows for an automated detection of cell stiffness

Mass and stiffness loading effects on resonators

- Resonators vibrate at their resonance frequency proportional to $\sqrt{\frac{k}{m}}$
- Stiffness loading effect can be disentangled from mass loading effect via analytical method:

$$\frac{\Delta f_n}{f_{0n}} = \left(\frac{3}{2}\frac{1}{\beta_n{}^4}\frac{\mathrm{d}^2\psi_n(\zeta)}{\mathrm{d}\zeta^2}^2 \frac{E_\mathrm{a}}{E_\mathrm{b}} - \frac{1}{2}\psi_n{}^2(\zeta)\frac{\rho_\mathrm{a}}{\rho_\mathrm{b}} \right) \frac{V_\mathrm{a}}{V_\mathrm{b}}$$

k contribute (+) **m** contribute (-)

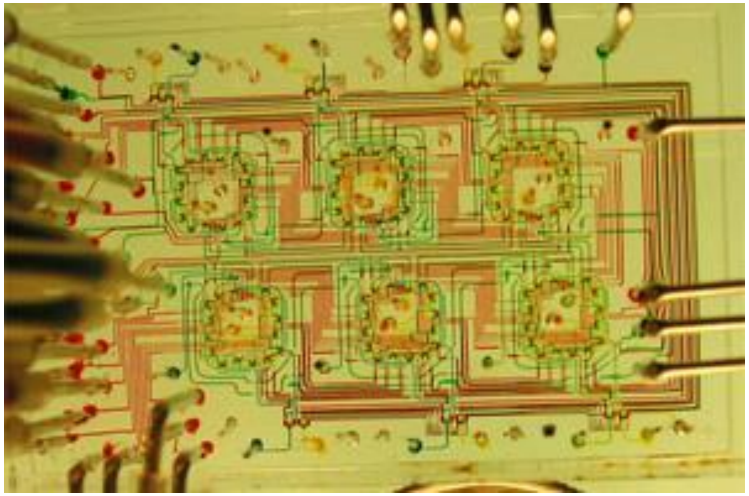


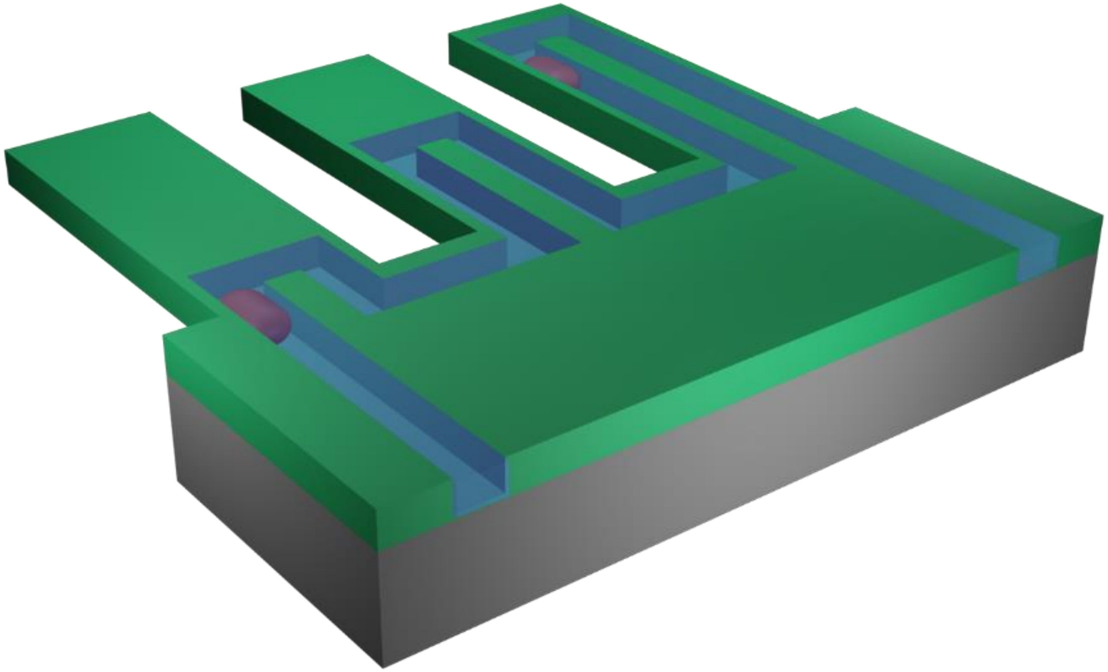
doi: 10.1073/pnas.1218806110

- The responsivity for the mass is proportional to the square of the mode shape amplitude
- The responsivity for the stiffness is proportional to the curvature of the vibration shape.

Solution – Hollow N/MEMS resonators

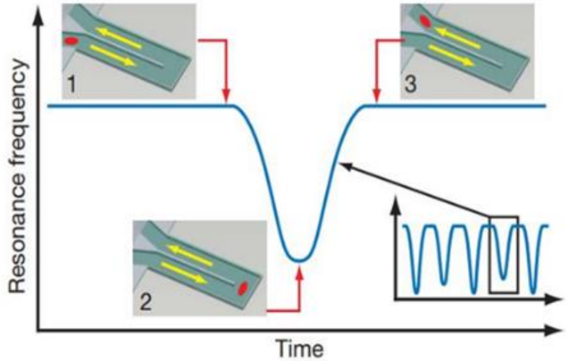
- Arrays of partially hollow cantilevers/beams
- Integrated electromechanical transduction
- Coupled to microfluidic network





Hollow resonators for bio: state of the art

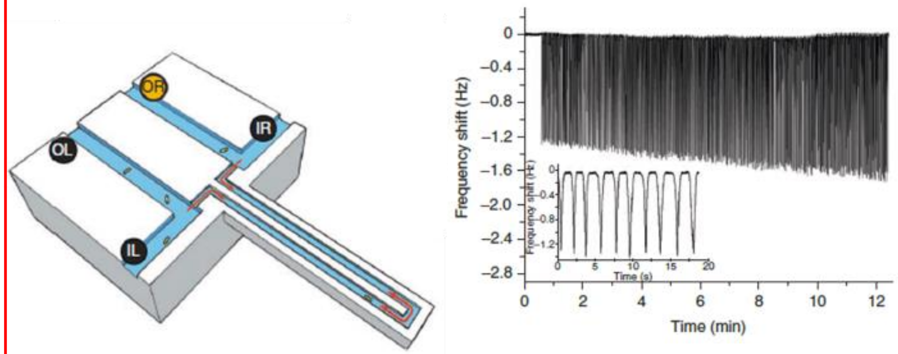
- Measure of single cell and nanoparticle mass



  - $\frac{\Delta f}{f} = -\frac{1}{2}\left(\frac{A}{m}\right) \cdot \Delta\sigma$

doi: 10.1063/1.1611625

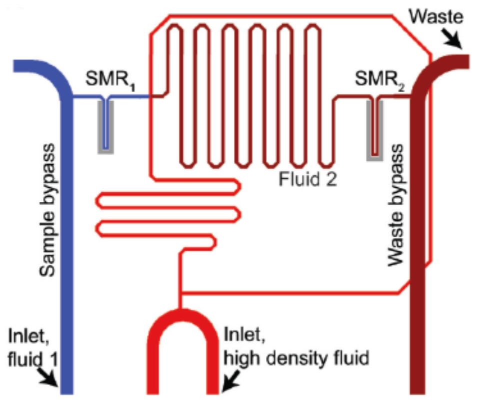
- Monitoring the growth of single cells:



  - $m_{buoyant} = V_{cell}(\rho_{cell} - \rho_{fluid})$

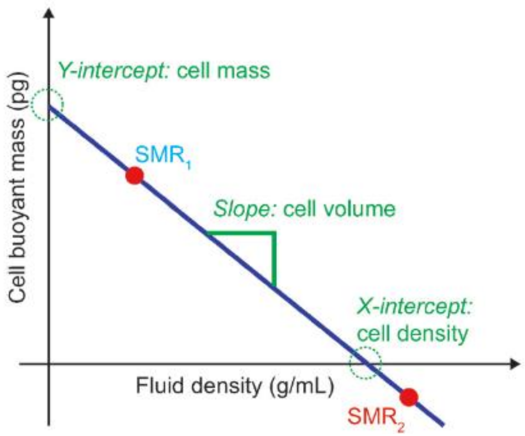
doi: 10.1038/nmeth.1452

- Measure of single cell mass, volume, density



$$m_{buoyant\_1} = V_{cell}(\rho_{cell} - \rho_{fluid\_1})$$

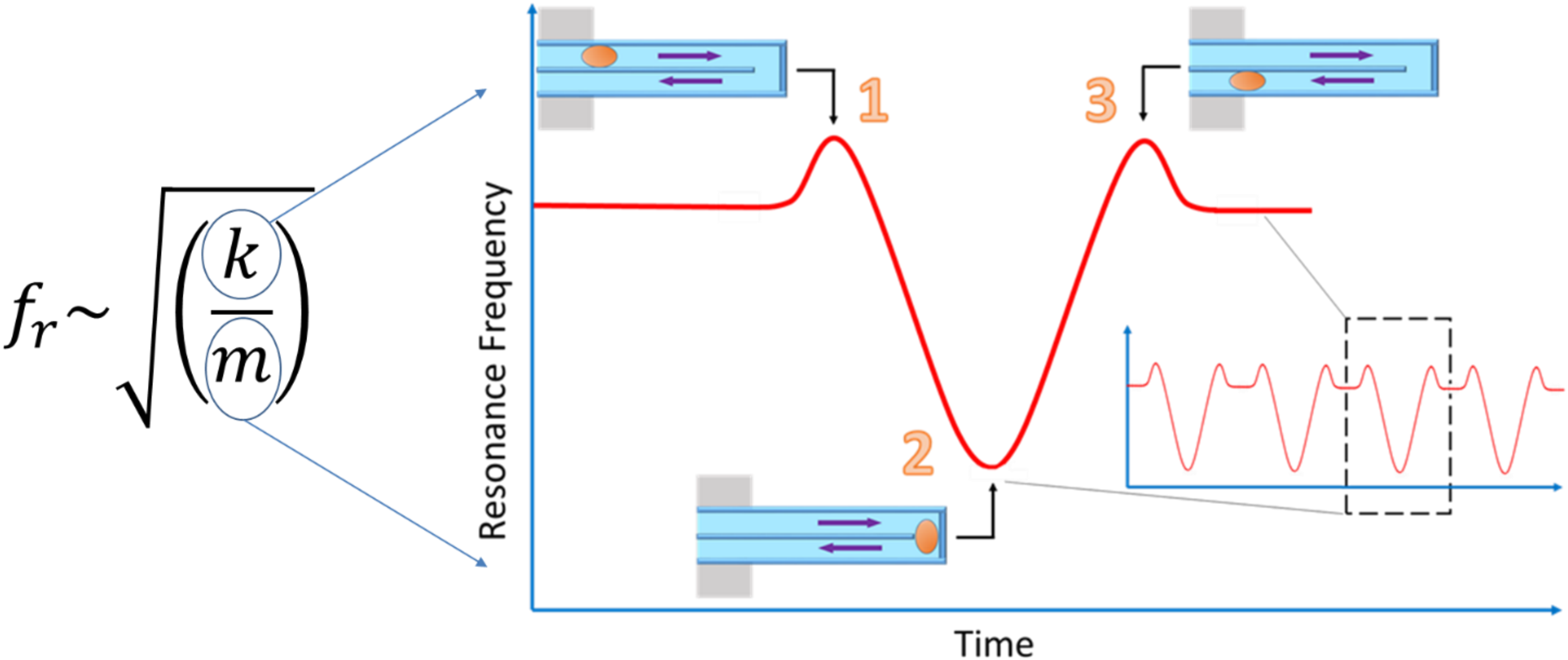
$$m_{buoyant\_2} = V_{cell}(\rho_{cell} - \rho_{fluid\_2})$$



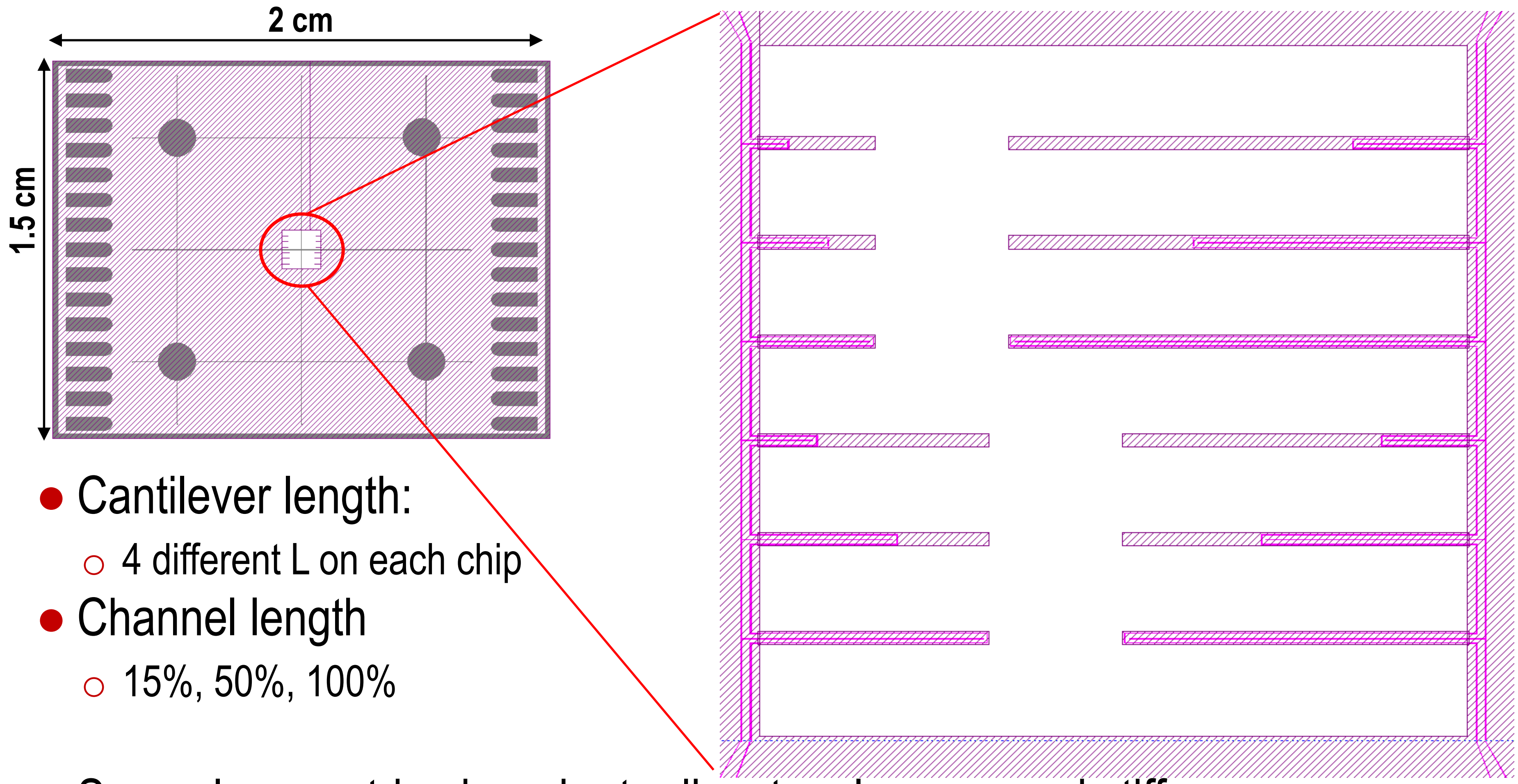
doi: 10.1039/C3LC51022K

What we want to measure

- $E = \boldsymbol{E_R} + jE_I = \boldsymbol{k} + j\eta$
- Cell constrained into the channel: promote elastic energy transfer from cell to resonator.



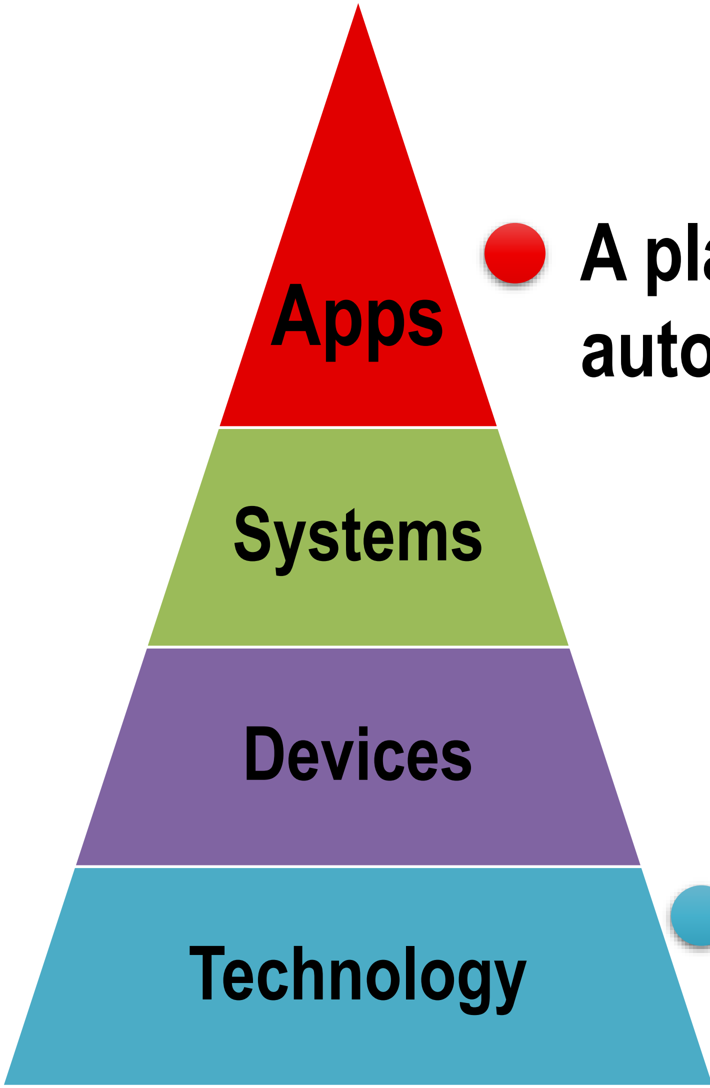
Design - Resonators



- Cantilever length:
  - 4 different L on each chip
- Channel length
  - 15%, 50%, 100%

- Several geometries in order to disentangle mass and stiffness change effect on resonator frequency.

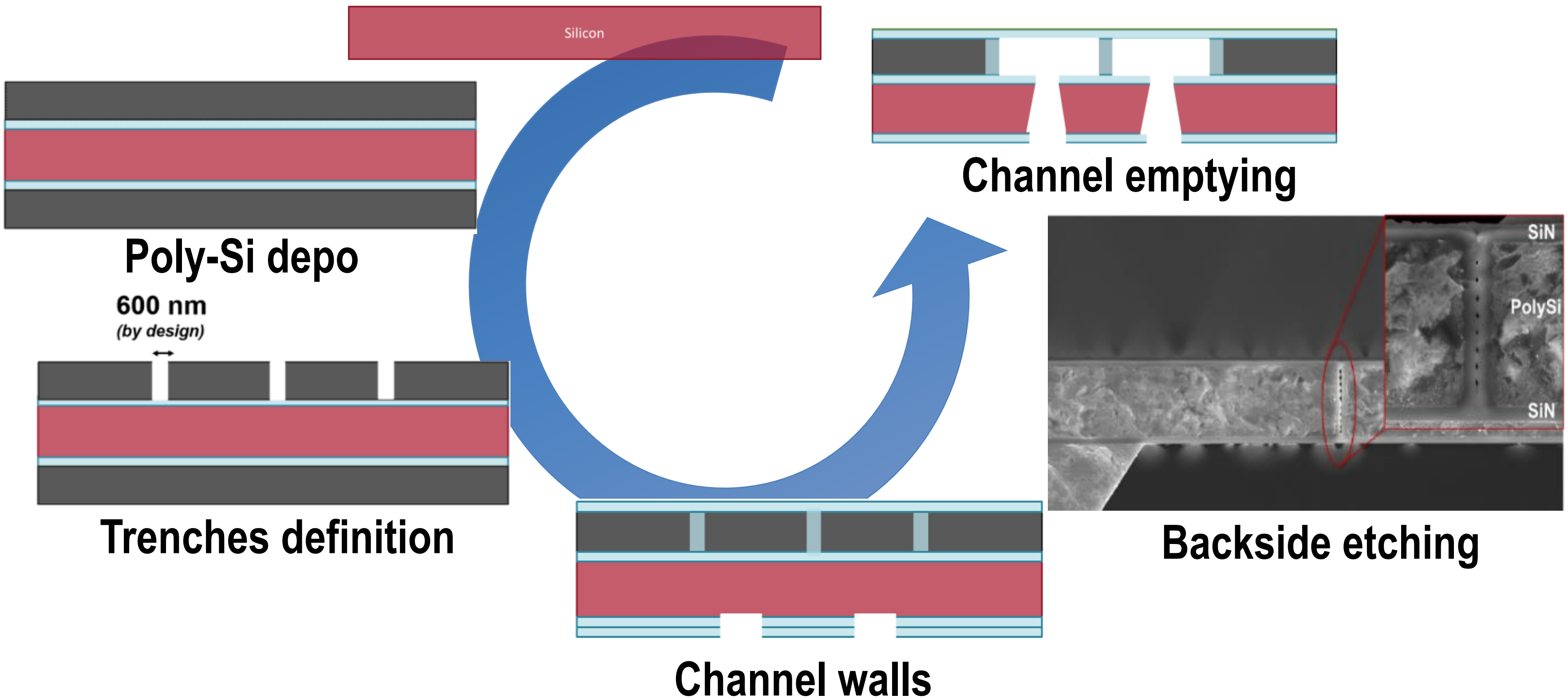
Research Objective #1



- A platform that allows for an automated detection of cell stiffness
- Fabrication of hollow N-MEMS – thin walled suspended microchannels

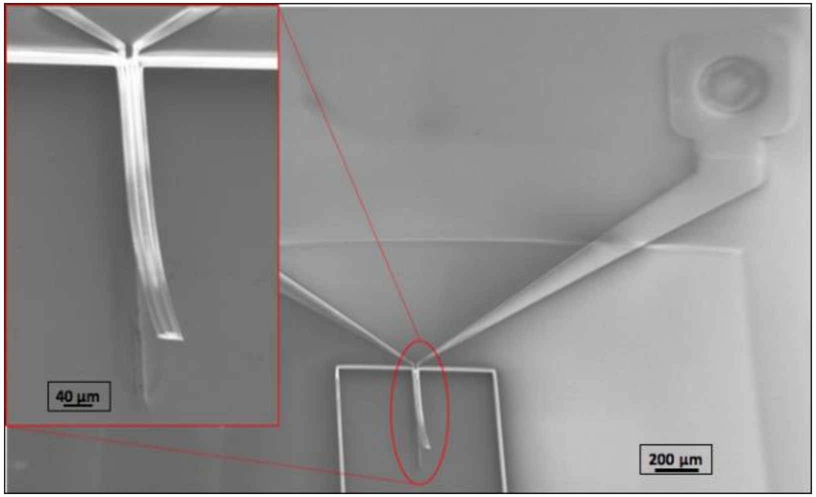
Suspended micro-channels fabrication

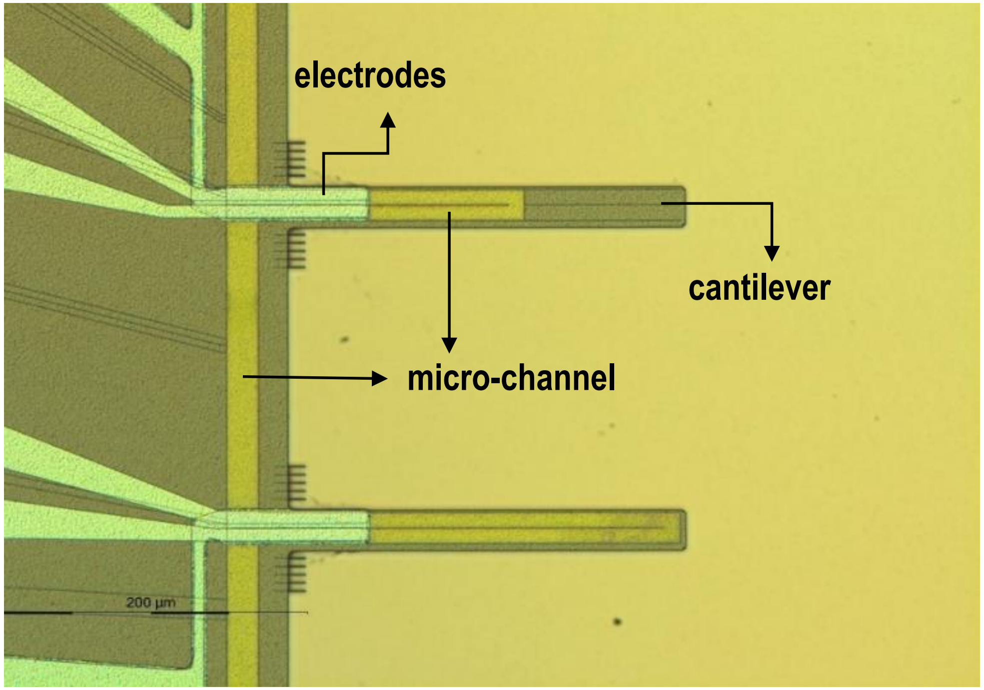
- *Flat surface,* to fabricate electrodes on top of our channels
- *Thin walls*, to have a better responsivity to stiffness of fluid/cell



Fabrication results

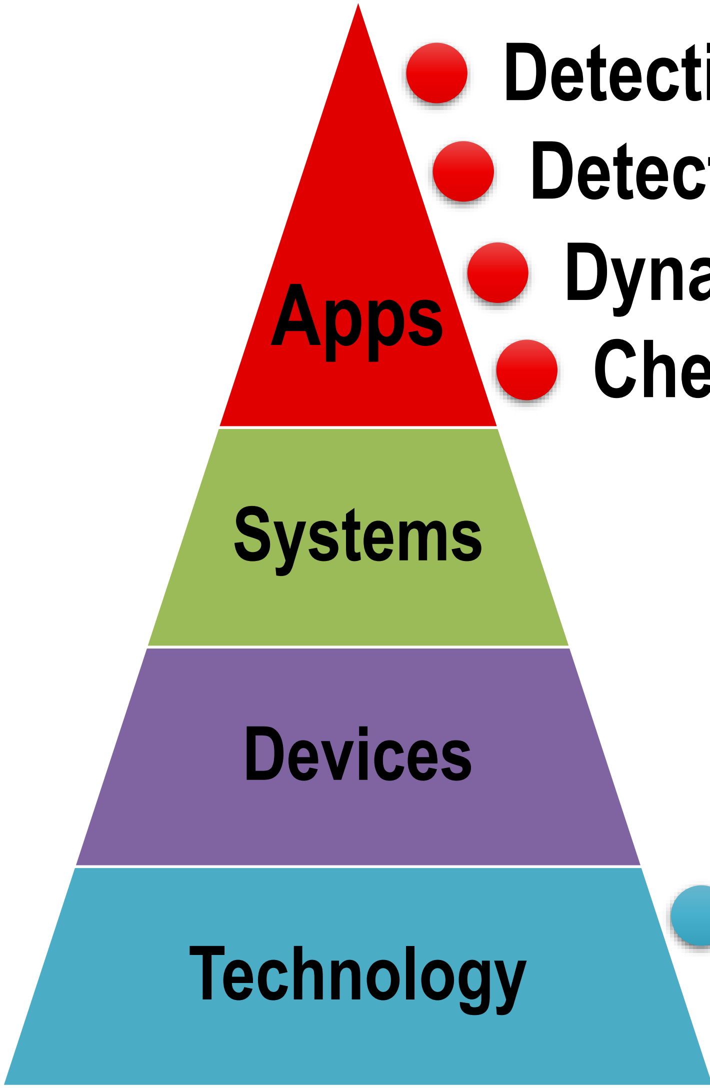
- All 40 steps have been optimized
  - Chips under test





- Very low yield caused by
  - Fragile walls → **Rim reinforcements in large membranes**
  - Long exposure to KOH during emptying process → **Two alternative processes**

Other applications

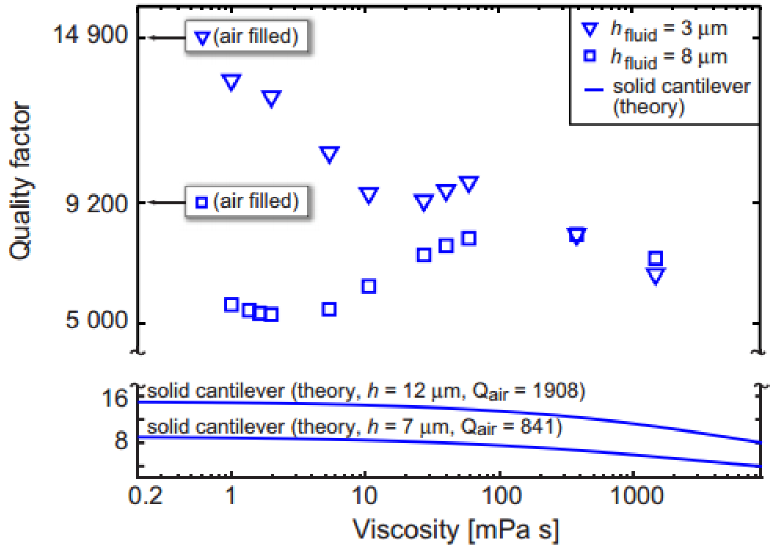


- Detection of cell stiffness
- Detection of biomolecules
- Dynamic cell calorimetry
- Chemical reactions monitoring

- Fabrication of hollow N-MEMS – thin walled suspended microchannels

Will the experiment work?

- FEM to simulate how the fluid affects
  - the frequency
  - the quality factor

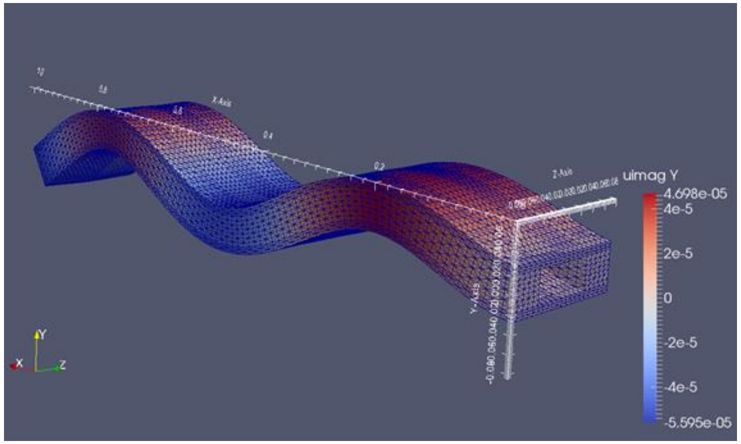


PRL 102, 228103 (2009)

Fluid Structure interaction (FSI)

Solid Theory: Euler Bernoulli	Fluid Theory: Navier Stokes
$$\rho A \frac{\partial^2 W}{\partial t^2} = EI \frac{\partial^4 W}{\partial x^4}$$	$$\rho\left(\frac{\partial v}{\partial t} + v\nabla v\right) = -\nabla p + \mu \nabla^2 v + \left(\frac{1}{3}\mu + \mu_v\right)\nabla(\nabla \cdot v)$$
↓ Lagrangian framework	↓ Eulerian framework

- Arbitrary Lagrangian Eulerian formulation (A.L.E.)
  - 3-D Modal analysis of the coupled system of beam with internal fluid



Prof. F. Gallaire (EPFL)

Fluid Structure interaction (FSI)

- Arbitrary Lagrangian Eulerian formulation (A.L.E.)
  - 3-D Modal analysis of the coupled system of beam with internal fluid
- Frequency shifts similar to simple calculations
- Qs match theory and experiment up to 60 mPa·s (refining the model)

5th Micro and Nano Flows Conference
Milan, Italy, 11-14 September 2016

3D FEM dissipation model of suspended micro channel resonators

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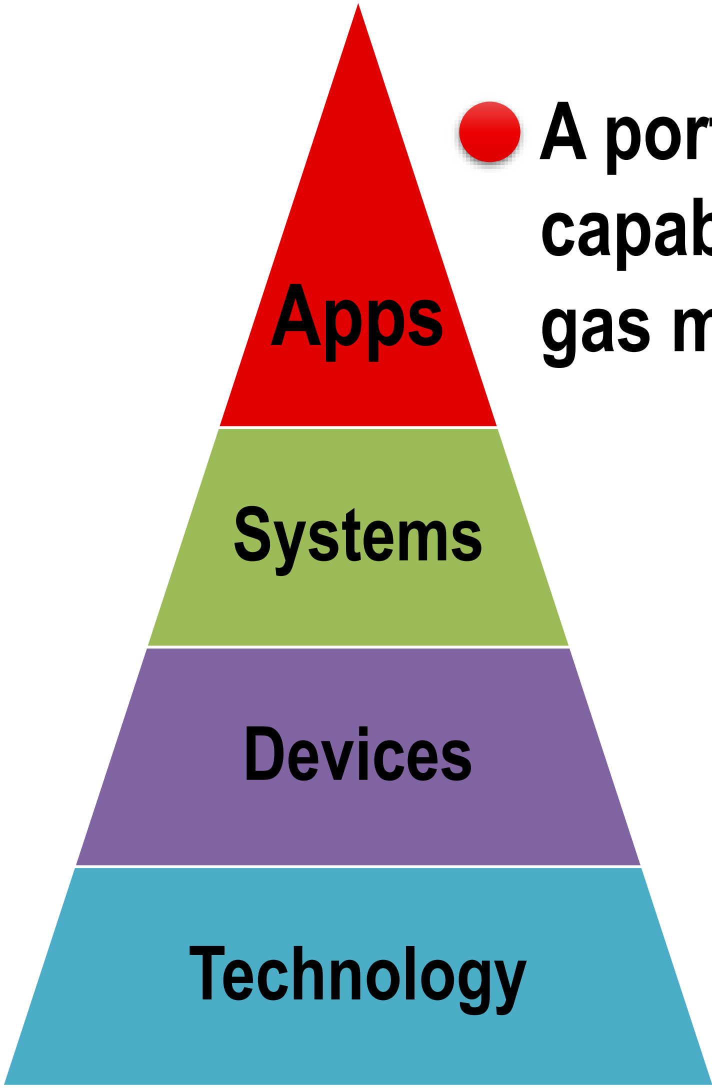
♠ These authors contributed equally to this work.

Multi-Physical detection

a.k.a. Focusing on what does matter

Research Objective #2

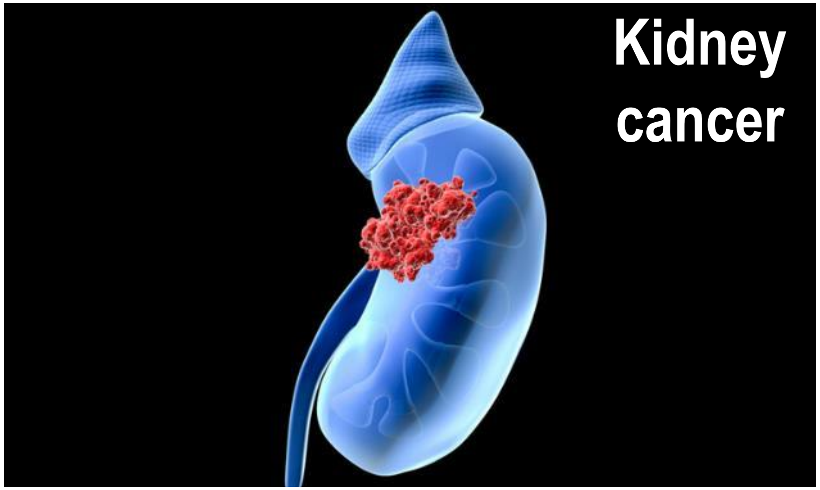


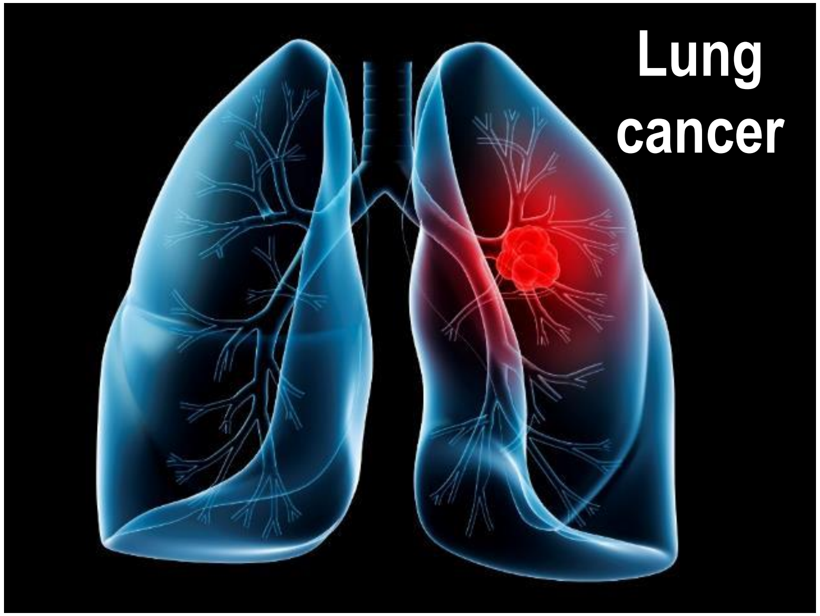
- A portable and reliable gas analyzer capable of addressing very complex gas mixtures


First responders
in a chemical
fire or attack

VOCs detection

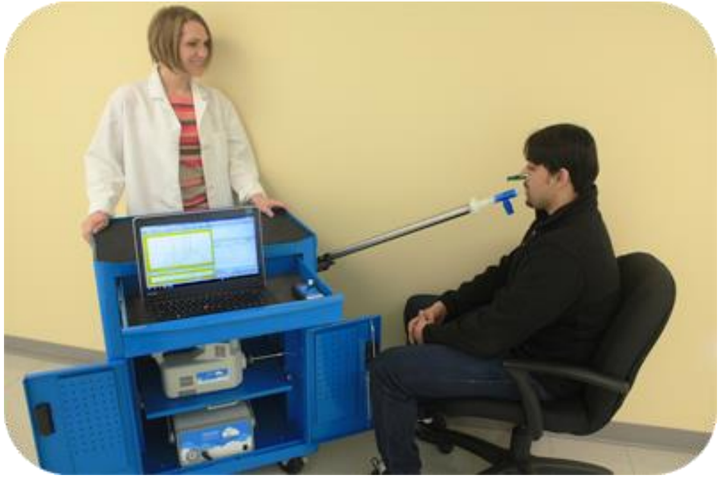
- Cancer
- Organ transplant rejection
- Radiation exposure
- Organ malfunction
- Immune system anomalies





VOCs detection

- Detection down to sub-ppb concentrations
- Resolving VERY complex mixtures
  - ↳ >100 different gases



Air sampling → Mass spec off-site
Several days/weeks

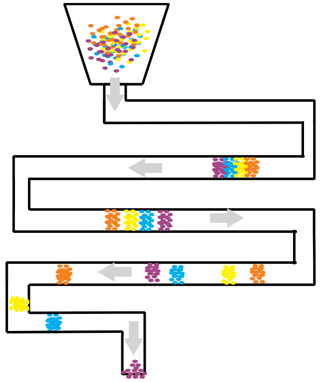
Why doesn't exist already?

VOCs detection

- Detection down to sub-ppb concentrations
- Resolving VERY complex mixtures

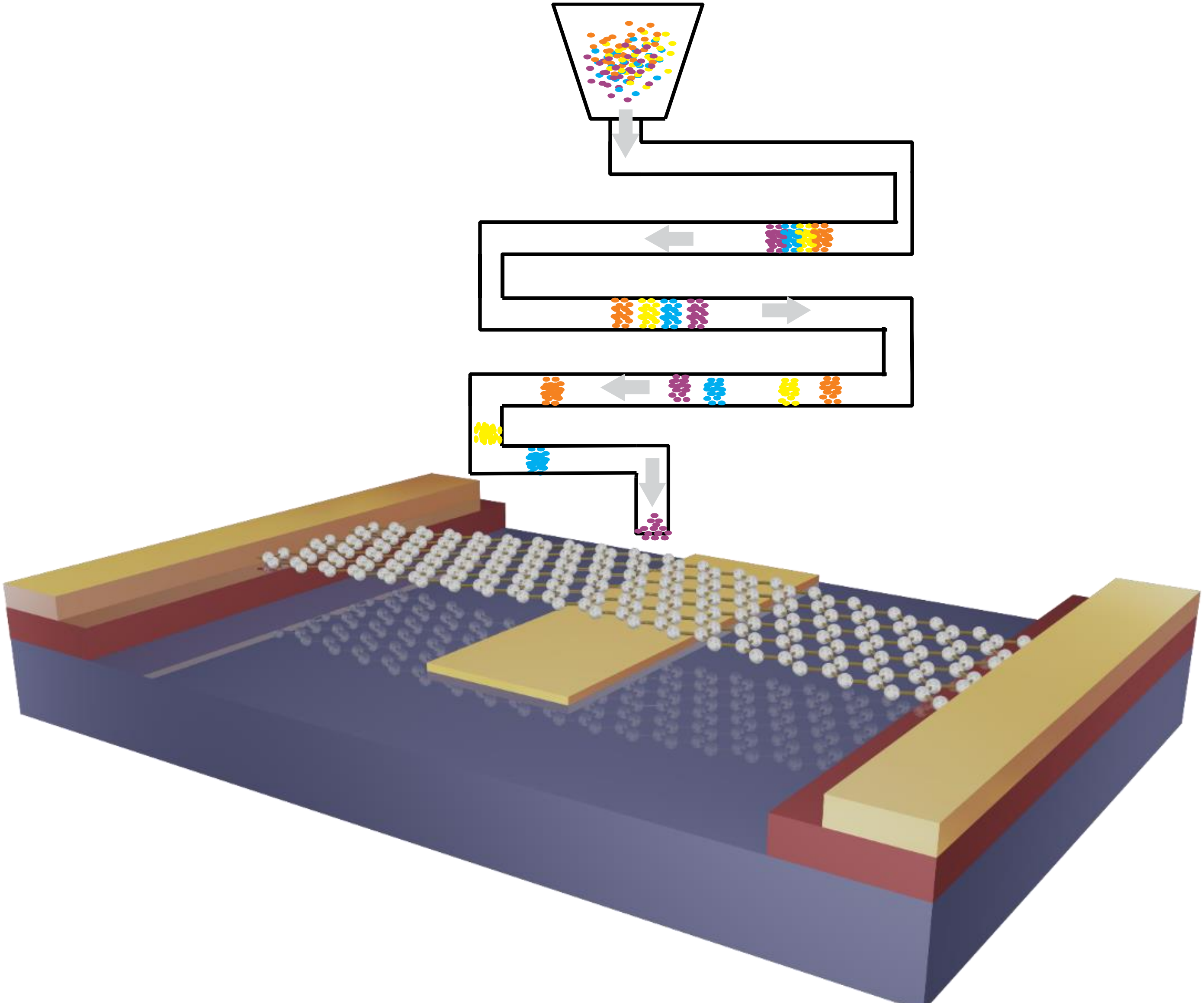
Selectivity, Selectivity and Selectivity

Chromatography ↔ **Multi-chemistry functionalization**

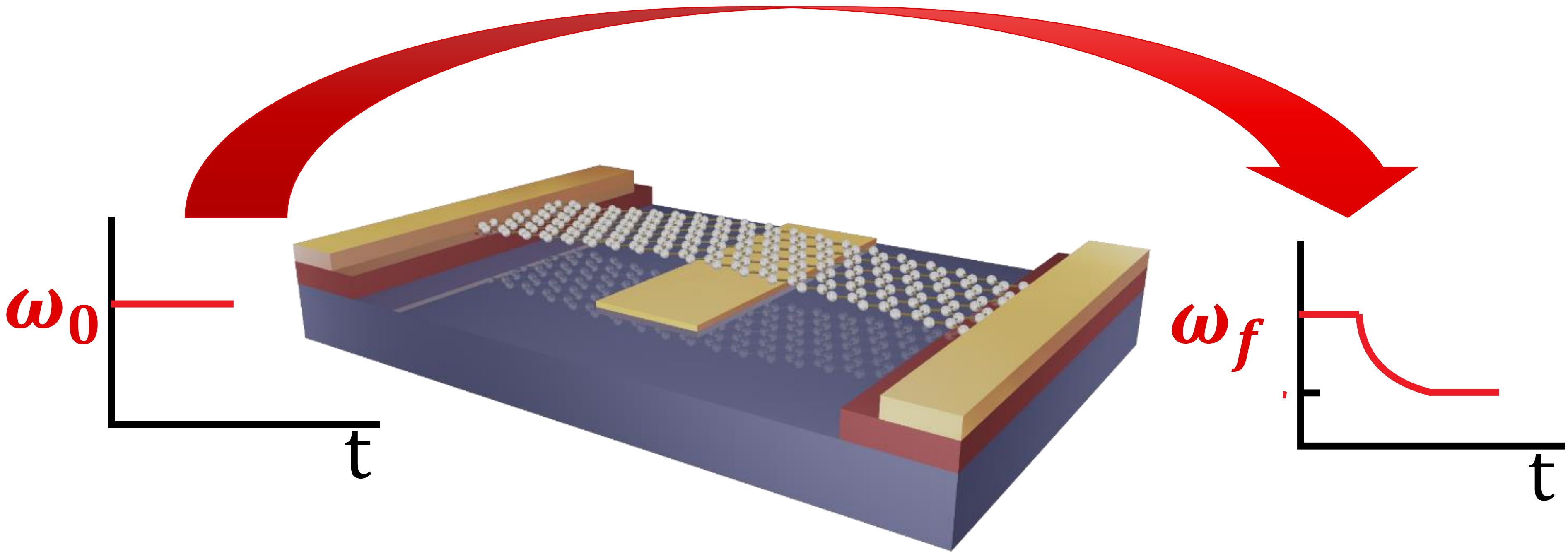


Issues with long-term stability and fabrication cost

2D NEMS – Multi-physical detection



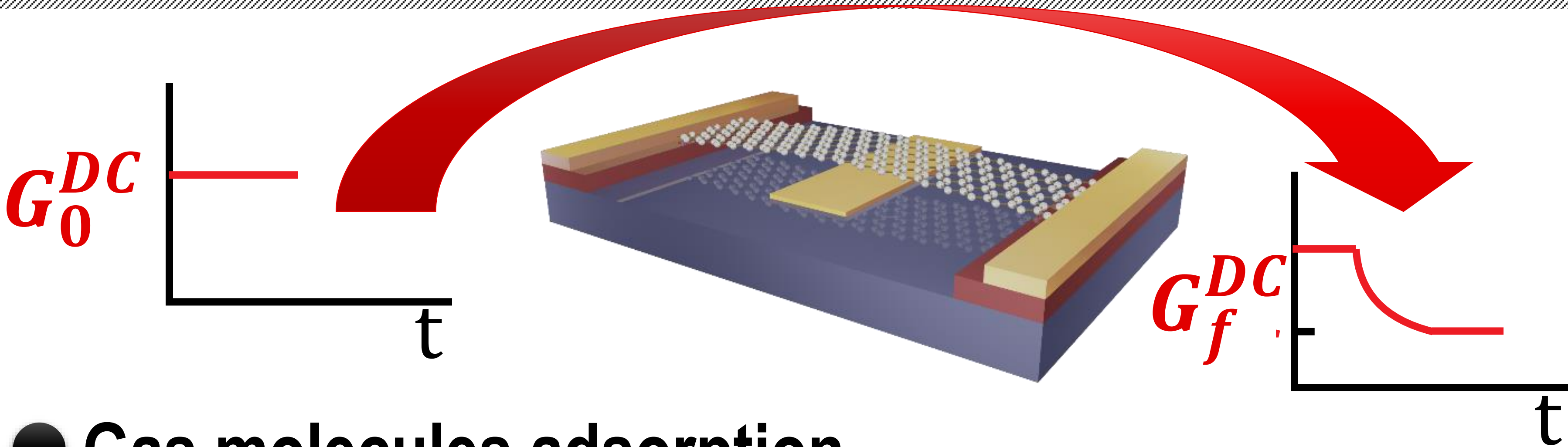
2D NEMS – Multi-physical detection - ω_0



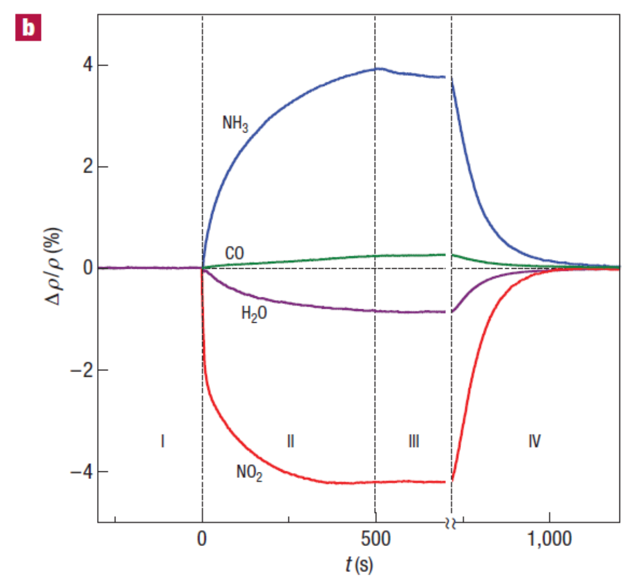
- Gas molecules adsorption changes **frequency**
- Response proportional to molecular mass

Chen, C.Y., et al. *Nature Nano* 4.12 (2009): 861-867.

2D NEMS – Multi-physical detection - G^{DC}

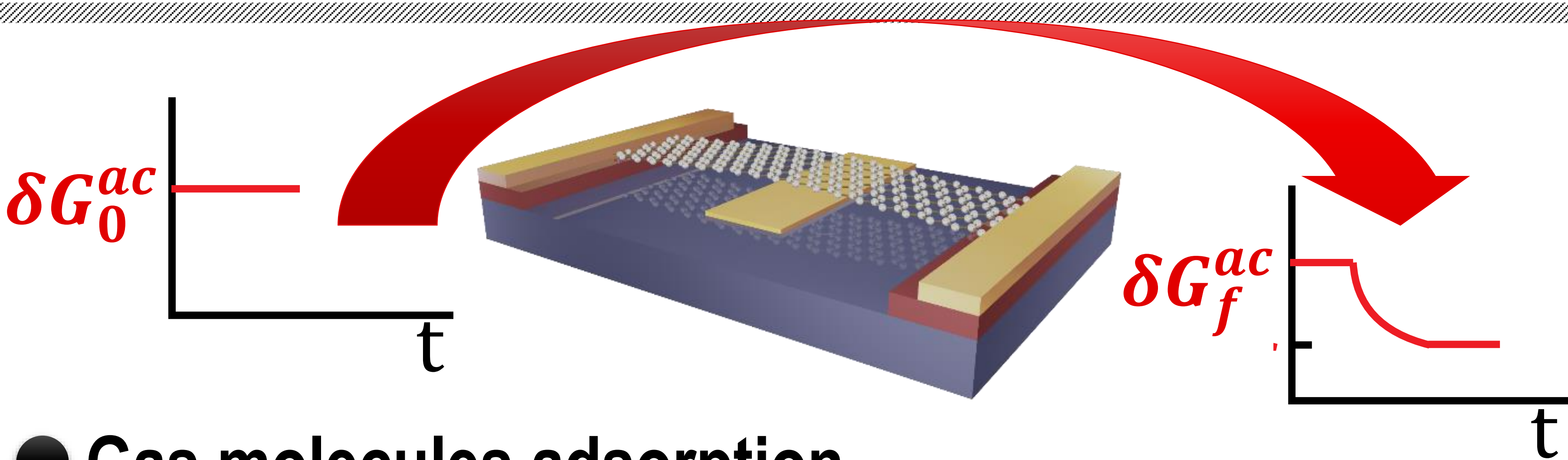


- Gas molecules adsorption changes **DC conductivity**
- Response proportional to molecular Work Function (chemical doping)

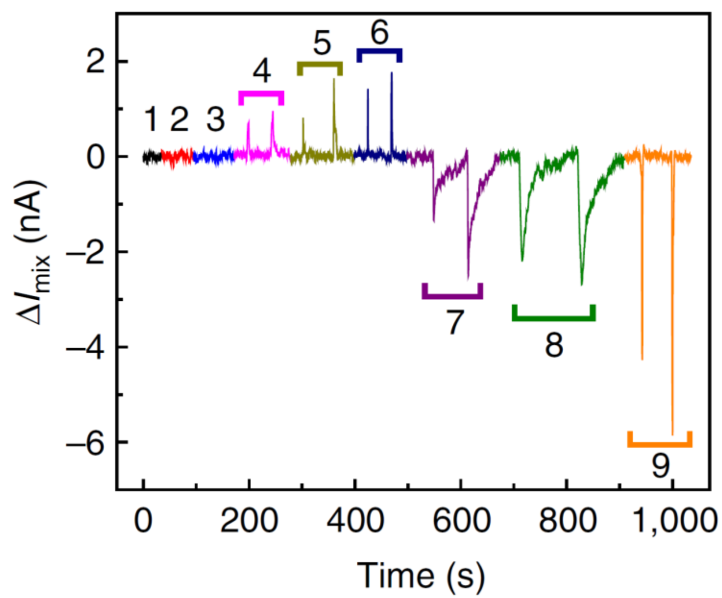


Schedin, F., et al. *Nature materials* 6.9 (2007): 652-655.

2D NEMS – Multi-physical detection - δG^{ac}

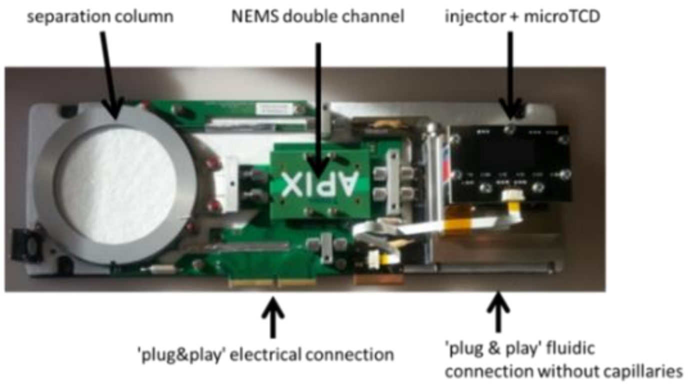


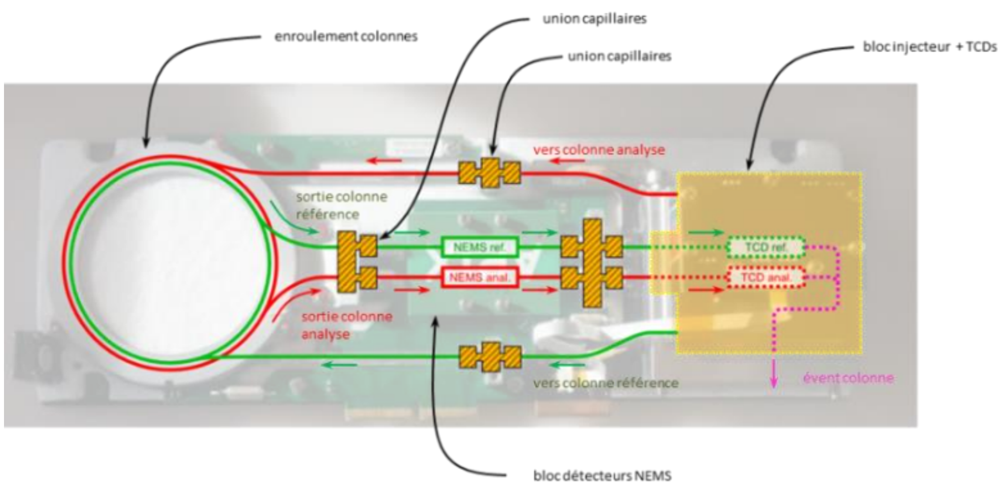
- Gas molecules adsorption changes **ac modulation of the conductivity**
- Response proportional to molecular polarity (dipole moment)

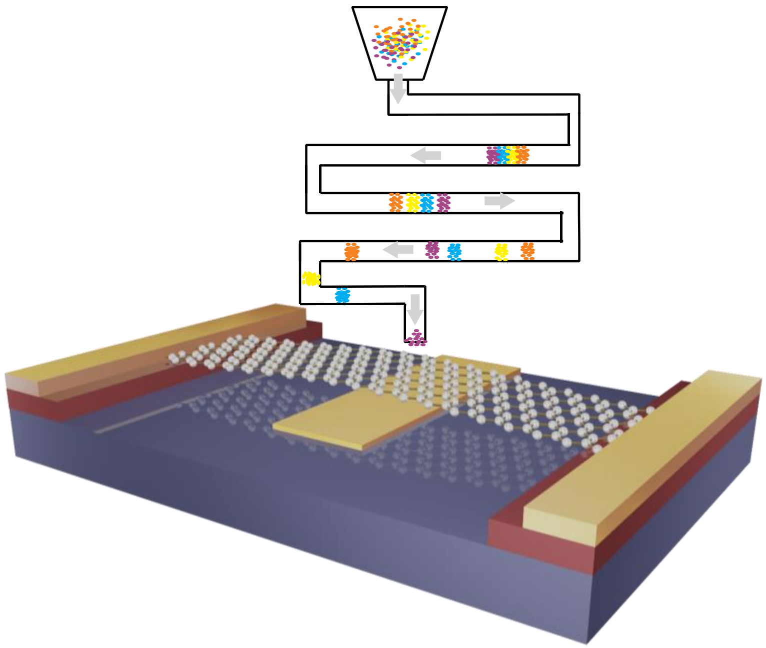


Kulkarni, G.S., et al. *Nature communications* 5:4376 (2014).

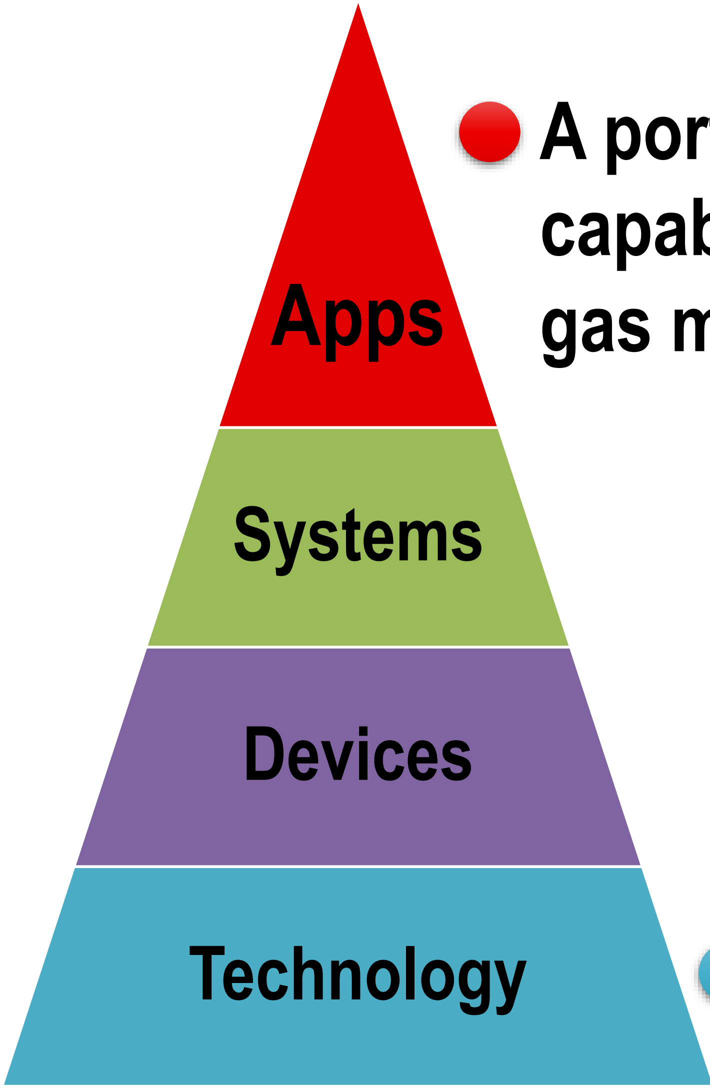
System integration with commercial GC







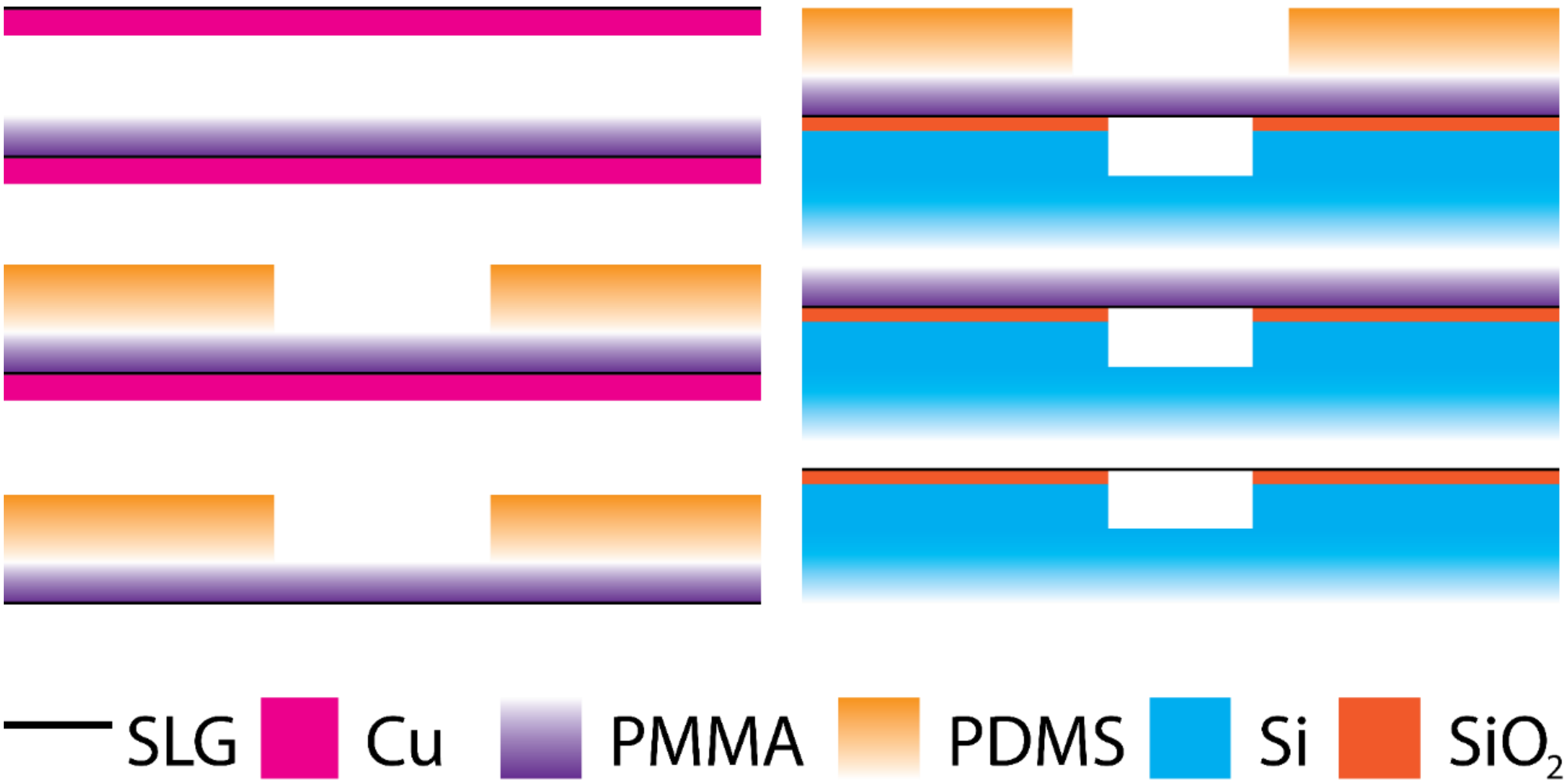
Research Objective #2



- A portable and reliable gas analyzer capable of addressing very complex gas mixtures

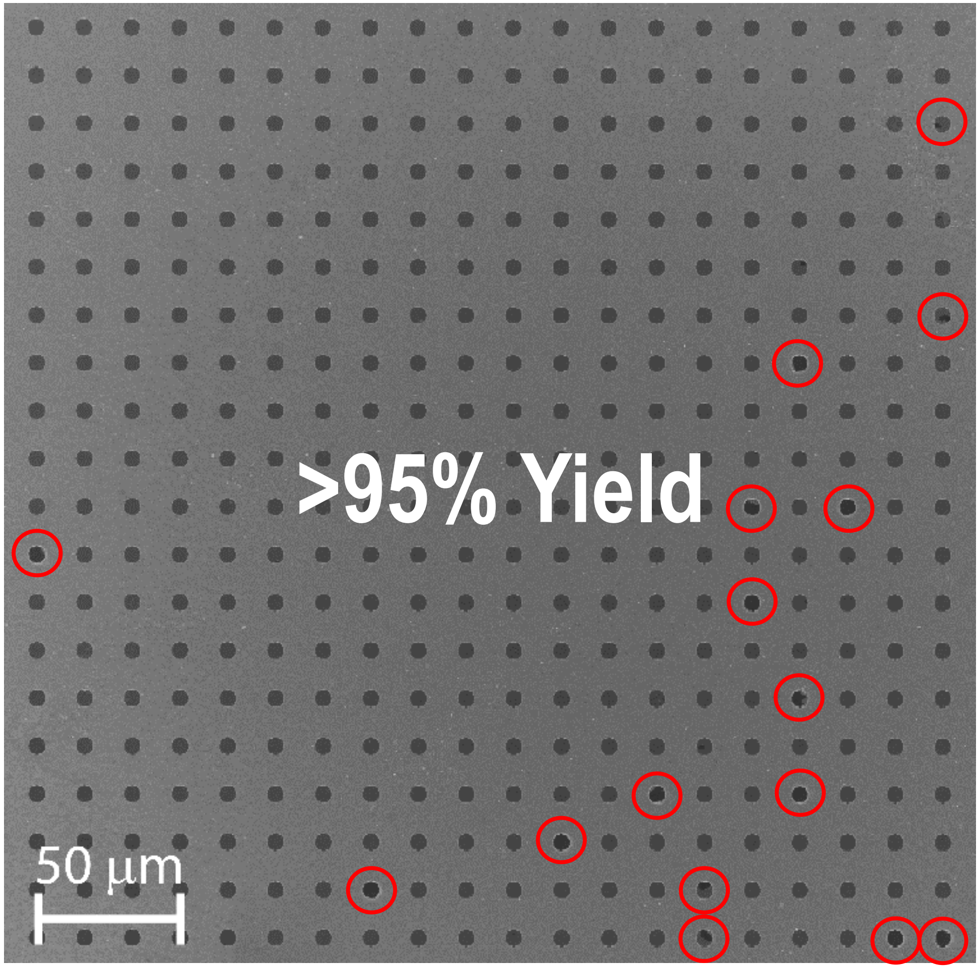
- Fabrication of monolayer 2D NEMS

Graphene Transfer – Dry Transfer



Suspended Graphene – Dry Transfer

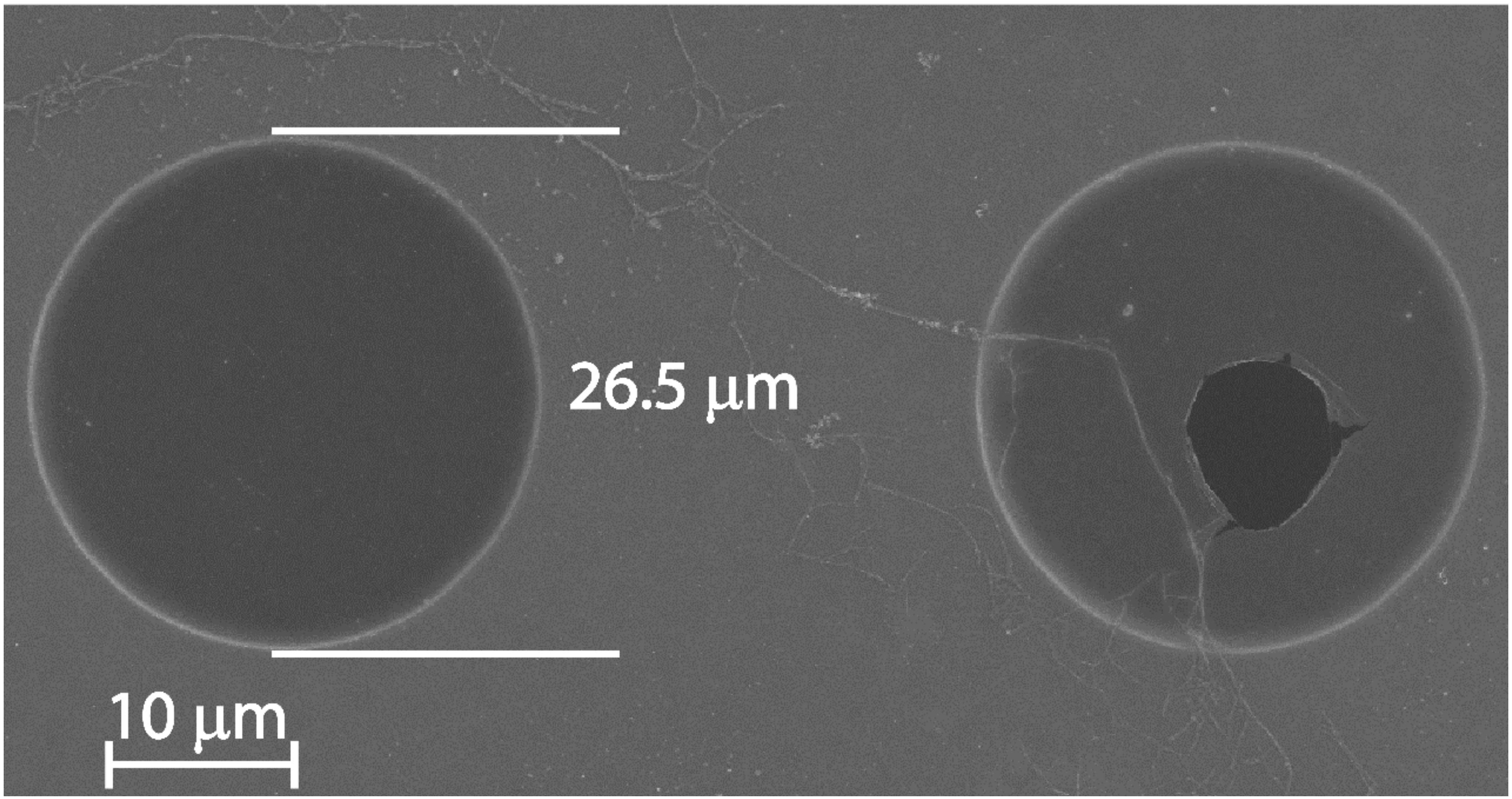
High yield using dry transfer



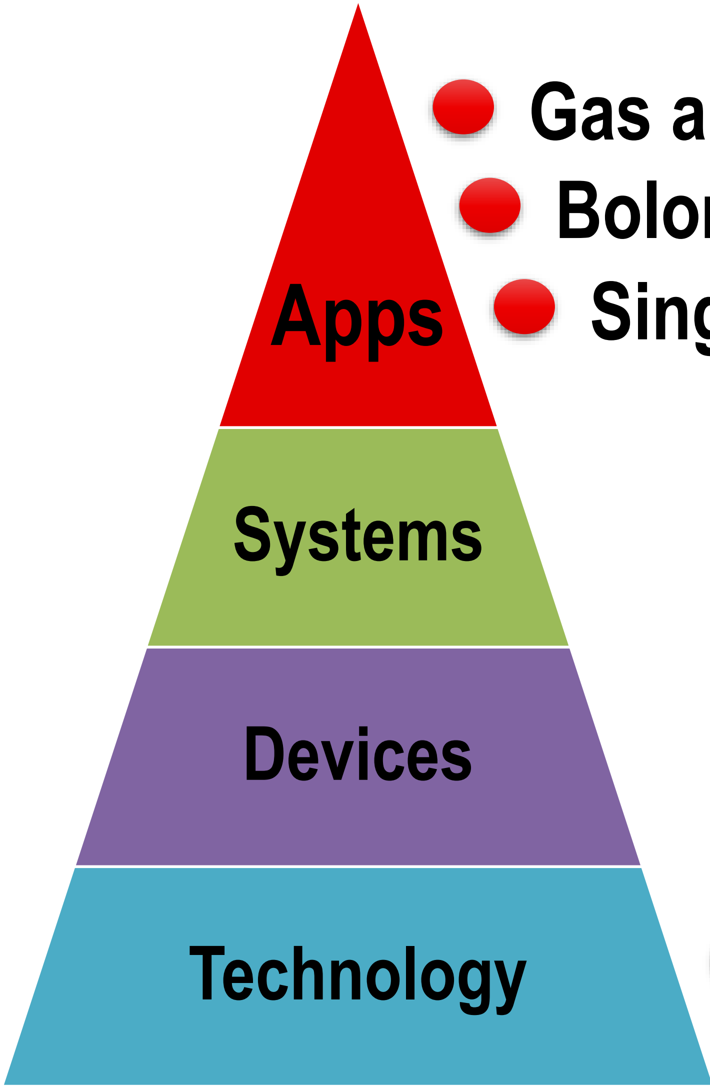
Broken Membrane

Suspended Graphene – Dry Transfer

Membranes with large aspect ratio, 74000, can be realized.



Other applications

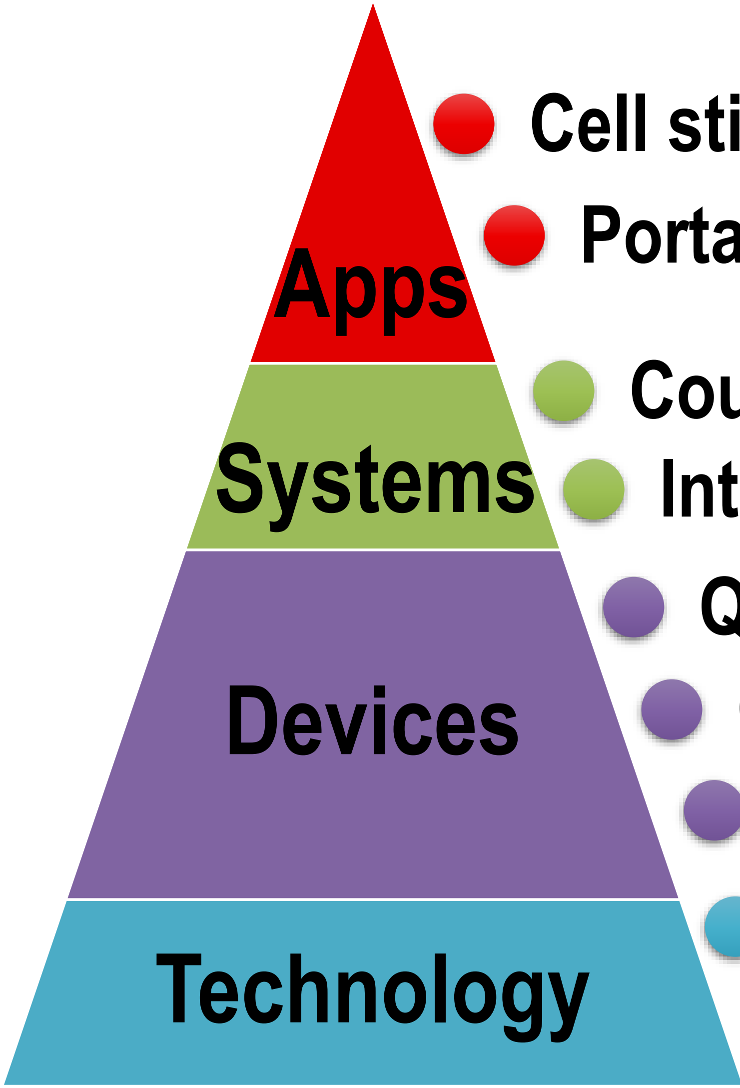


- Gas analyzer
- Bolometers
- Single molecule heat spectroscopy

- Fabrication of monolayer 2D NEMS

To sum up…

Advanced NEMS – Research overview



- Cell stiffness detection
- Portable gas analyzer
- Coupling to chromatograph column
- Integration with circuitry
- Q – acoustic losses **IFCS 2016**
- Q – intrinsic material losses **PRL 2015**
- Frequency fluctuations **NatureNano 2016**
- Hollow N-MEMS
- 2D NEMS

Why NEMS?

To do things that otherwise you can't

Thanks all of you for your attention

Any questions???