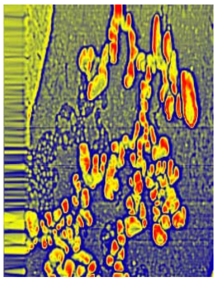
Interdisciplinary Nanomechanics:

From Acoustic Holographic Imaging to Microcantilever-based Bio-Chem Sensing



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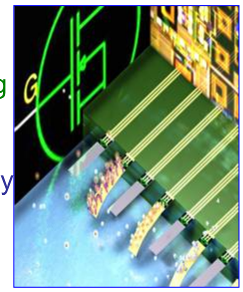
International Institute for Nanotechnology

Northwestern University



Acknowledgments:

NSF-MRI, SRC, NSF-NSEC, DARPA, NSF-ECS

NU*ANCE* Staff Development

NU*ANCE* Center

International Institute for Nanotechnology (IIN)

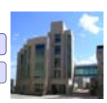
Steering Committee

Other Collaborators

Evanston Campus

Center for Nanofabrication & Molecular Self-Assembly

Central and Surface Facilities (NU*ANCE*, NIFTI, etc.)



NSEC - Nanoscale Science & Engineering Center Integrated Nanopatterning & Detection Technologies (PI: Mirkin)

NCLT - Nanotechnology Center for Learning and Teaching Developing NSE Educators

NIRTs - Nanoscale Interdiciplinary Research Teams

1. Evolution and Self-Assembly of Quantum Dots
2. Interphase Design for Extraordinary Nano Composites (PI: Brinson)
3. Atomic Layer Controlled Epitaxial Ferromagnetic Oxide Nanostructures (Co-PI: Chandrasekhar)
4. Electrical & Mechanical properties of Boron and Metal-Boride Nanowires (Co-PIs: Ruoff, Chang)
5. The Role of Nanoscale Colloids in Particle Aggregation and Trace Metal Scavenging in Aquatic Systems (Co-PI: Jean-Francois Gaillare)
6. Synthesis, Characterization & Modeling of Aligned Nanotube Arrays for Nanoscale Devices (Co-PI: Ruoff)
7. Novel Nanostructured Carbons from Self-Assembled Block Copolymer Precursors (Co-PI: Ruoff)
8. Ultra Nano Crystalline Diamond Films for Multifunctional MEMS/NEMS (Co-PIs: Schatz, Hersam)
9. Design of Nanoporous Molecular Square Catalysts Using Multiscale Modeling (PI:Snurr)

Network for Computational Nanotechnology PIs: M.Ratner, G.Schatz *(headquartered at Purdue)*

DURINTs - Defense University Research Initiative on NanoTechnology

1. Ultrasensitive & Selective Chip-Based Detection (PI: Mirkin)
2. Nano/Molecular Electronics (Co-PI: Ratner)

HSARPA Encoded Nanostructures for the Analysis of Bioterrorism Threats (PI: Mirkin)

MURIs - Multi-University Research Initiatives

1. Multi-Dimensional Surface Enhanced Sensing & Spectroscopy (PI: Van Duyne)
2. Surface Templated Bio-Inspired Synthesis and Fabrication of Functional Materials (PI: Mirkin)
3. 3-D Architectures for Future Electrochemical Power Sources (PI: Poeppelmeier)

URETIs - Univ Research, Eng & Tech Institutes

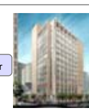
- Nanoelectronics and Computing (Co-PIs: Ratner, Hersam, Ho,Odom,Marks,Chang)
- Bioinspired Design & Processing of Multifunctional Nanoscomposites (Co-PIs: Ruoff, Belytschko, Brinson, Daniel, Messersmith, Schatz)

International Outreach

1. US-Ireland (Chang)
2. Us-South Africa (Kung)
3. US-India (Dravid)
4. Ongoing

Chicago Campus

Robert H. Lurie Medical Research Center



Institute for BioNanotechnology in Advanced Medicine (Stupp)

1. Spectral Markers for Early Detection of Colon Neoplasia (NIH)
2. Regenerative Scaffold Technologies for CHS & Diabetes (NIH)
3. Advanced Technologies for Cell Replacement Therapies in Diabetes (Juvenile Diabetes Research Foundation)
4. Incubator Program/Early Career Award (Baxter)
5. Bio-Technology for Wound Repair, Soft Tissue Engineering & Biosensing (Army)

Detection of HIV Targets by Gold Nanoparticle Probes (PI: Wolinsky)

Nanostructured Interfaces for Studying Problems in Cellular Biology, NIH Pioneer Award (PI: Mirkin)

Detection of Category A Pathogens by Gold Nanoparticles (PI: Wolinsky)

Application of Ti-O2-DNA Nanocomposites to Cancer Cells National Cancer Institute (PI: Woloschak)

Argonne National Laboratory

Center for Nanoscale Materials

Northwestern University Atomic- and Nanoscale Characterization Experimental (NUANCE) Center (Dravid)

Integrated, multi-faceted nanotech tools, techniques and facilities for research, education and outreach

Nanoscale Integrated Fabrication, Testing and Instrumentation (NIFTI)

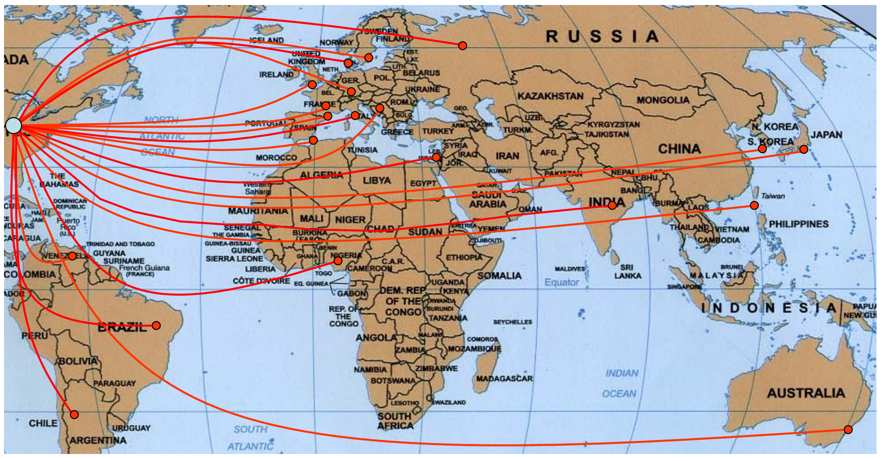
Electron Probe Instrumentation Center (EPIC)

Keck-II Surface Science Facility (Keck-II)

CCNE

NSF	AFOSR	DOD	NASA	HSARPA	NIH

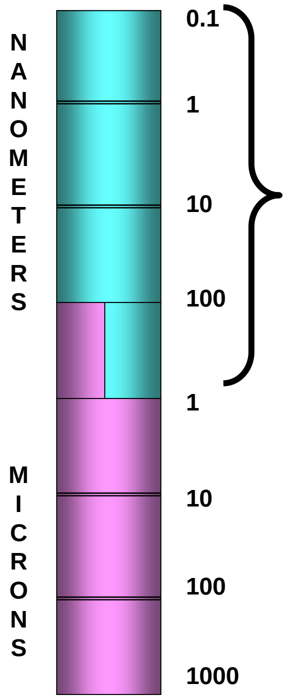
International Institute for Nanotechnology (IIN)



Collaborations in 18 Countries
Active exchange program with Ajou University
Sponsorship from Saarland, Germany government
MoU with IIT Bombay, India

Outline

- **Seeing the Invisible:**
  - Scanning Near-Field Ultrasound Holography (SNFUH)
  - ➔ *<u>Nanomechanical</u>* response to acoustics
- **MOSFET-embedded microcantilevers:**
  - Translating bio-chem binding into *<u>nanomechanics</u>*
  - Translating *<u>nanomechanics</u>* to electronic signal



Technique	Destructive?	Sub-surface?
TEM	Y	N
STM	N	N
AFM	N	N
SEM	N/?	N/?
NSOM	N	N/?
Optical Microscopy	N	N/?
Acoustic Microscopy	N	Y

Non-Destructive - Buried/Embedded Structures - 10 - 100 nm spatial resolution

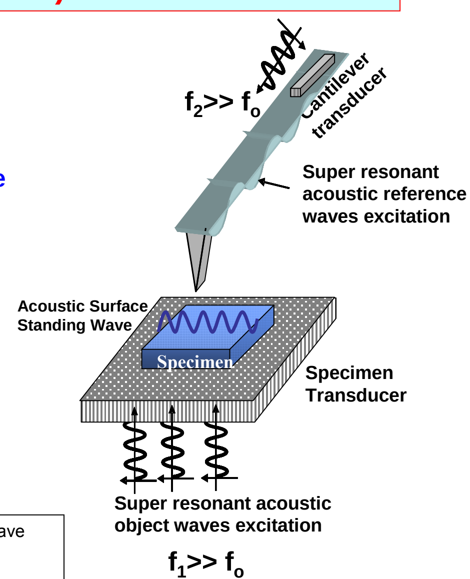
Scanning Near-Field Ultrasound Holography (SNFUH)

Near-Field SPM Platform:
➔ **Excellent Lateral Resolution**

Ultrasound source:
➔ **Non-destructive and Depth-Sensitive**

Holography Paradigm:
➔ **Sensitive to "*Phase*" Perturbations**

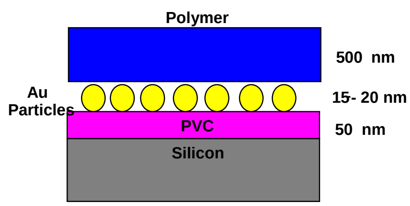
Detection of Perturbation to the Acoustic Standing Surface Wave via SPM Probe Detector

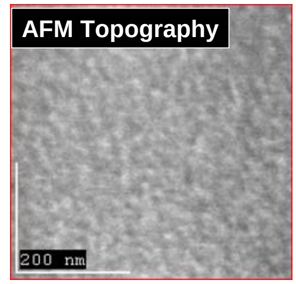


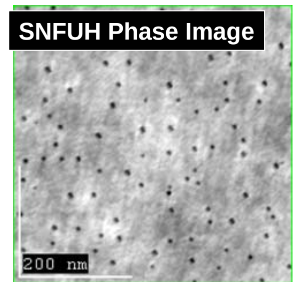
SNFUH: Holographic interference of specimen acoustic wave with reference cantilever, allows for extraction "phase' of acoustic wave – thereby revealing sub-surface nanoscale defects and features (NU patent, 2004, Science, Oct. 7, 2005))

Seeing the Invisible:

Scanning Near-Field Ultrasound Holography (SNFUH)







Revealing nanoparticles
~ 0.5 microns below the surface!

Implications for Non-Invasive Sub-Surface Imaging

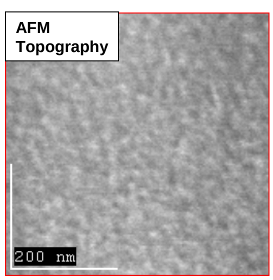
➔ ***Quantitative modulus imaging of polymers/soft-structures***

➔ ***Non-invasive monitoring of molecular markers/tags – signal pathways***

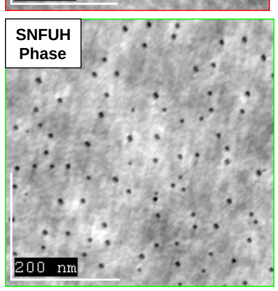
➔ ***Nanoscale non-invasive 3-D tomography***

➔ ***Non-destructive 3-D metrology***

Science, October 7, 2005

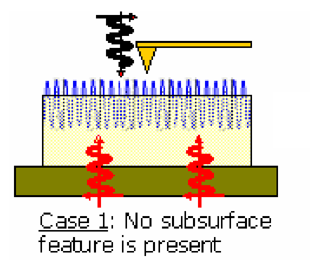


(A)



(B)

(C)



(D)

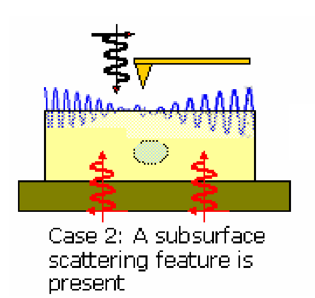
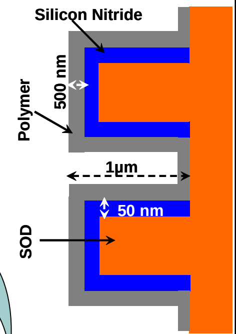


Figure 2: (A) Typical AFM (topography) image shows featureless top polymer surface, while the phase image of SNFUH clearly reveals the buried gold nanoparticles with high definition.

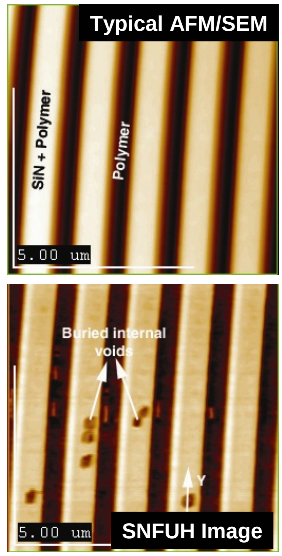
This is schematically explained in (C) and (D). In (C) no sub-surface scattering is present which does not perturb the standing wave while (D) shows perturbation to standing beat frequency due to sub-surface scattering, which is monitored by SPM tip.

Scanning Near-Field Ultrasound Holography (SNFUH)



Advantages over traditional metrology:

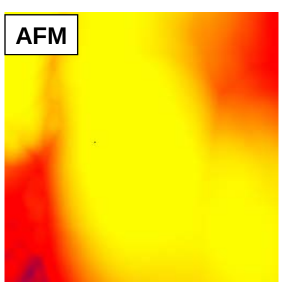
- Non-invasive: ***based on acoustic waves; no electron beams, no cross-sectioning***
- Sub-surface*: **all materials of interest are transparent to acoustic waves***
- Nano-scale resolution: ***detection at the scale of defects - nanometers***



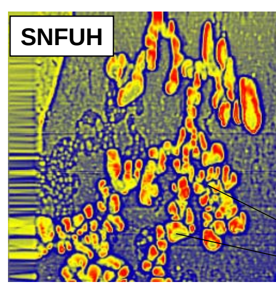
Look Ma, plenty of defects *underneath*!

Science, October 7, 2005

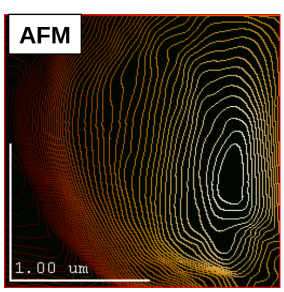
In-vitro Non-Invasive SNFUH Imaging in Cell Biology



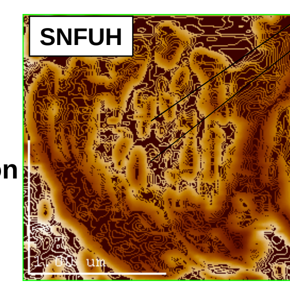
24 hr ➔ incubation



Malaria Parasites inside RBC



4 hr ➔ incubation



- **Seeing the Invisible:**
  - Scanning Near-Field Ultrasound Holography (SNFUH)
  - ➔ *Nanomechanical* response to acoustics
- **MOSFET-embedded microcantilevers:**
  - Translating bio-chem binding into *nanomechanics*
  - Translating *nanomechanics* to electronic signal

Systems Approach to Sensing & Diagnostics

DNAs, Proteins, Receptors..

System Packaging:

Pattern

DNA Hybridization
Protein-Protein binding

e.g., Integration w/CMOS and RF circuits

Binding Event

Signal Transduction

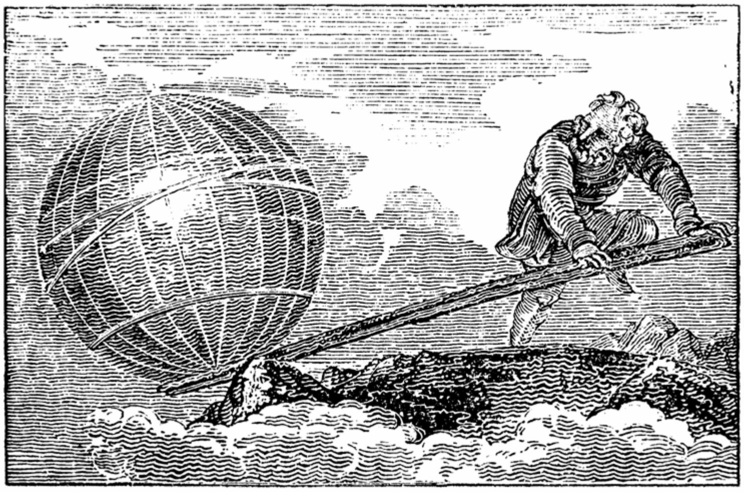
Mechanical
Electrical, Optical
Magnetic..

Signal Detection

- ➔ High sensitivity & specificity
- ➔ Fast response
- ➔ Fluid compatibility
- ➔ Low cost, reliability, reproducibility..

ARCHIMEDES

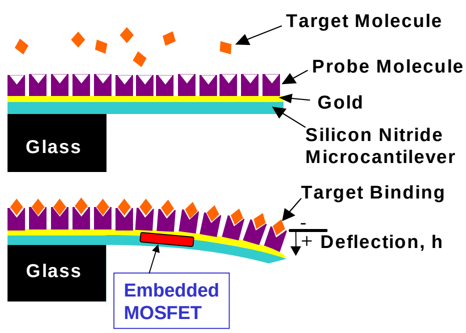
ΑΡΧΙΜΗΔΗΣ

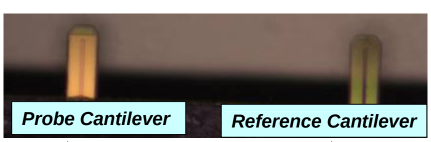


1. GIVE ME A PLACE TO STAND AND I WILL MOVE THE EARTH

2. GIVE ME A LEVER LONG ENOUGH AND I WILL MOVE THE EARTH

New ***All-Electronic*** ***Label-Free*** Transduction via MOSFET- Embedded Microcantilevers



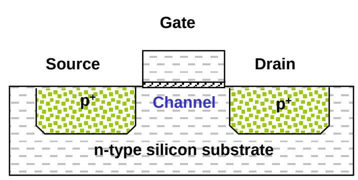


Differential MOSFET Signal

What is New?

Microcantilever Deflection *Stresses* MOSFET *Channel*

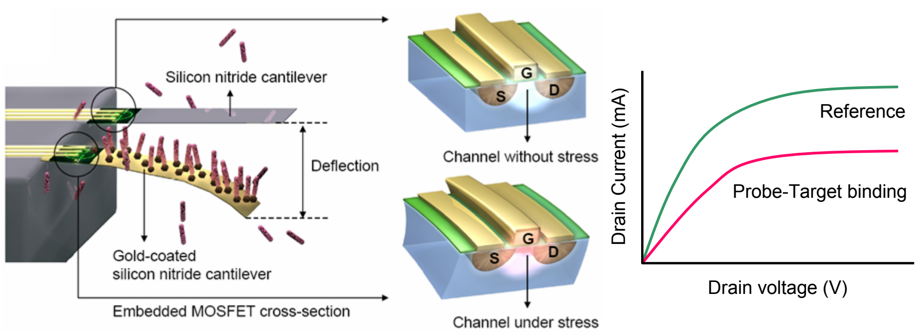
MOSFET Drain Current Changes with Microcantilever Bending



Selectivity: *Probe/receptor molecule selection*
Sensitivity: *Extent of bending and its detection*

NU patent: 2005
Science, March 17, 2006

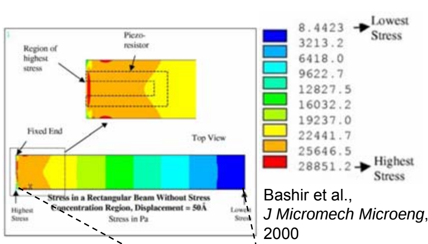
MOSFET-embedded microcantilever sensors



Microcantilever bending induced stress → Change in channel resistance → Modulation of carrier mobility → Change in the drain current

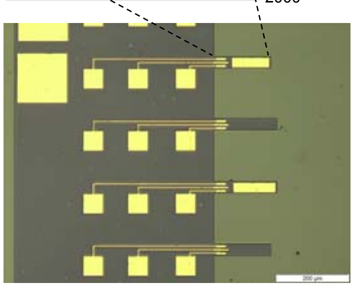
NU patent: 2004
Science, March 17, 2006

MOSFET-embedded Microcantilevers

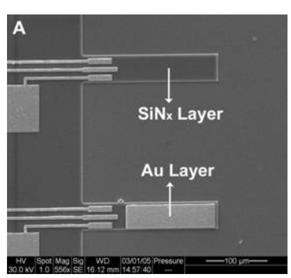


Bashir et al., *J Micromech Microeng*, 2000

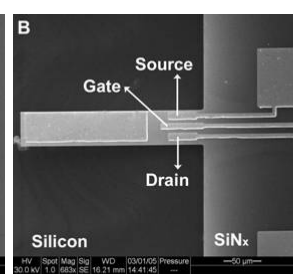
- MOSFETs embedded at the high stress region of a microcantilever



- Microcantilever arrays



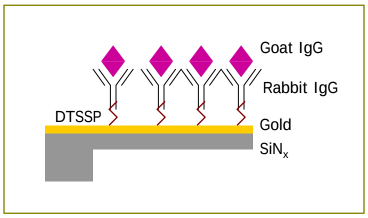
- A microcantilever pair composed of a gold-coated and a SiNx cantilever

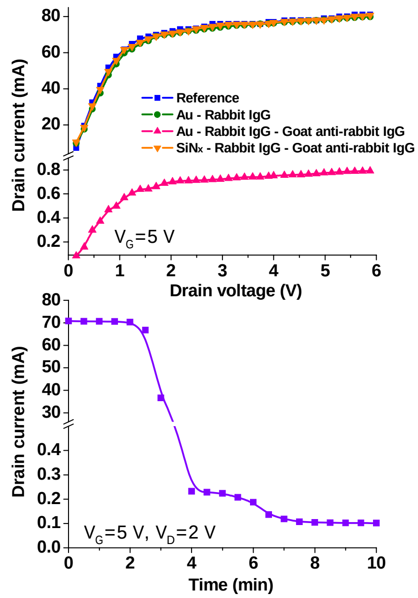


- MOSFET terminals

Detection of Antibody-Antigen binding

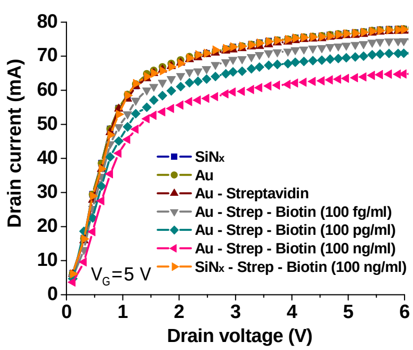
Detection of goat anti-rabbit antibodies (secondary IgG, 0.1 mg/ml) by rabbit IgG (primary IgG, 0.1 mg/ml)

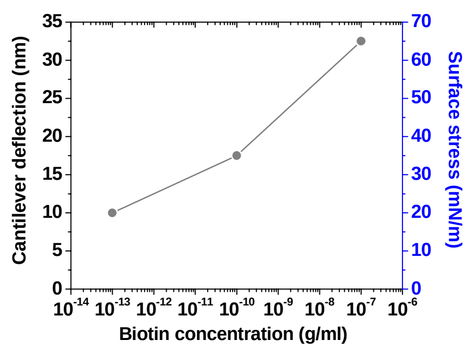




- Negligible change in ID for the gold coated cantilever with rabbit IgG
- A change is ID of almost two orders of magnitude with target binding
- No change in the SiNx reference cantilever
- Change in ID with time reaches a steady-state

Detection of Streptavidin-Biotin binding





- Streptavidin (10 µg/ml) – Biotin (100 fg/ml to 100 ng/ml)
- Negligible change in I_D of the streptavidin coated cantilever without target molecules
- I_D decreases (bending increases) with increasing target concentraion
- No change in the SiN_x reference cantilever

- Increase in the surface stress with increasing target concentration
- Surface stress sensitivity is of the same order as that of optical detection

Comparison with current major biosensors

Laboratory configured instrumentation

Surface Plasmon Resonance (SPR)

- High initial and operational costs
- No reference to compensate for the background

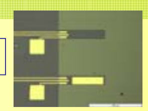
Enzyme-Linked Immunosorbent Assay (ELISA)

Ag-Ab reactions detected by indicator enzyme activity

- Require labeling
- Time consuming sample preparation and detection procedure

- **Label-free**
- **Real-time detection & monitoring**
- **Versatility**
  - **Measure binding kinetics, affinity of the interaction, analyte concentration, etc.**

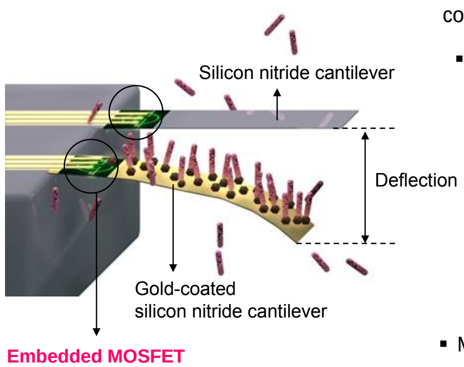
- **High specificity and sensitivity**
- **Superior dynamic range**
- **Low background**



MOSFET-embedded microcantilever sensors

- **Label- and optics-free, all electronic**
- **Direct integration with application-specific microelectronics**
- **Miniaturization of the device → Portable, wider-deployment**
- **Low-cost by mass-production**

Highlights of MOSFET-embedded microcantilever sensors

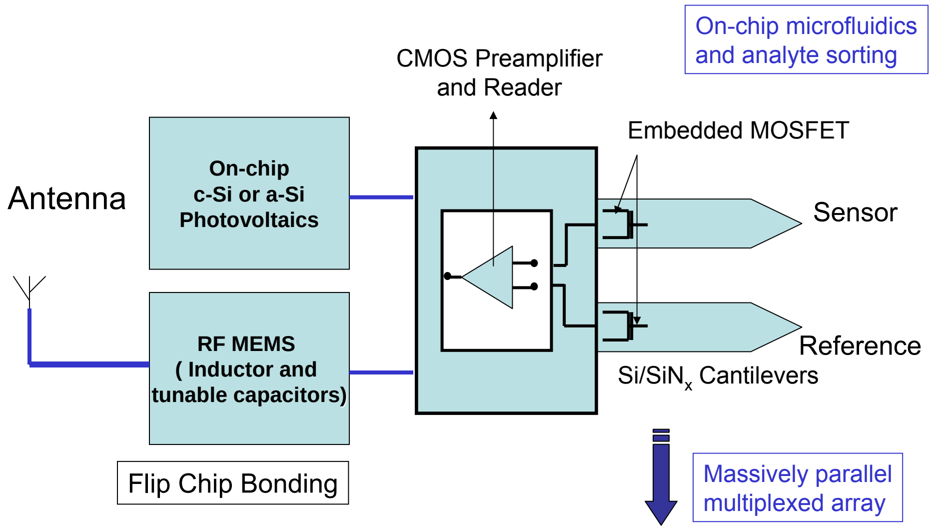


- High sensitivity
  - Detection of ~5 nm deflection by analyte concentration in ppt range
- Simple direct current measurement with large signal-to-noise ratio
- Label- and optics-free
- Massively parallel signal sensing
- Enable creating a portable device
- Differential signal minimizes noise
- Mass-production at low-cost
- Direct integration with application-specific microelectronics

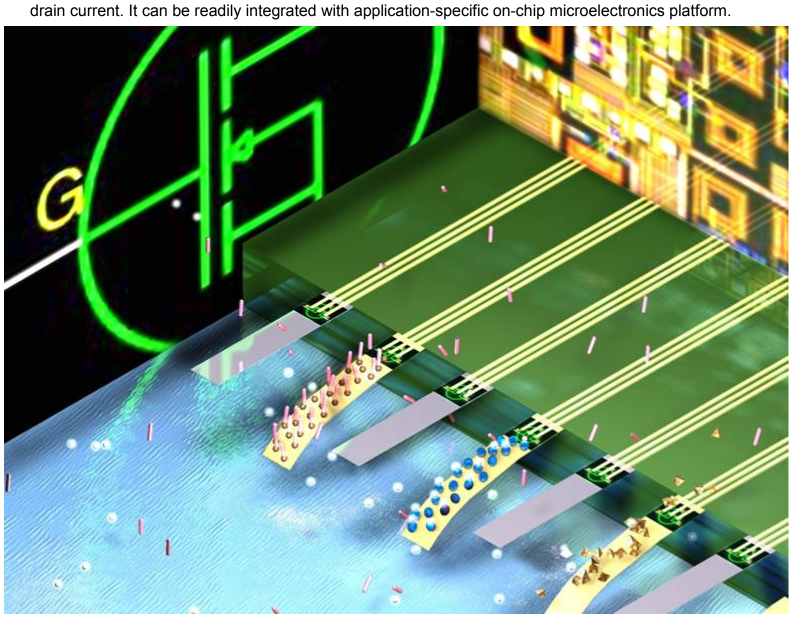
MOSFET-embedded microcantilevers may overcome the limitations imposed by currently available signal transduction and detection mechanisms

MOSFET-Embedded Microcantilever System:

Vision for Wider Deployment for Remote-addressing and Networking



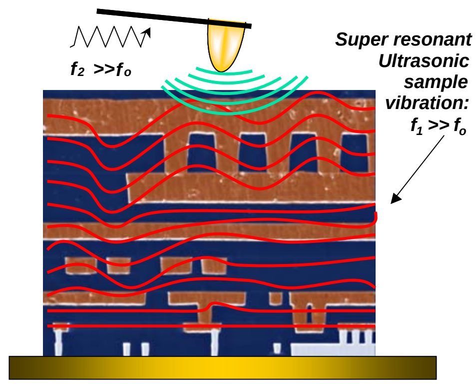
MOSFET-embedded microcantilevers: A new electronic transduction paradigm comprising two-dimensional microcantilever arrays with embedded-MOSFETs. An adsorption-induced surface stress at the functionalized cantilevers leads to precise, measurable and reproducible change in the MOSFET drain current. It can be readily integrated with application-specific on-chip microelectronics platform.



Combining MOSFET-Cantilevers and SNFUH: *Summary and Vision*

- ➔ Non-destructive
- ➔ Nanoscale resolution
- ➔ Sensitive to embedded/sub-surface structures/features
- ➔ 3-D nanoscale tomography

- ➔ Fast scanning with multiple SPM probes
- ➔ Integrated turn-key system with embedded software architecture



Further (Collaborative) Opportunities

Non-invasive sub-surface imaging with SNFUH:

- 1-D and 2-D parallel multi-probe SNFUH array
- Higher frequency piezo's
- Fundamentals of ultrasound-scattering in near-field regime: *modeling, simulation and 3-D tomography*

MOSFET-embedded microcantilevers for bio-chem sensing:

- MOSFET-embedded parallel/multiplexed 1-D and 2-D array
- On-chip lock-in, read-out and RF circuit for remote-sensing
- Back-end microfluidics, sampling and integration

Applications to hard, soft (biological/polymer) and hybrid structures