Realism in nanosensing: hard-won insights from the trenches

Michael Roukes
Robert M. Abbey Professor of Physics, Applied Physics, & Bioengineering
Co-Director, Kavli Nanoscience Institute
California Institute of Technology
roukes@caltech.edu
http://nano.caltech.edu
Abstract:
Nanosensors have the unprecedented capability to interact with absolute numbers of analytes down to the single molecular scale. The susceptibility of nanosensors to external perturbation, given their size, is unprecedented -- and this essential physics offers exceptional new opportunities. Indeed, we are here to explore, harness, and even celebrate these attributes!

As a archetypal case study of nanosensor physics, I will focus upon resonant NEMS sensors. I will describe the immense increase in responsivity obtained with device size reduction that yields, for example, atomic mass resolution. As an archetypal case study of nanosensor physics, we’ll focus upon resonant NEMS sensors. We will explore several noise mechanisms and backaction effects imposing ultimate physical limits to the sensitivity, and how matching considerations make it extremely challenging to embed these devices in practical measurement systems.

The unique properties of nanodevices, however, are not a panacea that absolves us from the need to contend with long-standing, overarching challenges posed by real-world sensing applications. From about a decade and a half’s work focused on metamorphosing nanosensors into nanosystems through large-scale integration, nature has taught us some hard lessons. In my talk I will share several of these, using examples from NEMS and other sensor systems. Among them are: (a) any stand-alone sensor is unlikely to be up to the full dynamic range of challenges posed in the real world; (b) complex combinations of real-world analytes are unlikely to be resolved by any “one-stop” generic approach; (c) arrays of sensors can often give enhanced performance over individual devices, but achieving such gains may require exceptionally careful attention to device variances; (d) careful choices of platform materials are essential to insure a rapid transitioning into large-scale integration and production en masse.

Although these sobering considerations may potentially force an initial downselection from amongst the panoply of exciting possibilities of emerging nanosensors; learning from the past, and considering real-world (not academic laboratory) conditions, will accelerate realization of practical nanosensor systems.
single-molecule NEMS-MS

AK Naik, MS Hanay, WK Hiebert, XL Feng, and ML Roukes,

Frequency Shift (kHz)

Time (s)

Background fluctuations

single molecule adsorption events
(precipitous jumps)

NAIK, Akshay
Staff Physicist

HANAY, Selim
Grad Student

HIEBERT, Wayne
Postdoc
Nanosensors have the unprecedented capability to interact with absolute numbers of analytes down to the single molecular scale. The susceptibility of nanosensors to external perturbation, given their size, is unprecedented -- and this essential physics offers exceptional new opportunities. Indeed, we are here to explore, harness, and even celebrate these attributes!
responsivity, noise, backaction, mismatch

... these are the four critical physical considerations.
As an archetypal case study of nanosensor physics, we’ll focus upon resonant NEMS sensors. I will describe the immense increase in responsivity obtained with device size reduction that yields, for example, atomic mass resolution. We will explore several noise mechanisms and backaction effects imposing ultimate physical limits to the sensitivity, and how matching considerations make it extremely challenging to embed these devices in practical measurement systems.
frequency-shift based mass sensing

\[ \Delta f \sim -\left( \frac{f_0}{2M_{\text{eff}}} \right) \cdot \delta m \]

Amplitude

Frequency

doubly-clamped beam resonator
minimum resolvable mass is determined by “gain” and noise

\[ \delta M \approx \frac{\partial M_{\text{eff}}}{\partial \omega_0} \delta \omega_0 \sim R^{-1} \sigma_A(\tau) \]

- Mass Resolution
- Allan Deviation

a measure of frequency-fluctuation noise
Maximizing mass responsivity leads to minimizing the resolvable mass

\[ \delta M \approx \frac{\partial M_{\text{eff}}}{\partial \omega_0} \delta \omega_0 \sim R^{-1} \sigma_A(\tau) \]

For any complex mechanical mode, modeled as a damped simple harmonic oscillator:

\[ R \approx -\frac{\omega_0}{2M_{\text{eff}}} \]

\[ \propto \frac{1}{\ell^4} \]

huge benefit in scaling downward!
size-scaling the minimum resolvable mass: resonant inertial mass sensors

- Quartz crystal microbalances:
  \[ M_{eff} \sim 1 - 100 \text{mg}; \quad \delta m \sim 1 \mu g \]

- SAW/FPW sensors (MEMS):
  \[ M_{eff} \sim 1 \mu g - 1 \text{mg}; \quad \delta m \sim 1 \text{ng} \]

- Microcantilevers (MEMS):
  \[ M_{eff} \sim 1 \text{ng} - 1 \mu g; \quad \delta m \sim 1 \text{fg} \]

- NEMS:
  \[ M_{eff} \sim 1 \text{fg} - 1 \text{pg}; \quad \delta m \leq 1 \text{zg} \]
Massive increase in responsivity: zeptogram mass sensitivity \( (1\text{ zg} = 10^{-21}\text{g})\)

SiC doubly clamped beam NEMS
UHF bridge configuration
\( (f_0 \sim 133 \text{ and } 190 \text{ MHz}) \)
Ultralow noise PLL readout

Nano Lett. 6, 583 (2006)

Massive increase in responsivity: zeptogram mass sensitivity

Ya-Tang Yang, Carlo Callegari, Xiaoli Feng, Kamil Ekinci, MLR

Ya-Tang Yang, Carlo Callegari, Xiaoli Feng, Kamil Ekinci, MLR

Mass responsivity \(~1\text{Hz/zg}\)
BUT... minimizing frequency-fluctuation noise is also critical !!!

\[ \delta M \approx \frac{\partial M^{\text{eff}}}{\partial \omega_0} \delta \omega_0 \sim R^{-1} \sigma_{A}(\tau) \]

a measure of frequency-fluctuation noise
Real-time zeptogram mass sensitivity

(1 zg = 10^{-21} g)

SiC doubly clamped beam NEMS
UHF bridge configuration
\( f_0 \sim 133 \text{ and } 190 \text{ MHz} \)
Ultralow noise PLL readout

Nano Lett. 6, 583 (2006)

Equivalent to about 30 Xe atoms...

Mass responsivity \sim 1 Hz/zg
As an archetypal case study of nanosensor physics, we’ll focus upon resonant NEMS sensors. I will describe the immense increase in responsivity obtained with device size reduction that yields, for example, atomic mass resolution. We will explore several noise mechanisms and backaction effects imposing ultimate physical limits to the sensitivity, and how matching considerations make it extremely challenging to embed these devices in practical measurement systems.
sources of frequency-fluctuation noise

Noise processes in nanomechanical resonators

A. N. Cleland
Department of Physics and iQUEST, University of California, California 93106

M. L. Roukes
Department of Physics, California Institute of Technology

(Received 15 February 2002; accepted 12 March 2002)

Nanomechanical resonators can be engineered to approach 1 GHz, with quality factors as high as strongly selective rf filters and low nonfundamental noise processes will be important. Important noise sources include thermomechanical noise, Brownian motion, and quantum effects. In this article, we develop a self-consistent theory to estimate the impact that these noise sources have on a nanomechanical resonator consisting of a doubly clamped beam.

Surface Adsorbate Fluctuations and Noise in Nanoelectromechanical Systems

Y. T. Yang, C. Callegari, X. L. Feng, and M. L. Roukes
Kavli Nanoscience Institute, Mail Code 114-36, California Institute of Technology, Pasadena, California 91125, United States

ABSTRACT: Physisorption on solid surfaces is important in both fundamental studies and technology. Adsorbates can also be critical for the performance of miniature electromechanical resonators. Here, we study physisorbed xenon (Xe) atoms on a silicon nitride nanomechanical resonator. We find that diffusion dominates the observed excess noise, which could be important in other low-dimensional nanoscale systems.

Detecting and characterizing frequency fluctuations of vibrational modes

Z. A. Maizelis, M. L. Roukes, and M. I. Dykman
1Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
2Kavli Nanoscience Institute, Mail Code 114-36, California Institute of Technology, Pasadena, California 91125, USA

(Received 15 July 2011; published 3 October 2011)

We show how frequency fluctuations of a vibrational mode can be separated from other sources of phase noise. The method is based on the analysis of the time dependence of the complex amplitude of forced vibrations. The moments of the complex amplitude sensitively depend on the frequency noise statistics and its power spectrum, which requires extensive separate circuitry and dedicated electronics.
responsivity, noise, backaction, mismatch

Mechanisms: adsorption-desorption noise, diffusion noise, charge fluctuations, temperature/energy fluctuations, ...etc.

sensor, actuators, transducers

Mechanisms: bias currents, voltages $S_{12}$ / reverse transfer => leakage, heating, activated processes, noise

... these are the four critical physical considerations.
As an archetypal case study of nanosensor physics, we’ll focus upon resonant NEMS sensors. I will describe the immense increase in responsivity obtained with device size reduction that yields, for example, atomic mass resolution. We will explore several noise mechanisms and backaction effects imposing ultimate physical limits to the sensitivity, and how matching considerations make it extremely challenging to embed these devices in practical measurement systems.
High-sensitivity piezoresistive cantilevers under 1000 Å thick

J. A. Harley\textsuperscript{a}) and T. W. Kenny

\textit{Department of Mechanical Engineering, Stanford University, Stanford, California 94305-4021}

(Received 1 March 1999; accepted for publication 17 May 1999)

Ultrathin, high-sensitivity piezoresistive cantilevers were constructed using vapor-phase epitaxy to grow the conducting layer. A fourfold reduction in thickness was achieved over the thinnest implanted piezoresistive cantilevers, allowing improved force or displacement sensitivity and increased bandwidth. In cantilevers 890 Å thick, the dopant is well confined to the surface, and the sensitivity is 70% of the theoretical maximum. A cantilever fabricated for high force resolution has a minimum detectable force of 8.6 fN/√Hz in air. Additionally, the 1/f noise is shown to follow the relation proposed by Hooge [Phys. Lett A 29, 139 (1969)], increasing in inverse proportion to the number of carriers. © 1999 American Institute of Physics. [S0003-6951(99)01728-3]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{SEMs of 0.087–0.090-μm-thick piezoresistive cantilevers. (a) 10 μm×8 μm. (b) 60 μm×4 μm. (c) 40 μm×20 μm. (d) 350 μm×44 μm. Note that image (d) is at 0.45% scale from the others.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Noise spectrum of cantilevers shown in Fig. 1 with 5 V bias. Peaks at 60 Hz and harmonics have been removed for clarity.}
\end{figure}
Scaling down: semiconducting nanopiezoresistor “issues”

Pros:
1. A large gauge factor

Cons:
1. Very high resistance
2. Scaling exacerbates “issues”
3. Noisy (Johnson + 1/f)
4. Large temp. coefficients
5. Difficult to fabricate (epi Si)
6. Expensive to produce

Gauge Factor is not the sole appropriate figure-of-merit for displacement transduction at nanoscale !!
Piezoresistively-detected resonant response from a family of SiC nanocantilevers to a 1nN AC drive signal vs. frequency using metallic piezoresistors, at room temperature in vacuo.

Piezoresistively-detected resonant response from a family of SiC nanocantilevers to a 1nN AC drive signal vs. frequency using metallic piezoresistors, at room temperature in vacuo.

Thermomechanical noise spectrum and Lorentzian fit (red trace) for a 123 MHz nanocantilever measured at room temperature and atmospheric pressure.

\[ 3.9 \times 10^{-15} \, \text{m/\sqrt{Hz}} \]
responsivity, noise, backaction, mismatch

sensor, actuators, transducers

responsivity

internal noise

backaction

physical signal

intrinsic noise

mismatch

Gauge factor

readout system

z_o

z_i

moral:

OPTIMIZE THE SYSTEM, in toto

OOPS,

Gauge factor figures here also!
(In the sense that impedance and noise depend on some of the same parameters.)

... these are the four critical physical considerations.
I now want to move toward addressing the organizer’s question as to whether we can think of there being a **universal sensor platform**. Let’s define nomenclature:

For an **AFM** (open loop): **cantilever**

- **sensor**
  - physical signal
- **transducer**
  - sensed signal
- **readout**
  - transduced signal
  - c/p

For an **AFM** (open loop):

- **force**
- **displacement**
- **piezoresistor**
  - resistance
  - I
- **readout**
  - o/p

A resonant **mass sensing system** is somewhat more complex:

- **resonator**
  - δ(mass)
- **phase-locked loop**
  - freq o/p
  - RF drive
- **readout**
  - error signal (freq shift)
  - o/p
Resonant Systems: Generic Platforms

I now want to move toward addressing the organizer’s question as to whether we can think of there being a universal sensor platform. Let’s define nomenclature:

For an AFM (open loop):
- **sensor**: cantilever
- **transducer**: piezoresistor
- **readout**: resistance

A resonant mass sensing system is somewhat more complex:
- **resonator**
- **phase-locked loop**
- **readout**
A generic **resonant sensing system** architecture:

![Diagram of resonant system]

- **High-Q resonant system:**
  - extremely sensitive to external perturbations if Q large
  - Maintained in steady-state operations by control system (by PLL or low-noise oscillator circuitry)
  - Low-phase-noise oscillator technology is well-validated/mature: large drive make feasible observations of *exceptionally* small changes
  - However if Q is large, time response ($\sim Q/\omega_0$) can be slow unless $\omega_0$ is high. So use UHF/microwave NEMS, *or* integrated photonic resonators.

**Perturbations:** (NEMS sensors)

- mass, force (*frequency shift in a nonlinear potential, i.e. position bias*), acceleration, displacement, temperature (*conducted through phonons*), microwave/IR/optical photons (*radiated energy*), chem/bio sensing (*chemical binding force detection via entropic and steric effects; calorimetric detection via enthalpic or absorption spectroscopy*); ...etc.
I will attempt to generalize the discussion (a little) by considering other state-of-the-art sensors such as resonant photonic devices.

A generic **resonant sensing system** architecture:

- **Resonator**
  - freq o/p
  - drive
  - perturbation
- **Control Loop**
  - error signal (freq shift)
- **Readout**
  - o/p
Photonic micro-ring resonators

$$m \lambda = 2\pi r n_{\text{eff}}$$


C. Gunn, Genalyte (2010)

Zero-power sensors: a promising idea?

- One last organizers’ thought to address: is there a way, power-wise, to get your data for nothing (and your chips for free?) Let’s take the archetypal case of thermoelectric μfluidic calorimeters.

Signal may be generated with zero power, but:
- Always have transmission lines to drive
- If wireless, transmitters have power budget
- **It COSTS to transmit information**

Furthermore:
- Signal may be embedded in 1/f band
- Costs to use active electronics to move to finite frequency (chopper/lock-in amps)
- **It COSTS to perform signal conditioning**
(hard) lessons learned

- The unique properties of nanodevices, however, are not a panacea that absolves us from the need to contend with long-standing, overarching challenges posed by real-world sensing applications. From about a decade and a half’s work focused on metamorphosing nanosensors into nanosystems through large-scale integration, nature has taught us some hard lessons.
(hard) lessons learned

- Among them are: (a) much, if not most of the work in applying nanosensors must be invested in embedding them into functional systems;

The following whirlwind tour of NEMS-MS work spanning 2000-2012 is presented, just for fun, as an example...
From proteins in solution to vacuum-based adsorption

- electrospray injection
- dual differential pumping
- dual hexapole ion guides
- faraday cup
- phase-locked UHF NEMS mass sensor (~428 MHz)

Wayne Hiebert
Selim Hanay
Akshay Naik
Philip Feng
Steve Stryker
(2004-08)
(hard) lessons learned

- (b) careful choices of platform materials are essential to insure a rapid transition into large-scale integration and production en-masse.
The Alliance for Nanosystems VLSI

Caltech – Kavli Nanoscience Institute, Pasadena

CEA/LETI-MINATEC, Grenoble

Functional validation of nanosystems
- >20 years in nanosystems and nanosciences
- Understanding of underlying physics: ultimate limits
- NEMS (nanoelectromechanical systems)
- Physics, Biophysics, Engineering
- Quick prototyping; Kavli Nanoscience Institute

Very-large-scale Integration
- 200 & 300 mm technological facilities
- Systems architecture and integration (from design to packaging)
- Applied research / applications
- Technology transfer to industry

22 March 2012
$B$-scale microelectronic foundry required...

- $B$-scale “foundry”
- fabrication of millions of nanodevices via standard 200mm (8") VLSI processes

CEA/LETI-MINATEC, Grenoble & Kavli Nanoscience Institute, Caltech
$B$-scale microelectronic foundry required…
(c) any stand-alone sensor is unlikely to be up to the full dynamic range of challenges posed in the real world;
Microsystems for gas phase chemical analysis
The “electronic nose” paradigm: a chemical sensor array

- Gaseous Analyte
- Sensor Array
- Chemical “fingerprint”
Well-documented problems with the e-nose paradigm:

- **Crosstalk**: “fingerprint” changes with exposure to multiple analytes.
- **Environmental fluctuations**: e.g., temperature, humidity.
- **Saturation**: Hard to look for analytes at few ppt level (“t” = trillion) in the presence of few percent H₂O, 1000 ppm smog, etc.
Caltech-Sandia Project: microGC + NEMS sensor array

**NEMS Nose:**

- microfluidic sample
- preconditioning
- and
- multiplexed, chemically-functionalized
- NEMS arrays

Microscale column (Sandia)

Species group A
Species group B
Species group M

Chemisorb-Coated NEMS Resonator Arrays (Caltech)
Chemical functionalization preferentially “sorbs” analytes from ambient (1 Atm)

**Ingredients:** Chemisorptive NEMS Sensor

(a) chemisorptive coating

μGC pulse

1ppt CWA to MGA yields a pulse from GC that is ~10ppb for 10ms (typ.)

(b) resonant NEMS mass sensor

Areal responsivity: ~ few pg cm⁻²Hz⁻¹

(c) control-loop readout

Frequency Resolution: ~1×10⁻⁸
Real time chemisorption measurements with two PMMA-coated NEMS resonators. Displayed are frequency shift steps upon of adsorption of difluoroethane gas molecules onto device surface.

These measurements are carried out at atmospheric pressure & room temperature.

The top and bottom traces are measured with 8 MHz and 128 MHz nanocantilever devices, respectively.

The minimum resolvable mass is ~100 zg.
Frequency shift response to DIMP (a CWA simulant) is linear from ppm concentrations → sub ppb levels

Sub-ppb sensitivity is comparable to that attained with state-of-the-art laboratory technologies for ultralight (non-sticky) analytes

RMS noise ~ 300 zg DIMP sensitivity (1 zg = 10^{-21} g) → 200 part-per-trillion concentration sensitivity attained at 1 Atm
Miniscule NEMS footprint: state-of-the-art sensing in chip-scale GC columns
Two devices with different selectivities:
1) DKAP: specifically sensitive to phosphonate nerve agents
2) PCL: highly absorptive, but unselective, polymer
Conventional "e-nose" paradigm is inadequate

Two devices with diff. selectivities:
1) DKAP: specifically sensitive to phosphonate nerve agents
2) PCL: highly absorptive, but unselective, polymer
(hard) lessons learned

- (c) complex combinations of real-world analytes are unlikely to be resolved by any “one-stop” generic approach;
Nanoelectromechanical Resonator Arrays for Ultrafast, Gas-Phase Chromatographic Chemical Analysis
Mo Li, EB Myers, HX Tang, SJ Aldridge, HC McCaig, JJ Whiting, RJ Simonson, NS Lewis, ML Roukes,
Nano Letters 10, 3899 (2010)
Miniscule NEMS footprint allows for massive scale-up

Commercial GC column

Outlet to FID detector

Functionalized NEMS array

Internal Gas Flow Profile

VLSI NEMS array (Electrically averaged)
Miniscule NEMS footprint allows for massive scale-up

- Commercial GC column
- Outlet to FID detector
- Functionalized NEMS array
- Internal Gas Flow Profile
- VLSI NEMS array (Electrically averaged)

Area: 2.5 mm x 250 μm
25,000 devices
(d) arrays of sensors can often give enhanced performance over individual devices, but achieving such gains may require exceptionally careful attention to device variances;
Electrically averaged NEMS arrays

\[
R_{tot} = \frac{1}{\sum_j \frac{1}{\sum_k R_{0,jk} (1 + \delta_{jk})}} \approx \frac{1}{\sum_j \frac{1}{\sum_k R_{0} (1 + \delta_{jk})}} \approx \frac{l}{m R_0 \left(1 + \sum_{j,k} \frac{\delta_{jk}}{lm}\right)}
\]

\[
V_{out} = C_{det} V_{bias} \frac{\Delta R_{tot}}{R_{tot}} = C_{det} V_{bias} \sum_{j,k} \frac{\delta_{jk}}{lm}
\]

In terms of dissipated power per device:

\[
P_{device} = \frac{V_{bias}^2}{l^2 R_0}.
\]

\[
V_{out} = C_{det} \sqrt{P_{device} R_0 l^2 \left(1 + \sum_{j,k} \frac{\delta_{jk}}{lm}\right)}
\]

\[
V_s = C_{det} \sqrt{P_{device} R_0 \sum_{j,k} \frac{\delta_{jk}}{m}} = C_{det} \sqrt{P_{device} R_{tot} \sum_{j,k} \frac{\delta_{jk}}{\sqrt{N}}}, \text{ where } N = lm
\]

Best-case scenario: All N resonator signals add coherently: \textbf{signal} \sim N

Noise adds incoherently: \textbf{total noise} \sim \sqrt{N}

Arrays can yield up to \sqrt{N} enhancement of S/N

\(~160x \text{ for 25,000 devices!}\)
(a) Top-view schematic of a $140 \times 20$ cantilever array. Individual devices are not visible in this image. The dotted red line shows the trajectory of the laser-based displacement transduction system used to acquire the spectra.

(b) Optically detected spectra of from cantilevers within the array as a function of the position of the laser readout beam. (Beam width is approximately 10 $\mu$m).
Scale-up with minimization of variance provides immense SNR improvement.

(a) Top-view schematic of a 140 × 20 cantilever array. Individual devices are not visible in this image. The dotted red line shows the trajectory of the laser-based displacement transduction system used to acquire the spectra.

(b) Optically detected spectra of from cantilevers within the array as a function of the position of the laser readout beam. (Beam width is approximately 10 μm).

Foundry attainable dimensional tolerances below 1% provide access to majority of array-based enhancement.
(hard) lessons learned

- (c, revisited for fluidic sensors) any stand-alone sensor is unlikely to be up to the full dynamic range of challenges posed in the real world;
Fluidic biosensors: the present “landscape”

Comparative advantages of mechanical biosensors
JL Arlett, EB Myers, ML Roukes,
Nature Nanotechnology 10, 3899 (2011)
Comparative advantages of mechanical biosensors
JL Arlett, EB Myers, ML Roukes,
Nature Nanotechnology 10, 3899 (2011)

Fluidic biosensors: a worthy goal – 1pM LOD/1m
But (non-specific) biological noise is a problem

Comparative advantages of mechanical biosensors
JL Arlett, EB Myers, ML Roukes,
Nature Nanotechnology 10, 3899 (2011)

Biological noise: \((1\text{nM})^{-1}\) avidity
Label-free capture probe affinity is also a challenge

Comparative advantages of mechanical biosensors
JL Arlett, EB Myers, ML Roukes,
Nature Nanotechnology 10, 3899 (2011)
...but, to end on a high note...

Although these sobering considerations may potentially force an initial downselection from amongst the exciting possibilities from within the emerging panoply of nanosensors...

...learning from the past, and considering real-world (not academic laboratory) conditions, will accelerate realization of practical nanosensor systems.