From MEMS to NEMS: Smaller Is Still Better

Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Science
University of Michigan
Ann Arbor, Michigan 48105-2122

(Last Month: Program Manager, DARPA/MTO)

MARC’06 Meeting
Jan. 25-26, 2006
Outline

• Introduction:
  - MEMS technology
  - integration with transistors: an early driver for MEMS

• Benefits of Scaling
  - size reduction
  - speed, energy conservation, complexity, economy

• DARPA/MTO Program Examples
  - Nano Mechanical Array Signal Processors (NMASP)
  - Chip-Scale Atomic Clock (CSAC)
  - Micro Gas Analyzers (MGA)

• Conclusions (What’s Next?)
MEMS: Micro Electro Mechanical Systems

- A device constructed using micromachining (MEMS) tech.
- A micro-scale or smaller device/system that operates mainly via a mechanical or electromechanical means
- At least some of the signals flowing through a MEMS device are best described in terms of mechanical variables, e.g., displacement, velocity, acceleration, temperature, flow

**Input:**
- voltage, current, acceleration, velocity, light, heat, ...

**Output:**
- voltage, current, acceleration, velocity, light, heat, ...

**Control:**
- voltage, current, acceleration, velocity, stress, light, heat, ...

Transducer to Convert Control to a Mechanical Variable (e.g., displacement, velocity, stress, heat, ...)

Angle set by mechanical means to control the path of light

[Wu, UCLA]
Other Common Attributes of MEMS

- Feature sizes measured in microns or less
- Merges computation with sensing and actuation to change the way we perceive and control the physical world
- Planar lithographic technology often used for fabrication
  - can use fab equipment identical to those needed for IC’s
  - however, some fabrication steps transcend those of conventional IC processing

[C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05]
Bulk Micromachining and Bonding

- Use the wafer itself as the structural material
- \textit{Adv.}: very large aspect ratios, thick structures
- \textit{Example}: deep etching and wafer bonding

![Micromechanical Vibrating Ring Gyroscope]

- [Najafi, Michigan]
- [Pisano, UC Berkeley]

- Silicon Substrate
- Glass Substrate
- Metal Interconnect
- Anchor
- Electrode
- Movable Structure
- Microrotor (for a microengine)

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Surface Micromachining

- Fabrication steps compatible with planar IC processing

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
• Completely monolithic, low phase noise, high-Q oscillator (effectively, an integrated crystal oscillator)

To allow the use of >600°C processing temperatures, tungsten (instead of aluminum) is used for metallization
Technology Trend and Roadmap for MEMS

Number of Mechanical Components

increasing ability to sense and act

Number of Transistors

increasing ability to compute

Majority of Early MEMS Devices (mostly sensors)

10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

CPU's

Pentium 4

ADXL-50

Inertial Navigation On a Chip

ADXL-278

Weapons, Safing, Arming, and Fusing

OMM 32x32

ADXL-78

Adaptive Optics

Optical Switches & Aligners

Digital Micromirror Device (DMD)

Terabit/cm^2 Data Storage

Integrated Fluidic Systems

Displays

Phased-Array Antenna

Distributed Structural Control

Future MEMS Integration Levels

Enabled Applications

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Benefits of Size Reduction: IC’s

• Numerous benefits attained by scaling of transistors:
  - Higher Current Drive
  - Lower Capacitance
  - Higher Integration Density
  - Lower Supply Voltage
  - Faster Speed
  - Lower Power
  - Higher Circuit Complexity & Economy of Scale

• But … some drawbacks:
  - poorer reliability (e.g., hot e- effects)
  - lower dynamic range (analog ckts suffer)
**Example: Micromechanical Accelerometer**

- **The MEMS Advantage:**
  - >30X size reduction for accelerometer mechanical elements
  - allows integration with IC's

**Basic Operation Principle**

\[ x \propto F_i = ma \]

- Tiny mass means small output ⇒ need integrated transistor circuits to compensate

---

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
C. T.-C. Nguyen, "From MEMS to NEMS: Smaller Is Still Better," MARC'06 Meeting, 1/25-26/05

- Increasing ability to compute
- Increasing ability to sense and act

<table>
<thead>
<tr>
<th>Number of Mechanical Components</th>
<th>Number of Transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^0</td>
<td>10^0</td>
</tr>
<tr>
<td>10^1</td>
<td>10^1</td>
</tr>
<tr>
<td>10^2</td>
<td>10^2</td>
</tr>
<tr>
<td>10^3</td>
<td>10^3</td>
</tr>
<tr>
<td>10^4</td>
<td>10^4</td>
</tr>
<tr>
<td>10^5</td>
<td>10^5</td>
</tr>
<tr>
<td>10^6</td>
<td>10^6</td>
</tr>
<tr>
<td>10^7</td>
<td>10^7</td>
</tr>
<tr>
<td>10^8</td>
<td>10^8</td>
</tr>
<tr>
<td>10^9</td>
<td>10^9</td>
</tr>
</tbody>
</table>

- Adaptive Optics
- Integrated Fluidic Systems
- Distributed Structural Control
- Terabit/cm² Data Storage
- Optical Switches & Aligners
- Inertial Navigation on a Chip
- Weapons, Safing, Arming, and Fusing
- OMM 32x32
- ADXL-50
- CPU's
- Pentium 4
- i-STAT 1
- ADXRS Caliper
- Analog Devices ADXRS Integrated Gyroscope
- Ti Digital Micromirror Device
- Digital Micromirror Device (DMD)

Adv.: small size, small sample, fast analysis speed
Adv.: faster switching, low loss, larger networks
Adv.: low loss, fast switching, high fill factor
Benefits of Size Reduction: MEMS

• Benefits of size reduction clear for IC’s in elect. domain
  ➔ size reduction ⇒ speed, low power, complexity, economy

• MEMS: enables a similar concept, but …

MEMS extends the benefits of size reduction beyond the electrical domain

Performance enhancements for application domains beyond those satisfied by electronics in the same general categories

- Speed ➔ Frequency ↑, Thermal Time Const. ↓
- Power Consumption ➔ Actuation Energy ↓, Heating Power ↓
- Complexity ➔ Integration Density ↑, Functionality ↑
- Economy ➔ Batch Fab. Pot. ↑ (esp. for packaging)
Nano Mechanical Array Signal Processors (NMASP)
Basic Concept: Scaling Guitar Strings

Guitar String

Vibrating “A” String (110 Hz)

Freq. Equation:
\[ f_o = \frac{1}{2\pi} \sqrt{\frac{k_r}{m_r}} \]

Mechanical Resonator

Performance:
- \( f_o = 8.5 \text{MHz} \)
- \( Q_{\text{vac}} = 8,000 \)
- \( Q_{\text{air}} \approx 50 \)
- \( L_r = 40.8 \mu\text{m} \)
- \( m_r \approx 10^{-13} \text{ kg} \)
- \( W_r = 8 \mu\text{m}, h_r = 2 \mu\text{m} \)
- \( d = 1000\text{Å} \)
- \( V_P = 5\text{V} \)
- \( \text{Press.} = 70\text{mTorr} \)

[Bannon 1996]
**3CC 3λ/4 Bridged μMechanical Filter**

**Performance:**
- $f_o=9$ MHz, $BW=20$ kHz, $PBW=0.2\%$
- $I.L.=2.79$ dB, $Stop. Rej.=51$ dB
- $20$ dB S.F.$=1.95$, $40$ dB S.F.$=6.45$

- $P_{in}=-20$ dBm

- Sharper roll-off
- Loss Pole

**Design:**
- $L_r=40\mu m$
- $W_r=6.5\mu m$
- $h_r=2\mu m$
- $L_c=3.5\mu m$
- $L_b=1.6\mu m$
- $V_P=10.47$ V
- $P=-5$ dBm
- $R_{Qi}=R_{Qo}=12k\Omega$

[S.-S. Li, Nguyen, FCS’05]

[Li, et al., UFFCS’04]
Nanomechanical Vibrating Resonator

- Constructed in SiC material w/ 30 nm Al metallization for magnetomotive pickup

Design/Performance:

\[ L_r = 1.1 \, \mu m, \, W_r = 120 \, \text{nm}, \, h = 75 \, \text{nm} \]

\[ f_o = 1.029 \, \text{GHz}, \, Q = 500 @ 4K, \, \text{vacuum} \]

[Figure showing design parameters and performance characteristics]
Scaling-Induced Performance Limitations

**Mass Loading Noise**

Contaminant Molecules

*Photons*

- Differences in rates of adsorption and desorption of contaminant molecules
  - mass fluctuations
  - frequency fluctuations

- Problem: if dimensions too small $\Rightarrow$ phase noise significant!

- Solution: operate under optimum pressure and temperature

**Temperature Fluctuation Noise**

- Absorption/emission of photons
  - temperature fluctuations
  - frequency fluctuations

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
1.51-GHz, $Q=11,555$ Nanocrystalline Diamond Disk $\mu$ Mechanical Resonator

- Impedance-mismatched stem for reduced anchor dissipation
- Operated in the 2\textsuperscript{nd} radial-contour mode
- $Q \sim 11,555$ (vacuum); $Q \sim 10,100$ (air)
- \textbf{Below:} 20 $\mu$m diameter disk

\textbf{Design/Performance:}
\begin{align*}
R &= 10 \mu m, \quad t = 2.2 \mu m, \quad d = 800 \text{Å}, \quad V_P = 7 V \\
f_0 &= 1.51 \text{ GHz (2\textsuperscript{nd} mode), } Q = 11,555 \\
Q &= 10,100 \text{ (air)}
\end{align*}

[Wang, Butler, Nguyen MEMS’04]
Miniatrization of RF Front Ends

**Problem:** high-Q passives pose a bottleneck against miniaturization.

- **RF Power Amplifier**
- **Diplexer**
- **925-960MHz RF SAW Filter**
- **1805-1880MHz RF SAW Filter**
- **26-MHz Xstal Oscillator**
- **897.5±17.5MHz RF SAW Filter**
- **Dual-Band Zero-IF Transistor Chip**
- **3420-3840MHz VCO**

**Diagram:**
- Antenna
- Diplexer
- RF BPF
- From TX
- LNA
- Mixer I
- RF PLL
- RXRF LO
- Mixer Q
- AGC
- A/D
- A/D
- Xstal Osc
- LPF
- AGC
- AGC

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC 06 Meeting, 1/25-26/05
Miniatuization of RF Front Ends

- Planar Spiral Inductor
- Raised Inductor $Q \approx 30-70$
- Ceramic RF Filter
- LNA RF Filter
- SAW RF Filter
- SAW IF Filter
- IF Amp
- Tunable Off-Chip LC Tank
- Quartz Xstal
- Channel Select PLL
- VCO

RF Phone

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Chip-Scale Atomic Clocks (CSAC)
NI ST F1 Fountain Atomic Clock

Vol: $\sim 3.7 \text{ m}^3$

Power: $\sim 500 \text{ W}$

Acc: $1 \times 10^{-15}$

Stab: $3.3 \times 10^{-15}/\text{hr}$

After 1 sec $\rightarrow$

Error: $10^{-15}$ sec

Loses 1 sec every 30 million years!
Benefits of Accurate Portable Timing

Better Timing
- More efficient spectrum utilization
- Faster frequency hop rates
- Faster acquire of pseudorandom signals
- Superior resilience against jamming or interception

Secure Communications
- Longer autonomy periods

Networked Sensors
- Larger networks with longer autonomy

GPS
- Fewer satellites needed
- Higher jamming margin
- Faster GPS acquire

DARPA

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
**Accurate Portable Timekeepers**

**High-Q Oscillators**
- Tank $Q \sim$ tens of thousands
- **Example**: crystal oscillator

- **Quartz**: vibrating mechanical resonance $\Rightarrow$ high $Q$, stable

- Stability quite good at carrier offset freqs. around 1 kHz
- $L\{f_m=1kHz\} = -140\text{dBc/Hz}$

- Accuracy (@ tiny offset freqs.) good, but not good enough for some applications

- Excellent stability at offset frequencies $\sim1\text{kHz}$
Atomic Clock Fundamentals

- Frequency determined by an atomic transition energy

Excite e- to the next orbital

$^{133}\text{Cs}$

$E = 0.000038 \text{ eV}$

$\nu = \frac{E}{\hbar} = 9\,192\,631\,770 \text{ Hz}$

$E = 1.46 \text{ eV}$

$\nu = \frac{E}{\hbar} = 352 \text{ THz}$

$\Rightarrow 852.11 \text{ nm}$
Hyperfine Splitting Freq.

\[ \nu = \frac{\Delta E}{\hbar} = 9,192,631,770 \text{ Hz} \]

Atoms become transparent to light at 852 nm

133Cs vapor at 10^-7 torr

Modulated Laser

\( \nu_o \) 4.6 GHz

\[ \lambda \]

Carrier (852 nm)

Close feedback loop to lock

\( \mu \text{wave osc} \)

\( \text{VCXO} \)

Photo Detector

Mod \( f \)
Miniaturizing Atomic Clocks

**Datum R2000**
- Vol: 9,050 cm³
- Power: 60 W
- Acc: $5 \times 10^{-11}$

**Temex RMO**
- Vol: 230 cm³
- Power: 10 W
- Acc: $1 \times 10^{-11}$

**NI ST- F1**
- Vol: ~3.7 m³
- Power: ~500 W
- Acc: $1 \times 10^{-15}$
- Stab: $3.3 \times 10^{-15}$/hr

**CSAC**
- Vol: 1 cm³
- Power: 30 mW
- Acc: $1 \times 10^{-11}$
- Stab: $1 \times 10^{-11}$/hr

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Chip-Scale Atomic Clock

- **133Cs vapor at 10⁻⁷ torr**
- Laser
- 4.6 GHz
- Mod f
- VCXO
- GHz Resonator
- in Vacuum

**Atomic Clock Concept**

**MEMS and Photonic Technologies**

- **Key Challenges:**
  - thermal isolation for low power
  - cell design for maximum Q
  - low power μwave oscillator

**Chip-Scale Atomic Clock**

- Vol: 1 cm³
- Power: 30 mW
- Stab: 1×10⁻¹¹
Pros and Cons of Miniaturization
Micro-Scale Oven-Control Advantages

**Macro-Scale**
- 2 cm³ Atomic Cell @ 80°C
- 2 cm
- Thermally Isolating Feet

**Macro-Oven** (containing heater and T sensor)
- Insulation
- Laser

**300x300x300 μm³ Atomic Cell @ 80°C**
- 25°C

**Micro-Scale**
- Heater
- Laser
- Long, Thin Nitride Tethers w/ Metal Leads
- T Sensor (underneath)

**T = P x R_{th}**
- \( R_{th} = 18 \text{ K/W} \)
- \( C_{th} = 40 \text{ J/K} \)

\[ P (@ 80°C) = 3 \text{ W} \]

3,000x lower power
240x faster warm up

Warm Up, \( \tau = 12 \text{ min.} \)

**P (@ 80°C) = 1 \text{ mW}**

Warm Up, \( \tau = 3 \text{ s} \)

**Comparison**
- \( R_{th} = 61,000 \text{ K/W} \)
- \( C_{th} = 4.8 \times 10^{-5} \text{ J/K} \)
Challenge: Miniature Atomic Cell

Large Vapor Cell

Tiny Vapor Cell

1,000X Volume Scaling

Surface/Volume

More wall collisions ⇨ stability gets worse

Wall collision dephases atoms ⇔ lose coherent state

Intensity

Mod f

9.2 GHz

Atomic Resonance

lowest Q

lower Q
**Challenge: Miniature Atomic Cell**

**Large Vapor Cell**

- 1,000X Volume Scaling

**Tiny Vapor Cell**

- Buffer Gas

**Solution:** Add a buffer gas

- Lower the mean free path of the atomic vapor

- Return to higher Q

**Intensity**

- 9.2 GHz

---

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
1st Chip-Scale Atomic Physics Package

Total Volume: 9.5 mm$^3$
Cell Interior Vol: 0.6 mm$^3$
Stability: 2.4 x 10$^{-10}$ @ 1s
Power Cons: 75 mW
**Tiny Physics Package Performance**

- **Experimental Conditions:**
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: ~80 °C
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70μW

**Stability Measurement:**
- **Open Loop Resonance:**
  - $Q = 1.3 \times 10^6$
  - Sufficient to meet CSAC program goals

- **Allan Deviation, $\sigma_y$:**
  - **Cs (D$_2$)**
  - **Rb (D$_1$)**
  - **Drift Issue**

- **Integration Time, $\tau$ [s]:**
  - CSAC Goal

- **Integration Time, $\tau$ [s]:**
  - 1 hour
  - 1 day

---

Physics Package Power Diss. < 10 mW

- Achieved via MEMS-based thermal isolation

Cesium cell
Heater/Sensor Suspension
Frame Spacer
VCSEL Suspension

VCSEL / Photodiode

Symmetricom / Draper Physics Package Assembly

Only ~5 mW heating power needed to achieve 80°C cell temperature

Schematic diagram showing various components, including:
- VCSEL
- Photodiode
- Frame Spacer
- Heater/Sensor Suspension
- Cesium cell

Graph showing measured and modeled power versus temperature.
A 9.95 cc, 153 mW Atomic Clock w/ Chip-Scale Physics Package

Symmetricom’s measured Allan deviation easily satisfies CSAC Phase 2 Goal

Power Budget < 200 mW

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Regulation</td>
<td>1</td>
</tr>
<tr>
<td>Microprocessor</td>
<td>8</td>
</tr>
<tr>
<td>Signal Processing</td>
<td>6</td>
</tr>
<tr>
<td>RF</td>
<td>75</td>
</tr>
<tr>
<td>VCSEL drive</td>
<td>2</td>
</tr>
<tr>
<td>Heater Power (air)</td>
<td>51</td>
</tr>
<tr>
<td>C-field</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>153</td>
</tr>
</tbody>
</table>

MEMS-based thermal isolation allows low physics package power consumption

Overlapping Allan Deviation, $\sigma(t)$

Frequency Stability

FREQUENCY STABILITY
MAC-3 W/PS-055

<table>
<thead>
<tr>
<th>$\tau$ (sec)</th>
<th>$\sigma(t)$ (x10^-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.76e-10</td>
</tr>
<tr>
<td>2</td>
<td>2.69e-10</td>
</tr>
<tr>
<td>4</td>
<td>1.87e-10</td>
</tr>
<tr>
<td>8</td>
<td>1.31e-10</td>
</tr>
<tr>
<td>16</td>
<td>9.73e-11</td>
</tr>
<tr>
<td>32</td>
<td>6.86e-11</td>
</tr>
<tr>
<td>64</td>
<td>5.55e-11</td>
</tr>
<tr>
<td>128</td>
<td>5.02e-11</td>
</tr>
<tr>
<td>256</td>
<td>5.18e-11</td>
</tr>
<tr>
<td>512</td>
<td>4.23e-11</td>
</tr>
</tbody>
</table>

9.95 cm³ Total Package Volume

Physics Package

Packaged CSAC

Power Regulation

Microprocessor

Signal Processing

RF

VCSEL drive

Heater Power (air)

C-field

Total:

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller is Still Better,” MARC’06 Meeting, 1/25-26/05
Atomic Clock Technology Progression

NI ST F1

HP 5071A
Vol: 29.700 cm³
Power: 50 W
Acc: 5x10⁻¹³

Datum R2000
Vol: 9,050 cm³
Power: 60 W
Acc: 5x10⁻¹¹

Temex RMO
Vol: 230 cm³
Power: 10 W
Acc: 1x10⁻¹¹

NIST PP
Vol: 9.5 mm³
Power: 75 mW+elect.
Stab: 10⁻¹¹/hr

Symmetricom CSAC
Vol: 9.95 cm³
Power: 153 mW
Stab: 5x10⁻¹¹/100s

Vol: ~3.7 m³
Power: ~500 W
Acc: 3.8x10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

Stab = Allan deviation/integration time

State-of-Practice

State-of-Research

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Micro Gas Analyzers (MGA)
**Micro Gas Analyzers**

- **Objective**: enable remote detection of chemical agents via tiny, ultra-low power, fast, chip-scale gas analyzers that greatly reduce the incidence of false positives

- **Approach**: use micromachining technologies to implement separation-based analyzers (e.g., gas chromatographs, mass spectrometers) at the micro-scale to enhance gas selectivity

**Conventional Sensor**

- Capacitor Plates
- Gas Sensitive Polymer
- ΔC ~ gas conc.

**Separation Analyzer**

- Species A
- Species B

- Result: species A & B now separated, can identify and analyze individually

- Problem: polymer has finite sensitivity to both A & B

- Result: species A & B slow, separate and can identify and analyze individually
Advantages of Miniaturizationization

### Portable Gas Chromatograph
- Size: 40,500 cm³
- Sensitivity: 1 ppb
- Analysis Time: 15 min.
- Energy Per Analysis: 10,000 J

### Chip-Scale Gas Chromatograph
- Size: 2 cm³
- Sensitivity: 1 ppt
- Analysis Time: 4 sec
- Energy Per Analysis: 1 J

**Reduction Factors**
- Size: 20,000X
- Sensitivity: 1,000X
- Analysis Time: 225X
- Energy Per Analysis: 10,000X
C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05

**Basic Approach: Separation Analyzer**

- **Input Gas Mixture**
- **Pre-Concentrator**
- **Separator**
- **Detector**
- **Electronic Processor**
- **Pump**

**Tiny Dimensions**
- fast time constants
- 10,000X gain factor via multi-staging
- enhanced sensitivity
- lower power
Multi-Stage Pre-Concentration

10 ppb

Heater

Absorbent Film

Heat ~2mW to Release Analyte

Release Analyte in Phase

Thin Concentrated Plug

To Separator

[5,000 ppb]

1,000 ppb

Heat ~2mW to Release Analyte

2,000 ppb

Release Analyte in Phase

3,000 ppb

5,000 ppb

10 ppb

Heater

Absorbent Film

To Separator

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Fast PHASED Pre-Concentration

• **Below:** 20-stage PHASED preconc./sep. analysis of a 720 ppm Hexane-in-Air sample at 60 cm/s sample velocity

![Graph showing MS output counts vs. time with labeled peaks for 17 Water, 43 ToFMS, and 86.]

- Only 300ms needed for sample absorption @ 20°C!

![PHASED chip with 20-stage preconcentrator and separator.]

- PHASED chip with 20-stage preconcentrator and separator

![Sample Expulsion @ 120°C illustration.]

- Sample Expulsion @ 120°C
Basic Approach: Separation Analyzer

- **Tiny Dimensions**
  - fast time constants
  - 10,000X gain factor via multi-staging
  - enhanced sensitivity
  - lower power

- **Miniaturization**

- **Input Gas Mixture**
  - Pre-Concentrator
  - Compacted Slice of Analytes
  - Separated Analytes
  - Detector
  - Electronic Processor
  - Pump
Scaling Leads to Faster Separation

• **Example**: gas chromatograph separation column
  - unique analyte interactions with the column walls
  - different analyte velocities
  - **result**: separation after a finite distance

![Diagram showing miniaturization of chromatography columns](image)

- **Wide Channel**
- **Thin Channel**
- **Stationary Phase**
- **Carrier Gas (Mobile Phase)**
- **Peak Broadens**
- **Peak Stays Thin**
- **Conc.**
- **x**
- **Conc.**
- **x**

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Scaling Leads to Faster Separation

**Example:** gas chromatograph separation column
- unique analyte interactions with the column walls
- different analyte velocities
- **result:** separation after a finite distance

![Diagram of gas chromatograph separation column](image)

**Miniaturize**

- Stationary Phase
- Wide Channel
- Thin Channel
- Carrier Gas (Mobile Phase)

- **Result of Scaling:** shorter column length; faster analysis time

---

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Gas Chromatography in Less Than 4s!

**Design/Measurement Data:**
- 0.75m x 100μ column
- 0.1μ DB-5 stationary phase
- Heart-cut 275 msec peak injection
- Temperature: ~30 deg C/sec
- H₂ carrier: 35-39 psi at 1 psi/sec

Sandia’s micro-GC Column

**Peak capacity:** >40, in 4 sec

**Chemicals:**
- Toluene
- DMMP
- DEMP
- DIMP
- n-dodecane
- 1-decanol
- 1,6-dichlorohexane
- 3-methylhexane
- Solvent

Green = Analyte
Blue = Inteferent
Basic Approach: Separation Analyzer

C. T.-C. Nguyen, "From MEMS to NEMS: Smaller Is Still Better," MARC’06 Meeting, 1/25-26/05

Input Gas Mixture → Pre-Concentrator → Compacted Slice of Analytes → Separator → Separated Analytes → Detector → Electronic Processor → Pump

Miniaturization

Tiny Dimensions
- fast time constants
- 10,000X gain factor via multi-staging
- enhanced sensitivity
- lower power

Tiny Dimensions
- faster separation
- lower power

Tiny Dimensions
- higher sensitivity
- faster refresh rate
- lower power
- arrays for specificity
Zeptogram Mass Sensors

Measurement noise level indicates ~7 zg of resolution

Nanomechanical Resonator

Nozzle

Shutter

Au

Nanomechanical Resonator

~100 zg

~100 zg Au atom clumps resolved!

100 zg Au atom clumps resolved!

133 MHz

190 MHz

>1 Hz/zg

\( \delta m (\text{zg}) \)

\( \text{Time (s)} \)

\( \text{Mass (zeptograms)} \)

\( \text{Frequency Shift (Hz)} \)

\( \text{Frequency Shift (Hz)} \)

\( 0 \)

\( 0 \)

\( 0 \)

\( 0 \)

\( 0 \)

\( 0 \)
**Example**: ion trap mass spectrometer (ITMS) 
\[\checkmark\] separate analytes by molecular weight

**Advantages of Miniaturization**:
\[\checkmark\] can support smaller mean free path \[\Rightarrow\] relaxed vacuum req.  
\[\checkmark\] **result**: substantially lower power requirement
Operation at 1.7 Torr!

Mass spectrum of DMMP by a single 1-mm ion trap @ 1.7 Torr

Highest pressure ever demonstrated!
40\(\mu\)m-Ion Traps Functional!

- Array of 40\(\mu\)m Si Ion Traps

- Should allow much higher pressure operation (~76 Torr)

- Xenon signal obtained at low He pressure (10\(^{-4}\) Torr)

- Xe ion peak

---

C. T.-C. Nguyen, “From MEMS to NEMS: Smaller Is Still Better,” MARC’06 Meeting, 1/25-26/05
Gas Chromatograph/Mass Spectrometer (GC/MS) is a “gold standard” in chemical gas detection with excellent immunity to false alarms.

**Agilent 6852A**
- Vol: 60,000 cm³
- Power: 20 W
- Energy/Analysis: 18 kJ
- Analysis Time: 15 min.

**LLNL**
- Vol: 40,500 cm³
- Power: 11.5 W
- Energy/Analysis: 10 kJ
- Analysis Time: 15 min.

**Sandia μChem Lab**
- Vol: 1,050 cm³
- Power: 4.5 W
- Energy/Analysis: 540 J
- Analysis Time: 2 min.

**MGA Objective**
- Vol: 2 cm³
- Power: <200 mW
- Energy/Analysis: 1 J
- Analysis Time: 4 s

**Problems**: too big, too slow, power hungry

**Solution**: use MEMS technology to miniaturize the GC/MS, which in turn makes it faster and more energy efficient.
Example: Micromechanical Accelerometer

- **The MEMS Advantage:**
  - >30X size reduction for accelerometer mechanical element
  - allows integration with IC’s

*Basic Operation Principle*

\[ x \propto F_i = ma \]

Tiny mass means small output \(\Rightarrow\) need integrated transistor circuits to compensate

Inertial Force

Spring

Proof Mass

Displacement

Acceleration

Analog Devices ADXL 78
Conclusions

• MEMS are micro-scale or smaller devices/systems that operate mainly via a mechanical or electromechanical means

• MEMS ⇒ NEMS offer the same scaling advantages that IC technology offers (e.g., speed, low power, complexity, cost), but they do so for domains beyond electronics:
  - resonant frequency↑ (faster speed)
  - actuation force↓ (lower power)
  - # mechanical elements↑ (higher complexity)
  - integration level↑ (lower cost)

• Micro ... nano ... *it’s all good*

• Just as important: MEMS or NEMS have brought together people from diverse disciplines ⇒ this is the key to growth!

• What’s next? ⇒ Nano-nuclear fusion? Chip-scale atomic sensors?
  - ... limitless possibilities ...