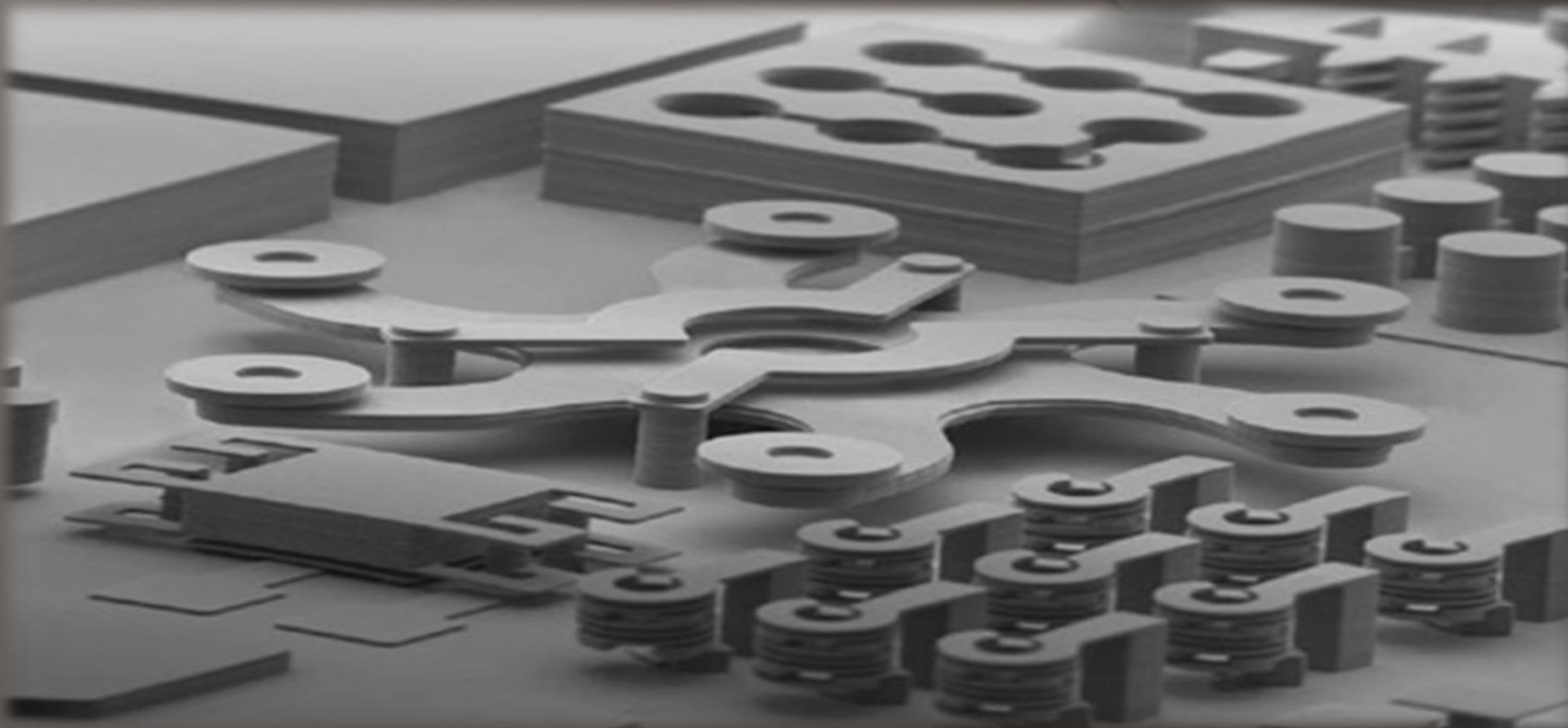


NanoElectroMechanical Systems
(NEMS)

Presented by : Hamed Fooladvand
Instructor : Dr. Golmohammadi

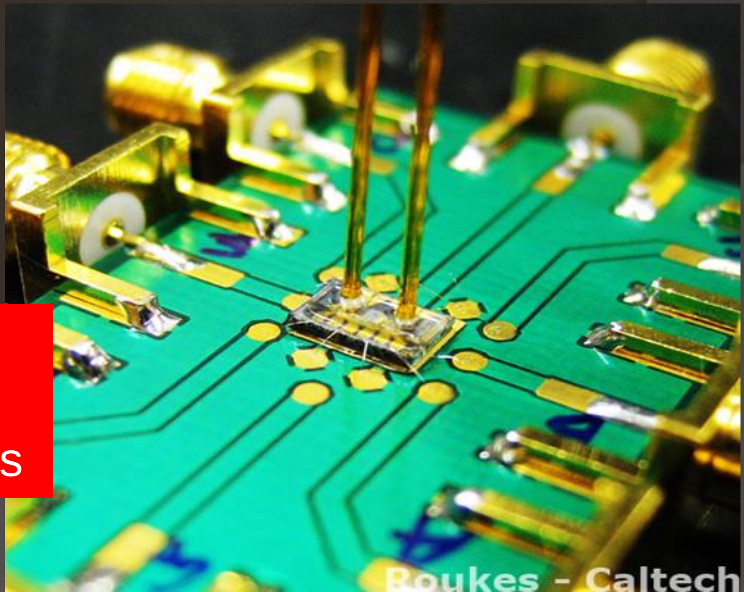
NANO Electronic Engineering Group
Electronic and Computer Engineering Department
The School of Engineering Emerging Technologies
University of Tabriz - Iran , December 2012

Outline

- How it all began…
  - Nanoelectromechanical Systems (NEMS)
- Basic Properties
- Typical Problems
- Fabrication Processes
- Application of NEMS
- Conclusion

How it all began…

- 1959-Richard Feynman offered a prize of $1000 "to the first guy who makes an operating electric motor - a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, in only 1/64 inch cube."
  - stimulate new fabrication technology
- 1960-Bill McLellan, using amateur radio skills, built the motor with his hands using tweezers and a microscope
  - 2000 rpm motor weighed 250 micrograms
  - 13 parts

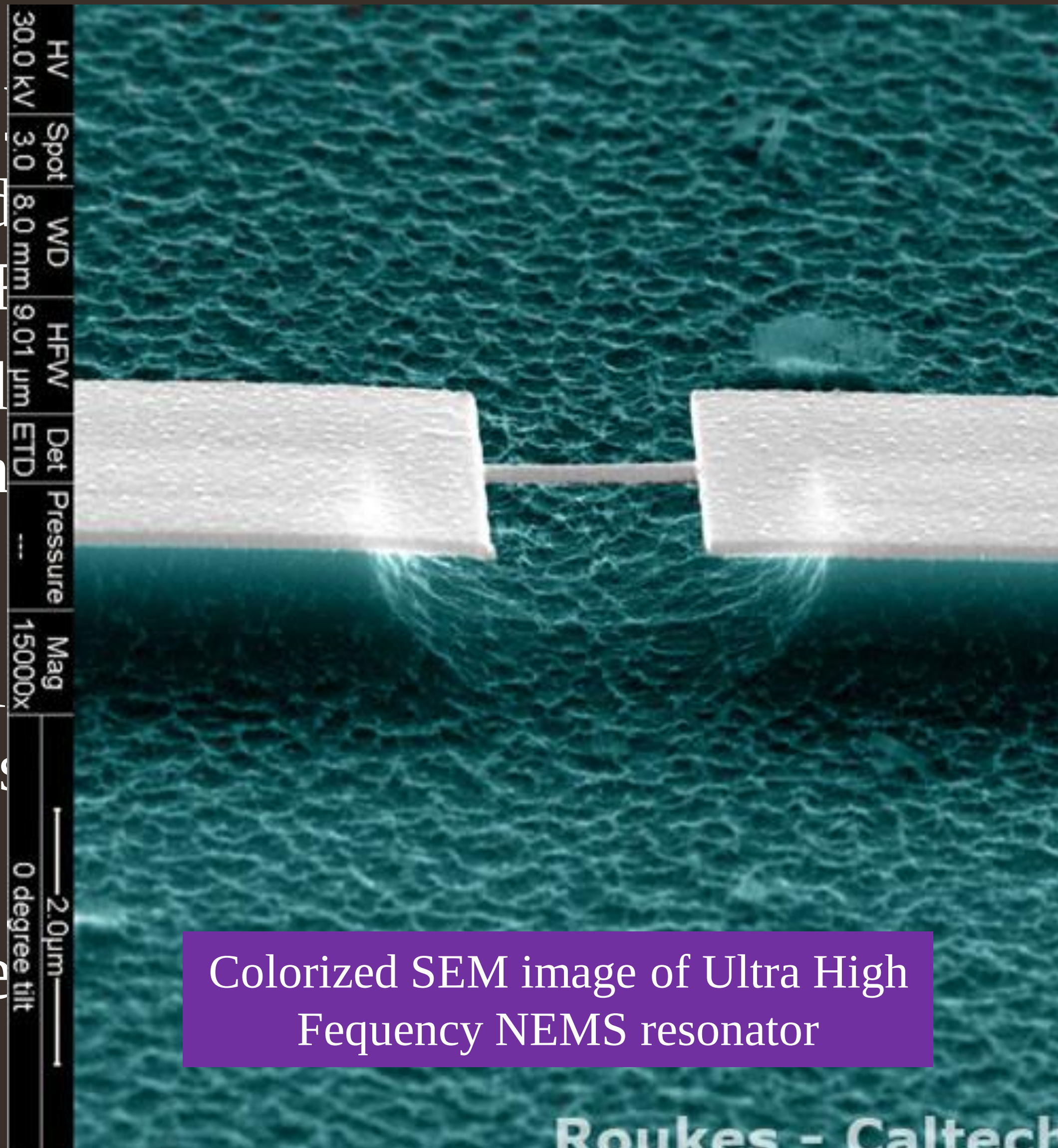


Nanochamber - ultrafast gas sensing with NEMS resonators

http://www.nanowerk.com/spotlight/spotid=2431.php
Image 1: http://nano.caltech.edu/gallery/group2.html

Nanoelectromechanical Systems (NEMS)

- In the 50
  - The field MEMS) caught up with
  - achieved motors many times sm
- NEMS
  - devices i unctionality on the nanos
- Research electrome ly



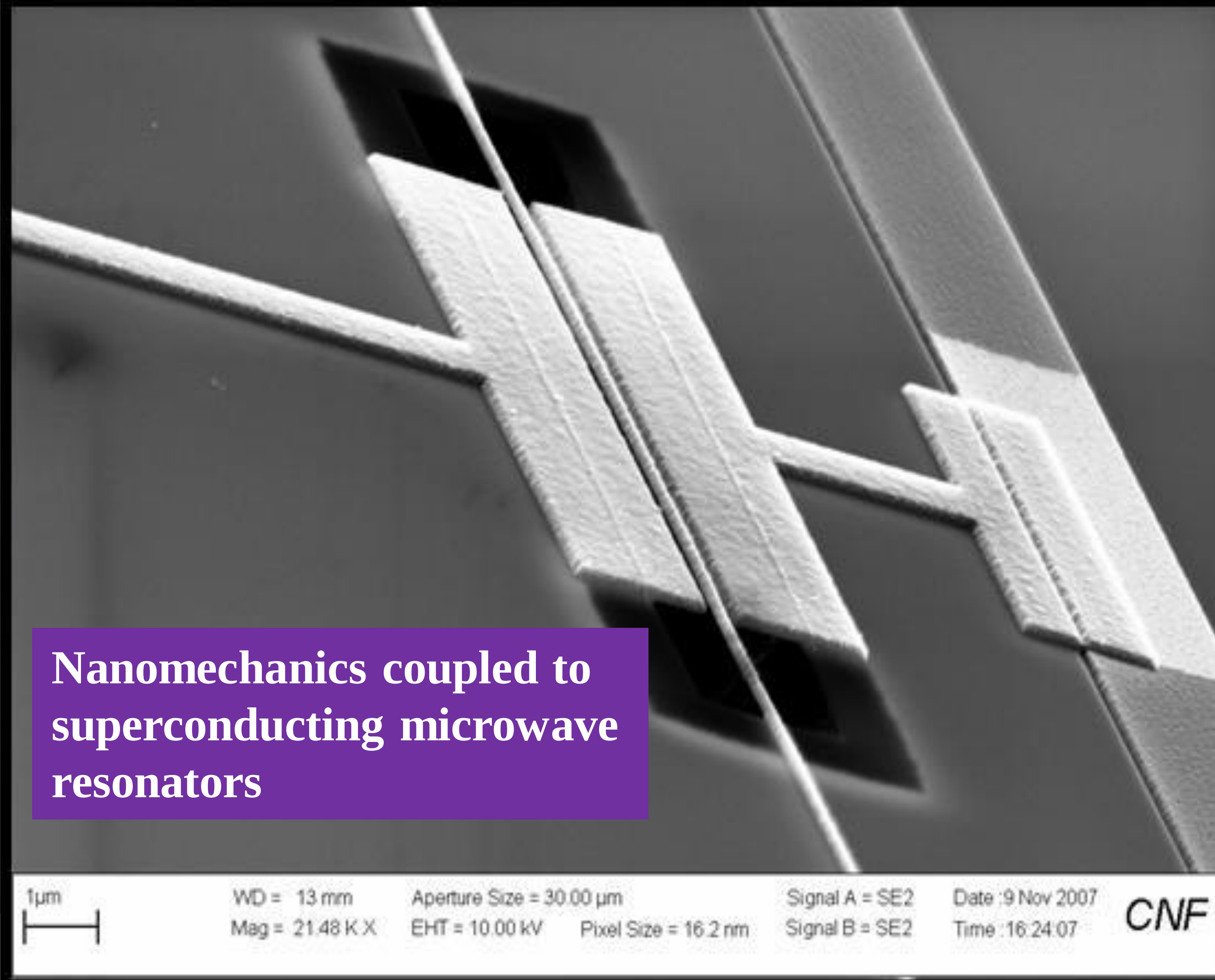
Colorized SEM image of Ultra High Fequency NEMS resonator

http://www.svtii.com/files/MEMS-NEMS-SVTI.pdf

Image 1: http://nano.caltech.edu/gallery/group2.html

Nanoelectromechanical Systems (NEMS)

- Used in aerospace, automotive, biotechnology, instrumentation, robotics, manufacturing and other applications
- Many functions
  - Sensing
  - Actuation
  - Communication



Nanomechanics coupled to superconducting microwave resonators

http://www.svtii.com/files/MEMS-NEMS-SVTI.pdf
Image 1&2: http://nano.caltech.edu/gallery/group2.html
http://www.kschwabresearch.com/articles/detail/11

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Basic Properties

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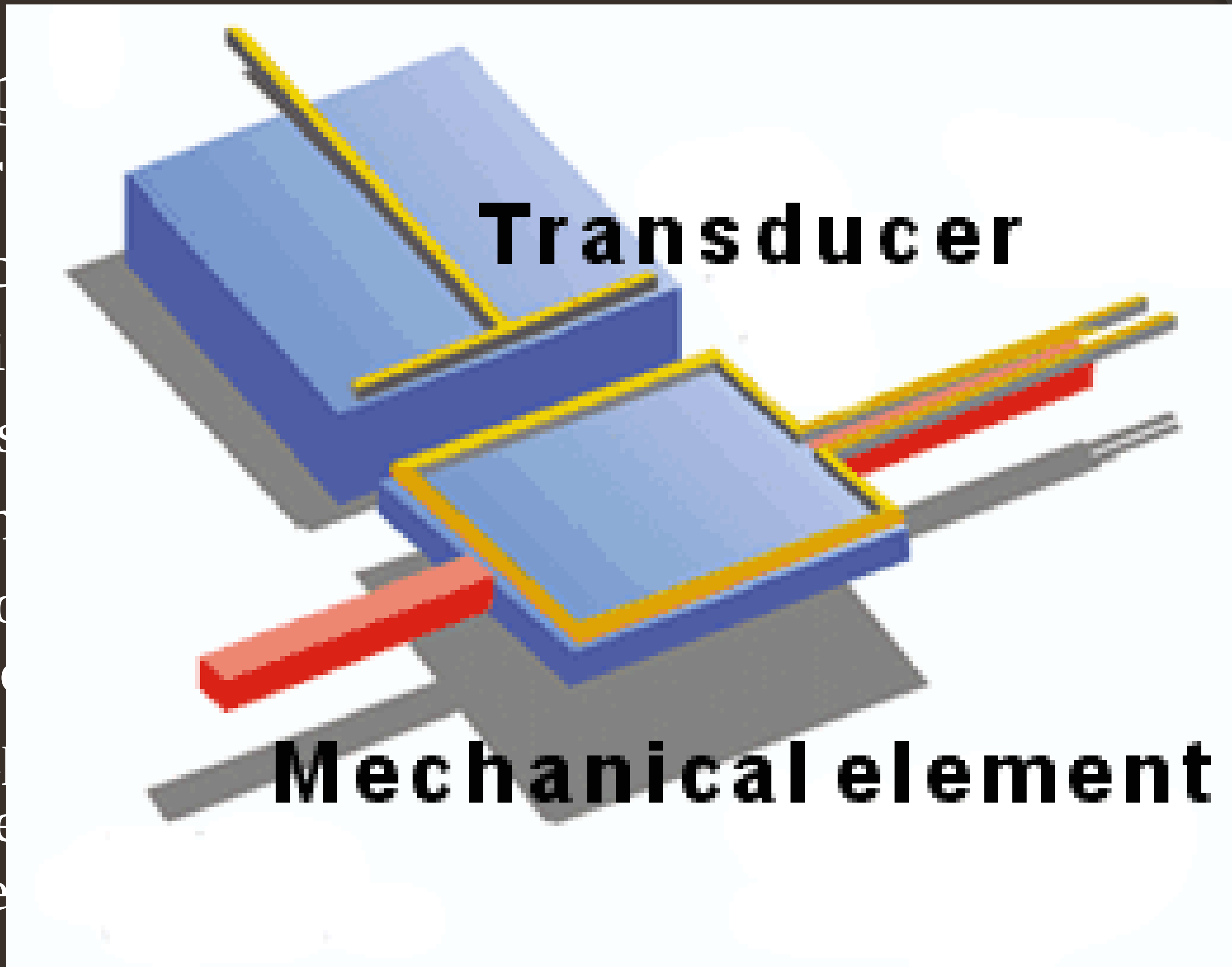
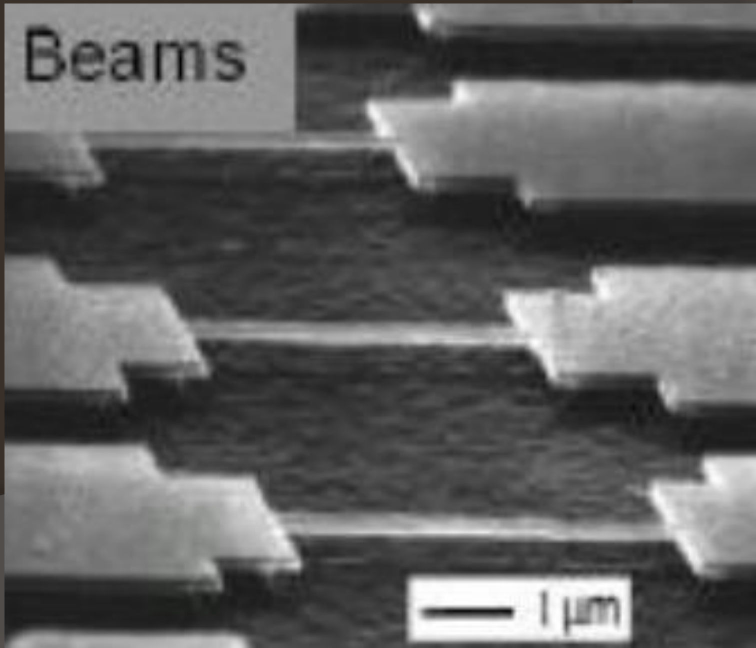


http://www.nanowerk.com/spotlight/spotid=2431.php
Image 1: http://palasantzas.fmns.rug.nl/NEMS.html

Basic Properties

- **Attain extremely high fundamental frequencies**
  - **mechanical responsitvity**
- **Dissipate very little energy**
  - **Characterized by the high quality or *Q* factor of resonance**
- **Extremely sensitive to external damping mechanisms**
  - **Crucial for building many types of sensors**
  - **Suppression of random mechanical fluctuations**
    - **Highly sensitive to applied forces**



http://www.nanowerk.com/spotlight/spotid=2431.php
http://palasantzas.fmns.rug.nl/NEMS.html
Image1: http://phycomp.technion.ac.il/~phr76ja/boston/what2.html

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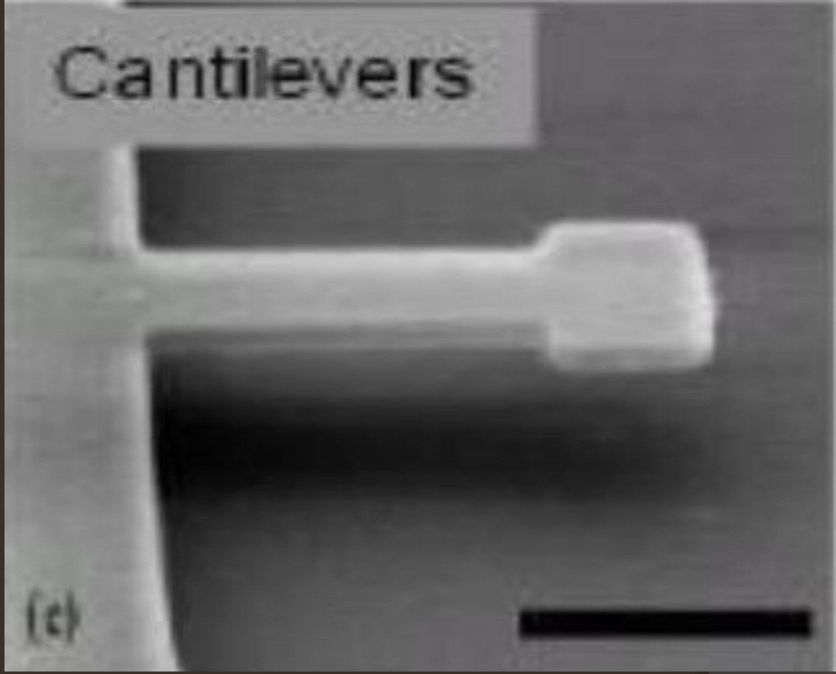
Typical Problems

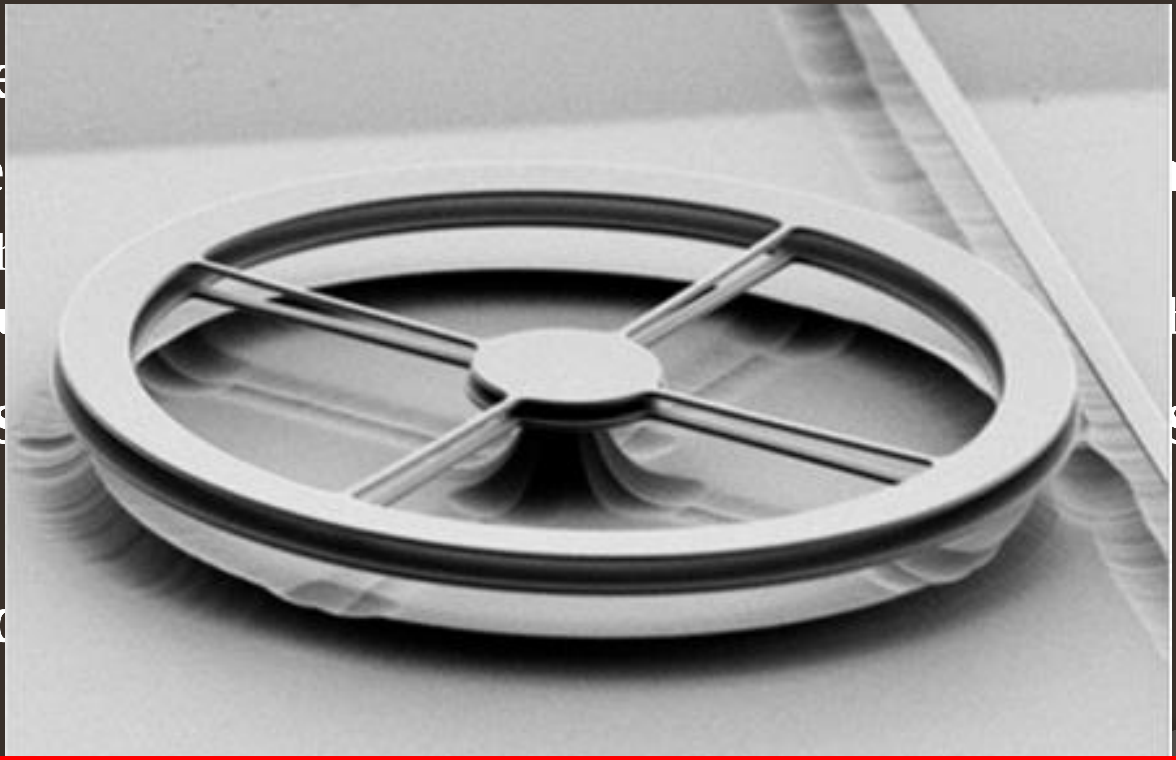


- Great promise as highly sensitive detectors
  - mass, displacement, charge, and energy
- An efficient, integrated, and customizable technique for actively driving and tuning NEMS resonators has remained elusive
- Electromechanical devices are scaled downward
  - transduction becomes increasingly difficult
    - Causing the creation of finely controlled integrated systems to fail

http://www.nanowerk.com/spotlight/spotid=2431.php
Image1: http://phycomp.technion.ac.il/~phr76ja/boston/what2.html

Typical Problems

- Resonator sizes continue to decrease to the nano-scale
  - Surface
    - Susce mechanisms
      - Such defects and impu hness
- Surfaces sipation in NEM
  - detailed

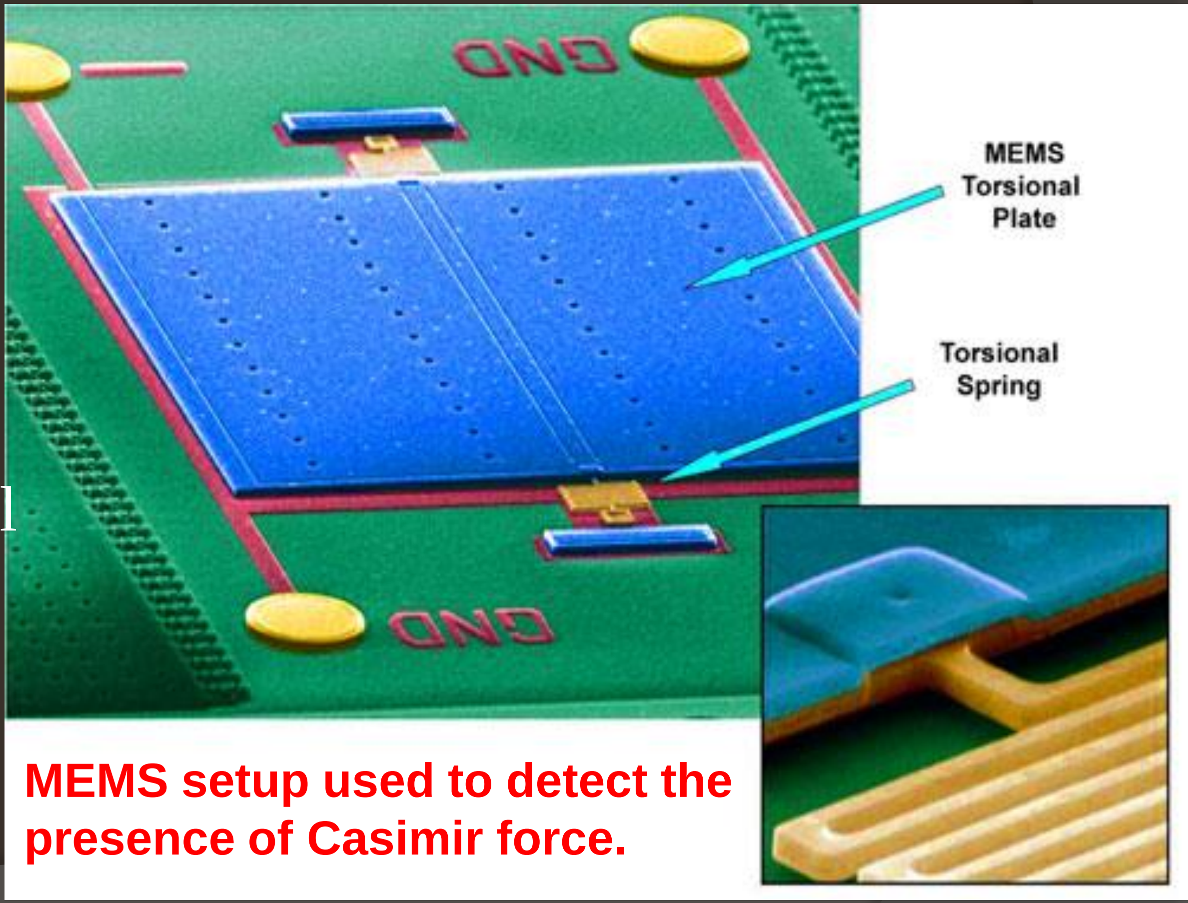


Nanoscale resonators exert relatively strong forces on tiny particles, leading the way to important advancements in MEMS and MOMS systems

http://www.nanowerk.com/spotlight/spotid=2431.php
http://www.gizmag.com/nanoscale-light-resonator/13401/picture/105479/ Image 1

Typical Problems

- Casimir Effect
  - quantum mechanical force that attracts objects a few nanometers apart
  - Very Strong Force
    - Hard to control devices
- Efficient actuation
  - creation of mechanical motion by converting various forms of energy rotating or linear mechanical energy

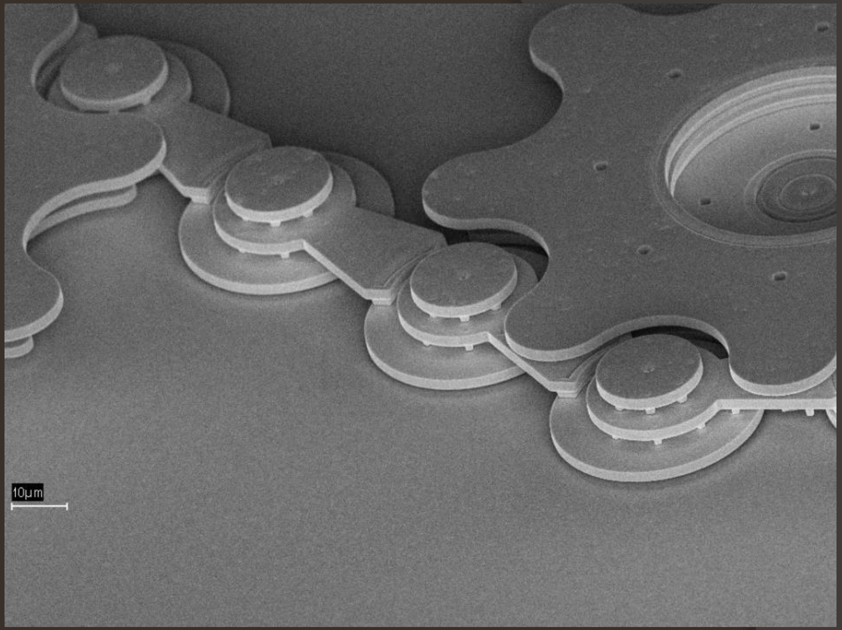


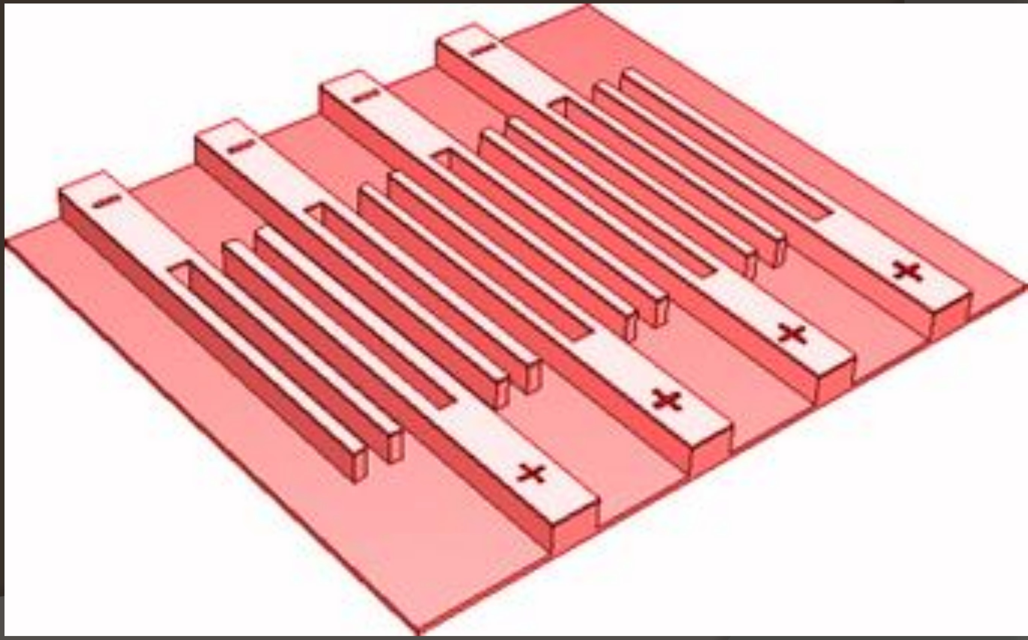
MEMS setup used to detect the presence of Casimir force.

http://www.semiconductor.net/article/444199-Scientists_to_Conquer_Casimir_Effect_Enable_NEMS.php

Typical Problems

- Fabrication
  - Scale down effects
    - Lithography
      - Wave length limitations
  - Integration with typical CMOS processes
- Mass Production
  - Packaging
    - Fragile
  - Cost





Top Image: http://www.texmems.org/
Bottom Image: http://www.nems.se/nimble.html

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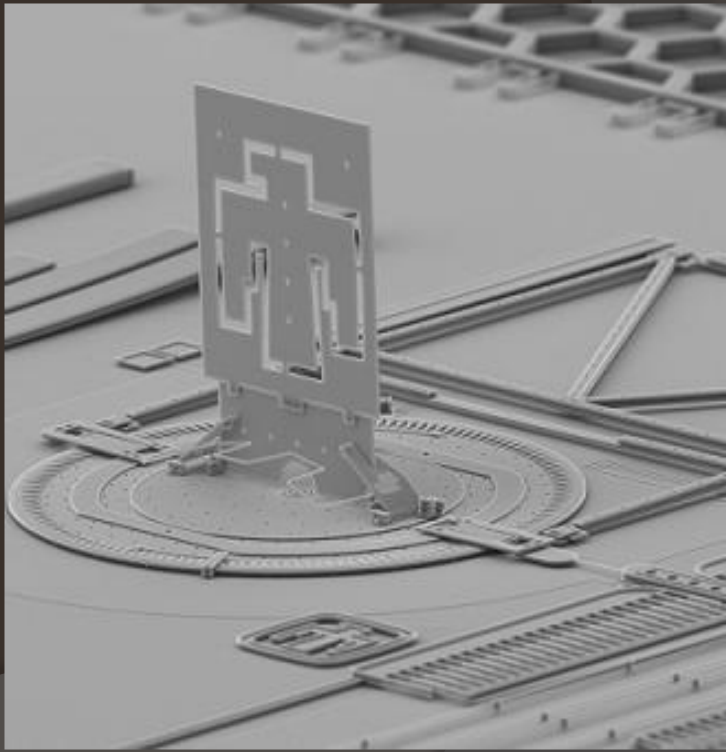
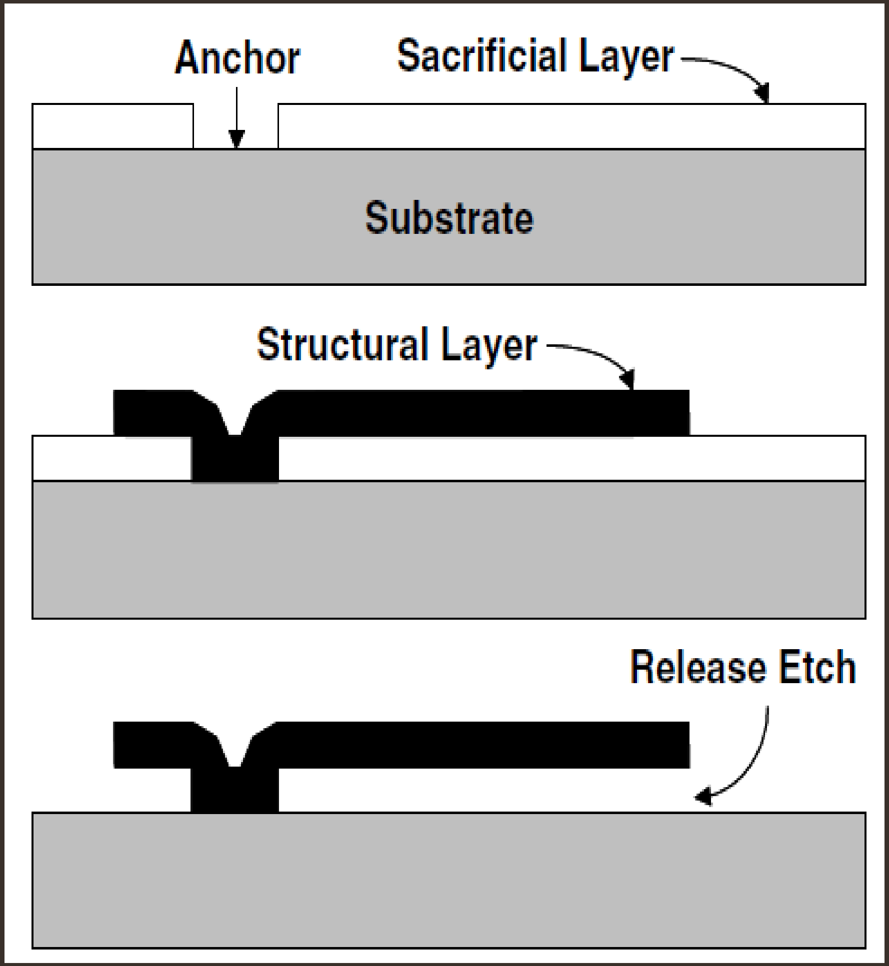
Fabrication Processes

- Basic Steps of Silicon Micromachining:
  - Lithography
  - Deposition of sacrificial and structural layers (PECVD, evaporation, sputtering)
  - Removal of Material (patterning)
  - Selective etching (RIE, Laser)
  - Doping
  - Bonding (Fusion, anodic)
  - Planarization

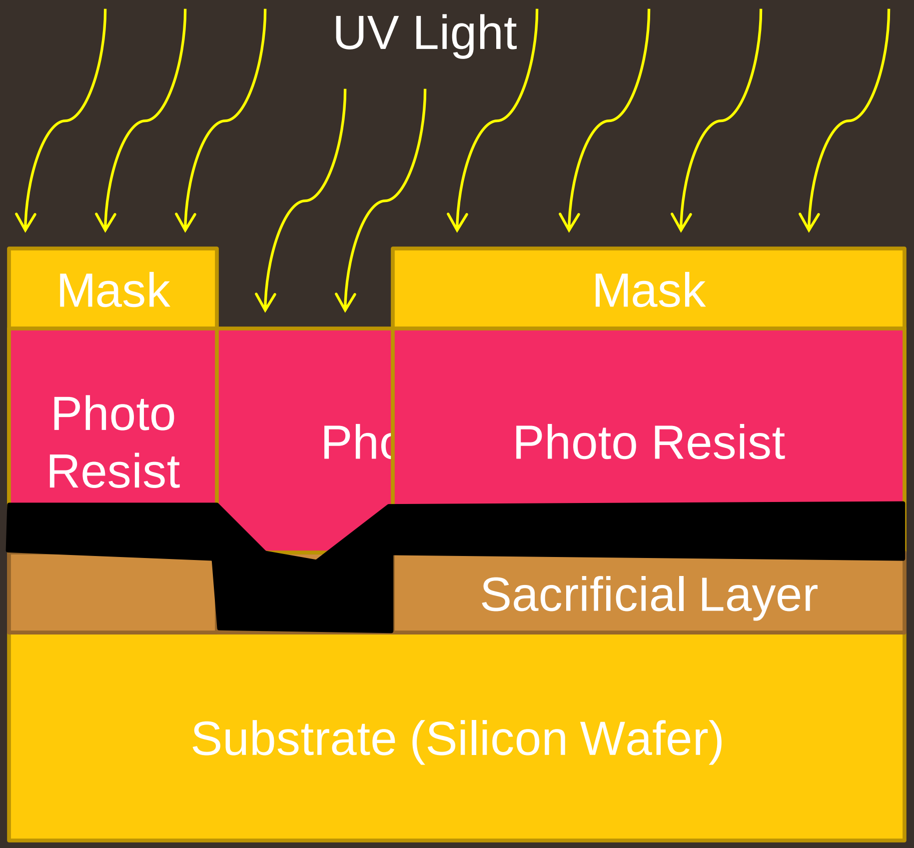


MEMS and NEMS: systems, devices, and structures *Nano- and microscience, engineering, technology, and medicine series* By: Sergey Edward Lyshevski
Image: http://hello-engineers.blogspot.com/2009/04/mems-fabrication-assembling-and-packing.html

Fabrication Processes



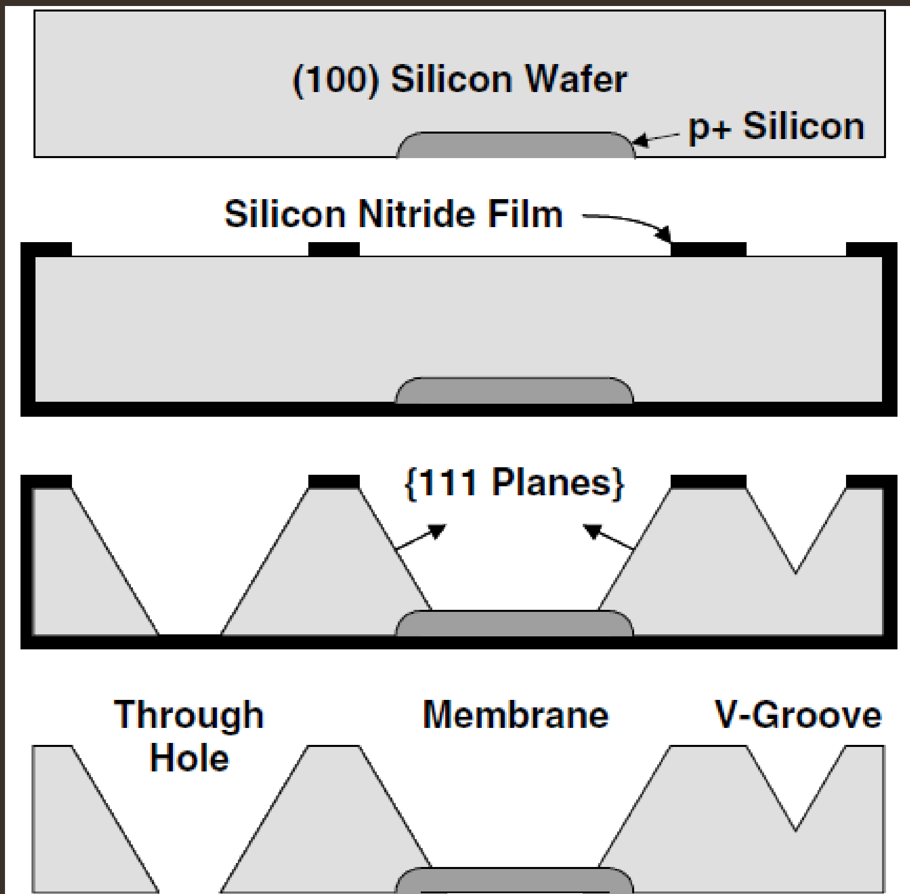
Surface Micromachining and sacrificial layer technique

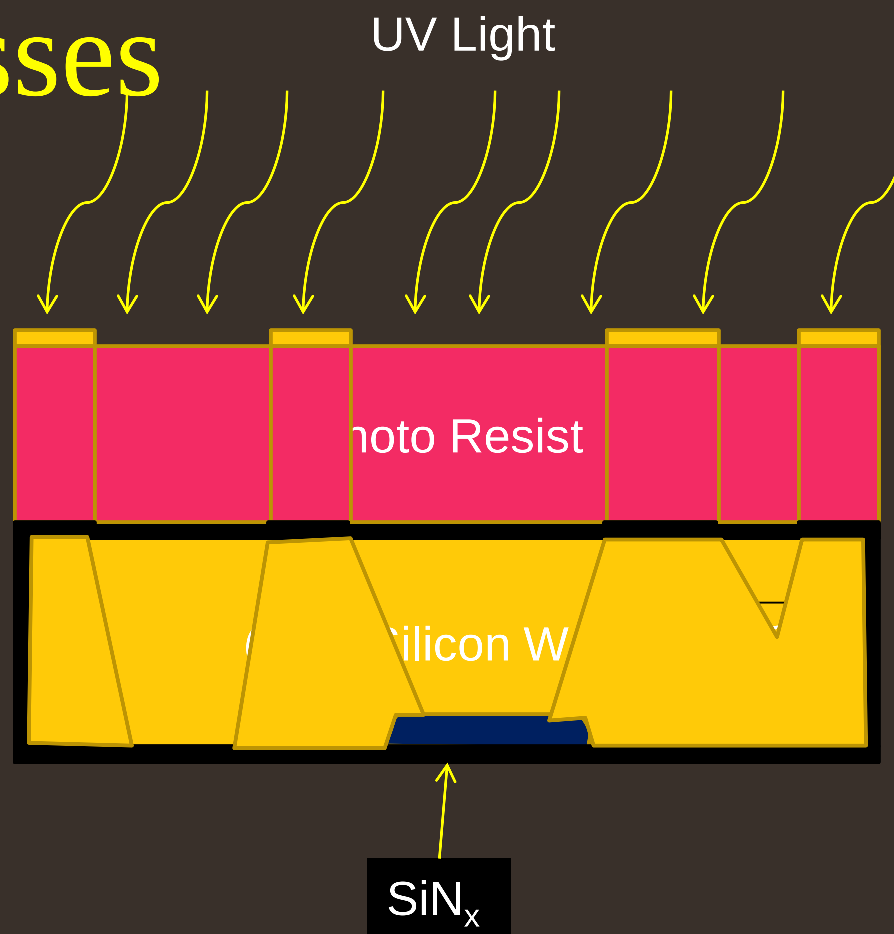


Animated Version

http://iopscience.iop.org/0964-1726/10/6/301/pdf/sm1601.pdf?ejredirect=migration

Fabrication Processes



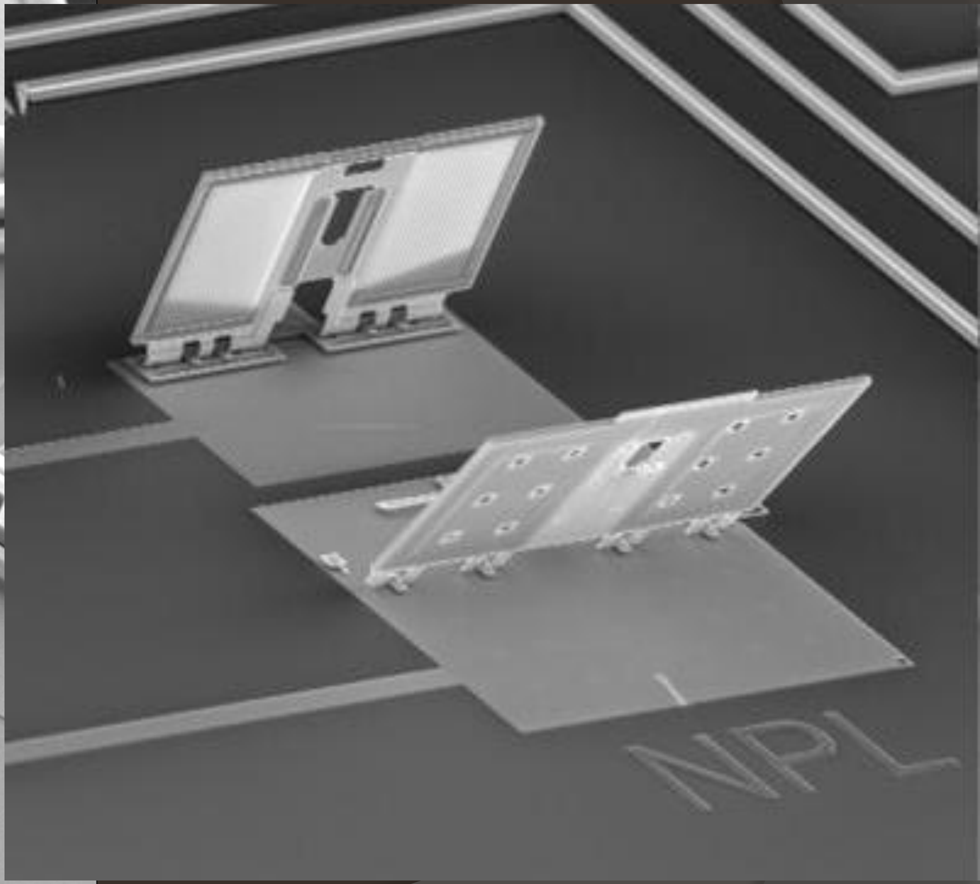


Bulk Micromachining along crystallographic planes

Animated Version

http://iopscience.iop.org/0964-1726/10/6/301/pdf/sm1601.pdf?ejredirect=migration

Fabrication Processes



Left image: http://www.memx.com/
Right Image: http://www.npl.co.uk/science-+-technology/nanoscience/surface-+-nanoanalysis/mems-particle-detector

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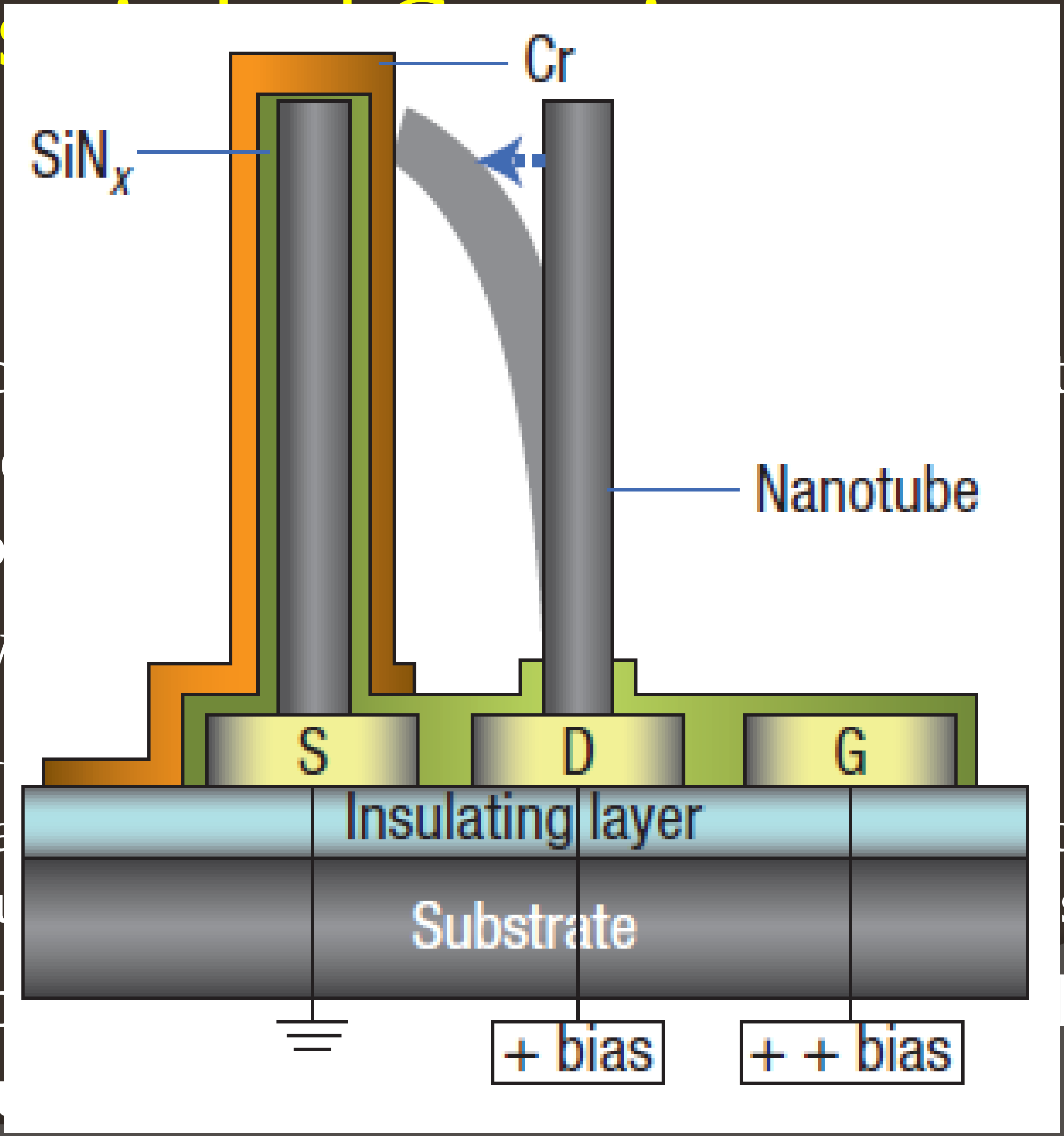
Application of NEMS:
NEM s

- Demand
  - Pushed
  - Researc … tructures
    - Magn
    - Carbo
- NEM sw
  - Vertical
    - mecha … carbon nanot … states
- Impossib … l location of nanot



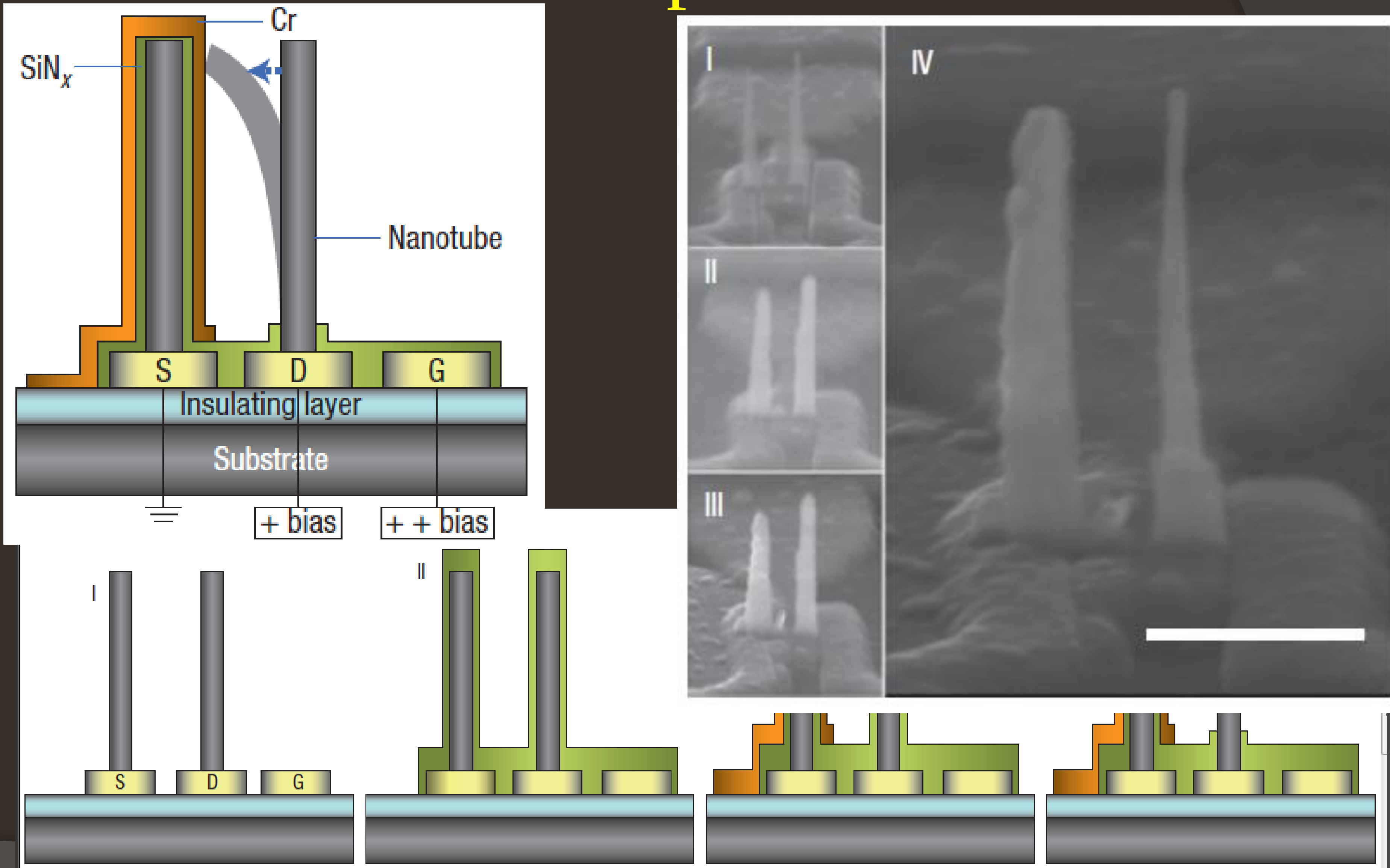
JAE EUN JANG, et. al . "Nanoscale memory cell based on a nanoelectromechanical switched capacitor" Nature Vol 3 January 2008 doi:10.1038/nnano.2007.417

Application of NEMS: NEM switched Capacitor

- Carbon Nanotube Fabrication:
  - Grown with controlled dimensions at pre-defined locations on a silicon substrate
    - Compatible with existing silicon technology
    - Vertical orientation allows for a significant decrease in cell area over conventional devices

JAE EUN JANG, et. al . “Nanoscale memory cell based on a nanoelectromechanical switched capacitor” Nature Vol 3 January 2008 doi:10.1038/nnano.2007.417

Application of NEMS: NEM switched Capacitor



JAE EUN JANG, et. al . “Nanoscale memory cell based on a nanoelectromechanical switched capacitor” Nature Vol 3 January 2008 doi:10.1038/nnano.2007.417

Application of NEMS: NEM switched Capacitor

- Data has been written to the structure
  - Theoretically it is possible to read data with standard dynamic random access memory sensing circuitry
- Simulations have been completed
  - high-k dielectrics instead of SiNx
    - increase the capacitance to the levels needed for dynamic random access memory applications

JAE EUN JANG, et. al . “Nanoscale memory cell based on a nanoelectromechanical switched capacitor” Nature Vol 3 January 2008 doi:10.1038/nnano.2007.417

Application of NEMS: Self Sustaining NEM oscillator

- Sensors based on nanoelectromechanical systems vibrating at high and ultrahigh frequencies
  - capable of levels of performance that surpass those of larger sensors
- NEM devices have achieved unprecedented sensitivity
  - Displacement, mass, force and charge detection
- Passive devices
  - Require external periodic or impulsive stimuli to excite them into resonance
- Novel autonomous and self-sustaining NEM oscillator
  - Generates continuous ultrahigh-frequency signals when powered by a steady d.c. source

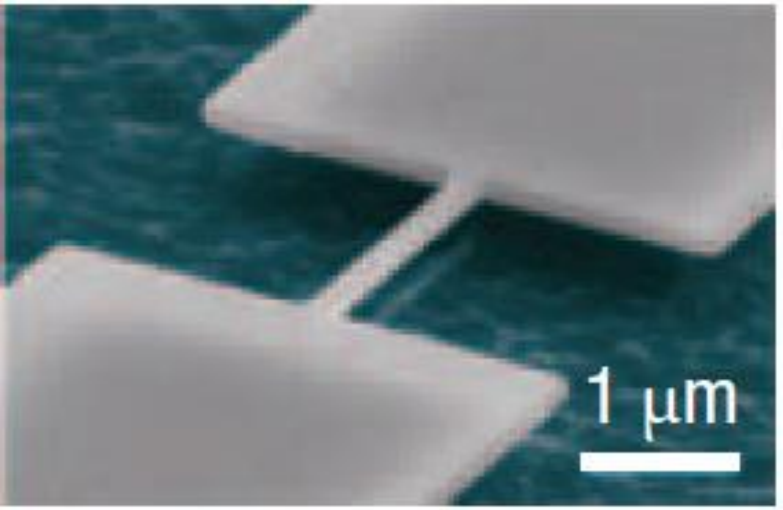
X.L. Feng, et.al. “A Self Sustaining Ultrahigh-frequency nanoelectromechanical oscillator” Nature Vol 3 June 2008 doi:10.1038/nnano.2008.125

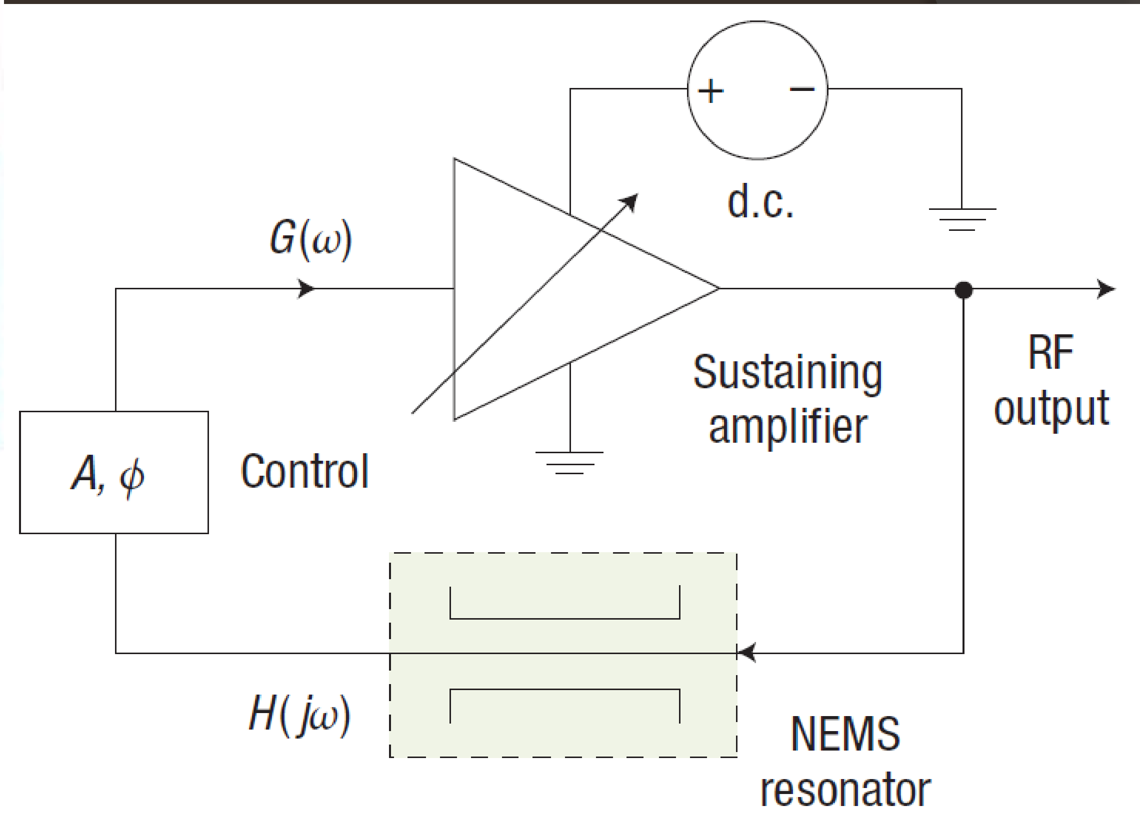
Application of NEMS: Self Sustaining NEM oscillator

- A self-sustaining ultra high frequency NEM oscillator
  - Frequency determining element in the oscillator is a NEM resonator
    - Embedded within a tunable electrical feedback network to generate active and stable self-oscillation
  - Excellent frequency stability
  - Linewidth narrowing and low phase noise performance

X.L. Feng, et.al. "A Self Sustaining Ultrahigh-frequency nanoelectromechanical oscillator" Nature Vol 3 June 2008 doi:10.1038/nnano.2008.125

Application of NEMS: Self Sustaining NEM oscillator





Dc=source voltage to increase the ac current volatage
Amplifier is amplifing the voltage from the phase controlled current
The resonator is filtering the current, allowing for only a certain freq to go through
H(jw) is a freq response
Control changes the phase

X.L. Feng, et.al. "A Self Sustaining Ultrahigh-frequency nanoelectromechanical oscillator" Nature Vol 3 June 2008 doi:10.1038/nnano.2008.125

Application of NEMS: Self Sustaining NEM oscillator

- Ultrahighfrequency oscillators provide a comparatively simple means for implementing a wide variety of practical sensing applications
- Opportunities for nanomechanical frequency control, timing and synchronization

X.L. Feng, et.al. “A Self Sustaining Ultrahigh-frequency nanoelectromechanical oscillator” Nature Vol 3 June 2008 doi:10.1038/nnano.2008.125

Application of NEMS: NEM Tunable Laser

- Tuning the frequency of an oscillator is of critical importance
  - Fundamental building block for many systems
    - Mechanical or Electronic
- Highly inadequate in optical oscillators
  - Particularly in semiconductor laser diodes
- Limitations in tuning a laser frequency (or wavelength)
  - include the tuning range and the speed of tuning
    - Typically milliseconds or slower
- Tuning is often not continuous
  - Requires complex synchronization of several electrical control signals

M.C.Y. Huang et.al "A Nanoelectromechanical tunable laser" Nature Vol 2 March 2008 doi:10.1038/nphoton.2008.3

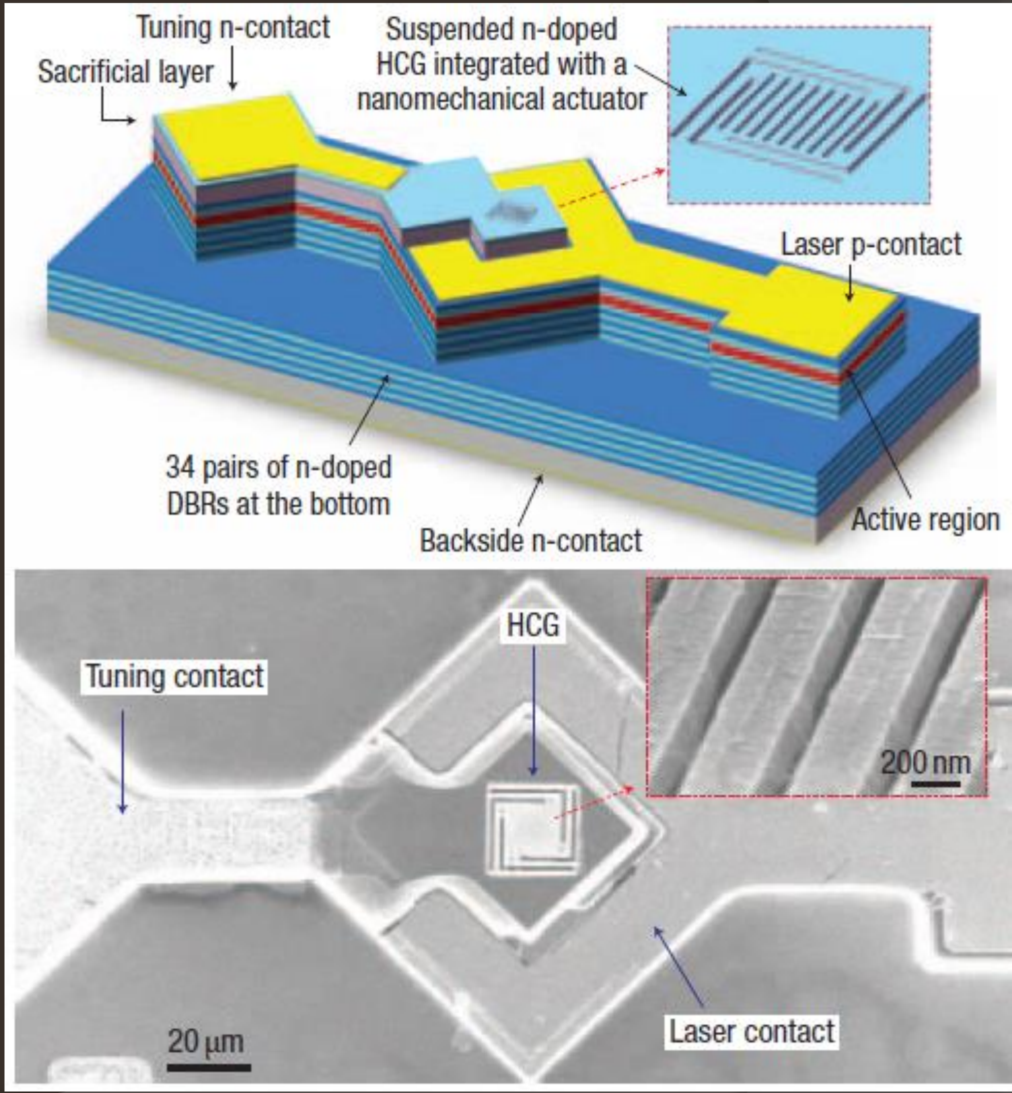
Application of NEMS: NEM Tunable Laser

- Nanoelectromechanical Tunable Laser
  - Lightweight NEM mirror based on a single-layer, high contrast grating (HCG)
    - Enables a drastic reduction of the mirror mass
    - Increases the mechanical resonant frequency
    - Increases the tuning speed
  - Allows a wavelength-tunable light source
    - Potential switching speeds of the order of tens of nanoseconds
    - Various new areas of practical application
      - bio- or chemical sensing, chip-scale atomic clocks and projection displays

M.C.Y. Huang et.al "A Nanoelectromechanical tunable laser" Nature Vol 2 March 2008 doi:10.1038/nphoton.2008.3

Application of NEMS: NEM Tunable Laser

- Schematic of the electrostatic-actuated NEMO-tunable VCSEL
- High Contrast Grating (HCG) is freely suspended above a variable air gap
  - Supported by a nanomechanical structure
    - cantilever
    - Bridge
    - folded beam
    - membrane



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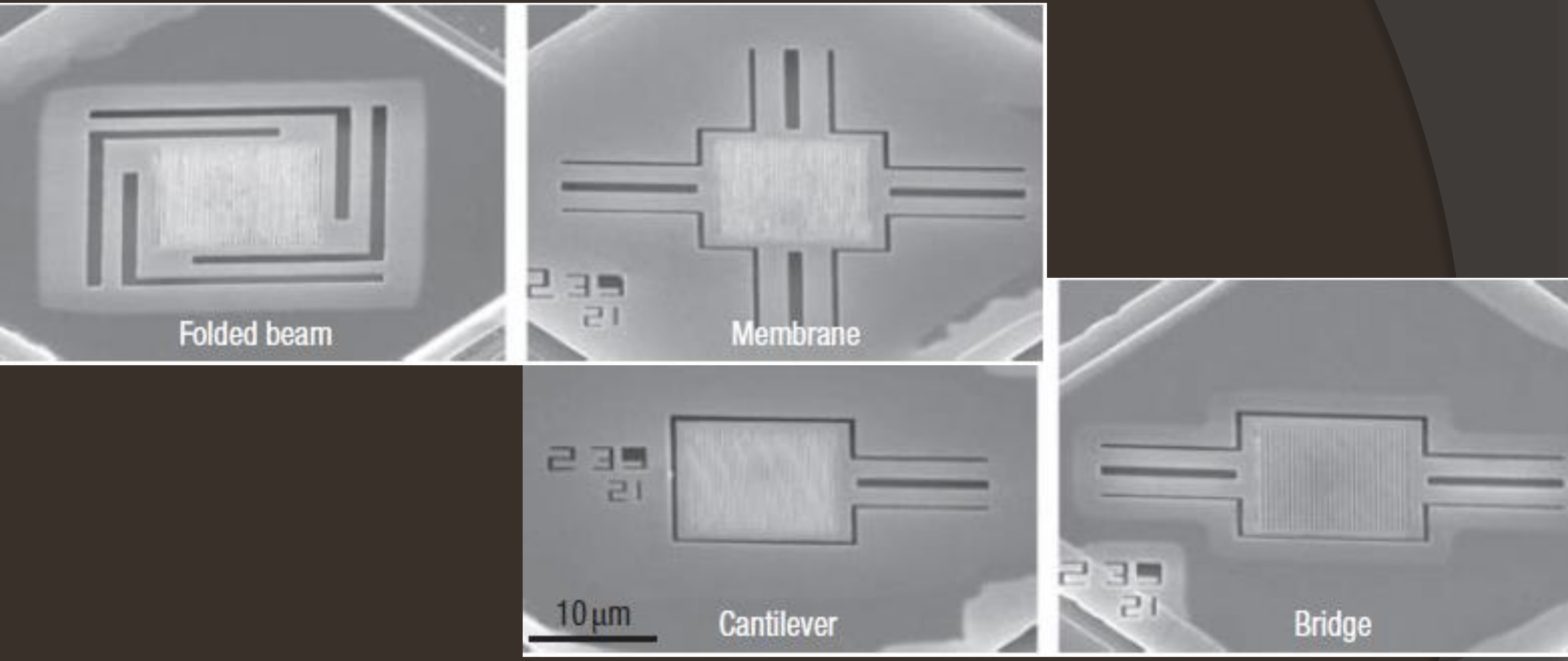
Application of NEMS: NEM Tunable Laser



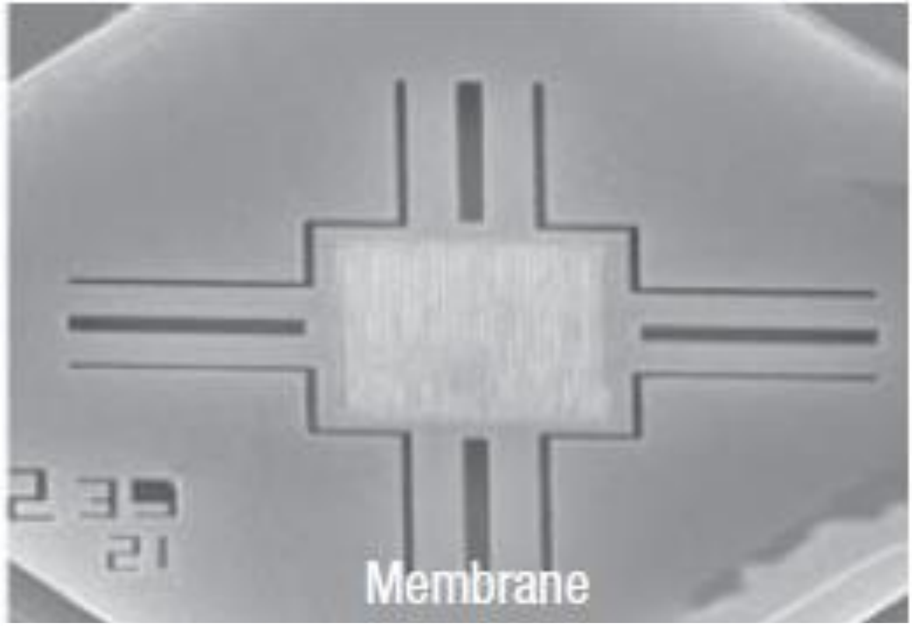
- Integration of the freely suspended HCG mirror with a variety of nanomechanical actuators that can be designed for different values of mechanical stiffness

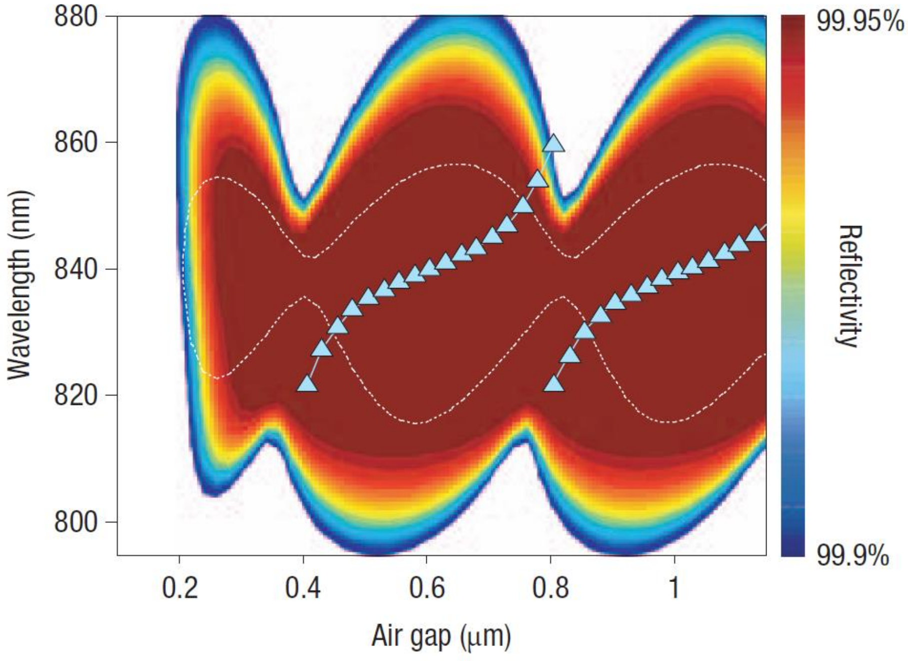
M.C.Y. Huang et.al "A Nanoelectromechanical tunable laser" Nature Vol 2 March 2008 doi:10.1038/nphoton.2008.3

Application of NEMS: NEM Tunable Laser

- Wavelength tuning is a function of the air-gap thickness below the NEM suspended HCG

- Blue Triangle Curves
  - Calculated laser emission wavelength (Wavelength)
- Color-coded Contour
  - HCG mirror reflection bandwidth (Reflectivity)





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Conclusion

- Nanoelectromechanical systems (NEMS) are used to measure extremely small masses and forces
- Measurements rely on a resonator oscillating at a very stable frequency so that a small change in the resonant frequency caused by, for example, a molecule landing on the resonator, can be readily detected
- Self-sustaining NEMS oscillators enable a wide spectrum of applications
  - Offer significant advantage over other frequency-shift detection as no source of external excitation is required
  - Yields an immense simplification of design that is crucial for next-generation, highly multiplexed sensing applications involving large arrays of devices

Conclusion

- A viable structure and fabrication process for a NEM memory cell for ultra-large-scale integrated memory applications
  - Proposed write–read scheme is similar to that of a conventional DRAM
    - Conventional sensing schemes
    - CMOS circuits
    - High integration densities due to the vertical nature of the NEM capacitor
- High-speed nanoelectromechanical tunable laser
  - Monolithically integrating a lightweight, single-layer HCG as the movable top mirror
  - results in a drastic reduction in mass
  - substantial improvement in tuning speed
  - Results in an optical mirror design for the next generation of NEMO-tunable devices

Any Questions!

I Appreciate for Your Attention Kindly

www.Fooladvand.tk