Lecture 14: Micro / Nano Electro Mechanical Systems (MEMS/NEMS)

Tuesday, November 28, 2017

Introduction: Much of the fascination and speculation surrounding Nanotechnology has been centered around the notion of nano-sized machines, particularly autonomous nano-sized "nano-bots." Closer to the current reality, the design, fabrication and testing of micro-electromechanical systems (MEMS) and Nano-Electro-mechanical systems (NEMS) have made some impressive progress. As Feynman pointed out in his famous lecture on nano-technology, due to both classical and quantum effects, the behavior of such tiny machines may be unique compared to their macroscopic counterparts. Below, an example of the mysterious "Casimir" force, which is a manifestation of the quantization of the electromagnetic field and the associated vacuum field fluctuations, was measured quite precisely using a tiny torsion balance (figures 1**A** and 1**B**). The force as a function of distance, shown in figure 1**C**, exceeded the power-law dependence of the electrostatic force, but is consistent with what is considered the first macroscopic measurement of the Casimir force (images from the journal *Science*[1]). The manufacture and application of such micro- to nano-scale machines is now a widespread and rapidly growing enterprise.

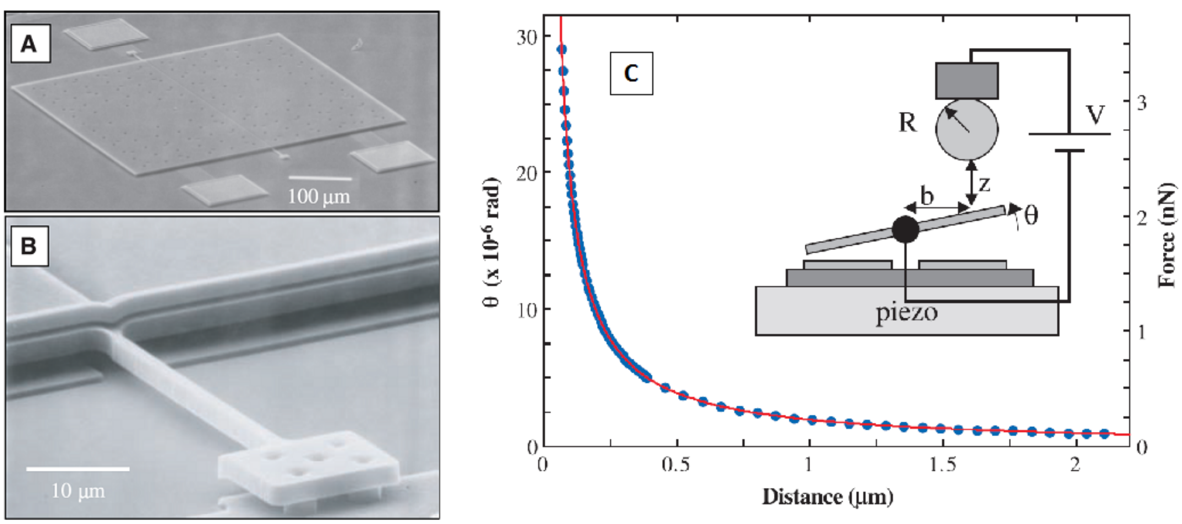

Figure 1: Nano-fabricated torsion balance **A** and **B** , designed to precisely measure the deflection due to the combined electrostatic and Casimir forces, and force vs. distance curve compared to theory **C**. From the journal *Science*[1].

Top-down nanofabrication: A MEM or NEM is usually an electrically actuated machine fabricated by top-down methods such as optical and electron beam lithography. The figure below shows a typical optical lithographic process. A substrate is coated with a photosensitive material, known as photoresist. A mask is illuminated by radiation of a frequency which the photoresist is sensitive to. Areas of the photoresist which are illuminated change their properties with respect to the un-illuminated or shadowed areas, and will generally be more conducive (resistant) to etching, for so-called positive (negative) photoresists. This process is illustrated in figure 2, and can be repeated layer by layer to build up three dimensional structures. The process for NEMS will generally be similar, except an electron-beam driven by a computer is used to modify the photoresist in the prescribed pattern, and a mask is not necessary. MEMS typically are in the micron scale feature size, while NEMS may have features down to the few nanometer scale.

[1] H.B. Chan, *et. al. Science* **291** 1941 (2001).

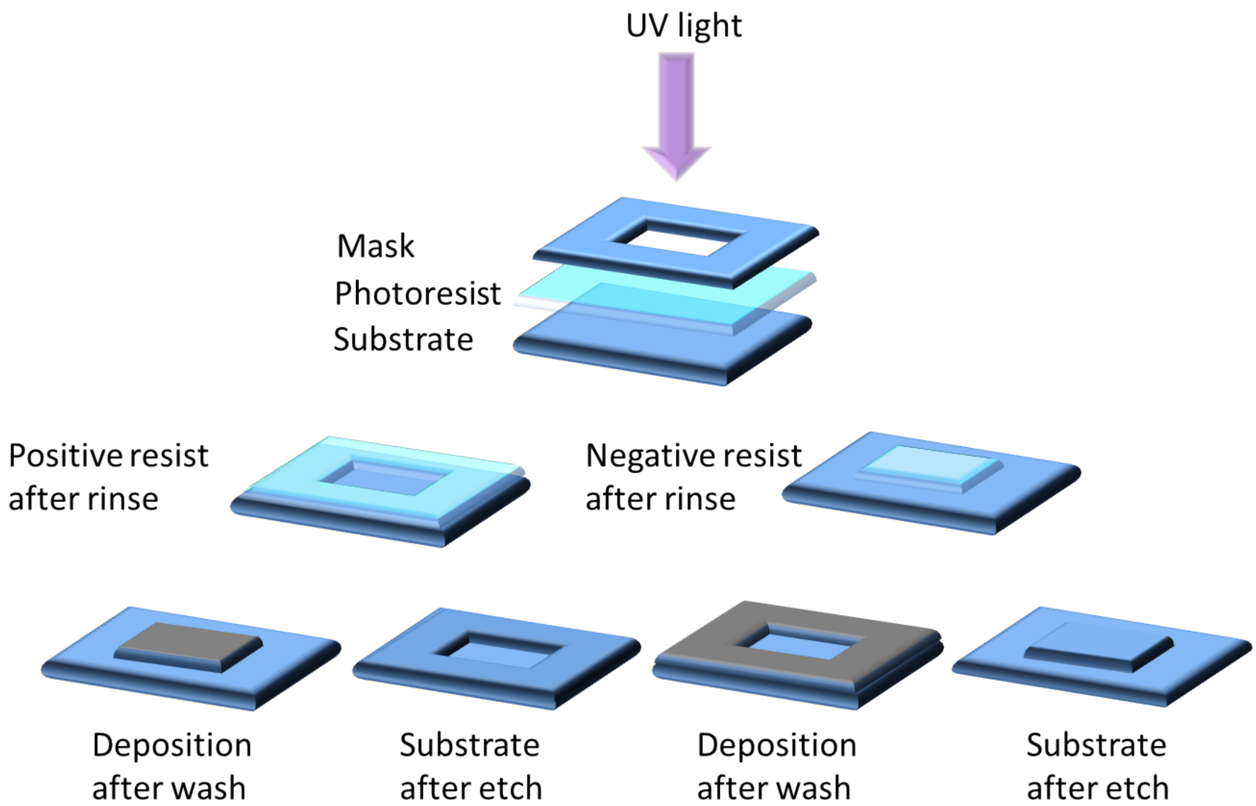

Figure 2: Lithography process illustrating common top-down approach to fabricating typical MEMS: Photoresist is illuminated through mask, the photoresist is developed, positive (negative) resist is removed (persists) according to the mask pattern. Materials can be addeded or removed by deposition (etching) to build up complex structures (see *e.g.* http://www.memsnet.org).

Examples of such nano-fabricated NEMS are shown in figure 3 below, where three terminal devices were fabricated by successive lithography and etching steps[2], to form electrically-driven nano-mechanical oscillators with very high resonant frequencies and high Q:

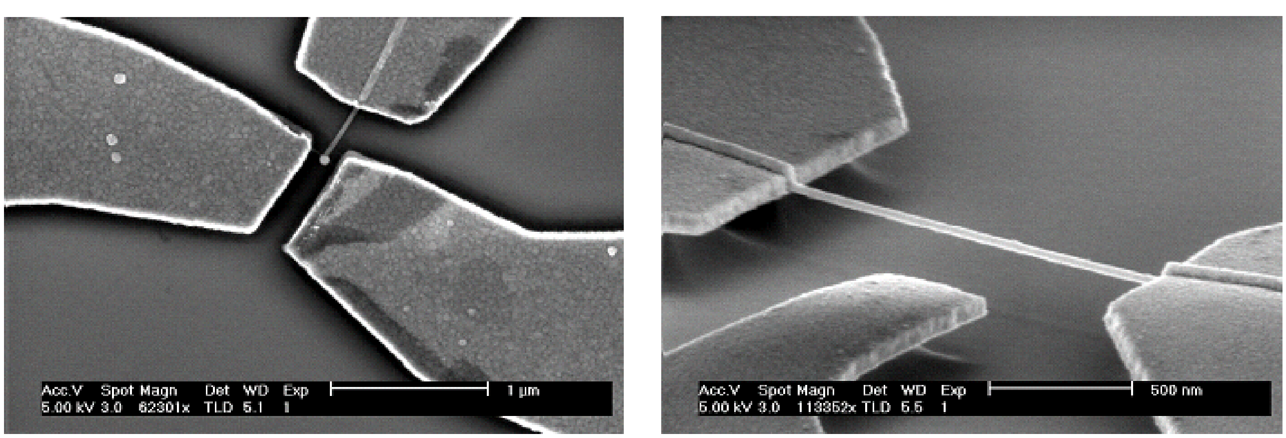

Figure 3: Lithographically defined three-terminal NEMS (From *Physical Review Focus*), these devices have resonant frequencies in the 10-100's of MHz range and exceedingly high Q.

[2]from *Physical Review Focus*

Oscillator model: Much of the interest in MEMS/NEMS is in the development of sensors. Applications are varied, but a major theme is to optimize the dynamical properties of MEMS/NEMS to exploit the change in the dynamical properties as the MEMS/NEMS interact with the enviroment. NEMS often take the form of a mechanical oscillator, *e.g.* a simple nano-sized beam. From the dynamical point of view, we saw that the beam equation is seperable and that the time dependence follows a second order differential equation, that is the damped harmonic oscillator equation. Thus an appropriate model for discussing the dynamical properties of NEMS/MEMS is the mass on a spring as shown in figure 4 below:

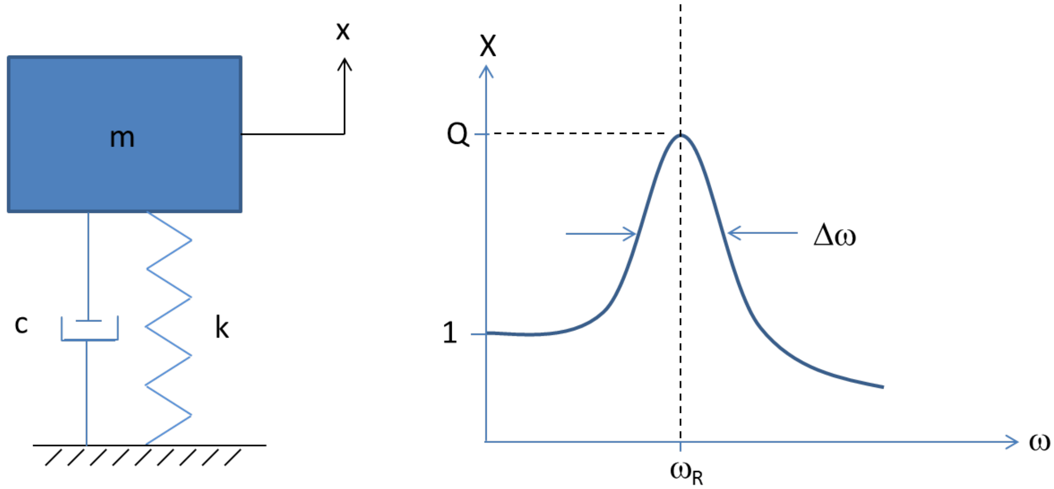

Figure 4: Damped harmonic oscillator is an appropriate model for the dynamical behavior of MEMS/NEMS. The important dynamical parameters are the resonant frequency, ω_R and Q-factor, as indicated above in the amplitude response curve, where $Q \approx \omega_R/\Delta\omega$ represents the system amplification on resonance.

We saw in connection with scanning probe microscopy that the amplitude response function takes the form:

$$\frac{A(\omega)}{A_o} = \frac{1}{\omega_o^2 - \omega^2 + i2\beta\omega} = \frac{1}{M_{eff}(\omega_o^2 - \omega^2 + i\omega\omega_o/Q)} \qquad \text{with} \qquad Q = \frac{\omega_R}{2\beta}$$

Where the second form explicitly takes into account that the mass is an effective mass, as would be ω_o^2, k *etc*, since we are actually dealing with a much more complex system than the dynamical model suggests. When the MEMS/NEMS oscillator interacts with it's surroundings, it is very often a mechanism to dissipate energy. Thus the final form above, with its' explicit dependence on Q, is an appropriate form, as it eliminates the damping β in favor of Q. Let us imagine we can partition the damping into two parts, an intrinisic damping and an external or extrinsic damping not associated with the oscillator itself but with it's interaction with the environment:

$$Q = \frac{\omega_R}{2(\beta_{\text{intrinsic}} + \Delta\beta_{\text{external}})} \qquad \text{or} \qquad \frac{1}{Q} = \frac{2\beta_{\text{intrinsic}}}{\omega_R} + \frac{2\Delta\beta_{\text{external}}}{\omega_R} = \frac{1}{Q_o} + \frac{1}{Q_{\text{ext}}}$$

This form readily shows the system sensitivity is dependent on Q_o, as the higher this is, the more sensitive the system will become to any external dissipation represented by Q_{ext}. This is the basis for applying NEMS/MEMS as ultra-sensitive detectors. For collisions between the NEMS/MEMS and a single or few molecules[3],

$$Q_{\text{coll}} \approx M_{eff}\omega_o \frac{v}{PA} \qquad \text{where} \qquad v = \sqrt{K_B T/m} \quad \text{is the thermal velocity and} \quad P \quad \text{is pressure}$$

it has been shown that $Q_{\text{coll}} \sim \frac{1}{P}$ for $l > l_{\text{MFP}}$, that is, MEMS/NEMS larger than the mean-free path, and $Q_{\text{coll}} \sim \frac{1}{P^{1/2}}$ for $l < l_{\text{MFP}}$, placing increasingly higher demands on Q_o to achieve single molecule sensitivity for ultra-small NEMS/MEMS. Higher Q_o is therefore an important goal for NEMS/MEMS sensing applications.

[3]K.L. Ekinci, *et. al. Rev. Sci. Inst.* **76** 061101 (2005).

Actuation of NEMS/MEMS: Actuating the MEM/NEM can be facilitated in a number of ways. Most often this is done electrostatically, or capacitively, by incorporating the MEMS/NEMS into some sort of three-terminal device, as shown in figures 3 and 5. This type of configuration can also sense the displacement of the NEMS/MEMS. For ultra-small NEMS, single electron charging effects may become important, including Couloumb blockade, *etc.*

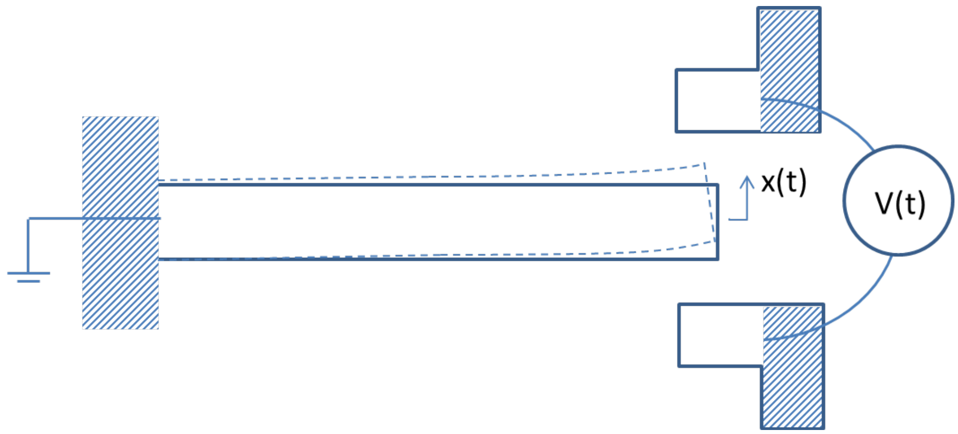

Figure 5: Capacitive or electrostatic actuation of NEM/MEM. The mechanical component is integrated into a three terminal device, and a time varying electric field produces a time-varying deflection, which can drive the NEM/MEM near a resonance.

While electrostatic actuation is common for NEMS, for MEMS, more motion or force may be required, therefore piezo-electric actuation is often implemented: If the device material is sufficienty piezo-electric, applying contacts and electric fields across these will deform the material acording to $\Delta l/l = -d_{31}|\mathbf{E}|$, where d_{31} is the tensor element which couples the transverse field to the longitudinal length through Poisson's ratio. One scheme for piezo-electric actuation of a beam is shown in figure 4, this is a piezoelectric transducer known as a bi-morph, made of highly piezoelectric materials which can produce large deformations for modest fields. These are normally used for actuators, but if the voltage is periodic and driven near the resonant frequency of the structure, this could drive the MEMS/NEMS into resonance. Piezo electrics may also detect the motion of the system through microphonic pick-up.

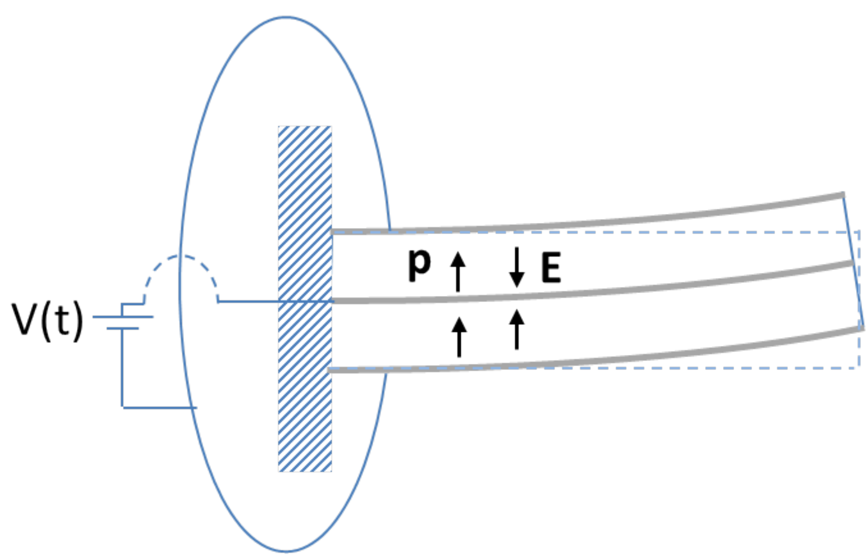

Figure 6: Piezo-electric actuator, wherein a buried electrode is used to create opposing fields, while the materials piezo-electric dipole $\mathbf{p}$ is constant. Thus an opposing torque $\tau = -\mathbf{p} \cdot \mathbf{E}$ is generated on either side of the center electrode, which causes an elongation / shrinkage $\pm\Delta l$ of the piezo-electric material on the opposite sides, which in turn produces a lateral deformation.

Yet another method of actuating MEMS/NEMS is using a magneto-motive force, as sketched in the figure 7 below. Here an alternating magnetic field $\mathbf{B}(t)$ or a time-varying current $I(t)$ can produce a driving force through the $v \times \mathbf{B}$ force, which may be used to actuate the MEMS/NEMS system.

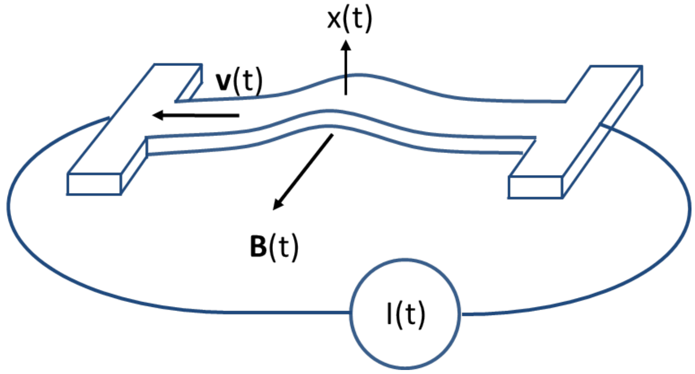

Figure 7: Magneto-motive actuation of MEM. A current flowing through the MEM is creates a drift velocity $\mathbf{v}$, either modulating a magnetic field $\mathbf{B}$, or the current $I(t)$, will produce a time-varying force $\propto \mathbf{v} \times \mathbf{B}$ in the x-direction, which can drive the MEM at it's resonant frequency.

Sensing methods for NEMS/MEMS: Once the NEMS/MEMS is created, and we have devised a way to actuate it, we still need to be able to detect the oscillation, preferably with high-sensitivity. Electrostatic, electro-motive and piezoelectric actuation inherently allows sensing the position of the MEMS/NEMS as well. However, there are instances where an independent measure of displacement is desired. Optical methods are one way. Below is show a linearly polarized beam sent through a polarizing beam splitter which slightly displaces one polarization from the other. When these two beams are reflected off the NEMS/MEMS surface, if the surface has moved, they will travel slightly different path lengths. When the two beams are recombined, the offset is undone, but the relative phases remain. Thus, the polarization is rotated by some anlge θ, which can be detected using a wave plate. A similar optical method which relies on interference has also been demonstrated to detect very small displacements.

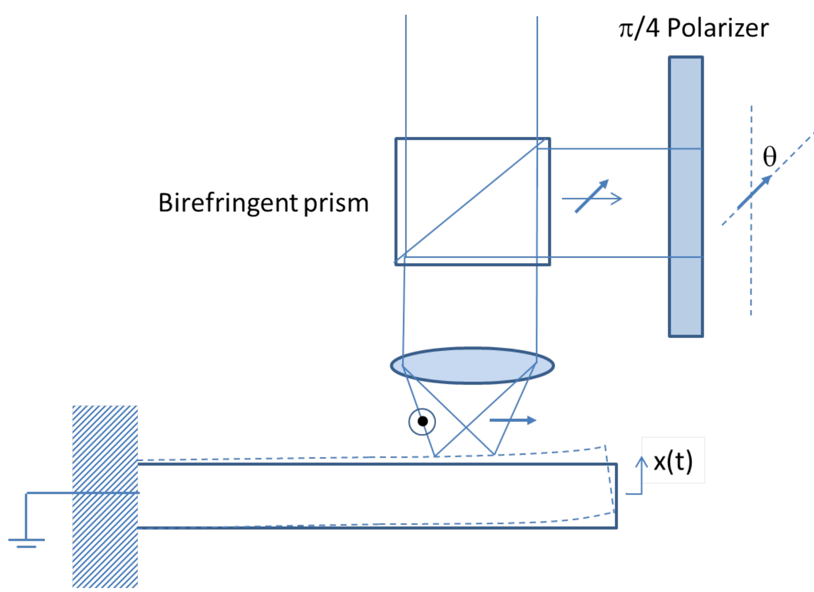

Figure 8: Optical method to detect very small discplacements, by using a Wollaston prism, which offsets two beams based on their polarization. When the reflections are recombined, the polarization is rotated and can be detected by a linear polarizer.

Applications of NEMS/MEMS:

Sensing Single Atoms or Molecules: A goal of NEMS is single atom or single molecule sensitivity. As reported in the journal *Nano Letters*, Xenon atoms impinging on a NEMS resonanator with $\omega_R \sim 190MHz$ were shown to systematically shift the resonant frequency, with a sensitivity in the 100's of zepto-gram range. An increase in the noise spectrum in the presence of Xe adsorbates was deduced to originate from surface diffusion of the Xe atoms, as shown in the figure. The figures below shows an artistists conception of an atomic beam impinging on the NEMS resonator, and atoms moving along the surface of the nano-sized beam[4] From the same reference, figure 10 below shows the measured response and the frequency shift versus adsorbed mass (the inset shows an SEM of the NEMS).

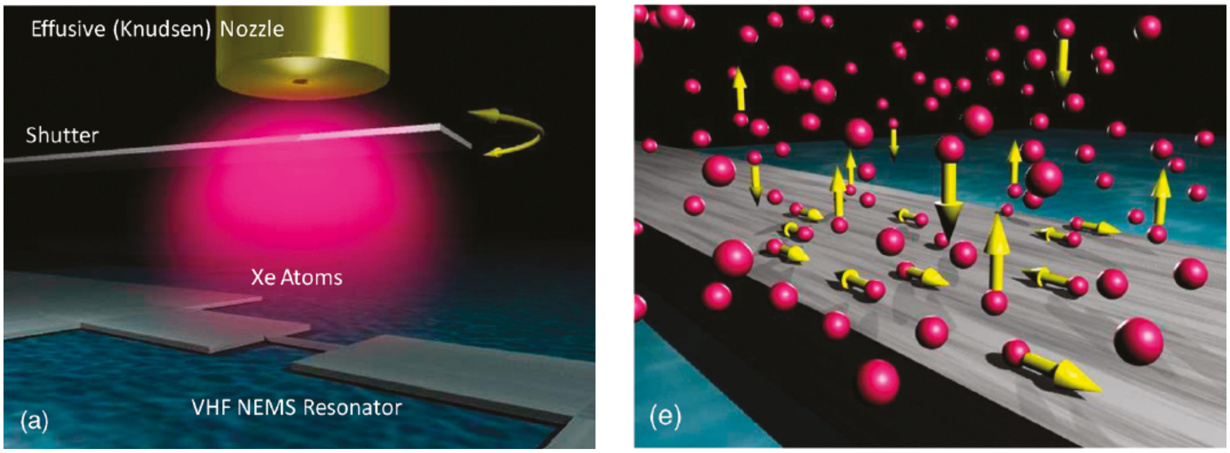

Figure 9: (left) Xenon atomic beam impinges on NEMS resonator, (right) artists depiction of surface adsorption and diffusion on NEMS surface. It was found that surface diffusion of Xe atoms induces a measurable increase in the noise spectrum of the NEMS (From *Nano Letters*[6]).

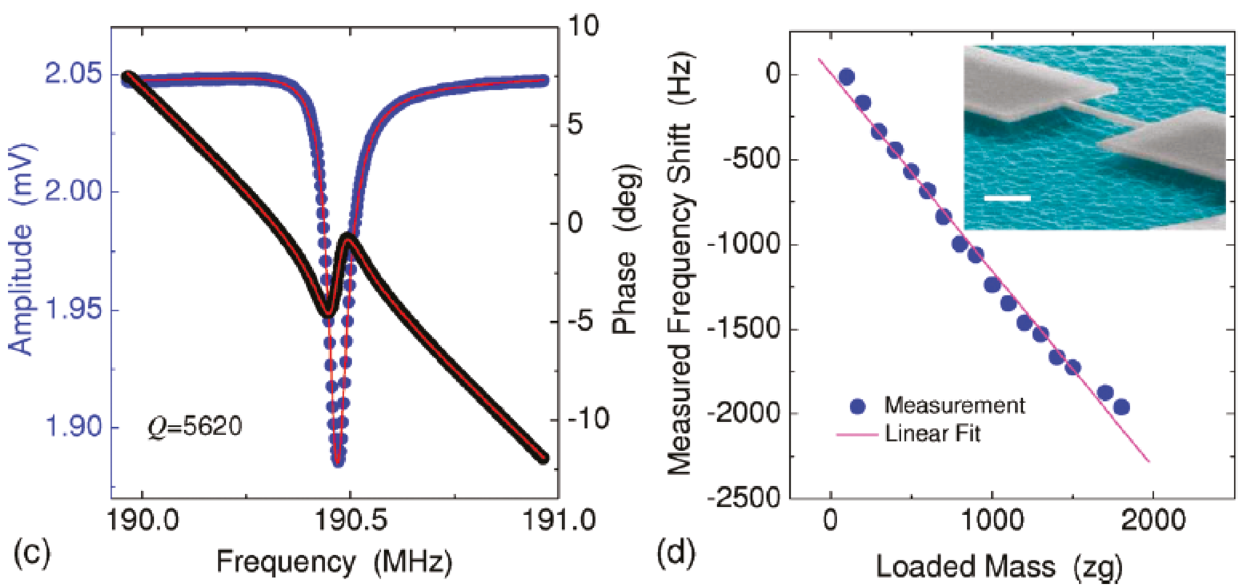

Figure 10: (left) Frequency response of NEMS resonator, (right) frequency shift of NEMS resonator as a function of adsorbed mass. Inset shows SEM image of NEMS resonator (From *Nano Letters*[6]).

[4]from Y.T. Yang *et. al.* *Nano Letters* **11** 1753 (2011).

Sensing the Casimir Force: As shown in the introduction, MEMS can have very high sensititivity and were used to measure a somewhat mysterious force due to fluctuations of the vacuum field, the Casimir force. The origins of this force are described here briefly: Just as the energy of particles of finite mass are quantized, and the manifestations of quantum mechanics become apparent on length scales commensurate with the deBroglie wavelength, the energies of massless particles such as the photon are also quantized, and manifest themselves on length scales commensurate with the wavelength and energies close to the single photon energy. The procedure for determining the quanta of energy and the allowed states is somewhat different than the procedures we used to calculate the energies of a particle of finite mass, but eventually the problem takes the form of the quantum harmonic oscillator discussed previously. The procedure is known as the "second-quantization", and in the context of the photon it refers to quantizing the electromagnetic field. The procedure follows from quantizing the vector potential $\mathbf{A}$, from which both electric and magnetic fields can be derived. After this procedure, wherein appropriate operators are defined, we may write the Hamiltonian for the electromagnetic field and it's Eigenfunctions in the following form:

$$\widehat{H} = \sum_m \hbar\omega_m \left(\hat{a}_m \hat{a}_m^\dagger + 1/2\right) \quad \text{with Eigenfunctions } |n\rangle \quad \text{and Eigenenergies } E_n = \hbar\omega_m(n + 1/2)$$

the state-vectors $|n\rangle$ represent the wavefunction of the electromagnetic field in a basis known as the "number representation", the name aludes to the fact that the number n is the number of quanta of $\hbar\omega_m$ (which we call "photons") in the m^{th}-mode of the electromagnetic field. The concept of a basis is one familiar in the study of linear systems, boundary value problems and group theory. In the state-vector picture, it can be imagined as a coordinate transformation. If we are interested in only the energy Eigenvalues, the details of the choice of basis will not be important here.

If we now look at the cavity formed by two reflecting walls, as shown in the figure below:

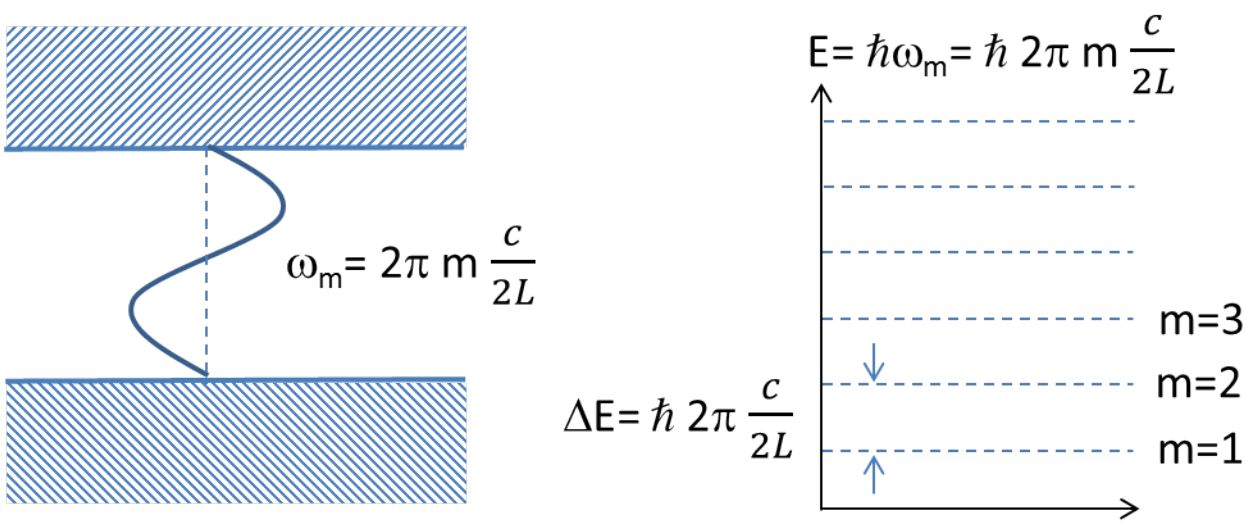

Figure 11: Defining the modes of a simple planar cavity, each mode must satisfy Maxwell's equations and the boundary conditions at a reflective surface, thus only modes with nodes at each wall are allowed. Sketched is the $m = 2$ mode. The energy spacings of these modes are shown on the righthand side of the figure.

we see that only modes with an integral number of 1/2-wavelengths may be supported. The energy in each of these modes will depend on the number of photons n in each mode. The Casimir force orginates from the fact that even if the number of photons $n = 0$, there remains a non-zero energy $\hbar\omega_m/2$ for every mode m. The lower limit on these modes in turn depends on the spacing L of the cavity walls. There is no upper limit, however, which would seem to point to an inconsistency in the theory, as the sum $\sum \hbar\omega_m/2$ would appear to be infinite. This difficulty, which is not entirely put to rest, is often avoided by simply calculating the number of modes per unit volume per unit energy. In doing this, we see that the spacing of these modes, and therefore the energy density, depends on the size of the cavity. If we imagine the universe is in an unimaginably large box, the lower limit of energy and the energy spacing of the modes in this box would approach zero, and therefore we can definitively say:

$$\rho_{\text{free space}} = \frac{\sum \frac{1}{2}\hbar\omega_m}{V}\bigg|_{\text{free space}} \quad > \quad \rho_{\text{cavity}} = \frac{\sum \frac{1}{2}\hbar\omega_m}{V}\bigg|_{\text{cavity}}$$

we just need to be careful how we define the volume and over what range of energies we take the sum. That is, the number of modes per unit volume, per unit energy, and thus the zero-point energy density ρ of free space should be larger than in the cavity, where the number of modes are restricted. This is the origin of the Casimir force. Since forces can be generated by changes in potential, we can imagine that the variation in zero-point energy density which appears near very small cavities, may produce a noticeable force. This is the case for the Casimir force, which can be calculated as:

$$F_z = -\frac{\partial U}{\partial z} \propto \Delta\rho_{\text{free space - cavity}} = -\frac{\pi^3}{360}\frac{Rhc}{z^3}$$

Where the final form is an analytical expression for a sphere over a planar reflecting surface[5]. This is precisely the form used by Capasso *et. al.* in interpreting their measurements made using a MEMS torsional balance, depicted in the figure below (from the journal *Science*[2]). A dielectric sphere was attached to a rod which could be actuated by a piezoelectric transducer, to precisely control the distance of the sphere to the MEMS detector. The above form for the Casimir force was validated in the data shown in figure 1.

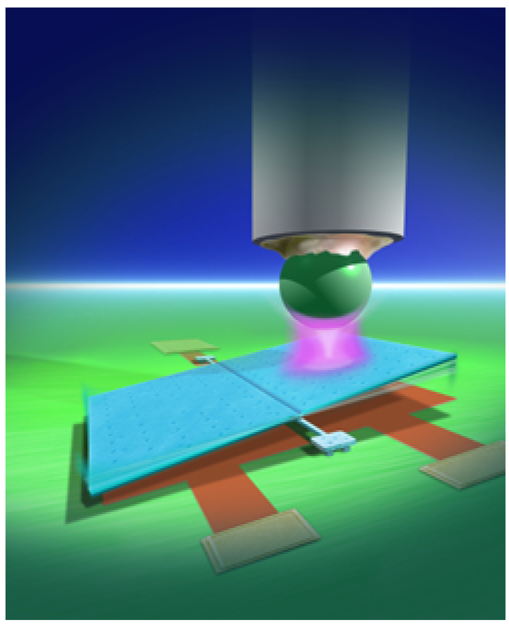

Figure 12: An artists' conception of the experiment of Capasso *et. al.* which used a MEM to measure the distance dependence of the Casimir force between the MEM and a sphere, brought close to the surface by a nano-metric actuator (From *Science* **291**, 1941 (2001)).

[5]H.J. De Los Santos, *Proc. IEEE* **91** 1907 (2003).