Displacement Detection Using Quantum Mechanical Electron Tunneling in Micro and Nano-electro-mechanical Systems

D. Taylor*, and K.L. Ekinci**

*Physics Dept., Boston University, Boston MA 02215, USA, drtaylor@bu.edu
**Aerospace and Mechanical Eng. Dept., Boston University, Boston MA, 02215, ekinci@bu.edu

ABSTRACT

Here, we investigate the applicability of quantum mechanical electron tunneling to displacement sensing in micro and nano-electro-mechanical systems (MEMS and NEMS). Our experiments were performed using an ultrahigh vacuum (UHV) scanning tunneling microscope (STM). A micro-scale silicon nitride membrane with clamped boundary conditions was fabricated using standard lithographic techniques. The STM tip was then brought into tunneling range over the center of the membrane. Dynamic motion of the device was detected in the tunnel current and measurements of the electromechanical response of the device were taken. In a second set of measurements, the tunnel bias between the membrane surface and the STM tip was modulated at a selected frequency to produce a signal at the "mixed down" or difference frequency — thus avoiding attenuation due to the amplifier. Finally, the sensitivity limits of this technique are discussed for displacement detection in NEMS.

Keywords: microelectromechanical systems (MEMS) nanoelectromechanical systems (NEMS), scanning tunneling microscopy, displacement detection

1 INTRODUCTION

Micro-electro-mechanical systems (MEMS) and, more recently, nano-electromechanical systems[1] (NEMS) are emerging as candidates for a number of important technological applications — such as ultra-fast actuators, sensors, and high frequency signal processing components. Finding precise methods for characterizing the electromechanical behavior of MEMS and in particular NEMS, however, remains a challenge.

Quantum mechanical tunneling of electrons between two metallic surfaces — with its strong dependence on the tunnel gap — has been shown to be a suitable method for studying displacements at this length scale. Displacement detection using a scanning tunneling microscope (STM) has been demonstrated in a number of micro-systems such as accelerometers[2],[3] and magnetometers[4]. Our experiment utilizes electron tunneling to measure the resonance frequency, $\omega_0 / 2\pi$, and the quality (Q) factors of a MEMS device. In the first set of measurements, the STM was used to detect the motion of this device *directly* in the vicinity of $\omega_0 / 2\pi$. In the second set of measurements, we made use of the inherent non-linearity in the tunneling current across the tunnel junction. The tunnel current signal was "mixed down" by modulating the potential difference between the STM tip and the device. Measurements made at the difference frequency exhibited less attenuation from the amplifier.

These results provide information about the specifics of electromechanical resonances in MEMS and NEMS and form a basis for future investigations of the mechanical properties of micro-scale and nanoscale devices using electron tunneling.

2 DEVICE FABRICATION

Now, we turn to a detailed description of the experimental procedure. We first illustrate the method for fabrication of a thin single crystal silicon nitride structure.

The fabrication procedure is illustrated in Figure 1 (a-g). The starting material for device fabrication is a 125-μm-thick undoped silicon (100) wafer, coated on both sides with an LPCVD grown silicon nitride (Si_3N_4). The Si_3N_4 thickness is 300 nm. Fabrication begins by defining an area approximately 120 μm^2 using electron beam lithography. Reactive ion etching is then performed with a plasma of He and SF_6 at a pressure of 300 mTorr with respective flow rates of 21 sccm and 13 sccm and a microwave power of 100 W. The etch rate under these conditions is ~5 nm/s. The vertical etch removes the Si_3N_4 layer exposing the Si. A subsequent wet etch in potassium hydroxide (KOH) dissolves the Si preferentially along the (100) plane, at a 57° angle to the (111) plane, with high selectivity. The wet etch terminates at the Si_3N_4 device layer to form a 300 nm thick membrane with clamped boundary conditions. Additional lithography is then performed on the device layer to prepare the sample for analysis in the STM. Metal contacts of layered Cr and Au are deposited with respective thicknesses of 7 nm and 25 nm.

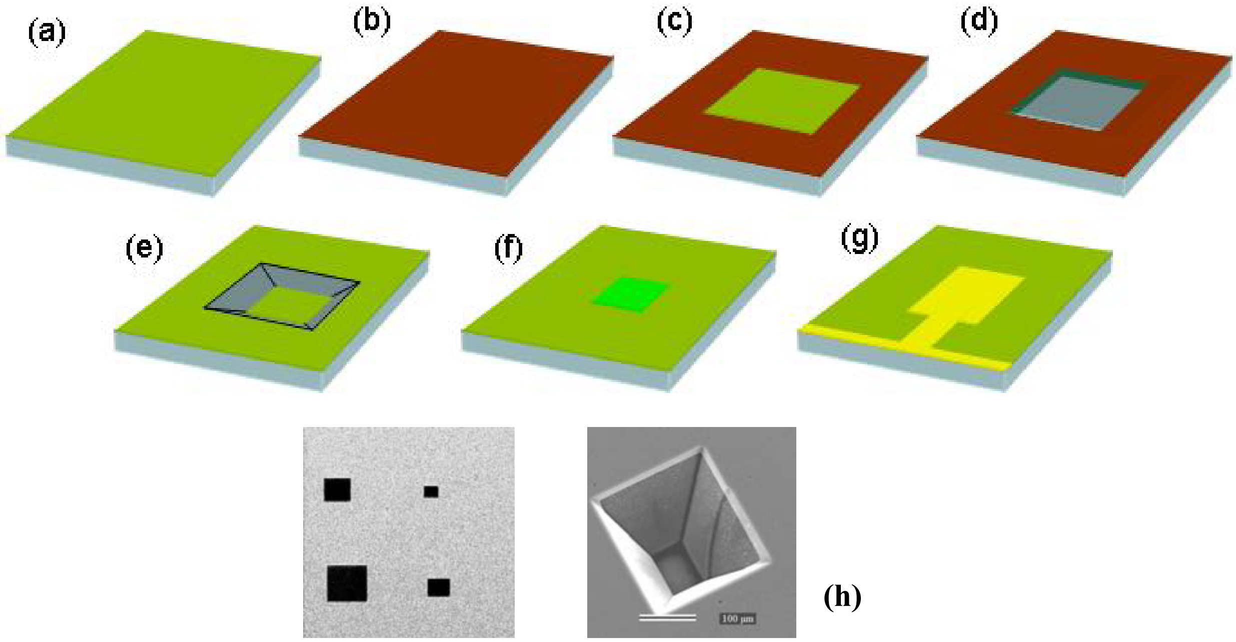


Figure 1: (a) the Si_3N_4-Si- Si_3N_4 wafer pre-processing (b) PMMA is spin-coated onto the backside of the wafer (c) electron beam lithography is used to pattern the backside of the wafer (d) reactive ion etching opens the SiN layer (e) A KOH wet etch dissolves the Si layer along the (100) plane. (f) shows the front side of the wafer with a 300 nm thick clamped SiN membrane. (g) additional lithography is used to pattern a metallic layer for actuation and STM analysis (h) an SEM micrograph, shown from the front, of four membranes with an SEM photograph, shown from the back, of a single membrane.

3 MEASUREMENTS

A custom built RHK Technology, Inc.[5] UHV STM was used to probe the small mechanical displacements of the fabricated devices. First, electrical connections were made to the device layer as well as to a gold layer beneath the membrane for electrostatic actuation. The sample was then loaded into the UHV chamber containing the STM. The tip was brought into tunneling (approximately a few angstroms gap distance) over the central region of the membrane.

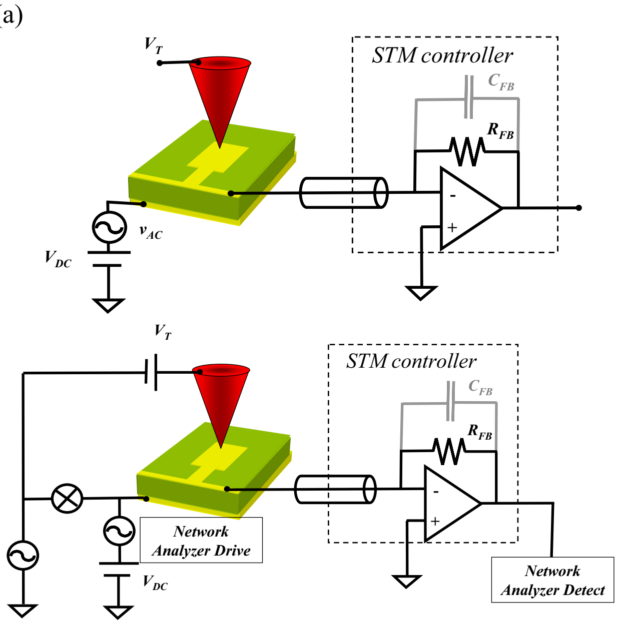
The device was driven electrostatically as shown in Figure 2 (a). Capacitive coupling between the actuation and device layers induced motion in the membrane when both AC and DC signals were applied to the actuating layer. A network analyzer was used to sweep the AC signal over a range of frequencies while simultaneously monitoring the response in the tunneling current at the STM tunnel current pre-amplifier output.

The maximum response was observed in the tunnel current at the natural resonance frequency of the device, measured at 12.248 kHz with a *Q* factor of 50 as shown in Figure 3. These values agreed well with the previously measured ones from an optical interferometry setup described elsewhere[6]. The amplitude of this response was seen to be dependent upon the amplitudes of both applied signals as well as the value of the tunneling current set. Additionally, significant attenuation of the signal was observed due to the fact that the value of the natural resonance exceeded the 3dB point of the current pre-amplifier, measured to be at ~3 kHz. The attenuation around 12 kHz due to this effect was estimated to be ~20dB.

A more complex measurement scheme is needed to get rid of the aforementioned attenuation. Such a scheme will be valuable for characterizing the behavior of smaller, high frequency devices.

In an effort to extend the applicability of STM measurements to higher frequency devices, we experimented with a second technique that makes use of the inherent non-linearity of the *IV* characteristics of a tunnel junction[7]. The tunnel current, I_T, across the tunnel gap is given by, $I_T \propto e^{-kz}$ where z is the gap separation and k is the electron tunneling decay constant proportional to the work function of the metal. The gap distance is given by a fiducial separation defined by the feedback setting added to the small amplitude of the membrane center's oscillatory motion at frequency ω_1. To measure higher frequency signals, a bias modulation signal of frequency ω_2 is applied to the tip itself. The nonlinearity in the *IV* and *Iz* characteristics of the tunnel gap then gives rise to a signal proportional to the tunnel gap at the sum and difference frequencies, *i.e.*

(a)



(b)

Figure 2: (a) The measurement scheme used to find the resonance and *Q* directly through the tunnel current. (b) The signal at the difference frequency is measured by modulating the tip-sample bias and sweeping the AC signal on the actuator using a network analyzer. The tunnel current is then fed back into the network analyzer.

$\omega = \omega_1 - \omega_2$ and $\omega = \omega_1 + \omega_2$. Thus, by carefully selecting ω_1 and ω_2, one can "mix down" the device response to low frequencies.

Initially, a constant potential difference of 15 V was established between the sample's actuation and device layers. Then, a fixed 11.250 kHz (100 mV) signal was applied simultaneously to both the bias and the actuation layer. A network analyzer signal sweeping 0.5 to 1.5 kHz (500 mV) at a 10 Hz resolution bandwidth was conventionally mixed with the AC signal on the actuator. The resulting sum frequency signal swept 11.750 kHz to 12.750 kHz, across the natural resonance of the membrane at 12.248 kHz. The peak, shown in Figure 3, was observed at approximately 1 kHz possessing the same width as the previously observed peak at 12.248 kHz. As expected, this position in the sweep corresponds to where the summed frequency signal crosses 12.248 kHz. Subsequent measurements conducted using different values for the fixed AC signal verify that the peak at 1 kHz corresponds to the "mixed down" signal of the natural resonance of the device.

4 NOISE ANALYSIS

Ultimately, the displacement measurement sensitivity of the technique is limited by the amount of current noise present in the measurement system. Given a small change in the gap separation, there will be a corresponding shift in the tunnel current. If the change is below the current noise threshold, then it becomes impossible to distinguish the response from the noise.

The tunnel current may be written in terms of the work function of the metal. Expressed in units of nanoamperes and angstroms,

$$I \propto e^{-1.025\sqrt{\phi}z}. \qquad (1)$$

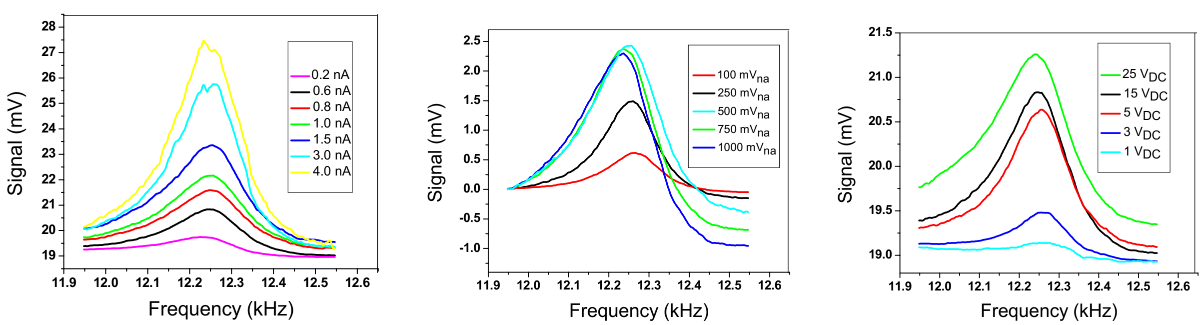
Inserting the theoretical work function for gold[8] of 5.4 eV gives

$$I \propto e^{-2.38z} \qquad (2)$$

Thus, the infinitesimal change in tunnel current for a small displacement is

$$\frac{\partial i}{\partial z} = -2.38I \qquad (3)$$

indicating that the so-called "responsivity" changes for



(a) (b) (c)

Figure 3: The amplitude of the resonant peak exhibited dependence on the feedback controlled tunnel current (a) the amplitude of the AC swept signal (b) and the amplitude of the DC voltage applied to the actuator.

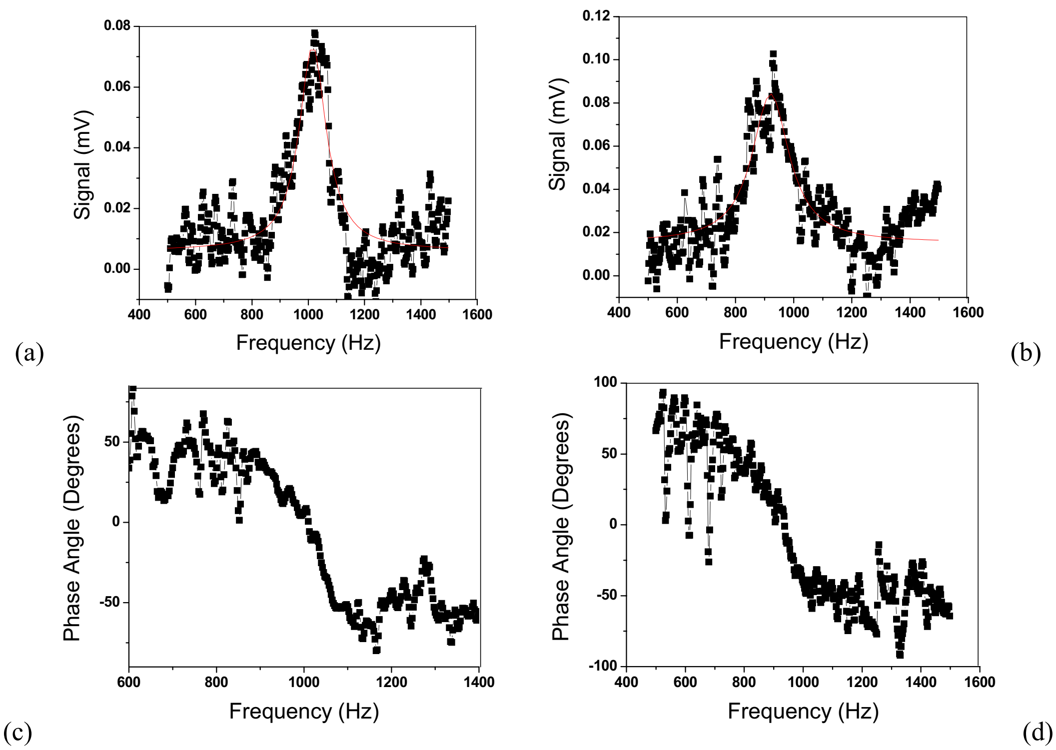


Figure 4: (a) The measured difference frequency signal for an applied AC voltage at 11.250 kHz mixed with a swept signal from 0.5-1.0 kHz. The summed frequency signal sweeps over the natural resonance of the device simultaneously with the difference frequency signal sweeping over 1 kHz (b) The same measurement performed with an applied AC voltage of 11.350 kHz (c)-(d) the respective phase plots.

different gap heights. Again, using a typical value for the feedback set tunnel current of 1 nA (corresponding to a gap of about 0.39 on gold) gives $\partial i/\partial z = -2.38$.

For our experiment, we used an RHK IVP 200 pre-amplifier. Previous measurements[9] quote average current fluctuations of 1.2 pA (parasitic capacitance) for a 1.5 kHz bandwidth. This corresponds to a current noise spectral density, $\sqrt{S_i} \sim 8\times10^{-4}$ pA/$\sqrt{\text{Hz}}$. To estimate the displacement sensitivity, we convert the current noise spectral density into displacement noise spectral density as

$$S_x = \frac{S_i}{\left(\partial i/\partial z\right)^2}. \quad (5)$$

Our displacement sensitivity is then $\sqrt{S_x} \sim 1.4\times10^{-2}$ fm/$\sqrt{\text{Hz}}$.

5 CONCLUSIONS

The use of quantum mechanical electron tunneling appears to be applicable to displacement measurements of high frequency devices. Using a scheme for "mixing down" the tunnel current signals, displacement detection at high frequencies can be realized. The sensitivity limits of the current measurements are set by amplifier noise processes.

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