Near-Surface Electronic Contribution to Semiconductor Elasticity

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The influence of the carrier concentration on the elasticity is measured for a microscale silicon resonator. UV radiation is used to generate a surface charge that gates the underlying carrier concentration, as indicated by the device resistance. Correlated with the carrier concentration change is a drop in the resonant frequency that persists for 60 hours following exposure. Model calculations show that the change in resonant frequency is due to the modification of the elastic modulus in the near-surface region. This effect becomes increasingly important as device dimensions are reduced to the nanometer scale, and contributes an important source of instability for micro and nano scale electro mechanical devices operating in radiation environments.

I. INTRODUCTION

Micro electromechanical systems (MEMS) functioning as oscillators, accelerometers, gyroscopes and seismometers have clear advantages over traditional sensing and timing technology for space based applications[1–4]. They are small, light-weight, integratable with silicon ICs, and use low power. These advantages are of particular importance for "pico" satellite applications[5, 6] where stringent size and weight limitations exist. Essential for any MEMS space based application is an understanding of the impact that high radiation environments encountered in space have on MEMS operation. Studies of radiation effects on commercially available MEMS components have described the impact that radiation induced electrostatic charging has on MEMS operation[7, 8]. A number of optomechanical studies have also been reported on the interaction of pulsed laser light with nanoscale mechanical resonators[9–15]. High speed optical excitation of charge carriers can induce mechanical oscillations, and alter mechanical resonant amplitudes. Non-radiative carrier recombination causes local heating which also temporarily modifies the resonant frequency. These works clearly demonstrate the impact of optically induced charge generation on material mechanical properties, however, these effects dissipate quickly once the pulsed laser light is removed.

Recently, our group showed how X-ray radiation causes long term changes to the elastic properties of silicon MEMS cantilevers[16, 17]. It was proposed that the modification was due to the de-passivation of bound hydrogen-boron pairs by the X-ray radiation. This releases holes, raising the carrier concentration and reducing the elastic modulus. The observed effects are dependent on the relationship between semiconductor carrier concentration and mechanical properties, as first described by Keyes[18]. Mechanical strain causes the electronic energy bands to shift, redistributing the available electron states. This modifies the free energy by an amount that is dependent on the concentration of carriers available for redistribution. This results in an additional electronic contribution to the elasticity that should be observable as a carrier concentration dependence in the Young's elastic modulus.[19] Semiconductors with different dopant concentrations have been observed to have different Young's modului [20], in rough agreement with Keyes' theory. However, direct measurements of the carrier concentration dependent Young's modulus have not been made. Surface charging can produce large changes in the near-surface carrier concentration due to band-bending, that might also be expected to change the near-surface elastic constants. In macro scale samples, the influence of the surface on the elastic constants is negligible; however, it becomes increasingly important as device dimensions decrease into the micro and nanoscale

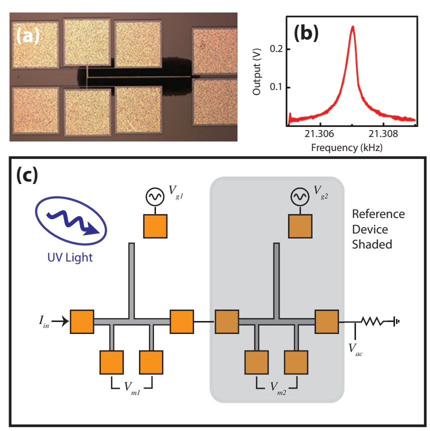

FIG. 1. (a) Optical microscope image of the resonator. The resonator beam is 655 microns long, 8 microns wide, and 15 microns thick. The voltage contacts on the base are separated by 110 microns. (b) Output versus driving frequency for a representative device. Nine different scans are plotted together to demonstrate the device reproducibility. (c) Schematic showing the measurement configuration. The asymmetric base is not shown.

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regimes[21].

In this paper, we explore how ultraviolet (UV) radiation influences the elastic properties of a micro scale silicon resonator. UV radiation differs from X-ray radiation in that the penetration depth is much lower (<15 nm), so that any observed changes should be due to the impact of the UV radiation on the near surface region. UV induced changes in the carrier concentration are detected using four-terminal resistance measurements. Simultaneously monitoring the resonant frequency of the resonator shows that the Young's modulus decreases as the carrier concentration increases, clearly demonstrating the impact of the free carrier concentration on the elasticity, independent of dopant concentration. Theoretical modeling shows that the impact of the surface carrier concentration on the elasticity increases dramatically as the surface to volume ratio of the resonator increases, implying that nanoscale electromechanical systems will be highly susceptible to near surface carrier concentration induced changes to the Young's modulus.

II. EXPERIMENTAL PROCEDURE

Figure 1 shows the device layout and experimental setup. The starting material for the resonator is a silicon-on-insulator (SOI) wafer with a device layer thickness of 15 microns, a buried oxide layer thickness of 2 microns and a handle layer thickness of 500 microns. The device layer is boron doped (p-type) to a resistivity of approximately 0.013 ohm-cm. T-shaped cantilevers are defined in the device layer using DRIE, and then released from the backside by subsequent dry etching. Prior to measurement, the sample chamber is evacuated using a turbo-molecular pump. The chamber is pumped for 72 hours, until the pressure is constant as measured at the pump inlet. The cantilever beam is actuated by an AC voltage on a nearby gate electrode, and is continuously driven during the course of the measurement.

The resistance of the base changes with the strain of the moving cantilever due to the piezoresistivity of the silicon, so that cantilever motion can be detected by monitoring the ac voltage generated across a sense resistor in series with the base. The base has an asymmetric design to maximize the resistance change [22]. Figure 1(b) shows the frequency response of a representative device measured in a vacuum chamber at a pressure of 2 x 10^{-6} mbar. A peak is observed at frequency of 21.307 kHz; high speed camera imaging confirms that this peak correlates with the cantilever resonance. In subsequent measurements, the resonant frequency of the cantilever and the four-terminal resistance of the base are monitored while the sample is exposed to light through a quartz window in the vacuum chamber. For reference, a second resonator is placed adjacent to the test device, but shielded from the light by a metal plate (see Fig. 1(c)). Comparison between the exposed and unexposed samples allows for changes due to carrier generation to be isolated from those due to temperature.

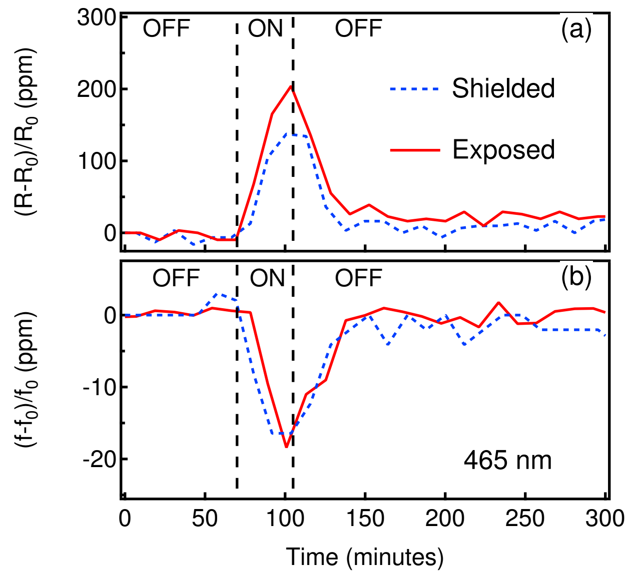

FIG. 2. (a) Change in in the four terminal resistance of the resonator beam and (b) change in the resonant frequency, for samples exposed and shielded from 465 nm blue light.

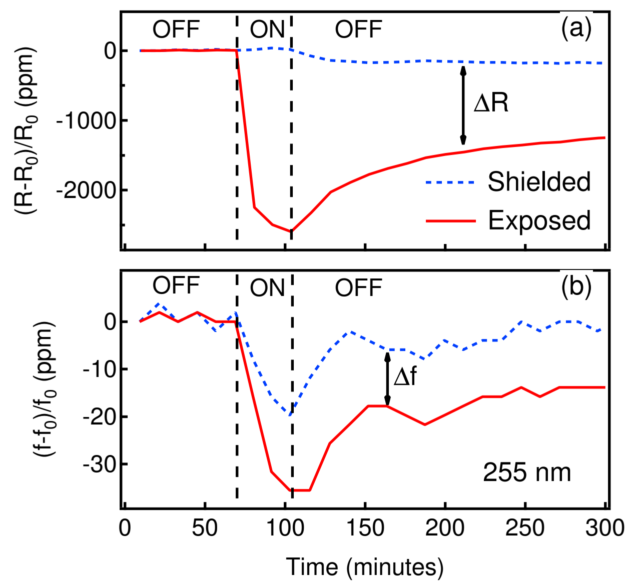

FIG. 3. (a) Change in in the four terminal resistance of the resonator beam and (b) change in the resonant frequency, for samples exposed and shielded from 255 nm UV light.

III. DEVICE MEASUREMENTS

As an initial demonstration of the measurement technique, the resonator was exposed to blue light of energy below the oxide band edge. The blue light source is an Engin LZ1-10D800 LED with peak wavelength of 425 nm and measured output power of 1.44 mW. Figure 2 shows the (a) four terminal resistance and (b) resonant frequency plotted as a function of time before, during, and after a 30 minute exposure to light from the 465 nm LED. The resistance increases and the resonant frequency decreases during exposure, with a similar change being observed in both shielded and unshielded devices. It is known that the silicon hole mobility and Young's modulus both decrease with increasing temperature, so that the observed changes can be attributed to heating of the sample chamber. Once the light is removed, the original signal is recovered in approximately 20 minutes, providing a measure of the thermal recovery time for the resonator. By comparison, Fig. 3 shows the impact that UV light from a 255 nm LED has on (a) the four-terminal resistance and (b) the resonance frequency. The UV source is a Thorlabs LED255J Optan UV LED with measured output power of 220 μW. The shielded device is now used to monitor the heating caused by the UV light; its resistance increases and resonant frequency decreases as before, and both recover in approximately 20 minutes following exposure. The exposed sample behaves very differently. Its resistance drops a large amount (rather than rising), while the resonant frequency drops below the reference value of the shielded device. Neither recover back to their original values over the 300 minute measurement.

The difference in signal between the shielded and exposed devices gives the change due to the UV light that is not due to heating. This is plotted as a function of time in Fig. 4 for the (a) resistance ΔR and for the (b) resonance frequency Δf. Both drop sharply following UV exposure, and then slowly recover back to their original values over approximately 60 hours. The similarity between the resistance recovery and the resonance frequency recovery suggests that the two are related, even though the total resistance change (2500 ppm) is 100 times larger than the total frequency change (25 ppm). Further analysis shows that the resistance and resonant frequency recover to their equilibrium values logarithmically with time, as is observed for many slow relaxation processes [23]. Measurements were repeated for 5 different sets of samples, and in each case, similar results were observed.

IV. DISCUSSION AND THEORETICAL MODEL

The effect of UV light on a silicon surface has been described in detail in the literature [24–26]. UV light is absorbed in the near surface region (with an absorption depth of 10 nm for 255 nm light). This creates highly excited electron-hole pairs with energies above the conduction and valence bands of the overlying native silicon oxide layer. Some amount of the excited charge Q_{ox} is transferred to the oxide, where it becomes trapped. Photovoltage [27] and second harmonic generation ex-

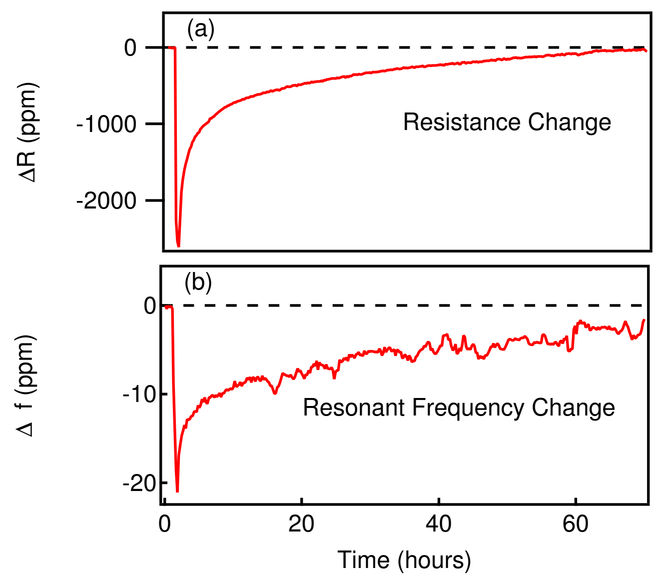

FIG. 4. Difference between (a) the four terminal resistance ΔR and (b) the resonant frequency Δf for the exposed sample and reference sample measured as a function of time following a 30 minute exposure to 255 nm light.

periments [28] have shown that the trapped oxide charge has an extremely long lifetime, and slowly decays over a period of 2-3 days following UV exposure. The surface oxide charge is balanced by an equal but opposite charge due to the accumulation or depletion of carriers in the underlying silicon. In the following it is shown that this change in surface carrier concentration can account for our experimentally observed behavior: the resistance of the silicon drops due to carrier concentration dependence of the conductivity, and the resonance frequency drops due to the carrier concentration dependence of the Young's modulus.

A. Resistance calculation

The first step in the resistance calculation is to determine the carrier concentration as a function of distance from sample surface, x. From standard semiconductor theory [29] the following relationship holds for the potential in the silicon $\phi(x)$:

$$\frac{\partial\phi(x)}{\partial x} = -\left(\frac{2kTp_0}{\epsilon}\right)^{\frac{1}{2}}\left[\left(e^{-\frac{q\phi(x)}{kT}} + \frac{q\phi(x)}{kT} - 1\right) + \frac{n_0}{p_0}\left(e^{\frac{q\phi(x)}{kT}} - \frac{q\phi(x)}{kT} - 1\right)\right]^{\frac{1}{2}} = g(\phi(x)) \quad (1)$$

where q is the charge, k is Boltzman's constant, T is the temperature, ϵ is the silicon dielectric constant and n_0 and p_0 are the equilibrium electron and hole concentrations in the bulk of the sample. Here, the function $g(\phi(x))$ has been introduced as shorthand for the right-hand side of the equation.

Using Eq. 1 and the relationship $Q_{ox} = \epsilon d\phi_s/dx$, the value of the surface potential ϕ_s can be determined as a function of Q_{ox}. Eq. 1 is then re-written through separation of variables and integration to give:

$$x = \int_{\phi_s}^{\phi(x)} \frac{d\phi(x')}{g(\phi(x'))} \tag{2}$$

Equation 2 is solved numerically to determine the relationship between $\phi(x)$ and distance x using the value of ϕ_s that corresponds to the chosen Q_{ox}. The hole and electron concentrations as a function of distance can then be calculated using

$$p(x) = p_0 \exp\left(\frac{-q\phi(x)}{kT}\right), \quad n(x) = \frac{n_i^2}{p(x)}$$

Figure 5 shows the (a) electron concentration and (b) hole concentration as a function of distance from the sample surface, for three different oxide charge concentrations. Reasonable magnitude variations in the oxide charge (on the order of 10^{13} cm^2), causes the silicon surface region to vary between accumulation, depletion and strong inversion.

To determine the change in resonator base resistance, the base cross-section is divided into two regions (see inset to Fig. 6): an outer surface region, with variable carrier concentration and conductivity σ, and an inner region, with carrier concentration and conductivity set to the bulk values. The width of the outer region is determined by the maximum depletion layer width, which as seen in Fig. 5 is approximately 20 nm. The mobility is assumed to be constant and equal to its bulk value throughout the entire sample [30]. The resistance is then determined using $R = L_b/\int_S \sigma dS$ where L_b is the length of the resonator base, and the conductivity is integrated over the base cross-section. Figure 6 shows the change in resistance from the flat-band condition as a function of oxide charge density. Negative oxide charge results in accumulation of holes and a decrease in resistance, while positive oxide charge depletes holes and increases the resistance. Very high positive oxide charge concentration inverts the surface carrier concentration, and the resistance again decreases. The calculation shows that a change in oxide charge concentration of about -10^{13} cm^{-2} (e.g., from 5×10^{12} cm^{-2} to -5 $\times10^{12}$ cm^{-2}) reduces the resistance by the experimentally observed value of 2500 ppm.

B. Resonant Frequency Calculation

Next, consider the influence of the surface oxide charge on the resonant frequency. It is known that a dc electric field between the beam and gate can reduce the resonant frequency due to "spring softening".[31] In our device, the oxide charge is screened by the highly doped silicon, so that the field outside of the silicon surface is extremely small. In addition, the distance between the beam and the gate is relatively large. Calculations of the resonant frequency shift due to spring softening were performed [32, 33] and show that the predicted resonant frequency change is an order of magnitude smaller than that observed experimentally. We have also considered the possibility that the mass of the resonator changes due to surface adsorbants generated by the UV exposure. Calculations show that the observed 20 ppm resonant frequency shift would require the deposition of 8 monolayers of nitrogen on the cantilever surface [32]. It is unlikely that multiple atomic layers would remain stable on the cantilever following UV exposure. In addition, atomic adsorption is expected to affect both shielded an unshielded devices equally. Note that de-adsorption from the cantilever, while more plausible, would cause the resonant frequency to go up, in disagreement with the observed results.

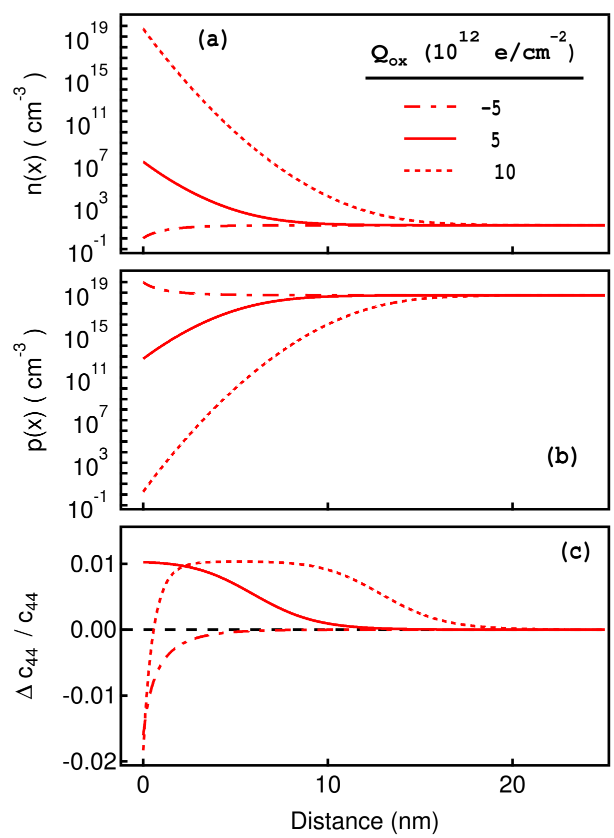

FIG. 5. (a) Electron concentration n(x) (b) hole concentration p(x) and (c) relative shear elastic constant $\Delta c_{44}(x)/c_{44}$ as a function of distance from the sample surface plotted for three different oxide charge concentrations.

Instead, consider the effect that the surface carrier concentration has on the resonant frequency. Once again, the beam is taken to be composed of two regions: a bulk region where the shear modulus c_{44} is constant, and a surface region where the shear modulus $c_{44} - \Delta c_{44}(x)$ varies as a function of distance x from the sample surface due to the changing carrier concentration. According to models by Keyes [34] and Csavinsky [35] the change in the shear elastic constant $\Delta c_{44}(n(x))$ due to the electron concentration n(x) and $\Delta c_{44}(p(x))$ due to the hole concentration p(x) are given by:

$$\Delta c_{44}(n(x)) = -\frac{4}{3}\left(\frac{4\pi}{3}\right)^{\frac{2}{3}}\left(\frac{m_n \Xi^2 n(x)^{\frac{1}{3}}}{h^2}\right) \tag{3a}$$

$$\Delta c_{44}(p(x)) = -\frac{1}{5}\left(\frac{8\pi}{3}\right)^{\frac{2}{3}}\left(\frac{m_p \Xi^2 p(x)^{\frac{1}{3}}}{h^2}\right) \tag{3b}$$

where m_n is the effective electron mass, m_p is the effective hole mass (assuming a non-parabolic heavy hole mass), Ξ is the deformation potential (taken to be 5.5 eV for electrons and 6.1 eV for holes), and $\Delta c_{44} = \Delta c_{44}(n) + \Delta c_{44}(p)$ is the change in c_{44} from its value in intrinsic silicon (79.51 GPa). The substrate used in this work is heavily doped with $N_A = 5.8 \times 10^{18} cm^{-3}$, so according to Eq. 3(b), c_{44} in the bulk of the sample is equal to 78.69 GPa. Figure 5(c) then shows the change in c_{44} from this bulk value as a function of distance x from the sample surface calculated using Eq. 3 and incorporating the variation in carrier concentration due to band bending shown in Fig. 5(a) and 5(b). The shear elastic constant changes by as much as 2% near the sample surface, recovering to its bulk value over a distance of about 20 nm.

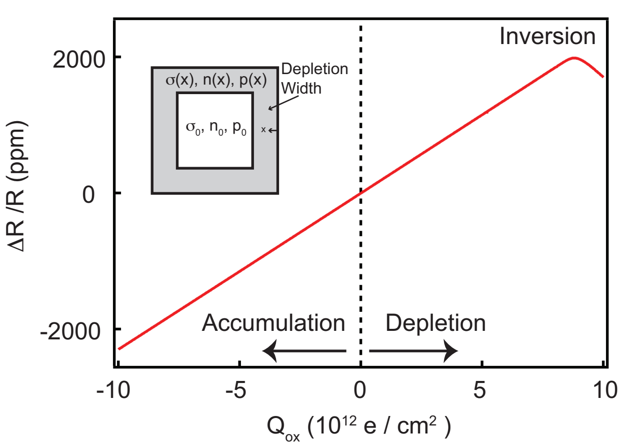

FIG. 6. Relative change in resistance as a function of oxide charge concentration calculated using the model described in the text. The inset shows a cross section of the beam indicated the different regions used in the calculation.

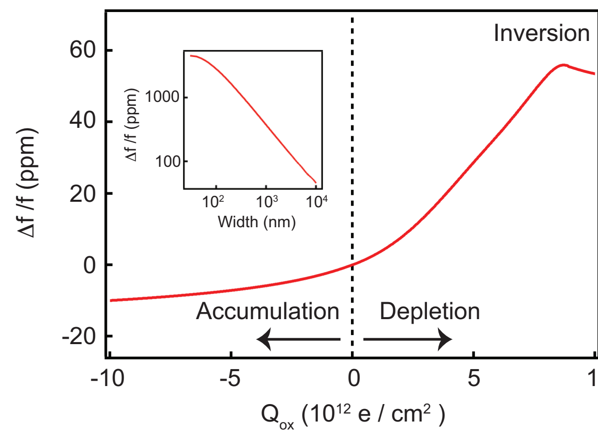

FIG. 7. Relative change in resonant frequency as a function of oxide charge calculated using the model described in the text. The inset shows the relative change in resonant frequency as a function of beam width plotted on a log-log scale. The oxide charge is taken to be $Q_{ox} = 8.71 \times 10^{13} e/cm^2$.

Using the surface modified elastic constant, the change in the beam resonant frequency is calculated as follows. First, the Young's modulus E is taken to be approximately equal to the shear elastic constant c_{44} (this is reasonable in the experimental beam geometry, where beam motion is mainly in the [110] direction). Next, following the method described in Ref. [36] , the beam cross-section is transformed into an equivalent shape with a constant elastic modulus. The moment of inertia I is then determined for the transformed geometry, and the resonant frequency calculated using

$$\omega = \left(\frac{\xi^*}{L}\right)^2 \sqrt{\frac{EI}{\rho A}} \tag{4}$$

taken from standard beam theory. Here, L is the beam length, A is the cross-sectional area, ρ is the silicon density, and $\xi^* = 1.875104$ from $1 + \cos\xi^* \cosh\xi^* = 0$. The results of this calculation are shown in figure 7, where the normalized change in resonant frequency is plotted as a function of oxide charge density. The model predicts that a change in oxide charge density of -10^{13} cm^{-2} (as was needed to produce the resistance change in Fig. 6) produces a decrease in resonant frequency close to the experimentally observed value of 25 ppm. The total change in resonant frequency will depend on the initial charge concentration. Note also that the photon energy of the UV light is large enough to produce additional carriers through the boron de-passivation mechanism described in Ref. [17] so it is possible that this mechanism also plays a role in modifying the carrier concentration, at least in the near surface region where the UV light is absorbed.

The impact of the surface oxide charge on the resonant frequency, while clearly detected, is relatively small for this micro-scale cantilever beam. As the device dimensions decrease and the surface-to-volume ratio increases, the impact of surface charging will also increase. The inset to Fig. 7 shows the maximum calculated change in resonant frequency due to an increase in surface oxide charge of 8.7 x10^{12} cm^{-2} as function of cantilever beam width. The resonant frequency change increases rapidly with decreasing dimensions, and is greater than 3000 ppm for sub 100 nm width beams. This is a substantial amount for MEMS oscillator applications where 1-10 ppm stability is desirable in order to substitute for quartz crystals in commercial applications[37]. The effects we describe were demonstrated for UV light, however, they would also occur for any type of radiation (gamma rays, high energy protons) with energy above the silicon / silicon-dioxide energy barrier. UV radiation can be easily blocked with a light-weight shield, but blocking space radiation requires a large amount of mass, negating the advantages of light-weight MEMS technology. [7]. The change in resonant frequency eventually saturates with constant UV exposure, however, exposure to high energy radiation would generate more surface states, making the resonator progressively more susceptible to radiation damage[38]. Radiation induced changes in mechanical properties due to carrier concentration changes would be particularly important in materials that exhibit persistent photoconductivity. This includes many compound semiconductors (including GaN and ZnO)[39, 40] amorphous silicon[41], and semiconductor nanostructures and membranes[42]. It is also noted that the instabilities and electric field induced shifts reported in the literature for nanometer scale resonators could in part be attributable to surface carrier concentration changes[43, 44].

V. CONCLUSION

In conclusion, the electronic contribution to the silicon elastic properties is measured for a micro scale resonator beam, independent of dopant concentration. Changes in the shear elastic modulus with carrier concentration on the sample surface can account for observed change in resonant frequency following UV exposure. Calculations show that these changes become increasingly important as sample size is reduced, and could constitute an important drift mechanism for MEMS or NEMS resonators operating in high radiation environments.

ACKNOWLEDGMENTS

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