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The Study of Radiation Effects in Emerging Micro and Nano Electro Mechanical Systems (M&NEMS)

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I. Introduction

Advances in fabrication techniques and material science present new opportunities for micro- and nano-scale electro-mechanical systems (M&NEMS) including electromechanical relays, force and pressure sensors, accelerometers, digital logic switches, as well as biosensors and micromirrors, offering the potential of expanded functionality with improved efficiency of size, weight, and power. These attributes are attractive for a range of application areas including consumer, medical, military, and space devices. As with any new technology, reliability is an important consideration, particularly for use in high-reliability applications in harsh environments. One particular consideration is exposure to radiation such as might be found in medical, space and military applications. The study of radiation effects on electronic devices has a decades-long history, and continues as electronic device dimensions continue to shrink and new materials are added to integrated circuits. The study of radiation effects in MEMS devices is more limited, largely having focused on devices fabricated in poly- and single-crystal silicon and silicon dioxide [1] with characteristic dimensions of tens to hundreds of micrometers (compared to tens of nanometers in today's digital electronic device technologies).

While the physics of the interaction of radiation with the constituent materials may be the same in electrical and M&NEM devices, the sensitivity and manifestations may differ depending on the relative operating principles and intended use of the particular devices. The degree of modification by radiation required to make a meaningful change in device operation may differ greatly between electrical and mechanical properties; however, the definition of meaningful change may also differ greatly. For example, oscillators used in GPS systems require parts-per-million level stability, while transistors used in integrated circuits may be able to tolerate parametric variations of several percent. An interesting intersection between these applications and device types is the use of M&NEMS as logic devices [2]–[6].

Previous work on the study of electrostatic MEM devices have shown high sensitivity to dielectric charging from ionizing radiation including changing capacitive calibration, collapsed parallel plates, and stuck comb drives typically due to trapped charge in dielectrics. While degradation due to total ionizing dose (TID) radiation exposure has appeared most commonly at doses as low as 10-100 krad(SiO₂), certain devices have demonstrated operation up to 3 Mrad(SiO₂) [1], [7]–[11]. Previous work has also found that the damage to materials by non-ionizing energy loss can alter their mechanical properties, thereby affecting functioning of NEMS [9], [12]–[16]. In particular, radiation-induced changes in the Young's modulus of MEMS cantilevers [12], [13] and behavior modification in RF switches [14]. Evidence of injection annealing due to gamma-induced charge has been reported, which enhances the reordering of dislocation damage and leads to a more stable configuration compared to pre-irradiation conditions in polycrystalline silicon [14]. Trapped charges in insulators have been shown to shift the output voltage of MEMS accelerometers under proton irradiation [9]. On the other hand, MEMS-based microengines have been shown to perform at radiation doses up to 10 Mrad(Si) [9].

Results reported for piezoresistive devices have indicated a weak sensitivity to dielectric charging from ionizing radiation that is manifested as a calibration change. Gradual output shifts were observed during irradiation, but were recalibrated after irradiation [1], [17], [18]. Trapped charge in the oxide around the piezoresistor can induce a depletion region in the semiconductor causing an increase in the resistance [17]. Effects due to displacement damage can cause deviations in mechanical responses due to changes in Young's modulus, but are typically small unless

exposed to a high fluence [1], [19]. The current body of research has shown that radiation sensitivity of MEM devices is dependent on a wide variety of factors such as geometry and materials [8].

The body of work so far largely examined the radiation effects in MEMS with characteristic dimensions of several tens to hundreds of micrometers and employing conventional materials such as Silicon, SiO₂ and SiN, polysilicon, and some polymers. However, the reduction of size and switching to alternative materials offer significant advantages for MEMS. Devices with nanoscale dimensions (typically termed NEMS) tend to operate at higher frequencies and consume less power than MEMS. NEMS can be better integrated and offer novel functionalities. Isolated two-dimensional (2D) materials are especially suitable for applications in ultra-miniaturized NEMS.

The pervasiveness of M&NEMS, along with the advancement in materials technologies, have stimulated an increased interest in understanding the potential of these technologies for use in radiation environments. The Jet Propulsion Laboratory's Micro Devices Laboratory is pursuing miniaturization technologies for space exploration [20], and Sandia National Laboratory has efforts in the construction of radiation-hardened inertial sensors [21]. The U.S. Defense Threat Reduction Agency (DTRA) has initiated multiple programs across several academic institutions and government labs to study the impact of radiation on a range of materials and emerging types of M&NEMS through their basic research program. The studies include silicon, silicon carbide, III-V, piezoelectric and ferroelectric, electro-optical, and 2D materials, and explore the impact of radiation on electrical, mechanical and optical properties and the manifestations in various modes of M&NEMS operation. This paper highlights the types of considerations and challenges of many of these ongoing studies

II. M&NEM Operating Principles, Materials, and Radiation

In general, operation of M&NEMS rely on mechanical deflection, oscillation, rotation, and gliding of their structural elements. These movements depend on the mechanical properties of the constituent materials. The idea behind the application of electro-mechanical devices is a correlated conversion between the mechanical and electrical (sensors) or electrical and mechanical (actuators) properties. These relationships can be accomplished in various manners; for example, (1) changing the spacing between two electrodes can change the capacitance, (2) change the stress in a material can change the electrical conductivity, or (3) application of a voltage to a material can cause internal dipoles to realign and modify the stress or shape of the material. Such conversions enable, among other things, measurement of forces, creation of resonant oscillators, and conversion between electrical and acoustic energy (in both direction). They can also enable the creation of micro-scale or even nano-scale switches (relays), which could in theory have nearly ideal switching characteristics with infinite off-state and zero on-state intrinsic impedance. These conversions are not new ideas, and in fact most are widely used today. It is the ability to fabricate smaller features with higher packing densities, integrate these types of functions more intimately with other functions, and advancements in material science, that are expanding the possibilities for application of these types of conversions. While bulk silicon has been the workhorse of both electronic and MEM devices, now M&NEMS are exploring and incorporating other materials using smaller dimensions and thinner films including silicon carbide and III-V materials, nitrides, polymers, ceramics, ferromagnetic and piezoelectric materials, and even the ultimate thin film: 2D materials such as graphene, MoS₂, BN, and others.

Radiation can create excess carriers through ionization, and/or can create structural damage through displacement of atoms, depending on the type of radiation and the material with which it interacts. These effects can result in transient changes in carrier densities in semiconductors, trapped charge at defect sites in insulators and semiconductors, and creation of new or different defect states in the bulk of materials or at material interfaces. Radiation can also cause secondary effects, for example increased temperature, or enhanced oxidation, which can in turn impact M&NEMS operation. The key to understanding the effects of radiation on M&NEMS is to understand how the radiation modifies the materials involved, and how these modifications impact the operating mechanisms of the particular type of conversion being exploited. For example, a sufficient change in carrier density may impact something that is relying on a piezoresistive effect; trapped charge may impact something that is relying on a capacitive or piezoelectric effect, and displacement damage may impact the value of Young's modulus, which determines the resonant frequency of an M&NEM resonator.

In order to develop this understanding, it is necessary to employ appropriate experiments and theoretical calculations. Integration of characterization and radiation exposure is a key aspect. While this is fairly well

developed for electronic devices, the unique requirements for many M&NEMS add some new considerations. For example, many devices (especially oscillators) need to operate under vacuum, and may be very sensitive to other variables such as temperature and atmospheric exposure. Others may use optical characterization. Environmental control and integration of characterization techniques with radiation test sources are key areas for experimental characterization of many M&NEM materials and devices. For theoretical modeling of M&NEMS, there are several finite element simulation packages that can be applied. Material and electrical parameters can be varied to simulate the impact of radiation-induced modifications. However, simulation of the modification processes directly is quite a bit more complex. The following sections highlight materials and test vehicles that are being investigated to elucidate the impact of radiation, noting particular test considerations and observation from initial tests where available.

III. Two Dimensional Materials, N&MEMS, and Radiation

Two-dimensional atomic crystals (2DACs) including graphene, monolayer boron nitride (BN) and molybdenum disulfide (MoS_2) are promising for M&NEMS applications [22]. Recent advances in fabrication have allowed each of these materials to be manufactured cheaply with control over factors like carrier mobility and the ability to transfer them between substrates [23]. Two-dimensional materials are uniquely suited for applications in NEMS. Despite their infinitesimal thickness, 2D materials are extremely robust mechanically. Pristine graphene can withstand strains up to 30% [24] and monolayer MoS_2 up to 18% [25] without breaking (compared to 1-2% ultimate breaking strain of silicon). This allows creation of highly tunable NEMS mixers, oscillators, and sensors. 2D materials are very stiff, with Young's modulus up to ~ 1 TPa for graphene. This allows the creation of nanomechanical resonators and oscillators with operating at frequencies higher than 1 GHz. 2D materials are also strongly respond to external influences – force, mass, and pressure. 2DACs have high electrical and thermal conductivities allowing for a great variety of applications including high speed resonators and oscillators, tunable resonators via electrical gating, loudspeakers, microphones, radios, and mass sensors [26]–[29].

As the ultimate thin-film geometry, 2DACs present unique considerations for the study of radiation effects. In cases where the 2DACs are in contact with other materials, such as might be the case in an electronic device, the effects of radiation in the adjacent material and at the interfaces can determine the response to radiation [30], [31]. While regions near supporting or contact structures may play a role, more generally for use in M&NEMS, the material is suspended. Displacement damage and ionization from irradiation can produce defects including vacancies, dislocations, and holes in 2DACs, which will affect electrical properties like carrier mobility and mechanical properties like breaking strength [32].

Researchers at the University of California at Berkeley use a Transmission Electron Microscope as a simultaneous source for radiation damage by electrons and characterization including imaging of the resulting defects [33]–[35]. An example finding is that triangular shaped defects are formed in BN when the electron exposure is performed at 500 °C, while hexagonal and parallelogram shaped defects dominate when the exposure is performed at above 700 °C [36]. As previously noted, it is important to connect the modifications to the material by radiation to the changes in the mechanical properties that might be important for M&MEMS applications. The UC Berkeley group has developed unique platforms allowing probing of mechanical properties of 2D materials together with a determination of their atomic structure using a TEM [33]–[35]. Specimens can, for example, be mechanically stressed and deformed inside the TEM by a nanomechanical manipulation probe containing force sensors, while the sample is imaged in real time by the TEM. The TEM serves as the “eyes” for the atomic structure and the nanomanipulation probe serves as the touch-sensitive “hands” mechanically probing the sample. The TEM electron beam energies and fluxes can be chosen so as to only minimally perturb the atomic structure of the specimen, or such that desired controlled electron-beam damage is achieved. Mechanical properties are recorded as the defect concentration or type is varied. The nanomanipulation probe allows simultaneous transport properties of the specimen to be recorded (e.g. electrical resistance, thermal conductance, and thermoelectric power); these transport properties are often closely linked to the defect structure of the specimen.

Recent studies by UC Berkeley researchers have also applied Raman spectroscopy and AFM measurements on 2D graphene membranes, finding that the elastic modulus of the film is insensitive to 3 MeV He^+ ion irradiation-induced defects until a threshold exposure dose (of order 10^{13} cm^{-2}), after which the modulus decreases rapidly, and that in multi-layer structures defects in a given layer may be passivated by interaction with the linked adjacent layers

[37]. Vanderbilt researchers have investigated changes in electrical transport and Raman spectra of suspended graphene under ion irradiation (Xe ions, 30 keV) of large area suspended two- and multi-terminal suspended graphene devices. Results showed dramatic differences (a factor of ~ 7) in defect-production rates between supported and suspended devices and differences of the nature of the defects short-range vs long-range electrical scattering effects.

Researchers at Vanderbilt are also studying the mechanical properties of circular 2DAC membranes. [38]. These samples have been measured using Atomic Force Microscopy (AFM) using methods similar to Lee *et al.* and Ruiz-Vargas *et al.* to measure mechanical properties such as force-displacement and elastic response (Young's modulus) [24], [39]. Raman spectroscopy is used to determine the number of layers of graphene and defect density following the methods of Cançado *et al.* [40]. The fabrication and characterization approach can be applied to multi- and monolayer graphene, as well as BN, and MoS₂ and their heterostructures, and as a function of exposure to different types and levels of radiation exposure.

Exposure to radiation and ex-situ characterization can be useful to study induced defects, however, the exposure to ambient environment can dramatically change properties of 2D materials, especially when defects are present. Indeed, defect-free graphene and other 2D materials are remarkably inert. However, any defects in these materials, including grain boundaries, edges, and vacancies, become centers of chemical activity. In the ambient environment these defects can interact with water, air, and residual hydrocarbons, dramatically changing material properties. The defects can move, anneal, and transform. Moreover, the presence of ambient contaminant severely hampers atomic-scale characterization of 2D materials via a TEM.

In addition to the aforementioned integration of in situ electron damage and characterization in a TEM, various other approaches are being pursued to enable the insitu testing of electro-mechanical properties with radiation exposure. One example constructed by Vanderbilt researchers is shown in Figure 1. In this device, a 2D material is suspended between two long metallic electrodes. These electrodes can be shifted up and down (thereby straining graphene) by varying the voltage applied to actuating electrodes A1 and A2. The carrier density in graphene can be varied separately, by changing the voltage on the gate electrode.

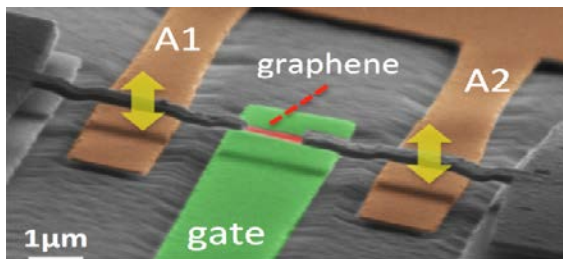


Figure 1: A platform for simultaneous probing of electrical transport and mechanical properties of 2D materials.

This device can be probed both electrically and using optical techniques to extract electrical and mechanical properties. Presently, electrical probing is well integrated with radiation sources such as X-ray and gamma ray sources, and particle accelerators, however optical characterization is not well integrated and requires ex situ measurements. This is another test consideration and area

of ongoing development.

Another approach to integrating the radiation exposures and characterization is the use of more conventional silicon micro machining MEMs techniques to implement a platform that can be used to manipulate and characterize other materials (e.g. 2DACs), for example within the TEM setup noted earlier. The concept is illustrated in Figure 2 and is an area of ongoing collaboration between Sandia National Laboratory, Vanderbilt, and UC Berkeley. One consideration is isolation of the region that is desired for radiation exposure from the rest of the platform, for which an aperture exposure from the back-side is the approach.

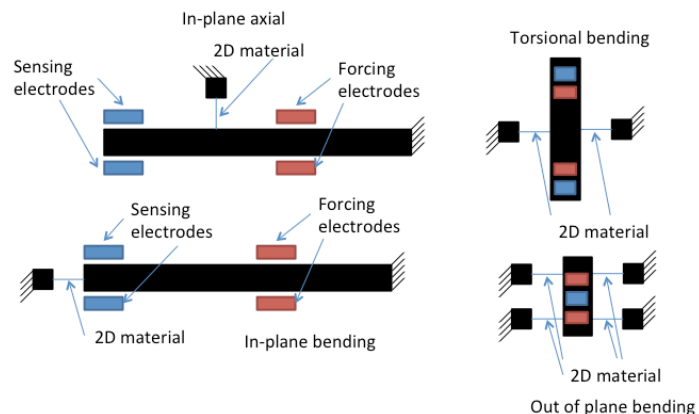


Figure 2: Test platform concept. The platform, to be fabricated using conventional micromachining/MEMs techniques, is designed to use single crystal silicon as a supporting structure for 2D materials. Geometry can be configured to apply either axial, bending or torsion strain to the 2D material. Structures will be forced and sensed electrostatically. Structures can also be designed to test isotropic vs. orthotropic behavior.

As noted previously, simulation of radiation interactions with materials is complex and not readily accessible in commercial software packages compared to simulations of M&NEMs device operation. For 2DACs, density functional theory and kinetic Monte Carlo simulations can be used to simulate atomic/molecular level interactions such as interactions with oxygen [41], [42]. For simulation of displacement damage due to energetic particles in 2DACs, the commonly used Stopping Range on Ions in Matter (SRIM) package [43] is not applicable. Present research as part of the studies described in this paper are investigating the application of Monte Carlo calculations to describe the process of defect generation in mono-layer graphene and other 2DACs. In general, interaction cross sections are very small for monolayer materials compared to bulk materials, and thus fairly high exposure doses have been reported in the limited studies to date. Interesting however is that from our preliminary calculations of defect yields, which agree with published results, the indications are that even for ions incident normal to the plane of the 2DAC, the defect generation is dominated by in plane, multiple-vacancy events. This is an area of ongoing research.

III. Resonators

MEMS resonators potentially provide a low cost, single-chip alternative to quartz-crystal resonators for clocks or frequency references in RF communication systems [44]. MEMS resonators can also be used as highly sensitive and selective bio-chemical or gas sensors [45]. MEMS logic and memory elements can be made from nonlinear resonators in which multiple states exist [3], [46].

The resonant properties of M&NEM structures are inherently coupled to the mechanical properties of the materials and dimensions of the fabricated structures. Measurement of resonant parameters as a function of radiation exposure is one approach being pursued to explore the impact of radiation on the electro-mechanical properties of constituent materials. Examples of structures under investigation include suspended silicon cantilevers, suspended SiC cantilevers, thin SiC membranes, GaN cantilevers, 2D graphene membranes (and other 2D material variants), and 2D material cantilevers.

A device structure such as shown in Figure 1 can serve as a resonator. Figure 3 illustrates an experimental platform consisting of monolayer graphene or MoS₂ NEM resonators that actuate and read-out. This allows for measurement of mechanical properties like Young's modulus. An AC voltage is applied between the 2DAC and an underlying electrode to create mechanical oscillations. The amplitude can be observed electrically by measuring transconductance. By analyzing changes of the resonant frequency as a function of applied forces, the built-in strain, Young's modulus, and the thermal expansion coefficient can be measured. Mechanical breaking strength of 2DACs can be determined by increasing the externally applied gate voltage. Since the mechanical parameters are determined electrically, the test structure can be integrated with radiation sources to elucidate changes in mechanical properties as a function of radiation exposure.

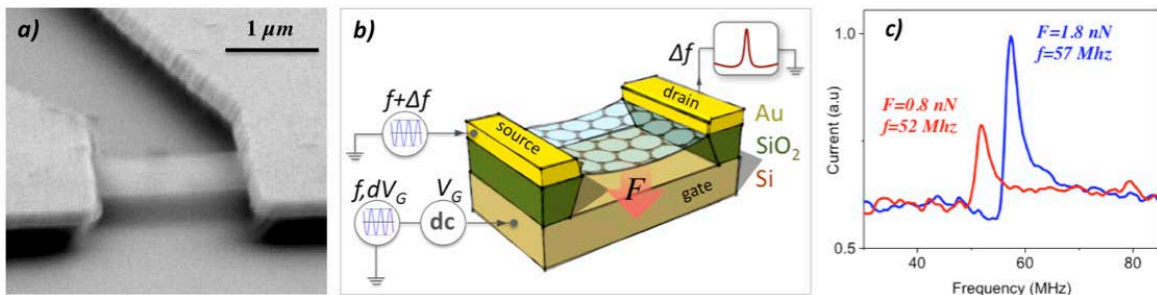


Figure 3: Graphene NEMS resonators. a) SEM image of a suspended graphene resonator device. A single layer sheet of graphene (middle) is supported by two gold electrodes. A silicon back gate electrode is located under graphene. b) Cartoon view of the device. Mechanical oscillations of suspended graphene are driven by applying a small AC signal between graphene and the gate. A DC gate bias results in a constant force acting on graphene. The oscillation amplitude is obtained via a mixing scheme, by measuring the conductance across graphene. c) The resonant frequency of suspended graphene changes when electrostatic forces act on it.

Another example is a resonator test structure, shown in Figure 4, consisting of an electrostatically driven horizontal resonating cantilever fabricated from a silicon-on-insulator substrate and employing a piezo-resistive sensing mechanism, developed by researchers at the University of Louisville [47]. An AC electrostatic excitation causes the cantilever beam to oscillate, and introduces compression and tension on opposite faces of the cantilever base. The

resistance of the base changes with strain due to the piezoresistivity of the silicon. The beam has an asymmetric design that maximizes the voltage difference measured across the device under deflection. During testing, the frequency of the gate voltage is varied and the voltage output monitored to determine the resonant response of the cantilever. The influence of radiation exposure on the frequency characteristics can then be tested. As with many M&NEMS structures (especially resonators) the resonance is sensitive to temperature and pressure, as well as ambient exposure (meaning they need to operate under vacuum). While there are approaches for encapsulation of silicon MEM structures such as [48], the variations of geometries and materials of interest, and accessibility of the material layers of interest for some radiation exposures and characterization techniques, constrains the efficacy and applicability of this approach for the basic research level. Instead, a custom test fixture was assembled to allow exposure using the ACACOR 10keV X-ray source at Vanderbilt while and keeping the sample at a constant vacuum pressure during the exposure, room temperature annealing, and electrical measurements. Responses to X-ray exposures are being compared to those from exposure to UV light, and to ions (protons and heavy ions), to gain further insight into ionizing vs non-ionizing radiation effects.

Cantilevers fabricated under a variety of experimental conditions, in different material systems, and with different geometries, can be studied and compared to gain insight into the influence of radiation exposure on material and processing parameters. For example, comparisons are being made for silicon devices with and without surface oxides to isolate charging effects, and with and without hydrogen passivation to test the influence of radiation on hydrogen-boron bond breaking. An example result is shown in Figure 5, where X-rays cause a shift in the resonant frequency that cannot be explained by temperature or pressure changes, and are not due to typical bulk oxide charge trapping such as might be seen in MOS structures since the device is suspended and all oxides are etched away (except for residual native oxide). These results were obtained at a dose rate of 10.5 krad(SiO₂)/minute. After a 10 hour anneal, the device returns to its original resonant frequency. The mechanisms responsible for the radiation-induced changes are still under investigation with surface charge trapping, dopant passivation/depasivation, persistent photoionization (modification of carrier densities), and gas ionization and adsorption being considered.

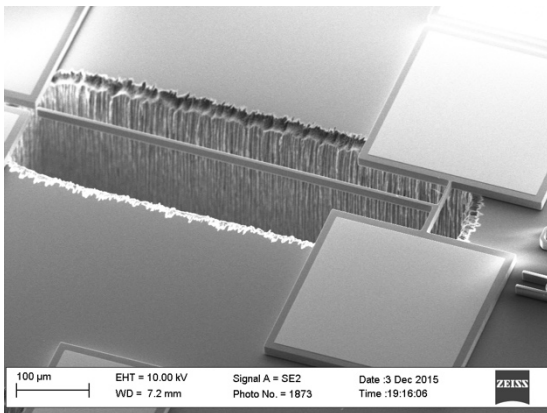


Figure 4: Scanning electron microscope (SEM) image of test resonator structure.

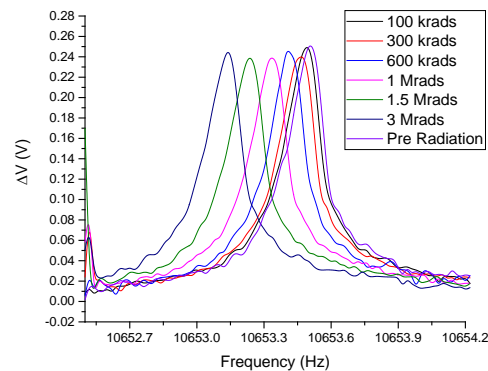


Figure 5: Effect of X-ray radiation on resonant frequency

Samples have also been fabricated with built-in Hall

probes to monitor carrier concentration changes during radiation exposure. Comparison to structures in other material systems, as well as variation of geometry, will be used to further explore the radiation effects mechanisms. For example, Silicon Carbide (SiC) micromechanical resonators including both microdisk resonators and cantilever resonators developed and fabricated by researchers at Case Western Reserve University (CWRU) are being studied for comparable radiation test condition.

Two-dimensional MoS₂ drumhead nanomechanical resonators vibrating at megahertz (MHz) frequencies have been irradiated with gamma rays. Upon exposure over 24 or 12 hours, the MoS₂ resonators exhibited ~1.3–2.1% resonance frequency upshifts [49]. The radiation effects observed thus far in SiC microdisk resonators and cantilever resonators have been weak, and the variations of important quantities such as resonance frequencies and quality (*Q*) factors have been quite small. However, it should be noted that for resonators, even small changes can be significant since related applications can require much tighter control than devices that might be used in electronic devices such as digital logic circuits.

IV. Logic Switches and Gates

The long-term quest for zero-leakage, abrupt switching, ultralow-power logic device has stimulated exploration of logic switches based on contact-mode NEMS [2], [4], [50]–[58] and references therein. This has been driven by the fundamental advantages that NEMS offer, at least including: (i) ideal abrupt switching with zero off-state leakage, (ii) suitability for high-temperature operation and potentially in other harsh or extreme environments (including those in which the devices are exposed to radiation), and (iii) potential for very small footprints. For radiation environments, one of the potentially most attractive attributes could be an inherent resistance to transient radiation (single-events and photo-currents). Very little work has been done in the study of radiation effects mechanism in such devices, in large part due to the immaturity of the technologies which have suffered from contact failure and reliability issues.

Recently, researchers at CWRU have demonstrate robust SiC NEMS logic devices with record longevity in ambient air, at both room and high temperatures ($\sim 500^\circ\text{C}$) as shown in benchmarking data presented in Figure 6 [4], [50]–[53]. The SiC NEMS switch is shown in Figure 6. In parallel to SiC, CWRU and CEA-Leti groups have also jointly developed novel Si nanowire NEMS logic switches (Figure 7) in which ultrasensitive piezoresistive readout [59]–[61] provides an additional new means for the real-time monitoring of nanoscale contact properties and device characteristics evolution during long cycles. CWRU has developed unique and genuinely nanoscale electromechanical switching devices with both two- and three-terminal structures. A focus has been gate-coupled nanocantilevers made of poly-SiC on insulator (SiO_2) because they are uniquely suited for NEMS for the outstanding mechanical, chemical and thermal properties of SiC crystal. The inset SEM image in Figure 6b illustrates the configuration of the gate-controlled electrostatic nanocantilever for realizing three-terminal lateral NEMS switches. Most devices have thicknesses, widths, and gaps $\sim 200\text{--}300\text{nm}$ or smaller.

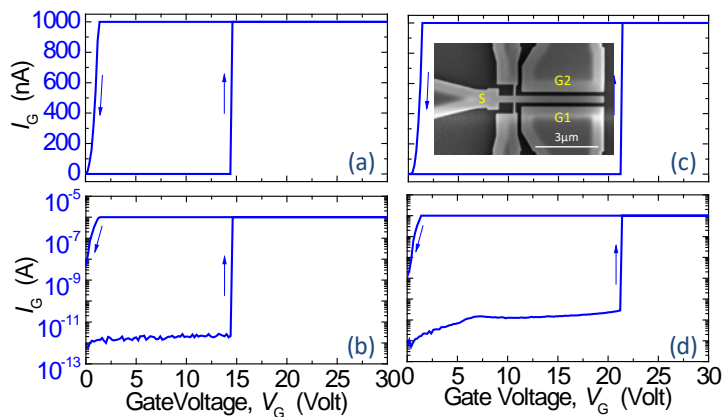


Figure 7: Example of thin SOI NEMS – measured switching behavior of a cantilever-SiNW cross-beam structure with length $L \approx 5\mu\text{m}$, width $w \approx 300\text{nm}$ and air gap $g \approx 250\text{nm}$ actuated by V_G applied to G1. (a) & (b) First cycle, in linear & logarithmic scale. (c) & (d) Second G1-S ‘pull-in’ switching after overcoming the stiction to G1 (pull-off) by applying a 0–120V sweeping voltage to gate G2.

In the category of very thin SOI Si NEMS switches developed and tested in the collaboration between CEA-Leti and CWRU, two types of structures have been studied: (i) singly-gated, doubly-clamped thin SiNWs; and (ii) mechanically ‘cross’ jointed/coupled cantilever-SiNW structures (see Figure 7c, inset), also electrostatically coupled to two gates. All devices are made by 8”-wafer-scale manufacturing in a 160nm-thick silicon-on-insulator (SOI) technology. Boron ion implantation and annealing steps enable homogeneous p-type doping of around 10^{19}cm^{-3} in the SOI. Advanced electron-beam & DUV lithography and reactive ion etching (RIE) define the nanoscale structures, followed by vapor HF for releasing the cantilevers and SiNWs.

The ability of the devices to operate for significant times and cycling in ambient environments is expected to be beneficial in relaxing some of the constraints on the experimental radiation studies. Current research collaborations supported by DTRA between CWRU, CEA-Leti, and Vanderbilt will include radiation response characterization of these logic switches.

Researchers at the University of California, Berkeley has developed 4- and 6-terminal relays that exhibits steep switching behavior, hysteresis, and a large on/off current ratio [5], [6], [62]. In principle, this configuration has the potential to operate at extremely low voltages and may be able to use less energy than CMOS logic [63]. The configuration allows operation as a combinatorial logic gate (not just a single switch). These devices currently consist of a moveable body electrode over a fixed gate, drain, and source where the body is supported by four flexure beams. There is a 100 nm air gap between the contacts body electrode and the contacts on the substrate. These devices are operated by applying a sufficient voltage between the body and gate [6], [64]. Failure mechanisms

of these devices have been explored and show that possible issue could include charge trapping in the dielectric (Al_2O_3), a shift in the on and off voltages over many cycles, and the body being permanently stuck in the “on” state [62]. Radiation studies have been limited by the tendency for oxidation of the metal contact electrodes, which can cause changes in inherent stiction forces if the devices are exposed to atmosphere for extended periods, and make it difficult to delineate the impact of radiation. As with other devices discussed, the need for storage and testing under vacuum is one of the challenges in the study of these devices in the current embodiment.

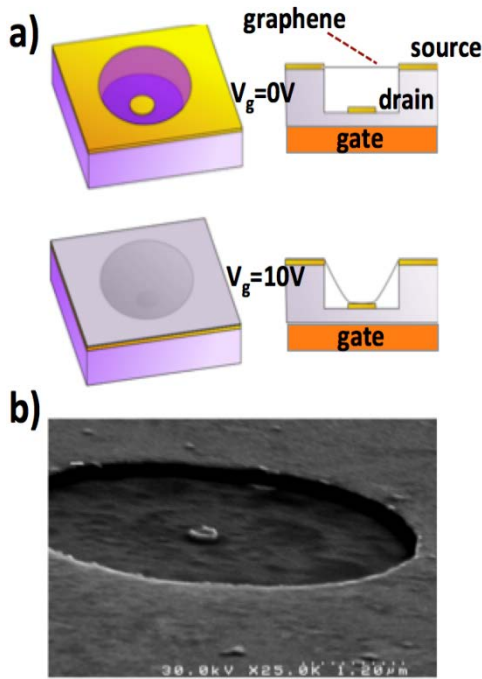


Figure 8: 2DAC NEMS switches: a) Device operation. b) SEM image of a finished device.

2DACs also have the potential to serve as logic switches. When deposited on insulator, 2DAC materials have an adhesion force will keep them in place [65]. Depositing 2DACs on a platform that is designed to have portions of the 2DACs suspended allows for the possibility of a switch configuration as shown in Figure 8. A layer of graphene can be electrostatically actuated by the drain electrode it is suspended over by applying a potential between the source and drain. Models show that 10V or greater will cause the graphene to touch the electrode and allow current to flow. When the potential is removed, the graphene will return to its initial position. This design has advantages like a high on/off current ratio and low on resistance and high-frequency operation due to the monolayer structure and ability to apply mechanical strain [26].

V. Piezoelectric Micro-machined Ultrasonic Transducers

Piezoelectrically actuated MEMS have the potential to simultaneously achieve large force, high working frequency, high energy density, low power consumption, and no electromagnetic interference, which make them suitable for applications in space or nuclear reactors. A common piezoelectric MEMS application is the Piezoelectric Micro-machined Ultrasonic Transducers (pMUTs). pMUT-based resonators can be used to generate signals of a precise frequency.

The materials operate on the principle of conversion between applied forces, which rearrange internal dipole charge distributions resulting in an external net potential (voltage) change, and vice versa. Previous work in the relevant material systems indicate that a high concentration of defects tends to exist in a typical as-processed PZT films, particularly at the interfaces with the adjacent electrode materials, and usually associated with acceptor oxygen vacancy complexes [66]. Radiation-induced charge can become trapped in these pre-existing defects near the PZT/electrode interface [67]. The trapped charges change the strain and stress in the PZT membrane due to the reverse piezoelectric effect, and therefore can lead to a shift the resonant frequency.

pMUT arrays fabricated using a combination of thin film and bulk micromachining processes on a 4 inch SOI wafer and were irradiated at Vanderbilt University with 10 keV X-rays [68]. Results showed the resonant frequency and capacitance changes with increasing X-ray dose are dependent on the magnitude and polarity of the applied bias during exposure. The calculated surface charge density σ shows similar trends, indicating that the resonant frequency shifts are closely related to the buildup of radiation-induced charge. Further work will be done with similarly fabricated micromirrors.

VI. Nano-optomechanical Systems

Unlike the majority of MEMS/NEMS devices which operate in capacitive or piezoelectric actuation modes, nano-optomechanical (NOMS) use light to actuate and interrogate nanomechanical devices, and thus requires no metallic or doped electrodes. Reduced parasitic effects and cross-talk due to electromagnetic interference are also among the recognized benefits of NOMS [69]–[73]. In addition, optical readout also offers unparalleled high measurement precision for sensing and transduction.

When non-electrical actuation schemes (including optical methods) are implemented, radiation-induced mechanical degradation of MEMS/NEMS structural materials constitutes the primary cause of system performance deterioration or baseline drift. Nevertheless, studies on the impact of structural material degradation on MEMS/NEMS reliability have only been reported for a small set of materials [16], [74], [12], [75]–[78], [14], and fundamental insights into the material transformations that account for the measured property modification are still lacking. In this regard, NOMS present unique advantages to isolating mechanical damaging effects caused by radiation and correlate the observed property change with corresponding material defect identities.

NOMS allows accurate quantification of radiation damage caused by intrinsic material mechanical property change rather than extrinsic factors such as malfunctioning of drive and control electronics which account for many instances of radiation-induced MEMS/NEMS failure. The materials used in NOMS are relatively simple, including only one or at most two types of materials (e.g., Si, SiN, or SiO₂) and usually do not involve metals or doped semiconductors. Therefore, the investigation of radiation effect can be focused on the key structural materials for MEMS/NEMS, avoiding ambiguity in interpretation of the results. NOMS interrogation can be coupled with in-situ micro-analytical techniques such as micro-Raman spectroscopy and correlative light/electron microscopy to elucidate the structural origin for measured property variations.

In addition to being a preferred test vehicle to extract general information applicable to MEMS/NEMS materials and system design, NOMS are anticipated to be a comparatively radiation resistant platform since they are immune to dielectric charging common in M&NEMS failures [1], [13]. NOMS sensors can be deployed at the radiation site and monitored remotely in real-time using optical fibers while leaving the testing equipment in a radiation-free environment. This configuration is useful for in-situ characterization of NOMS devices during radiation exposure and potential applications such as temperature and pressure sensing inside nuclear reactors [79].

Figure 9a schematically illustrates an archetypal NOMS testing device consisting of a pair of grating couplers for light input/output and an optical waveguide. A section of the waveguide is suspended from the substrate via undercut etching.

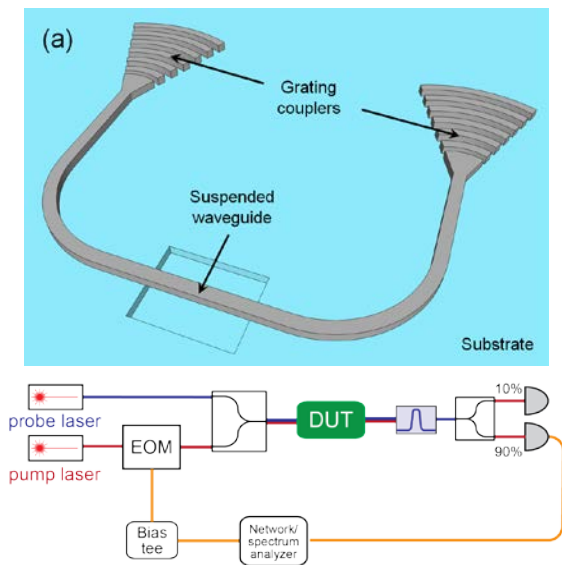


Figure 9: (a) Schematic illustration of a NOMS testing device; (b) block diagram of the NOMS measurement setup.

Interaction of the optical mode propagating in the waveguide and the substrate produces a transverse gradient optical force acting on the waveguide towards the substrate [2]. The use of grating couplers enables a multitude of devices to be interrogated in parallel using a standard fiber-optic array interface. Figure 9b illustrates the device characterization setup using a pump-probe configuration. During testing, a modulated pump laser beam is coupled into the waveguide that generates optical force to actuate the mechanical oscillation of the suspended waveguide section. Displacement of the suspended waveguide leads to a spectral shift of Fabry-Perot fringes formed between the input and output grating couplers, and the resulting intensity oscillation in the temporal domain is monitored using a probe laser light. For real-time tracking of the resonance frequency, a phase-locked loop setup can be implemented.

To quantify the undamped mechanical resonance frequency and quality factor, the measurement will be conducted in moderate vacuum ($< 10^{-4}$ Torr). Since the measured parameters solely depend on elastic moduli of the waveguide material, results obtained from irradiated and as-fabricated devices can be compared to assess

radiation-induced effects in the waveguide material. However, the radiation-induced effect may be submerged by the thermal drift of the mechanical resonance frequency. To suppress such noises, the temperature coefficient of frequency (TCF) of the device need to be minimized and accounted for by careful calibration during the study. Besides suspended waveguides, other NOMS device platforms including cantilevers, clamped-clamped beams, and torsional paddles can be similarly used for radiation hardness testing to reveal intrinsic material property modifications due to radiation.

Three structural materials that are ubiquitously used in MEMS/NEMS, namely Si (including a-Si), silicon mononitride (SiN) and silicon carbide (SiC) are currently being tested using the NOMS platform at Massachusetts Institute of Technology. All three materials provide high refractive indices and excellent optical transparency in the infrared for making optical waveguide devices. The optical interrogation method has been used to quantify optical refractive index modification induced by Co-60 γ -radiation in these materials as shown in Figure 10. In addition, the optical interrogation identified surface oxidation as the main mechanism accounting for the observed refractive index change, which is confirmed by X-ray photoelectron spectroscopy (XPS) analysis. Characterizations of the material mechanical properties are currently underway.

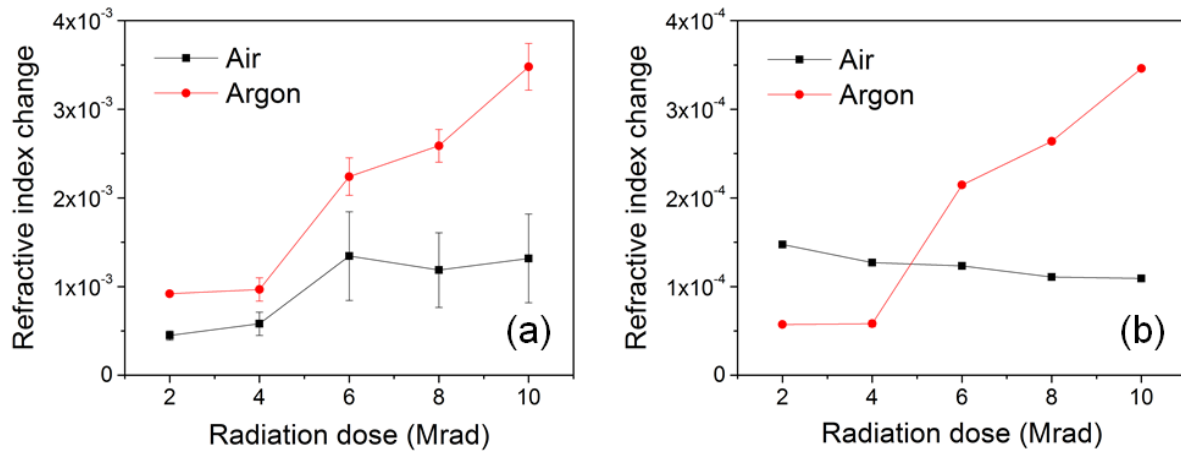


Figure 10: Measured material refractive index change induced by Co-60 gamma-radiation for (a) a-Si (hydrogenated amorphous silicon); and (b) silicon nitride.

VII. Conclusions

Advances in materials and fabrication technologies have dramatically expanded the possibilities for applications of M&NEMS, including more intimate integration with electronic circuits. While silicon has been the workhorse for such devices, largely due to the dominant fabrication and materials knowledge infrastructure due to silicon microelectronics, an array of material are now being pursued and deployed for M&MEMs including SiC, III-V materials, thin-film piezoelectric and ferroelectric, electro-optical and 2D atomic crystals such as graphene, BN, and MoS₂. The miniaturization, functionality and low-power operation offered by these types of devices are attractive for many applications areas including medical, space and military uses, here exposure to radiation is a reliability consideration. In addition, M&NEMS-based logic devices have potential to have high inherent resistance to transient radiation effects such as single-event effects found in space environments. Developing an understanding of the impact of radiation on the materials and device operation is a requisite along the path to adoption for applications in radiation environments. M&NEMS present unique considerations and challenges for experimental characterization as noted in this paper, and exciting opportunities for researchers such as the ones involved in the projects associate with the work described here to develop new approaches to address these challenges and advance the understanding of the mechanisms of the radiation effects and manifestations in the operation on M&NEMS.

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