IOP Publishing Semiconductor Science and Technology
Semicond. Sci. Technol. 32 (2017) 013005 (14pp) doi:10.1088/1361-6641/32/1/013005

Topical Review

The study of radiation effects in emerging micro and nano electro mechanical systems (M and NEMs)

Charles N Arutt[1,15], Michael L Alles[1], Wenjun Liao[1], Huiqi Gong[1], Jim L Davidson[1], Ronald D Schrimpf[1], Robert A Reed[1], Robert A Weller[1], Kirill Bolotin[2], Ryan Nicholl[2], Thang Toan Pham[3], Alex Zettl[3], Du Qingyang[4], Juejun Hu[4], Mo Li[5], Bruce W Alphenaar[6], Ji-Tzuoh Lin[6], Pranoy Deb Shurva[6], Shamus McNamara[6], Kevin M Walsh[6], Philip X-L Feng[7], Louis Hutin[8], Thomas Ernst[8], Brian D Homeijer[9], Ronald G Polcawich[10], Robert M Proie[10], Jacob L Jones[11], Evan R Glaser[12], Cory D Cress[12] and Nazanin Bassiri-Gharb[13,14]

[1] Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN 37235, USA
[2] Department of Physics, Vanderbilt University, Nashville, TN 37235, USA
[3] Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA
[4] Department of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[5] Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA
[6] Department of Electrical and Computer Engineering, University of Louisville, Louisville, KY 40292, USA
[7] Department of Electrical and Computer Engineering, Case Western Reserve University (CWRU), Cleveland, OH 44106, USA
[8] CEA-Leti, MINATEC Campus, 17 rue des Martyrs, F-38054, Grenoble Cedex 9, France
[9] Sandia National Laboratories, Albuquerque, NM 87123, USA
[10] Army Research Laboratory, Adelphi, MD 20783, USA
[11] Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC 27695, USA
[12] Electronics Science & Technology Division, Naval Research Laboratory, Washington, DC 20375, USA
[13] G W Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[14] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

E-mail: charles.n.arutt@vanderbilt.edu

Received 30 June 2016, revised 6 October 2016
Accepted for publication 17 October 2016
Published 9 December 2016

Abstract

The potential of micro and nano electromechanical systems (M and NEMS) has expanded due to advances in materials and fabrication processes. A wide variety of materials are now being pursued and deployed for M and NEMS including silicon carbide (SiC), III–V materials, thin-film piezoelectric and ferroelectric, electro-optical and 2D atomic crystals such as graphene, hexagonal boron nitride (h-BN), and molybdenum disulfide (MoS_2). The miniaturization,

[15] Author to whom any correspondence should be addressed.

functionality and low-power operation offered by these types of devices are attractive for many application areas including physical sciences, medical, space and military uses, where exposure to radiation is a reliability consideration. Understanding the impact of radiation on these materials and devices is necessary for applications in radiation environments.

Keywords: MEMS, NEMS, radiation effects, silicon carbide (SiC), 2D materials, micromachined cantilevers

(Some figures may appear in colour only in the online journal)

1. Introduction

Advances in fabrication techniques and material science present new opportunities for micro- and nano-scale electromechanical systems (M and 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 [1–5]. 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 [6]. 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 with characteristic dimensions of tens to hundreds of micrometers (compared to tens of nanometers in today's digital electronic device technologies) [7].

While the physics of the interaction of radiation with the constituent materials may be the same in electrical and M and 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 [7–9]. An interesting intersection between these applications and device types is the use of M and NEMS as logic devices [1–5].

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 [7]. While degradation due to total ionizing dose (TID) radiation exposure has appeared most commonly at doses as low as 10–100 krad (SiO_2), certain devices have demonstrated operation up to 3 Mrad (SiO_2) [7, 10–14]. 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 [12, 15–19]. In particular, radiation-induced changes in the Young's modulus of MEMS cantilevers [15, 16] and behavior modification in RF switches [17]. 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 poly crystalline silicon [17]. Trapped charges in insulators have been shown to shift the output voltage of MEMS accelerometers under proton irradiation [12]. On the other hand, MEMS-based microengines have been shown to perform at radiation doses up to 10 Mrad (Si) [12].

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 [7, 20, 21]. Trapped charge in the oxide around the piezoresistor can induce a depletion region in the semiconductor causing an increase in the resistance [20]. 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 [7, 22]. 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 [11].

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, SiO_2 and SiN, polysilicon, and some polymers [7]. 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 [23].

The pervasiveness of M and 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 [24], and Sandia National Laboratory has efforts in the construction of radiation-hardened inertial sensors [25]. The US 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 and 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 and NEMS operation. This paper highlights the types of considerations and challenges of many of these ongoing studies.

2. M and NEM operating principles, materials, and radiation

In general, operation of M and 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 [7]. 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 and 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, MoS_2, BN, and others [26, 27].

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 and NEMS operation [8, 9]. The key to understanding the effects of radiation on M and 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 and NEM resonator [7, 28, 29].

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 [8, 9], the unique requirements for many M and 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 [30, 31]. 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 and NEM materials and devices. For theoretical modeling of M and 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 [8, 9]. 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.

3. 2D materials, N and MEMS, and radiation

Two-dimensional atomic crystals (2DACs) including graphene, monolayer hexagonal boron nitride (h-BN) and molybdenum disulfide (MoS_2) are promising for M and NEMS applications [26]. 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 [27]. 2D 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% [32] and monolayer MoS_2 up to 18% [33] 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 operating at frequencies higher than 1 GHz. 2D materials 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 [34–37].

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 [38, 39]. While regions near supporting or contact structures may play a role, more generally for use in M and 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 [40].

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 [41–43]. 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 [44]. 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 and 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 [41–43]. 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 multilayer structures defects in a given layer may be passivated by interaction with the linked adjacent layers [45]. 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 in the nature of the defects short-range versus long-range electrical scattering effects.

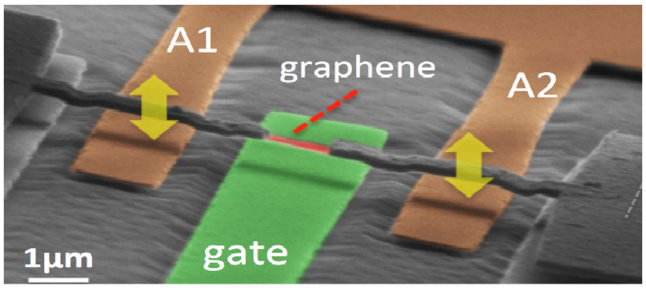

Figure 1. A platform for simultaneous probing of electrical transport and mechanical properties of 2D materials.

Researchers at Vanderbilt are also studying the mechanical properties of circular 2DAC membranes. [46]. 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) [32, 47]. Raman spectroscopy is used to determine the number of layers of graphene and defect density following the methods of Cançado *et al* [48]. The fabrication and characterization approach can be applied to multi- and monolayer graphene, as well as BN, and MoS_2 and their heterostuctures, 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 *in-situ* 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. 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

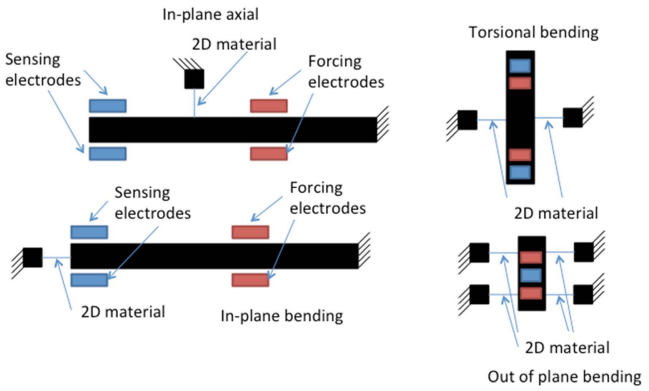

Figure 2. The platform, to characterize other materials to be fabricated using conventional micromaching/MEMS techniques, is designed to use single crystal silicon as a supporting structure for 2D materials. Geometry can be configured to apply either axial, bending or torsion strain to the 2D material.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

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 micromachining 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.

As noted previously, simulation of radiation interactions with materials is complex and not readily accessible in commercial software packages compared to simulations of M and 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 [49, 50]. For simulation of displacement damage due to energetic particles in 2DACs, the commonly used stopping range on ions in Mmatter (SRIM) package [51] 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 mono-layer 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.

4. Resonators

MEMS resonators potentially provide a low cost, single-chip alternative to quartz–crystal resonators for clocks or frequency references in RF communication systems [52]. MEMS resonators can also be used as highly sensitive and selective bio-chemical or gas sensors [53]. MEMS logic and memory elements can be made from nonlinear resonators in which multiple states exist [2, 54].

The resonant properties of M and 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 MoS_2 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.

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 (SOI) substrate and employing a piezo-resistive sensing mechanism, developed by researchers at the University of Louisville [55]. 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 and 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 [56], the variations of geometries and materials of interest, and accessibility of the material layers of interest for some

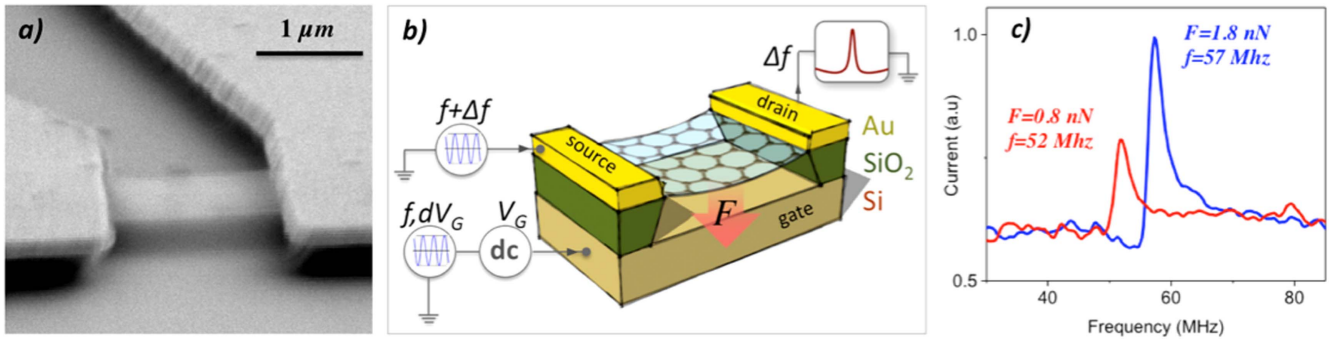

Figure 3. Graphene NEMS resonators. (a) SEM image of a suspended graphene resonator device. A single layer sheet of graphene (middle) is supported by two gold electrodes. A silicon back gate electrode is located under graphene. (b) Cartoon view of the device. Mechanical oscillations of suspended graphene 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.

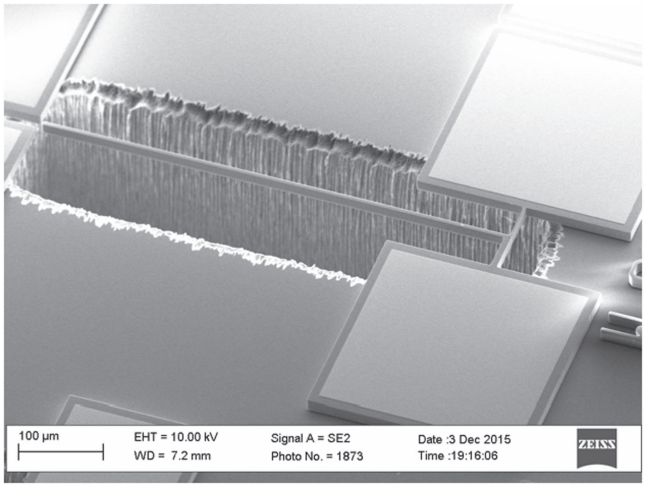

Figure 4. Scanning electron microscope (SEM) image of test resonator structure.

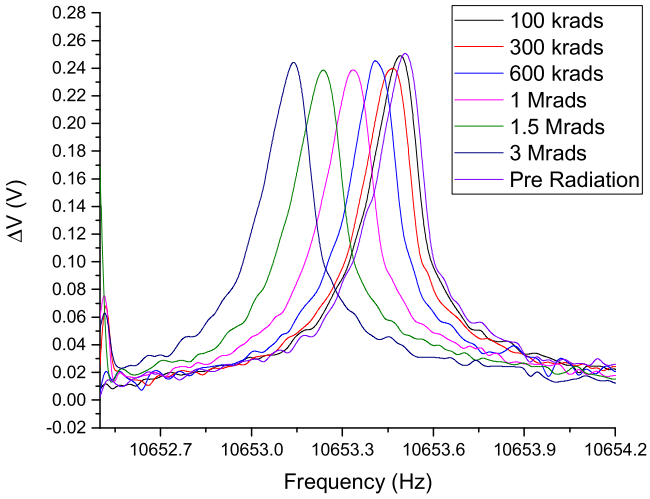

Figure 5. Effect of x-ray radiation on resonant frequency.

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 10-keV x-ray source at Vanderbilt while 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 versus 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(SiO_2) min^{-1}. After a 10 h 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/depassivation, persistent photoionization (modification of carrier densities), and gas ionization and adsorption being considered.

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. 2D MoS_2 drumhead nanomechanical resonators vibrating at megahertz (MHz) frequencies have been irradiated with gamma rays. Upon exposure over 24 or 12 h, the MoS_2 resonators exhibited ~1.3%–2.1% resonance frequency upshifts [57]. The

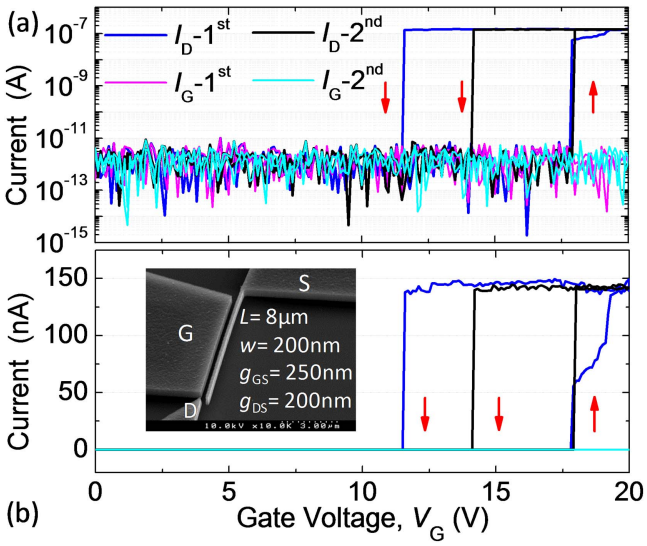

Figure 6. First two switching cycles with hysteresis, measured in a SiC NEMS switch, with currents in logarithmic scale (a) and linear scale (b), respectively. Inset of (b) is an SEM image of the actual device, with dimensions listed.

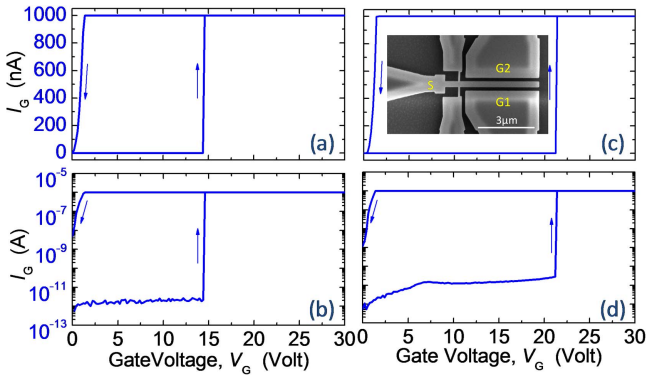

Figure 7. Example of thin SOI NEMS—measured switching behavior of a cantilever-SiNW cross-beam structure with length $L \approx 5\ \mu$m, width $w \approx 300$ nm and air gap $g \approx 250$ nm actuated by V_G applied to G1. (a) and (b) First cycle, in linear and logarithmic scale. (c) and (d) Second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

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 for electronic devices that might be used, for example, in digital logic circuits.

5. 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 [1, 3, 23, 58–65] 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 photocurrents). Very little work has been done in the study of radiation effects mechanisms 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 demonstrated robust SiC NEMS logic devices with record longevity in ambient air, at both room and high temperatures (∼500 °C) as shown in benchmarking data presented in figure 6 [4, 58–61]. 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 [66–68] 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 on 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 6(b) illustrates the configuration of the gate-controlled electrostatic nanocantilever for realizing three-terminal lateral NEMS switches. Most devices have thicknesses, widths, and gaps ∼200–300 nm or smaller.

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 7(c), inset), also electrostatically coupled to two gates. All devices are made by 8″-wafer-scale manufacturing in a 160 nm thick 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 and DUV lithography and reactive ion etching 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 have developed 4- and 6-terminal relays that exhibits steep switching behavior, hysteresis, and a large on/off current ratio [4, 5, 69]. In principle, this configuration has the

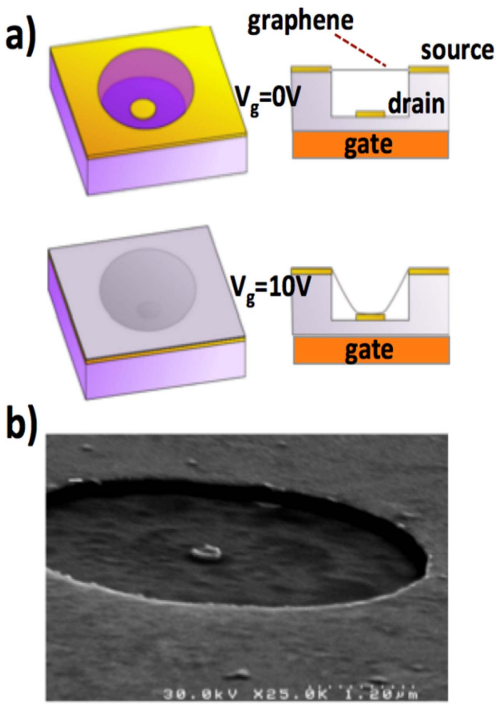

Figure 8. 2DAC NEMS switches: (a) device operation. (b) SEM image of a finished device.

potential to operate at extremely low voltages and may be able to use less energy than CMOS logic [70]. 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 [5, 71]. Failure mechanisms of these devices have been explored and show that a 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 [69]. 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.

2DACs also have the potential to serve as logic switches. When deposited on an insulator, 2DAC materials have an adhesion force that will keep them in place [72]. 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 10 V 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 [34].

6. Piezoelectric MEMS

Piezoelectric MEMS devices, based on lead zirconate titanate (PZT), potentially offer lower voltage operation, larger temperature range stability, a reduced sensitivity to electromagnetic fields, and greater scalability in comparison to traditional electrostatic- and magnetic-based MEMS. Furthermore, the extremely large piezoelectric and dielectric response of PZT presents an opportunity for integrating multiple functionalities at the micron and nanometer scale, including sensing and actuation capabilities, energy harvesting for self-powered devices, miniaturized multilayer capacitors, and logic control mechanical relays. 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. This multi-functional nature presents a pathway towards a 'More than Moore' era, yielding a 'radiation insensitive PZT-based MEMS/NEMS alternative to traditional CMOS with reduced size, weight, and power requirements for military systems operating in extreme environments, especially extreme radiation environments.'

Many factors suggest that computational systems based on piezoelectric MEMS/NEMS technologies are inherently more robust in extreme radiation environments, especially in regards to single-event-effects and the ability to operate *during* radiation exposure, than traditional CMOS technology. This has been supported, in part, by recent systematic efforts examining the fundamental radiation induced response of PZT films and the electromechanical response of PZT MEMS logic devices [73–75]. In particular, the PZT-based mechanical logical devices displayed remarkable robustness, switching properly during active radiation exposure (dose rate = 856 rad(Si) s^{-1}), finally failing at a TID that exceeded 15 Mrad(Si) [74]. Nevertheless, gradual degradation in key dielectric, ferroelectric, and electromechanical responses are observed, and the atomic-scale origin of the radiation-induced material and device damage remain largely unknown. Thus, there is a fundamental knowledge gap in this potentially transformative technology, thereby motivating continued comprehensive radiation effects studies aimed at deconvoluting the basic mechanisms of these intrinsically multi-functional materials.

Figure 9 provides a summary of the many potential radiation vulnerabilities associated with three different functional locations within a piezoMEMS structure; the complexity of the analysis may also be inferred from the figure. Based on prior work, the ultimate failure of the device likely results from accumulated damage in the piezoelectric active layer, through defect-domain wall interactions, which diminish its electromechanical response. In a relay, the

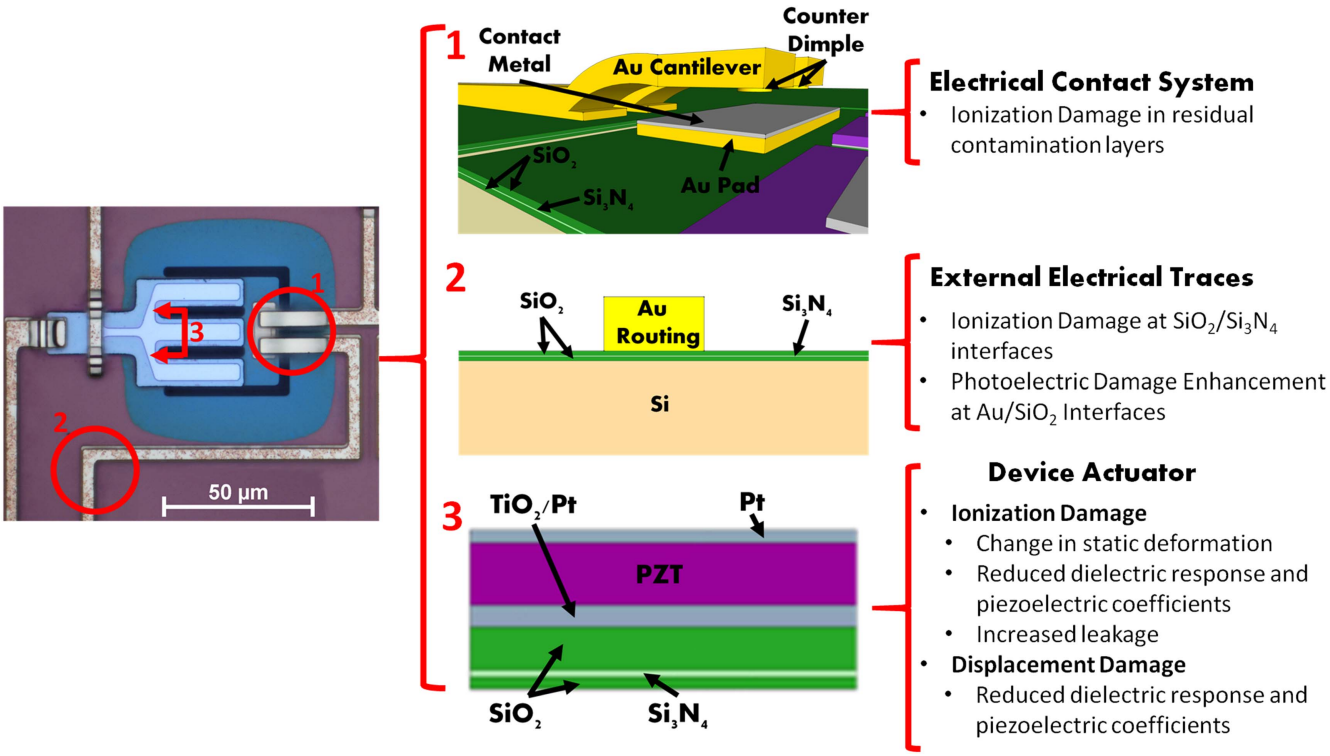

Figure 9. Schematic representation of a piezoMEMS mechanical logic architecture and impact of radiation on various functional locations.

reduction of the piezoelectric coefficient manifests as an increase in actuation voltage needed to open or close the relay. Radiation-induced alteration of the concentration and spatial distribution of defects can affect both the intrinsic (i.e. lattice strain) and extrinsic (e.g., domain walls' motion contribution) electromechanical responses. Domain wall motion is known to give rise to a significant fraction of the electromechanical response of PZT (up to and exceeding 50%) [76], making the FE response to radiation critically important to the functionality of MEMS/NEMS. In the actuator (feature 3 in figure 9), the Pt electrodes shield the active PZT layer from the $SiO_2/Si_3N_4/SiO_2$ elastic layer, therefore, trapped charges in the elastic layer will have no *direct* impact on the actuation voltage. However, trapped charges may alter the local ground potential of the actuators in reference to the support electrical traces (feature 2 in figure 9), and thereby may lead to cross-talk interactions if separation between traces is too small. It is clear from this investigation that the study of radiation-induced effects in piezoMEMS devices presents an exciting area of research that will enable researchers to develop devices that achieve greater robustness and greater performance.

Another 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 [77]. Radiation-induced charge can become trapped in these pre-existing defects near the PZT/electrode interface [78]. 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 in the resonant frequency.

pMUT arrays fabricated using a combination of thin film and bulk micromachining processes on a 4 inch SOI wafer were irradiated at Vanderbilt University with 10 keV x-rays [28]. 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.

7. 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 [79–83]. 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 [15, 17, 19, 74–88] 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 SiO_2) 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 and NEMS failures [7, 16]. 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 [89].

Figure 10(a) 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. 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 [1]. The use of grating couplers enables a multitude of devices to be interrogated in parallel using a standard fiber-optic array interface. Figure 10(b) illustrates the device characterization setup using a pump-probe configuration. During testing, a modulated pump laser beam is coupled into the waveguide that generates an 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.

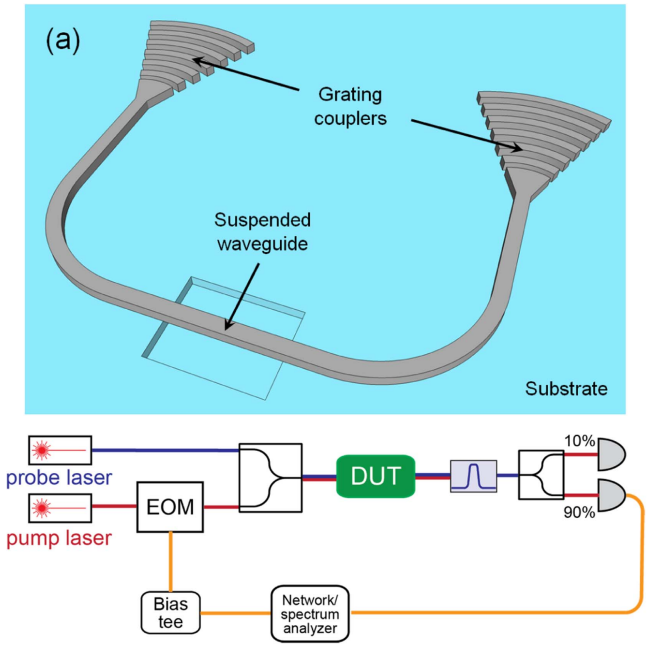

Figure 10. (a) Schematic illustration of a NOMS testing device; (b) block diagram of the NOMS measurement setup.

To quantify the undamped mechanical resonance frequency and quality factor, the measurement is 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 of the devices 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 11. 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 analysis. Characterizations of the material mechanical properties are currently underway.

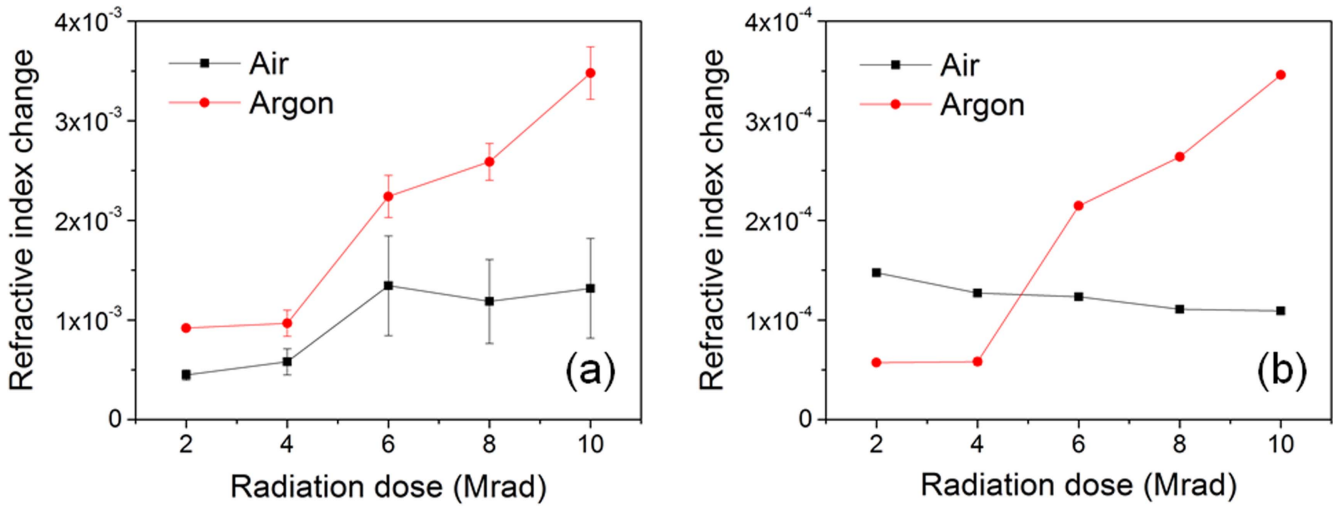

Figure 11. Measured material refractive index change induced by Co-60 gamma-radiation for (a) a-Si (hydrogenated amorphous silicon); and (b) silicon nitride.

8. Conclusions

Advances in materials and fabrication technologies have dramatically expanded the possibilities for applications of M and 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 materials are now being pursued and deployed for M and MEMs including SiC, III–V materials, thin-film piezoelectric and ferroelectric, electro-optical and 2D atomic crystals such as graphene, BN, and MoS_2. 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 and 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 and 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 associated 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 of M and NEMS.

Acknowledgments

This work is supported by the Defense Threat Reduction Agency Basic Research Program, Grants number: HDTRA1-15-1-0027, HDTRA1-15-1-0035, HDTRA1-15-1-0036, HDTRA1-15-1-0039, and HDTRA1-15-1-0060.

References

[1] Feng X L, Matheny M H, Zorman C A, Mehregany M and Roukes M L 2010 Low voltage nanoelectromechanical switches based on silicon carbide nanowires *Nano Lett.* **10** 2891–6

[2] Yao A and Hikihara T 2014 Logic-memory device of a mechanical resonator *Appl. Phys. Lett.* **105** 123104

[3] Newman L H 2013 Silicon carbide nanomechanical switches built to last *IEEE Spectrum: Technology, Engineering, and Science News* http://spectrum.ieee.org/semiconductors/devices/silicon-carbide-nanomechanical-switches-built-to-last (accessed: 17 June 2016)

[4] Yaung J, Hutin L, Jeon J and Liu T J K 2014 Adhesive force characterization for MEM logic relays with sub-micron contacting regions *J. Microelectromech. Syst.* **23** 198–203

[5] Nathanael R, Pott V, Kam H, Jeon J and Liu T J K 2009 4-terminal relay technology for complementary logic *2009 IEEE Int. Electron Devices Meeting (IEDM)* pp 1–4

[6] Bustillo J M, Howe R T and Muller R S 1998 Surface micromachining for microelectromechanical systems *Proc. IEEE* **86** 1552–74

[7] Shea H R 2011 Effects of radiation on MEMS *Proc. SPIE* **7928** 79280E

[8] Srour J R, Marshall C J and Marshall P W 2003 Review of displacement damage effects in silicon devices *IEEE Trans. Nucl. Sci.* **50** 653–70

[9] Fleetwood D M 2013 Total ionizing dose effects in MOS and low-dose-rate-sensitive linear-bipolar devices *IEEE Trans. Nucl. Sci.* **60** 1706–30

[10] Lee C I, Johnston A H, Tang W C, Barnes C E and Lyke J 1996 Total dose effects on microelectromechanical systems (MEMS): accelerometers *IEEE Trans. Nucl. Sci.* **43** 3127–32

[11] McClure S S, Edmonds L D, Mihailovich R, Johnston A H, Alonzo P, DeNatale J, Lehman J and Yui C 2002 Radiation effects in micro-electromechanical systems (MEMS): RF relays *IEEE Trans. Nucl. Sci.* **49** 3197–202

[12] Edmonds L D, Swift G M and Lee C I 1998 Radiation response of a MEMS accelerometer: an electrostatic force *IEEE Trans. Nucl. Sci.* **45** 2779–88

[13] Miyahira T F, Becker H N, McClure S S, Edmonds L D, Johnston A H and Hishinuma Y 2003 Total dose degradation of MEMS optical mirrors *IEEE Trans. Nucl. Sci.* **50** 1860–6

[14] Knudson A R, Buchner S, McDonald P, Stapor W J, Campbell A B, Grabowski K S, Knies D L, Lewis S and Zhao Y 1996 The effects of radiation on MEMS accelerometers *IEEE Trans. Nucl. Sci.* **43** 3122–6

[15] Bandi T, Polido-Gomes J, Neels A, Dommann A, Marchand L and Shea H R 2013 Proton-radiation tolerance of silicon and SU-8 as structural materials for high-reliability MEMS *J. Microelectromech. Syst.* **22** 1395–402

[16] Shea H R 2009 Radiation sensitivity of microelectromechanical system devices *J. MicroNanolithography MEMS MOEMS* **8** 031303

[17] Wang L, Tang J and Huang Q A 2011 Gamma irradiation effects on surface-micromachined polysilicon resonators *J. Microelectromech. Syst.* **20** 1071–3

[18] Buchner S *et al* 2007 Response of a MEMS microshutter operating at 60 K to ionizing radiation *IEEE Trans. Nucl. Sci.* **54** 2463–7

[19] Schanwald L P, Schwank J R, Sniegowsi J J, Walsh D S, Smith N F, Peterson K A, Shaneyfelt M R, Winokur P S, Smith J H and Doyle B L 1998 Radiation effects on surface micromachined comb drives and microengines *IEEE Trans. Nucl. Sci.* **45** 2789–98

[20] Holbert K E, Nessel J A, McCready S S, Heger A S and Harlow T H 2003 Response of piezoresistive MEMS accelerometers and pressure transducers to high gamma dose *IEEE Trans. Nucl. Sci.* **50** 1852–9

[21] McCready S S, Harlow T H, Heger A S and Holbert K E 2002 Piezoresistive micromechanical transducer operation in a pulsed neutron and gamma ray environment *2002 IEEE Radiation Effects Data Workshop* pp 181–6

[22] Marinaro D G, McMahon P and Wilson A 2008 Proton radiation effects on MEMS silicon strain gauges *IEEE Trans. Nucl. Sci.* **55** 1714–8

[23] Feng P X L 2015 NEMS switches: opportunities and challenges in emerging IC technologies *2015 Int. Conf. on IC Design Technology (ICICDT)* pp 1–6

[24] Collaborations to Develop Miniaturization Technologies for Space Exploration | Nano and Micro Systems | Capabilities | Microdevices Laboratory | NASA Jet Propulsion Laboratory California Institute of Technology (Online) available: http://microdevices.jpl.nasa.gov/capabilities/nano-and-micro-systems/miniaturization-technologies.php (accessed: 27 June 2016)

[25] Sandia National Laboratories: MicroElectroMechanical Systems (MEMS) (Online) available: http://sandia.gov/mstc/mems/ (accessed: 27 June 2016)

[26] Novoselov K S, Jiang D, Schedin F, Booth T J, Khotkevich V V, Morozov S V and Geim A K 2005 Two-dimensional atomic crystals *Proc. Natl Acad. Sci. USA* **102** 10451–3

[27] Butler S Z *et al* 2013 Progress, challenges, and opportunities in two-dimensional materials beyond graphene *ACS Nano* **7** 2898–926

[28] Liao W, Zhang E X, Alles M L, Zhang C X, Gong H, Ni K, Sternberg A L, Fleetwood D M, Reed R A and Schrimpf R D Total ionizing dose effects on piezoelectric micromachined ultrasonic transducers *IEEE Trans. Nucl. Sci.* accepted

[29] Gong H *et al* Total-ionizing-dose effects in piezoresistive micromachined cantilevers *IEEE Trans. Nucl. Sci.* accepted

[30] Blondy P, Crunteanu A, Pothier A, Tristant P, Catherinot A and Champeaux C 2007 Effects of atmosphere on the reliability of RF-MEMS capacitive switches *Microwave Conf., 2007 (European, Munich)* pp 1346–8

[31] Lamhamdi M, Pons P, Zaghloul U, Boudou L, Coccetti F, Guastavino J, Segui Y, Papaioannou G and Plana R 2008 Voltage and temperature effect on dielectric charging for RF-MEMS capacitive switches reliability investigation *Microelectron. Reliabil.* **48** 1248–52

[32] Lee C, Wei X, Kysar J W and Hone J 2008 Measurement of the elastic properties and intrinsic strength of monolayer graphene *Science* **321** 385–8

[33] Castellanos-Gomez A, Poot M, Steele G A, van der Zant H S J, Agraït N and Rubio-Bollinger G 2012 Elastic properties of freely suspended MoS_2 nanosheets *Adv. Mater.* **24** 772–5

[34] Chen C, Lee S, Deshpande V V, Lee G-H, Lekas M, Shepard K and Hone J 2013 Graphene mechanical oscillators with tunable frequency *Nat. Nanotechnol.* **8** 923–7

[35] Zhou Q and Zettl A 2013 Electrostatic graphene loudspeaker *Appl. Phys. Lett.* **102** 223109

[36] Jensen K, Weldon J, Garcia H and Zettl A 2007 Nanotube radio *Nano Lett.* **7** 3508–11

[37] Jensen K, Kim K and Zettl A 2008 An atomic-resolution nanomechanical mass sensor *Nat. Nanotechnol.* **3** 533–7

[38] Zhang C X, Zhang E X, Fleetwood D M, Alles M L, Schrimpf R D, Song E B, Galatsis K, Newaz A K M and Bolotin K I 2013 Total ionizing dose effects and reliability of graphene-based non-volatile memory devices *2013 IEEE Aerospace Conf.* pp 1–8

[39] Zhang C X, Zhang E X, Fleetwood D M, Alles M L, Schrimpf R D, Song E B, Kim S M, Galatsis K and Wang K L W 2012 Electrical stress and total ionizing dose effects on graphene-based non-volatile memory devices *IEEE Trans. Nucl. Sci.* **59** 2974–8

[40] Banhart F, Kotakoski J and Krasheninnikov A V 2011 Structural defects in graphene *ACS Nano* **5** 26–41

[41] Chang C W, Okawa D, Garcia H, Majumdar A and Zettl A 2007 Nanotube phonon waveguide *Phys. Rev. Lett.* **99** 045901

[42] Demczyk B G, Wang Y M, Cumings J, Hetman M, Han W, Zettl A and Ritchie R O 2002 Direct mechanical measurement of the tensile strength and elastic modulus of multiwalled carbon nanotubes *Mater. Sci. Eng.* A **334** 173–8

[43] Jensen J 2007 Static and dynamic Jahn–Teller effects and antiferromagnetic order in PrO_2: a mean-field analysis *Phys. Rev.* B **76** 144428

[44] Pham T, Gibb A L, Gilbert S M, Song C and Zettl A 2016 Formation and dynamics of electron-irradiation-induced defects in hexagonal boron nitride at elevated temperatures *Materials Research Society Spring Meeting (Phoenix, Arizona)* (Spring) presented at the

[45] Liu K *et al* 2015 Self-passivation of defects: effects of high-energy particle irradiation on the elastic modulus of multilayer graphene *Adv. Mater.* **27** 6841–7

[46] Nicholl R J T, Conley H J, Lavrik N V, Vlassiouk I, Puzyrev Y S, Sreenivas V P, Pantelides S T and Bolotin K I 2015 The effect of intrinsic crumpling on the mechanics of free-standing graphene *Nat. Commun.* **6** 8789

[47] Ruiz-Vargas C S, Zhuang H L, Huang P Y, van der Zande A M, Garg S, McEuen P L, Muller D A, Hennig R G and Park J 2011 Softened elastic response and unzipping in chemical vapor deposition graphene membranes *Nano Lett.* **11** 2259–63

[48] Cançado L G, Jorio A, Ferreira E H M, Stavale F, Achete C A, Capaz R B, Moutinho M V O, Lombardo A, Kulmala T S and Ferrari A C 2011 Quantifying defects in graphene via Raman spectroscopy at different excitation energies *Nano Lett.* **11** 3190–6

[49] Puzyrev Y S, Wang B, Zhang E X, Zhang C X, Newaz A K M, Bolotin K I, Fleetwood D M, Schrimpf R D and Pantelides S T 2012 Surface reactions and defect formation in irradiated graphene devices *IEEE Trans. Nucl. Sci.* **59** 3039–44

[50] Zhang E X, Newaz A K M, Wang B, Zhang C X, Fleetwood D M, Bolotin K I, Schrimpf R D, Pantelides S T and Alles M L 2012 Ozone-exposure and

annealing effects on graphene-on-SiO_2 transistors *Appl. Phys. Lett.* **101** 121601
[51] James Ziegler—SRIM & TRIM (Online) available: http://srim.org/ (accessed: 27 June 2016)
[52] Uranga A, Verd J and Barniol N 2015 CMOS–MEMS resonators: from devices to applications *Microelectron. Eng.* **132** 58–73
[53] Waggoner P S and Craighead H G 2007 Micro- and nanomechanical sensors for environmental, chemical, and biological detection *Lab. Chip* **7** 1238–55
[54] Xu Y, Lin J-T, Alphenaar B W and Keynton R S 2006 Viscous damping of microresonators for gas composition analysis *Appl. Phys. Lett.* **88** 143513
[55] Shurva P D, McNamara S, Lin J T, Alphenaar B, Walsh K and Davidson J Axial asymmetry for improved sensitivity in MEMS piezoresistors *J. Micromech. Microeng.* **26** 095014
[56] Stanford Micro Structures Sensors Lab (Online) available: http://micromachine.stanford.edu/?p=projects&id=17 (accessed: 27 June 2016)
[57] Lee J, Krupcale M J and Feng P X-L 2016 Effects of γ-ray radiation on two-dimensional molybdenum disulfide (MoS_2) nanomechanical resonators *Appl. Phys. Lett.* **108** 023106
[58] He T, Yang R, Ranganathan V, Rajgopal S, Tupta M A, Bhunia S, Mehregany M and Feng P X L 2013 Silicon carbide (SiC) nanoelectromechanical switches and logic gates with long cycles and robust performance in ambient air and at high temperature *2013 IEEE Int. Electron Devices Meeting* pp 1–4
[59] Engineering researchers report on nanoscale energy-efficient switching devices *ScienceDaily* (Online) available: https://sciencedaily.com/releases/2013/12/131209160811.htm (accessed: 17 June 2016)
[60] He T, Yang R, Rajgopal S, Tupta M A, Bhunia S, Mehregany M and Feng P X L 2013 Robust silicon carbide (SiC) nanoelectromechanical switches with long cycles in ambient and high temperature conditions *2013 IEEE 26th Int. Conf. on Micro Electro Mechanical Systems (MEMS)* pp 516–9
[61] He T, Ranganathan V, Yang R, Rajgopal S, Bhunia S, Mehregany M and Feng P X L 2013 Time-domain AC characterization of silicon carbide (SiC) nanoelectromechanical switches toward high-speed operations *2013 Transducers Eurosensors XXVII: The 17th Int. Conf. on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS EUROSENSORS XXVII)* pp 669–72
[62] Feng X L, Matheny M H, Karabalin R B, Zorman C A, Mehregany M and Roukes M L 2009 Silicon carbide (SiC) top-down nanowire electromechanical resonators *TRANSDUCERS 2009–2009 Int. Solid-State Sensors, Actuators and Microsystems Conf.* pp 2246–9
[63] Feng X-L, Karabalin R B, Aldridge J S and Roukes M L 2012 Nano-electro-mechanical systems switches *US Patent* US8258899 B2
[64] Feng P X-L, Matheny M, Karbalin R and Roukes M L 2012 Very low voltage, ultrafast nanoelectromechanical switches and resonant switches *US Patent* US8115344 B2
[65] He T, Yang R, Rajgopal S, Bhunia S, Mehregany M and Feng P X L 2013 Dual-gate silicon carbide (SiC) lateral nanoelectromechanical switches *2013 8th IEEE Int. Conf. on Nano/Micro Engineered and Molecular Systems (NEMS)* pp 554–7
[66] Yang R, He T, Marcoux C, Andreucci P, Duraffourg L and Feng P X L 2013 Silicon nanowire and cantilever electromechanical switches with integrated piezoresistive transducers *2013 IEEE 26th Int. Conf. on Micro Electro Mechanical Systems (MEMS)* pp 229–32
[67] Koumela A, Hentz S, Mercier D, Dupré C, Ollier E, Feng P X-L, Purcell S T and Duraffourg L 2013 High frequency top-down junction-less silicon nanowire resonators *Nanotechnology* **24** 435203
[68] Yang R, He T, Tupta M A, Marcoux C, Andreucci P, Duraffourg L and Feng P X-L 2015 Probing contact-mode characteristics of silicon nanowire electromechanical systems with embedded piezoresistive transducers *J. Micromech. Microeng.* **25** 095014
[69] Chen Y, Nathanael R, Yaung J, Hutin L and King Liu T-J 2013 *Reliability of MEM Relays for Zero Leakage Logic* vol 8614, pp 861404–861404–7
[70] Kam H, Liu T J K, Stojanovi V, Markovic D and Alon E 2011 Design, optimization, and scaling of MEM relays for ultra-low-power digital logic *IEEE Trans. Electron Devices* **58** 236–50
[71] Qian C, Peschot A, Chen I R, Chen Y, Xu N and Liu T J K 2015 Effect of body biasing on the energy-delay performance of logic relays *IEEE Electron Device Lett.* **36** 862–4
[72] Conley H, Lavrik N V, Prasai D and Bolotin K I 2011 Graphene bimetallic-like cantilevers: probing graphene/substrate interactions *Nano Lett.* **11** 4748–52
[73] Bastani Y, Cortes-Pena A Y, Wilson A D, Gerardin S, Bagatin M, Paccagnella A and Bassiri-Gharb N 2013 Effects of high energy x ray and proton irradiation on lead zirconate titanate thin films' dielectric and piezoelectric response *Appl. Phys. Lett.* **102** 192906
[74] Proie R M, Polcawich R G, Cress C D, Sanchez L M, Grobicki A D, Pulskamp J S and Roche N J H 2013 Total ionizing dose effects in piezoelectric MEMS relays *IEEE Trans. Nucl. Sci.* **60** 4505–11
[75] Brewer S J *et al* 2016 Effect of top electrode material on radiation-induced degradation of ferroelectric thin film structures *J. Appl. Phys.* **12** 24101
[76] Bassiri-Gharb N, Fujii I, Hong E, Trolier-Mckinstry S, Taylor D V and Damjanovic D 2007 Domain wall contributions to the properties of piezoelectric thin films *J. Electroceram.* **19** 47–65
[77] Benedetto J M, Moore R A, McLean F B, Brody P S and Dey S K 1990 The effect of ionizing radiation on sol-gel ferroelectric PZT capacitors *IEEE Trans. Nucl. Sci.* **37** 1713–7
[78] Schwank J R, Nasby R D, Miller S L, Rodgers M S and Dressendorfer P V 1990 Total-dose radiation-induced degradation of thin film ferroelectric capacitors *IEEE Trans. Nucl. Sci.* **37** 1703–12
[79] Marquardt F and Girvin S M 2009 Optomechanics *Physics* **2** 40
[80] Kippenberg T J and Vahala K J 2008 Cavity optomechanics: back-action at the mesoscale *Science* **321** 1172–6
[81] Li M, Pernice W H P, Xiong C, Baehr-Jones T, Hochberg M and Tang H X 2008 Harnessing optical forces in integrated photonic circuits *Nature* **456** 480–4
[82] Li M, Pernice W H P and Tang H X 2009 Broadband all-photonic transduction of nanocantilevers *Nat. Nanotechnol.* **4** 377–82
[83] Li M, Pernice W H P and Tang H X 2010 Ultrahigh-frequency nano-optomechanical resonators in slot waveguide ring cavities *Appl. Phys. Lett.* **97** 183110
[84] Tazzoli A, Cellere G, Autizi E, Peretti V, Paccagnella A and Meneghesso G 2009 Radiation sensitivity of ohmic RF-MEMS switches for spatial applications *IEEE 22nd Int. Conf. on Micro Electro Mechanical Systems, 2009. MEMS 2009* pp 634–7
[85] Gomes J and Shea H R 2011 Displacement damage effects in silicon MEMS at high proton doses *Proc. SPIE* **7928** 79280G
[86] Niklaus M, Rosset S and Shea H 2010 Array of lenses with individually tunable focal-length based on transparent ion-implanted EAPs *Proc. SPIE* **7642** 76422K

[87] Gkotsis P, Kilchytska V, Fragkiadakis C, Kirby P B, Raskin J P and Francis L A 2012 Effects of fast neutrons on the electromechanical properties of materials used in microsystems *J. Microelectromech. Syst.* **21** 1471–83

[88] Wang L, Tang J and Huang Q-A 2012 Gamma and electron beam irradiation effects on the resistance of micromachined polycrystalline silicon beams *Sensors Actuators Phys.* **177** 99–104

[89] Fernandez A F, Gusarov A I, Brichard B, Bodart S, Lammens K, Berghmans F, Decréton M, Mégret P, Blondel M and Delchambre A 2002 Temperature monitoring of nuclear reactor cores with multiplexed fiber Bragg grating sensors *Opt. Eng.* **41** 1246–54