Friday Morning, November 11, 2016

MEMS and NEMS
Room 102B - Session MN+MS-FrM

Radiation Effect in Emerging Micro/Nano Structures, Devices, and Systems

Moderators: Michael Alles, Vanderbilt University, Philip Feng, Case Western Reserve University

8:20am **MN+MS-FrM1 Radiation Effects in Emerging MEMS/NEMS Devices***, **Jacob Calkins,*** Defense Threat Reduction Agency

Recent advance in MEMS based computing, signal filtering, and sensing offer significant opportunities for reducing the size, weight, cost, and power requirements of Department of Defense (DoD) systems while improving reliability in extreme environments. Natural and manmade high radiation environments are one of the most extreme environments where DoD systems must both survive and continue to function. This high radiation environment includes satellites in Earth orbit and robots or unmanned vehicles responding to nuclear disasters. This Defense Threat Reduction Agency (DTRA) basic research program seeks to investigate, understand, and model the fundamental effects of radiation on MEMS/NEMS devices.

Gamma rays, x-rays, as well electrons and ions are expected to deposit charge in dielectrics and may also charge the sealed gas environment in which the devices operates. Neutrons, protons, and ions may change the underlying mechanical properties, optical properties, and ferroelectric or piezoelectric properties of MEMS materials. All types of radiation may alter the surface chemistry and morphology causing changes in the performance of physical and electrical contacts. It is expected that MEMS devices will be resistant to upsets or changes in state due to individual strikes by high energy particles. However, nanoscale devices may be susceptible to either the physical impact or the associated charge deposition. It is important to understand these fundamental effects of radiation on MEMS/NEMS devices and materials before they are incorporated in critical DoD systems.

This talk introduces the DTRA basic research radiation effects program and the radiation effects in MEMS/NEMS topic.

8:40am **MN+MS-FrM2 Effect of Top Electrode Material on Radiation-Induced Degradation of Ferroelectric Thin Films***, **Nazanin Bassiri-Gharb,** S.J. Brewer, C.Z. Deng, C.P. Callaway,* Georgia Institute of Technology*; M.K. Paul,* Woodward Academy*; K.J. Fisher,* Riverwood International Charter School*; J.E. Guerrier, J.L. Jones,* North Carolina State University*; R.Q. Rudy, R.G. Polcawich,* Army Research Laboratory*; E.R. Glaser, C.D. Cress,* Naval Research Laboratory **INVITED**

The effects of gamma irradiation on the dielectric and piezoelectric responses of $Pb[Zr_{0.52}Ti_{0.48}]O_3$ (PZT) thin films were investigated for structures with conductive oxide (IrO_2) and metallic (Pt) top electrodes. All samples showed a general degradation of various key dielectric, ferroelectric, and electromechanical responses when exposed to 2.5 Mrad(Si) ^{60}Co gamma radiation. However, the low-field, relative dielectric permittivity, ε_r, remained largely unaffected by irradiation in samples with both types of electrodes. Samples with Pt top electrodes showed substantial degradation of the remanent polarization and overall piezoelectric response, as well as pinching of the polarization hysteresis curves and creation of multiple peaks in the permittivity-electric field curves post irradiation. The samples with oxide electrodes, however, were largely impervious to the same radiation dose, with less than 5% change in any of the functional characteristics. The results suggest a radiation-induced change in the defect population or defect energy in PZT with metallic top electrodes, which substantially affects motion of internal interfaces such as domain walls. Additionally, the differences observed for devices with different electrode materials implicates the ferroelectric-electrode interface as either the predominant source of radiation-induced effects (Pt electrodes) or the site of healing for radiation-induced defects (IrO_2 electrodes).

9:20am **MN+MS-FrM4 Radiation Survivability of MEMS Microelectronic Circuits with CNT Field Emitters***, **Jason Amsden**, E.J. Radauscher, T. von Windheim,* Duke University*; K.H. Gilchrist,* RTI International*; S.T. Di Dona, Z.E. Russell,* Duke University*; L.Z. Scheick,* Jet Propulsion Laboratory, California Institute of Technology*; J.R. Piascik,* RTI International*; C.B. Parker,* Duke University*; B.R. Stoner,* RTI International*; J.T. Glass,* Duke University **INVITED**

Radiation survivability of MEMS microelectronic circuits with carbon nanotube field emitters

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INVITED ABSTRACT

Solid-state technology dominates the consumer electronics market because of the low cost associated with large-scale integration. However, there are numerous applications in which solid-state devices are unreliable or do not provide adequate performance, particularly applications with military systems operating in high radiation environments. In these applications, vacuum microelectronic devices present an attractive alternative. Despite the performance advantages, the use of vacuum electronics has been limited because there is no versatile and reliable microscale platform that enables integration of large numbers of vacuum circuit elements on a single substrate. To address this need, RTI International in collaboration with Duke University has been developing a Microelectromechanical systems (MEMS) platform that enables integration of high-performance microelectronic vacuum components into functional circuits on a single silicon substrate.[1] We have demonstrated a wide variety of vacuum electronic devices including vacuum triodes and ion sources using a freestanding panel approach fabricated with the Polysilicon Multi-User MEMS Process (PolyMUMPS) with integrated carbon nanotube field emission cathodes. While these devices avoid the radiation-induced charge carrier problems in solid-state devices, other effects of radiation on this MEMS platform have not been studied. The presentation will present our preliminary findings on the radiation effects on this vacuum microelectronics platform.

1. Stoner, B. R.; Piascik, J. R.; Gilchrist, K. H.; Parker, C. B.; Glass, J. T., A Bipolar Vacuum Microelectronic Device. *Electron Devices, IEEE Transactions on* **2011**, *58*, 3189-3194.

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10:00am **MN+MS-FrM6 Radiation Effects in Integrated Photonics and Nano-OptoMechanical Systems***, Q. Du,* Massachusetts Institute of Technology*; B Li,* University of Minnesota*; D. Ma, A. Agarwal, **Juejun Hu**,* Massachusetts Institute of Technology*; M. Li,* University of Minnesota **INVITED**

We present integrated photonic devices and Nano-OptoMechanical Systems (NOMS) as highly sensitive

and accurate platforms for quantifying radiation effects in optical materials and MEMS/NEMS systems.

Our approach benefits from the high precision of optical interrogation techniques. Further, compared to

traditional capacitive or piezoelectric actuated devices, NOMS are immune to extrinsic

degradation associated with driving circuit and metal contact failure or charge-trapping in dielectrics, and

are thus ideal test vehicles to measure radiation-induced, intrinsic optical and mechanical material

property modifications. In this talk, we will discuss design, fabrication and characterization of optical and

NOMS devices based on Si, SiN and SiC materials as well as gamma-ray radiation effects in these

devices. Defect identities responsible for the observed optical and mechanical property shifts are clarified

through spectroscopy and microscopy characterization techniques to unravel the radiation damage

mechanisms in these devices.

10:40am **MN+MS-FrM8 Radiation Effects in 2D Materials and Nano Electrical Mechanical Devices***, **Michael Alles**, K.I. Bolotin,* Vanderbilt University*; A. Zettl,* University of California at Berkeley*; B. Homeijer,* Sandia National Laboratories*; J.L. Davidson, R.D. Schrimpf, R.A. Reed, R.A. Weller, D.M. Fleetwood, W. Liao, R.J. Nicholl,* Vanderbilt University **INVITED**

The dramatic reduction in size and power consumption offered by micro- and nano-scale electromechanical systems (M&NEMS) offer compelling advantages for adoption in many areas, including space and military systems. Mission reliability and survivability of next-generation space-borne systems depends critically upon a detailed understanding of the radiation response and reliability of the constituent devices when exposed to the relevant radiation environment. M&NEMS may be employed for a variety of sensor and actuation applications, oscillators, and have potential to be incorporated as high-reliability solid-state (logic) switches.

While there has been considerable study of radiation effects on some of the common materials (single and poly crystalline silicon, and silicon-dioxide), the study in the context of MEMS has been more limited, and mainly experimental. The general indication is that depending on the operating principal, MEMS can be sensitive to radiation-induced charging of insulators, and to displacement damage at very high exposure doses of energetic particles.

More recently, fabrication process, namely the ability to create nano-scale structures, and the introduction of new materials (esp. 2D and CNTs), have expanded the opportunities for M&NEMS. The Defense Threat Reduction Agency (DTRA) has recently initiated multiple projects in the study of various aspects and configurations of M&NEMS. This talk will discuss a specific project which seeks to advance the understanding of the effect of radiation on the relevant electro-mechanical properties of the constituent materials and structures, focusing on 2D materials and CNTS, and the implications for space and military applications.

The key question for this work is: *How does radiation damage to constituent materials impact the mechanical and electrical basis of operation of M&NEM structures?* In particular, cumulative damage by non-ionizing energy loss can, in principle, alter the mechanical properties of structures such as cantilever's and 2D membranes, and surface effects and trapped charge in insulators can impact electrical operating conditions. Presently, the extent to which such effects impact the operation of advanced M&NEM devices is unclear. This particular project combines expertise and experience in materials science, M&NEMS, and radiation effects of the University of California at Berkeley, Sandia National Laboratories, and Vanderbilt University to conduct a systematic study of the impact of relevant radiation types on the key operating properties of novel M&NEM structures, and to capture observed effects in finite element models.

11:20am **MN+MS-FrM10 Influence of Radiation on MEMS Oscillators***, **Bruce Alphenaar**,* University of Louisville*; M.L. Alles, H. Gong,* Vanderbilt University*; P. Deb Shurva, J.T. Lin,* University of Louisville*; J.L. Davidson,* Vanderbilt University*; S. McNamara, K. Walsh,* University of Louisville*; W. Liao, R.A. Reed,* Vanderbilt University **INVITED**

The beneficial size, weight, and power requirements provided by micro-electromechanical (MEMS) and nanoelectromechanical (NEMS) memory, logic and sensors for systems operating in extreme radiation environments make it essential that the effects of radiation on MEMS/NEMS devices be investigated. Here we report on the influence of radiation on a micro-scale oscillator consisting of a electrostatically driven silicon cantilever fabricated from a silicon-on-insulator wafer. The position of the cantilever is detected by the piezoresisitve change in an asymmetric silicon beam supporting the cantilever. Prior to radiation exposure, the frequency response of the oscillator remains very stable, provided temperature and pressure are kept constant. Four different radiation sources are used, covering a range of excitation energies: 1) UV B (265 nm) photons 2) 10 keV X-rays 3) 0.8 MeV protons and 4) 2.0 MeV protons. Exposure to 10 keV X-rays at 10.5 krads/minute causes the resonant frequency to shift downwards by approximately 0.4 Hz (50 ppm change) following 2.1 Mrads irradiation. Once the X-ray exposure is removed, the device returns to its original state after an annealing time of 10 hours. The long annealing time and a correlation to the silicon resistance change shows that sample heating is not an important factor. A comparison to UV B results suggests that the frequency shift is related to charge accumulation in the silicon cantilever. Exposure to 0.8 MeV shows permanent change to the resonant frequency suggesting that displacement damage has occurred. This work was funded by the Defense Threat Reduction Agency under contract HDTRA-15-1-0027.

12:00pm **MN+MS-FrM12 Radiation Effects on Silicon Carbide (SiC) Nanomechanical Devices***, **Philip Feng**,* Case Western Reserve University

We report on exploratory research effort on investigating fundamental radiation effects in resonant-mode and contact-mode microelectromechanical systems (MEMS/NEMS) enabled by silicon carbide (SiC) micro/nanostructrues. We calibrate and compare the radiation effects in a few selected MEMS/NEMS resonators – namely, SiC microdisk resonators, SiC membrane resonators, SiC-on-insulator (SiCOI) cantilever beam resonators, and resonant switches.

We focus on discovering fundamental effects of SiC MEMS/NEMS devices due to exposure to radiation sources representative of space and nuclear environments, and attaining comprehensive, in-depth understandings of how these radiations affect the key attributes and performance of the devices. The main properties and metrics include resonance frequency, quality (*Q*) factor, multimode responses, off-state leakage, on-current, on-voltage, switching speed, surface and nanocontact properties, reliability and lifetime, *etc*.

In this work, we have carefully performed experiments on extensive testing of multimode SiC MEMS/NEMS resonators and resonant switches, before and after controlled radiation exposure with designed dosage and energetic parameters of the radiation sources. Furthermore, we have done extensive computer simulation studies on the effects of implanting protons (hydrogen ions, H+) into SiC thin layers on silicon (Si) substrate and on SiO2, and explore the ion implantation conditions that are relevant to experimental radiation of SiC device layers.

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