Probing Ion Radiation Effects in Si Crystal by 3D Integrated Resonating Thin Diaphragms

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***Abstract*—We report on experimental study and analysis of the effects of energetic heavy ion radiation upon mechanical properties of single-crystal silicon (Si) diaphragm resonators, by exploiting a novel 3D scheme of using a vertical stack of 5 micromachined vibrating Si diaphragms exposed to energetic oxygen ions. We have observed different frequency redshifts in different layers in the stack, which can be explained by different types and magnitudes of damage induced by the oxygen ions radiation. The integration design not only scientifically enables probing different radiation effects in a 3D fashion, but also economically evades very expensive, repetitive tests on individual devices, which provides a powerful tool for the investigation of radiation effects on MEMS and other micro/nanoscale systems.**

Keywords—radiation effects; microelectromechanical systems (MEMS); resonator; diaphragm; oxygen ions; 3D integration

I. INTRODUCTION

The need for radiation studies in semiconductor materials arose as a matter of urgency in the late 1950s when the emergent semiconductor industry was developing device technologies for space and military applications [1]. 'Space-radiation' (*e.g.*, solar, galaxy) and 'man-made radiation' environments (*e.g.*, nuclear plant, nuclear weapons, hospitals, labs) can expose devices to radiation at doses that can lead to severe damage [2]. In the past several decades, a large body of work has been performed to understand radiation effects on mainstream solid state electronic devices [1,3-4], in particular on MOS devices [3] and integrated circuits [4]. In recent years, microelectromechanical systems (MEMS) have seen widespread adoption in consumer, military and aerospace products due to their small size, low power consumption, and in some cases, monolithic integration with control and sense electronics [5]. As a result, the reliability of MEMS for many applications in ordinary and relatively benign environments has been well established [6]. However, the study of mechanical degradation due to radiation-induced damage is an area where limited research has been conducted. Most tests have been performed on MEMS that utilize electrostatic sensing and actuation, and radiation-induced total ionizing dose effects have been identified as a mechanism which can potentially limit the reliability of such devices. Importantly, these tests often treat devices in a lumped fashion, and are not able to analyze damage in segments of bulk materials or functional devices.

In this work, we report on the first 3D integrated MEMS platform for probing radiation effects of oxygen ions on Si, by exploiting an innovative scheme consisting of an array of five vertically stacked Si diaphragms. These devices feature large capturing areas combined with multiple resonance modes, and are vertically stacked to directly probe the radiation effects of high energy oxygen ions in the same radiation beam.

II. EXPERIMENTAL TECHNIQUES

The micromachined Si diaphragm resonators employed in the experiments are 2 mm × 2 mm in lateral dimensions and 2±0.5 μm in thickness (from Norcada). We perform transport of ions in matter (TRIM) simulations to calculate interactions of oxygen ions with Si diaphragms and find the stop range of oxygen ions in Si is 7.3 μm, which determines the number of the stack to be at least 4 to fully stop the ions, as shown in Fig. 1. An additional diaphragm is integrated as a control device.

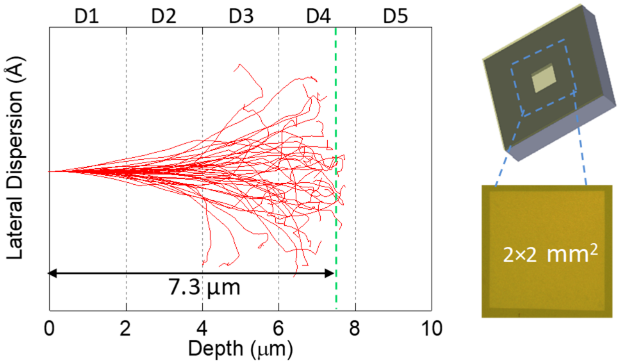

Fig. 1. TRIM simulation of oxygen ion interactions with single-crystal Si. The results show that the stopping range for the oxygen ions is at ~7.3μm. Insets show images of a typical Si diaphragm, with lateral dimensions of 2mm × 2mm and thickness of 2 ± 0.5μm.

A. Radiation Exposure Experiment

A S-series Pelletron radiation system is employed to radiate energetic ions to the stack of Si diaphragms, as illustrated in Fig. 2(a). The devices are exposed to 10.3 MeV oxygen ions for 8 hours, corresponding to a total fluence of 5.6 $\times 10^{13}/\text{cm}^2$.

B. Multimode Resonance Detection

The multiple flexural resonances of the Si diaphragm resonators in vacuum are investigated by using an ultrasensitive optical interferometry system, as shown in Fig. 2(b), which consists of: (i) a 405nm amplitude-modulated laser to photothermally excite the flexural vibrations; (ii) a 633nm He-Ne laser to measure the multimode flexural vibrations of devices; (iii) a photodetector to transduce the time-varying optical interferometric signal into electrical signal; (iv) a network analyzer to modulate the drive and to measure response.

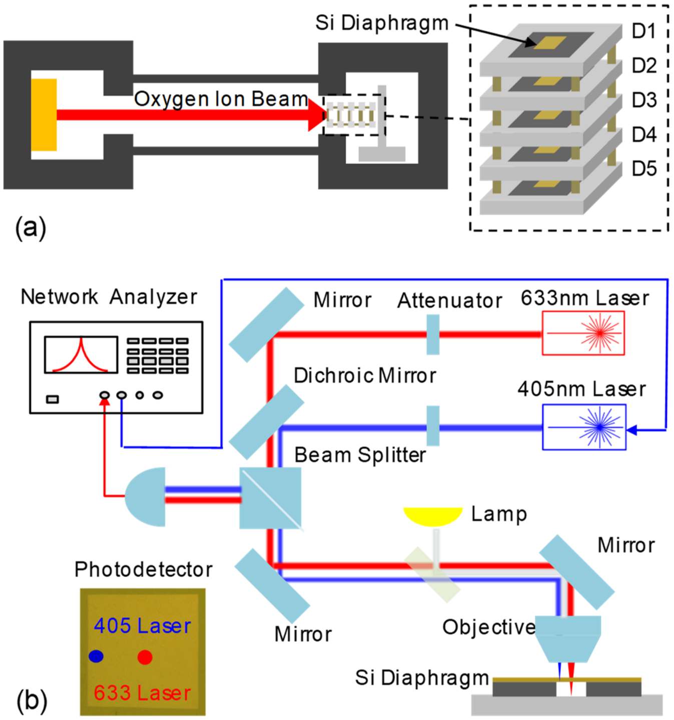

Fig. 2. (a) Schematic illustration of the radiation apparatus. Five Si diaphragms are stacked into a 3D scheme using a designed chip holder and positioned in the test chamber. (b) Schematic illustration of the resonance characterization system. Inset shows the laser positions on the diaphragms.

III. RESULTS AND DISCUSSIONS

For each diaphragm, we have measured wide range spectra before and after oxygen ions irradiation, of which the first 3 vibrational modes are shown in Fig. 3. After radiation, diaphragms D1 and D2, which oxygen ions are expected to pass through, present modest multimode redshifts ranging from 0.854 kHz to 1.674 kHz, and 0.847 kHz to 1.189 kHz, corresponding to an average fractional frequency shift of -10.52% and -7.01%, respectively. In contrast, for devices D3 and D4, in which most ions are expected to stop, each resonance shifts much more dramatically, with a frequency shift of $\Delta f/f \approx$ -27.28% and -20.44%. To the best of our knowledge, this amount of change is the largest ever reported for MEMS devices upon radiation. From perspectives of device structure and radiation exposure conditions, we attribute these large shifts to the very large capturing area of the diaphragms, the heavy and energetic oxygen ions, and high ion dose. Device D5 exhibits minimal frequency shifts among the 5 diaphragms because few oxygen ions reach and interact with D5.

Figure 4 shows the simulated radiation damage of ions on the 3D stack by TRIM to help explain the experimental observations. It can be seen that D4 has the largest number of target atom displacements made by the incidents ions and all the recoiling target atoms. The displacements will lead to either a target vacancy or a replacement collision. D3 has less displacement damage than D4, but experience much more ionizing events, which makes it show similar magnitude of frequency shift as D4. The damage in D1 and D2 is mainly ioinzing events, resulting in moderate frequency modification.

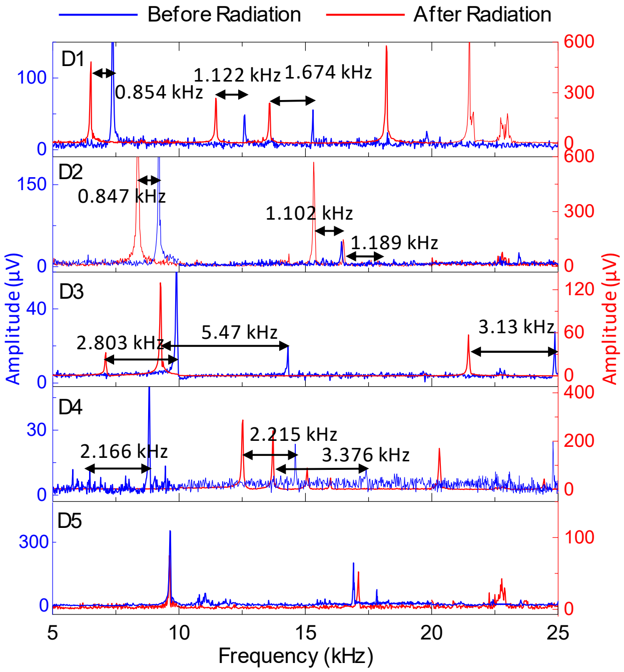

Fig. 3. Multimode resonances measured from the 3D integrated Si diaphragms and the measured frequency shifts in response to the oxygen ions radiation.

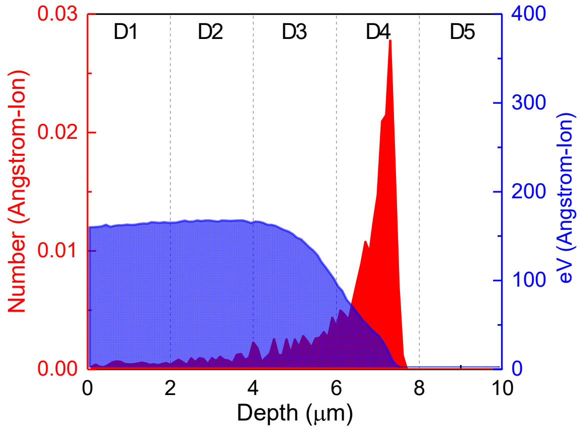

Fig. 4. Radiation damage on the 3D stack of Si diaphragms simulated by TRIM. Displacement damage is shown in red and ionization damage in blue.

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