Radiation Effects in 2D Material / High-K Dielectric Interfaces

S. J. Koester,[1] C. Kim,[1] R. D. Schrimpf,[2] D. M. Fleetwood,[2] M. L. Alles,[2] R. A. Reed,[2]
and E. X. Zhang[2]
[1]*University of Minnesota-Twin Cities, Minneapolis, MN*
[2]*Vanderbilt University, Nashville, TN*

Abstract: Two-dimensional (2D) materials such as graphene and MoS_2 have numerous applications for future electronic and photonic systems. Their extreme surface sensitivity suggests that their response to ionizing radiation will be very dependent upon the details of the surrounding dielectric structure. In this work we describe results and new methodologies for characterizing the radiation response of graphene and 2D MoS_2/high-K dielectric interfaces.

Background: Most of the prior work on radiation effects in two-dimensional (2D) materials has been performed on graphene [1]. It has been shown that graphene is very sensitive to radiation-induced charge trapping in the surrounding dielectrics [2]. Nearly all of the previous work has been performed on unpassivated graphene device structures and, due to the extreme sensitivity of the radiation response to the adjacent materials, radiation studies on device structures that are representative of the realistic environments are needed. Transition-metal dichalcogenides such as MoS_2 [3] have gained considerable attention due to their large band gaps and monolayer nature. Very few studies of the radiation response of MoS_2 field-effect transistors (FETs) [4] with realistic dielectric structures have been reported. In this work, we illustrate a new device and circuit based method to evaluate radiation effects in graphene and 2D MoS_2/high-K structures.

Evaluation Techniques and Results: Fig. 1 shows results on inverted graphene/high-K capacitors [5] where a methodology has been established to measure the density of border traps near the graphene/high-K interface which can be applied to study radiation-induced defects in these devices. This basic device structure can further be used to study the effects of total ionizing dose irradiation on chemical dopants, and preliminary results [6] on the effect of surface doping in graphene and MoS_2 FET structures are shown in Fig. 2. Due to its large band gap, MoS_2 offers a tremendous opportunity to test the effect of single-event effects (SEEs) in 2D materials. By comparing the response of particle beams to optical pulses, differentiating information on the location of the charge generation should be possible. As shown in Fig. 3, it is expected that much faster transient responses will be observed for charge generated in the MoS_2 compared to the high-K layers. We have also developed numerous circuit-based test structures to evaluate radiation effects in 2D materials. These methods rely upon previous work used to characterize defect generation in silicon-based devices [7-8]. In this methodology an "odometer" test vehicle is used to detect extremely-small changes in the device properties on μs to ms time scales. This test structure is shown in Fig. 4, and can measure the beat frequency between two ring oscillators, where one is subject to radiation. We expect that these structures can used as an ultra-sensitive method of characterizing radiation effects in graphene and MoS_2 materials.

Conclusion: In conclusion, 2D materials are very promising for incorporation into future DoD systems due to their capability to realize devices with novel functionality as well as their ability to dramatically extend the scalability of conventional logic and memory systems. The methodologies described in this paper offer the potential to provide precise knowledge of where radiation-induced traps and defects are created in these materials, and the extent to which single-event effects are fundamentally different compared to silicon-based materials.

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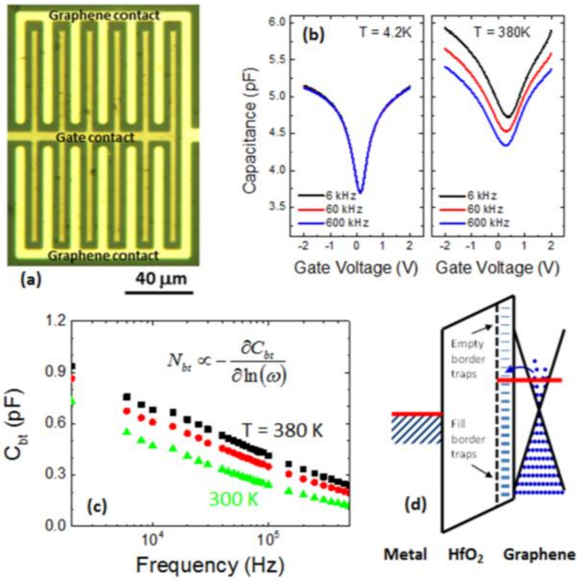


FIG. 1. (a) Two-terminal graphene-high-K-metal capacitor structure, (b) Experimental temperature-dependent C-V studies of graphene / high-K capacitors, (c) Border-trap capacitance vs. frequency showing expected behavior, and extracted border trap density of 1-2 x 10^{18} cm^{-3}/eV. (d) Border-trapping mechanism in graphene/HfO_2 interfaces [5].

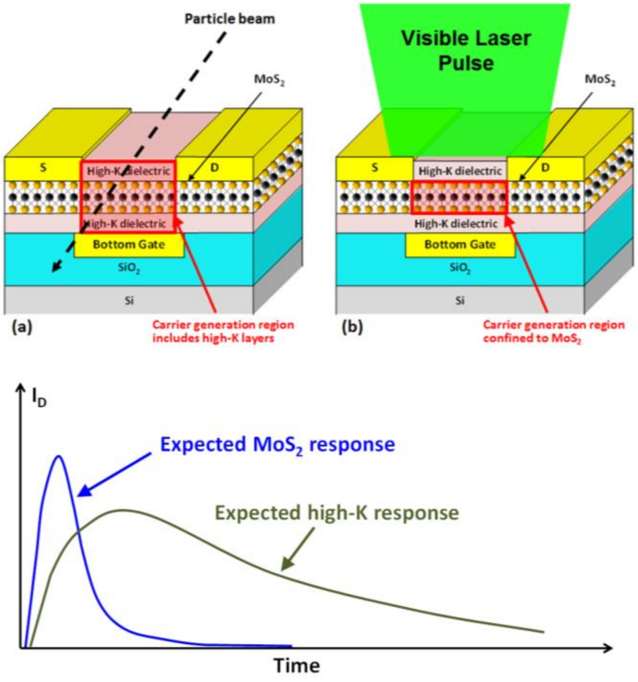


FIG. 3. Diagrams of SEE experiments on MoS_2/high-K FETs using a (a) particle beam (b) optical beam. (c) Expected pulse response if carrier response is dominated by MoS_2 or high-K layer. The optical beam serves as a control since carriers are only generated in the MoS_2.

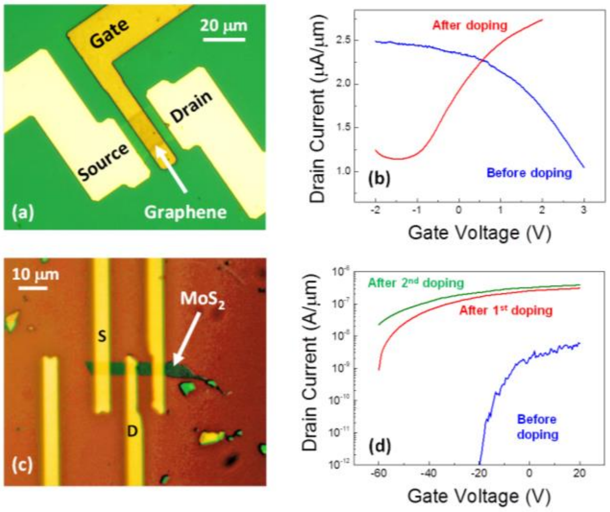
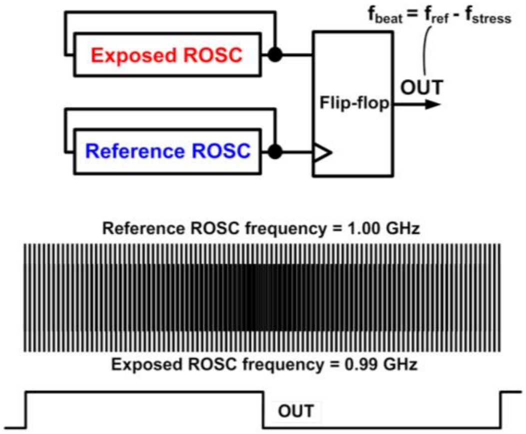
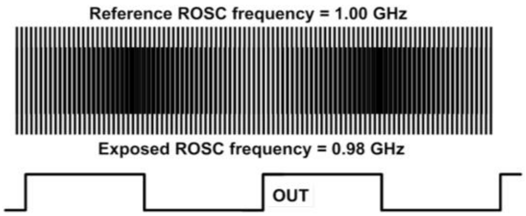


FIG. 2. (a) Optical micrograph of completed graphene/high-K FET. (b) I_d vs. V_g characteristics of graphene FETs before and after spin-on n-type doping. (c) Optical micrograph of MoS_2 FET. In this device, the substrate was utilized as the gate, with the two leads shown used as source and drain. (d) I_d vs. V_g characteristics for MoS_2 FET before and after multiple doping steps. [6].



(a) Before radiation



(b) During or after radiation

FIG. 4. "Odometer" test vehicle for high precision real time radiation effect analysis. The beat frequency between the reference and exposed ring oscillators (ROs) is measured using digital logic gates. A 1% shift in the exposed RO frequency translates into a 50% change in the output count, allowing very high resolution measurements.