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# Tracking ion irradiation effects using buried interface devices

D.B. Cutshall[b], D.D. Kulkarni[a], A.J. Miller[a], J.E. Harriss[a], W.R. Harrell[b], C.E. Sosolik[a,*]

[a] Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA
[b] Holcombe Department of Electrical and Computer Engineering, Clemson University, Clemson, SC 29634, USA

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ABSTRACT

We discuss how a buried interface device, specifically a metal-oxide-semiconductor (MOS) capacitor, can be utilized to track effects of ion irradiation on insulators. We show that the exposure of oxides within unfinished capacitor devices to ions can lead to significant changes in the capacitance of the finished devices. For multicharged ions, these capacitive effects can be traced to defect production within the oxide and ultimately point to a role for charge-dependent energy loss. In particular, we attribute the stretchout of the capacitance-voltage curves of MOS devices that include an irradiated oxide to the ion irradiation. The stretchout shows a power law dependence on the multicharged ion charge state (Q) that is similar to that observed for multicharged ion energy loss in other systems.

## 1. Introduction

Although the dissipation of an impacting ion's energy when it strikes a solid target is not a simple process, significant efforts have gone into tracking this energy and its effects for various charge states, target materials, and incident ion kinetic energies, see e.g. Ref. [1]. For example, in multicharged ions the mechanisms important to the energy transfer can begin well outside the target through electron transfer and secondary deexcitations (electron and photon) and these can continue to play a role as the ion penetrates the target and slows in the subsurface region [2–5].

Much analysis has focused on the above-surface role of this energy dissipation, looking at sputtering and the formation of surface features [6–10]. However, even in the cases where no discernable surface features are observed, such as the recent measurements made on ultrathin 2-D material targets, the above-surface charge exchange component has to be included in order to accurately describe the energy exchange and its dependence on the ion characteristics [11]. The continued development of experimental methods that can track or record the effects of ion irradiation and energy deposition both during and after the ion exposure will only improve our understanding of the underlying physical phenomena involved.

In this work we demonstrate the use of a semiconductor device platform that can be utilized to track energy deposition by ions. Semiconductor devices have a long history in radiation effects testing, and our efforts here are focused on the use of low kinetic energy ions (few keV range). The ion energy deposition characteristics in this kinetic energy range are often overlooked as minor, given their shallow implantation depths and lower damage relative to the ions found in most applied contexts (e.g. MeV). However, as we show for multicharged ions on metal-oxide-semiconductor (MOS) devices, the device sensitivity can be quite dramatic. For these MOS structures, ion-induced damage to the oxide within the structure leads to flux- and charge-dependent changes in the device that are revealed in the capacitance signature.

As we discuss below and illustrate in Fig. 2, the capacitance voltage (CV) curve for an irradiated capacitor shows distinct changes relative to data taken on a pristine device. In particular, the curves are shifted along their voltage axis and appear stretched out in terms of overall curvature. In previous work, we have addressed the shift in the irradiated CV curves, which is typically referred to as the "flatband shift" [12,13]. By looking at the dose- and charge-state dependence of the flatband shift, we have shown that it depends linearly on dose within our experimental range and depends on charge as a power law ($Q^{2.2}$) [13]. For these previous measurements, the fluence for each sample was measured and corrected to include its spatial dependence and account for the Faraday cup area under which it was measured. More specifically, we were able to utilize a two-dimensional Gaussian fit to the profiles obtained for each irradiating beam to account for the spatial variation across the dosed area of each of our samples. This data analysis technique, which we utilize again here in analyzing the stretching out of the CV curves, allows us to use the beam profile to accurately account for dose dependence as in our previous work [13].

The organization of this paper is as follows. In Section 2 we describe the experimental setups and the device processing steps used in these measurements. In Section 3, we present data measured on capacitor

* Corresponding author.
*E-mail address:* sosolik@clemson.edu (C.E. Sosolik).

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devices and discuss charge state-dependent effects seen in those data. Our methods and results are summarized in Section 4.

## 2. Experiment

The measurements described here were conducted in the multiply charged ion laboratory at Clemson University. The multicharged ions were $Ar^{Q+}$ (Q = 4,8 and 11) obtained from an EBIS-SC ion source whose setup and basic operation are described in Ref. [14]. The kinetic energy was held constant at approximately 1 keV for the $Ar^{Q+}$.

The targets irradiated by the $Ar^{Q+}$ ions were uncapped, i.e. no top metal contact, MOS devices. All of the MOS devices used in this work were obtained from oxidized Si wafers (Si-Tech) which had a ~50 nm top layer of $SiO_2$. The Si was p-type ($\rho$ = 5–10 Ω-cm) with < 100 > orientation, and had a backside Ohmic contact that was formed after an etch with 49% HF, a triple rinse in deionized water, and a thermal evaporation of Al (~ 1 µm thick). Each wafer was sintered in a quartz furnace at 450 °C with a nitrogen purge and then cleaved square (12 × 12 mm$^2$) and stored in vacuum until irradiation with $Ar^{Q+}$ ions. Following the ion exposure a matrix of Al contacts (0.5 µm thick, 1 mm diameter, 2.5 mm center-to-center spacing) was thermally evaporated onto the $SiO_2$ through a shadow mask. A finished matrix of Al/$SiO_2$/Si devices is shown in Fig. 1. Overall there were nine samples, each with a matrix of devices, that were irradiated with multicharged ion beams of various charge states and fluences, with one pristine sample serving as the control.

The ion exposures conducted on each oxidized, i.e. uncapped, Si sample were monitored throughout each irradiation using a Faraday cup in the same plane as the sample. From the beam current measurements, the nominal ion fluences were calculated to be in the range of ~3 × 10$^{13}$ to ~1 × 10$^{14}$ ions/cm$^2$. As in our previously reported results using ions extracted from our EBIS-SC source [14,13], the beams produced were Gaussian-distributed (FWHM ~3 mm) as determined by a beam viewer (HRBIS-4000 from Beam Imaging Solutions) and from the deconvolved, translated Faraday cup measurements. As we note in Section 3 below, the distribution of the beam across the sample allowed the post-irradiation characteristics of each device to be referenced to a particular on-sample dose at the site of the device.

For the work presented here, we are interested in the capacitance-voltage (CV) characteristics of each irradiated device relative to both a pristine device and relative to devices irradiated with different ion doses and/or charge states. These data were extracted from the finished MOS devices using high frequency CV curves that were measured with an HP 4280A 1 MHz CV meter. The CV data were taken ex-situ in a shielded probe station that isolated devices from light, vibration, and EM interference. Typical CV curves are shown in Fig. 2 for both pristine and irradiated MOS devices.

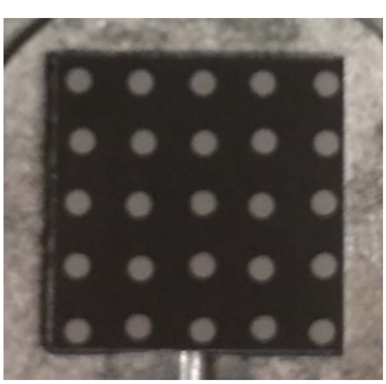

**Fig. 1.** Representative metal-oxide-semiconductor (Al/$SiO_2$/Si) devices fabricated in-house for these measurements. The MOS devices are deposited as a 5 × 5 matrix of Al dots post-irradiation, and the individual top contacts for each MOS device are 1 mm in diameter.

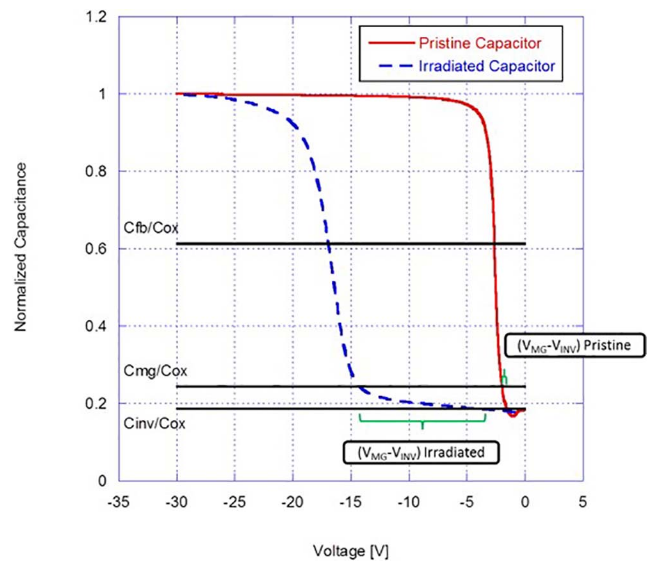


**Fig. 2.** High frequency (HF) capacitance-voltage (CV) curves obtained for a pristine MOS capacitor (solid line) and a capacitor where the oxide was exposed to a multicharged ion beam before the top metal contact was deposited (dashed line) A 30 mV waveform was used for all HF CV measurements.

## 3. Results and discussion

For our MOS capacitors, the data were obtained for three charge states of Argon through an examination of specific characteristics of the CV curves of the devices. In looking at such curves, one can see that a pristine HF CV curve (Fig. 2) has a characteristic shape as the voltage is swept from large negative values towards zero. This voltage-dependent change in capacitance primarily reflects the role of the underlying semiconductor in the structure, as its bands bend and an inversion of the semiconductor surface occurs [15]. For an irradiated capacitor the CV curve (Fig. 2) shows a similar shape; however, the curve is shifted along the voltage axis and it appears stretched out in terms of its overall curvature.

Our goal in the work presented here was to examine the stretched out nature of the CV curves, referred to as “stretchout” within the field of MOS research [15]. The presence of stretchout is also a reflection of damage within the oxide related to ion irradiation in our data, although its appearance is actually directly related to the presence of interface traps at the Si/$SiO_2$ interface [15,16]. Stretchout for CV curves can be tracked by analyzing the difference between the midgap ($V_{MG}$) and inversion ($V_{INV}$) voltages, which are indicated in Fig. 2. The midgap voltage refers to the point in applied voltage at which the semiconductor or Si surface becomes intrinsic while the inversion voltage indicates the onset of strong inversion at that surface. In both cases, calculations of the corresponding midgap and inversion capacitance values ($C_{MG}$ and $C_{INV}$) [15,16] and comparison to the measured CV curves allow these voltage values to be determined.

For our irradiated and encapsulated oxide samples, sets of ~25 MOS capacitors were deposited in an array and we then measured CV curves and extracted the appropriate voltages to determine the extent of stretchout at each point on the sample. However, as noted above and reported previously in Ref. [13] the spatial dependence of our multicharged ion source, which has a FWHM of a few millimeters, leads to a distribution of the ion dose across the capacitor array. Therefore, a similar analysis was performed using a two dimensional Gaussian fit to our beam profile which was then correlated to the individual capacitor results. These positional measurements revealed, unlike the flatband data [13], that the stretchout effects were in the saturated dose regime. Therefore, our dose-dependent data, and ultimately, a reporting of a “per ion” influence on the capacitance stretchout, is referred to as the

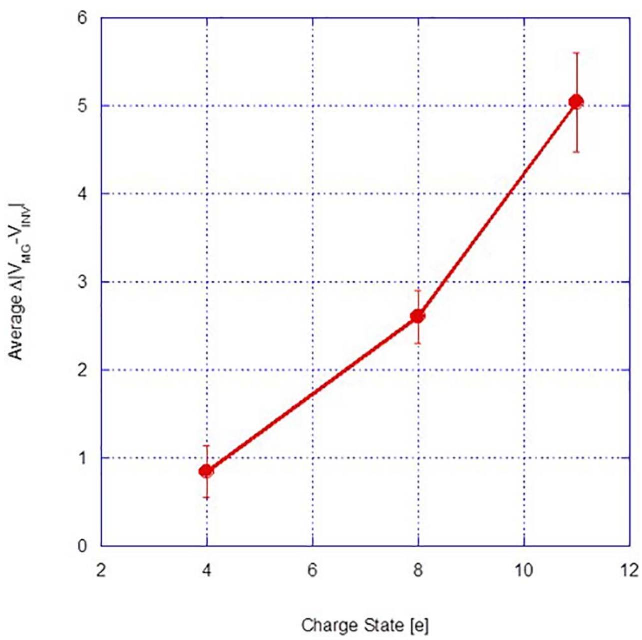


**Fig. 3.** A plot of the "per ion" average difference between the midgap ($V_{MG}$) and inversion ($V_{INV}$) voltages for irradiated MOS capacitor structures exposed to three different Argon charge states (Q = 4,8 and 11).

Average $\Delta|V_{MG}-V_{INV}|$. These values are shown for the three charge states of Argon used here in Fig. 3. As the plot indicates, the dependence of the stretchout on the incident ion charge state ($Q^{\alpha}$) appears supra-linear with $\alpha \sim 1.7$.

While our extracted charge state dependence for stretchout could be related to charge state dependent stopping within the oxide, as we have also found a $Q^{2.2}$ dependence of the flatband voltage shift in MOS capacitors previously [13], we note that the underlying damage mechanisms within the oxide would be different. Namely, stretchout is related to interface trap formation in the device [15,16] whereas flatband shifts occur due to electronic excitations or damage spread throughout the bulk oxide itself [13,12]. Nevertheless, the similarity between the near-quadratic dependence observed here for stretchout, in our own results for flatband [13], and, most recently, for energy loss in the passage of slow highly charged Xe ions through carbon nanomembranes [17], may indicate a relationship between multiply charged ion energy loss and the below-surface damage seen in our oxide data. These different results may all point to a role for preequilibrium stopping in the full description of multicharged ion irradation as was detailed in Refs. [4,5] and as such, the topic is one that is worthy of further study experimentally.

## 4. Summary

We have shown that MOS devices can be used to record the effects of ion energy loss in oxides. For MOS structures, the irradiation of the underlying oxide structure in the device and its encapsulation under a top metal contact preserves the energy loss signature as changes in the capacitance-voltage characteristics which are linear with respect to the ion flux. These C-V changes also follow a near-quadratic dependence on ion charge state that is similar to the ion energy loss dependence observed in experiments on carbon nanomembranes.

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