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# High fluence swift heavy ion structure modification of the $SiO_2$/Si interface and gate insulator in 65 nm MOSFETs

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ABSTRACT

In this work, a study of the structure modification, induced by high fluence swift heavy ion radiation, of the $SiO_2$/Si structures and gate oxide interface in commercial 65 nm MOSFETs is performed. A key and novel point in this study is the specific use of the transmission electron microscopy (TEM) technique instead of the conventional atomic force microscope (AFM) or scanning electron microscope (SEM) techniques which are typically performed following the chemical etching of the sample to observe the changes in the structure. Using this method we show that after radiation, the appearance of a clearly visible thin layer between the $SiO_2$ and Si is observed presenting as a variation in the TEM intensity at the interface of the two materials. Through measuring the EDX line scans we reveal that the Si:O ratio changed and that this change can be attributed to the migration of the Si towards interface after the Si-O bond is destroyed by the swift heavy ions. For the 65 nm MOSFET sample, the silicon substrate, the SiON insulator and the poly-silicon gate interfaces become blurred under the same irradiation conditions.


## 1. Introduction

As MOSFETs are scaled down to the size of nanometer nodes, great importance is being given to the study of the nanoscale effects from the external environment on the device performance and reliability [1,2]. In particular, owing to their application in aerospace and avionics technology [3,4], focus has been turned to the effects of swift heavy ion (SHI) irradiation on the deep submicron MOSFETs. In such devices the insulator layer is ultrathin and subject to reliability issues if modified by environmental radiation factors. Thus, it is crucial for the application of these devices that any structural modifications at the nanometer scale are fully understood and characterized. Indeed, much research has already shown that when penetrating a solid material, SHIs lose their energy predominately through inelastic interactions with the electrons in the material, the electronic excitations rapidly heat the local volume close to the ion path and the local temperature can reach 1800 K. This process results in a narrow trail of permanent damage along the ion path, known as the ion latent track [5,6]. These reports include studies on track formation and its effects in quartz and the structure of latent tracks in amorphous $SiO_2$ [3,7].

Until now several techniques have been employed to characterize these ion latent tracks including small angel X-rays scattering (SAXS) [8], channeling Rutherford backscattering (C-RBS) [9], SEM [10], scanning force microscopy (SFM) [11] and AFM [12,13]. However, the most commonly used method to reveal latent tracks in the bulk and on the surface of nanostructure is specific chemical etching followed by surface imaging. This is possible as the latent tracks often exhibit a different chemical reactivity than the unmodified surroundings thus leave detectable holes or hillocks in the remaining layers after etching. One example is the conical holes that remain in the $SiO_2$ layers after etching with hydrofluoric acid [14,15,10]. Another example is the reports of the existence of nano-hillocks at the $SiO_2$-Si interface after the $SiO_2$ layer is completely etched away [16]. However, at high fluence the flux of ions is such that the concentration of latent tracks significantly increases in the material. When the concentration of the latent tracks becomes large, the ion latent track creation is more complex and the neighboring tracks can overlap. This would result in the nano holes and/or hillocks merging together across the gaps that would nominally separate them when irradiated at lower fluence, thus making it difficult to fully distinguish and characterize them using the conventional etching methods. It is due to this difficulty

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that previous experiments performed on $SiO_2$-Si structures have been limited to fluence of $1 \times 10^{10}$ ions/cm$^2$ and below to minimize the track length and prevent Overlap.[17] In fact, owing to these reasons few studies have been performed on material interfaces under a relatively high influence of SHI irradiation, yet alone on an actual MOSFET device with a gate length under 100 nm. To solve this challenge, a different approach is required.

One technique that is showing promise as a potential solution in the higher fluence is TEM. The technique allows for the imaging of thin cross sections of the whole device or interface which is important as cross-sectional imaging can be employed to study the radiation induced structural modifications from an interface point of view. Another advantage of the using the cross section is that it is also possible to use energy dispersive X-ray spectroscopy (EDX) mapping to observe the migration of different elements before and after radiation, not only showing the damage as in the case of etching but also providing information on how the hillocks and holes are formed and their composition. In this paper, we apply the TEM technique in this manner to study both $SiO_2$/Si films and MOSFETs from a commercial 65 nm CMOS system irradiated with ion fluence of $1 \times 10^{12}$ ions/cm$^2$. We find that there is a clear modification of the interface in both the $SiO_2$/Si films and gate oxide of the MOSFETs. This can be understood as a migration of the Si and a change in the Si:O ratio.

## 2. Experimental methods

In this study there were two types of samples studied, a two layer $SiO_2$/Si film structure and n-channel 65 nm MOSFETs. The MOSFETs were as received from SMIC (Semiconductor Manufacturing International Corp. Of China) whereas the $SiO_2$/Si film structures were fabricated by thermally evaporating 10 nm and 110 nm of silicon dioxide on P-type silicon substrates after standard RCA cleaning. For the 65 nm MOSFET, the capacitive equivalent thickness of the gate insulator is 2.35 nm and the channel length was 60 nm. The MOSFETs were not encapsulated and the device terminals were kept floating during irradiation.

In order to carry out the heavy ion irradiation study, Sn ions with an energy of 414 MeV were used. All experiments were performed using the Heavy Ion Research Facility in Lanzhou (HIRFL) at the Institute of Modern Physics, Chinese Academy of Sciences. The incident ion beam was applied normal to the surface of the devices with a fluence of $1 \times 10^{12}$ ions/cm$^2$ at room temperature. The actual number of ion hits on an individual device can be statistically evaluated. The electronic and nuclear energy loss as well as the range of the ion were estimated using SRIM 2013. After radiation, the samples were subjected to TEM analysis. The precision focused ion beam (FIB) technique was used to prepare the final thin cross sectional slices used in the TEM measurements. All the TEM imaging was carried out using an FEI Tecnai G2 F2 instrument.

## 3. Results and discussion

As mentioned, one of the key problems in studying the effects of SHI radiation is that at high fluence the damage is no longer discernable using conventional etching-imaging methods. In order to overcome this, cross sectional imaging of the interface using TEM was performed. To establish if this was feasible a simple Si/$SiO_2$ film structure was firstly studied. The films were prepared as described in the experimental section with thicknesses of 10 nm and 110 nm and then FIB was used to prepare the cross sections for the TEM measurements. Fig. 1 shows the TEM micrographs of the two samples before and after irradiation. The first point to note is that the interface between the Si and $SiO_2$ is clearly visible before irradiation in both the 10 nm and the 110 nm structures (Fig. 1a and c) making it possible to observe any irradiation-induced modifications. A more important observation is that the $SiO_2$ layers in both structures appear to be uniform across the layer and also possess a reasonably sharp interface with the Si layer. It is worth noting at this stage that the thinner 10 nm device has an additional layer of Pt. This is a protective capping layer to prevent degradation during the FIB preparation of the cross sections.

Having established it was possible to image the cross sections in both the thick and thin layer structures the samples were subjected to Sn radiation at the high fluence of $1 \times 10^{12}$ ions/cm$^2$ at room temperature. Fig. 1b and d show the cross sections after irradiation. It is clear to see that the layers are still distinguishable after irradiation which makes it possible to differentiate the damage from the film. What becomes immediately noticeable is that there is a change in the uniformity of the $SiO_2$ layer. This appears as a visibly darker sub layer in the $SiO_2$ at the interface with the Si layer and can be understood by considering the density of the material in this region. If the Sn ions were to break the bonding in the oxide layer and the Si or the O atoms were to migrate from one layer to the other at the interface, then one would expect a ratio change between the Si and O atoms in this region. This would consequently change the density thus inducing a change in the color of this region in the TEM micrograph. The presence of modifications at the interface is not unusual given the previous reports of the existence of hillocks and holes at the interface after irradiation with lower fluence [5]. However, what is interesting is that the modified region appears as a rough but continuous layer rather than a series of individual hole or hillock features. If one calculates the average real impact density of the Sn ions for a given area, then it becomes clearer as to the difference in observations. This calculation was performed and a value of 10,000 ions per μm$^2$ was obtained. Now, considering the diameter of a typical hillock/hole feature is in the order of 5–8 nm [18] then it is almost certain that these nano features will overlap. This would lead to a merging of the features thus appearing as a continuous rough layer as observed in the sample. One may initially attribute the darker layer observed in the micrographs to the transitional interface layer present in the fabrication of such films, however this would not be the case for the following reasons. Firstly, the transitional layer is present before and after radiation so would be expected to appear the same on both micrographs which the observed film does not. Secondly and most importantly, the transitional layer is typically only a few monolayers thick and thus making it in the order of 0.6–1.5 nm [19]. However, the observed layer is thicker ranging from 3 to 30 nm and therefore cannot be explained simply by the transitional layer alone.

Since it is not possible to ascertain the exact nature of the Si:O ratio directly from the TEM micrographs, EDX mapping was employed to determine the elemental composition through the cross section of the structure. In particular, the composition of Si and O was studied. Fig. 2 shows the EDX mapping results. In order to firstly confirm whether the Sn ions were passing through the sample completely an EDX map of the Sn ions was measured after irradiation. The results are shown in Fig. 2a where it is just possible to observe some spots dispersed in what would nominally be the two films. It is possible that Sn ions can become trapping centers for operational devices in the form of impurity levels in the band gap and also can distort the crystal lattice. However, whilst these spots indicate some of the ions are remaining in the sample, the concentration is extremely low with the highest density being below the interface and hence are expected to insignificantly affect the performance. The O and Si elements were then mapped after irradiation and the results are presented in Fig. 2b and c.

It is possible to gain a more quantitative analysis of the difference in composition before and after irradiation by taking a percentage elemental composition line scan through the EDX map.