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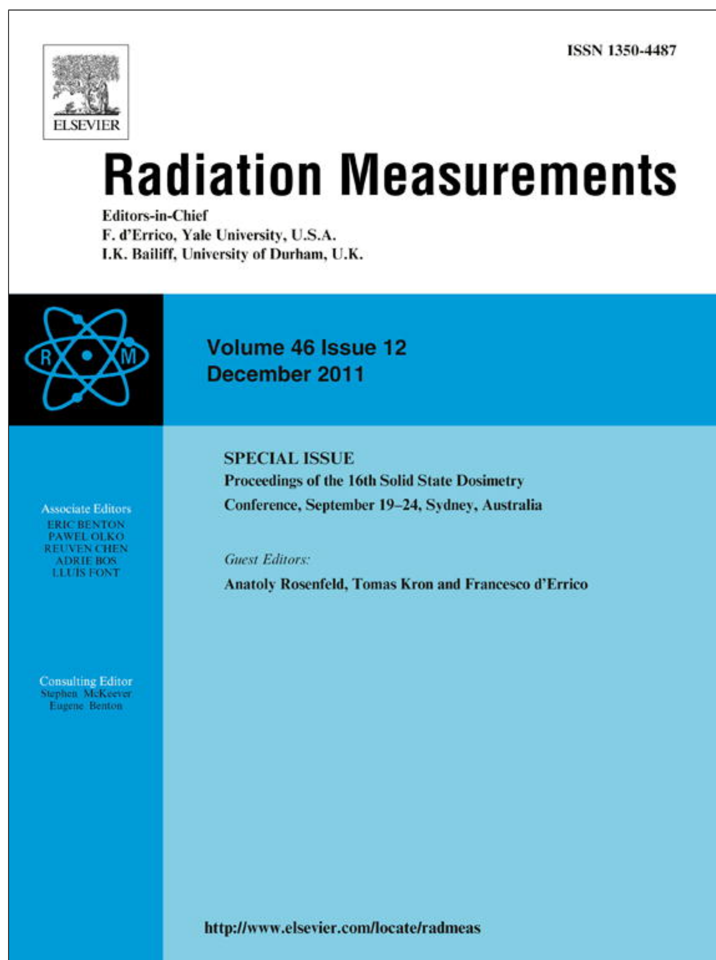

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Influence of structural defects on thermostability and radiation sensitivity of Si MOSFET dosimeters

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The metal oxide semiconductor field effect transistor (MOSFET) dosimeters have recently become commercially available. For this reason, it is not surprising that the study of radiation interactions with MOS materials, devices, and circuits has been a major theme of many articles. The purpose of this study was to investigate the influence of structural defects on thermostability and radiation sensitivity of Si MOSFET dosimeters. It was shown that the near-surface layers of silicon have a complex defective structure which consists from the disordered layer of silicon and the layer of dislocation networks. Grain boundaries of disordered layer form additional energy levels close to the midgap of silicon. These states are ionized under radiation effect and form positive charge. This positive radiation-induced charge becomes additional to the oxide charge and it changes (increases) radiation sensitivity of Si MOSFET detectors. However, these states are the additional source of charge carriers under temperature increasing and lead to changing of detector's parameters.

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1. Introduction

The various types of radiation making up the natural and weapon-enhanced environment—X-rays, gamma rays, electrons, protons, alpha particles and heavier ions—all deposit significant amounts of ionizing energy in semiconductor devices. In semiconductors and insulators, the energy deposited by the ionizing radiation generates charge in the form of electron–hole pairs that can migrate through the material and become trapped at certain locations, often resulting in an alteration of the properties of the irradiated device. The fraction of the total charge generated by the impinging radiation eventually trapped during the collection is called the charge yield. This yield depends on the type and the energy of the radiation and on the structure and operating conditions of the device. In many cases, nearly all the charge recombines or is collected at contacts in such a way that the ionizing radiation has little effect on the device (Oldham and McLean, 2003).

A widely known and widely studied semiconductor structure that exhibits sensitivity to ionizing radiation is based on the presence of a silicon dioxide-silicon (SiO_2–Si) interface and its nearby regions, found in all Si MOS devices. Gate oxides and field oxides used in Metal Oxide Semiconductor Field Effect Transistor (MOSFET) to isolate portions of the circuit from each other can cause large changes in device properties (MOSFET threshold voltage shift, increased leakage current and degraded timing parameters) because of the internal creation and trapping of charge. In addition, the imperfections located at the SiO_2–Si interface result in the radiation-induced growth of defects in the form of "interface states" within the Si near the interface that can lead to different failure mechanisms than those due to the trapped charge in the oxides. Whether device degradation and failure will be due to oxide-trapped charge or interface state effects is determined in a very complex manner by the interplay of a variety of parameters, including type of radiation, dose rate, temperature, magnitude and sign of bias applied during irradiation, oxide quality and thickness, and post-oxide growth processing temperatures. The complicated nature of the radiation response of CMOS devices and circuits, and their importance to space and defense systems, has led to many years of study of radiation effects in MOS-based devices, and the publication of an enormous number of papers on this subject (Cheung et al., 2004; Litovchenko and Barubash, 1990).

This paper concerns the study of the influence of structural defects on Si MOSFETs dosimeters. The presence of structural defects in the bulk of semiconductor material or at the interface improve the radiation sensitivity of Si MOSFET detectors, but have a negative influence on the thermostability of Si MOSFET detectors.

The silicon wafers were oxidized in dry oxygen at 1150 °C (the oxide thicknesses were 0.1–1.5 μm) followed by etching in

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a hydrofluoric acid solution and treatment of the silicon surface by selective etchants (SE). The Secco-ethchant and the Sirtl-etchant were used for the (100) and (111) surfaces, respectively.

The following techniques and equipment were used for examination of the MOSFET detectors structure:

- Scanning electron microscopy (SEM), a Cam Scan-4D scanning electron microscope-analyzer with a Link-860 energy-dispersion analyzer system (the mass sensitivity of the device being 0.01% and the beam diameter varied between 5×10^{-9} and 1×10^{-6} m, according to a "Zaf" program code used),
- Auger electron spectroscopy (AES), a Riber LAS-3000 spectrometer (spatial resolution 3 μm, analyzer energy resolution 0.3%),
- Secondary ion mass spectrometry (SIMS), a Cameca-3F analyzer,
- Optical methods using an MMR-2R metallographic microscope, and
- A capacity-voltage curve tracer with computer-aided processing of information.

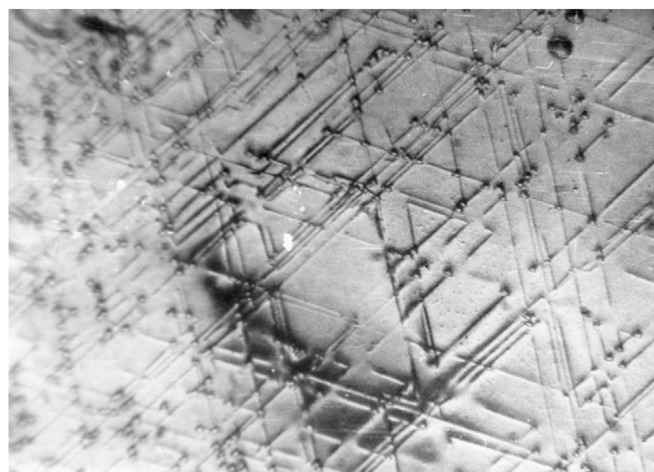

Fig. 2. SEM image of a typical dislocation network pattern upon selective etching in the Sirtl-etchant for 10 min (1×2300).

2. Results and discussion

The thermostability of detectors depends on diffused impurity of alkali metal ions such as Na, K, Ca, etc., which drift toward the Si–SiO_2 interface under the action of an electric field. These alkali metal ions generate surface mobile charge which can change I–V and C–V characteristics of Si MOSFET detectors. The thermostability of Si MOSFET detectors results to be inversely proportional to the dioxide thickness. In fact, an increase of the dioxide thickness raises the alkali metal ions density at the interface and in the dioxide where positive charge is localized during radiation effect. The radiation sensitivity has different behavior: an increment of dioxide thickness lead to an increase of radiation sensitivity (Oldham, 1984). It can be explained by increasing of positive charge in the dioxide. However, it was found that exist additional energy levels at the near-surface layers of Si–SiO_2 interface which can influence on radiation sensitivity. For this reason, we carried out the experiments to investigate the structure of near-surface silicon in MOSFET detectors.

A typical pattern of the silicon surface after the removal of an oxide layer 1 μm thickness and selective etching for 5 min is shown in Fig. 1. The absence of etch pits typical for a crystalline structure and the impossibility to observe the silicon surface using an electron microscope (the surface was charged heavily) allowed us to conclude that the silicon surface after the removal of SiO_2 had a highly disordered structure close to a fine-grained polycrystalline. If we consider that mechanical stresses decrease with depth obeying the $1/r$ law (Matare, 2000), we can conclude that the most disordered layer is directly adjacent the silicon oxide layer. The thicknesses of these layers are proportional to those of the grown oxides, which is attributable to the increase in the mechanical stresses at the interface with increasing the oxide layer thicknesses. The irregularly shaped pits can be associated with the oxide formed under enhanced diffusion of oxygen along initial structural defects.

On further 5 min of SE, dislocation networks are formed on the silicon surface (Fig. 2). The dislocation networks are decorated by SiO_x. This is supported by the fact that further etching can be performed without an oxidant, that is, in the HF solution alone, which is also confirmed by an Auger spectroscopy analysis. The occurrence of the dislocation networks visible with an electron microscope argues for developing of an ordered crystalline structure in silicon. On further 3 min of etching the silicon surface, the dislocation networks disappear, which can be due to the layered structure of the silicon wafer (Fig. 3). Single dislocations and slip lines are observed (Fig. 4). Given the selective etching velocity is

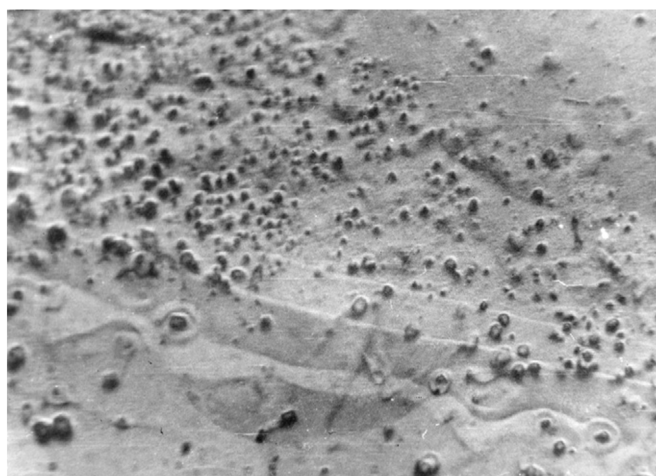

Fig. 1. Optical image of the silicon surface after removal of an dioxide layer and SE for 5 min (1×1000).

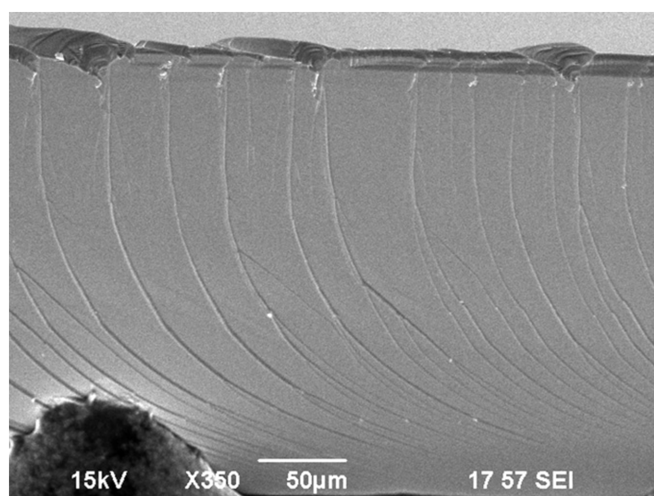

Fig. 3. A typical SEM image of the silicon wafer cleavage with a layered structure.

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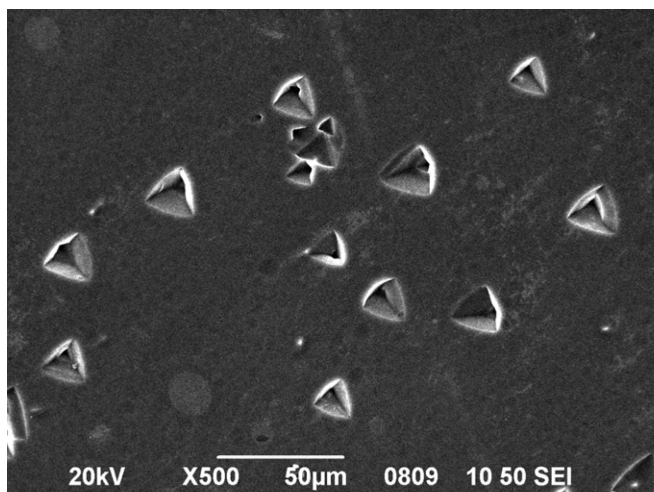

Fig. 4. A typical SEM image of single dislocations on the silicon surface upon SE for 13 min.

about 3 μm/min, the depth of the dislocation networks can be calculated. This was about 30 μm for an oxide depth of 1 μm and SE time of 10 min. On further 3-min etching the silicon surface, the dislocation networks disappeared, which suggests a 40 μm depth of a low bound of the dislocation network. The thickness of the silicon layer with dislocation networks was about 10 μm. Evidently, the dislocation networks are formed at the disordered silicon–crystalline silicon interface due to the difference in the thermal expansion coefficients ($\alpha_1 = 7.6 \times 10^{-6}\ ^\circ C^{-1}$ for disordered silicon and $\alpha_2 = 2.5 \times 10^{-6}\ ^\circ C^{-1}$ for crystalline silicon (Matare, 2000)). This causes the relative deformations ϵ, which can be calculated as

$$\epsilon = (\alpha_1 - \alpha_2)t \tag{1}$$

where t is the temperature in degrees Celsius. The relative deformation is approximately 0.58% ($t = 1150\ ^\circ C$). However, if we take into account the diffusion of oxygen into silicon during oxidation, the relative deformation will vary considerably. This results in further accumulation of mechanical stresses at the interfaces. In this case, a term depending on the parameters of thermodiffusion oxygen can be introduced in Eq. (1)

$$\epsilon_1 = \omega C \tag{2}$$

where ω is the Vegard's coefficient, which takes into account the oxygen atom size and position in the lattice (interstitial or substitutional position), and C is the oxygen concentration (in atomic fractions) (Abe and Bullis, 2000).

As shown above, the dislocation networks occur at the disordered silicon–crystalline silicon interface and disappear at the interface between two nearest silicon layers (the layer with networks and the following layer).

The Auger analysis shows that the oxygen concentration was maximum at the silicon oxide–silicon interface (up to 6.4%) and decreased with the silicon depth (Table 1). It is well known that oxygen in silicon produces electrically active donor levels due to oxygen-vacancy complexing at 1150 °C (Tu and Tersoff, 2006; Reivi, 1984) according to the following reaction:

$$\begin{aligned} O_i + V_{Si} &= O_{Si} \\ O_{Si} + V_1 &= O_{Si}^{2+} V_n^- + e^- \end{aligned} \tag{3}$$

where O_i is an interstitial oxygen atom, O_{Si} is the substitutional oxygen atom, V_{Si} is the silicon vacancy, V_1 is the silicon vacancy adjacent to the substitutional oxygen, and $O^{2+}V_n^-$ is the formation of silicon vacancy and the substitutional oxygen atom. The first reaction transforms an interstitial oxygen atom to a substitutional one, while the second reaction shows how this substitutional oxygen joints the nearest adjacent vacancy, donating one of its valence electrons. Since it is at these temperatures that thermal oxidation of silicon occurs, it may be suggested that oxygen is electrically active at the SiO_2–Si interface. The irradiation of the structures with γ- or neutron radiation, causes the injection of electrons from the additional "interface states" into the conduction band with a following drift in a potential barrier field. The positive post irradiation charge is formed at the near-surface silicon layer.

Table 1
Calculations of Auger-spectra of elements in near-surface regions of silicon in SiO_2–Si structures (without considering oxide).

Element	Amount, % [atomic percent] (depth 2–3 μm)	Amount, % [atomic percent] (depth 10–12 μm)
K	0.00	0.00
C	0.348	0.452
Na	0.05	0.04
Si	92.675	95.245
O	6.393	3.742

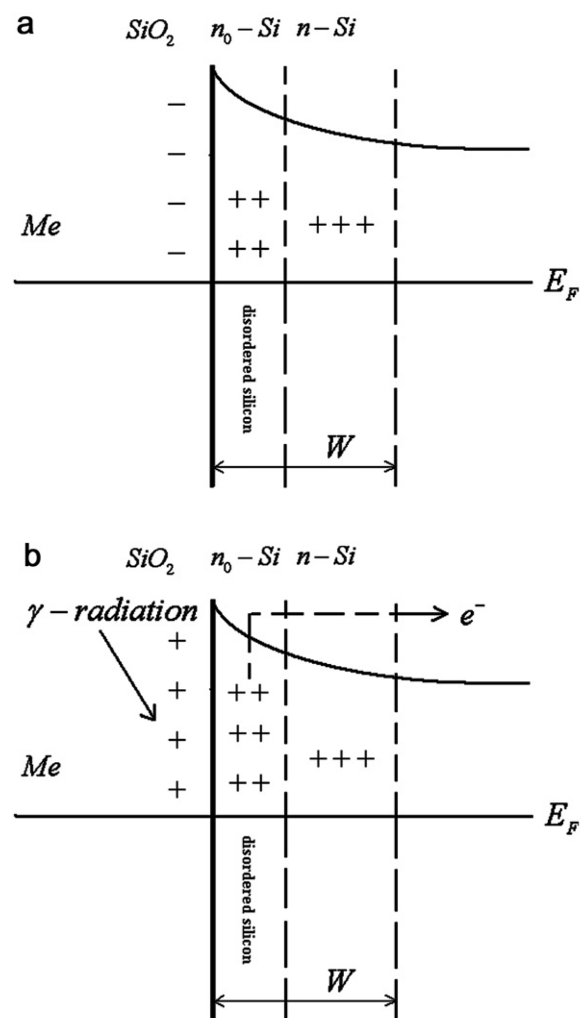

Fig. 5. Energy diagram p-Si MOSFET before irradiation. b. Energy diagram p-Si MOSFET after irradiation.

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This positive charge causes the additional flat band voltage shift. Besides, this positive charge changes the carrier mobility and the MOSFET drain current. The energy diagram of MOS structure before (a) and after (b) irradiation, taking into account donor states of disordered silicon, is shown in Fig. 5(a, b).

3. Conclusions

Thus, we have shown that the near-surface layers of silicon have a complex defective structure which consists from the disordered layer of silicon and the layer of dislocation networks. Grain boundaries of disordered layer form additional energy levels close to the midgap of silicon. These states are ionized under radiation effect and form positive charge. This positive radiation-induced charge becomes additional to the oxide charge and it changes (increases) radiation sensitivity of Si MOSFET detectors. However, these states are the additional source of charge carriers under temperature increasing and lead to changing of detector's parameters. The thickness of disordered layer depends on the magnitude of elastic stresses at the interface. Elastic stresses depend on initial silicon defects, on dioxide thickness, on parameters of oxidizing process. The thicker dioxide film causes the increasing of disordered layer and, as consequence of this, increases sensitivity parameters and degrades thermostability.

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