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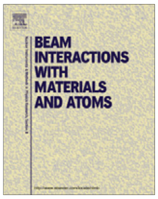

Ge nanocrystals embedded in SiO_2 in MOS based radiation sensors

Aliekber Aktağ [a], Ercan Yilmaz [a,*], Nader A.P. Mogaddam [b], Gülnur Aygün [c], Ayten Cantas [c], Raşit Turan [b]

[a] *Physics Department, Abant Izzet Baysal University, 14280 Bolu, Turkey*
[b] *Physics Department, Middle East Technical University, 06531 Ankara, Turkey*
[c] *Physics Department, Izmir Institute of Technology, 35430 Urla, Izmir, Turkey*

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ABSTRACT

In this work, the effects of gamma radiation on the Raman spectra of Ge nanocrystals embedded in SiO_2 have been investigated. SiO_2 films containing nanoparticles of Ge were grown using the r.f.-magnetron sputtering technique. Formation of Ge nanocrystals was observed after high temperature annealing in an inert atmosphere and confirmed by Raman measurements. The intensity of the Raman signal originating from Ge nanocrystals was found to decrease with increasing gamma radiation. The study also includes the gamma radiation effects on MOS structure with Ge nanocrystals embedded in SiO_2. The gamma radiation effects from 500 up to 4000 Gray were investigated. Capacitance–voltage measurements were performed and analyzed. Oxide traps and interface trap charges were calculated. Results show that MOS structure with Ge nanocrystals embedded in SiO_2 is a good candidate to be used in radiation sensors, especially at high radiation doses.

1. Introduction

In recent years, group IV nanocrystals embedded in SiO_2 have attracted much attention. The main focus has been on Si nanocrystals in SiO_2 [1], but Ge nanocrystals have also been studied [2–4]. The primary reason to study group IV nanocrystals is twofold. Firstly, nanocrystals have been shown to serve as efficient light emitters and are, therefore, interesting for optical applications. Secondly, these materials are fully compatible with silicon-based electronics that dominate the electronic industry. This makes group IV nanocrystals a promising candidate in electronic applications [5,6]. Ge nanoclusters in SiO_2 layers have been produced by either ion implantation of Ge into SiO_2 layers or by magnetron sputtering of SiO_2 co-doped with Ge, in both cases followed by heat treatment.

Radiation sensors require high sensitivity and linear performance over the intended energy range, real-time response, low noise and acceptable reliability [7]. Different materials, geometric arrangements and physical detection techniques have been used to meet these requirements. Among these, MOS based radiation sensors have attracted special attention because of their superior sensitivity as well as the excellent compatibility with the existing CMOS technology [8,9]. MOS capacitors consist of a semiconductor substrate covered by an oxide layer upon which a metal electrode gate is deposited. Formation of radiation induced charges in the oxide and/or at the semiconductor/oxide interface generates a measurable signal upon exposure to radiation such as gamma ray, neutrons, electrons, and X-rays. The influence of radiation on MOS characteristics is found to depend on the dose, parameters and types of the device structure including the insulator thickness [10].

The effect of process and device parameters on the device performance has been the subject of many investigations [11–13]. The suitability and usability of MOS devices as a radiation sensor depends on the device sensitivity which is directly related to the gate insulator and its interface with the underlying semiconductor. There exists optimum thickness for the gate insulator for a given dose. The type of the trap states responsible for the voltage shift has been addressed in several studies. The voltage shift are mostly due to trapped oxide charges rather than the interface states [14–16].

The effect of using a Ge-rich layer on radiation sensing has been studied in this work. SiO_2 + Ge, which is believed to be an alternative dielectric in the microelectronic technology, has been employed in the MOS capacitors used for radiation sensing. Radiation effect on the MOS capacitors with SiO_2 dielectric layer has previously been studied to some extent [17,18]. In this paper, we present an evaluation of SiO_2 + Ge based MOS devices as a radiation sensor and we could not make direct comparison with the SiO_2 based devices from the sensitivity point of view. In one of our previous studies [19], the radiation response from SiO_2 MOS capacitors was examined. SiO_2 MOS capacitors were damaged by a high radiation dose above 300 Gray. We could not obtain C–V response at lower dose from Ge doped MOS capacitors only, so we could not make a direct comparison of these two systems. It is

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* Corresponding author. Tel.: +90 374 254 10 00/1335; fax: +90 374 253 46 42.
E-mail address: yilmaz@ibu.edu.tr (E. Yilmaz).

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shown that MOS capacitor with SiO_2 + Ge dielectric exhibits better resistance to ionizing radiation at high doses, which makes them very useful at these radiation levels.

2. Experimental details

The samples used here comprised a 100 nm Ge rich SiO_2 layer sandwiched between two SiO_2 films deposited on n-type < 100 > Si substrate by RF magnetron co-sputtering from two independent target materials with powers of 300 W for SiO_2, 20 W for Ge. The bottom SiO_2 layer with the thickness of about 100 nm was deposited on Si to restrain Ge atoms from growing epitaxially on the Si substrate in the post-annealing process. The top SiO_2 layer with the thickness of about 40 nm was deposited to impede the diffusion of Ge atoms out of the surface. After growth, wafers were cleaved and annealed in a quartz tube furnace under flowing N_2 gas at ambient pressure for 1 h at 900 °C. In general, the formation mechanism for Ge nanocrystals embedded in a SiO_2 matrix undergoes the familiar sequence of nucleation and growth, often followed by coarsening of nanocrystals due to Ostwald ripening.

In order to study the response of MOS capacitors to gamma irradiation over a wide range of dose, samples were irradiated using the Co-60 gamma source from 500 to 4000 Gray at a dose rate of 0.018 Gy/s. The gate bias during irradiation (V_{irr}) was 0.

3. Results and discussions

The formation Ge nanocrystals and evolution of nanostructures upon gamma radiation were studied by Raman spectroscopy. Raman spectra were taken on a confocal micro-Raman (HR800, Jobin Yvon), attached with Olympus microanalysis system and a charge-coupled device (CCD) camera providing a resolution of $\sim 1\ cm^{-1}$. The spectra were recorded out in backscattering geometry with the 632.8 nm line of He–Ne laser at room temperature.

The effect of gamma-radiation dose on the chemical composition and phase of the Ge nanocrystals were determined by Raman spectroscopy, carried out at room temperature. The Si substrate Raman spectra is narrowed and the peak at $521\ cm^{-1}$ is right shifted to $522\ cm^{-1}$ as shown in Fig. 1. The Raman scattering spectra intensity dependence on the gamma-radiation dose from 0.1 to 16 Gy was found to decrease as shown in Fig. 1.

Similarly, Raman spectra of the Ge nanocrystals embedded in the SiO_2 matrix show a peak at $300\ cm^{-1}$ in Fig. 2 corresponding to the Ge–Ge phonon mode confirming the formation of nanocrystalline Ge after thermal annealing at 900 °C for 1 h in N_2 [20–23]. The decrease of Raman spectra intensity is due to the decreasing number of Ge–Ge due to bond braking by irradiation. The blue shift of the nanocrystalline Ge peak after irradiation is likely to result from increase of local compressive stress [20].

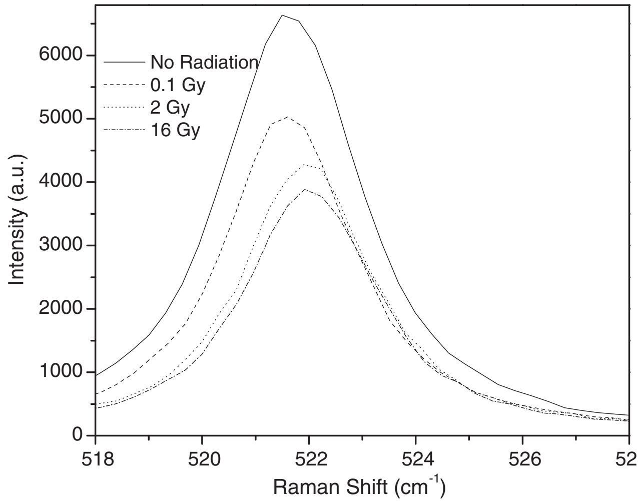

Fig. 1. Raman scattering spectra of the Si–Si bonds of the substrate: nonirradiated and radiated with 0.1, 2.0 and 16.0 Gy doses.

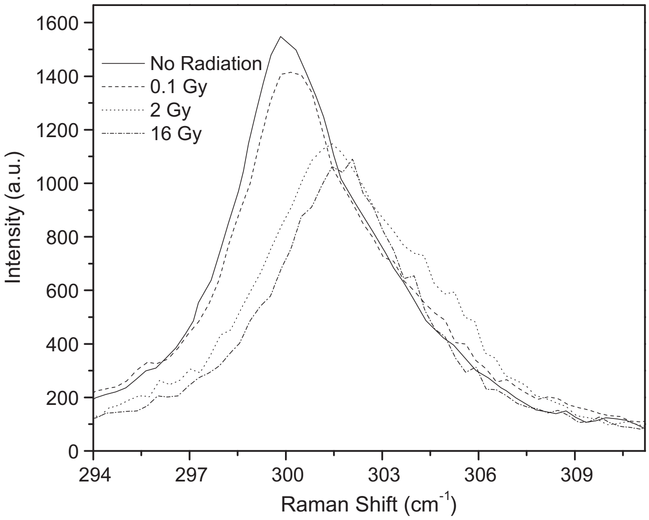

Fig. 2. Raman scattering spectra of the Ge nanocrystals: nonirradiated and radiated with 0.1, 2.0 and 16.0 Gy doses.

The response of the fabricated MOS capacitor to gamma radiation was determined from the shift in the flat band upon irradiation. Fig. 3 shows a typical C–V behavior of the MOS capacitors before and after the gamma irradiation. It is widely accepted that there are two different contributions to the flat band-voltage shift, one is attributed to oxide-trapped charge and the other is interface trapped-charge [24].

If these devices are to be used as radiation sensor they need to be calibrated against radiation dose. Fig. 4 shows the calibration curves vs. gamma-radiation dose. The doses applied to the devices were varied from 0.5 to 4 kGray. The response of the devices is generally found to be almost linear over this dose range.

We have also observed the mid-gap voltage shift (ΔV_{mg}) from the C–V curve. Because, the mid-gap voltage shift caused by irradiation is only due to the oxide-trapped charge [25]. Using these values the net oxide trap-charge densities (ΔN_{ot}) can be estimated by [26].

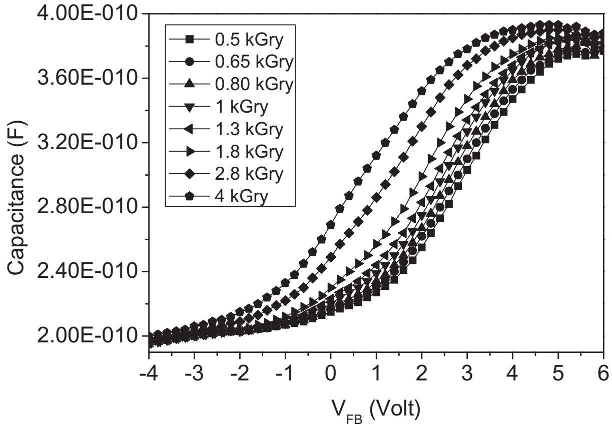

Fig. 3. 1 MHz C–V curves for Ge + SiO_2 capacitor (T = 900 °C, 1 h, N_2), irradiated to total dose from 50 to 400 krad.

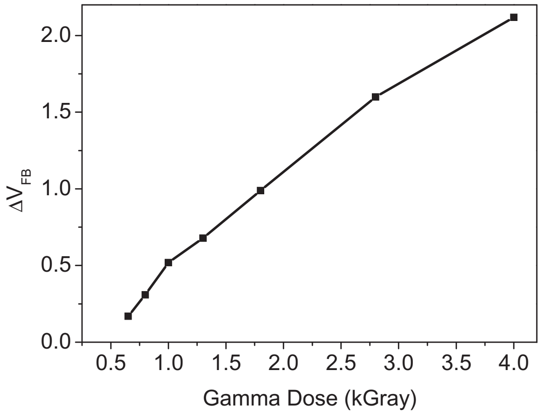

Fig. 4. Flatband voltage shift of Ge + SiO_2 capacitor vs. total dose.

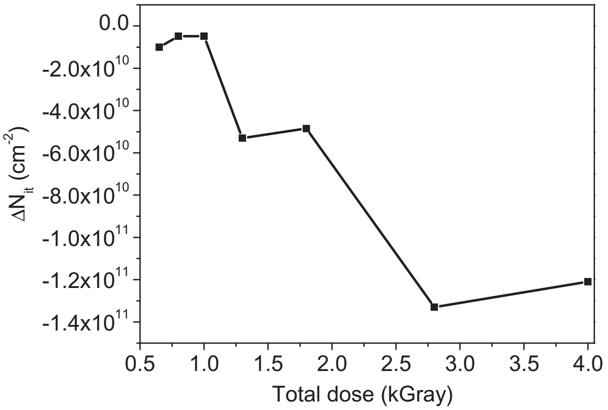

Fig. 5. Interface trap density ΔN_{it} of Ge + SiO_2 capacitor vs. total dose.

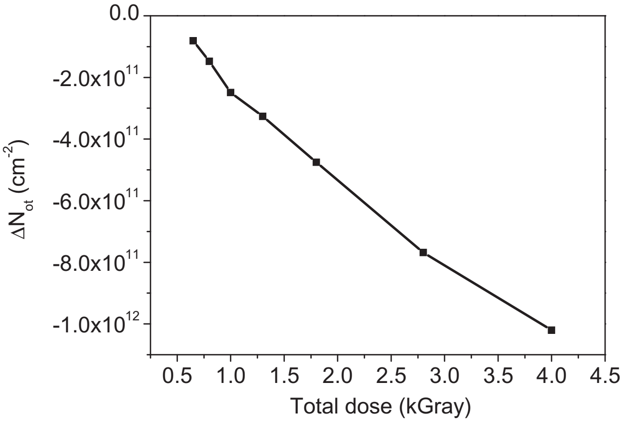

Fig. 6. Oxide trap density ΔN_{ot} of Ge + SiO_2 capacitor vs. total dose.

$$\Delta N_{\mathrm{ot}} = -\frac{C_{\mathrm{ox}} \Delta V_{\mathrm{mg}}}{qA} \tag{1}$$

where C_{ox} is the oxide capacitance measured in accumulation, $-q = (1.602 \times 10^{-19}\,\mathrm{C})$ electronic charge and A is the area of capacitor. From this equation, ΔN_{ot} was calculated as $\sim 1.1 \times 10^{11}\mathrm{cm}^{-2}$ after 0.5 kGray and $\sim 1.0 \times 10^{12}\ \mathrm{cm}^{-2}$ after 4 kGray for the SiO_2 + Ge thin film MOS device. After that, the flatband voltage shift (ΔV_{FB}) was calculated. This takes into account both the oxide-trapped charge and the charge trapped on interface traps between flatband and mid-gap [25]. Similarly, the interface trap-charge densities (ΔN_{it}) can be estimated from mid-gap-to-flatband stretch-out of the C–V curves by [26–28]

$$\Delta N_{\mathrm{it}} = \frac{C_{\mathrm{ox}}(\Delta V_{\mathrm{fb}} - \Delta V_{mg})}{qA} \tag{2}$$

where C_{ox} is the oxide capacitance measured in accumulation and A is the area which is calculated from the radius of the mask. The diameter of the mask is about 0.8 mm. Using Eq. (2) we estimated ΔN_{it} as $\sim 1.0 \times 10^{10}\,\mathrm{cm}^{-2}$ after 0.6 kGray and $\sim 1.2 \times 10^{10}\,\mathrm{cm}^{-2}$ after 4 kGray. Figs. 5 and 6 show interface trap charge density and oxide trap charge density which increases almost linearly from 0.5 to 4 kGray.

4. Conclusions

The gamma-radiation doses applied to the devices in this work are incredibly high since technology targets values generally about 1000 Gray for device applications. For the first time, very high radiation dose effects to ultra thin SiO_2 + Ge as an alternative gate dielectric were studied. Excellent dielectric properties such as high dielectric constant, low leakage current and excellent reliability were demonstrated. These results suggest that SiO_2 + Ge is a promising material for the future gate dielectric application particularly at high radiation doses. Active semiconductor components in satellites are sensitive to the accumulated ionization radiation dose. These components are easily integrated to the required microelectronic circuitry, which a very important advantage. Ge doped radiation sensors which we report here are likely to have the advantage of being an active semiconductor device which can be used at very high doses with a better resistance to the radiation damage.

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