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Impact of Gamma Ray and Neutrons Radiation Effects on Al/SiO_2/Si Structure

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ABSTRACT

The metal-oxide-semiconductor (MOS) structure was fabricated from p-type (Boron doped) SSP silicon <100>. The interfacial oxide layer was SiO_2 while aluminium's metal gate thickness was (~250 nm) thermally evaporated with silver contacts. Four of the prepared structures were exposed to gamma radiation from the Ra^{226} source with a duration of (10, 20, 30, 40) days respectively, while another four structures were exposed to neutrons irradiation using (^{241}Am -^{10}Be) source for (5, 7, 9, 12) days respectively. The last MOS was not exposed to any radiation. Characterization measurements were carried out to compare the behaviour of MOS structures after being irradiated. The main result is that there is a significant increase in the current due to the decrease of barrier height of irradiate MOS devices as well and C-V measurements illustrate negative voltage shifts in the irradiated devices as a result of the buildup of interface states and the generation of electron-hole pair as a result of the radiation.

Keywords: MOS, C-V measurements, gamma ray, neutrons radiation.

INTRODUCTION

The MOS structure generally comprises a metal-oxide-semiconductor (Chen *et al*., 2013). It is an essential part of the integrated circuits and space applications which can resist severe atmospheric environments with highly ionizing radiation fields as well as high temperatures (Simeonov, 2008; Simić *et al*., 2013). In this study, we use Al/SiO_2/Si as a MOS system that represents a kind of capacitor because it stores the electric charges in its oxide layer SiO_2 (Markna *et al*., 2016; Ibarra *et al*., 2015). When an external electric field is applied to an MOS device by placing a negative bias on the gate, the electrons on the gate attract holes from the semiconductor surface and form an accumulation layer. When gate bias increases, the electrons are removed from the gate, so holes leave the accumulation layer and as a result, the semiconductor becomes neutral everywhere, in this case, the bias is called flat band voltage. As the gate bias becomes positive, holes are repelled from the semiconductor (in the case p-type semiconductor) and the positive gate charge is balanced with the negative acceptor ions then and forms a depletion layer on the surface of the semiconductor. When gate bias increases more, holes are repelled at the semiconductor surface and the electrons appear and form a thin inversion layer (Mahani *et al*., 2020). The MOS capacitor is affected by charges that exist in the oxide (the insulator) (Al-Ahmadi, 2020). There are two surface charge regions as a result of the existence of the insulator called (Si/SiO_2 interface and gate/SiO_2 interface) these surface regions in real MOS contain localized electronic states called traps, traps exist at Si/SiO_2 interface due to many factors associated with the MOS structure (Tataroglu *et al*., 2005). The ionizing radiation exposure (such as gamma ray, neutrons radiation, etc) was the more important factor inducing traps (Rosenfeld *et al*., 1999) so, trap density at the insulator increases when the energy of radiation is enough to generate electron-hole pairs by subsequent reactions. The electric field of the oxide causes the electrons moving towards the Si-SiO_2 interface and be injected into the silicon bulk while the holes (less mobile) are trapped at the Si-SiO_2 interface (Chen *et al*., 2001). That creates positive charges in the insulator (Afanas' ev *et al*., 1995; Schwank *et al*., 2008). Generally, traps in MOS structures are classified into four types: Interface-trapped charge, oxide-trapped charge, fixed oxide charge and mobile ionic charge (Spieler, 1997).

These traps usually cause shifts in the threshold or flat band voltage, high leakage current as well and increasing dispersion in the low-frequency capacitance-voltage (C-V) characteristic of the MOS capacitors (Hughes, 1977). Researchers studied the various levels of ionizing radiation (gamma rays and neutrons) on the structural and electrical properties of the MOS structure, (Ergin *et al*., 2010) studied the effects of gamma radiation on the HfO_2 MOS capacitor by ^{60}Co source at low doses and various exposure time, they measured and analyzed the mid gap and flat band voltage shifts in MOS devices, results indicate that gamma radiation does not cause considerable variations in the HfO_2 MOS devices. (Jafari *et al*., 2015) also study the effects of ^{60}Co gamma source on the n-channel MOS transistors with the dose rate of 0.2 rad/s in SiO_2 in several doses and different biases, the results showed that the interface trapped charges that exist result of irradiation improve the accuracy of the threshold voltage shift estimation in MOS transistors. (Shi *et al*., 2021) deal with the synergistic effect of neutrons and gamma irradiation on MOS structure with an HfO_2 insulator, they confirm the formation of the oxide-trapped charges in the HfO_2–SiO_2 layer, also, the effect of the interface state increased with the energy deposition in the oxide at lower fluences but it decreasing above the critical fluence, they conclude the existence of the synergistic effect of these ionizing radiation in damaging HfO_2 MOS devices. In 2023 (Li *et al*., 2023) studied the effects of neutron radiation fields on (pMOS) ionizing radiation dosimeter, the neutron energy loss can introduce oxide charges then, the space charge effects induced by the oxide charges result in a reduction in the hole yield, that cause to decrease the sensitivity of threshold voltage (ΔV_{th}) to ionizing radiation such as gamma radiation.

This project aims to study the effect of irradiation (by neutrons and gamma rays) on MOS capacitors and characterize their structural, morphological and electrical properties using I-V, C-V, SEM and XRD measurements.

EXPERIMENTAL DETAILS

Nine samples of MOS were prepared. The MOS structure was fabricated from p-type (Boron doped) SSP silicon <100> with <0.01 Ω.cm resistivity. The interfacial oxide layer was SiO_2 (300 nm) and the metal gate thickness was (200 nm) aluminium thermally evaporated under 1×10^{-4} Torr With a circular dot of 1 mm diameter silver contacts on the aluminium gate. This was followed by the thermal evaporated deposition of a silver contact on the whole backside of the MOS structure. Four of the prepared samples were exposed to gamma radiation from Ra^{226} (186 keV with the activity of 1.96 µCi) source with a duration of (10, 20, 30, 40) days respectively, while another four samples were exposed to neutrons irradiation using (^{241}Am-^{10}Be) source with a flux of 3×10^5 $n/cm^2.s$ and energy 5.71 MeV For (5, 7, 9, 12) days respectively. The last sample was not exposed to any radiation. IV, C-V measurements were performed using LCR-6100 with 1kHz and XRD and FE-SEM carried out using (XRD-6000 SHIMADZU), FE-SEM (JSM7600F) to determine the reliability of the MOS capacitors in radiation environments.

RESULTS AND DISCUSSION

(Table 1) shows the different periods of exposure of MOS structures to the gamma radiation. Fig. (1) shows the obtained XRD results for pristine and gamma-irradiated samples. The peak of SiO_2 oxide for the pristine sample was in the position (2θ=38.7º), all other SiO_2 peaks of the irradiated samples have shifted towards the larger diffraction angle, in addition, these peaks had changes in their intensity, highest intensity of the peak in (2θ=39.4º) when the time of exposure to gamma radiation was 20 days and then began to decrease with increasing the time of exposure. The aluminum (Al) thin film peaks also shifted from (2θ=61.9º) for the pristine sample towards the largest values of the diffraction angle, the largest shift of aluminum peak position was (2θ=62.5º) in the 20-day gamma irradiated sample as shown in (Table 3).

Table 1: Shows the intervals of radiation by gamma-ray

Sample name	Time of radiation
pristine(pure)	0 day
G1(gamma)	10 days
G2(gamma)	20 days
G3(gamma)	30 days
G4(gamma)	40 days

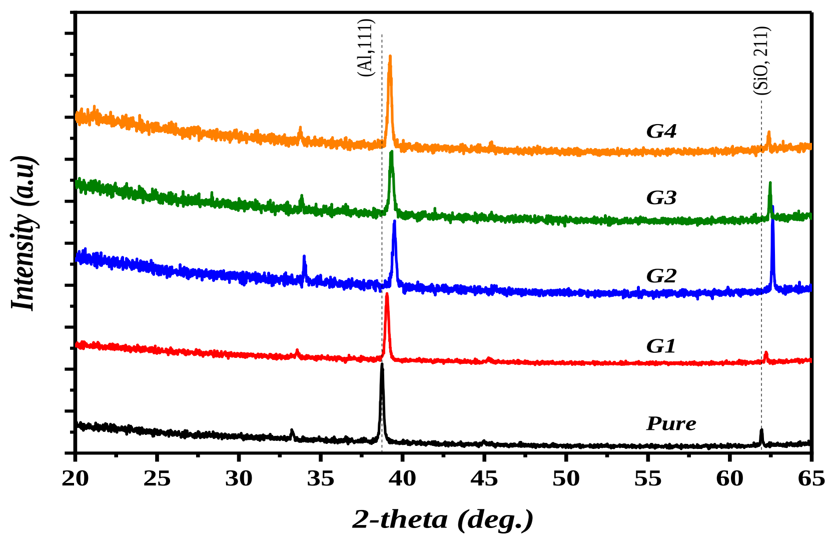

Fig. 1: XRD patterns of the Pure MOS and Gamma irradiation MOS structure.

(Table 2) shows the different periods of exposure of MOS structures to neutron radiation. The XRD pattern obtained from the irradiated samples is shown in Fig. (2). The SiO_2 oxide peaks disappeared in the first three intervals of exposure but in the last interval of 12 days of neutron exposure, it emerged clearly in (2θ=62.1°) with a small shift from the pristine peak position and a relatively larger intensity value, while all the Aluminum thin films peaks were present clearly and with a small shift from pristine diffraction peak position. The largest shift was in the 5 days of neutron irradiation (2θ=39.3°) set in (Table 3). These shifts in peak position in both patterns of gamma and neutrons irradiate MOS structures indicate the existence of displacement damage that occurs by the energy of radiation that alters the crystal properties and may produce new material in the irradiate structures, and the perturbation of the position peaks and the intensity values may result from the changes in chemical properties of the MOS materials (Shi *et al*., 2021; Spieler, 1997).

Table 2: Shows the intervals of neutron irradiation

Sample name	**Time of radiation**
pristine(pure)	0 day
N1(neutron)	5 days
N2(neutron)	7 days
N3(neutron)	9 days
N4(neutron)	12 days

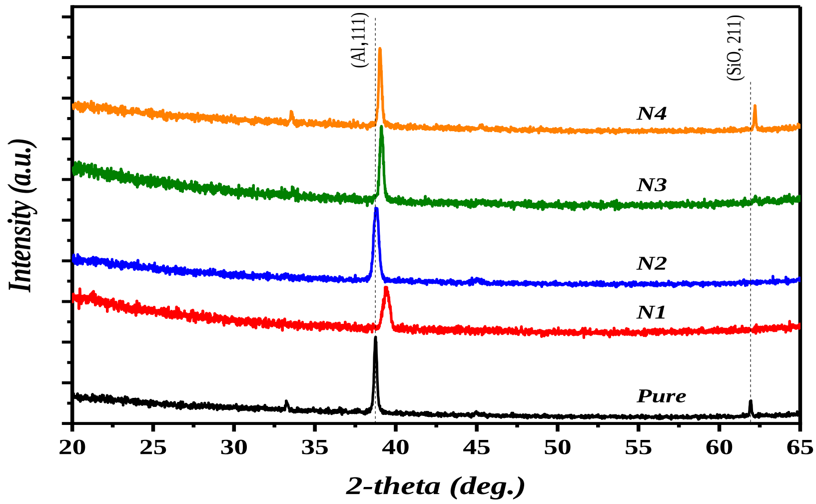

Fig. 2: XRD patterns of the Pure MOS and neutrons irradiation MOS structure.

From the XRD results set in (Table 3), We can distinguish the effects of the type and intervals of radiation on the crystalline size of Al and SiO_2 thin films in MOS structures. The largest value of crystalline size calculated by the Debye-Scherrer formula (Al Refaei *et al*., 2021; Noori, 2019) was 66.7nm of Al thin film for pristine structure when irradiated by gamma radiation the MOS structures showed a decrease in the crystalline size. The smallest value was 41.9nm obtained for the sample irradiated for 30 days by γ-radiation. While the crystalline size of Al thin films irradiated by neutron radiation showed a large decrease of 20.1nm at first, then with increasing the time of irradiation the crystalline size increased greatly to 65.6nm. The largest crystalline size for SiO_2 thin films was 251nm for the sample irradiated for 20 days by gamma radiation, and the smallest crystalline size was 41.9nm for the sample irradiated for 30 days by gamma radiation, however, when the samples were exposed to neutron radiation, the SiO_2 crystalline size ranged from zero to 84.7nm in the 12 days irradiation. From these results, we can conclude that the crystalline size of Al thin film decreased with both gamma and neutron radiation except in the last interval of neutron irradiation, while the crystalline size of the SiO_2 layer was perturbed, which indicates that the effects of radiation on the insulator properties larger than in the gate metal.

Table 3: In-depth XRD results of the Pure MOS, gamma and neutron irradiations MOS structure; (SiO_2 peak values in RED – Al peak values in BLACK)

Sample	2-theta (deg.)	d-spacing (Å)	FWHM (deg.)	Crystallite (Å)	Crystallite	Micro strain
Pure	38.716	2.324	0.159	667	66.7	0.174
Pure	61.9185	1.49739	0.1288	889	88.9	0.08425
G1	39.023	2.306	0.201	505	50.5	0.228
G1	62.1891	1.49152	0.1447	766	76.6	0.09731
G2	39.465	2.282	0.181	472	47.2	0.242
G2	62.5939	1.48284	0.0579	2514	251.4	0.02949
G3	39.293	2.291	0.209	419	41.9	0.273
G3	62.4429	1.48607	0.1363	828	82.8	0.08974
G4	39.188	2.297	0.217	452	45.2	0.254
G4	62.3539	1.48798	0.1292	1202	120.2	0.06191
N1	39.386	2.286	0.456	201	20.1	0.569
N2	38.759	2.321	0.132	474	47.4	0.245
N3	39.087	2.303	0.232	448	44.8	0.257
N4	39.004	2.307	0.159	656	65.6	0.176
N4	62.1882	1.49154	0.1338	847	84.7	0.08806

The images obtained from FE-SEM measurements for pristine and irradiated samples are shown in Fig. (3). The grain size value of the pristine sample was (85.3-89.6) nm but in irradiated samples there was a decrease initially in the 10 days gamma irradiated sample (49.9-37.9) nm, then the values showed an increase with the increasing time of gamma irradiation. Where its range was (70.5-52.9) nm in the 20 days irradiated sample, (120.8-80.5) nm in the 30 days irradiated sample, and finally its range was (110.2-73.8) nm in the 40 days gamma irradiated sample. This increase in grain size range with an increase in the time of exposure to radiation leads to the decrease in the area of the grain's boundary and hence, causes an increase of the conductivity due to decreased charge carriers scattering, the surface of gamma irradiates structures be more homogenous, as shown in FE-SEM images. The grain size value of samples exposed to neutron radiation was (56.1-54.3) nm for 5 days of the irradiated sample while it was (67.5-44) nm for 7 days of irradiation, but it was (55.8-34.4) nm for 9 days and finally was (58.3-32.7) nm for 12 days neutron irradiation time, these values indicate to the increasing of the boundary area of grains cause more scattering of charge carrier and decrease the conductivity of the MOS structures, also, the surfaces of MOS that exposed to neutrons irradiation reveal cracks as well as many irregular shapes and size of grains in their surfaces.

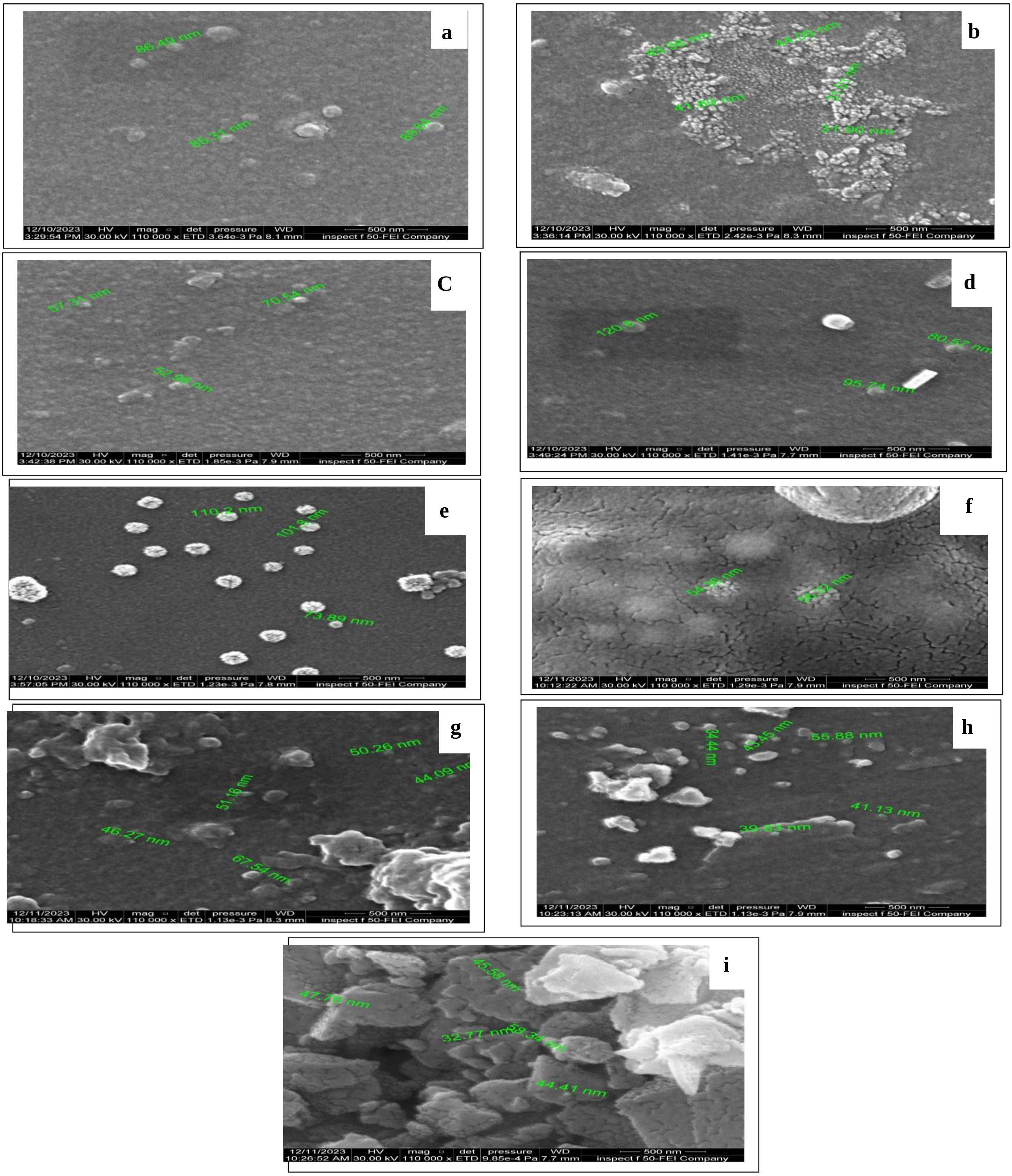

Fig. 3: The obtained FE-SEM images for (a) Pure/pristine, (b) 10 days gamma irradiation, (c) 20 days gamma irradiation, (d) 30 days gamma irradiation, (e) 40 days gamma irradiation, (f) 5 days neutrons irradiate, (g) 7 days neutrons irradiate, (h) 9 days neutrons irradiate and (i) 12 days neutrons irradiate.

Fig. (4) shows the I-V characteristics of the fabricated MOS for pristine devices and gamma-irradiated devices while Fig. (5) shows the I-V characteristics of the fabricated MOS for pristine devices and neutrons-irradiated devices. both Fig. (4, 5) illustrate the effect of ionizing radiation (gamma and neutrons) on the electrical characteristics of devices where the pristine current has the smallest value compared with the values of currents in gamma or neutron irradiated cases except the current that was obtained from MOS device after 10 days gamma irradiation, the increase in the current values of irradiated devices can be attributed to the defects formed in the MOS devices caused by the radiation energy absorbed in the insulator layer that liberates charge carrier which causes changes in the number of generation and recombination Centre, then due to the influence of local electric field the generated electrons and holes travel in the bulk according to its mobility amount. (Nikolić *et al.*, 2015).

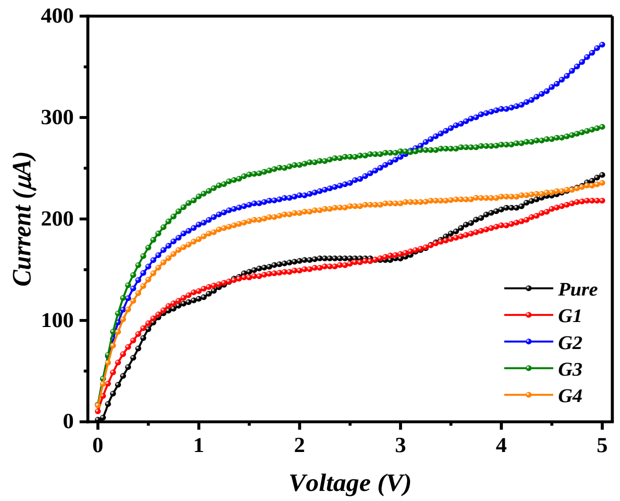

Fig. 4: I-V characteristics for Pure MOS and gamma irradiated MOS structures.

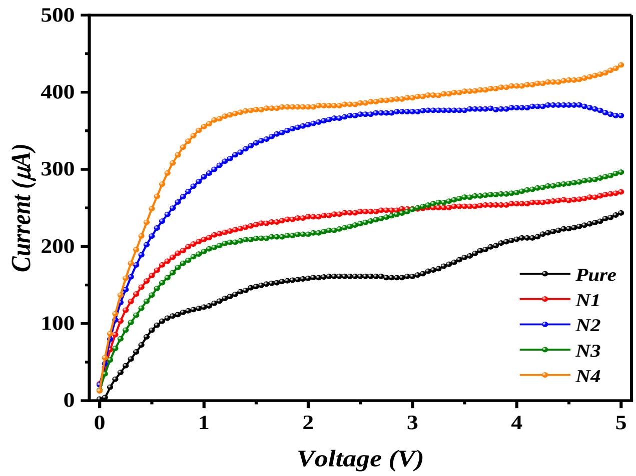

Fig. 5: I-V characteristics for pure MOS and neutrons irradiated MOS structures.

As can be seen in Fig. (6, 7) the C-V characteristics of pristine and irradiated MOS devices measured at 1kHz, both figures show that there is an evident parallel shift ΔV toward the negative voltage direction of the C-V characteristics of irradiated devices, this shift was due to a buildup of interface states in addition to the created positive charges trapped in the SiO_2 during the irradiation process (Rosenfeld *et al.*, 1999; Hughes, 1977). This result is consistent with (Ergin *et al.*, 2010; Kahraman *et al.*, 2020).

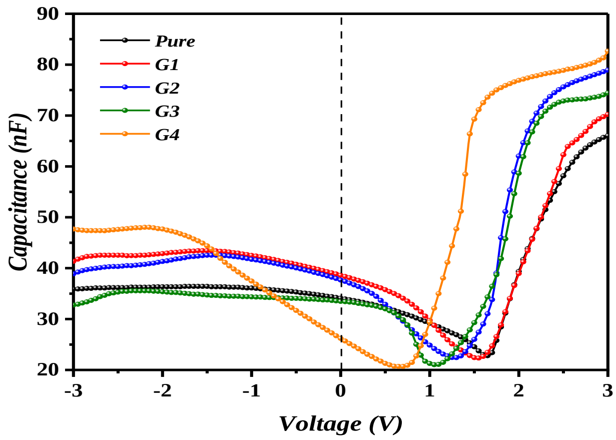

Fig. 6: C-V characteristics for pure MOS and gamma irradiated MOS structures.

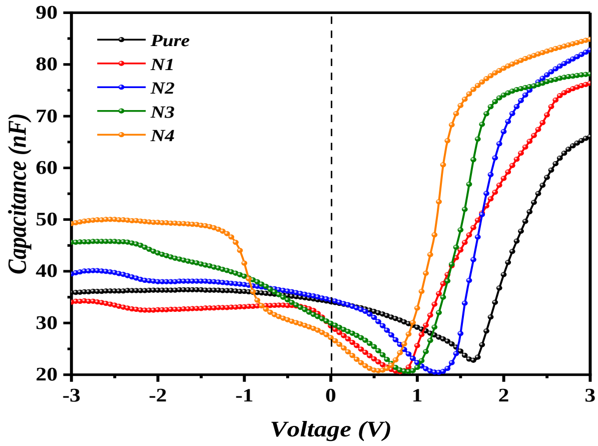

Fig. 7: C-V characteristics for pure MOS and neutrons irradiated MOS structures.

CONCLUSIONS

Four of the fabricated MOS structures were irradiated by gamma radiation, the other four MOS structures were exposed to neutron radiation, and the last MOS structure was kept without any radiation to contrast it with irradiated structures. Results of XRD measurements show that gamma and neutron radiation cause a little shift in peak position. The maximum shift of the SiO_2 peak resulting from gamma radiation was in the 20-day irradiation while the maximum shift of the SiO_2 peak resulting from neutron irradiation was in the 12-day irradiation. While SiO_2 peaks disappear in the (5, 7, 9) days of neutron radiation. Results of SEM measurements of gamma structures irradiation reveal there are no cracks or strange shapes in the surfaces as well as there are some spherical shapes of grains created and their values increase with increasing time of irradiation. SEM for neutron irradiating MOS structures showed the existence of cracks on their surface, especially within 5 days of exposure. Also, there are many irregular shapes and sizes of grains on their surfaces in all neutron-irradiated devices.

I-V measurements show increasing in the current values measuring for the irradiated devices (for gamma and neutrons MOS exposure), especially in neutron exposure, because of the decrease in barrier height values with the increase in time of radiation exposure, while saturation current values increase with radiation intervals.

Finally, from the obtained C-V curves measurement, the main observed result of ionizing radiation (gamma and neutrons) was the negative voltage shift in threshold voltage and flat-band voltage, due to the buildup of interface states and electron-hole pairs generations.

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تأثيرات اشعة كاما واشعاع النيترونات على نبيطة Al/SiO_2/Si

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الملخص

تم تصنيع تركيب معدن–اوكسيد–شبه موصل Al/SiO_2/Si من السليكون المطعم بالبورون SSP باتجاهية <100>. كـانت طبقة الاوكسيد البينية SiO_2 والبوابة المعدنية من الالمنيوم المترسبة بواسطة التبخير الحراري (~250 نانومتر) وذات الاقطاب من الفضة.

تم تعريض اربعة نماذج محضرة لإشعاع كاما المنبعث من المصدر Ra^{226} بطاقة (186 keV) ونشاط اشعاعي (1.96µCi) للفترات الزمنية (10,20,30,40) يوما على التوالي، وتعريض اربعة نماذج اخرى للإشعاع النيتروني باستخدام المصدر النيتروني (^{241}Am -^{10}Be) بفيض (3×10^5 n/cm^2.s) وطاقة (5.71 MeV) وللفترات الزمنية (5,7,9,12) يوما على التوالي. في حين تم ابقاء النموذج الاخير بدون اي تعرض للإشعاع. تم اجراء قياسات الخواص على النماذج لأجل مقارنة سلوك تراكيب MOS بعد الاشعاع. ان قياسات C-V تبين وجود ازاحة سالبة للفولتية في التراكيب المعرضة للإشعاع وهي ناتجة عن تكون مستويات في الواجهة بالإضافة الى توليد ازواج الكترون-فجوة.

الكلمات الدالة: MOS، قياسات C-V، اشعة كاما، الاشعاع النيتروني.