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Thermal annealing effects on the electrical characteristics of alpha particles irradiated MIS device $AuTa_2O_5GaAs$

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An alpha particle-irradiated MIS device made of $AuTa_2O_5GaAs$ was used to study how thermal annealing affects the I-V characteristics and how the current changes with annealing temperature, radiation energy, and voltage biassing. The super-gate of the MIS structure was made by using thermal evaporation to build a 1000°A thick layer of gold under a vacuum of about 10-5 torr. At room temperature, the devices were exposed to alpha particles from the radioactive source ^{226}Ra (0.5 Ci) with energies of 5.1, 4, 3, 1.8, and 1.2 MeV for 0–30 minutes. After 30 minutes of annealing at 150, 200, and 300 ºC in a vacuum of 10-3 torr, the current-voltage (I-V) characteristics of the irradiation devices were found. During thermal annealing, different results were seen with bias voltages of 0.4, 1, and 2 V and temperatures of 150, 200, and 300 ºC. Annealing the device at 150 ºC doesn't change how stable it is, but annealing it at 300 ºC causes ohmic conduction in the device's properties. The device's current can be fixed best when the device is heated to 200 ºC and then cooled. Also, thermal annealing seems to have different effects on the I–V electrical characteristics of the devices depending on the energy of the particles and the voltage biassing.

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1. Introduction

Most microelectronic technologies rely on MIS transistors, which are one of the fundamental building blocks, and MIS charge-coupled devices (CCDs), which are widely employed in optical processing. Most of the time, the oxide is used as the base for nuclear and electronic detectors. Knowing the structure of MIS is important to understand how it affects the insulator composition negatively. It has been demonstrated that the MIS is a useful framework for investigating semiconductor surface effects [1]. The most fragile part of the MIS is the insulator layer, which is made of tantalum oxide (Ta_2O_5). About three orders of magnitude less current flows across its surface in the amorphous state (10^{-10} A cm^{-2}) than in the crystalline state (10^{-7} A cm^{-2}) [2, 3].

High dielectric constant and low state density are features of the highly randomized tantalum oxide (a-Ta_2O_5) [4]. Since the breakdown field decreases with increasing temperature, crystallization begins at temperatures of 500 °C or above [5]. These benefits have led to random tantalum oxide's widespread adoption for use in a variety of electronic applications, including integrated circuits, optical waveguide devices, high-temperature resistors, and oxygen sensors [6, 7].

Radiation damage may occur when electronic equipment and systems are exposed to radiation for an extended period or above a certain limit, causing a decrease in performance [8]. The effects of radiation on a material change depending on the nature of the radiation or particles that are incident on the material. Several factors, including the mass and charge of the particle, the kind and energy of the radiation, and the nature of the irradiated material, all play a role. As a

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result, the radiation dose (irradiation rate) and energy are considered to be two crucial elements in determining the extent and nature of radiation damage within a substance [9]. At the interface, dissatisfied or dangling bonds and trapped charges cause damage [8]. There are heavier charged particles than electrons, and those are protons and alpha particles. Following the Coulomb principle, they engage in some form of interaction with the material, either with the atomic nuclei or the orbital electrons. When these particles move through a material, they ionise and excite any atoms they encounter, causing damage unless the energy of the particles is extremely high. Depending on the interaction energy and the energy barrier, these particles may interact with the nuclei of atoms if their energy is relatively high and higher than the interaction threshold energy. Interactions of the types (P, n), (P, γ), (α, P), (α, n), (α, γ), (P, Pn), and others are possible when the matter is exposed to protons or alpha particles with reasonably high energy (tens MeV) [9].

Radiation has four main effects on the matter: making impurities, moving atoms out of their normal places, ionising the material by removing electrons from bombarded atoms, and releasing large amounts of energy in a small area due to thermal heating [10]. Positive vacuum charges and electron-hole pairs are created when ionizing radiation strikes oxide insulators, leading to the buildup of charges. A greater number of electron-hole pairs is produced because these charges encourage electron tunnelling and gap reconnection. Positive charges that induce trapping holes are formed immediately during thermal annealing at 350 ^{o}C for 30 minutes [11], which also removes most of the interfacial levels.

The amount of energy that is deposited in the matter after it has been irradiated is determined by the specifics of the radiation that was used to irradiate the substance. Since alpha particles have such a short range, they dissipate all of their energy at a relatively shallow depth inside the device, typically between 16.48 and 2.88 m within the GaAs layer [12]. Energy deposition is a random process, so knowing the free path rate of carriers in the material is crucial. Detectors made of GaAs are annealed for 90 minutes at 450 degrees Celsius [13] to reduce radiation-induced flaws. In the case of Ga_2O_3 devices, annealing at 500 °C was found to restore the carrier concentration after exposure to alpha particles, while annealing at 450 °C showed considerable recovery after exposure to proton radiation [14]. One of the processes used to change the unsaturated dangling bonds is thermal annealing [8]. So, the effects of thermal annealing on devices that have been exposed to alpha particles will depend on the annealing temperature, time, and dose of alpha particles [10].

The effects of thermal annealing and radiation, including neutrons, protons, alpha particles, beta, gamma, and X-rays, on the electrical, dynamic, structural, and thermal stability of different MIS and MOSFETs devices have been investigated in several studies [8, 14–20]. This study examines the influence of thermal annealing on the electrical characteristics and thermal stability of MIS devices made of AuTa_2O_5GaAs that have been annealed following irradiation with alpha particles of varying energies. In addition, the device current will be analyzed as a function of annealing temperature, alpha particle energy, and biassing voltage.

2. Experimental

2.1. Devices preparation

The MIS device AuTa2O5GaAs was prepared by first washing gallium arsenide (GaAs) with trichloroethylene (TCE), then acetone, and then isopropyl alcohol (IPA) for 5 minutes to remove organic and inorganic impurities. The GaAs substrate was submerged in deionized (DI) water for two minutes to remove the native oxide from the substrate's back surface. Next, the substrate was submerged in a chemical etching solution consisting of HCl, H2O2, and H2O in a volume ratio of 3:1:150 ml while being agitated for 15 seconds. Lastly, the substrate was lifted and put into a pot of boiling deionized water to wash away any ions that were still in the solution.

The ground of the n-GaAs semiconductor was covered with insulating tantalum oxide (Ta_2O_5) using the sputtering method. At a pressure of 10^{-5} torr, 300 mg of 99.99% pure gold (Au) was thermally evaporated to create the ohmic contact on the rear surface of the semiconductor. Afterward, the sample was annealed for 0.5 hours at 400 ^{o}C and 10-3 torr. Metal masks were used to create tiny circles with an area of 7.852 x 10^3 cm, which were then subjected to thermal evaporation at a pressure of 10^{-5} torr to deposit a thin layer of gold (Au) with a thickness of 1000 A^o to construct the meta-metal gate.

Once dried (after 48 hours), the silver paste was used to adhere the sections of the assembled device to the To-5 header base. The thermo-compression bonding technique was then used to join the deposited gold electrodes with tiny wires. The layers of the fabricated device were as follows in thickness: gallium arsenide (GaAs) at 450 m, tantalum oxide (Ta2O5) at 0.05 m, and gold (Au) at 0.1 m. Bigdag equipment used a laser to determine the thickness of the layers involved.

2.2. Device irradiation

The devices were subjected for 30 minutes to alpha particles from the radioactive element ^{226}Ra (0.5 µCi) at energies of 5.1, 4, 3, 1.8, and 1.2 MeV, with cumulative exposures every 3 minutes. These energies were obtained by placing polymeric sheets of varying thicknesses in front of the radioactive source to attenuate the radiation. The energy of these polymeric sheets was measured with a multi-channel analyzer and a standard radioactive source of Americium, ^{241} Am (0.5 Ci).

2.3. Measurements and device annealing

The device's forward and reverse bias current against voltage (I-V) curves were measured after it was exposed to alpha radiation for 30 minutes and then heated to the right temperatures. The process of thermo-annealing was done with a machine made just for the job. The thermocouple sensor was firmly attached and wired to the thermal controller circuit. Part of the setup is a rotary pump that creates the vacuum required for the annealing process. In this experiment, we compared the I-V characteristics of irradiated and unirradiated (non-annealed) devices. The cryostat, annealing system, and ramp-voltage generator were all made by us in the lab on a local level.

3. Results and discussion

3.1. Changes in I-V characteristics caused by annealing in an irradiated device

After annealing at 150–300 oC, the I–V characteristics of devices that were exposed to alpha particles with energies ranging from 5.1 meV to 1.2 meV are shown in Figures 1a–e.

Figure 1a shows the I-V characteristics of the device that was heated and then hit with 5.1 MeV alpha particles. At 150 ºC, there is no difference in forward or reverse bias current between annealed and non-annealed devices irradiated with the same energy (irrad. stand.), but there is a consistent increase between 200 and 300 ºC. Annealing at 200 and 300 ºC results in a wide range of current increases at forward bias voltages of 0.4–2 V. This is because annealing at these temperatures reduces the number of compensating defects, thereby lowering the resistance of the voltage barrier [21] and increasing forward conduction.

As can be seen in Figure 1b, the device exposed to 4.0 MeV of alpha particles exhibits very good stability, with no discernible shift in current versus voltage in the forward bias during annealing at 150 and 200 ºC, but a significant and noticeable shift in current observed at 300 ºC. At 150 and 200 ºC, the current is much higher in the reverse-biased devices than in the irradiated non-annealed (irrad. stand) and non-irradiated non-annealed (stand) devices. At 300 °C, the rise in current is proportional to the increase in forward conduction, so the value of the current in the reverse bias is equal to that in the forward bias, where ohmic conduction is dominating. Figure 1c shows that annealed electronics seem to behave the same when exposed to 3 meV or 4 meV of alpha particles. Since both forward and reverse biases make the current go up a lot around 300 ºC, this suggests that the conduction changes to an ohmic type.

Annealing a device and subjecting it to alpha particles with an energy of 1.8 MeV causes it to behave differently than it did at lower energies. Forward and reverse bias currents exhibit a sharp rise at 150 °C (Figure 1d). This rise proceeds in the same manner, but at a slower rate, during annealing above 150 °C up to 300 °C. The value of the current for both biases is almost the same at all three annealing temperatures. This suggests that the device has ohmic conductivity. Figure 1e shows that the I-V characteristics of the annealed devices that were irradiated with 1.2 MeV (which is close to 0.1 MeV, which is where the device absorbs the most alpha particle energy) [12] were different from those of the devices that were irradiated with lower energies.

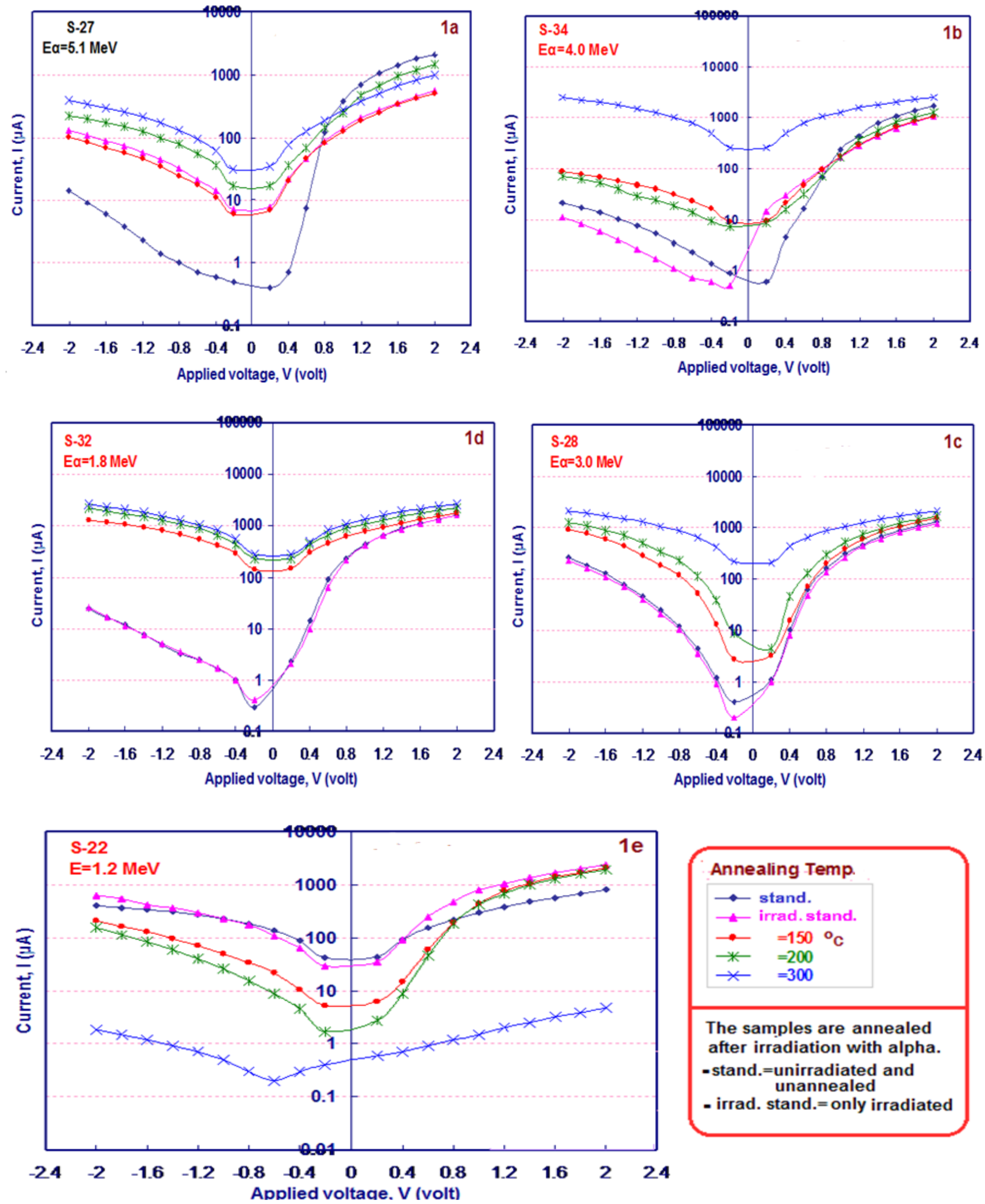

Fig. 1. The I-V characteristics of annealed devices after being irradiated with various energy of alpha particles.

3.2. Current versus annealing temperature of irradiated-annealed device

Figures 2a–e shows the relationship between the current (I) and the annealing temperature (T_{an}) at voltages of 0.4, 1, and 2 V so that we can learn more about how annealing affects devices exposed to alpha particles with energies between 1.2 and 5.1 MeV.

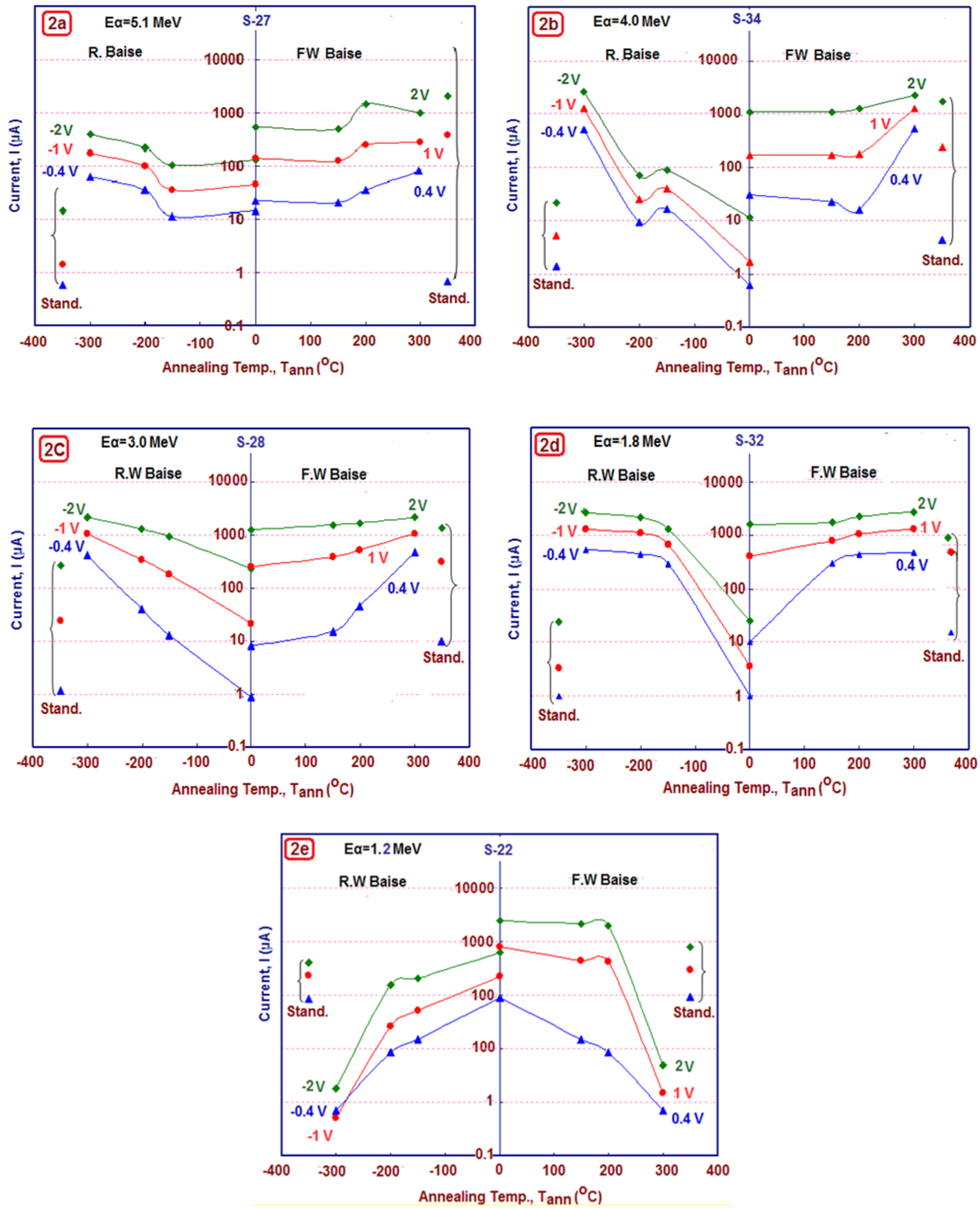

Fig. 2. Shows how current changes with annealing temperature in devices hit with alpha particles of varied energy0.4, 1, and 2 V.

Figure 2a shows that after 150 °C annealing at certain voltages, the devices are stable, and 5.1 MeV irradiation does not change the flow of current in the devices that have been annealed. Annealing at 200 °C, on the other hand, causes the current to rise at both the forward and reverse bias voltages. Even at 300 °C, which is the annealing temperature, the current keeps going up, but at a slower rate than when it was going forward. The forward bias current also shifts between the annealing temperatures of 200 and 300 °C. There is an increase at low voltage (0.4 V), a hold at medium voltage (1.0 V), and a decrease at high voltage (1.1 V) (2.0 V).

Figure 2b shows that, for devices that have been annealed and then exposed to 4 eV alpha particles, the current is also steady in the forward direction while annealing at 150 °C. It stays slightly stable up to 200 °C before starting to rise at voltages of 1 and 2 volts for annealing above

200 ºC. As annealing goes on, the current rises at three different voltages, but they all end up at the same value. The concentration of the carriers may be recovered by annealing at temperatures greater than 300 °C [14], and it is projected that annealing at these temperatures will have no discernible effect on the strength of the current. Annealing temperatures cause a significant increase in current with reverse bias. The current stays the same for all three voltages. The only place where it drops quickly is when the temperature goes from 200 to 300 °C. This decrease in current suggests that relaxation occurred in the device between the 150 and 200 ºC annealing temperatures.

Figure 2c shows that a device irradiated with 3 MeV shows a modest rise with applied voltages of 0.4, 1, and 2 V after being annealed at 150 ºC, similar to what was seen with the lower energy. At voltages of 1 and 2 V, the minor increase extends up to 300 ºC, whereas annealing over 150 ºC up to 300 ºC leads to a significant increase in current at 0.4 V. Under reverse bias, the annealing temperature causes a huge rise in current. The rate of growth is highest at low voltages of 0.4 V and goes down at high voltages of 2 V. When the annealing temperature is raised above 300 degrees Celsius, the current should reach the same level in both forward and reverse biases, even though the energy released will be the same. This means that at temperatures above 300 degrees Celsius, the current will have nothing to do with the voltage.

Figure 2d shows that at voltages of 1 and 2 V, a slight increase in forward direction current is observed with increasing annealing degree for devices irradiated with 1.8 MeV. However, at 0.4 V, the current sharply rises at 150 °C and remains constant at that amount up to 300 °C. At all three applied voltages, the current's behaviour when reversed is similar. The current quickly and significantly increased during annealing at 150 °C before levelling off and becoming stable at temperatures higher than 150 °C up until 300 °C. For the annealing states under investigation, the rate of increase of current with applied voltage appeared to be consistent. In contrast to what occurred in annealed devices irradiated with the energies of 5.1, 4, and 3 MeV, Figure 2d reveals that the current stability qualities at this level of increase can be projected to temperatures over 300 ºC. But when the devices are exposed to 1.2 MeV of energy, they don't work the same way as when they are in normal conditions. Figure 2e shows that as the annealing process continues, the current at all three applied voltages drops, both in the forward and reverse biases. But when the temperature goes over 200 ºC, the current drops quickly and significantly, and the rate of drop is faster at low voltages of 0.4 V.

3.3 Current versus alpha energy of irradiated-annealed devices

As illustrated in Figures 3a-c, the forward and reverse bias currents vary with alpha particle energy at different annealing temperatures and applied voltages. According to the diagrams, the largest rise in current can be seen at 1.8 MeV, while the maximum drop can be seen at 1.2 MeV. When compared to both the irradiated non-annealed device (irrad. stand.) and the non-irradiated non-annealed device, the current in irradiated non-annealed devices changes the most when they are annealed at 300 °C (stand.).

Based on these figures, it is clear that there is no clear and consistent link between changes in current and the energy or dose of alpha particles. The unpredictable (unsystematic) behavior of alpha particles in MIS devices is analogous to what is observed in polymers. Depending on the energy or dose of the alpha particle, the number of polymer free radicals can either increase ("generation") or decrease ("rebounding") [22].

Notably, the standard models for alpha energies used in both irradiated non-annealed devices (irrad. stand.) and non-irradiated non-annealed devices (stand.) were calibrated with one of the devices' samples, the model S-34 (Figure 1b).

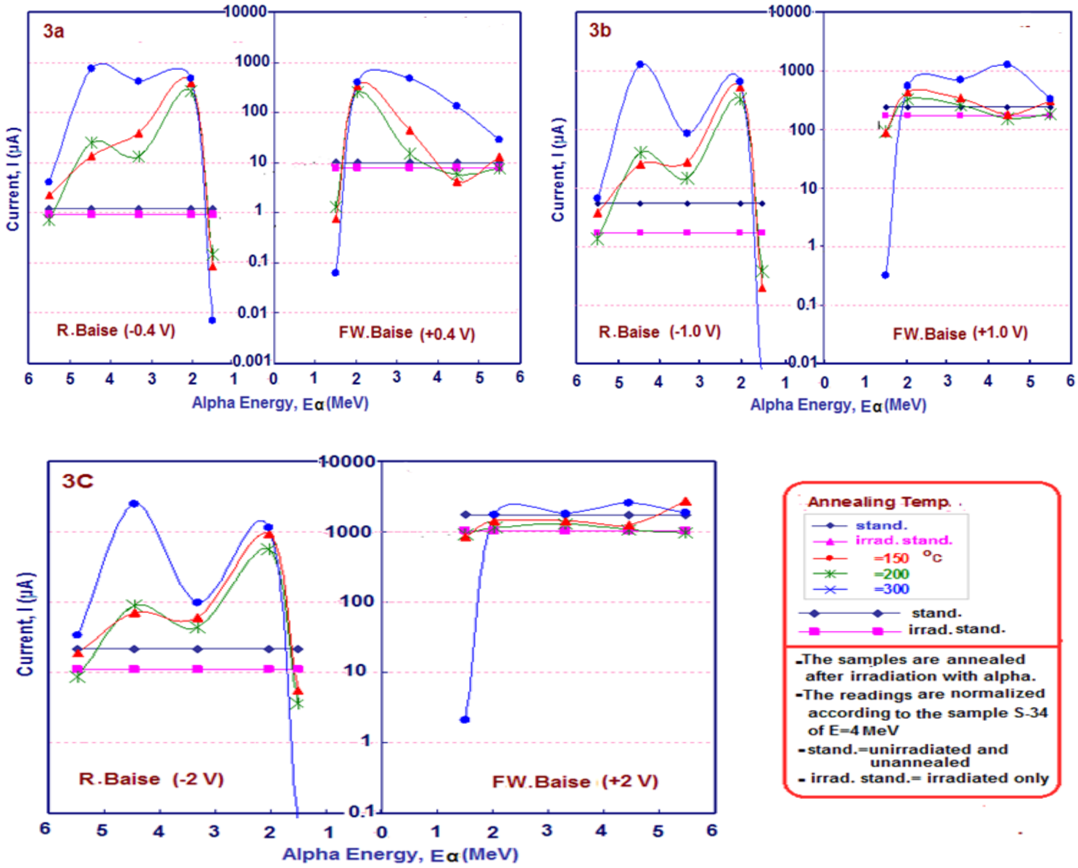

Fig. 3. Current versus alpha-particle-energy variation at different annealing temperatures and reverse bias voltages.

High-energy alpha particles are known to travel quickly and far with minimal energy loss, while low-energy particles travel slowly and have a considerable amount of energy dissipated in a relatively short distance. So, high-energy particles won't do much damage to a large area of the material, and the damaged area won't collect a lot of charge carriers [21]. But the low-energy particles will produce a lot of charge carriers and do a lot of damage to matter over a short distance. When alpha particles come into contact with matter, they cause localised damage, which leads to the formation of many different kinds of defects [10, 23]. Figures 1, 2, and 3 show that alpha particle irradiation does not have a consistent effect on the device. This is in contrast to gamma rays, which damage all matter in the same way and cause a single type of defect.

So, the results of annealing after being exposed to alpha-particle irradiation are different from those before. In the first scenario, the annealing process will not be able to repair all of the damage that the alpha particles have caused to the device. These areas are regarded as faults and the centers for the formation of new charge carriers in the device since their potential energy is greater than that of the remainder of the undamaged parts due to the energy obtained from the alpha particles. If, on the other hand, the device isn't exposed to alpha irradiation before annealing, there won't be any places where alpha irradiation caused damage (called defects) and there won't be any places where extra charge carriers can gather.

Radiation characteristics (intensity, energy, dose, particle mass, and charge) and device composition are major determinants of the energy received by damaged regions [24]. The potential energy received by these regions when irradiated with low-energy particles is greater than that obtained when irradiated with higher-energy particles because the rate of energy loss per unit length for low-energy particles is larger. Since low-energy particles have a higher rate of energy dissipation per unit length, the potential energy of the damaged region generated by low-energy particles will be higher than that formed by high-energy particles, and the kinetic energy of the accumulated charge carriers will have a bigger impact on the output current.

In a reverse bias, positive charges carry current, while negative charges do the same job in a forward bias. So the reverse bias current is smaller than the forward bias current because the number of negative carriers is often greater than the number of positive carriers. Consistent with this, and referring again to Figures 2a-e for the change in current with annealing temperature, it is discovered that for annealed devices after irradiation with alpha energies of 5.1, 4, and 3 MeV, the carriers are largely produced over a long distance of damage far from the device surface, which is approximately 15.48, 11.9, and 8.35 m inside GAAs [12], resulting in lower energy and numbers of the carriers. For this reason, carriers cannot recombine or leave the damaged regions using the energy they get during annealing at a low temperature of 150 ºC. Thus, in contrast to the non-annealed irradiation standard device, the forward bias voltage generates a constant current (irrad. stand.).

4. Conclusions

As the intensity of the irradiation increases, the I-V properties of the device are affected in a wide variety of ways by the alpha particles. There appears to be a correlation between the device's temperature and its erratic electrical behaviour in forward and reverse biases, suggesting that annealing the device following irradiation with alpha particles may not have fixed the device's electrical properties. To reduce the number of defects, more energy is introduced into the broken areas, where it either recombines the charge carriers and fixes hanging or unsaturated bonds or causes the carriers to gain energy, prompting them to migrate and repel further away from the device's damage centres.

The findings demonstrated that exposure to alpha radiation and thermal annealing can degrade performance, have no effect on reliability and performance, correct current, and improve some aspects of an electronic device. The MIS device's thermal stability and I-V properties were unaffected by alpha-particle irradiation, and neither thermal annealing nor annealing at higher temperatures was necessary. The device's current rectification was maximized during thermal annealing at 200 degrees Celsius. The device exhibited ohmic conductivity at temperatures of 300 degrees Celsius.

This suggests that several factors, such as the intensity and dosage (irradiation duration) of alpha particles and the annealing temperature, have a random impact on the electrical properties of the MIS device. In turn, this will change the way these devices usually work.

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