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Impact of Gamma Radiation on Fabricated Aluminum Gallium Nitride/Gallium Nitride Test Structures for Radiation-Hard Electronics

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Research Article

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Abstract

The AlGaN/GaN high electron mobility transistors (HEMTs) have recently received significant attention due to their radiation-tolerance and harsh environment tolerance because of their wide bandgap, high electron mobility, and thermal stability. In this research, the AlGaN/GaN HEMT wafers were diced and patterned to produce two-terminal devices of channel length 100 μm utilizing photolithography and lift-off techniques followed by thermal annealing. The devices were electrically evaluated using current-voltage (I-V) measurements performed by Keithley 2634B SourceMeter. For the purpose of studying radiation-related changes in the electrical behavior, the devices were irradiated with 60Co (Cobalt-60) gamma rays at absorbed doses of 100 cGy, 500 cGy, and 1000 cGy. The I-V measurements were carried out both before and after the irradiations under the same conditions. Experimental findings demonstrated radiation dose dependence of electrical characteristics of the fabricated devices. The values of the forward bias current were found to reduce from 0.01697 A for the initial condition to 6.52×10^{-4} A, 0.009103 A, and 0.007126 A for exposures at 100 cGy, 500 cGy, and 1000 cGy, respectively. The results show that the reduction is due to the effects caused by defect formation, charge traps, and carrier scattering effects. This shows the ability of the fabricated devices to respond to low-dose gamma radiation for use in electronic systems.

I. INTRODUCTION

Gallium nitride (GaN) and silicon carbide (SiC) are wide-bandgap semiconductors that have received considerable interest owing to their excellent electrical and thermal characteristics. The AlGaN/GaN high-electron-mobility transistors (HEMTs), among many wide bandgap technologies, show high electron mobility, high breakdown voltage, and high power handling capacity [1]. Space exploration, nuclear facilities, particle accelerators, and defence applications have led to an increasing number of electronic devices operating in the presence of high radiation levels. Ionizing radiation may create defects, traps, and charge generation, thus reducing the performance of the device [2]. While several investigations have been carried out on AlGaN/GaN HEMTs responses to radiation, an understanding of the radiation dose dependence of fabricated samples electrical behavior is also critical [3]. This paper examines the impact of gamma irradiation on two-terminal fabricated devices based on AlGaN/GaN HEMTs by assessing changes in I-V characteristics due to irradiations at varying levels of gamma dosage [4]. In this study, two-terminal AlGaN/GaN HEMT test structures have been fabricated and their electrical characteristics measured before and after being subjected to Cobalt-60 gamma irradiations. This experiment conducted a dose dependent examination at 100 cGy, 500 cGy, and 1000 cGy to observe the impact of gamma irradiation on the electrical characteristics of the developed devices [5]. Despite numerous studies conducted into radiation effects on AlGaN/GaN HEMTs, current literature mostly addresses radiation effects in the complete structure of transistor or commercial power device subjected to high radiation doses. Contradictory outcomes concerning the effect of gamma radiation on enhancement or degradation in performance further suggest an unclear understanding of the defect formation and charge trapping mechanisms involved in such processes [6]. Few studies have been carried out on fabricated AlGaN/GaN HEMTs test structures subjected to lower doses of 60Co gamma

radiation by means of direct DC electrical measurements. Hence, a systematic study of fabricated AlGaN/GaN test structures subjected to 100 cGy, 500 cGy, and 1000 cGy of 60Co gamma radiation is needed [7].

II. DEVICE FABRICATION AND EXPERIMENTAL PROCEDURE

A. *AlGaN/GaN HEMT Material Preparation*

AlGaN/GaN HEMT wafer samples were obtained, which were then mechanically cut to size so that devices could be fabricated from them. Samples were first cleaned by using RCA1 and RCA2 solvents before any processing occurred [8].

B. Device Fabrication

The technique of photolithography was used for designing the contact areas on the AlGaN/GaN structure. The metal contacts were made by depositing them in layers of aluminum/chromium/gold with thicknesses 150 nm/40 nm/250 nm, respectively, using the lift-off technique to make two terminal devices. Thereafter, thermal annealing was done at 850 ℃ at 47 sec [9].

Fabrication Flow Chart

Fabrication began with the selection of an AlGaN/GaN HEMT wafer, after which the wafer was cut into pieces, ready for device fabrication. Cleaning was then done on the diced pieces to get rid of surface impurities before fabrication began. Photolithography was used to pattern the devices, and then contact metallization was carried out on the exposed areas. Metal lift-off was done to clean up excess metal and create the correct contact structure. Thermal annealing was done as the last step to improve the metal-semiconductor contact [10].

C. Electrical Characterization

Before the exposure of the fabricated AlGaN/GaN HEMT devices to ionizing radiation, their electrical properties were evaluated at room temperature through a Keithley 2634B SourceMeter. The current-voltage (I-V) measurements were made by subjecting the device under test to a linear sweep of the voltage range between − 4 V and + 4 V while monitoring the corresponding current response. The I-V results served as the basis for comparing the effects of radiation exposure on the electrical performance of the fabricated devices [11].

D. Gamma Irradiation Procedure

In order to study the effect of gamma radiation, the fabricated structures of AlGaN/GaN HEMT devices were irradiated using a gamma emitter Cobalt-60 (60Co). 60Co gamma emitter is a common choice of isotopic radiation source that produces gamma rays with two prominent photon energies of 1.17 MeV and 1.33 MeV with an average value of 1.25 MeV. Before the irradiation process, the electrical properties

of the fabricated devices were studied to establish their electrical behavior [12]. The fabricated structures were subjected to absorbed gamma dose values of 100 cGy, 500 cGy, and 1000 cGy. Irradiations were performed in a controlled manner before performing electrical characterizations for each absorbed dose value. The electrical properties of the structures were measured under identical measurement conditions as used in pre-irradiation characterization tests. For every absorbed dose value, electrical characterizations were performed through I–V measurement experiments. In this way, the effect of 60Co gamma radiation on the electrical behavior of the fabricated structures was examined [13].

III. RESULTS AND DISCUSSION

A. Pre-Irradiation Electrical Characteristics

Before exposing the two terminal test structures that were fabricated from AlGaN/GaN HEMTs to the gamma ray irradiation process, they were subjected to electrical characterization through current-voltage (I-V) analysis. There was an observable flow of current when the two terminals were under forward and reverse biases, thus signifying electrical connection between the fabricated metals and the semiconductor material. As shown in Fig. 2, at the reference point (0 cGy(Pristine)), the forward bias current was 0.01697 A, while the reverse bias current was 0.016018 A. The similarity between forward and reverse current values shows that the two-terminal device fabricated had almost symmetrical conduction properties over the studied voltage range. The symmetry is an indication that the contacts fabricated did not have any significant rectifying properties and served to inject carriers efficiently. This observation is additional evidence that the photolithography, lift-off, and annealing steps were successful in fabricating electrically functional contacts. Moreover, the relatively high current obtained before irradiation is an indication of good electrical properties of the developed structure. The measurement of this current is very important because it acts as a basis for comparison after irradiation to evaluate any changes that may have been brought about by the exposure to the 60Co gamma radiation. Therefore, any change in the current after exposure is mostly a result of radiation damage to the AlGaN/GaN structure [14].

B. Effect of 100 cGy Gamma Irradiation

Figure 4 represents the I-V plots of the prepared AlGaN/GaN structure both before and after exposure to 100 cGy 60Co gamma irradiation. The results show a considerable decrease in the current across the whole voltage range for the exposed sample. There is an obvious decrease in the forward bias current from 0.01697 A to 6.52×10^{-4} A (i.e., ~ 96.16%), and also there is a decrease in the reverse bias current from 0.016018 A to 0.002192 A (i.e., ~ 86.31%). The effect indicates the generation of radiation-induced defect and trapping states in the AlGaN/GaN structure, which would lower the carrier flow through the structure [15].

C. Effect of 500 cGy Gamma Irradiation

Figure 5 shows the I-V characteristics of the AlGaN/GaN test device before and after 500 cGy 60Co gamma radiation treatment. In contrast to the pristine device, irradiation leads to a decrease in current at all voltages; however, the current is significantly greater than that measured after 100 cGy irradiation. The current at the chosen forward voltage decreases from 0.01697 A to 0.009103 A, which corresponds to 46.36%, and the reverse current decreases from 0.016018 A to 0.006857 A (57.19% decrease). The restoration of a part of the initial current in comparison with the irradiation regime of 100 cGy suggests the existence of competing radiation effects, e.g., charge redistribution, trap filling, or defects' annealing. Yet, the current values remain smaller than those for the pristine device, and therefore carrier scattering continues to dominate charge transport in this AlGaN/GaN structure. This demonstrates that the electrical behavior of the investigated AlGaN/GaN structure still depends strongly on the total dose of gamma irradiation [16].

D. Effect of 1000 cGy Gamma Irradiation

Figure presents the I-V curves of the AlGaN/GaN structure fabricated after being exposed to 1000 cGy Co-60 gamma irradiation. There is clearly seen the decrease in the current flow through the fabricated device under all voltages. At the chosen forward bias voltage, there is a decrease in current from 0.01697 A to 0.007126 A. In other words, the drop in current corresponds to 58.01%. At the same time, the reverse current is equal to 0.009528 A; it is lower than the pristine value but is higher than the current found at 500 cGy [17].

In general, it should be assumed that radiation-induced defects and trapping centers continue to increase in number with increasing radiation dosage in the fabricated structure. As a result, carrier transport becomes less effective. It is necessary to admit that although the AlGaN/GaN structure tested under 60Co gamma irradiation stays electrically operational, it shows the clear decrease in its performance. Therefore, one can conclude about the influence of radiation effects on the properties of the fabricated structure.

E. Comparative Analysis

Table I. Variation in Forward-Biase Current

Dose (cGy)	Current at selected Voltage	%Change
0	0.01697	0
100	6.51734×10 − 4	−96.16%
500	0.009103	−46.36%
1000	0.007126	−58.01%

%Change=(I_dose-I_0)/I_0 ×100 (1)

where I0 = Pristine (un irradiated/at 0 cGy) current, and Idose=Current after Irradiation

From Table I, it is clear that 60Co gamma irradiation has a profound effect on the forward bias current in the fabricated AlGaN/GaN HEMT test structure. At 100 cGy, there is a drastic fall in the current from 0.01697 A to 6.51734×10^{-4} A, corresponding to a decrease of 96.16%. With the increase in irradiation dose to 500 cGy, there was a partial recovery of the current to 0.009103 A; however, the current at this dose is still 46.36% lower than that before irradiation. Further increase in the irradiation dose to 1000 cGy caused a slight drop in the current to 0.007126 A.

The decrease in the current implies that radiation-induced defects and traps are introduced in the AlGaN/GaN structure due to the 60Co gamma irradiation. Figure 7 shows non-monotonic behavior between 100 cGy and 500 cGy irradiation doses in the fabricated structure. This may imply the presence of competing effects, for example, introduction of defects and the annealing of the defects or redistribution of charges, as has been noted in earlier studies [18].

F. Radiation Damage Mechanism

The modifications made to the electrical properties of the fabricated AlGaN/GaN devices may be associated with the creation of defects due to the impact of 60Co gamma rays on these devices. The interaction between gamma photons and the AlGaN/GaN materials may create interface traps, deep level defects, and charge traps within the structure. Defects may absorb charge carriers and increase their scattering. In turn, this leads to the decrease in the mobility of charge carriers and changes their concentration. The modified carrier concentrations cause changes in the conductance of the material [5].

IV. APPLICATIONS OF THE STUDY

It can be seen from the obtained experimental data that the electrical parameters of the manufactured AlGaN/GaN HEMT test structures are dependent on the influence of gamma rays 60Co, showing changes in the conduction process related to different doses. Radiation effect analysis reveals the possibility of the use of AlGaN/GaN devices in various applications exposed to radiations [7].

A. Space Electronics

The AlGaN/GaN structure is thought to be a promising device for space electronics because of its wide energy bandgap, breakdown field, and natural radiation tolerance. The effect caused by radiation on the electrical behavior of the device described in the experiment gives valuable information on the applicability of AlGaN/GaN structures to satellites, deep space exploration, and communications systems working under ionizing radiation [1,19].

B. Nuclear Electronics

The observed reaction of the artificially created structures to the radiation produced by 60Co gamma rays can be useful for use in a nuclear environment, whereby electronics are subjected to ionizing

radiation regularly. The electronic products could be used in the control systems of nuclear reactors and radiation sensors among others [20].

C. Radiation Dosimetry

As the change in the value of current with an increase in the gamma dose is quantifiable, the fabricated structures can be used as potential candidates for the sensing of radiation. The changes in electrical properties with respect to the gamma dose can be utilized for measuring the gamma dose [21].

D. Defense and Aerospace Systems

The ability of the fabricated structures to remain electrically functional after exposure to 60Co gamma radiation highlights their potential for deployment in aerospace, defense, and other harsh-environment electronic systems. Understanding radiation-induced electrical degradation is essential for the design of reliable electronic components intended for operation under extreme environmental conditions [22,23].

V. CONCLUSION

The following is a presentation of the fabrication and radiation analysis of the fabricated two-terminal AlGaN/GaN HEMT based devices for investigating the electrical performance under the impact of the low dose 60Co gamma ray irradiation. Fabrication techniques such as photolithography, lift off and annealing were used while characterizing was done by carrying out the I-V measurement tests at room temperature. The devices were exposed to gamma rays at cumulative absorbed doses of 100 cGy, 500 cGy, and 1000 cGy respectively. According to the results obtained from the experiments, it is found that there exists a significant effect of 60Co gamma rays on the electrical properties of fabricated devices. It is clear that there occurs a considerable decrease in the value of current after the irradiation process. This indicates that there is an effect due to the existence of radiation-induced defects and charge trapping sites on the movement of charges in the AlGaN/GaN heterostructure. The highest amount of degradation occurred at a dosage of 100 cGy and a partial recovery at 500 cGy with a decrease in current at 100 cGy. In general, it is confirmed from this study that fabricated structures made of AlGaN/GaN possesses sensitivity to low doses of 60Co gamma radiation, providing useful information on radiation induced-degradation in terms of electrical properties of the material. The results acquired during this study give insights into radiation impacts on AlGaN/GaN compounds and confirm their possible use in radiation-tolerant electronic components, aerospace systems, and radiation monitoring devices based on semiconductor materials. Possible further research includes Hall-effect measurements, defect characterization, and dose-range finding studies including effect of gamma radiation on three terminal AlGaN/GaN HEMT (High electron mobility transistor). Overall, the results obtained in this paper advance the field of radiation-tolerant AlGaN/GaN technology.

Declarations

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Figures

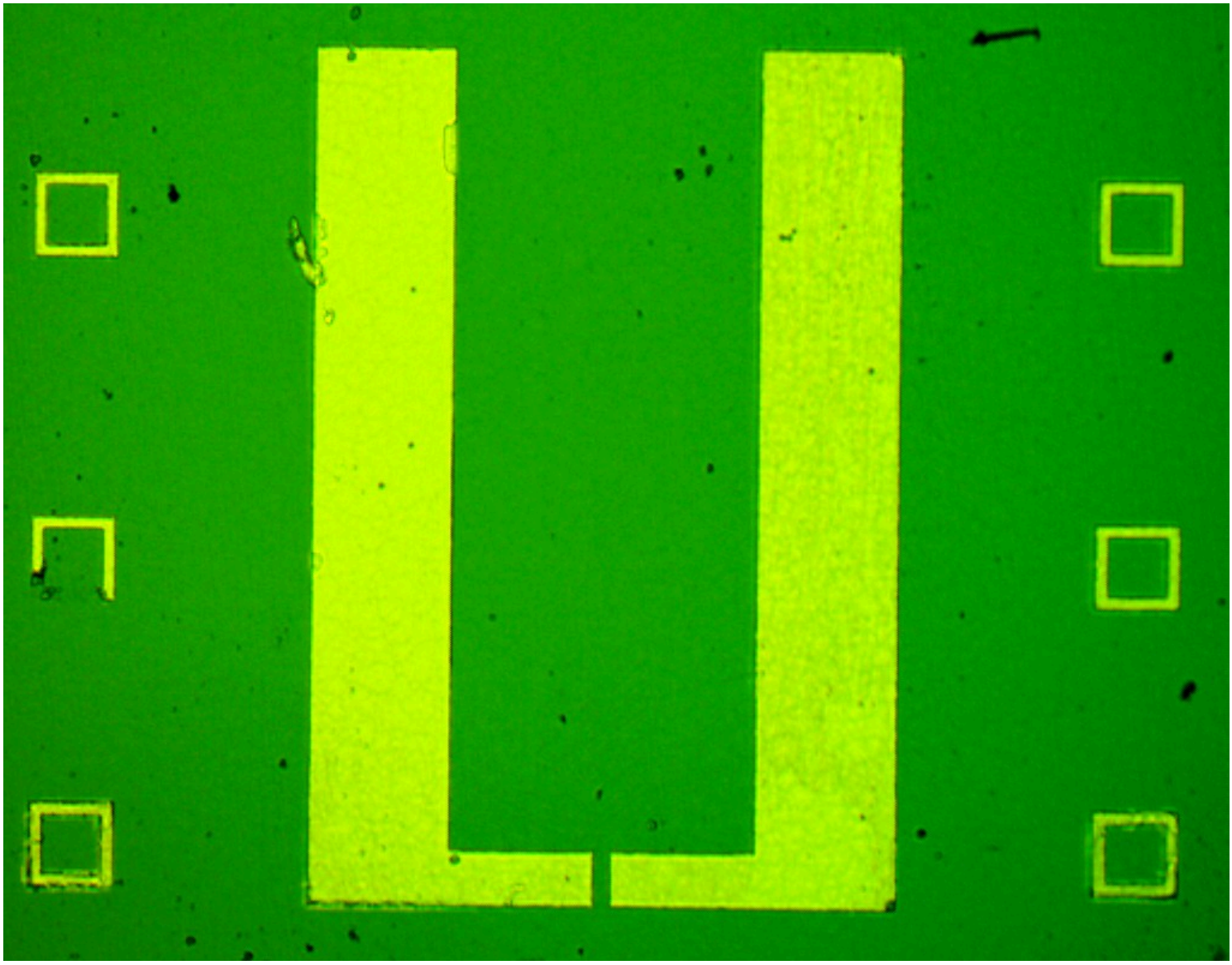


Figure 1

Optical Microscopy Image of two terminal AlGaN/GaN HEMT Fabricated device after annealing

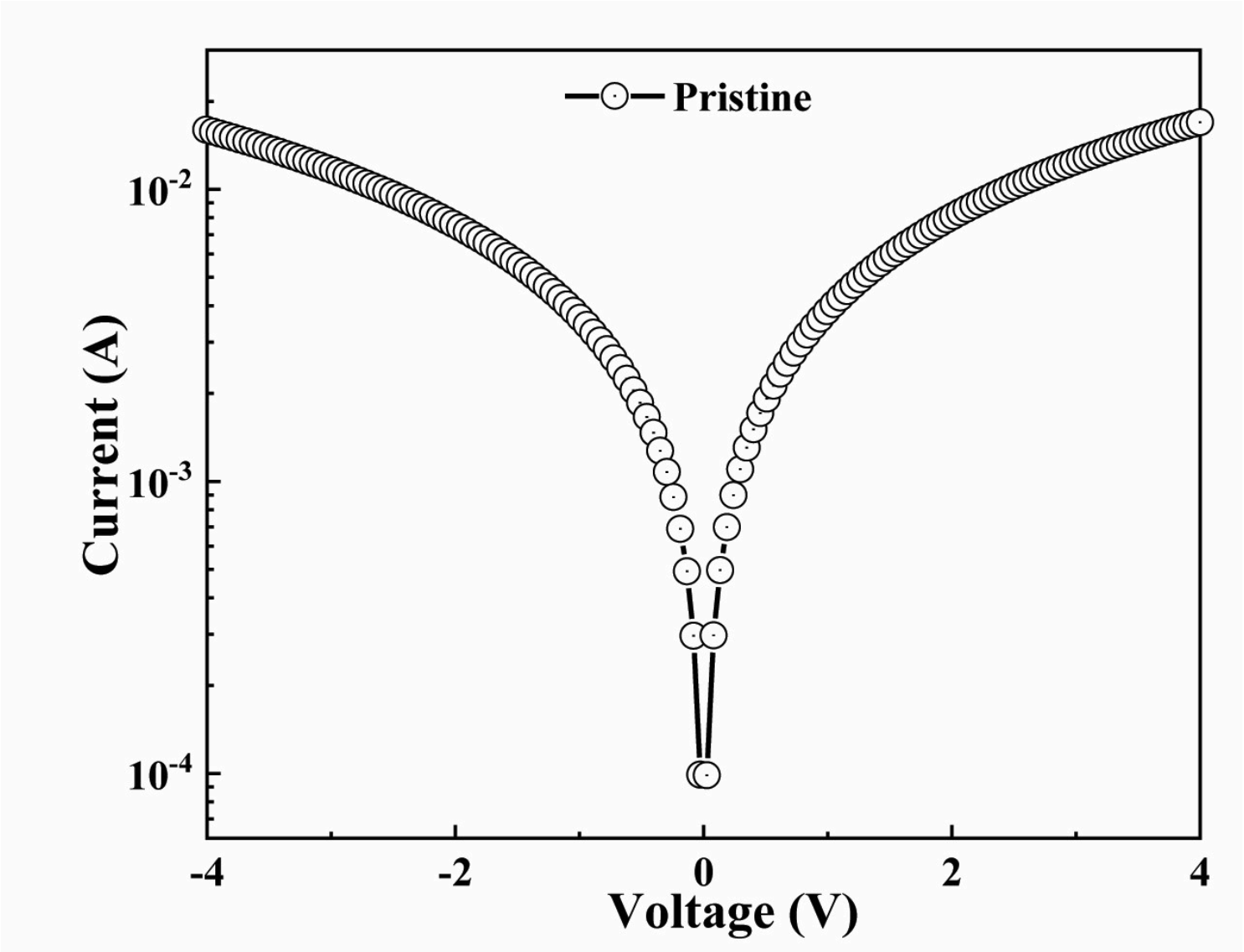


Figure 2

I–V Characteristics Before Gamma Irradiation (Pristine (0 cGy)) Fig. 2. I–V Characteristics Before Gamma Irradiation (Pristine (0 cGy))

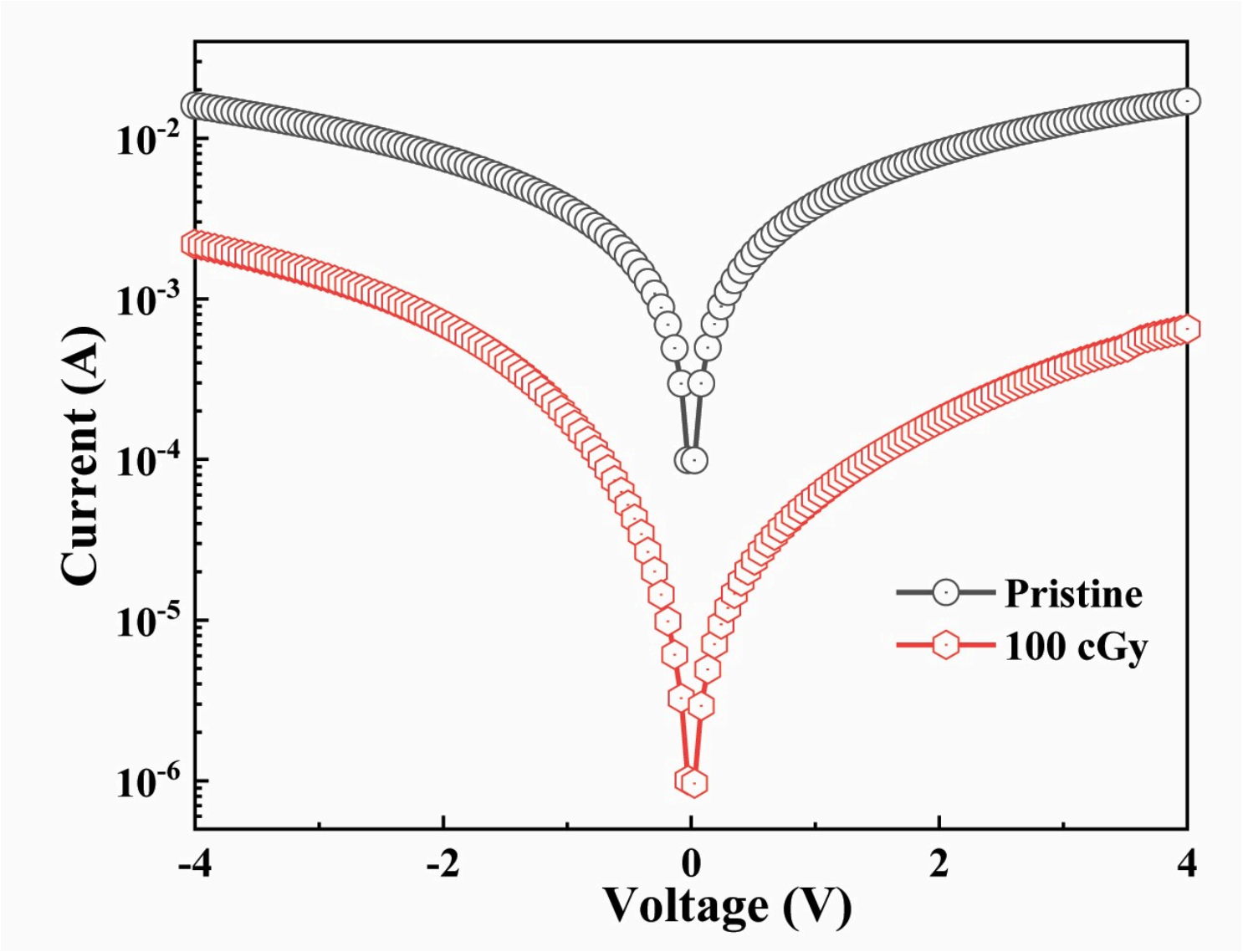


Figure 3

Effect on pristine I–V Characteristics after 100 cGy Exposure

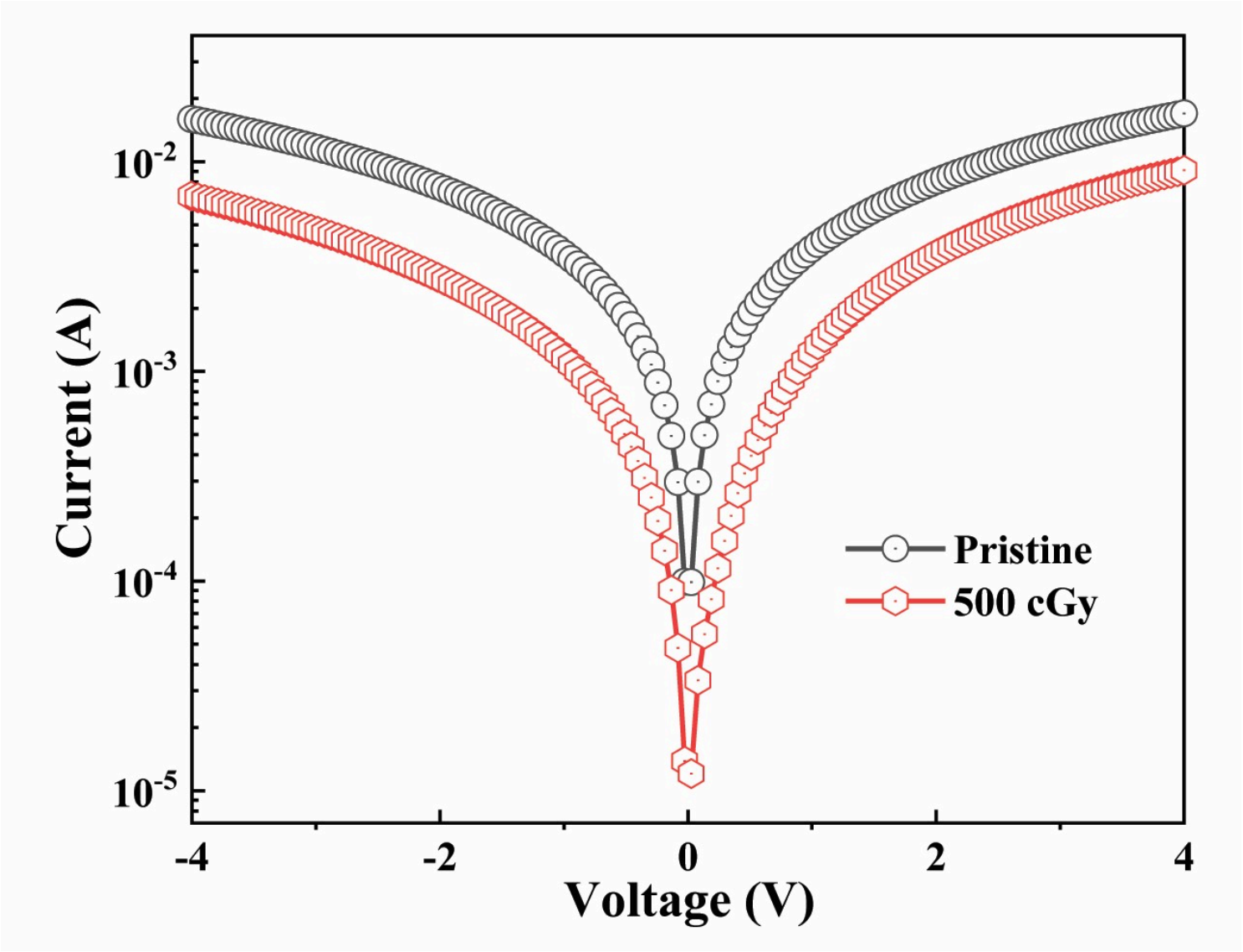


Figure 4

Effect on pristine I–V Characteristics after 500 cGy Exposure

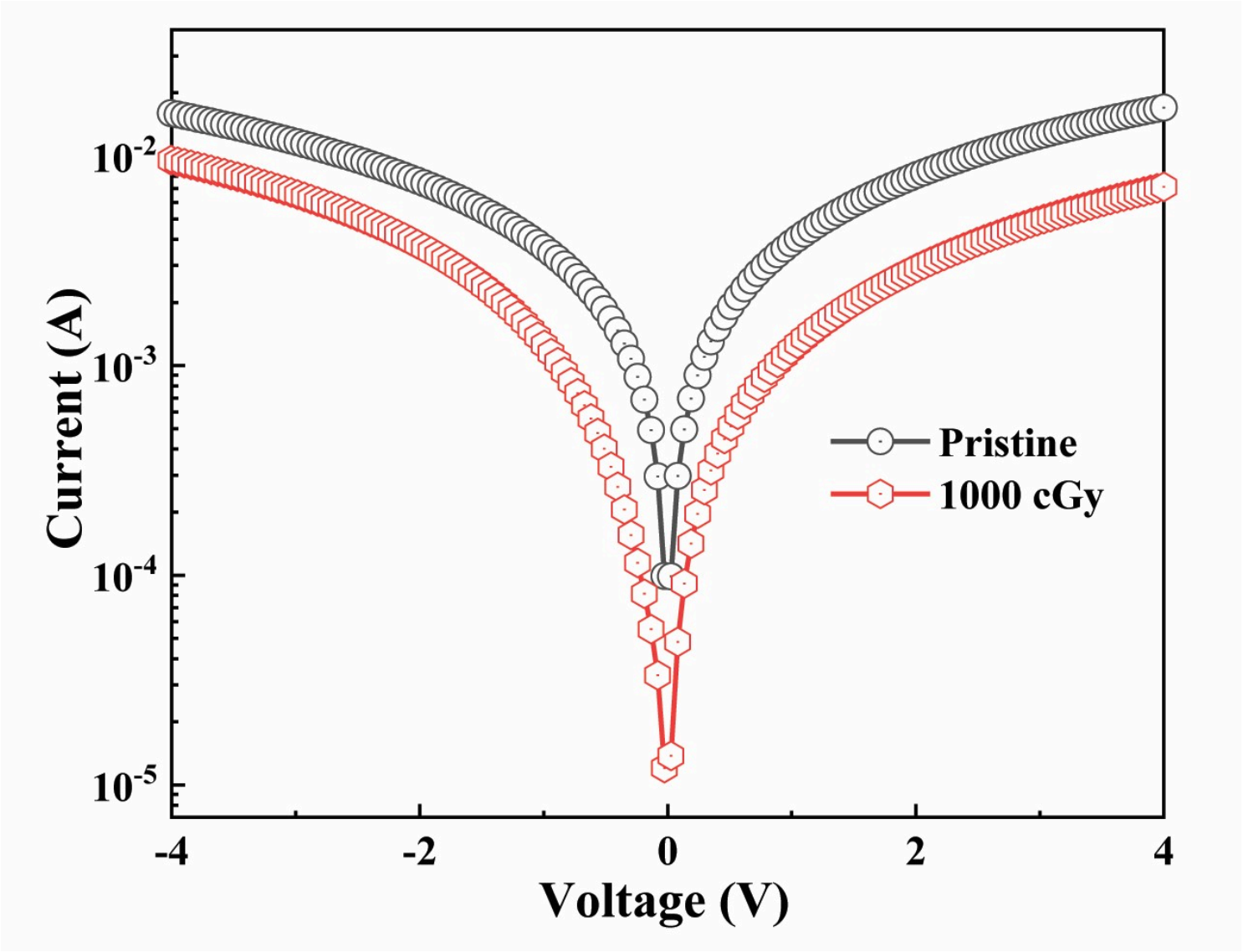


Figure 5

60Effect on pristine I–V Characteristics after 1000 cGy Exposure

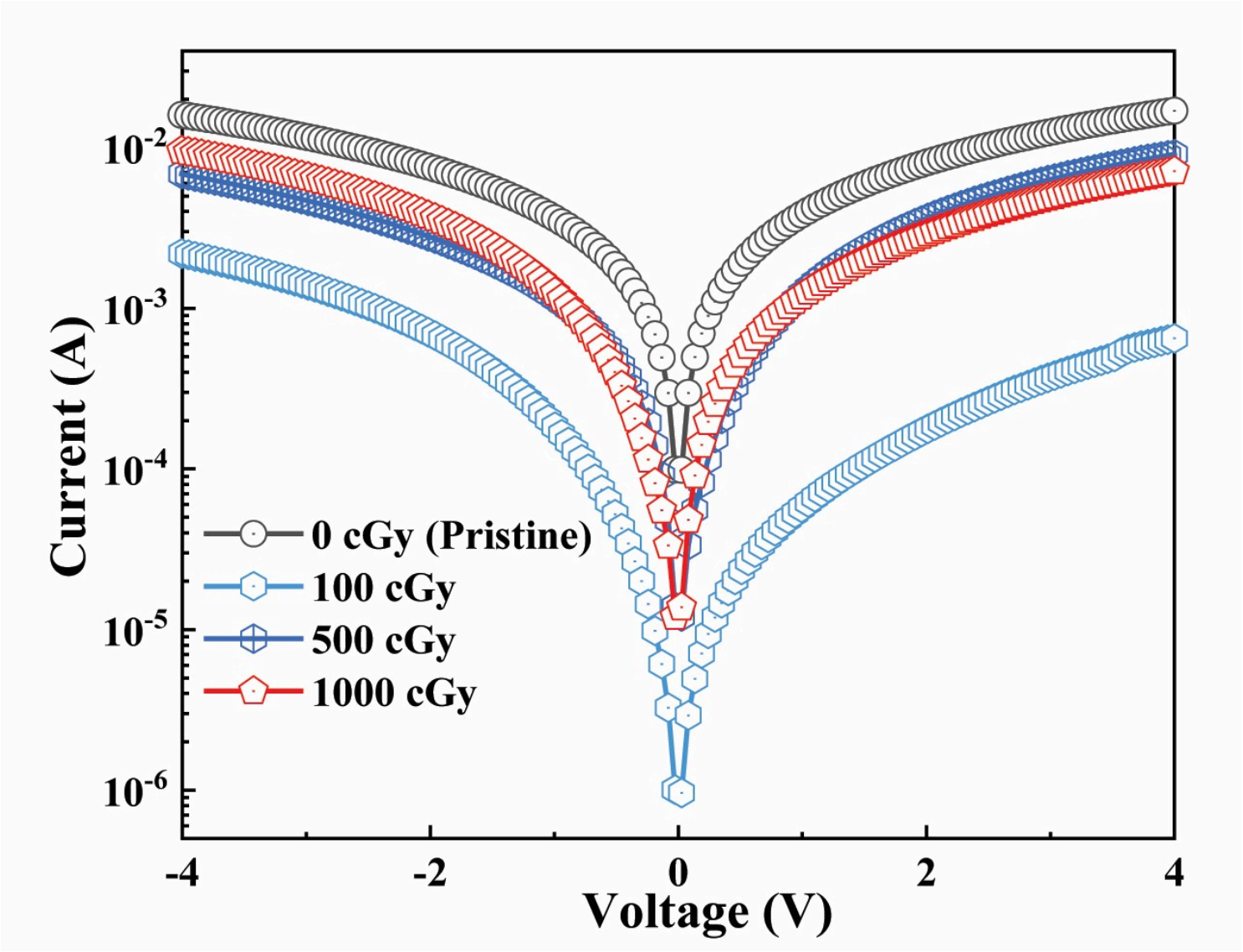


Figure 6

Comparison of I–V Characteristics at Different Gamma Doses (0 cGy, 100 cGy, 500 cGy, 1000 cGy