Difference of radiation tolerance with p- and n-type JFETs

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Keyword(s): COTS device, electron irradiation degradation, junction field effect transistor, electrical

Abstract

The radiation tolerance by 2 MeV electrons irradiated to the commercial-off-the-shelf (COTS) p- and n-JFETs was studied. For the situation of p-JFET, the drain current (I_D) of the input characteristics decreased by electron irradiation. The I_D decreasing attributed to the increase of channel resistance by electron irradiation. In contrast, for n-JFET, the I_D decreases at the fluence lower than $1x10^{15}$ e/cm^2, then the I_D increases at the fluence higher than $5x10^{15}$ e/cm^2. The anomalous I_D behavior of n-JFET could be explained by considering extending and narrowing of the n-channel.

1. Introduction

In electronic devices such as various sensors and attitude control used in satellites and space stations, a number of semiconductor devices are used. Semiconductor devices have highly sensitive to radiation, such as in nuclear power industries and in space. It is difficult to replace semiconductor devices in radiation environments. Therefore, very high reliability and radiation tolerance are required to the semiconductor devices used in radiation environments. However, development of the integration of semiconductor devises for space application needs high cost. Cost reduction of electronic devices and high integration could be realized alternating to the commercial semiconductor. An important segment of the aerospace/military integrated circuit market is taken by radiation-hard devices, with and increasing importance for space applications. The optimization of the overall reliability performance is becoming of key importance as the space community is more using the commercial-off-the-shelf (COTS) approach and is thereby also greatly interested in the feasibility of the use of more advanced materials and components. Therefore, it is important to accumurate information the radiation torelance for various COTS devides. We had been studied on radiation tollerance of semiconductor devices such as InGaAs photodiodes [1], SiC MESFET [2], SiGe MOSFET [3], and so on. The junction field effect transistor (JFET) is important device used in the electrical circuit for amplification the audio frequency signal. Also, JFET used in radiation environments, because it has high radiation hardness. For MOSFETs, degradation of the input characteristics by irradiation complicated, because some defects (interface defects at oxide and semiconductor, oxide defects, *etc*) correspond to the degradation. For the JFETs, the degradation became mainly causes from increasing channel resistance by irradiation, because of the JFET channel thicker than that of MOSFET. Therefore, the JFET used about Rad-Hard device for front end device [4] in radiation ambient and radiation detector [5]. However, detailed of the degradation mechanism of JFETs in radiation did not cleared, because it have few reports about radiation irradiation effects for electrical properties [6 - 8]. These studies discussed about gamma-ray or neutron irradiation effects/degradation of the JFETs, and there are few reports on the results of electron irradiation to the JFETs. It is important that the evaluation of electron irradiation effects of semiconductor devices for use in space. In this study, electron irradiation degradation of electrical properties for commercial p- and n-type JFET are evaluated.

2. Experimental

The Si p- (2SJ103 TOSHIBA) and n-JFETs (2SK117) were evaluated for samples. Both devices were normally applied for low noise audio amplifier. Devices without applied bias voltage were irradiated at room temperature by 2-MeV electrons in the acceleration reactor at the Takasaki Japan Atomic Energy Agency (JAEA). The electron fluence was varied from $1x10^{13}$ to $1x10^{16}$ e/cm^2. Before and after electron irradiation, the electrical performance has been evaluated by the input (I_D-V_G) characteristic with a drain voltage (V_D) at 10 V and gate voltages (V_G) ranging from 0 to 1.4 V for p-JFET and -0.5 to 0 V for n-JFET, respectively, using a semiconductor parameter analyser (HP-4156C). The threshold voltage (V_{TH}) was extracted from linear extrapolation of the input characteristics. Also, capacitance/voltage (C/V) characteristic between the source/drain and gate electrodes is studied using Agilent DL8000. From the C/V characteristic, depletion widths at the p- and n-JFET channel are studied.

3. Results and discussion

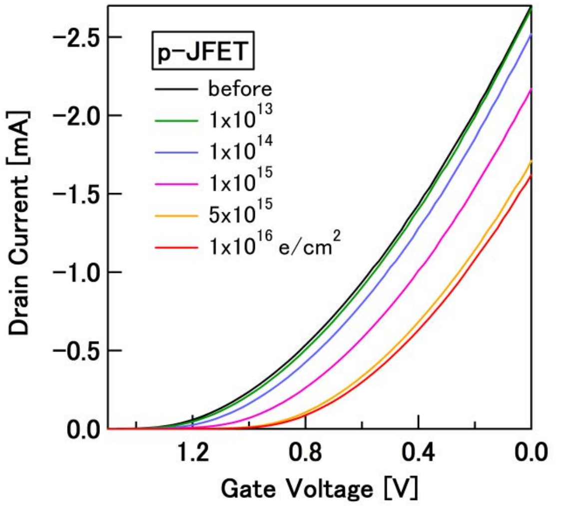

Fig. 1. Input characteristics of the p-JFETs before and after the electron irradiation.

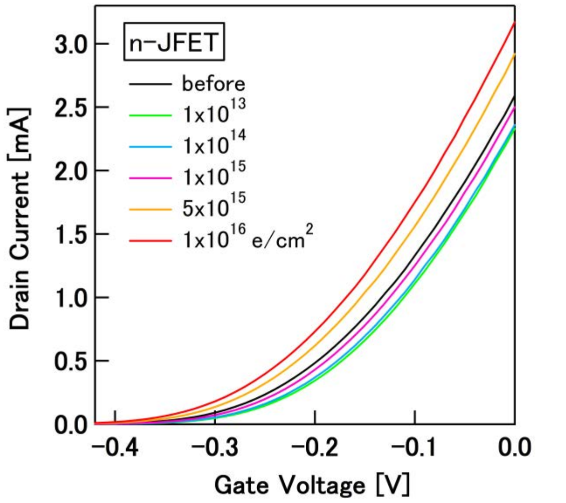

Fig. 2. Input characteristics of the n-JFETs before and after the electron irradiation.

Figure 1 shows the input characteristics of p-JFET for different electron fluences. It could be observed that I_D decreases by electron irradiation. On the other hand, I_D decreases at the fluence lower than $1x10^{15}$ e/cm^2, then I_D increases at the fluence higher than $5x10^{15}$ e/cm^2 in n-JFET, as shown in Fig. 2. It seems the channel resistance for n-JFET increases at the fluence lower than $1x10^{15}$ e/cm^2, then the channel resistance decreases at the fluence higher than $5x10^{15}$ e/cm^2. To consider the channel resistance of JFETs, the swing at subthreshold region determined by eq. (1) is estimated. The swing means the required gate voltage for one decade increasing I_D.

$$\mathrm{Swing} = \frac{\mathrm{d}V_G}{\mathrm{d}\log_{10}(I_D)} \qquad \text{(eq. 1)}$$

The swings determined by input characteristics for p- and n-type JFETs are shown in Fig. 3. The swing for p- and n-JFET increased with increasing electron fluence, but the values are different with the conduction type. This result could be said that resistance of p-JFET larger increased by electron irradiation. From the result, the increasing of I_D for p-JFET by electron irradiation could not explain using the change of channel resistance.

Figure 4 shows the V_{TH} shifts of the p- and n-JFET before and after the electron irradiation. The I_D change inferred by V_{TH}. For p-JFET, the V_{TH} shifts toward positive. It corresponds to channel narrowing by the electron irradiation. However, the V_{TH} shift for n-JFET changes negative to positive with increasing electron fluence. This result indicates that the channel width extended by the electron irradiation. Therefore, it could be said that the channel width extending leads I_D increasing.

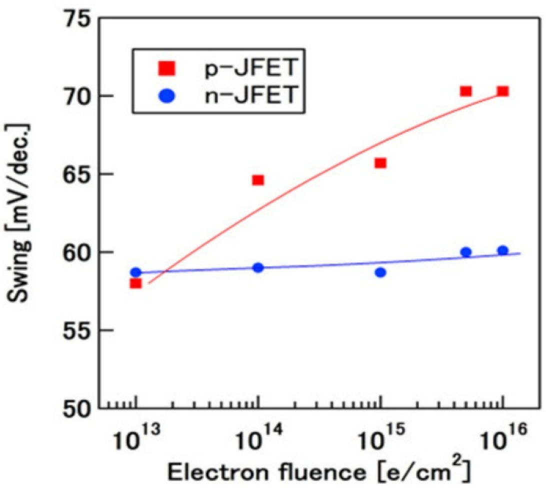

Fig. 3. The swings determined by input characteristics of the p- and n-JFETs.

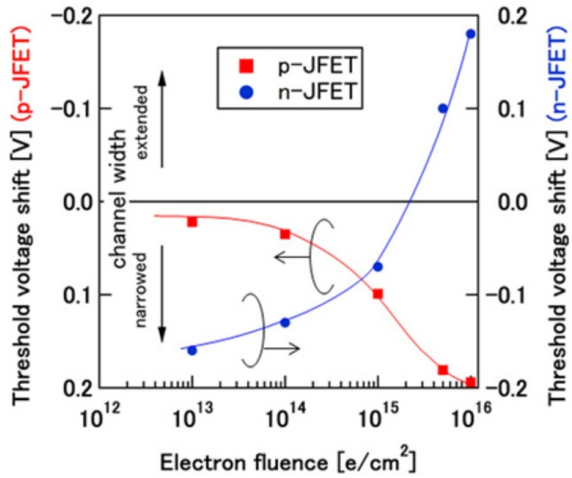

Fig. 4. Shift of V_{TH} by electron irradiation for p- and n-JFETs.

The depletion width inferred with carrier density of the p- and n-region. Therefore, the carrier density of p- and n-channel estimated from C/V characteristic of source/drain and gate electrodes. Unfortunately, the area of pn junction at the gate had not been known. Therefore, change ratio of carrier density before and after the electron irradiation determined damage factor D_C as eq. (2).

$$D_C = \frac{n_{after}}{n_{before}} \qquad \text{(eq. 2)}$$

where, n_{after} and n_{before} are carrier density after and before the electron irradiation. Figure 5 shows D_C at the channel of p- and n-type JFET. As shown in Fig. 5, although, the carrier density at the p-channel has decreased by electron irradiation, there is little decrease of carrier density at the n-channel. Generally, phosphorous or arsenic atom is used as donor and boron atom is used as acceptor in Si. Accordingly, the number of knock-on atom by electron irradiation of phosphorous or arsenic atom smaller than that of boron atom. The knock–on atom deactivate as an acceptor or a donor. Under these assumptions, depletion layer at the pn junction easily extended to the p-region by electron irradiation. The depletion width of n-JFET became narrowed by the irradiation caused by deactivation of acceptor. It could be considered the n-channel extended by electron irradiation.

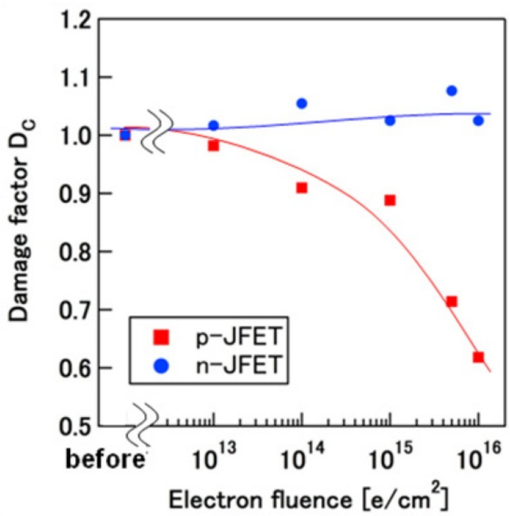

Fig. 5. The damage factor of carrier density (D_C) for the p- and n-channel after the electron irradiation.

4. Conclution

To purpose of accumulate the information of radiation tolerance the COTS devices. Electrical properties of electron irradiated p- and n-JFETs were studied. For p-JFET, decreasing the I_D corresponds to the increasing channel resistance by electron irradiation. It could be confirmed by subthreshold swing increasing. In contrast, the I_D decreases at the fluence lower than $1x10^{15}$ e/cm^2, then I_D increases at the fluence higher than $5x10^{15}$ e/cm^2 in n-JFET. Also, the threshold voltage shift changes negative to positive with increasing electron fluence. These behaviors corresponds to the considering the difference the number of knock-on atoms (acceptor and donor) by electron irradiation. It could be confirmed from the C/V characteristics, the amount of deactivated acceptor larger than donor. Therefore, the channel width extended by electron irradiation because deactivation of acceptor at p-type gate and the depletion layer narrowed.

Acknowledgments

Part of this work was supported by Grant-in-Aid for Scientific Research (No. 12009 and No. 12064) from the Japanese Ministry of Education for Science, by Inter-University Laboratory for the Joint Use of JAEA Facilities.

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