Paper

Radiation damages of SiGe devices

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Abstract Results are reported on the formation of lattice defects and the degradation of the electrical performance of $Si_{1-x}Ge_x$ epitaxial diodes and heterojunction bipolar transistors (HBTs) after irradiation at room temperature with 2-MeV electrons, 1-MeV fast neutrons and 20-MeV protons. The influence of particle fluence and germanium content is studied, while the radiation source dependence is also investigated by comparing irradiation for different particles with respect to the damage coefficient and the number of knock-on atoms. Based on the observed recovery behavior resulting from isochronal thermal annealing, some possible explanations for the observed degradation and its dependence on germanium content are presented. In addition, the degradation of the electrical performance of $Si_{1-x}Ge_x$ S/D diodes, which have been irradiated at room temperature with 2-MeV electrons, is reported with the performance of p-Ge-MOSFETs at liquid nitrogen temperature. Finally, an outlook will be given as future work.

Keywords: Radiation damage, SiGe device, degradation, lattice defect, recovery

1. Introduction

In these days when the use of nuclear reactors, high-energy particle accelerators and artificial satellites expands, the development of semiconductor devices, which can normally operate in a radiation-rich environment, is extensively taking place everywhere [e. g. 1]. There is, however, few available reports on the damage created by radiation in $Si_{1-x}Ge_x$ devices and its recovery behavior due to thermal annealing. It is necessary to consider the degradation mechanism of the $Si_{1-x}Ge_x$ devices by irradiation for an improvement of the reliability of such electronic devices in radiation-rich environments. Although many studies of the lattice defects induced by irradiation in Si, Ge and recently $Si_{1-x}Ge_x$ with their native property properties have been reported, little is known on the nature of the lattice defects formed in strained $Si_{1-x}Ge_x$ epitaxial layers. In the present paper, the degradation of the electrical performance of $Si_{1-x}Ge_x$ epitaxial diodes and heterojunction bipolar transistors (HBTs), which are irradiated at room temperature with fast neutrons, electrons and protons, is investigated as a function of fluence and germanium content. Some possible explanations on for the germanium content dependence of radiation damage in $Si_{1-x}Ge_x$ devices are also presented. Recently, to enhance carrier mobility the strained Si layers on SOI or $Si_{1-x}Ge_x$ layers have been applied. However, little is known on the effects of irradiation on $Si_{1-x}Ge_x$/Si heterojunction diodes, operating as source/drain (S/D) stressor junctions in deep submicron p-MOSFETs. Then, the degradation of the electrical performance of embedded $Si_{1-x}Ge_x$ S/D diodes and p-Ge-MOSFETs, which have been irradiated at room temperature with 2-MeV electrons, is also investigated together with the performance of p-Ge-MOSFETs at liquid nitrogen temperature, and future work is also outlined for practical application in space.

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2. Experimental

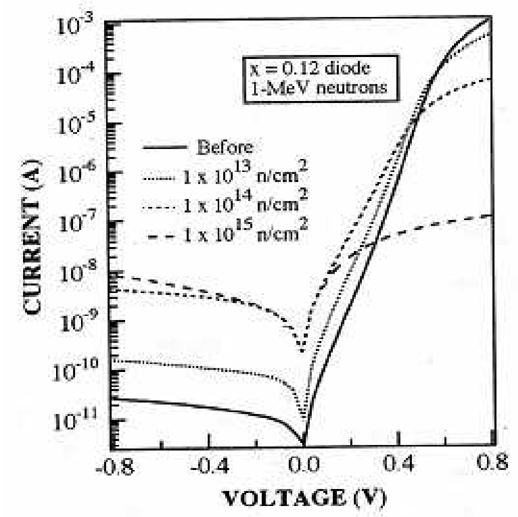
n^+-Si/p^+-$Si_{1-x}Ge_x$ epitaxial diodes and n^+-Si/p^+-$Si_{1-x}Ge_x$/n-Si epitaxial HBTs, which were fabricated on strained $Si_{1-x}Ge_x$ epitaxial layers grown on CZ silicon substrates using an ultra high vacuum chemical vapour deposition system were used in this study. For the diodes, the dopants and their concentrations in the Si substrate grown $Si_{1-x}Ge_x$ epitaxial layer were boron atoms with about 10^{15} cm^{-3} and for the HBTs were phosphorus atoms with about 10^{15} cm^{-3}. The germanium content of the $Si_{1-x}Ge_x$ epitaxial layer with nominal thickness 100 nm was x = 0.08, 0.12 and 0.16. The active boron concentration of the strained $Si_{1-x}Ge_x$ epitaxial layers for diodes and HBTs was about 6 x 10^{17} and about 2 x 10^{18} cm^{-3}, respectively. The diode area was between 10^2 and 10^4 μm^2. The emitter area of the HBTs ranged from 1.75 x 10^2 to 25 x 10^2 μm^2. [2-5] The devices were irradiated by fast neutron with 1-MeV at room temperature in the irradiation tube of Rikkyo university reactor (Triga Mark II). The neutron fluence was varied between 10^{11} and 10^{15} n/cm^2. The devices are irradiated with 2-MeV electrons using the linear electron accelator at Takasaki JAEA. This electron fluence was varied from 10^{16} to 10^{17} e/cm^2. To compare radiation damages, proton irradiation by TIARA at Takasaki JAEA was also performed.

Before and after irradiation, the current/voltage (I/V) and capacitance/voltage (C/V) characteristics of the diodes were measured with applied voltages ranging from -0.8 to 0.8 V for diodes. Base (I_B) and collector (I_C) current as a function of base-emitter voltage (V_{BE}) from 0 to 1 V at collector/emitter voltage (V_{CE}) of 1 V (Gummel plot) were measured for the HBTs. The active boron concentration in the $Si_{1-x}Ge_x$ epitaxial layer of the diodes was calculated from the results of C/V measurements assuming the relation that the square of the capacitance is inversely proportional to the reverse voltage. The hole and electron capture levels in the $Si_{1-x}Ge_x$ epitaxial layers of the diode structures were studied using the deep level transient spectroscopy (DLTS) method in the temperature range between 77 and 300 K. The DLTS measurements were performed to observe the electron capture levels in the collector region of the HBTs, namely the ones present in the n type Si substrate. The emission rate window used in this these measurements was 4.71 msec. In the diodes, the applied filling pulse was ranging from -0.8 to 0 V to observe hole capture levels for and from -0.8 to 0.5 V for electron capture levels. For the HBTs, a voltage from -0.8 to 0 V was applied to measure the electron capture levels. The capacitance/temperature (C/T) characteristics were also examined simultaneously with the DLTS spectra using a reverse voltage (V_R) of -0.8 V.

3. Results and discussion

Figures 1 (a) and (b) show the I/V characteristics of the diodes and HBTs with x = 0.12 for different neutron and electron fluences, respectively. In figure 1 (a), it is noted that both the reverse and forward current increase. Interesting to note is also that the forward current is lower after irradiation for a forward voltage (V_F) larger than 0.5 V. The reason for this might beis an increased resistivity of the Si substrate. For the fluence of 1 x 10^{15} n/cm^2, normal diode performance is not observed.

(a)



(b)

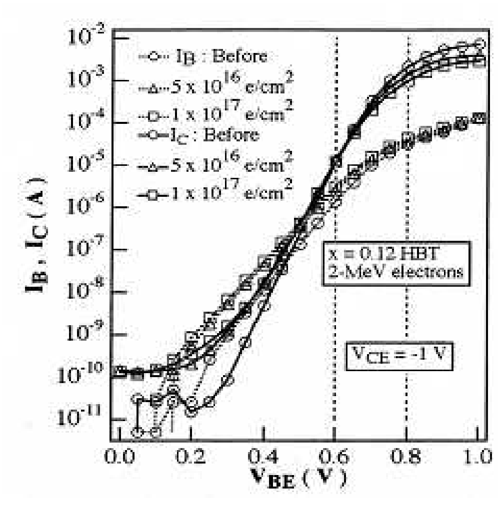


Fig. 1 Influence of irradiation on electrical performance of $Si_{1-X}Ge_X$ epitaxial devices: (a) diode (neutron irradiation) and (b) HBT (electron irradiation).

The same tendency is observed for the diodes with x = 0.16. It is found from the Gummel plot of figure 1 (b) that IB increases by irradiation and that I_C increases until V_{BE} is 0.6 V, while is decreases above this voltage. The decrease of IC at high forward voltage is thought to be caused by the increase of the resistance of the Si substrate due to the formation of electron capture levels [2, 3].

As seen in figure 1 (a), the reverse current at -0.8 V increases with increasing neutron fluence. The forward current at 0.4 V increases until 10^{14} n/cm^2, while it decreases above this fluence. due to the increase of the resistance in the Si substrate and the degradation of the aluminium contacts by irradiation. The degradation of the x = 0.12 diode is more remarkable than that of the x = 0.16 diode. No specific changes of the I/V characteristics after neutron irradiation are observed for 10^{11} n/cm^2. Same tendency is observed for proton and electron irradiation.

It is well known that the damage introduction rate decreases with increasing acceleration voltage and dopant concentration. From C/V characteristics of x = 0.12 diodes for different neutron fluences, it is noted that the capacitance in the $Si_{1-x}Ge_x$ epitaxial layer decreases after irradiation and that this decrease is much larger for 10^{14} n/cm^2. This decrease of active boron is mainly caused by the deactivation of boron, which can be associated with the generation of electrically active lattice defects. From these observations it can be concluded that the electrical damage in $Si_{1-x}Ge_x$ epitaxial devices caused by irradiation increases with increasing fluence, and that it decreases with increasing germanium content [4].

It is found from the Gummel plot of figure 1 (b) that I_B increases by irradiation and that I_C increases until V_{BE} is 0.6 V, while it decreases above this voltage. The decrease of I_C at high forward voltage is thought to be caused by the increase of the resistance of the Si substrate due to the formation of electron capture levels [2, 3]. The degradation of I_C/I_B(= h_{FE}) is proportional to the electron fluence, and that is the most remarkable pronounced for x = 0.08. For an electron fluence below 1 x 10^{16} e/cm^2, the degradation of the electrical performance of the HBT's was not observed, though the diode characteristic degraded for the same fluence. It is well known that the damage introduction rate decreases with increasing acceleration voltage and dopant concentration. From C/V characteristics of x = 0.12 diodes for different neutron fluences, it is noted that the capacitance in the $Si_{1-x}Ge_x$ epitaxial layer decreases after irradiation and that this decrease is much larger for 10^{14} n/cm^2. This decrease of active boron is mainly caused by the deactivation of boron, which can be associated with the generation of electrically active lattice defects. From these observations it can be concluded that the electrical damage in $Si_{1-x}Ge_x$ epitaxial devices caused by irradiation increases with increasing fluence, and that it decreases with increasing germanium content [4].

Figure 2 (a) and (b) show a typical DLTS spectrum of the electron capture levels and the C/T characteristics in x = 0.12 diodes which were irradiated by 2-MeV electrons for the different fluences, respectively. As shown in figure 2 (a), some hole capture levels and one electron capture level is are observed in $Si_{0.88}Ge_{0.12}$ epitaxial layers, while no hole capture level is detected for 10^{15} e/cm^2. The energy level of the electron capture leveltraps is calculated to be about (Ec - 0.54 eV) from standard Arrhenius plots. The electron capture levels induced in $Si_{1-x}Ge_x$ epitaxial layers of x = 0.12 diodes might be associated with interstitial boron complexes as deduced from their energy level and annealing behavior [5]. From the C/T profile indicated in figure 5 (b), it is also found that an abrupt deactiva¬tion of

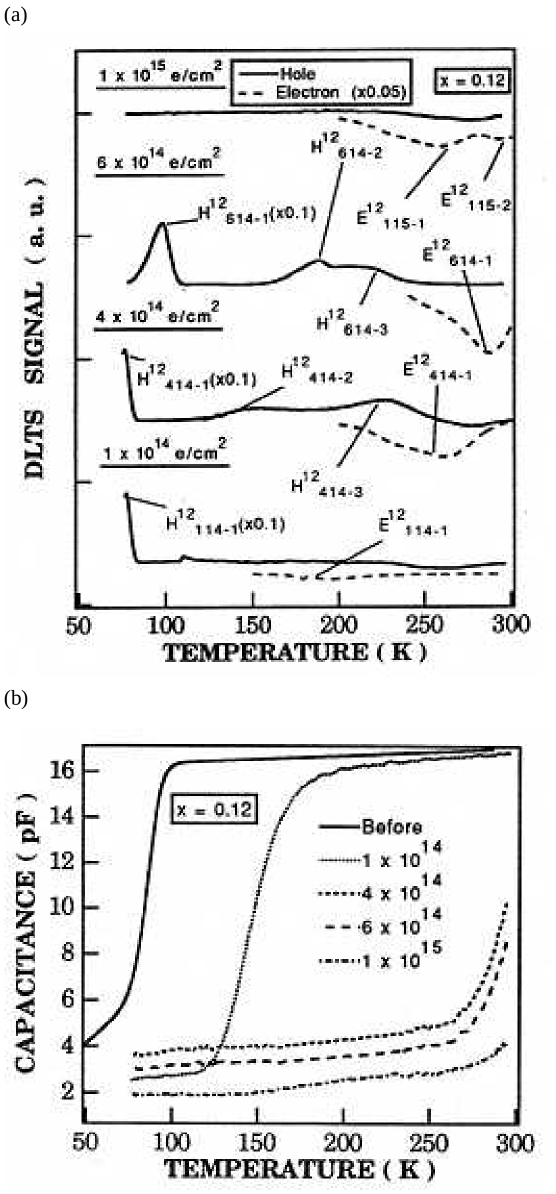


Fig. 2 DLTS spectrum (a) and C/T profile (b) in a x = 0.12 diode irradiated with different electron fluences.

active boron near 280 K is taking place. [6]

The defect density of electron capture levels for 1 x 10^{14} n/cm^2 is about 1 x 10^{16} cm^{-3}. The introduction rate (η), which is defined as the ratio of the deep level density to the neutron fluence, is calculated to be 100 n^{-1}cm^{-1}. In general, for irradiation with 1-MeV electrons, it is known that η is smaller than 1 e^{-1}cm^{-1} [7]. However, the impurity concentration in the samples used in previously research is about 10^{15} cm^{-3}, while in the present study if it is above 10^{17} cm^{-3}. Extrapolating their results to the present dopant concentration shows that η can become indeed larger than 1. It is well known that the damage by neutron irradiation is larger than that for electron irradiation due to the difference of particle mass. From these facts one can easily presume that η for neutron irradiation is also larger than 1. As suggested by figure 1(a), the increase of reverse current by neutron irradiation is caused by generation centres induced in the $Si_{1-x}Ge_x$ epitaxial layer. This means that the recombination-generation current is also dominant in forward current after irradiation for V_F<0.5 V. Moreover, only electron capture levels are induced in the $Si_{1-x}Ge_x$ epitaxial layers with an energy level about the middle of the band gap. Based on these observations, it is clear that the increase of the diode current by neutron irradiation is caused predominantly by the electron capture levels. Table I shows the damage coefficients (n^{-1}, e^{-1}Acm^2 and n^{-1}, e^{-1}cm^{-1}) for I_R (a) and N_B (b) of diodes as a function of germanium content for 1-MeV neutrons and 2-MeV electrons, respectively.

Table I Damage coefficients for I_R (a) and N_B (b) as a function of germanium content for neutrons and electrons.

(a)

	x = 0.08	x = 0.12	x = 0.16
1-MeV neutron	2.9x 10^{-13}	1.8x 10^{-13}	1.1x 10^{-13}
1-MeV electron	3.5x 10^{-16}	2.7x 10^{-16}	2.1x 10^{-16}

(b)

	x = 0.08	x = 0.12	x = 0.16
1-MeV neutron	-21.7	-10.2	-3.4
1-MeV electron	-0.63	-0.40	-0.17

As mentioned above, the damage coefficients for neutron (also proton) irradiation are larger than those for electron irradiation. In order to investigate the radiation source dependence of degradation, one can calculate the number of knock-on atoms ($N_{dn,\ e}$). The average energy of primary knock-on atoms $<E_{pn}>$ for neutron irradiation is given by [8]

$$<E_{pn}> = \frac{E_{p\max} + E_d}{2} \tag{1}$$

where $E_{pmax.n}$ and E_{dn} are the maximum energy for knock-on atoms and the displacement energy, respectively. $E_{pmax.n}$ approximately agrees with the ratio of incident energy and atomic mass [8]. If E_d for silicon and germanium atoms is both 25 eV and the average energy for fast neutrons is 1.5 MeV [9], $<E_{pn}>$ for silicon and germanium is calculated to be 1.07 x 10^5 and 4.13 x 10^4 eV, respectively using eq. (1). If the primary knock-on cross section $\sigma_{pn}(E)$ is neutron cross section, that for silicon and germanium is obtained 3.0 x 10^{-24} and 3.5 x 10^{-24} cm^2, respectively [10]. Then, the fractional displacement concentration (C_{dn}) is given by

$$C_{dn} = \sigma_{pn}(E)\ \nu(<Ep>) \tag{2}$$

where $\nu n(<Ep>)$ is the number of displacement atoms per collision by one knock-on atom. Therefore, N_{dn} for silicon and germanium is estimated to be 315 and 145 cm^{-3}, respectively. With x = 0.12 one can calculate 295 cm^{-3}.

For electron irradiation, $E_{pmax.e}$ and $<E_{pe}>$ are given by the next two equations [11],

$$E_{P\max} = \frac{2(E + 2m_0c^2)}{Mc^2} \quad (3)$$

$$< E_{Pe} >= E_d \ln(\frac{E_{p\max.e}}{E_d}) \quad (4)$$

where E, m_0, M and c is the incident energy, the electron rest mass, the mass of the target atom and the speed of light in vacuum, respectively. From these equations, $<E_{Pe}>$ of Si and Ge for 1-MeV is calculated to be 45 and 21 eV, respectively. The primary knock-on cross section for 1-MeV electrons ($\sigma_{pe}(E)$) is 28 x 10^{-24} and 31 x 10^{-24} cm^2, respectively [12]. Then, the number of knock-on atom of Si and Ge for 1-MeV electrons (N_{de}) is calculated to be 1.25 and 0.65 cm^{-3}. Therefore, N_{de} for a $Si_{1-x}Ge_x$ epitaxial layer with x = 0.12 germanium content is 1.18 cm^{-3}. Table II lists N_d for different values of x. The rates of damage coefficient between neutron (proton) and electron irradiation agrees with the rate of calculated N_d values.

Table II Number of knock-on atoms (N_d, cm^{-3}) for different germanium contents.

	x= 0	x= 0.08	x= 0.12	x= 0.16	x= 1
1MeV neutron	315	301	295	288	145
2MeV electron	2.50	2.49	2.48	2.47	2.40

To confirm the interpretation on radiation source dependence of the degradation, one can calculate the nonionizing energy loss (E_l) [14]. E_l can be described the following equation.

$$E_l = (N/A) <Ep> \sigma_p(E) \quad (5)$$

where N and A are Avogadro's number and the atomic mass, respectively.

Using this equation, E_l for 1-MeV electrons and neutrons is calculated to be 27 x 10^{-3} $keVcm^2g^{-1}$ and 4.5 x 10^{-3} $MeVcm^2g^{-1}$, respectively. The ratio of E_l between neutron (and proton) and electron irradiation is 166 times and approximately agrees with the rate of K and N_d value. This means that the radiation source dependence can be explained by N_d and E_l. From these considerations, it is clear that the difference in irradiation damage between neutrons and electrons is due to the different number of knock-on atoms, which is attributed to the difference of mass and the possibility of nuclear collisions, with a difference of nonionizing energy loss.

The performance degraded by irradiation recovers due to thermal annealing after irradiation. The activation energy of electron trap levels and device performance is nearly same [13, 14] This result means that induced lattice defects in $Si_{1-x}Ge_x$ substrate are mainly responsible for the degradation of device performance.

Recently, the germanium content dependence of radiation damage in embedded $Si_{1-x}Ge_x$ S/D diode has been studied [15]. In this report, the reverse current slightly increases with electron fluenence as shown in figure 3.

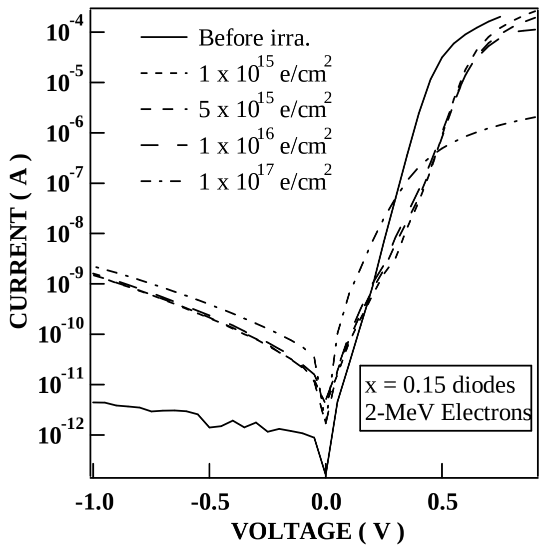


Fig. 3 Influence of electron irradiation on I/V characteristics of embedded $Si_{1-x}Ge_x$ S/D diode.

Moreover, the detailed degradation mechanism for Ge diodes and p-Ge-MOS FETs has been studied taking into account the effect of stress on the radiation damage and the device performance together with liquid nitrogen temperature performance for practical application in space. Figure 4 shows the input characteristics of p-Ge-MOSFETs measured at room temperature (RT) and 77 K.

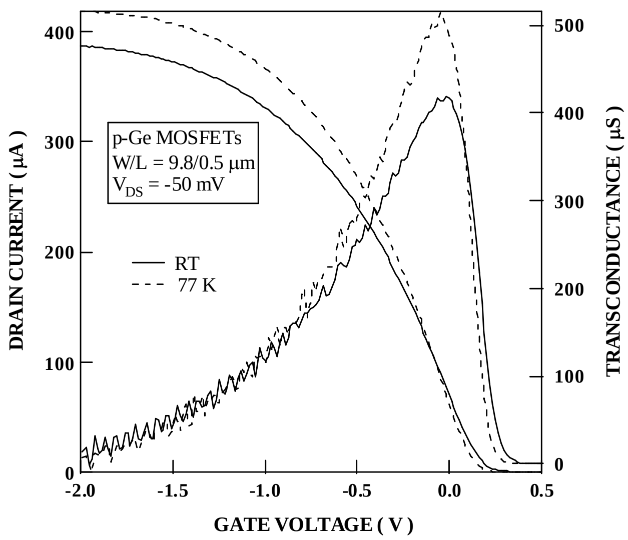


Fig. 4 Drain current and transconductance as a function of gate voltage for input characteristics at RT and 77 K.

From this figure, it is found that the drain current, and transconductance (g_m) increase at 77 K, while the threshold voltage (V_{Th}) becomes more negative. The hole mobility at RT and 77 K is 309 and 381 cm^2/Vs, respectively. This increase of parameter at low temperature can be expected from the $T^{-3/2}$ reduction of the phonon scattering, suggesting an increase of the Coulomb scattering at lower temperature. [16]

3. Conclusions

The following conclusions can be made from the electrical, C/T and DLTS measurements performed after electron and neutron irradiation and subsequent isochronal annealing of $Si_{1-x}Ge_x$ diodes and HBTs.

1. The degradation of the electrical performance of $Si_{1-x}Ge_x$ devices increases with increasing neutron and electron fluence, while it decreases with increasing germanium content.

2. An electron capture level is induced in the 0.12 $Si_{1-x}Ge_x$ epitaxial layer of the diodes by irradiation. This level is related to an interstitial boron complex and is mainly responsible for the increase in reverse current.

3. After irradiation, one hole and several electron capture levels are observed in the base region of x = 0.12 $Si_{1-x}Ge_x$ HBT. This hole and electron capture levels are associated with a boron -vacancy complex and interstitial boron, respectively. Electron capture levels, which are related to the E center (V-P) and the divacancy (VO_2), are induced in the collector region

4. The electron capture levels induced in the base and collector regions of HBTs are thought to be mainly responsible for the increase of the base current and the decrease of the collector current.

5. The damage coefficient for neutron and proton irradiation is larger than that for electron irradiation. This difference is due to the different number of knock-on atoms, which is correlated with the difference of mass and the possibility of nuclear collisions for the formation of lattice defects.

6. The degraded performance recovers by thermal annealing. The activation energies of the reverse current for x = 0.12 diodes and of h_{FE} for x = 0.08 HBTs, irradiated by neutrons are calculated to be 0.22 and 0. 60 eV, respectively.

7. For $Si_{1-x}Ge_x$ S/D diodes irradiated by 2-MeV electrons and 70-MeV protons, after irradiation, the reverse current increases, while the forward current and reverse capacitance decrease. Based on consideration of the damage factor and coefficient at difference fluences and radiation sources, the radiation damage becomes smaller with increasing ermanium content. Also, for proton irradiation, the damage is about three orders of magnitude larger than for electrons due to the different particle mass and collision probability to induce lattice defect by atomic displacement.

8. For p-Ge-MOSFETs, an increase of the drain current and g_m is observed both before and after electron irradiation by operating the devices at 77 K. This results can be expected as reduction of the phonon scattering, suggesting an increase of the Coulomb scattering at lower T.

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