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Recovering behavior of JFET transistors after gamma ray irradiation

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ABSTRACT

The recovery of damaged discrete Si-JFET transistors after irradiation with gamma ray doses was investigated. After a long time of relaxation, the samples were submitted gradually to different heating cycles with a maximum temperature of 140 °C. At the end of the relaxation and annealing cycles, some radiation damage was recovered. The obtained recovery by annealing was higher than that resulting from relaxation alone. Evaluation of the irradiation and recovery effects, including the efficiency process, was performed using measurements of electronic noise.

1. Introduction

The JFETs were considered hard and resistible components towards radiation. Although they are not fully immune to radiation, they suffer from degradation in their properties when they are exposed to high radiation doses, such as space applications and particle accelerator experiments (Wang et al., 1975; Manfredi et al., 1999). This damage can be represented by defects in the bulk of the semiconductor constituting the main component of JFETs and other electronic devices. Interaction of gamma rays with the semiconductor gives rise to ionizing energy losses. The effect of low and high doses on JFET samples irradiated by gamma rays have been largely analyzed in our previous works (Assaf, 2002, 2009).

Despite irradiation damages of devices, there is a chance of restoring some of the original properties either by time relaxation or by the thermal annealing process. In fact, after an external perturbation caused by irradiation, semiconductor junctions and atomic lattice relax to equilibrium conditions. This tendency is explained by the fact that once the defects are created, they will reorder to form more stable states. The defects reordering depends on the nature of the device and on the conditions during irradiation (Srour et al., 2003). From the energy point of view, the creation of defects in the crystalline semiconductor is followed by energy relaxation according to the valence force field model (Wagner, 2004), while, the thermal annealing recovery is carried out by submitting the damaged samples to different heating cycles (Citterio et al., 1996). The effect of this type of recovery could be explained by the fact that both vacancies and interstitial atoms in the lattice, constructed after irradiation, become mobile at sufficiently high temperature, and then become recombined (Manfredi et al., 1999; Holbert). At higher temperature, vibration of the atoms in the lattice increases providing a mechanism by which an interstitial atom can migrate to a vacancy and hence fix both defects (Holbert).

In this work, a full investigation analysis of the relaxation and annealing behavior of JFET samples was carried out. This study is based on the measurement of the electronic noise generated within the JFET samples before and after irradiation, and after the recovery processes.

2. Gamma ray induced damage

The ionizing energy losses in the semiconductor generate mainly electron–hole pairs that transport or recombine according to the standard device behavior. In the model of the semiconductor band gap, electrons–holes either cross the gap or are captured by energetic centers. Surface damage is the main effect of ionization, which is due to accumulated charges causing an alteration in the electrical and DC properties of devices. There is also a chance for a secondary effect known as atomic displacements, where atoms may be displaced in silicon through Compton scattered electrons. These displacements create discrete energetic centers in the band gap, which constitute points defects in the atomic lattice. The presence of these energy levels can cause several processes to occur, such as generation, recombination, trapping, removing and tunnelling of electrons and hole carriers (Dentan, 2002). Individual processes or a combination of them produce electronic noise. This noise is widely used to evaluate the effects of radiation on semiconductors devices. In irradiated JFETs, the most important contributions of noise are leakage current and generation–recombination noise as pointed out in many previous

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reported works (Manfredi et al., 1999; Assaf, 2002, 2009; Cesura et al., 1993).

3. Characterization of irradiation effects by electronic noise

For the purpose of evaluating the irradiation and recovery effects, a methodology similar to that presented in previous works (Manfredi et al., 1999; Assaf, 2002, 2009) is applied. It is based on the measurement of the JFET internal noise and injected signal values at the output of the experimental setup. Thus we can calculate the equivalents noise of charge (ENC) parameter, which represents the noise to signal ratio and then is proportional to the noise. The experimental setup is composed of a pulse generator, a charge preamplifier (CPA), a head amplifier (HA) and a multi-channel analyzer (MCA). The JFET under test is placed in the first amplification stage of the CPA, where the generated noise in the remaining stages of CPA was negligible. The JFET noise is in fact composed of many noise types' contribution. The total *ENC* corresponding to these noise types is given generally by the following equation (Assaf, 2002, 2009; Dentan, 2002; Cesura et al., 1993; Lubelsmeyer et al., 1997):

$$ENC = (ENC_1^2 + ENC_2^2 + ENC_3^2 + ENC_4^2)^{1/2} \quad (1)$$

Eq. (1) shows that there are four terms referring to the four following noise sources: thermal noise, shot or $1/f$ noise, G–R noise and the noise of leakage current. The ENC is usually studied as a function of the shaping time τ of the HA filter, i.e. the $ENC(\tau)$ function. The contribution of each *ENC* term depends on the JFET characteristics and on its physical conditions. For fixed CPA, HA, temperature and noise sources, the terms of Eq. (1) are related to the JFET parameters and τ as follows:

(i) ENC_1 is inversely proportional to the transconductance g_m of JFET and τ; it is then dominant in the lower range of τ.
(ii) ENC_2 is independent of τ; its intrinsic value is small compared with the other contributions (Cesura et al., 1993).
(iii) The most important contribution in our case is ENC_3, because it is attributed to the noise source raised specifically after irradiation, and is known as the Lorentzian or G–R noise. This type of noise is related to the modulation of the JFET channel current induced by charge trapping in the bulk defects with different time constants (Wang et al., 1975; Manfredi et al., 1999; Dentan, 2002). The dependence of ENC_3 on τ is complicated, and it is found to be dominant in the middle of the $ENC(\tau)$ curve (Assaf, 2009).
(iv) ENC_4 is proportional to τ and I_{gss}, whereas I_{gss} is the leakage current of JFET. ENC_4 increases with irradiation; therefore its influence will occur in the high range of τ.

4. Irradiation and recovery of samples

4.1. Irradiation

Discrete commercial transistors of silicon N-channel JFET of the type 2N 4836 were used. All the samples were irradiated by different doses of the ^{60}Co γ-source up to 12 000 kGy.

4.2. Recovery by relaxation

The total *ENC* of irradiated samples is calculated for different relaxation times ranging from a few days to several months. Maximum recovery by relaxation occurred at the end of the first month and it saturates for a longer time.

4.3. Recovery by annealing

After a long relaxation, the samples were submitted to different thermal annealing cycles accomplished by gradual heating inside an oven. To study the temperature effects, three heating cycles labeled Ann1, Ann2 and Ann3 were used, with temperature ranges between 30 °C and three maximum temperatures T_{max} reported in Table 1. T_{max}=140 °C is the maximum temperature supported by the samples. The duration of each cycle

Table1
Temperature ranges of different annealing cycles.

Annealing cycle	Temperature range (°C)
Ann1	30–100
Ann2	30–120
Ann3	30–140

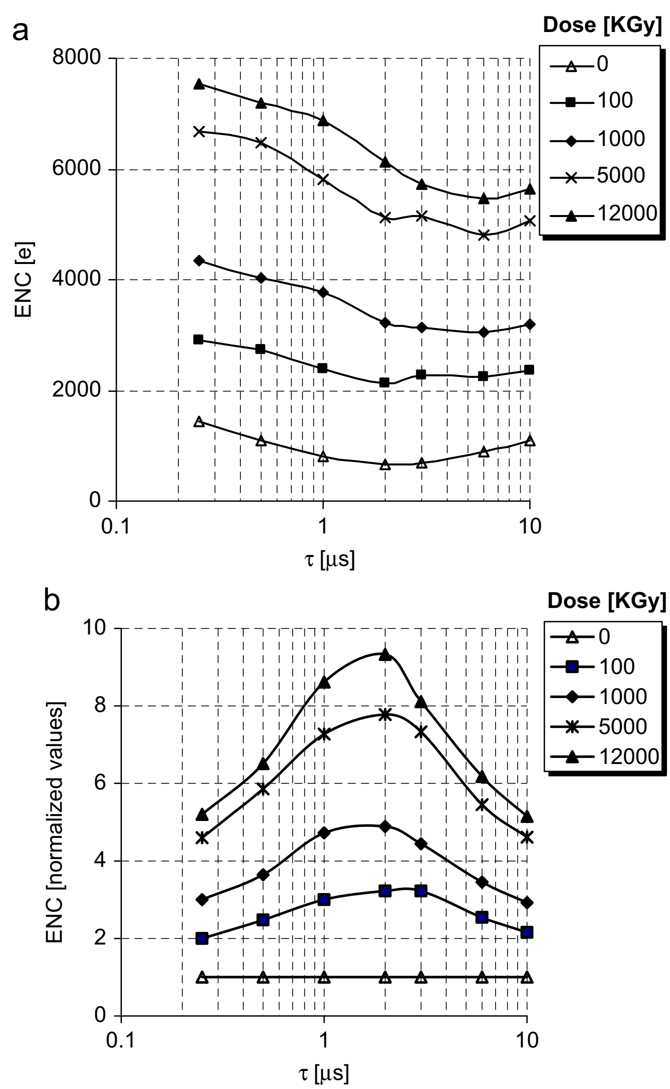

Fig. 1. Equivalent noise of charge (ENC) versus τ resulting from effect of gamma irradiation on JFET samples at different dose values: (a) ENC real values and (b) ENC normalized values.