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# Characterization of a power bipolar transistor as high-dose dosimeter for 1.9–2.2 MeV electron beams

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## ABSTRACT

Results of the characterization studies on a power bipolar transistor investigated as a possible radiation dosimeter under laboratory condition using electron beams of energies from 2.2 to 8.6 MeV and gamma rays from a $^{60}$Co source and tested in industrial irradiation plants having high-activity $^{60}$Co $\gamma$-source and high-energy, high-power electron beam have previously been reported. The present paper describes recent studies performed on this type of bipolar transistor irradiated with 1.9 and 2.2 MeV electron beams in the dose range 5–50 kGy. Dose response, post-irradiation heat treatment and stability, effects of temperature during irradiation in the range from −104 to +22 °C, dependence on temperature during reading in the range 20–50 °C, and the difference in response of the transistors irradiated from the plastic side and the copper side are reported. DLTS measurements performed on the irradiated devices to identify the recombination centres introduced by radiation and their dependence on dose and energy of the electron beam are also reported.

## 1. Introduction

Irradiation of silicon crystals with high-energy particles and $\gamma$ rays results in the generation of electron–hole pairs (ionization) and introduction of a variety of defects into the crystal lattice (displacement damage). These defects play a major role in the control of minority carrier lifetime, the most sensitive semiconductor characteristic in the bipolar devices and a quantity on which a large variety of electrical parameters of power semiconductor devices depends (Rai-Choudury et al., 1976; Baliga and Sun, 1977; Carlson et al., 1977; Brotherton and Bradley, 1981; Fuochi, 1994). Because of this property the use of silicon devices as possible radiation dosimeters was taken into consideration many years ago. Their use for the dosimetry of high-energy photon and electron beams, mainly in the field of radiation therapy, began in the early 1960s (Jones, 1960, 1963; Parker and Morley, 1967; Scharf, 1967) and since then they have been used for many years also in the field of radiation protection and industrial radiation processing (Dixon and Ekstrand, 1982; Rikner and Grusell, 1987; Mc Laughlin et al., 1989; Barthe, 2001).

Considering that the reduction of charge carrier lifetime is proportional to the irradiation dose, a bipolar power transistor was tested in previous studies as a possible routine dosimeter under standard laboratory conditions (Fuochi et al., 1999) and in high-activity gamma and high-power electron beam facilities (Fuochi et al., 2004) with good results. Based on these results, it was decided to test the dosimetric performances of these transistors for 1.9 and 2.2 MeV electron beams in the high dose range (5–50 kGy) by irradiating them from both the plastic and the copper side to check for any difference in the response.

In a previous study (Fuochi et al., 2009) a post-irradiation recovery of response as high as 10% over 10 days at room temperature was observed. To overcome this problem the transistors were submitted to post-irradiation thermal treatment at 100 and150 °C for 30 min following the recovery behaviour for 50 days. The post-irradiation thermal treatment at 150 °C was found to be the most effective solution to the problem (Fuochi et al., 2009), thus this procedure was also used in the present work.

Two other quantities affect the transistor response: the temperature during irradiation and the temperature during transistor response measurement (readout). The dependence of lifetime response on the temperature during irradiation was studied in the range from − 104 to +22 °C for the absorbed dose to water of 6 and 26 kGy. The dependence of the transistor response on the temperature during the lifetime measurements was also studied in the range of 20–50 °C.

Since the charge carrier lifetime is strongly dependent on the type and concentration of the irradiation-induced defects in the

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silicon crystal, an analysis of the lifetime response as for formation of these defects was attempted. For this reason deep level transient spectroscopy (DLTS) was performed on the thermally treated irradiated transistors to identify the radiation-induced defects and their behaviour after thermal treatment.

It should also be mentioned that in the case of gated transistors irradiation by protons, electrons and gamma rays results in the formation of oxide traps and semiconductor–oxide interface traps which increases the surface recombination velocity (see for instance Ball et al., 2002; Minson et al., 2004; Schrimpf et al., 2008 and references therein). Since in our ungated transistor a large surface area over the base region is covered by silicon dioxide, surface effects, not investigated in the present paper, could play a non-negligible role on the charge storage time of irradiated devices. However, the aim of our work is neither to analyse nor to describe in detail the device physics, but to check the possibility to use a power bipolar transistor as a radiation dosimeter for 1.9–2.2 MeV electron beams in the high dose range such as it was previously done for gamma rays and higher energy electron beams (Fuochi et al., 2004, 2006).

## 2. Experimentals

### 2.1. Semiconductor device and its measuring circuit

The n–p–n power bipolar transistor BULT118 type used for this study consists of a three-layer structure realized with multi-epitaxial planar technology (Fig. 1) encapsulated in a SOT-32 package with one side, made of epoxy molding compound ($1.2\pm0.1$ mm thick) containing 16% Si and 1% Sb having density 1.83 g/cm$^3$ and the other side presenting a copper plate (0.5 mm thick), on which the silicon die is soldered. The device is designed for use in lighting applications and low cost switch-mode power supplies. Its mechanical characteristics have been already described (Fuochi et al., 1999). Since the previous studies (Fuochi, 1994) had shown that the decrease of charge carrier lifetime in any type of power semiconductor device is proportional to the absorbed dose, the attention was focused on this characteristic of the transistor.

The lifetime measurement is obtained by using a resistive load switching test circuit shown in Fig. 2, which allows to measure a physical parameter $T$ (storage time) related to the charge carrier lifetime $\tau$ and defined by the equation

$$T=\tau\ln(Q_s/\tau I_b)$$

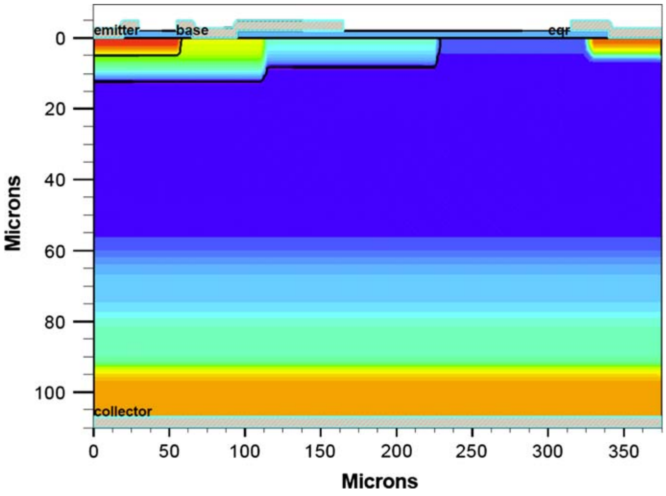

**Fig. 1.** Cross section of power bipolar transistor BULT118 used in this study.

where $Q_s$ is the stored charge and $I_b$ the turn-on base current. By selecting the appropriate driving condition $V_{BB}$, $R_{BB}$, $V_{CC}$, and $I_{B1}$, $T$ can be considered as a function of the charge carrier lifetime $\tau$ only which is the dosimetric parameter.

The parameter $T$ was measured in the temperature range 20–50 °C by connecting the measuring circuit of Fig. 2 to a Peltier-effect thermocell. The response of transistors to the radiation was plotted against dose to water as measured by the reference dosimeters. Here the transistor response $R$ is defined as

$$\mathrm{R}=1/T_i-1/T_0$$

where, $T_0$ and $T_i$ are the pre- and post-irradiation values.

### 2.2. Irradiation sources and procedures

#### 2.2.1. Calibration of transistor dosimetry system

Electron irradiations of transistors, at room temperature, were carried out at Aérial Institute, Illkirch (France) using their Van de Graaff electron accelerator. Irradiations were performed with electron beams having mean energies of 1.9 and 2.2 MeV determined from the depth-dose distribution using a stack of polystyrene plates interleaved with B3 dosimeter films (ISO/ASTM, 2005a).

The dose rate was about 90–100 Gy/s and the beam current was 100 μA for both irradiations. The absorbed dose to the transistors was determined by simultaneously irradiating a set of alanine dosimeters, which are traceable to the UK National Physical Laboratory, in the Aérial calibration phantom and quantified in terms of dose to water. The measured dose has an expanded uncertainty of 5% at $k=2$. The mean temperature of the transistors at highest dose (45.2 and 48.7 kGy) was about 35 °C. This value was calculated as the average of the temperatures before and after irradiation, which were measured with a calibrated thermistor embedded inside the calibration phantom.

Four transistors were irradiated together for each dose point and irradiation was done with no bias voltage applied, but with all pins floating.

#### 2.2.2. Irradiation at controlled temperature

Irradiations at controlled temperature were done using a thermostatic box from Aérial inside which a resistive heater warms up an aluminium plate that is partially immersed in a cooling bath made of different mixtures of water, ice, dry ice and/or liquid nitrogen, depending on the target temperature. The transistors to be irradiated, packed in a thin, tight PE envelop to avoid condensation moisture, were placed, with the plastic side facing the impinging electrons, inside a PE calibration phantom placed in close contact with the aluminium plate and surrounded by the cooling bath. A thermocouple inserted in the PE phantom and connected to the temperature control equipment allowed the measurement of the temperature during irradiation. Before irradiation, sufficient time was allowed for the phantom temperature to reach equilibrium. The temperature of the PE phantom during irradiation was determined as the average of temperatures before and after irradiation.

The accelerator parameters used for the irradiation at controlled temperature were: electron beam energy 1.9 MeV, beam current 50 μA and dose rate 105 Gy/s. Three transistors, in each pack, were irradiated at two different doses: 6.3 and 25.9 kGy. The dose rate, total dose and irradiation uniformity were determined by irradiating a set of alanine dosimeters in the same configuration as used for the irradiation of the transistors, but at room temperature.