Investigation of Irradiated Monolithic Transistors for Space Applications

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Abstract

In this paper experimental results on radiation effects on a BICMOS high speed commercial technology, manufactured by STMicroelectronics, are reported. Bipolar transistors were irradiated by neutrons, ions, or by both of them. Fast neutrons, as well as other types of particles, produce defects, mainly by displacing silicon atoms from their lattice positions to interstitial locations, i.e. generating vacancy-interstitial pairs, the so-called Frenkel pairs. Defects introduce trapping energy states which degrade the common emitter current gain β. The gain degradation has been investigated for collector current I_c between 1 μA and 1 mA. It was found a linear dependence of $\Delta(1/\beta) = 1/\beta_i - 1/\beta$ (where β_i and β are the gain after and before the irradiation) as a function of the concentration of Frenkel pairs. The bipolar transistors made on this technology have shown to be particularly radiation resistant. Both base and collector currents have been also systematically investigated.

Key words: Bipolar Transistor, Nuclear Irradiation, Frenkel Pair, Space Qualification
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1 Introduction

The continuous evolution of mission requirements and their electronic technologies, combined with the need to meet the space environment, particularly radiation, constitute challenges for component engineers and designers. For instance, the increased activities in space for communications, military and scientific research has required to take into account that the electronics employed for these purposes contain most advanced devices and circuits (VLSI and ULSI). These advanced VLSI and ULSI based electronics, have very high density of devices with very small features and may have radiation sensitivity.

Inside the Earth magnetosphere there are two Van Allen regions[1] of trapped fast particles (mostly electrons and protons). A few years ago, the analysis of SAMPEX data [2]-[4] have shown the existence of belts containing heavier nuclei like N, O, Ne with energies of the order of 10 MeV/a. The AMS mission data (Space Shuttle flight STS-91, June 1998[5]) have shown the existence of trapped and quasi-trapped high energy (up to few GeV/c's) protons, electrons and positrons, generating the so called *AMS belts*, located at low Earth orbit. Furthermore, there are Galactic Cosmic Rays (GCR), which consist mainly of protons, alpha particles, a lesser amounts of low-Z and medium-Z nuclei up to iron, and an even lesser amount of heavier-Z atoms. These primary cosmic rays generate a flux of particle toward the Earth and toward any region inside its magnetosphere, as well inside the solar cavity. As a consequence, a satellite located at any orbit will undergo a flux of energetic particles.

The flux of GCR's is low compared to trapped particles, but it is an hazard to spacecraft electronics, because GCR's can penetrate shielding materials [6]. After a standard aluminum shield of 100 mils (see for instance Sect. 5.4 in [6]) fast energetic charged particles (namely above 22.5 MeV for protons and 90 MeV/a for iron ions) will be able to make radiation damages. In this case, each isotopic element of these penetrating charged particles (see for instance, fluxes and energy distributions of protons, helium, carbon and iron shown in Sect. 23 of Ref. [7]) releases a dose and loses an amount of energy by a Non Ionizing Energy Loss (NIEL) process ([8] and references therein), which are non negligible fractions of those ones of the proton component. As a consequence, when a 100 mils aluminum shield is taken into account the proton component is expected to contribute with an important, but not dominant, fraction of both the dose and the NIEL deposition. The knowledge of fast charged particle fluences (and their time dependence) inside the Earth magnetosphere makes possible to determine the expected Frenkel pairs concentration (FP) due to NIEL and the absorbed dose both generated by penetrating charged particles impinging on semiconductor devices (i.e. in microelectronics), once defined the duration and the orbit of a satellite, and, in general, of any pay-load.

The presence of this complex radiation environment has drawn attention to the important influence of space radiation on the characteristics of devices and circuits of the electronics systems. To account for the space environment in which the large number of electronic circuits are going to be introduced, investigations of the interdependence effects between the type, intensity, duration of irradiations typical of space environment have to be carried out on basic components (like MOS and bipolar transistors) of VLSI technologies. These basic components are indeed the essential part of any circuit, thus the knowledge of irradiation influence on them is critical (see for instance [9]-[15] and references therein). Many of the bipolar integrated circuits used in space systems, including operational amplifiers, comparators, voltage regulators, are used to accomplish analog functions.

This knowledge has to be complemented by latch up and single event upset investigations for an effective implementation of any VLSI circuit, whose design can, in turn, depend on such effects. However, the qualification of a VLSI technology, i. e. of its basic components, with regard to the radiation resistance is certainly needed for any design consideration, because a non radiation resistant technology cannot be employed in a radiation environment. For instance bipolar junction transistors (BJT), which may have important applications in analog or mixed-signal IC's and BICMOS (Bipolar complementary metal-oxide semiconductor) circuits because of their current-drive capability, linearity, and excellent matching characteristics, have to be studied. In fact, when bipolar integrated circuits are exposed to radiation in space, one of the primary mechanisms of degraded operations is the reduction of the current gain.

For this purpose, an investigation on radiation effects on a BICMOS high speed commercial technology manufactured by STMicroelectronics has been undertaken and, with the present data, extended up to medium-Z ions like Ar and Kr (available at the GANIL accelerator).

2 Irradiations and Measurements

The neutron irradiation was performed at the Triga reactor RC:1 of the National Organization of Alternative Energy (ENEA) at Casaccia, Rome. The flux of the reactor, in the energy range of 10 keV – 10 MeV, was about 7.29x10^{11} n/cm^2s, at the reactor power of 1MW. The mean fast neutron energy above 10 keV is about 0.83 MeV. The value of the hardness parameter for the neutron spectrum in the energy range 10 keV - 10 MeV was about 0.6 . The Spectral Index (SI) of the exposure environment (see for instance Refs. [16],[17]), namely the ratio of the neutron fluence above 10 keV over the neutron fluence above 3 MeV, is SI = 18.6 . The obtained fluences, integrated for energies larger than 10 keV, were in the range of 1.35x10^{13} n/cm^2 - 1.35x10^{15} n/cm^2 .

n [n/cm^2]	C (HE) [ion/cm^2]	C (ME) [ion/cm^2]	Ar [ion/cm^2]	Kr [ion/cm^2]
1.35x10^{13}	5.2x10^{10}	1.0x10^{11}	1.0x10^{10}	1.0x10^{9}
1.35x10^{14}	1.0x10^{11}	5.0x10^{11}	5.0x10^{10}	5.0x10^{9}
6.75x10^{14}	5.1x10^{11}	1.0x10^{12}	1.0x10^{11}	1.0x10^{10}
1.35x10^{15}	1.0x10^{12}	5.0x10^{12}		5.0x10^{10}
	5.0x10^{12}	1.0x10^{13}		
	1.0x10^{13}			

Table 1: Particle fluences in $particles/cm^2$. For neutrons, the fluences are those for fast neutron with kinetic energy above 10 keV.

The C ions were made available at GANIL (Grand Accelerateur National d'Ions Lourds, Caen), at two different energies: ^{12}C accelerated at 95 MeV/a [High Energy, C (HE)], and ^{13}C ions at energy of 11.1 MeV/a [Medium Energy, C (ME)]. Fluences as large as 10^{13} C/cm^2 were obtained.

In addition to irradiations with fast neutrons and C ions previously carried out (see Ref. [14]), ^{36}Ar ions at 13.6 MeV/a and ^{86}Kr ions at 60 MeV/a were also made available to investigate the radiation effects at medium-Z values and are summarized in Table 1.

The investigated devices were manufactured by ST-Microelectronics, using a standard high speed BICMOS technology.

Both npn and pnp devices were characterized, using an HP4142B modular DC source-monitor , controlled by a workstation HP-C160. The forward voltage applied to the emitter-base junction (V_{be}), was in the range (0.2-1.2) V, which allows to measure the value of forward (common emitter) gain $\beta = I_c/I_b$ for collector currents, I_c , with the base and collector grounded and where I_b is the base current. The investigated collector currents were within the range $10^{-6} < I_c < 10^{-3}$ A .

The measurement was done using the same setup before and after irradiation. Due to the intrinsic technological spread of the β values, all the samples were measured before irradiation, in order to evaluate the gain variation, due to irradiation, for each sample. For each fluence, at least two transistors were irradiated. All the measurements were done at the temperature T ~ 25°C . The irradiated samples were measured at a temperature T ~ (20 - 24) °C .

3 Displacement Defects calculation

There has been substantial progress in understanding the degradation produced in microcircuit transistors elements [18]-[22] by fast neutrons (i.e. typically above 10 keV), which induce displacement damages. Because neutrons with energies below 10 keV induce negligible atomic displacements with regard to fast neutrons[23], the reactor neutron fluence usually takes into account only fast neutrons when damage effects in silicon devices are under investigation.

Fast neutrons, as well as other types of particles, produce defects, mainly by displacing silicon atoms from their lattice positions to interstitial locations. i.e. generating vacancy-interstitial pair, the so-called Frenkel pairs. Displacements produced in silicon during neutron irradiation have been widely studied [21]-[24]. Neutrons with sufficient large energies (i.e. fast neutrons) can cause the displacement of a silicon atom, referred to as primary displacement, from its lattice location. The displaced ion can, in turn, generate secondary displacements following a cascading effect.

In literature (see for instance [22],[23],[25]), the damage effect due to displacements induced by neutrons is expressed by the damage function *D(E)* in units of $MeV\ cm^2$, also called the displacement kerma function, whose value at 1 MeV is the ASTM standard [9] *D(1MeV)* = 95 $MeV\ mb$. The damage function accounts for both the cross section for displacing silicon atoms and the energy released in creating displacements. The kerma displacement cross section is given by:

$$D(E) = \sum_k \sigma_k(E) \int f_k(E, E_R) P(E_R)\ dE_R \tag{1}$$

where E is the incoming neutron energy, $\sigma_k(E)$ is the cross section for the *kth* reaction, in which $f_k(E, E_R)$ is the probability that a recoil energy E_R is generated and finally $P(E_R)$ is the partition energy, i.e. the part of the recoil energy deposited in displacements calculated, for instance, in the framework of the Lindhard screened potential scattering theory, based on the Thomas-Fermi model and further developments [26]-[29]. The damage function is given in literature (see for instance [23] and references therein).

The energy density E_{dis} , i.e. the energy per cm^3, deposited trough atomic displacements by neutrons characterized by the neutron spectral fluence $\phi(E)$

in $n/(cm^2\ MeV)$, is given by:

$$E_{dis} \;=\; N \int\limits_{E_{\min}} D(E)\ \phi(E)\ dE\ \ [MeV\ cm^{-3}] \tag{2}$$

where N is the number of atoms per cm^3 in the bulk silicon. For reactor neutrons the value of E_{dis} varies slightly for $E_{\min}$ in energy range up to 10 keV. In the case of the Triga reactor RC:1 neutron spectrum, the E_{dis} value varies by no more than 0.5 % for $E_{\min}$ values in energy range up to 10 keV.

E_{dis} , as computed by means of Eq. 2, is the Non Ionizing Energy Loss (NIEL in units of MeV/cm) per cm^2.

The concentration of Frenkel pairs (FP), i.e. the number of Frenkel pairs per cm^3, can be evaluated in the Kinchin-Pease model from the value of E_{dis} given in Eq. 2, as

$$FP \;=\; \frac{E_{dis}}{2\ E_d} \tag{3}$$

where E_d , about 25 eV , is the energy required to displace a silicon atom from its lattice position to an interstitial location [30],[31],[32].

In the case of the Triga neutron spectrum (see Sect. 2), Eq. 3 yields to a Frenkel pairs concentration of about 54.1 per incoming neutron per cm^2 with energy above 10 keV. This value accounts also for the low energy part of the neutron spectrum, i.e. below 10 keV, which contributes by no more than 0.5% to the FP overall value. The calculated Frenkel pairs concentration (as used in the present paper) per incoming neutron per cm^2 has to be decreased by about 20% in the modified Kinchin-Pease model [32], i.e. only 0.8 E_{dis} is the energy density available for Frenkel pairs creation. The Frenkel pairs concentrations generated inside the irradiated samples at the Triga reactor are computed by multiplying the neutron fluences given in Table 1 by the Frenkel pairs concentration per incoming neutron per cm^2 above 10 keV. The Frenkel pairs concentrations is expected to be almost uniform for fast incoming neutrons. In fact their cross section is between (2 - 8) barn, namely their interaction length is between (10 - 2.5) cm .

Similarly to an incoming neutron, an incoming ion may interact and displace a silicon atom from its lattice position. This primary displacement is followed by a cascading process, in which secondary displacements are induced by the recoil silicon atom. In the case of an incoming ion the secondary cascade is typically smaller with regard to order of a hundred Frenkel pairs in the case of incoming neutron.

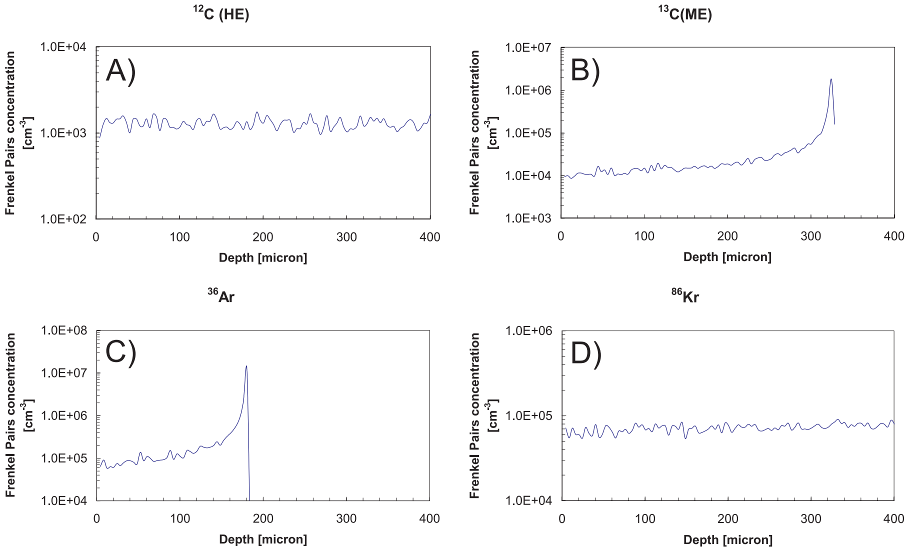

Fig. 1. Frenkel pairs concentration as a function of the production depth in silicon for incoming (A) C(HE), (B) C(ME), (C) Ar, (D) Kr ions.

Furthermore, the cross section for creating a primary displacement is larger for the interaction of an ion on silicon than for the interaction of a neutron on silicon. However the dominant mechanism for generating atomic displacements is via silicon to silicon secondary displacement.

Ion ranges (as well as the Frenkel pairs concentrations) depend on energy. As a consequence for every irradiation, it is necessary to take into account the depth at which the device is realized inside the substrate. We have investigated in details the first 20 μm deep substrate layer to study the few μm's extension of the active device region, located underneath the oxide superficial structures, by using the Monte Carlo simulation program TRIM[34]. This procedure has been applied for all incoming ions.

The results of such simulations are shown in Figs. 1 (A,B,C,D) for C (HE), C (ME), Ar and Kr, respectively. Their ranges in silicon are about 12.6 mm, 320 μm, 180 μm, and 1.3 mm, respectively. Simulations show the concentrations of Frenkel pairs are almost uniform up to a depth much larger than 20 μm for all incoming ions. The value of FP increases as the depth increases.

In addition, the samples are mounted inside a package with removable upper lid for the irradiations, so that there is no degradation of the incoming ion energy on it.

The average Frenkel pairs concentrations generated per incoming C (ME), C (HE), Ar and Kr ions per cm^2 (see Sect. 2) and calculated by means of the Monte Carlo simulation program TRIM[34] are 1.2x10^3, 10.7x10^3, 7.2x10^4 and 6.4x10^4 respectively. The overall Frenkel pairs concentrations created by ion irradiations are computed by multiplying the ion fluences of Table 1 by the corresponding average Frenkel pairs concentration per incoming ion per cm^2.

3.1 Messenger-Spratt Equation and NIEL Scaling

Defects introduce trapping energy states which degrade the minority carrier lifetime. As well known, bipolar transistors operation derives from the physical and electrical behavior of majority and minority carriers in the junctions which constitute the transistor. In fact, minority carriers are injected into the base at the emitter-base junction, transported to the collector and retrieved, as majority carriers, across the base-collector junction. For instance, the effect of radiation on bipolar devices is the reduction of the common emitter current gain, which can be described in terms of the reduction of the minority carrier lifetime.

The relationship between the variation of the inverse of the gain and the fast neutron fluence is provided by means of the Messenger-Spratt Equation ([18]-[20] and references therein):

$$\Delta\left(\frac{1}{\beta}\right) = \frac{1}{\beta_i} - \frac{1}{\beta} = \frac{1}{\omega_T}\,\frac{\Phi_n}{K} \tag{4}$$

where β and β_i are the common emitter current gain before and after the irradiation, ω_T is 2π times the common emitter gain bandwidth product, K the relevant damage constant which depends also on the base resistivity (see for instance [33]) and Φ_n the fast neutron fluence in n/cm^2 :

$$\Phi_n = \int_{E_{\min}} \phi(E)\, dE \tag{5}$$

where $E_{\min}$ value is usually taken at about 10 keV.

The ratio Φ_n/K can be written as (see Eq. 5.15 in Ref. [21]):

$$\frac{\Phi_n}{K} = \sigma_m\, \nu_e\, N \int_{E_{\min}} \sigma_c(E)\, \phi(E)\, dE \tag{6}$$

where v_e is the average speed of minority carriers; σ_m and $\sigma_c(E)$ are the cross section for the absorption of minority carriers by recombination centers and the cross section of neutrons of energy E for creation of recombination centers in silicon.

So long (for instance in absence of saturation effects) we can assume that the number of recombination centers produced in silicon is proportional to the energy going into atomic (displacement) processes, we have that the concentration of recombination centers is proportional to the energy density E_{dis} released trough displacement processes (Eq. 2) and to the concentration of the Frenkel pairs FP (Eq. 3):

$$N \int_{E_{\min}} \sigma_c \phi(E) dE \;\propto\; N \int_{E_{\min}} D(E)\phi(E)\, dE \;=\; E_{dis} \tag{7}$$

where E_{dis} , namely the NIEL per cm^2, is linearly related to the concentration of the Frenkel pairs (FP) generated.

From Eqs. 6 and 7, Eq. 4 can be rewritten as:

$$\Delta\left(\frac{1}{\beta}\right) \;\propto\; \frac{NIEL}{\omega_T} \;=\; \frac{\lambda}{\omega_T}\, FP \tag{8}$$

where λ is independent of the damage function, which is accounted by E_{dis} and, in turn, by FP.

The Messenger-Spratt equation predicts a linear dependence of the inverse of the gain variation on the concentration of Frenkel pairs (FP) generated by incoming neutrons.

To a first approximation, Eq. 8 can be applied to the case of damages induced by ions as already observed for irradiations with neutrons and C ions in Ref. [14], namely there is a NIEL scaling of the gain variation of bipolar transistors. In the space radiation environment, as already mentioned, medium-Z isotopes largely contribute to the NIEL deposition. Thus, irradiations with Ar and Kr ions can allow to verify the validity of Eq. 8 also for the case of medium-Z ions.

This way, it is possible to set up a method to qualify monolithic technologies to be operated in the space radiation environment, namely testing them for the expected NIEL deposition, but without requiring any specific incoming particle.

4 Bipolar Transistors Behaviour

4.1 Gain Variation in Bipolar Transistors

In a previous paper[14], it has been already shown that also for the case of small area npn transistors (with the emitter region of 5 μm x 5 μm and irradiated with both C ions and neutrons) there is a similar gain degradation when the concentration of the created Frenkel pairs (CF), interstitial-vacancy, is the same. This occurs in spite of the large difference in the absorbed dose between neutron and C irradiations for generating an equal amount of FP concentration. The gain degradation has been investigated for collector currents I_c between 1 μA and 1 mA. It was found [14] a linear dependence of $\Delta\,(1/\beta)$ as a function of the concentration of Frenkel pairs. The slope value $k(I_c)$ depends on the I_c value and on both the type and the area of the transistor. In fact, the small area transistors have slightly larger ω_T values (i.e. a larger cut-off frequency) than those ones with large area, while pnp lateral transistors have lower cut off frequencies than the vertical pnp and npn transistors (namely about 20 MHz versus 2-6 GHz). The bipolar transistors made on this technology have shown to be particularly radiation resistant. For instance, the npn small area transistors have shown values of $\Delta\,(1/\beta)$ variation lower than about 10% for a FP concentration larger than about $2.7\text{x}10^4$ cm^{-3} and an ionizing dose deposited by medium energy C ions larger than 0.5 Mrad even for collector currents as low as 1 μA . As a consequence, they are well suited even for space missions with large expected total doses of a few hundreds krad and requiring usually low power consumption.

Two additional irradiations (with Ar and Kr ions) have been carried out, to confirm the linear dependence between $\Delta\,(1/\beta)$ and the concentration of Frenkel pairs.

In Figs. 2 (Figs. 3), it is shown $\Delta\,(1/\beta)$ for small (large) area with the emitter region of 5 μm x 5 μm (50 μm x 50 μm) npn transistors at I_c = 1, 50 and 1000 μA, for the full set of irradiations. The overimposed line is the linear fit to data. The general agreement with a linear dependence as predicted by Eq. 8 is observed over the full range of the investigated collector currents, namely up to 1 mA for both the small and large area transistors.

In Figs. 4 (5), the experimental data show a linear dependence of $\Delta\,(1/\beta)$ for pnp vertical (lateral) transitors on the Frenkel pairs concentration over the full range of collector currents under investigation, namely from 1 μA to 1 mA . At the lowest FP concentration, the experimental errors are large to take into account the different gain variation observed among the three irradiated samples.

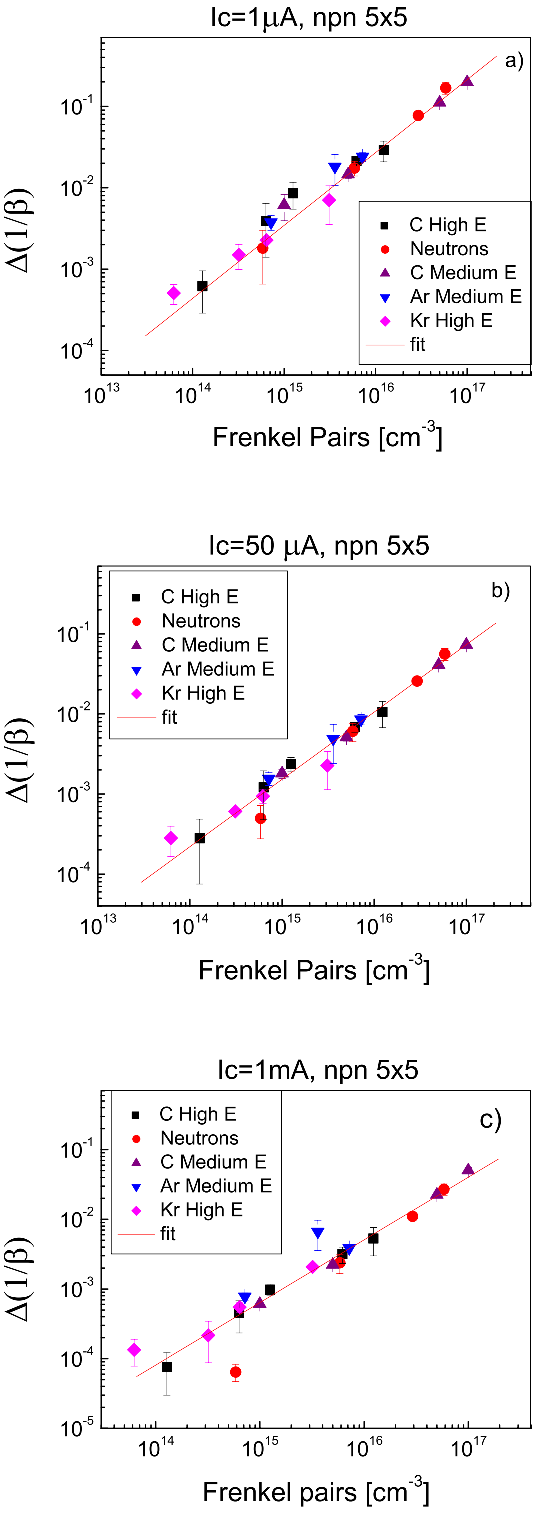

Fig. 2. Linear dependence of the quantity $\Delta\,(1/\beta)$ on the concentration of Frenkel pairs, for npn (small area with the emitter region of 5μm x 5μm) transistors and collector currents of (a) 1 , (b) 50 and (c) 1000 μA.

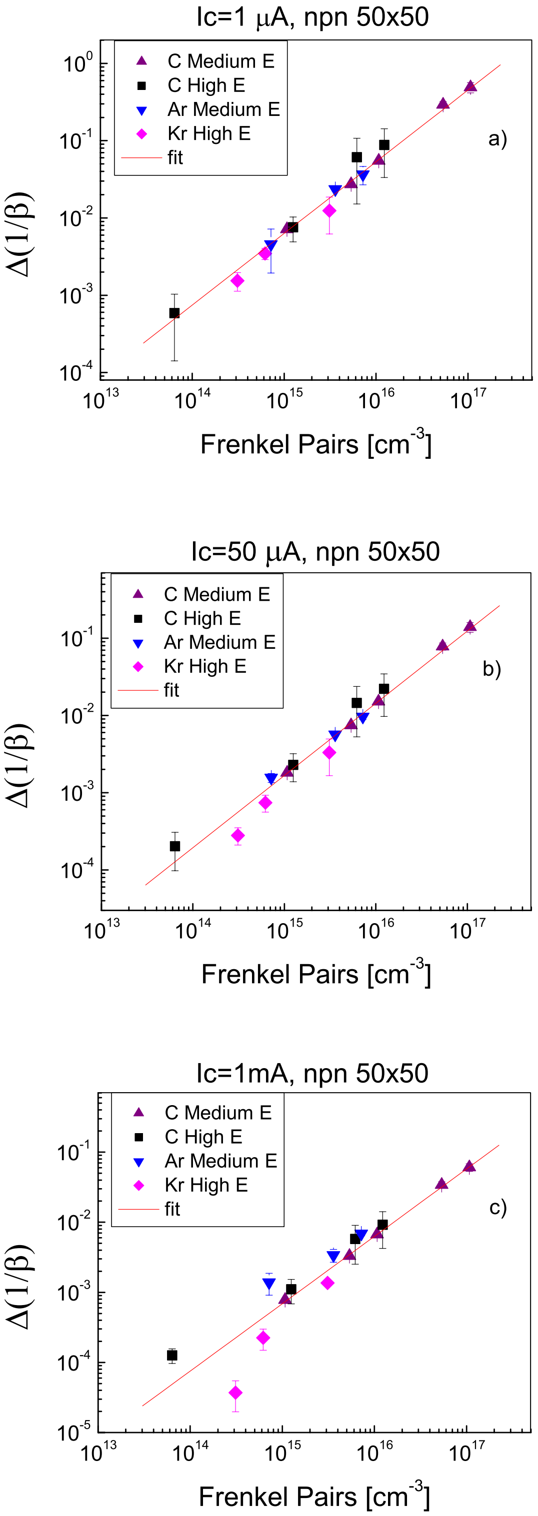

Fig. 3. Linear dependence of the quantity $\Delta(1/\beta)$ on the concentration of Frenkel pairs, for npn (small area with the emitter region of 50μm x 50μm) transistors and collector currents of (a) 1 , (b) 50 and (c) 1000 μA.

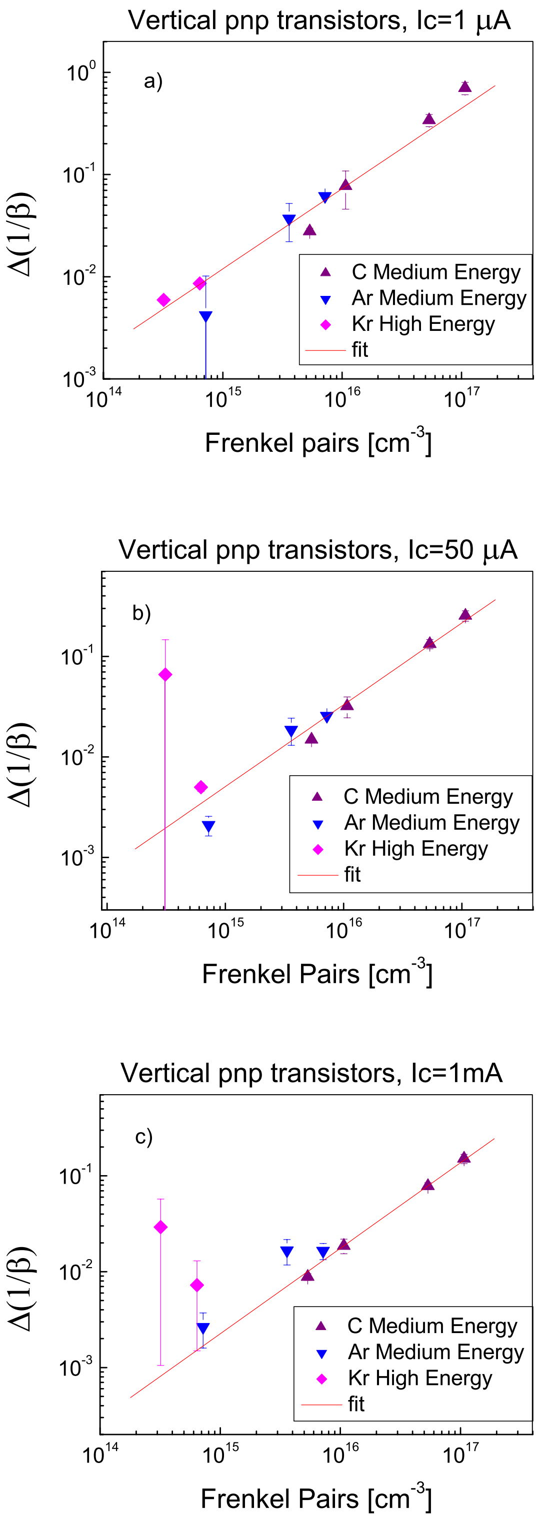

Fig. 4. Linear dependence of the quantity $\Delta\,(1/\beta)$ on the concentration of Frenkel pairs, for vertical pnp transistors and collector currents of (a) 1 , (b) 50 and (c) 1000 μA.

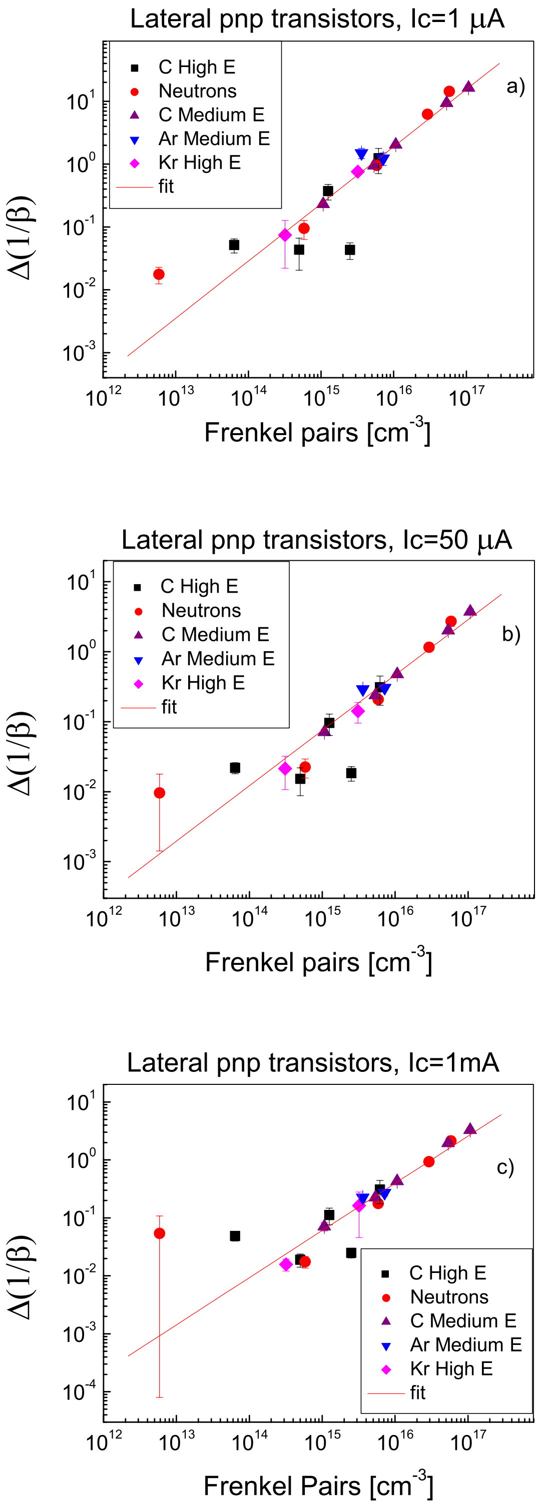

Fig. 5. Linear dependence of the quantity $\Delta\left(1/\beta\right)$ on the concentration of Frenkel pairs, for lateral pnp transistors and collector currents of (a) 1 , (b) 50 and (c) 1000 μA.

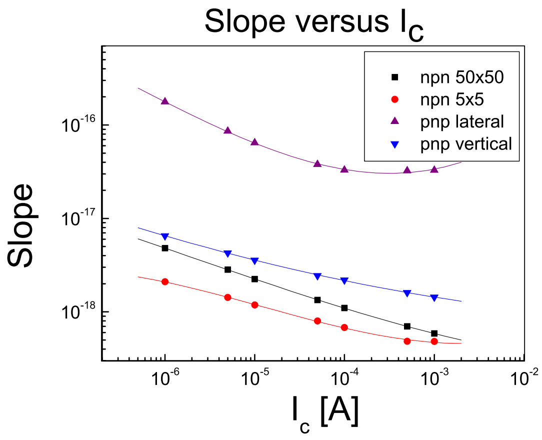

Fig. 6. Dependence of parameter $k(\mathrm{I}_c)$ on the collector current, I_c, for large emitter area region npn transistors (npn 50x50), for small emitter area region npn transistors (npn 5x5), for vertical pnp transistors (pnp vertical) and for lateral pnp transistors (pnp lateral).

Lateral pnp transistors, as already mentioned, have the lowest cut-off frequency and their dependence on the Frenkel pairs concentration (FP) is linear but with the largest slope.

Type of transistor	b_0	b_1	b_2	b_3
npn 50 x 50	-18.542	0.074	0.071	0.004
npn 5 x 5	-17.141	1.020	0.262	0.018
pnp lateral	-13.544	1.951	0.386	0.020
pnp vertical	-17.846	0.163	0.064	0.003

Table 2: Fitted coefficients for the polynomial expression given in Eq. 9 for large emitter area region npn transistors (npn 50x50), for small emitter area region npn transistors (npn 5x5), for vertical pnp transistors (pnp vertical) and for lateral pnp transistors (pnp lateral).

The $k(\mathrm{I}_c)$ dependence on the collector current is shown in Fig. 6 for the small and large emitter area transistor region, and for vertical and lateral pnp transistors. The slope dependence on the collector current has been fitted by the polynomial expression:

$$k(I_c) = b_0 + b_1 I_c + b_2 I_c^2 + b_3 I_c^3 \tag{9}$$

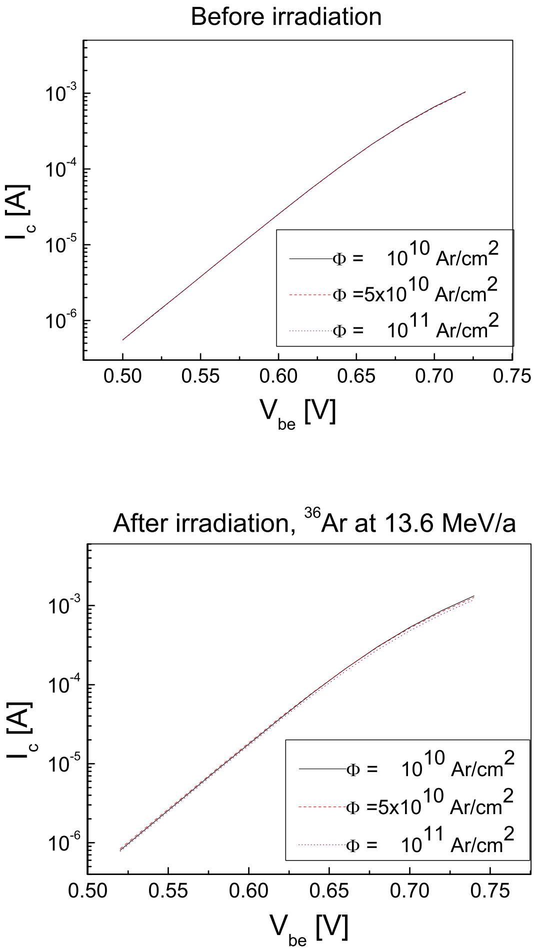

Fig. 7. Collector current, I_c, dependence on V_{be}. The data are for npn transistor with large emitter area region of 50 μm x 50 μm before and after the irradiation with Ar ion.

where collector current I_c is in ampere. The fitted values of b_i coefficients are shown in Table 2.

4.2 Collector Currents behaviour in irradiatated Bipolar Transistors

As well known, in bipolar transistors minority carriers are injected into the emitter-base junction. These carriers are collected as majority carriers in the base-collector junction. The corresponding currents ratio I_c/I_b is the common emitter gain β (Sect. 2), whose behaviour after irradiation has been discussed in Sects.4.1.

Base and collector currents behaviour before and after the irradiations have been systematically investigated as function of the base emitter voltage V_{be}

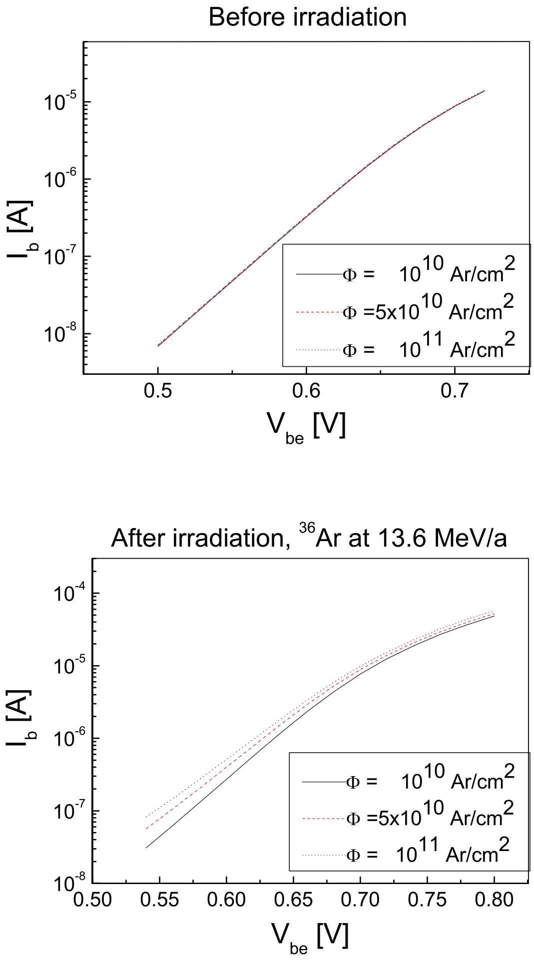

Fig. 8. Base current, I_b, dependence on V_{be}. The data are for npn transistor with large emitter area region of 50 μm x 50 μm before and after the irradiation with Ar ion.

for both npn and pnp transistors. As an example in Figs. 7 and 8, the collector current (I_c) and the base current (I_b) of npn transistor with large emitter area region of 50 μm x 50 μm are shown before and after the irradiation with 10^{10}, 5 x 10^{10} and 10^{11} Ar ion/cm^2 fluences. In Fig. 7, collector currents are shown within the investigated range $10^{-6} < I_c < 10^{-3}$ A, corresponding to $0.51 < V_{be} < 0.72$ before the irradiation and $0.53 < V_{be} < 0.76$ after the irradiation with largest Ar ion fluence. In Fig. 8, base currents I_b are shown for same ranges of V_{be} values.

For all the investigated Ar and Kr fluences, collector currents are only slightly affected by irradiations at any given base emitter voltage value (V_{be}).

Larger variations are observed in the case of base currents, namely base currents are larger after irradiation at any given value of V_{be}. For instance at the largest Ar fluence, only for $V_{be} > 0.6$ V , base currents increase by less than 100 % . As a consequence, the gain degradation is mostly affected by the behaviour of the base current.

5 Conclusions

For space application the known $\Delta\left(1/\beta\right)$ dependence on the concentration of Frenkel pairs allows the possibility to evaluate the total amount of the gain degradation of the VLSI bipolar transistors due to the flux of penetrating charged particles, in particular for energetic cosmic rays during the full life of operation of any pay-load. In fact, the total amount of expected Frenkel pairs can be computed taking into account the isotopic spectra, and subsequently related to the overall gain degradation. It has to be pointed out that in cosmic rays there is relevant flux of particles up to medium-Z nuclei, which are within the range of ions presently investigated.

For these types of devices, the gain degradation has been investigated for collector currents I_c between 1 μA and 1 mA. It was found, in agreement with the prediction of the Messenger-Spratt equation, an almost linear dependence of $\Delta\left(1/\beta\right)$ as a function of the concentration of Frenkel pairs (FP). The slope depends on the I_c value and on both the type and the area of the transistors.

Damage effects are observed to be larger, i.e. a larger slope has been observed for the linear dependence of $\Delta\left(1/\beta\right)$ on FP, in the large (with the emitter region of 50 μm x 50 μm) area devices than in the ones with smaller area, which have slightly larger cut-off frequencies.

Lateral pnp transistors have a lower cut-off frequency than the vertical pnp and npn transistors, namely about 20 MHz versus 2-6 GHz. Accordingly to the Messenger Spratt equation, their dependence of $\Delta\left(1/\beta\right)$ on the Frenkel pairs concentration (FP) has been observed to be linear, but with a larger slope.

For all the fluences, the data show that collector currents are slightly affected by the irradiations at any given base emitter voltage value (V_{be}). Larger variations are observed in the case of base currents, namely base currents are larger after irradiation at any given value of V_{be}. Thus the gain degradation is mainly affected by the behaviour of the base current.

References

[1] L.Van Allen, Ludwig and R.McIlwain,"Observation of High Intensity Radiation by Satellites 1958 Alpha and Gamma", IGY Satellite Series Number 3, 73 Natl. Acad. Sci., Washington D.C., 1958.

[2] W.R. Cook, A.C.Cummings, J.R.Cummings, T.L.Garrard, B.Kecman, R.A.Metwaldt, R.S.Selesnick and E.C.Stone, IEEE Trans. Geosci. Remote Sensing 31(1993), 557.

[3] J.R. Cummings, A.C.Cummings, R.A.Metwaldt, R.S.Selesnick, E.C.Stone and T.T. von Rosenvinge, IEEE Trans. Nucl. Sci. 40 (1993), 1459; Geophys. Res. Lett. 20 (1993), 2003.

[4] R.A. Mewaldt, R.S.Selesnick and J.R. Cummings, "Anomalous Cosmic Rays: The Principal Source of High Energy Heavy Ions in the Radiation Belts", Radiation Belts Models and Standards, AGU Geophysical Monograph 97 (1997), 35.

[5] M.Aguilar et al. (AMS Collaboration), Phys. Rep. 366 (2002) 331.

[6] J.Barth, "Short Course on Applying Computer Simulation Tools to Radiation Effects Problems", 1997 IEEE Nuclear and Space Radiations Effects Conferences (Snowmass Village 21-25 1997).

[7] K. Hagiwara et al., Particle Data Group, Review of Particle Physics, Phys. Rev. D 66 (2002), 010001.

[8] S.R. Messenger et al., IEEE Trans. on Nucl. Sci. 46 (1999), 1595.

[9] A.Baschirotto, R.Castello, A.Gola, G.Pessina, M.Rattaggi, P.G.Rancoita, M.Redaelli, A Seidman, Nucl. Instr. and Meth. A 362 (1995) 466.

[10] A.Baschirotto, R.Castello, A.Gola, C.Onado, G.Pessina, P.G.Rancoita, M.Redaelli, A.Seidman, Nucl. Instr. and Meth. B 114 (1996) 327.

[11] A.Baschirotto, R.Castello, C.Onado, G.Pessina, P.G.Rancoita, A.Seidman, Nucl. Instr. and Meth. B 122 (1997) 73

[12] D.M.Fleetwood et al., IEEE Trans. Nucl. Sci. 41 (1994), 1871.

[13] A.H.Johnston, G.M.Swift and B.G.Rax, IEEE Trans. Nucl. Sci. 41 (1994), 2427.

[14] A.Colder et al., Nucl. Instr. And Meth. In Phys. Res., B 179 (2001), 397.

[15] A.Colder et al., "Effects of ionizing radiation on BiCMOS components for space application", Proc. of the European Space Component Conference (Toulose 24-27 September 2002), ESA SP-507 (2002), p. 377.

[16] J.G.Kelly and J.G.Williams, IEEE Trans on Nucl. Sci. 35 (1988), 1242.

[17] T. Angelescu, Nucl Instr. And Meth. In Phys. Res. A 345 (1994), 303.

[18] G.C.Messenger, IEEE Trans. on Nucl. Sci. 39 (1992), 468; see also references therein.

[19] G.C.Messenger, IEEE Trans. on Nucl. Sci. 55 (1972), 160.

[20] G.C.Messenger, IEEE Trans. on Nucl. Sci. 13 (1966), 141.

[21] G.C.Messenger and M.S.Ash, "The Effects of Radiation on Electronic Systems", Van Nostrand Reinhold Company, New York, 1986; see also the Second Edition in 1992.

[22] A. I. Namenson, E.A. Wolicki and G.C. Messenger, IEEE Trans. on Nucl. Sci. 29 (1982), 1018.

[23] A.M.Ougouag et al., IEEE Trans on Nucl. Sci. 37 (1990), 2219.

[24] A.Holmes-Siedle, L.Adams, Handbook of Radiation Effects, Oxford University Press, 1993.

[25] ASTM E722-85.

[26] J.Lindhard, V.Nielsen, M.Scharff and P.V. Thomsen, Danske Vidensk. Selsk. Mat.-Fys. Medd. 33 vol. 10 (1963), 10

[27] C.A.Coulter, D.M.Parkin, Jou. Nucl. Mat. 88 (1980), 249.

[28] C.A.Coulter, D.M.Parkin, Trans. Am. Nucl. Soc. 27 (1977), 300.

[29] C.A.Coulter, D.M.Parkin, Jou. Nucl. Mat. 85&86 (1979), 611.

[30] G.H. Kinchin and R.S. Pease, Rep. On Progress in Phys. vol. 18 (1955), 1.

[31] P.Sigmund, Rad. Eff., vol 1 (1969), 15.

[32] M.J.Norgett, M.T.Robinson and I.M.Torrens, Nucl. Engin. and Des. 33 (1975), 50.

[33] J.R. Srour, IEEE Trans. on Nucl. Sci. 20 (1973), 190.

[34] J.F.Ziegler, J.P.Biersack, U.Littmark, "The Stopping and Range of Ions in Solids", Pergamon Press, New York, 1985.