Random Telegraph Signals Generated in Transistors Due to Gamma Ray Irradiation: Online Study of the Device Characteristics

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Author's Contribution

This work was carried out by all the authors. The first author carried out the experiments which were designed jointly by all the authors. The paper was written jointly by all the authors. All the authors have read and approved the final manuscript

ABSTRACT

Commercial transistors have been irradiated with photon of 6 MeV and15 MeV energies and the device characteristics were studied during irradiation process. Along with expected reduction in current gain due to charge carrier trapping and other effects, considerable amount of noise signals resulting from modulation of RTS also have been observed which was seen to be died out within 30 seconds after the irradiation. The possible source and the nature of noise signals were analyzed. The similarities between the low varying random signals with 1/f noise are discussed.

Keywords: Random Signals, Displacement effect, Space radiation effect

I. INTRODUCTION

In many cases, particularly in the space environment, electronic devices are exposed to intense high energy radiations like gamma rays electrons, protons, mesons and heavy ions. These radiations affect the performance of the devices [1, 2] which may affect the data processed and transferred by the devices [3, 4]. There are three naturally occurring sources of space radiation [3]. Radiation in the magnetosphere and the Van Allen belt consists of both electrons and protons, Galactic cosmic radiation (GCR) consists of low flux ionized atoms originated outside the solar system, and solar particle events (SPE) consists of electrons protons alpha particles and heavier particles injected to interplanetary space which may get accelerated to near relativistic speed by the interplanetary shock waves. In addition to the particles, electromagnetic radiations including X rays or gamma rays are also a major component in space radiation.

Soft X-rays generate no displacement damage in silicon because the generated electrons transfer too low energy to kick silicon atoms off their lattice sites. The energy threshold for displacement damage, i.e. the generation of traps, would be about 170 KeV [5]. Hence hard X rays can lead to rare displacements in silicon.

Studies on the effect of space radiation on electronic devices started from the time of first space exploration and is still continuing for the reason that new devices and technologies are being introduced very often along with miniaturization and attempt to achieve high speed and packing density. Most of the

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literatures on the study of the effect of radiation on electronic devices discuss the possible displacement effects and ionization effects leading to modification of characteristics of the various devices after exposure to certain energy or dose of radiation. Systematic study on the transient effect and other in-situ measurement are still lacking.

S.L. Peter and R.E. Sharp [6] explained the post irradiation effect on bipolar transistor in terms of charge trapping in the passivating oxide layer above the device and at the interface between oxide layer and silicon. The trapped charges lead to increased bulk recombination and an increased surface recombination velocity leading to leakage current and reduced gain.

J. L. Wirth and S. C. Rogers [7] modified the continuity equation and diffusion equation for minority carriers, and in the case of transistor, in the charge control model, by adding extra terms for the prompt and delayed photo currents to incorporate the transients during the time of radiation. The prompt component of the photo current is created as electron hole pair which is swept out immediately within 10-9 seconds and flows from N to P region. Delayed component of photo current is due to the generated e-h pair in the bulk of the device. Since both prompt current and delayed current are from N to P region, there is a transient leakage current superimposed on the steady state leakage current.

D. R Alexander [8] described the excess carrier in p and n regions of a diode exposed to ionizing radiations in terms of ionizing dose rate, step function response, recombination effects, internal fields on the diffusion component of photo current, and a structural component.

It is the inquisitiveness of the time to make quantitative and qualitative evaluation of the performance peculiarities of these devices during the time the device exposed to radiation. The design of modern radiation detectors with embedded amplifiers and data processing system, electronic space application systems etc. may need the consideration of such a study. Keeping the above facts in view, we have measured and analyzed the variation of characteristics of the transistor 2N 2222 during the time of exposure to gamma rays

Commercial transistor 2N 2222 has been irradiated separately with 6 MeV and 15 MeV photons from LINAC. The collector characteristics are studied during the irradiation at a constant base current. The details of the experiments are discussed in section 2below and the result is analyzed in section 3

2. THE EXPERIMENTAL SETUP

2.1. Device and systems

The experiments were performed at Caritas Cancer Institute, Kottayam using medical linear accelerator - Seimens Primus Plus LINAC- providing 6 & 15 MV photon. The energy, total dose and dose rate of the gamma radiation beam can be fixed from the control room. The nature of the beam spread also can be adjusted by automated system. The beam is made narrow and uniform with minimum spread. Dose linearity error is kept less than ±1%[9].

The experimental set up is designed to obtain online data from device being exposed. The transistor 2N 2222 under test is connected to ExpEyes [10] which serves as programmable data acquisition system. A computer system installed with ExpEyes software is connected to ExpEyes hardware by means of a long USB cable of 1 meter length which is also shielded for radiation protection. .

ExpEyes was configured for the data acquisition from the transistor. It is built around a 16 bit micro controller programmed in C language to control the hardware modules ADC, DAC, amplifiers, oscillators, digital and analogue input and output connectors and sensor input connectors. A hardware communication library written in python installed in a PC can communicate with hardware module. Users can make use of the various classes in the hardware communication library from python development environment to control the hardware. Other python modules such as eyeplot.py and eyemath.py can be included in the python program for graphics and data functionalities. The built in code is used for the experiment for characteristic study. ExpEyes has a constant current output which is set to 12 micro-ampere to provide the base current of the transistor. The equipment has an accuracy of 1.22 mV /bit. A peer to peer network is employed to control this PC (PC-1) from another PC (PC-2) located in the control room of radiation lab via remote desk top access tool 'VNC'. A twisted pair CAT 5 network cable is employed which give good performance up to 100 MHz.

2N2222 - silicon planar epitaxial NPN transistor in TO 92 packages from NTE Electronics is used to study the variation in the characteristics of transistors. It has been reported that the radiation effect has a very little variation with regard to packaging and orientation for the same device technology [6]. Hence, the orientation of transistor to the radiation beam is neglected. The maximum rating of collector current for this transistor is 800 mA, max VBE is 5 V and VCE is 30-40 Volts. The maximum junction temperature is 200 0C.

2.2. Data acquisition and deduction

The experimental set up is shown in Fig 1. The transistor is positioned exactly at the beam line by the help of laser cross beams provided with the machine The transistor under test is connected to ExpEyes by means of shielded copper wires of 10 cm long. ExpEyes is then connected to PC-1 arranged inside the lab by means of a USB cable of 1 meter long. ExpEyes is pre-calibrated with the USB cable provided with the instrument to connect with PC-1 which has the ExpEyes Software to control the ExpEyes hardware. PC-2, arranged in the control room, is connected to PC-1 by means of a cable (CAT 5) of 30 meters long and ExpEyes parameters are set using PC-2. The experimental arrangement is shown in fig.1 and the dataflow sequence of the experimental setup is shown in fig 2.

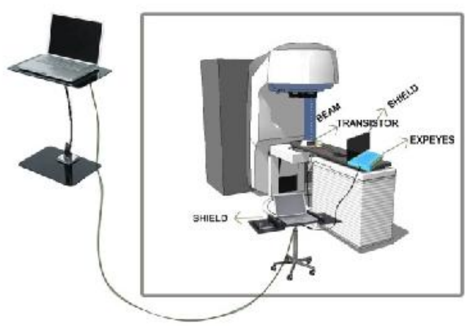

Figure 1

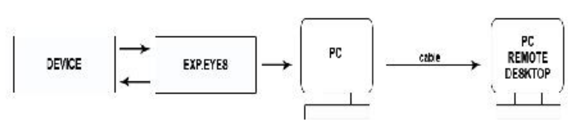

Figure 2

Initially, pre-irradiation characteristics of the transistor 2N 2222 is measured by invoking ExpEyes software code from PC-2 for a base current setting of 12 micro amperes while the voltage is set to vary linearly with time. The data is plotted.

The LINAC is set for 6 MV X-ray photon and for a dose of 300 RAD at a dose rate of 300 MU/minute. The dose measurements were done automatically by the machine setup and displayed on the screen. Towards the end of the exposure, ExpEyes is invoked to collect the transistor collector current data against the voltage, at fixed intervals of time to form a time series data. The experiment is repeated for doses of 500, 1000 and 2000 RADs for the same dose rate and is also plotted in Fig. 3, as red, green and blue curves respectively. It is seen that, total dose doesn't seem to have much effect in the characteristics under 6 MV gamma radiation except for the random signal or noise current produced by the device.

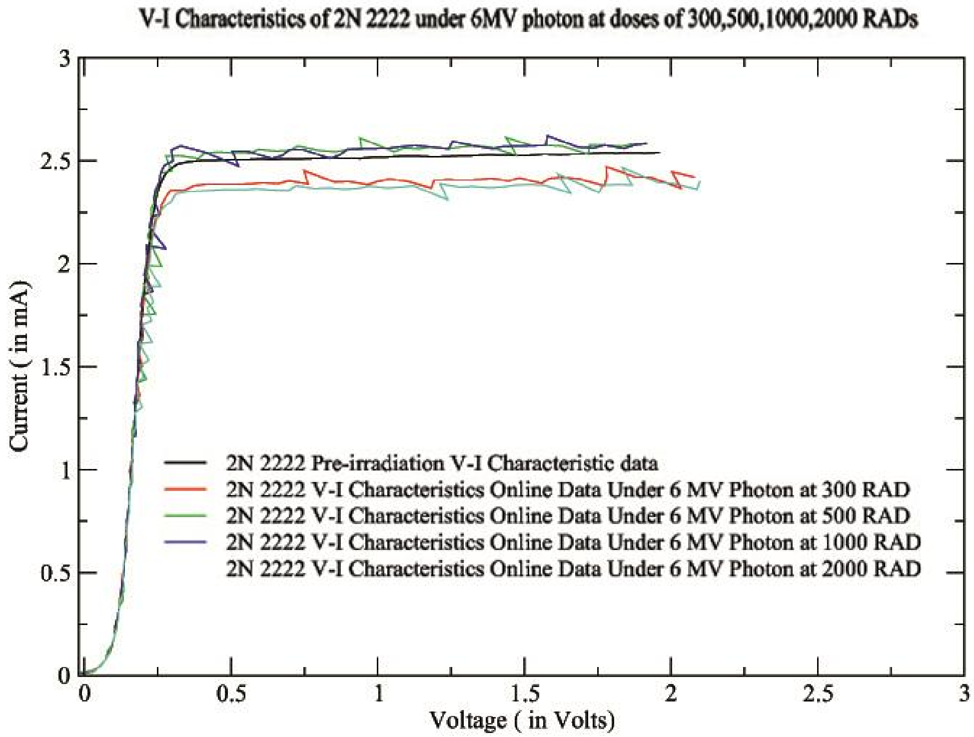

Figure 3: Effect of cumulative dose of 6 MV –rays to produce random noise.

The results obtained in the above observation naturally prompted to study the effect of varying dose rate of the irradiated gamma rays and hence the measurement was repeated for a total dose of 500 RADS with dose rates of 300 MU/minutes and 50 Mu/minute for the same base current. The results are plotted in fig. 4 It is seen that the variation in dose rate does not have significant effect on collector current.

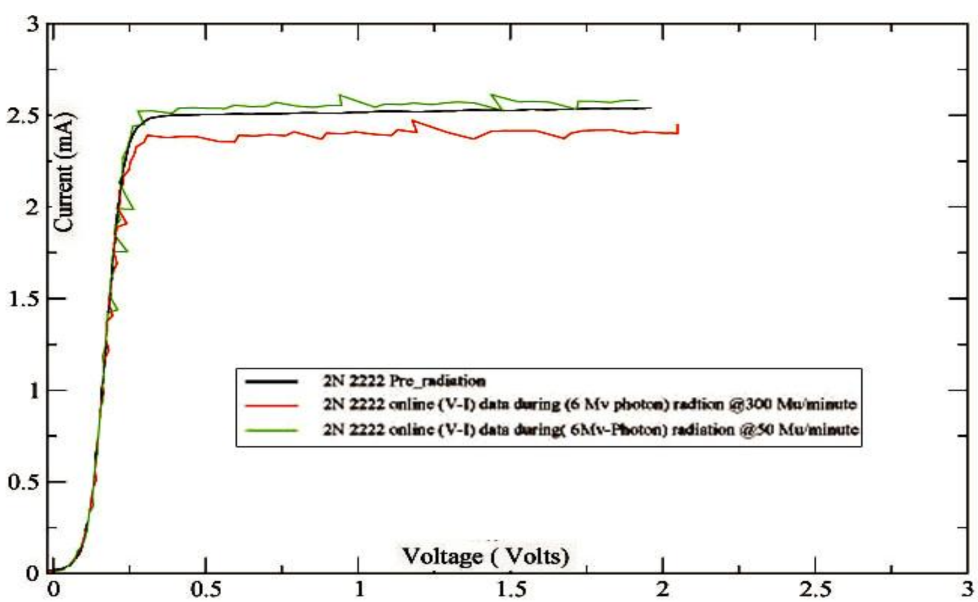

Figure 4: Effect of dose rate of 6 MV -rays to produce random noise.

In fig .4 the pre irradiation characteristic (shown in black) is compared with the characteristics after irradiation with 6 MV X-ray photon under different dose rates of 300 MU / minuets(red) and 50 MU /minutes(green) for the same base current of 12 micro amperes at the end of achieving the same total dose of 500 RAD. It is seen that the variation of dose rate does not have significant effect on the collector current.

In order to observe the effect of photon energy, the experiment was repeated for a photon energy of 15 MV at a cumulative dose of 1000 RAD with dose rates 500 MU/minute and 50 MU/minute and are plotted in fig.5. It can be seen that there is significant reduction in collector current. Further, it is interesting to note that there is no significant dependence of collector current on the dose rate. In order to check the dependence on cumulative dose, the experiment is repeated for cumulative dose of 500 RAD with a dose rate of 500MU/minute and is plotted in fig. 6 along with the data for 1000 RAD at same dose rate.

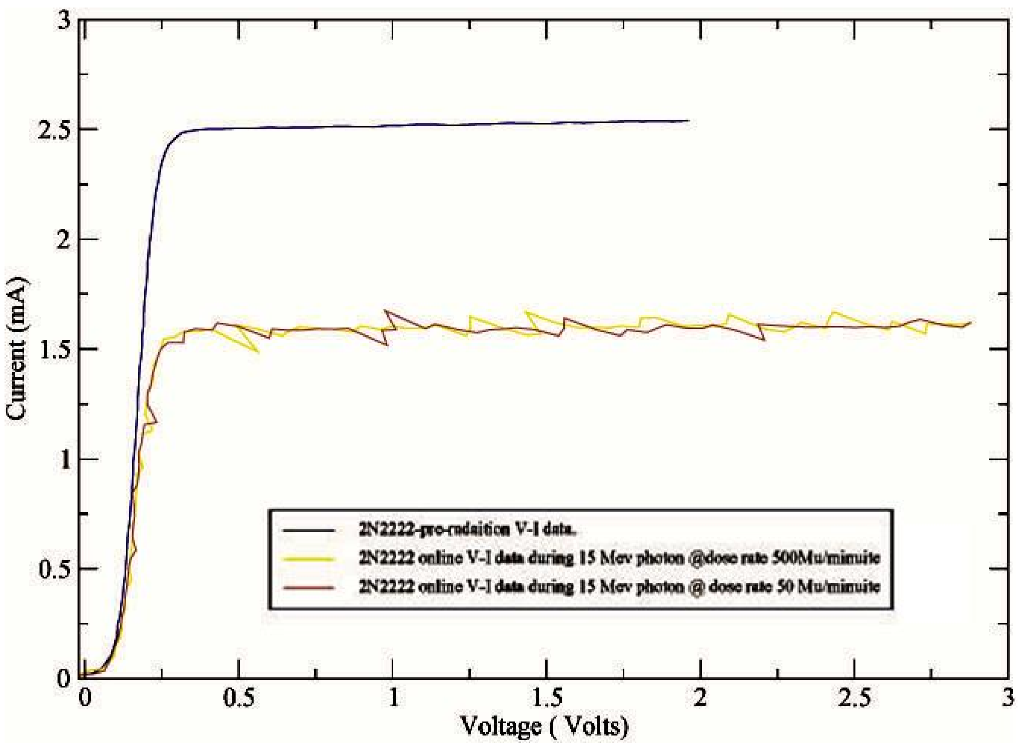

Figure 5: Effect of dose rate of 15 MV -rays to produce random noise.

From the above observations it is seen that the collector current is significantly varied for a gamma exposure of 15 MV, where as the photon of 6 MV does not produce significant change in the collector current. Further, dose rate or cumulative dose does not have any command on the collector behavior.

It is interesting to note that in all the above cases, the collector current shows a low varying random fluctuation. The close analysis reveals that it reflects the superposition of multiple frequency random telegraphic signals on the steady state collector current.

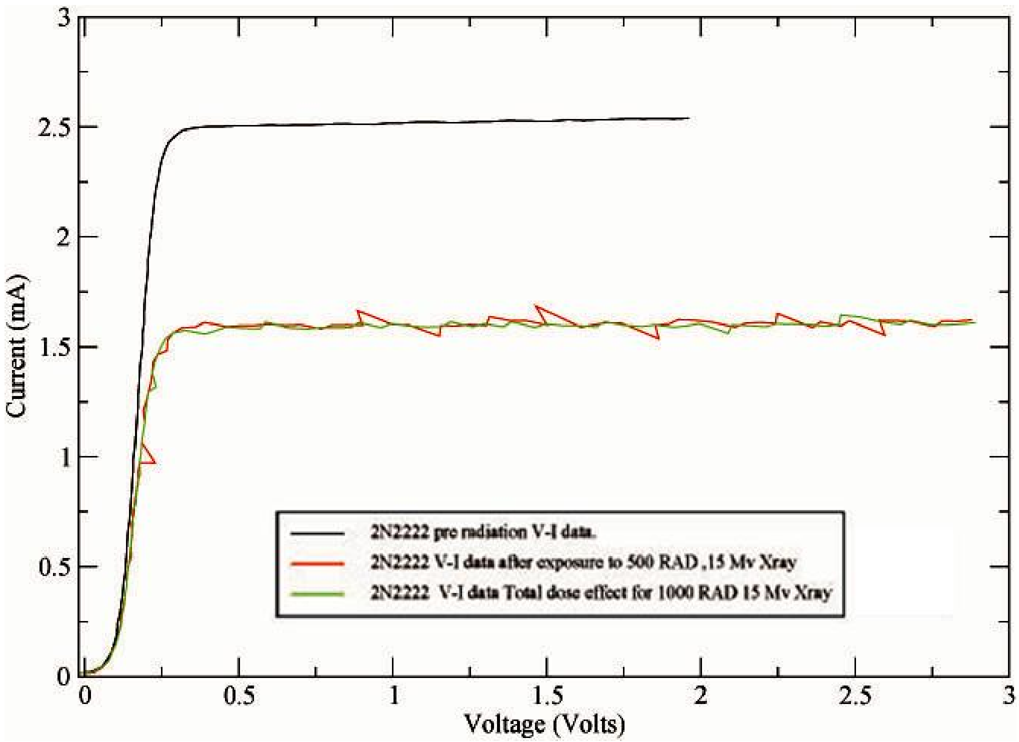

Figure 6: Effect of cumulative dose of 15 MV –rays to produce random noise

3. RESULTS AND DISCUSSION

The significant decrease in the steady state collector current may be attributed to the trapping of charge carriers in the surface trap centers formed in between silicon and the oxide layer due to irradiation. This effect is expected to persist even after irradiation and subjected anneal out due to various causes including room temperature annealing in due course.

Analysis of Random signals

During, the irradiation of transistor device by gamma rays, in addition to e-h pair generation there are rare events of displacement [11,12] which in turn causes trapping and release of charge carriers and cause random telegraphic signals of randomly varying time base. The possible superposition of all such waveforms gives rise to the observed low varying patterns on the collector current is discussed below.

Gamma and X-rays produce rare displacement through Compton scattering [13]. The defect site generated due to radiation induced displacement effect may cause alternate capture and emission of carriers with the result that the device resistance value may switch discretely. This will cause low frequency noise referred to as Random Telegraph Signal. The study of RTS can give insight in to the defect location in the device.

The energy of the trap centers [14] that falls in the range of energy gap of semi conductors will cause temporary energy states in the band gap region where the carriers may first absorbed and then released [15]. When the carriers are absorbed, they will no more be available for conduction causing a reduction in current and the current will be enhanced when the carriers are released. The capture and release may have a wide range of time constant depending on the position of energy level in the band gap. The trap centre with energy near the middle of the band gap is easily filled and easily released while this time constant will vary exponentially with the location of their energy level move away from the mid gap. [14].

A free carrier in a conducting media stopped by the trap centre may not be available for current transport. Random telegraphic signal observed in the experiment may be thought of as the modulation of charge carriers with wide spread relaxation time described by Poisson point process. The number of points in the disjoint interval is independent. The number of possible events may be large, but each of which is rare. Hence Poisson distribution model is appropriate [16]. The probability of observing m events (Telegraphic signal) in a time T is:

$P(m, T) = [(vT)^m/m!]\ exp(-vT)$ ....(1) where v is the mean rate of transition per second. $vT = \lambda$ is the intensity of the Poisson point process

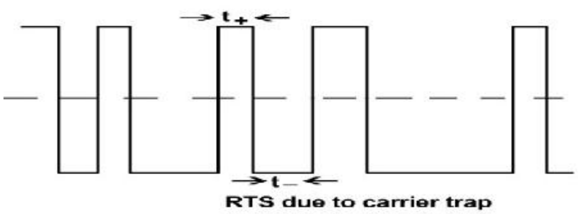

Figure 7: Random Telegraph Signals due to carrier traps.

The capture emission kinetics of the individual defects could be understood by considering the probability of transition from high current state (state 1) to low current state (state 0) and back at a definite interval of time. The superposition of such states due to all the defect centers or the modulation of RTS signals from all such defect centers will lead to the low frequency noise signals similar to 1/f noise. Assume that probability per unit time for transition from state 1 to state 0 is $1/\tau'_1$ and that from state 0 to state 1 to state 0 is $1/\tau'_0$. Let $A(t)$ is the probability that there is no transition from state 1 to state 0 in a time t . Then the probability that the state 1 will not make a transition between 0 and t and that do make a transition to state 0 between t and $(t+dt)$ is given by,

$P_1(t)\ dt = A(t) / \tau'_1$ ….. (2)

Similarly probability of not making a transition
between time 0 and t+dt is the product of probability of not making a transition between time (0 and t) and that between (t and t+dt) as given below.

$A(t+dt) = A(t)(1-dt/\tau'_1)$ ……3)

ie, $[A(t+dt) - A(t)]/dt = - A(t)/\tau'_1$ …..(4)

Or, $dA(t)/dt = - A(t)/\tau'_1$ …..(5)

On Integration $A(t) = exp(-t/\tau'_1)$ …..(6)

Eqn. (3) yields

$P_1(t) = 1/\tau'_1\ exp(-t/\tau'_1)$ …..(8)

Hence, the probability that the state 0 will not make a transition between 0 and t and that do make a transition to state 1 between 't and (t+ dt)' is given by,

$P_0(t) = 1/\tau'_0\ exp(-t/\tau'_0)$ …..(9) .

Thus the up and down transitions have exponential characteristics distributed in time. Hence the relaxation times of various states have exponential distribution, even though the capture and emission process is purely random as in equation (1).The formation of lattice defect introduced during the passage of radiation introduce energy level within the band gap as in fig (8). Most active traps are near the intrinsic level and as the energy level pass away from the mid-gap there is an exponential decrease in the relaxation time [14].

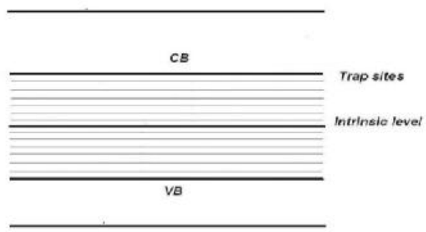

Figure 8: Radiation induced energy levels within the band gaps

The low frequency noisy wave form observed to have super imposed on the constant collector current region of the Gummel plots is the result of linear superposition of exponential relaxation processes caused by defect sites. The auto correlation function of the RTS signal as in Fig. 7 could be written as

$$\Phi_t(x) = a^2 \exp(-t/\tau_z) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

The power spectrum due to noise signal characterized by an exponential autocorrelation function may be calculated by Eienstein- Wiener-Khintchine theorem. According to which

$$S_{X(\omega)} = 4 \int_0^{\infty} \Phi_X(\tau) \cos(\omega\tau) d\tau \quad \ldots\ldots\ldots(11)$$
$$S_{X(\omega)} = (2a)^2 \,.(\tau_Z / [1+ \omega^2\tau_z^2]) \quad \ldots\ldots\ldots(12)$$

If $p(\tau_z)$ is the probability distribution of τ_z ,then, Power spectral density of total carrier fluctuation is

$$S_n(\omega) = 4\Phi_n(\tau=0) \int_0^{\infty} (\tau_Z\, p(\tau_z) / [1+ \omega^2 \tau_z^2]) \ldots\ldots (13)$$

Thus, If a noisy wave form z (t) has an exponential relaxation process with time constant τ_z the power spectral density has the general form

$$S_{Z(\omega)} = g(\tau_z)/[1 + \omega^2\tau_z^2] \quad \ldots\ldots(14)$$

where $g(\tau_z)$ depends on the generation mechanism of random pulse train. The linear superposition of all such relaxation process with time constant distributed between τ_1 and τ_2 is obtained by integrating $S_{Z(\omega)}$ from τ_1 to τ_2. Hence we get,

$$S_{X(\omega)} = \int_{\tau 1}^{\tau 2} S_Z(\omega)\, p(\tau_z)\, d\tau_z \quad \ldots\ldots(15)$$

$$S_{X(\omega)} = \int_{\tau 1}^{\tau 2} p(\tau_z) g(\tau_z)/[1 + \omega^2\tau_z^2]\, d\tau_z \ldots\ldots (16)$$

The product $p(\tau_z)g(\tau_z)$is equal to a constant P, the above integral reduces to

$$S_X(\omega) = P[\tan^{-1}(\omega\tau_2) - \tan^{-1}(\omega\tau_1)] / \omega \ldots. (17)$$

If $(\omega\tau 2) >> 1$ and $0 <= (\omega\tau 1) << 1$, then the above equation become
$S_X(\omega) = K/\omega$ ……………………………(18) where K is a constant.

Thus the superposition of relaxation process due to radiation induced trap centers can give rise to a power spectrum of the form above which has the same nature of the power spectrum due to 1/f noise.

4.CONCLUSIONS

The low varying signal over collector current observed on the Gummel plots of common emitter configuration of gamma irradiated transistors described in above experiment is analyzed to have been due to the Random Telegraphic Signals originated from the selective trapping and release of carriers in the radiation induced trap centers in the band gap region of semiconductor. The relaxation time of various trap centers are related by an exponential auto-correlation function. The trapping and release of carriers from individual trap site may be considered as pulse trains of varying time constant and superposition of all such pulse trains due to trapping and release of carriers from various trap sites can give rise to noise signals. The power spectrum of such noise signals is similar to 1/f noise. This must be distinguished from the normal 1/f noise generated in various electronic devices and systems.

ACKNOWLEDGEMENTS

The authors deeply acknowledge UGC, Government of India, for granting FDP fellowship for PhD work. We also extend our gratitude to Karitas Hospital, Department of Radiation Oncology; Kottayam, India for providing us the facility of gamma irradiation.

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