

***Chapter 2***

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***MOTIVATION, LITERATURE SURVEY AND EXPERIMENTAL  
TECHNIQUE***

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## 2.1 Motivation for the present work

Explosive growth of electronics in the later half of 20<sup>th</sup> century has made it possible to use electronic systems in radiation environments, for example, in nuclear reactor and space system instrumentation. However, these environments are prone to radiation wherein a high density of high-energy radiation exists. Hence, when semiconductor devices operate in such a high dense radiation environment, the electronics of the space systems display changes in the electrical characteristics. These changes can have significant effect on the performance of the devices/circuits operating in the radiation environment. Hence it is essential to know the changes in the device characteristics due to radiation effects, so that specific design margins can be built either into the devices or in the circuits to make them survive and continue to operate in the radiation environment. Thus the study of radiation induced effects on semiconductor devices has emerged as an active field of research and development for the past two decades and various space agencies around the world are engaged in research and development in this field.

When semiconductor electronic devices are exposed to photonic or particle radiation (viz.  $\gamma$ -rays, X-ray, electrons, neutrons, protons or heavy ions, etc.) they undergo severe degradation. The damage or degradation may be permanent or transient. The degradation behaviour is a complex process and is dependent not only on the nature of the device but also on the radiation characteristics viz., dose, dose rate, species and the energy of radiation. The study of the effect of ionizing radiation on semiconductor devices is thus very important both from the basic as well as application point of view. From the basic point of view, it is very important to have a broader understanding of the degradation

process. From the application point of view, it is important to quantitatively estimate the degradation in electrical parameters and to take appropriate corrective action when they need to be operated in the radiation environment. Excellent literature is available on effects of radiation viz.,  $\gamma$ -rays, neutrons, electrons, protons, heavy ions on variety of semiconductor devices including Bipolar Junction Transistor (BJT's), Metal Oxide Semiconductor (MOS) devices, Complimentary MOS (CMOS) devices, etc [1-26]. However, the basic mechanism of radiation-semiconductor interaction leading to device degradation is yet not completely understood. While the mechanism of radiation induced degradation in integrated circuits is complex for obvious reasons, the study on a basic 3-terminal BJTs can provide useful insight into mechanism of degradation. Keeping this in mind, we have undertaken the study of radiation induced effects in a basic semiconductor device, namely, bipolar junction transistor. Bipolar junction transistors continue to play an important role in integrated-circuit technology, viz., in analog or mixed signal ICs and BiCMOS circuits because of their current drive capability, linearity and excellent matching characteristics. Many of the BJTs and bipolar integrated circuits find application in space systems. It is therefore essential to characterize these devices for radiation induced effects. In the recent years, there is growing need for developing countries to go for indigenization. As such indigenously made devices are being planned for use in space applications. There is rather little data on the radiation-induced effects on devices indigenously made in India. Hence there is a need to establish radiation response of indigenous devices in comparison to international vendor's parts of the similar family.

## **2.2 Literature survey - Effect of radiation on bipolar junction transistors**

Exposure of semiconductor devices to ionizing radiation is known to cause a number of effects, which result in the degradation of the device. In bipolar transistors one important parameter is the degradation of the forward current gain [1]. The degradation of gain is derived from degradation of the transport of minority carriers across the base region. Although a number of bipolar junction transistors have been studied for gain degradation, it appears that there are only few reports on the actual measurements of gain as a function of fluence/dose of the incident ionizing radiation. In the following a brief literature on several aspects of gain degradation in BJT is reviewed.

The degradation of forward current gain in terms of transport of minority carriers across the base region has been discussed elaborately in ESA reports [1]. The effect of  $\alpha$ -ray, reactor neutrons, electrons and protons on various types of discrete devices has been described in this report. The minority carrier lifetime damage constant for various types of transistors for reactor neutron, electron and proton irradiation are reported [2]. Brown has exposed 2N1613 *npn* BJT for proton and electron and effects are reported in terms of gain damage figure [3-4]. Poch and Holmes-Siedle have studied 2N2102 BJT for  $^{60}\text{Co}$   $\alpha$ -ray irradiation [5].

Victor A.J. et al have studied the correlation of displacement effects produced by electrons, protons, and neutrons in silicon [6]. This study is limited to the degradation of excess carrier lifetime and device electrical parameters directly related to it. The degree

to which displacement effects may be correlated in order to predict semiconductor device response based on response data to another type of radiation have been discussed in this study. Burke E.A. has studied the energy dependence of proton-induced displacement damage in silicon [7]. He has reviewed the calculations of non-ionizing energy deposition in silicon as a function of proton energy between 1-1000 MeV and has made measurements of displacement damage factors for bipolar transistors. Ratios of proton energy loss to neutron energy loss with experimental ratios of displacement damage factors are also compared. Summers G.P. et al have measured displacement damage factors  $K_p$  as a function of collector current for proton irradiation of 2N2222A (*npn*) and 2N2907 (*pn*p) switching transistors and 2N3055 (*npn*) power transistors over the energy range 5 to 60.3 MeV [8-9]. The measurements of  $K_p$  are compared to values of the neutron damage factors  $K_n$ , measured on the same device for 1 MeV equivalent neutrons. They have shown that protons were more damaging than neutrons i.e. for 5 MeV protons  $K_p/K_n$  is about 8.5 compared to 1.8 for 60.3 MeV protons.

High-energy electron induced displacement damage in silicon bipolar transistors was studied by Dale C.J. et al [10]. They have made measurements of displacement damage factors for electron irradiated (4 to 53 MeV) bipolar silicon transistors and extended the correlation between nonionizing energy loss (NIEL) and damage factors reported by Summers et al. Using devices from the same lot as in the Summers et al work, electron damage factors are normalized to neutron (1 MeV equivalent) damage factors and compared with new calculations of nonionizing energy deposition for electron with energies upto 1 GeV. It was found that to first order, the correlation remains linear for

both *n*-type and *p*-type silicon. Deviations observed are explained in terms of differences in the fraction of initial vacancy interstitial pairs which recombine. These differences are shown to correlate linearly with the low energy component of the primary knock-on-atom (PKA) spectrum. Deep level transient spectroscopy (DLTS) measurements show oxygen and dopant related defect levels as well as divacancies. Defects concentrations scaled linearly with gain degradation show no differences between electron and proton plus neutron irradiated material. These results are consistent with a damage mechanism involving migration of vacancies to form well-separated stable defects whose qualitative nature is independent of PKA spectrum.

Nichols D.K. et al have studied ten different types of transistors [11]. The total ionizing dose response of these transistors have been measured using  $^{60}\text{Co}$   $\gamma$ -rays and 2.2 MeV electron with exposure levels of 750, 1500 and 3000 Gy (Si). Gain measurements are made for a range of collector-emitter voltages and collector currents. Similarly, Xapsos M.A. et al have studied displacement damage produced by the  $^{60}\text{Co}$   $\gamma$ -ray and monoenergetic electron beam [12]. They have given a general method for relating  $^{60}\text{Co}$   $\gamma$ -ray and monoenergetic electron induced displacement damage. This approach was based on the concept of effective *displacement damage dose*, which is analogous to ideas used to study ionizing radiation effects.

Messenger G.C. and Spratt have studied several silicon and germanium transistors for neutron induced effects [13-14]. On the basis of experimental data and first order theory, they have proposed a relation between the minority carrier lifetime and neutron fluence.

Similarly, Sanga M.M. and Oldham W.G. have made measurements of minority carrier lifetime in neutron irradiated special uniform-base transistors and  $n^+p$  gated diodes [15]. An anomalous mechanism in  $pn$  silicon transistors due to thermal neutrons irradiation was reported by Arimura I. and Rosenberg C [16]. They have identified the damage mechanism as due to the result of a  $[B^{10} (n, \alpha) Li^7]$  reaction in the emitter region of the device whereby energetic  $\alpha$ - and Li-particles are emitted and subsequently produce damage in the base region of the device. They have identified that the Li recoil is responsible for the larger damage ratio between the thermal and fast neutron irradiation of silicon transistors.

Total dose effects on bipolar devices were studied by Schrimpf et al, Schmidt et al, Nowlin et al, Enlow et al and Fleetwood et al [17-23]. They have found two basic mechanisms involved in all of the effects of total dose on the gain degradation of bipolar transistors: (a) accumulation of positive trapped charges in the oxides and (b) accumulation of interface states at the silicon-silicon dioxide interface. Similarly, Kosier et al have compared the hot carrier stress and ionizing radiation stress [24-26]. They have observed that although both types of stress lead to qualitatively similar changes in the current gain of the device, the physical mechanisms responsible for the degradation are quite different. In the case of hot carrier stress, the damage is localized near the emitter-base junction, which causes the excess base current to have an ideality factor of two. For ionizing radiation stress, the damage occurs along all oxide-silicon interfaces, which causes the excess base current to have an ideality factor between one and two for low total doses of ionizing radiation and an ideality factor of two for large total doses. On the

basis of these results and Shockley-Read-Hall (SRH) recombination theory, Kosier et al and Schrimpf et al have proposed excess base current model for gain degradation in bipolar devices against the total dose[17, 24-26].

A comparison of ionizing radiation induced gain degradation in lateral, substrate and vertical *pn*p bipolar junction transistors is reported by Schmidt et al [18,31]. They have concluded that the effects of ionizing radiation on lateral and substrate *pn*p structure are different from the effects on vertical *pn*p structure. Of the three *pn*p's, the lateral *pn*p suffers the most current gain degradation while the vertical *pn*p suffers the least current gain degradation due to ionizing radiation. As the dose rate decreases, the current gain decreases as a result of more trapped positive oxide charge and interface charges present in the oxide at lower dose rates. The current gain degradation in the lateral, substrate and vertical devices is attributed to excess base current. However, in the lateral *pn*p, a second order contribution to current gain degradation is present and the collector current decreases slightly. They have identified four mechanisms responsible for the current degradation in *pn*p bipolar junction transistors: (1) depletion of the p-type emitter; (2) recombination at the base surface; (3) electron injection into the emitter; and (4) surface hole depletion.

The study of radiation induced effects in semiconductor devices is under progress since about 20 years in our country. Rad-hard device developers mainly take up the radiation induced studies in semiconductor devices. This study involves the use of particle accelerator facility for exposure of devices to particle radiation. Accelerator facility in

India has been established only for the past two decades. As the maintenance of particle accelerator facility is very expensive, the availability of beam time to users is rather limited. As such there are very few reports of irradiation studies on semiconductor devices. Further, most of these studies involve off-line measurements of changes in electrical parameters. Bhat B.R., et al. have conducted  $\alpha$ -ray, electron irradiation studies on bipolar devices [32-34]. They have tested several types of devices for  $\alpha$ -ray as well as mono energetic electron. These tests have been carried out to assess the radiation tolerance limit to qualify the devices for space applications. Rajendra Singh et al. have studied the swift heavy ion effects on the Schottky barrier diode [35]. Gnanaprakash et al. have studied the effect of  $\alpha$ -ray, electron, lithium and oxygen ions on MOSFET of the type 3N187 [36].

Although a large number of reports on radiation induced effects on BJT's are available in the literature, it appears that there is rather little experimental data on the fluence dependence of current gain of the transistor. The main focus of this thesis is to characterize the radiation response of commercial indigenously made BJT's which find applications in space systems. The emphasis is on the degradation of forward current gain of the transistors as a function of accumulated dose/fluence of different radiations. The transistors have been exposed to  $^{60}\text{Co}$   $\gamma$ -rays, 8 Mev electrons and 24 MeV protons to understand the extent and nature of radiation induced changes in the electrical characteristics of the transistors.

## 2.3 Experimental technique and measurement methodology

This thesis involves the study of radiation induced effects in few selected BJT's which are planned for specific space applications. Indigenously made devices made by Continental Device India Limited (CDIL) have been selected to study the effect of photonic as well as particle radiation. The devices are exposed to following radiation:

- (i)  $\text{Co}^{60}$   $\gamma$ -ray at ISRO Satellite Centre, Bangalore.
- (ii) 8 MeV electron beam, at Microtron facility, Mangalore University and
- (iii) 24 MeV proton beam and heavy ions, at Pelletron facility at Nuclear Science Centre, New Delhi.

A brief description of these irradiation facilities is given below.

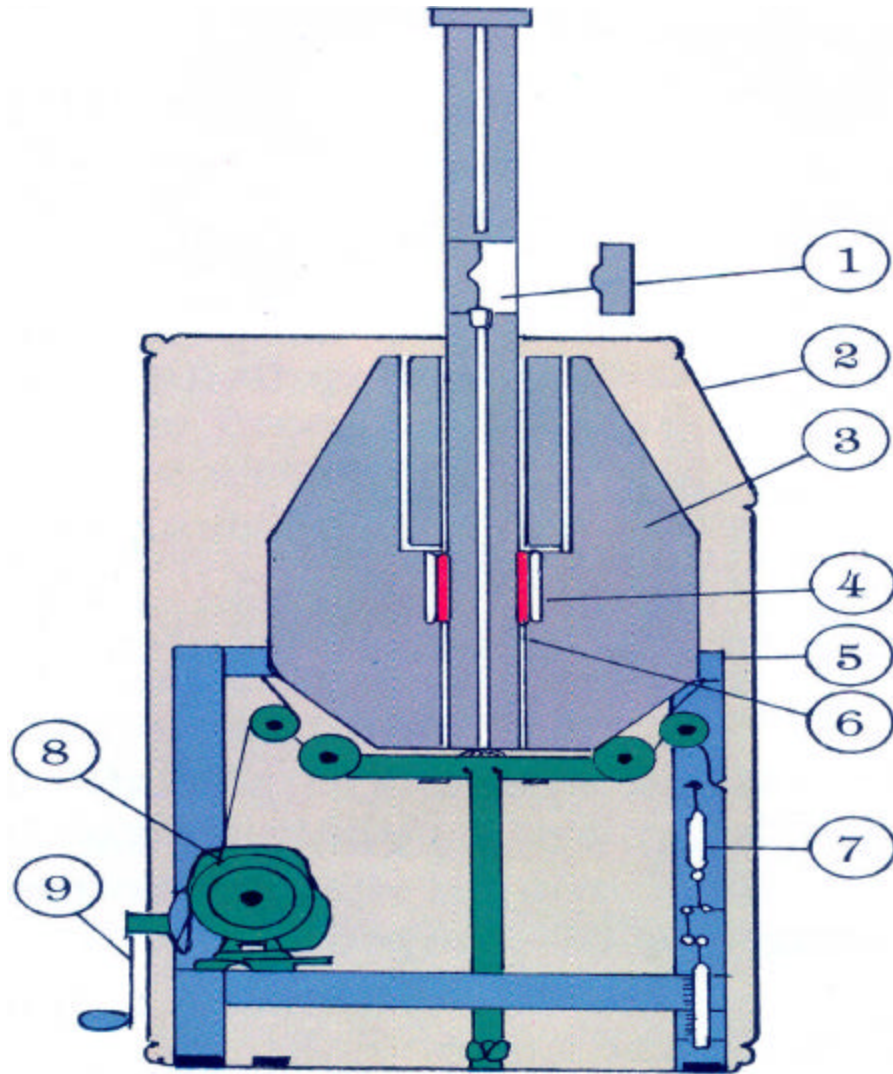
### 2.3.1 Gamma ray irradiation facility

For  $\gamma$ -ray induced studies,  $\text{Co}^{60}$   $\gamma$ -ray irradiation facility (Blood Irradiator-2000) available at ISRO Satellite Centre (ISAC), Bangalore has been utilized (Figure 2.1). The Blood Irradiator-2000 is a compact, portable, self-shielded type Cobalt-60  $\gamma$ -ray irradiator. Atomic Energy Regulatory Board (ABRB), India, approves the safe design and use of self-contained dry source storage gamma irradiator (category-1). The unit is designed to house Cobalt-60 source of 675 Ci and provides an irradiation volume of about 2000 c.c. approximately. The doubly encapsulated sealed radioactive source is used in cylindrical form, which are completely contained in a dry container called flask unit. The sealed sources are shielded at all times, making it human accessible. The irradiation

chamber is located in vertical shaft (Drawer). The shaft moves up and down with the help of a drive system, which enables exact positioning of the irradiation chamber in the center of the radiation field. Access holes of 8 mm diameter are provided in the vertical shaft for introduction of connecting wires for electrical parameter measurements and thermocouple sensors etc. for temperature measurement inside irradiation zone.

Specifications of the  $\gamma$ -irradiator (Blood Irradiator-2000):

- i) Cobalt-60 source capacity: 675 Ci
- ii) Dose rate at maximum capacity at the time of installation: 9.23 Gy/min
- iii) Irradiation volume: 2000 cc approximately.
- iv) Energy of  $^{60}\text{Co}$   $\gamma$  - photon: 1.17 MeV & 1.30 MeV



1. Sample chamber
2. Control panel
3. Biological shield for the source
4. Source cage
5. Supporting table
6. Central shaft incorporating access tube
7. Tension arrangement for wire rope
8. Drive system
9. Hand crank

Figure 2.1 Schematic diagram of the Cobalt-60 Gamma irradiator.

### 2.3.2 Microtron facility

The high-energy electron irradiation facility is available for electron irradiation at Microtron Centre, Mangalore University, Mangalore, Karnataka. The mono-energy electron of the 8 MeV can be obtained from this accelerator. In a Microtron, charged particles are accelerated by RF electric field of constant frequency in a uniform magnetic field. The basic principle of operation of the microtron is illustrated in Figure 2.2.

Electrons move in circular orbits, all orbits having common tangent at the axis of accelerating RF cavity. The synchronization of electron motion with accelerating field is achieved by the period of each succeeding orbit to be larger than the former by an integral multiple of the RF period.

Specifications of the electron beam during irradiation are as follows:

Beam energy	8 MeV
Pulse current	35 mA (max)
Beam size	3 mm x 5 mm
Pulse duration	2.3 $\mu$ s
Pulse repetition rate	2 Hz (max)
Dose rate at 30 cm	33.333 Gy/min

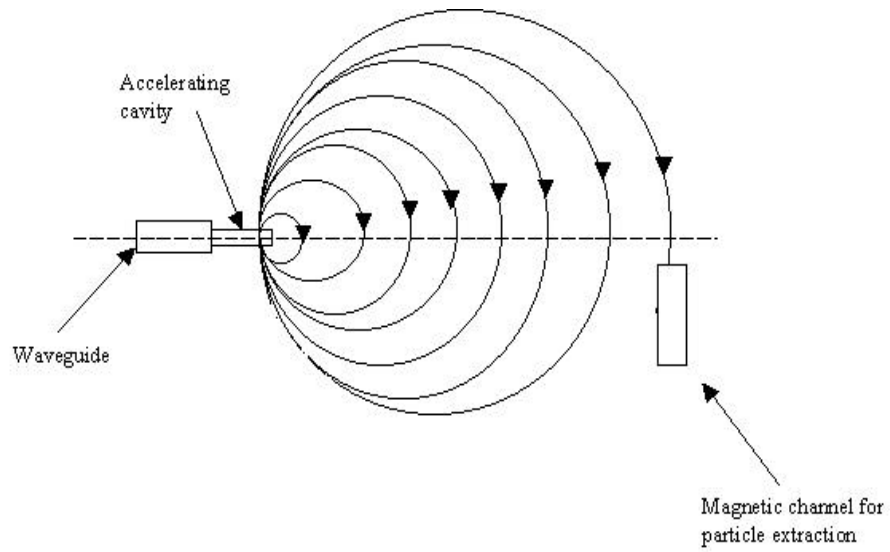


Figure 2.2 Particle motion in a Microtron.

### 2.3.3 Pelletron facility

A 15 UD Pelletron facility is available for proton and heavy ion irradiation at Nuclear Science Centre (NSC), New Delhi. It is capable of accelerating almost any ion from hydrogen to uranium to energies ranging from few MeV to hundreds of MeV. In this machine, negative ions are produced and pre-accelerated to energy  $\sim 400$  keV and injected into strong electric field inside an accelerator tank filled with SF<sub>6</sub> insulating gas. The center of the tank is a terminal shell which is maintained at high voltage ( $\sim 15$  MV). The negative ion on traversing through the accelerating tubes from the top of the tank to the positive terminal gets accelerated. On reaching the terminal they pass through a stripper, which removes some electrons from the negative ions, thus transforming the negative ions into positive ions. These positive ions are then repelled away from the positively charged terminal and are accelerated to ground potential to the bottom of the tank. In this manner, same terminal potential is used twice to accelerate the ions. On exiting from the tank, the ions are bent into horizontal plane by analyzing magnet, which also select a particular beam of ion. The switching magnet diverts the high-energy ion beams into various beam lines into the different experimental areas of the beam hall. The entire machine is computer controlled and operated from the control room. Figure 2.3 shows the schematic of the acceleration of ions in pelletron.

For the present work, we have used 24 MeV proton beam in Radiation Biology beam line for irradiation and measurement. Specifications of the proton beam during irradiation are as follows:

Energy of the beam	24 MeV
Beam current	~1 pA
Beam size	18 mm x 12 mm
Beam flux	$10^9$ p/cm <sup>2</sup> /s

## 2.4 Experimental details

The investigated devices are irradiated in biasing conditions. The biasing circuits used are shown in the Figure 2.4 (a) and (b). Biasing circuits are designed on the basis of manufacturer's data on devices [37]. When the devices are irradiated in the biased condition, any sudden change in the circuit parameter due to irradiation can be noticed at once [38]. The  $\alpha$ -ray irradiation was carried out at ISRO Satellite Centre, Bangalore. The in-situ measurements were made using of HP-4145B Semiconductor Parameter Analyzer (SPA) and pre and post-irradiation measurement of electrical parameters were carried out using the TESEC transistor tester (Model No. 8001-TT). The electron irradiation was carried out at Microtron Centre, Mangalore University, Mangalore. The in-situ measurements were made using the Keithley source measurement unit (Model No. 236) and the pre and post-irradiation measurements were made using the TESEC transistor tester unit. The proton irradiation was carried out at Nuclear Science Centre, New Delhi. The in-situ measurements were made using discrete power supply and current and voltage meters. The pre and post-irradiation measurements were made using of TESEC transistor tester unit at ISAC, Bangalore.

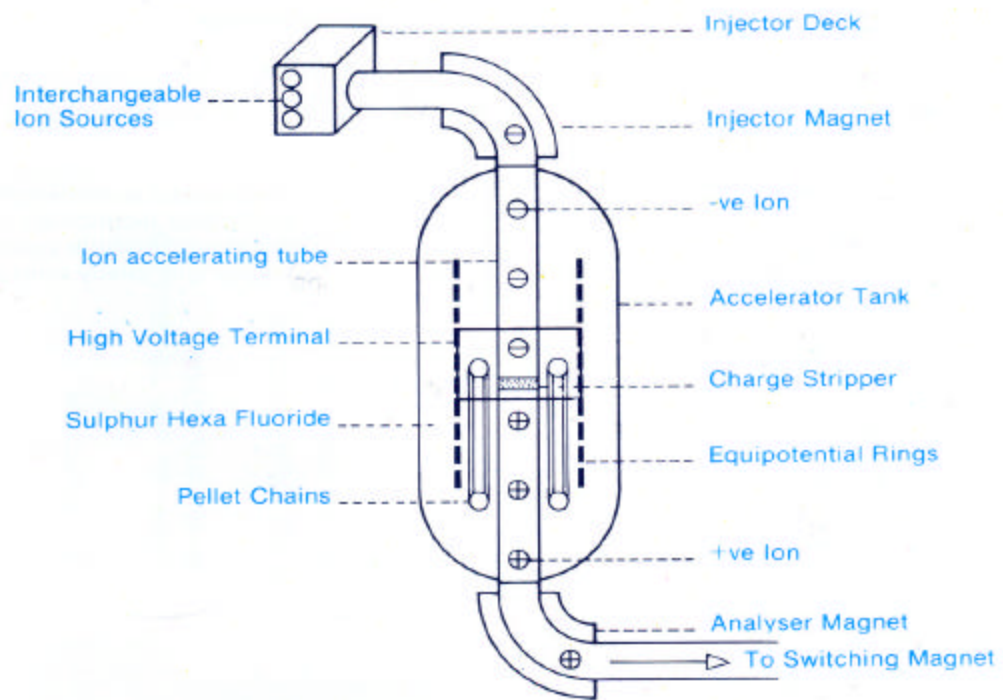


Figure 2.3 A schematic diagram showing the acceleration of ions in pelletron machine.

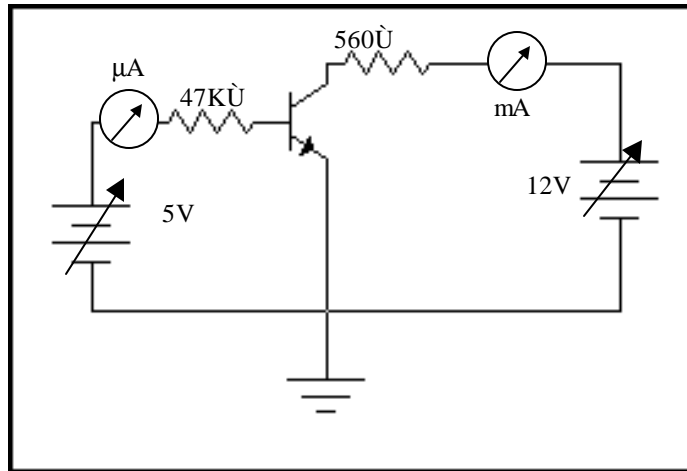


Figure 2.4 (a) Biasing circuit for *nnp* transistor

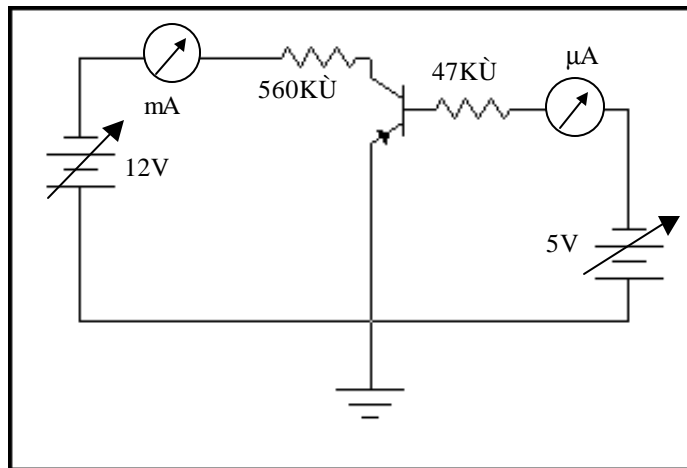


Figure 2.4(b) Biasing circuit for *pnp* transistor

During the proton irradiation, in-situ measurements of device characteristics were made in the data room. Proton is a hazardous particle. Hence entry to beam hall either during irradiation or immediately after irradiation is prohibited. Thus measurements are made in the data room by drawing cables from the target board to data room. For this purpose, a 25 m cable was drawn from the beam hall to the data room. In order to verify the effect of the use of such a long cable length on the measured values, test measurements were made with and without such long length cable. The measurement showed that the effect of long cable length is negligible. This was as expected since for dc measurements, the cable impedance is not important. Figure 2.5 shows the measured base current ( $I_B$ ) as function of collector current ( $I_C$ ) with and without 25 m length cable.

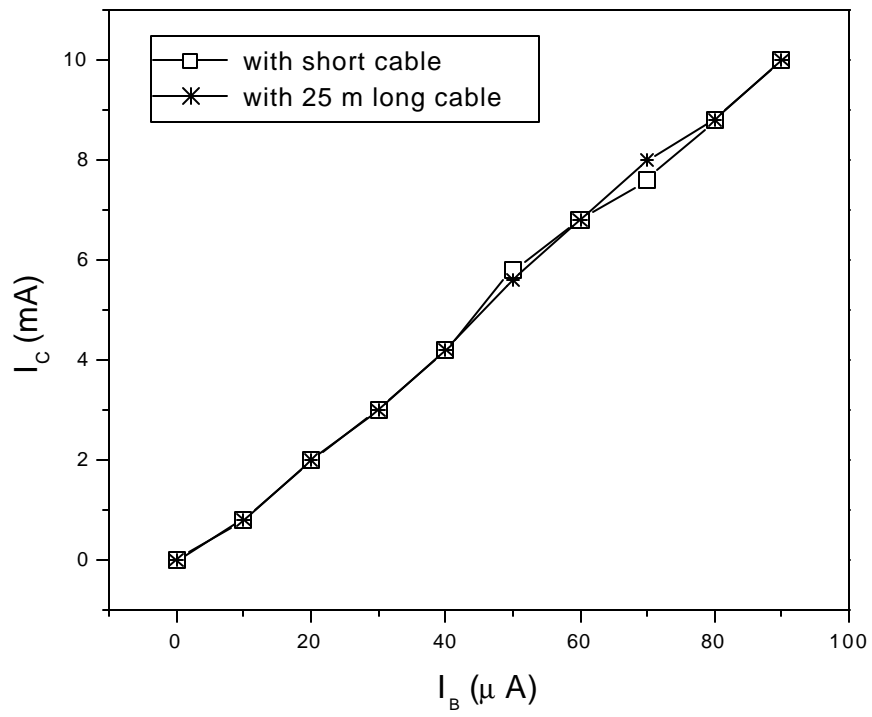


Figure 2.5 Collector current as a function of base current of the transistor.

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