Chapter 6

SIMULATION OF ENERGY AND FLUENCE DEPENDENCE OF HEAVY ION INDUCED DISPLACEMENT DAMAGE FACTOR IN BIPOLAR JUNCTION TRANSISTORS

*** The results of this chapter have been published in *Radiation Effects & Defects in Solids*, **Vol. 159**, 273 (2004)

6.1 Introduction

Displacement damage studies performed using radiation, which produce predominantly isolated defects, are important both from a basic as well as applied point of view. Majority of such studies have been reported with monoenergitic electron beams, protons, neutrons and with Co^{60} ã-ray [1-11]. However, there is rather little experimental or theoretical study on the heavy ion induced displacement damage. While the effect of *ã* -rays and lighter particles on semiconductor devices can be studied using *ã* -ray source and particle accelerators, it is rather cumbersome to study the effect of heavy ions under laboratory conditions. Further, the accelerators are recently becoming less accessible and more expensive to use. A general approach which allows Co^{60} *ã*-ray induced study to be related to particle irradiation effects will be of use to reduce cost of heavy ion testing of semiconductor devices. Such attempts have been made earlier [1]. But no general methodology has emerged which allows the correlation of the *ã* –ray / electron induced effects with that due to heavy ions. Thus there is enough scope for theoretical simulation of the effect of heavy ions on semiconductor devices. Theoretically estimated effects could be used as a rough guide to understand the order of the effect in comparison to *ã* -ray induced effects.

Displacement damage in silicon due to Co^{60} ã-ray exposure can be analyzed in terms of the photon induced secondary electron spectrum as discussed in Chapter 3. The secondary electrons produce displacement damage in the bulk of the semiconductor. On the other hand, heavy ions can directly produce displacement damages in the bulk of the device, similar to electron, neutron and protons.

We have undertaken a theoretical calculation of the variation of displacement damage factors as a function of energy and rad equivalent fluence in bipolar junction transistor for various particulate radiation viz. He, Si, Cl, Ti, Ni, Br, Ag, I and Au. The calculation is based on the experimental data on ã-ray induced gain degradation in a commercial spaceborne BJT 2N3019 (described in chapter 3). The methodology of simulation and results obtained are described in the following sections.

6.2 Conversion of dose into fluence

In the present work, we have used Co^{60} *ã* -ray induced displacement damage factor determined for space borne commercial transistor 2N3019 (*npn*) in the theoretical simulation of heavy ion induced effects. The transistor was exposed to Co^{60} *ã* -source in the biased condition and the transistor forward current gain was measured as a function of the *ã*-dose using Semiconductor Parameter Analyzer (HP-4145B). Displacement damage reduces the forward current gain $\boldsymbol{b}$(dc) by shortening the minority carrier lifetime [12]. The reduction in $\boldsymbol{b}$ with incident particle fluence is related to displacement damage factor by Messenger-Spratt equation [4,11].

$$\boldsymbol{b} = \frac{\boldsymbol{b}_0}{(1+\boldsymbol{b}_0 K \ddot{o})} \qquad (6.1)$$

where $\boldsymbol{b}_0$ and $\boldsymbol{b}$ are the gain values before and after irradiation, φ is the fluence and K is displacement damage factor.

When devices are exposed to any high-energy particle, then the absorbed energy by the device per unit mass is expressed in rad (Radiation Absorbed Dose). The relation between the absorbed dose and particle fluenec is as follows

$$\text{Dose} = \text{Fluence} \times \text{Stopping power} \quad (6.2)$$

where dose is expressed in rads, fluence in # / cm^2 and stopping power in MeV-cm^2/g. The stopping power of an ion in a medium is the Linear Energy Transfer (LET). The LET of an ion in Si can be estimated by TRIM (Transport of Ions in Matter) programme [13-15]. This program gives the detailed history of the ion interaction with the target (Si) viz., range of the ion in the target, energy loss of an ion by electronic and nuclear interaction. Here, the LET of an ion is the sum of the energy losses of an ion by electronic and nuclear interaction. The total loss of ion energy in the target is the energy gain or absorbed by the target. An estimate of the displacement damage factor for heavy ions can be made by converting the ã-dose rad (Si) into equivalent heavy ion fluence. Then, the rad equivalent of fluence of an ion of given energy in Si is estimated using the relation

$$1\,\text{rad equivalent of an ion fluence of energy E} = \frac{1}{(1.6 \times 10^{-8} \times \text{LET of the ion of energy E})} \quad (6.3)$$

Here, the factor 1.6 x 10^{-8} is used for conversion of units. A factor of 1.6 x 10^{-6} converts MeV to ergs, and a factor of 1 x 10^{-2} converts a damage energy in ergs to a unit analogous to rad [2,7]. The rad equivalent of heavy ion fluence for a given energy of the heavy ion is calculated using the above equation for various ions. Here, a few of them are considered for simulation viz., He, Si, Cl, Ti, Ni, Br, Ag, I and Au. These are some of the popular ions available for experimental study in a particle accelerator facility. Similarly, the rad equivalent fluence of above mentioned heavy ions are calculated for several energy values. The heaviest of these ions (Au) has a fluence of about 1.12 x 10^{3} ions/cm^2 while the lightest (He) has a fluence of about 8.99 x 10^{5} ions/cm^2. It is found that 1 rad equivalent of these ions fluence (at 100 MeV) decreases as the mass number increases (Table 6.1). The energy of ion at maximum LET is also indicated in the Table 6.1. Using the Messenger-Spratt equation, knowing the rad equivalent of heavy ion fluence and gain degradation obtained from Co^{60} ã-ray induced study, the displacement damage factors are calculated.

Table 6.1 Energy of the ion at maximum LET and its rad equivalent fluence.

Ion	Energy of the ion at maximum LET MeV	rad equivalent fluence of 100 MeV ion #/ cm^2
proton	0.08	1.0537×10^7
deuteron	0.15	6.2096×10^7
He	0.45	7.287×10^4
Si	24	5947
Cl	30	4086
Ti	60	2592
Ni	70	1895
Br	140	1588
Ag	240	1289
I	330	1236
Au	900	1126

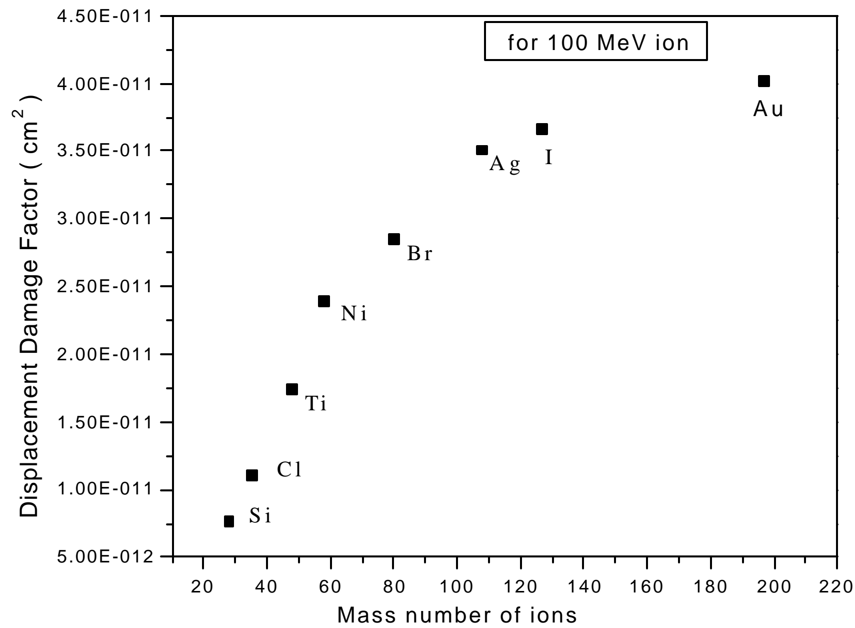

Figure 6.1 Displacement damage factor as a function of mass number of the ions.

6.3 Results and discussion

The displacement damage factor is calculated for He, Si, Cl, Ti, Ni, Br, Ag, I and Au ions at 100 MeV energy using Messenger-Spratt equation. It is found that the displacement damage factor increases as the mass number of the ion increases. (Figure 6.1). Similar variation in K with mass number of the ion is obtained for other energies also.

The displacement damage factor depends on the energy of the ion also. In the case of proton (3-175 MeV), deuteron (4-40 MeV) and helium (16-65 MeV) the damage factor is known to decrease as the particle energy increases in the energy range indicated [4, 16]. But for heavy ions there is hardly any report of the energy and fluence dependence of displacement damage factor. It is well established from TRIM calculation that the LET of the ion initially increases, reaches a maximum and then decreases as the energy increases. We have made a theoretical estimation of the dependence of displacement damage factor on the energy of the ion. Rad equivalent of ion fluence in Si is estimated for different values of energy of the ion over a wide range (KeV - GeV). From the experimental values of the forward current gain (h_{FE}) as a function of Co^{60} ã-dose for the investigated 2N3019 bipolar transistor, the displacement damage factors have been calculated, using Messenger-Spratt equation, as a function of energy of the ion (Figure 6.2). It is seen from the figure that the displacement damage factor reaches a maximum at a particular value of the energy of the ion and then decreases with increase in energy. The damage factor reaches a maximum at a value of ion energy which corresponds to maximum LET.

A plot of the variation of the damage factor as a function of energy is shown in Figure 6.3 for one representative ion (Au) for increasing value of fluence. It is seen that the maximum value of displacement damage factor decreases as the ion fluence increases. Further an estimation of the variation of K as a function of rad equivalent fluence of Au-ion for two values of energy (10 MeV and 100 MeV) has been made (Figure 6.4). The estimation reveals the similar decrease of K with ion fluence for both ion energy. The estimation of the variation of K with ion fluence has been extended to other ions viz., Si, Cl, Ti, Ni, Br, Ag and I. Figure 6.5 shows the variation of K with fluence for different ions of energy 100 MeV.

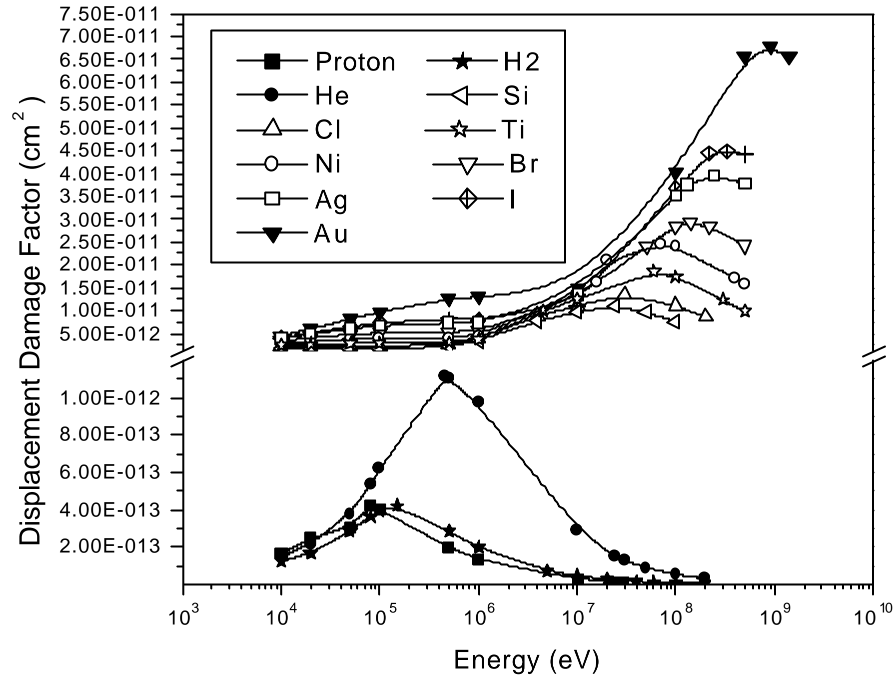

Figure 6.2 Energy dependence of displacement damage factor.

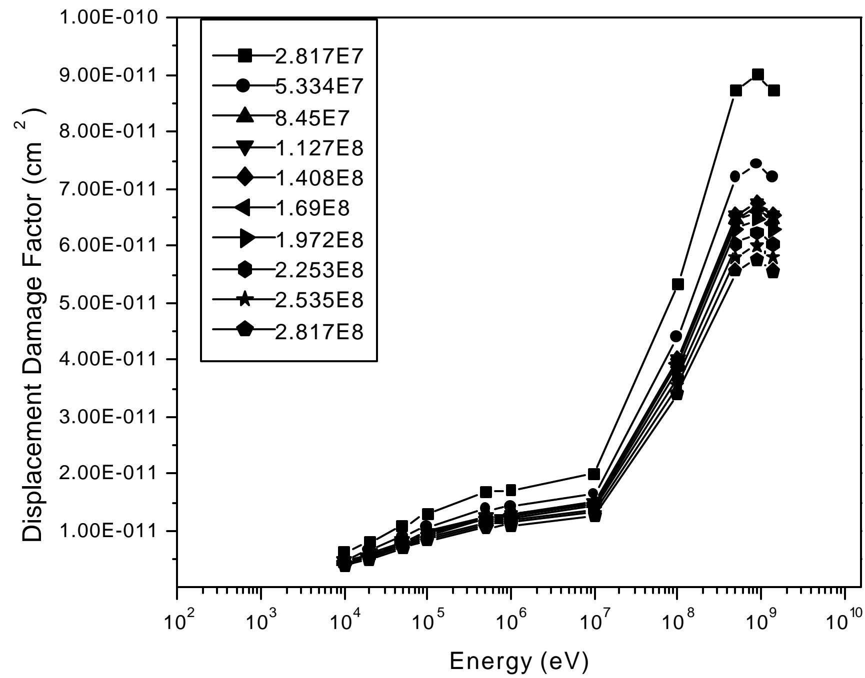

Figure 6.3 Displacement damage factor as a function of energy at different fluence of Au-ion.

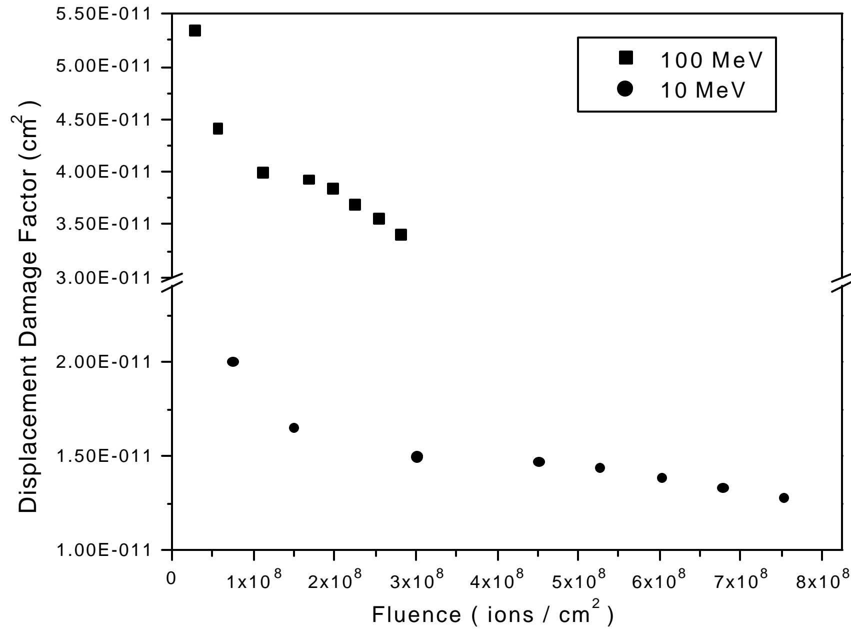

Figure 6.4 Displacement damage factor as a function of fluence of Au-ion.

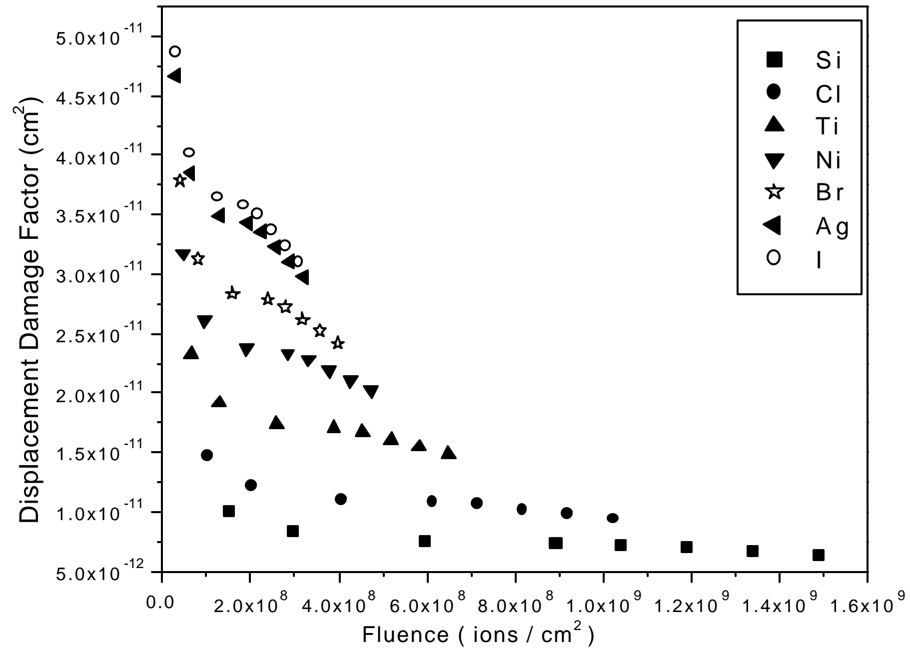

Figure 6.5 Displacement damage factor as a function of 100 MeV ion fluence.

Summers et al [3,4] have reported the experimentally determined damage factor ratios for bipolar junction transistors (2N2222A, 2N2907A) for protons, deuterons and helium ions to 1 MeV equivalent (Si) neutrons as a function of energy. In this work, the devices were first exposed to neutrons and then to protons/deuteron/helium. We have made a theoretical estimation of the variation of K with energy of proton, deuteron and helium for 2N3019, which belongs to the same family of transistors investigated by Summers et al. Figure 6.6 shows the comparison of variation of K with energy (Summers et al and our estimation). In this plot, the K values recalculated from the reported values of K/K_n (where K is displacement damage factor of ion and K_n is displacement damage factor of 1 MeV equivalent neutrons) have been compared with our estimation. The observed difference of one order magnitude in K may be attributed to the fact that this estimation is based on data on devices exposed only to Co^{60} γ-rays as against successive exposure to neutron and then to proton/deuteron/helium (Summers et al work). These estimations are verified by experimentally measuring the displacement damage factor for the same type of transistor exposed to 8 MeV electron. Figure 6.7 shows the experimentally measured variation of displacement damage factor as a function of electron fluence. Figure 6.8 shows the variation of K with rad equivalent proton fluence at 24 MeV [17]. The variation of K with 24 MeV proton fluence determined experimentally for another transistor of the same family (2N2219A) is also shown. The variation exhibits the same trend as in the case of variation of K as a function of fluence for different heavy ions (Figure 6.5). Thus the mechanism of radiation induced displacement damage appears to be almost similar for light as well as for heavy ions as indicated by our theoretical simulation.

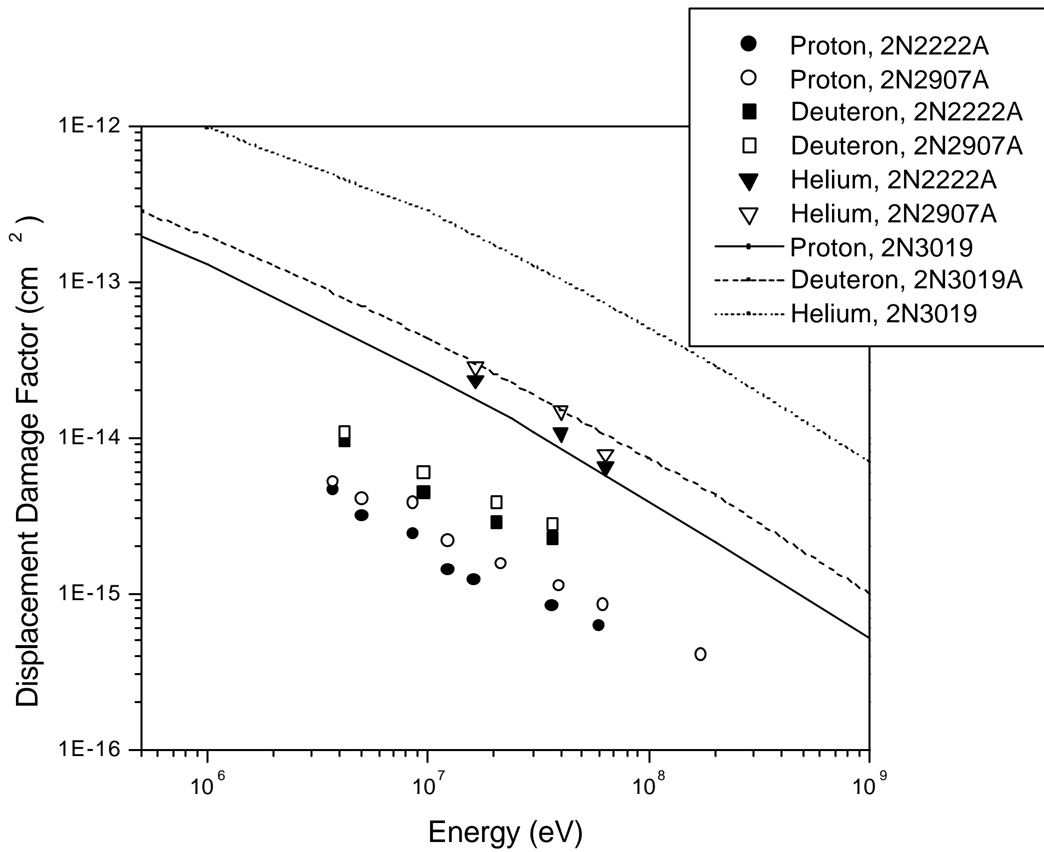

Figure 6.6 Variation of displacement damage factor as a function of energy (data points: Summers et al work; lines: our estimation).

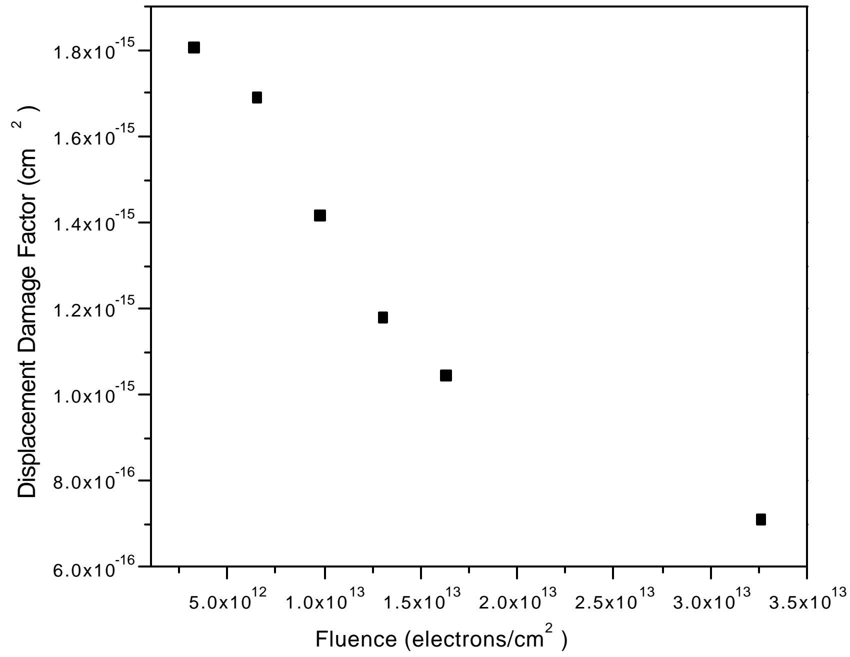

Figure 6.7 Displacement damage factor as a function of 8 MeV electron fluence.

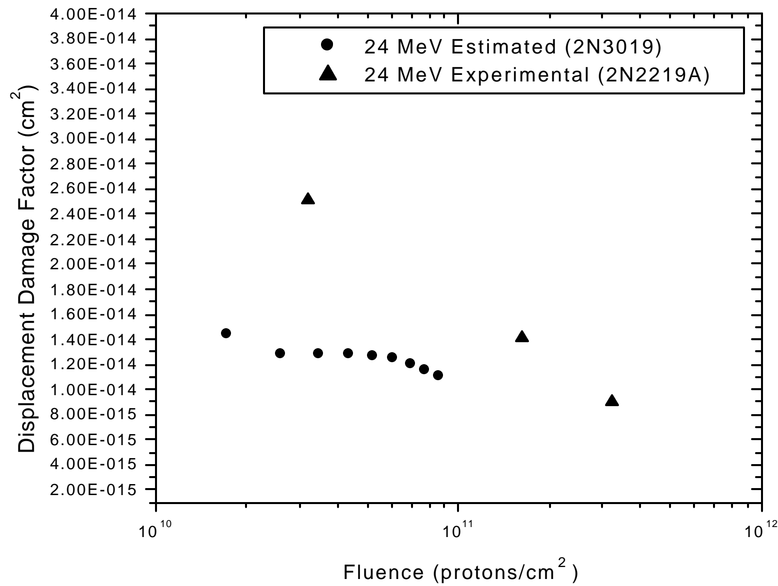

Figure 6.8 Displacement damage factor as a function of proton fluence.

6.4 Conclusion

The theoretical simulation of the variation of displacement damage factor as a function of energy and fluence of heavy ions can be made if data on ã-ray induced displacement damage are available. The estimated displacement damage factor in Si bipolar junction transistor monotonically increases as the mass number of the ion increases for a given energy. The damage factor also increases as the energy of the ion increases upto an energy corresponding to maximum LET and then decreases with increasing energy for a given heavy ion. The maximum value of K marginally decreases as the accumulated rad equivalent fluence increases for a ion of given energy. The estimated variation of K with energy and fluence serves to predict approximately the order of the damage factor and its variation with fluence and energy. The results are almost consistent with the experimentally measured K and its variation as a function of electron and proton fluence. The mechanism of radiation induced displacement damage appears to be almost similar for light as well as for heavy ions as indicated by our theoretical simulation.

References

[1] Xapsos M.A., Summers G.P., Blatchley C.C., Colerico C.W., Burke E.A. Messenger S.R. and Shapiro P., "Co^{60} Gamma Ray and Electron Displacement Damage Studies of Semiconductors", *IEEE Trans. Nucl. Sci.* **Vol.41**, 1945(1994).

[2] Dale C.J., Marshall P.W., Burke E.A., Summers P.G., and Wolicki E.A., "High Energy Electron Induced Displacement Damage in Silicon", *IEEE Trans. Nucl. Sci.,* **Vol. 35**, 1208 (1988).

[3] Summers G.P. Wolicki E. A., Xapsos M. A., Marshall P., Dale C. J., Gehlhausen M. A. and Blice R. D. "Energy Dependence of Displacement Damage Factors for Bipolar Transistors", *IEEE Trans. Nucl. Sci.,* **Vol. NS-33**, 1282 (1986).

[4] Summers G.P. Burke E.A., Dale C. J, Wolicki E. A., Marshall P. W. and Gehlhausen M. A. "Correlation of Particle-Induced Displacement Damage in Silicon", *IEEE Trans. Nucl. Sci.,* **Vol. NS-34**, 1134 (1987).

[5] Victor A.J. " Correlation of Displacement Effects Produced by Electrons, Protons and Neutrons in Silicon", *IEEE Trans. Nucl. Sci.,* **Vol. NS-22**, 2663(1975).

[6] Messenger G.C., "Displacement Damage in Silicon and Germanium Transistors", *IEEE Trans. Nucl. Sci.* **Vol. NS-12,** 53(1965).

[7] Raymond J.P. and Petersen E.L., "Comparison of Neutron, Proton and Gamma Ray Effects in Semiconductor Devices", *IEEE Trans. Nucl. Sci.,* **Vol. NS-34**, 1622(1987).

[8] Messenger G.C. and Ash M.S., "The Effect of Radiation on Electronic Systems", Van Nostrand Reinhold Company, New York,1986.

[9] Olesen H.L. "Radiation Effects on Electronic Systems", Ch. 2, Plenum press, New York, 1966.

[10] Srour J.R. Long D.M. Millward D.G. Fitzwilson R.L. and Chadsey W.L., "Radiation Effects on and Dose Enhancement of Electron Materials", Noyes Publications, New Jersey, 1984.

[11] Nichols, D.K., Price, W.E. and Gauthier, M.K. "A Comparison of radiation damage in transistors from cobalt-60 gamma rays and 2.2 MeV electrons", *IEEE Trans. Nucl. Sci,* **NS-29**, 1970 (1982).

[12] *Radiation Design Handbook*, European Space Agency-PSS-01-609, 1993, Section 7.

[13] Ziegler J.F., Biersack J.P., and Littmark U. “The Stopping and Range of Ions in Solids”, Vol. 1, *New York, Pergamon* , 1985.

[14] Ziegler J.F. and Biersack J.P., “The Stopping and Range of Ions in Solids”, TRIM Computer Program. *New York, Pergamon*,1985.

[15] Vladimir Zajic and Peter Thieberger, “Heavy Ion Linear Energy Transfer Measurements During Single Event Upset Testing of Electron Devices”, *IEEE Trans. Nucl. Sci.,* **Vol. 46**, 59(1999).

[16] Burke E.A., “Energy Dependence of Proton Induced Displacement Damage in Silicon”, *IEEE Trans. Nucl. Sci.* **Vol. NS-33**, 1276(1986).

[17] Kulkarni S.R., Asiti Sarma, Joshi G.R., Ravindra M.and Damle R., “Proton and gamma ray induced gain degradation in bipolar transistors”, *Radiation Effects & Defects in Solids* **Vol. 158,** 647 (2003).