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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

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Radiation Effects Section
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ABSTRACT

Neutron radiation effects on diode current-voltage characteristics have been studied for a variety of diodes over 1×10^{13} to 3×10^{15} n/cm^2 1 MeV equivalent neutron fluence range. A classification scheme consisting of three types of neutron effects on diode forward characteristics is proposed here for the first time. For constant forward current I_F higher than that in the generation-recombination regime, the diode voltage V_F either increases with fluence Φ (Type 1 diode), or V_F first decreases with Φ at lower fluence levels and then increases with Φ at higher fluence levels (Type 2 diode), or V_F decreases with Φ at all fluence levels used in this work (Type 3 diode). Most of the previous results on p-n junction diodes correspond to Type 1 diode results. Type 2 diode results are rather rare in the literature. Several examples of Type 2 diode results are presented here. Type 3 diode results are reported here for other types of diodes not reported earlier. These results are explained qualitatively in terms of the theories for a p-n junction and for radiation effects on semiconductors. It is shown here that a Type 3 diode could be developed as a high neutron fluence monitor with three orders of magnitude higher upper limit than the Harshaw p-i-n diode neutron fluence monitor under evaluation at the US Army Aberdeen Proving Grounds, Aberdeen, Md. The results also suggest a methodology for radiation hard diode development.

RÉSUMÉ

Les effects de radiation de neutrons sur la carractéristique courant-voltage de diodes ont étés étudiés pour une variété de diodes sur une gamme neutron-fluance équivalente de 1×10^{13} à 3×10^{15} n/cm^2 1 MeV. Une astuce de classification consistant de trois types d'effets de neutron sur la carractéristique avant de diodes est proposée ici pour la première fois. Pour un courant avant constant I_F plus élevé que celui du régime génération-recombination, le voltage de diode V_F ou alors augmente avec la fluance Φ (diode du type 1), ou alors V_F diminue pour commencer avec Φ sous faible niveau de fluance pour ensuite augmenter avec Φ sous plus fort niveau de fluance (diode du type 2), ou alors V_F diminue avec Φ sous tout niveau de fluance utilisé dans ce travail (diode du type 3). La plupart des résultats anterieurs sur les diodes à jonction p-n correspondent aux résultats des diodes du type 1. Les diodes du type 2 sont plutôt rares dans la littérature. Plusieurs exemples de diodes du type 2 sont présentés ici. Les résultats des diodes du type 3 sont observés ici pour d'autres types de diodes non reportés plus tôt. Ces résultats sont expliqués qualitativement en termes des théories pour une jonction p-n et pour les effects de radiations sur semiconducteurs. Il est prédit qu'une diode du type 3 pourrait être développée comme monitrice de haute fluance de neutron avec une limite supérieure de trois ordes de grandeur plus élevée que la diode p-i-n monitrice de fluance de neutron sous évaluation à l'US Army Aberdeen Proving Grounds, Aberdeen, Md. Les résultats suggèrent aussi une méthodologie de développement de diode à l'épreuve des radiations.

EXECUTIVE SUMMARY

Neutron radiation effects on the current-voltage (I-V) characteristics for a variety of diodes have been studied over 1×10^{13} to 3×10^{15} n/cm^2 1 MeV equivalent neutron fluence range. A classification scheme consisting of three types of neutron radiation effects on diodes is suggested here for the first time. These results and all prior similar results can be grouped into three categories corresponding to Type 1, Type 2,and Type 3 diodes as defined later in this work.

Most of the earlier results for neutron radiation effects on diodes correspond to Type 1 diodes. Type 2 diode results are rather novel in character. There have been only few reports on such effects on diodes in the literature. Type 3 diode results are observed here for other types of diodes not reported earlier. These results can be explained qualitatively on the basis of the existing theories for a p-n junction and for radiation effects on semiconductors.

Applications of these results with vastly improved performance in two areas is predicted. These results show that a Type 3 diode could be used for high neutron fluence measurements. This monitor has at least three orders of magnitude higher upper limit for neutron fluence measurement than the Harshaw p-i-n diode neutron fluence monitor which is under evaluation at the US Army Aberdeen Proving Grounds, Aberdeen, Md. Further, the results also suggest the possibility of developing a radiation hard diode.

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1.0 INTRODUCTION

It is well known that nuclear radiation can destroy or substantially degrade the performance of semiconducting electronic devices and systems. The permanent damage can be estimated from an analysis of their pre and post irradiated electrical characteristics. As a first step in understanding the radiation damage mechanisms in such devices, it was decided to study the electrical characteristics of different variety of diodes including p-n junction, p-i-n and Schottky diodes. Degradation of electrical parameters and eventual total failure of such devices can begin at as low as $(10^{11}\text{-}10^{12})$ n/cm^2 1 MeV equivalent fluence range. Such devices are amongst the simplest of all semiconducting device structures and the corresponding results are therefore more amenable to analysis. An in-depth investigation of nuclear radiation effects on these devices can also lead to a better understanding of radiation effects in more complex semiconducting devices consisting of 2 or more p-n junctions.

In the present report, we give results on the effects of neutron irradiation on the current-voltage (I-V) characteristics of twelve different types of commercial p-n, p-i-n and Schottky diodes. It was observed that all of these results can be divided into three groups which are described later on in this report.

Most of the published work on neutron radiation effects on I-V characteristics of diodes could be classified into one group[1-5]. The second type of results described here are rare in the literature[3] and will be discussed in some detail. The third type of results have been reported previously for a select type of diodes, i.e. p-i-n diodes, only[6]. This type of results have been observed in this work for other types of diodes also. Preliminary results on neutron radiation effects on different diodes studied in this report were presented earlier by one of the authors [7]. This work has led to an in-depth radiation damage study due to different types of radiations for a specific diode, viz. MRD 500 p-i-n diode made by Motorola Co. These results are being reported separately in a companion DREO Report[8].

There have been several investigations on nuclear radiation damage in p-n and p-i-n diodes[1-5]. This is mainly due to their application in a variety of electronic devices in different frequency regimes and their use as a radiation monitoring sensor. Recently, there has been a renewed interest in this field due to their application in electro-optical systems and in high energy physics experiments in new high energy high intensity colliders [9-11].

Radiation damage in a semiconducting device occurs mainly due to ionization and displacement damage in semiconducting materials and oxide barrier regions of the device [1,3]. In the present paper, we will be concerned with radiation effects due to displacement damage only. Briefly, the interaction between nuclear radiation and semiconductor lattice could lead to different types of defects in the lattice structure. The defect could be simple, such as a Frenkel defect, or be a complex defect pair, such as a vacancy-vacancy pair or a variety of possible complexes between the vacancy, impurity atom and host lattice. These defects lead to localized impurity levels within the energy gap of the host semiconductor. The energy and other characteristics of these levels could vary to a great extent. Thus, both shallow and deep levels with different charge states are observed although deep defect states are more common. The characteristics of these states affect the electrical properties of the semiconductor material and hence, the semiconducting device under study.

The major and most common source of degradation of diode characteristics on neutron irradiation is due to the degradation of minority carrier lifetime. Reduction in minority carrier lifetime due to irradiation could lead to a reduction in conductivity modulation effect in the high current regime. Another source of device degradation is the reduction of base conductivity on irradiation. In addition, in the generation-recombination region, there will also be excess forward current due to additional recombination centers created by neutron radiation. The latter effect could be ignored if one is working well outside this regime. The relative contributions from these different phenomena depend upon the current level, and device electrical and physical parameters. Further, the relative significance of these effects could change with irradiation. As a result, a diverse variety of neutron radiation effects on diodes, as observed in the present work, are possible.

Section 2 gives the details of experimental procedures and some specifications of the samples used in this work. Sections 3 and 4 give the results of experimental measurements and their discussions respectively. Possible applications and main conclusions are summarized in Sections 5 and 6 respectively.

2.0 EXPERIMENTAL MEASUREMENTS

Appendix A gives some of the pertinent specifications of the different types of diodes studied in this work. These diodes provide a representative sample of diodes currently in commercial use. The I-V characteristics of the diodes were measured with a Hewlett-Packard HP 4145B semiconductor parameter analyzer operated under the control of an IBM-PC through an HP-IB interface. All measurements were taken at $\simeq 25°C$.

In the present work, typical I-V characteristics for an unirradiated diode represent an average of I-V characteristics of six diodes of the same type. Typical forward and reverse I-V characteristics for unirradiated diodes were determined for all twelve different types of diodes used in this work. These measurements also assisted to some extent in defining the range of I-V measurements that can be carried out without thermally annealing the irradiated diodes.

The diodes were neutron irradiated at the US Army Pulse Radiation Facility (APRF), Aberdeen Proving Grounds, Aberdeen, MD. All devices were irradiated with junctions shorted to avoid damage due to radiation-induced photocurrents and static charges. Five separate batches of diodes were prepared with each batch containing the twelve types of diodes. These batches of diodes were irradiated with 1 MeV neutron fluence of 1×10^{13}, 1×10^{14}, 3×10^{14}, 1×10^{15}, 3×10^{15} n/cm^2.

The I-V characteristics of neutron irradiated diodes were measured approximately one month after their removal from the reactor. This delay was required to allow neutron activation products to decay sufficiently to permit their safe handling. Each I-V characteristic of an irradiated diode in this report represents an average of measurements taken for several (two to four) devices of the same kind. The temperature of the devices was maintained at $\simeq 25°C$ during neutron irradiation. Device characteristics were also measured at this temperature to minimize any annealing effects.

3.0 EXPERIMENTAL RESULTS

All of our results and the published results for the forward I-V characteristics of neutron irradiated diodes could be divided into three groups. The corresponding diodes are termed as Type 1, Type 2 and Type 3 diodes respectively. We limit our discussion to the voltage region beyond the generation-recombination region in the diode forward characteristics. Thus, the present results and discussion are applicable to the diffusion and high current regimes in a diode.

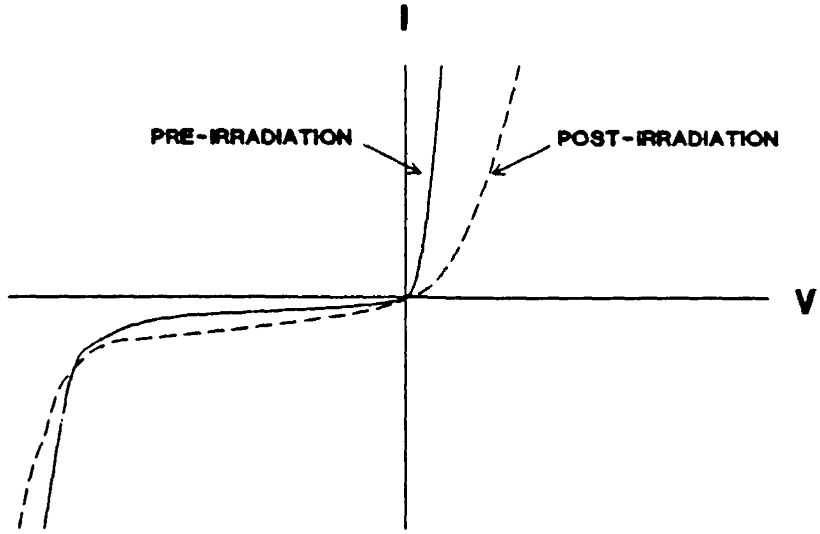
3.1 PRIOR RESULTS

Typical previous results for neutron radiation effects on p-n junctions and some p-i-n diodes are shown in Figs. 1a and 1b [1-2]. These results show that the rate of change of current with voltage decreases with irradiation. Thus, an increase in the diode forward voltage at constant current on neutron irradiation is reported in most previously published results for neutron radiation effects on p-n junctions. At the same time, the reverse leakage current increases and breakdown voltage becomes more negative with irradiation. These results correspond to Type 1 diodes described below.

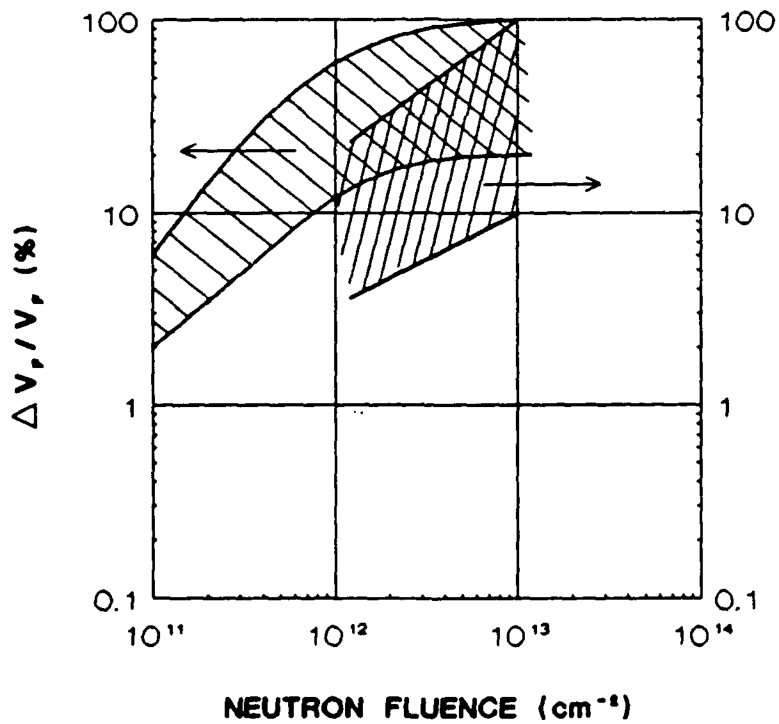
3.2 PRESENT WORK: FORWARD I-V CHARACTERISTICS

A wide range of neutron radiation effects on the I-V characteristics of diodes were observed. Figures 2 and 3 show representative results for the I-V characteristics of some of these diodes before and after irradiation with neutrons. These results can be grouped into three categories as discussed below.

Type 1 Diode - Figure 4 shows pre- and post-irradiation forward I-V characteristics of 1N914 switching diode and 1N5711 Schottky diode. It is noted that the I-V characteristics of the diodes in this group are shifted to higher voltages on irradiation. This corresponds to an increase in the diode voltage at constant current on irradiation. Such diodes are named as Type 1 diodes in this report. It should be pointed that most of the published results on neutron radiation effects on p-n junctions (see Figs. 1a and 1b) fall under this category.

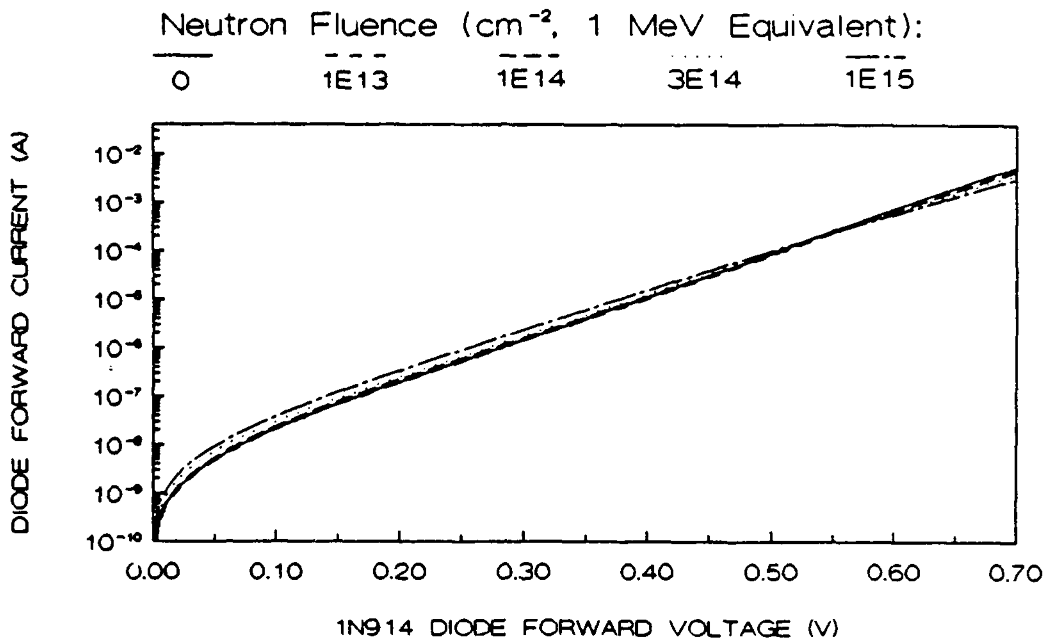


(a)

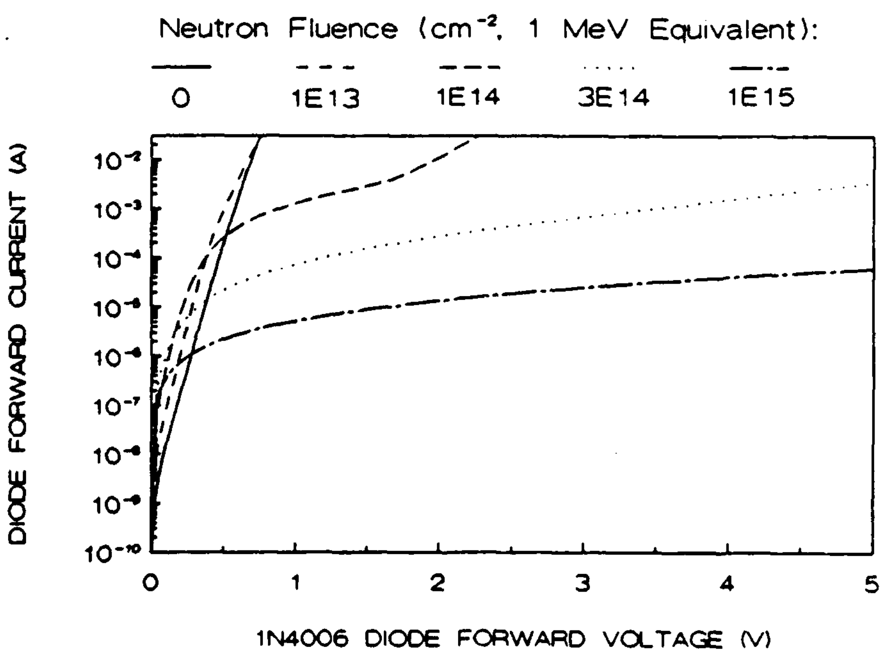


(b)

Fig. 1 Typical I-V characteristics (Fig. 1a) and percentage change in forward voltage and reverse current (Fig 1b) of diodes before and after neutron irradiation from the published data [1,2].

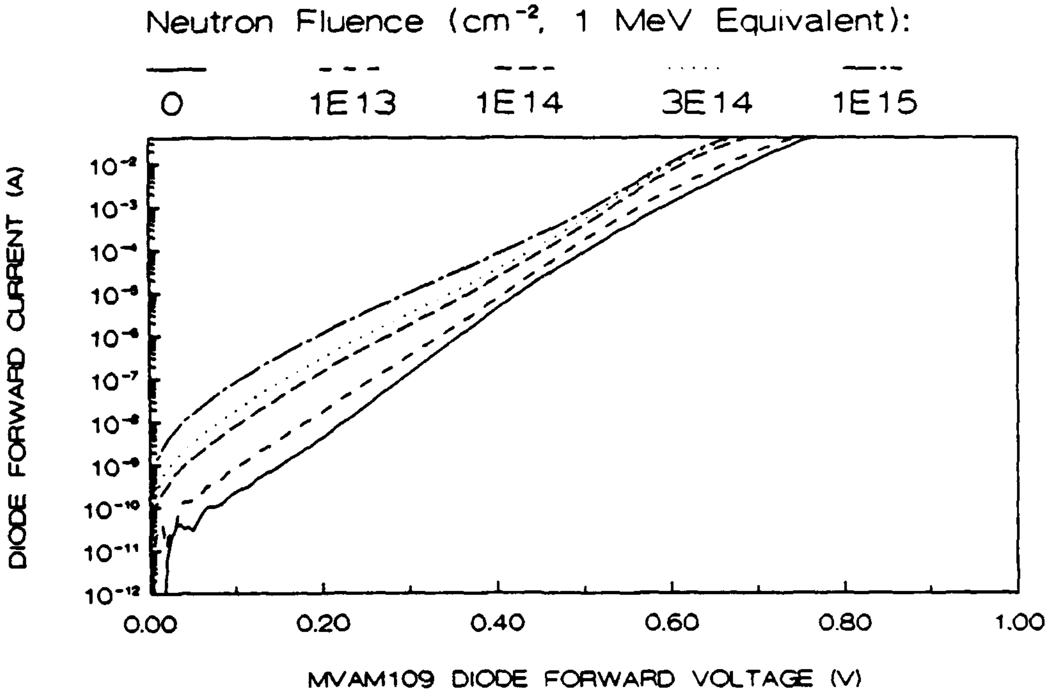


(a)

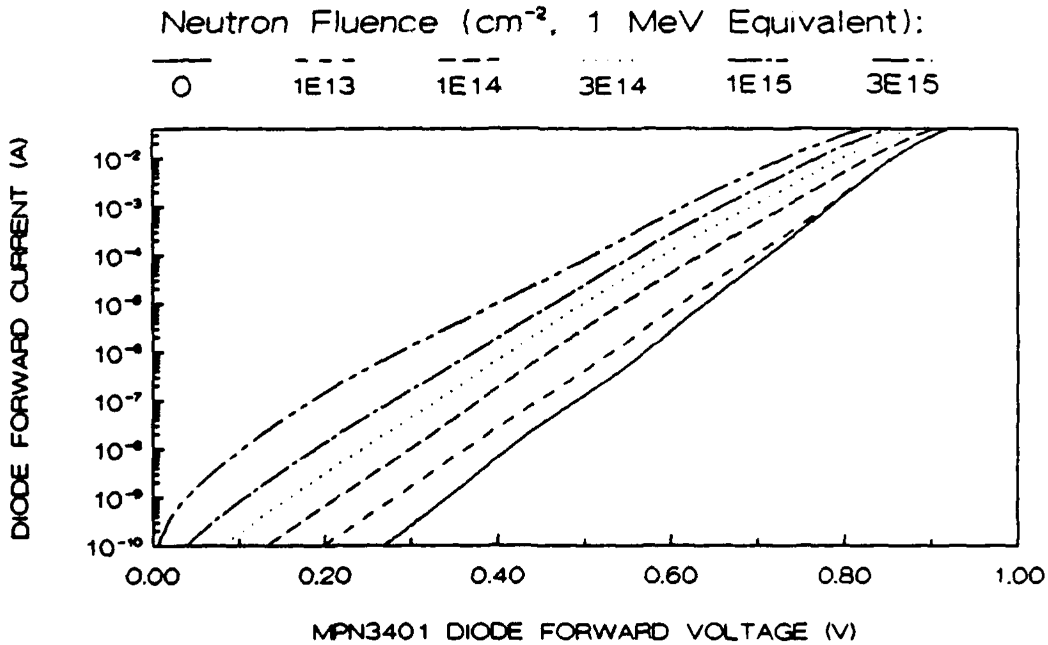


(b)

Fig. 2 Forward log I-V characteristics of (a) 1N914 and (b) 1N4006 diodes before and after neutron irradiation.

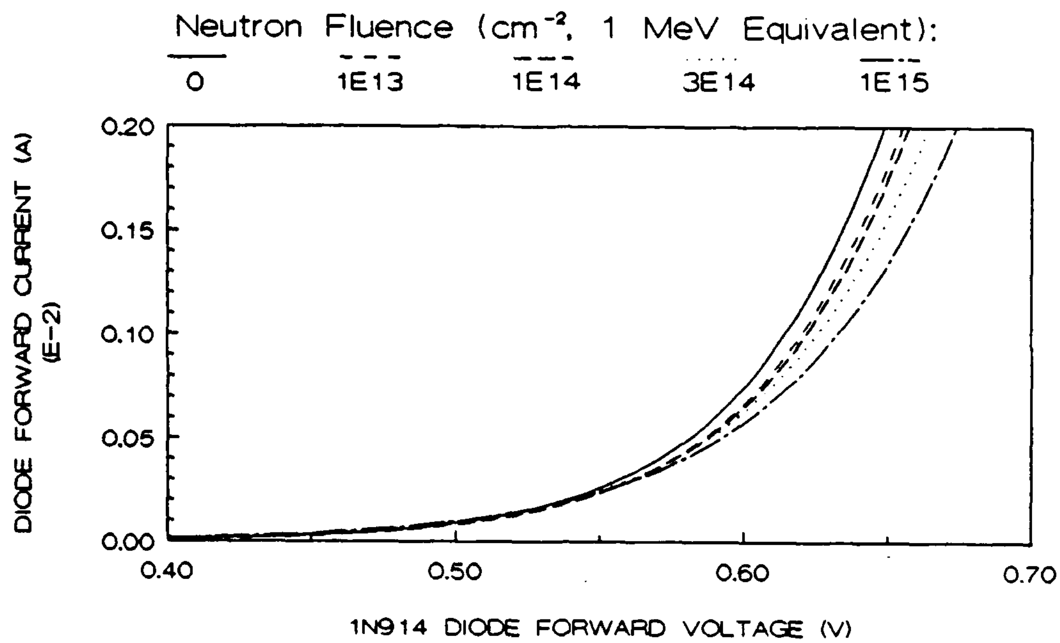


(a)

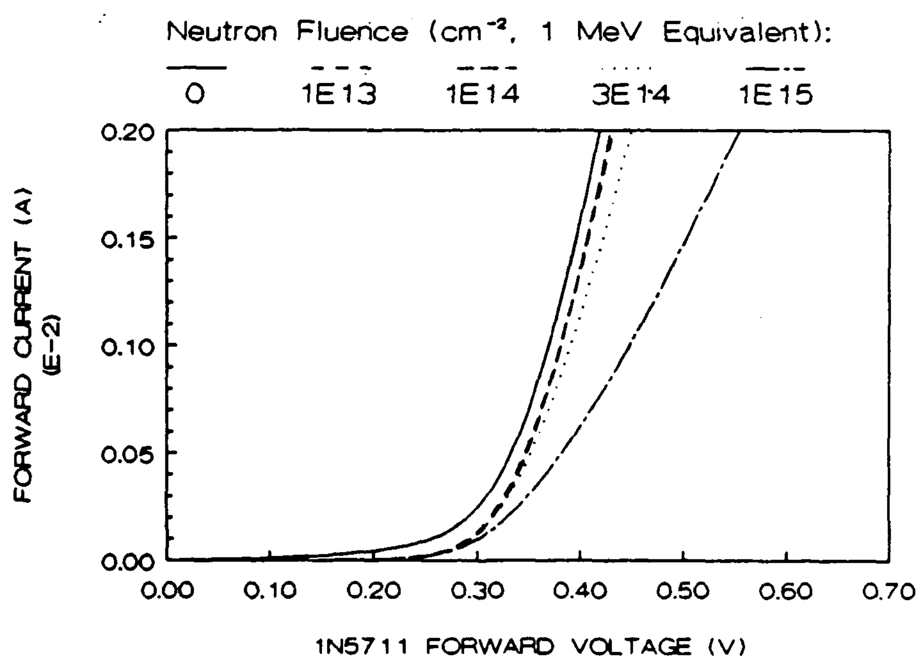


(b)

Fig. 3 Forward log I-V characteristics of (a) MVAM109 and (b) MPN3401 diodes before and after neutron irradiation.



(a)



(b)

Fig. 4 Forward I-V characteristics of Type 1 diodes before and after neutron irradiation.

Type 2 Diode - Next, we describe a different type of neutron radiation effect observed for some of these diodes. Such effects on diodes are not commonly known and should be carefully interpreted. Figure 5 gives the pre- and post-irradiated I-V characteristics for 1N1344, 1N3210, 1N4006 and 1N5404 rectifier diodes. The I-V characteristics of the diodes in this group are shifted to lower voltages on irradiation up to a certain radiation level which varies with the diode. Above this level, the shift in I-V characteristic is reversed. The I-V characteristic is now shifted back to higher voltages towards the I-V characteristic for the unirradiated diode. At some higher fluence level which varies with the diode, the I-V characteristic of the radiated diode is shifted towards higher voltages even beyond the I-V characteristic for the unirradiated diode. Thus, in such diodes, the forward voltage across the diode at constant current first decreases with radiation initially up to a certain fluence level. Above this fluence level, the diode voltage at constant current begins to increase with radiation and eventually becomes equal to that for the unirradiated diode at that current level. Above this radiation level, the diode voltage continues to increase with fluence.

Thus, on irradiation, the change in diode forward voltage at constant current, as compared to its pre-irradiated value, $\Delta V = (V)_{irradiated} - (V)_{unirradiated}$, is increasingly negative with increasing neutron fluence up to a certain fluence level. Above this level, the absolute change, $| \Delta V |$, in diode forward voltage begins to decrease with fluence and eventually becomes zero. On further increasing the fluence, the change in diode forward voltage, ΔV, is positive and increases with fluence. The diodes with this type of radiation response are termed as Type 2 diodes in this report. There have been few results in the literature which correspond to Type 2 diodes [3].

Type 3 Diode - A third type of neutron radiation effect on the I-V characteristics of some diodes used in this work is shown in Figs. 6a,6b which show pre- and post-irradiation forward voltage I-V characteristics of MPN3401 switching diode, 4735A and 4751A Zener diodes, and BB405B, MVAM 109 and MVAM 115 varactor diodes. On

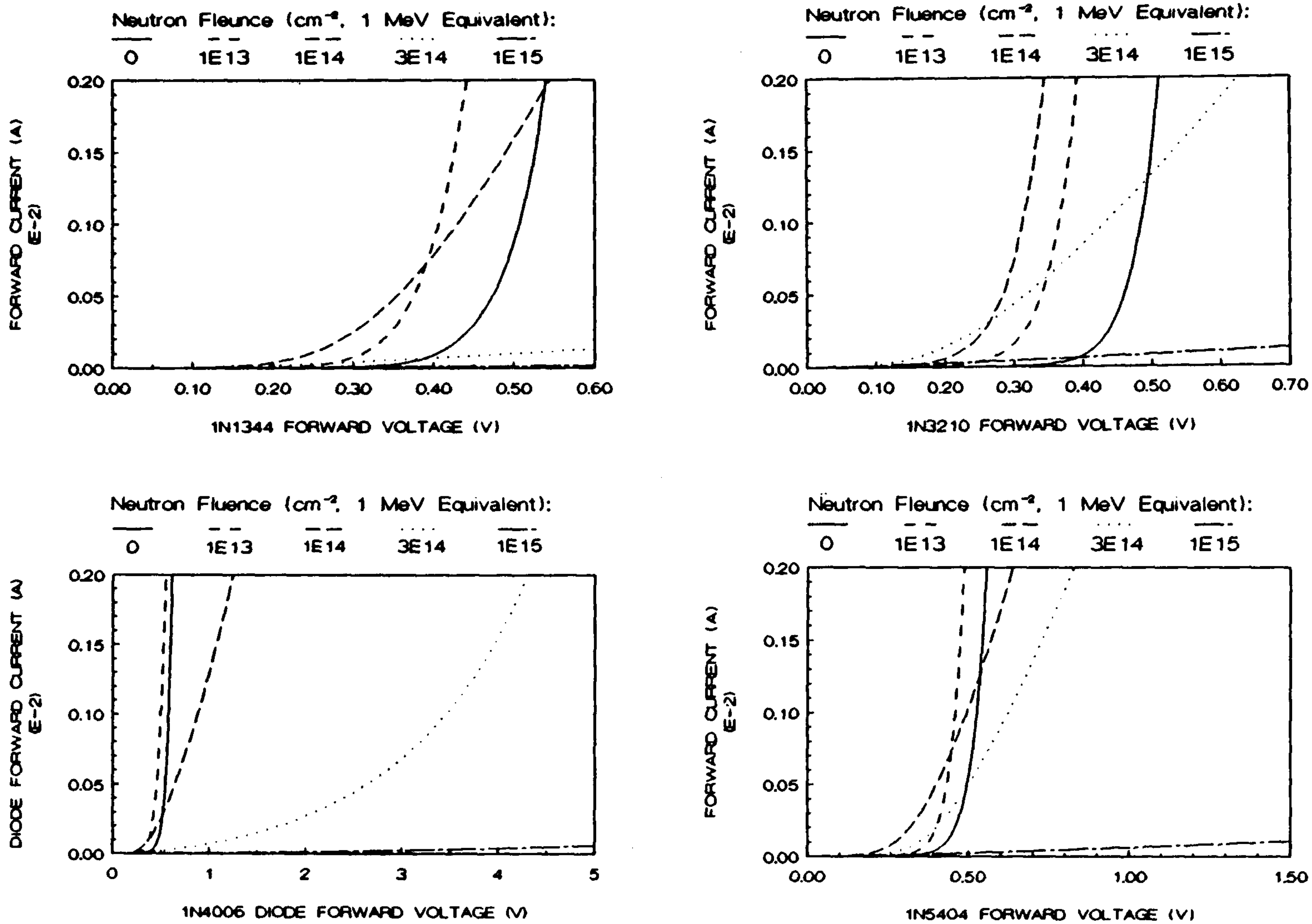


Fig. 5 Forward I-V characteristics of Type 2 diodes before and after neutron irradiation.

irradiation, the I-V characteristic of this type of diode is shifted increasingly to lower voltages for all levels of irradiation used in this work. The change in diode forward voltage, ΔV, is always negative and $|\Delta V|$ increases with neutron fluence level. Diodes with this type of radiation response are termed here as Type 3 diodes. As far as is known to us, similar type of radiation response has been reported for p-i-n diodes only[5,6]. In the present work, we report this behaviour for other type of diodes also.

It is useful to examine the forward voltage V_F at a fixed forward current I_F vs. log Φ for these diodes. Figures 7a, 7b, and 7c give V_F vs log Φ at $I_F = 0.4$ mA for Type 1, Type 2, and Type 3 diodes respectively. Using this data, the change of forward voltage ΔV_F at a constant $I_F = 0.4$ mA is determined at different radiation levels. These results are shown in Figures 8a, 8b, and 8c for Type 1, Type 2, and Type 3 diodes respectively. It should be noted that the selected constant current level is arbitrary so long as it is outside the generation-recombination region. The suggested classification of radiation effects on diodes would be valid at some higher current level such as 2 mA also as can be seen from Figs. 4-6.

For Type 1 diodes, there is a small, approximately linear increase in the change in diode forward voltage, ΔV_F, at a fixed current I_F, with log Φ up to a certain fluence level $\approx 10^{14}$ n/cm^2 as shown in Figs. 7, 8 and 4. Beyond this level, ΔV_F increases sharply and non-linearly with log Φ. These results are similar to the previous results on neutron radiation effects on diodes[1-5,12] and will be discussed further in this report.

For Type 2 diodes (see Figs. 7, 8 and 5), ΔV_F is negative and $|\Delta V_F|$ increases with log Φ. Beyond a certain fluence level, the increase in $|\Delta V_F|$ with fluence reaches a maximum value. Above this fluence level, $|\Delta V_F|$ begins to decrease with fluence although ΔV_F still remains negative. The fluence, at which the radiation-induced change in the I-V characteristic reverses its trend, varies with the diode and is termed here as Φ_{Rev}. At some value of $\Phi > \Phi_{Rev}$, ΔV_F becomes zero. At still higher fluence levels, ΔV_F becomes positive and increases non-linearly with fluence.

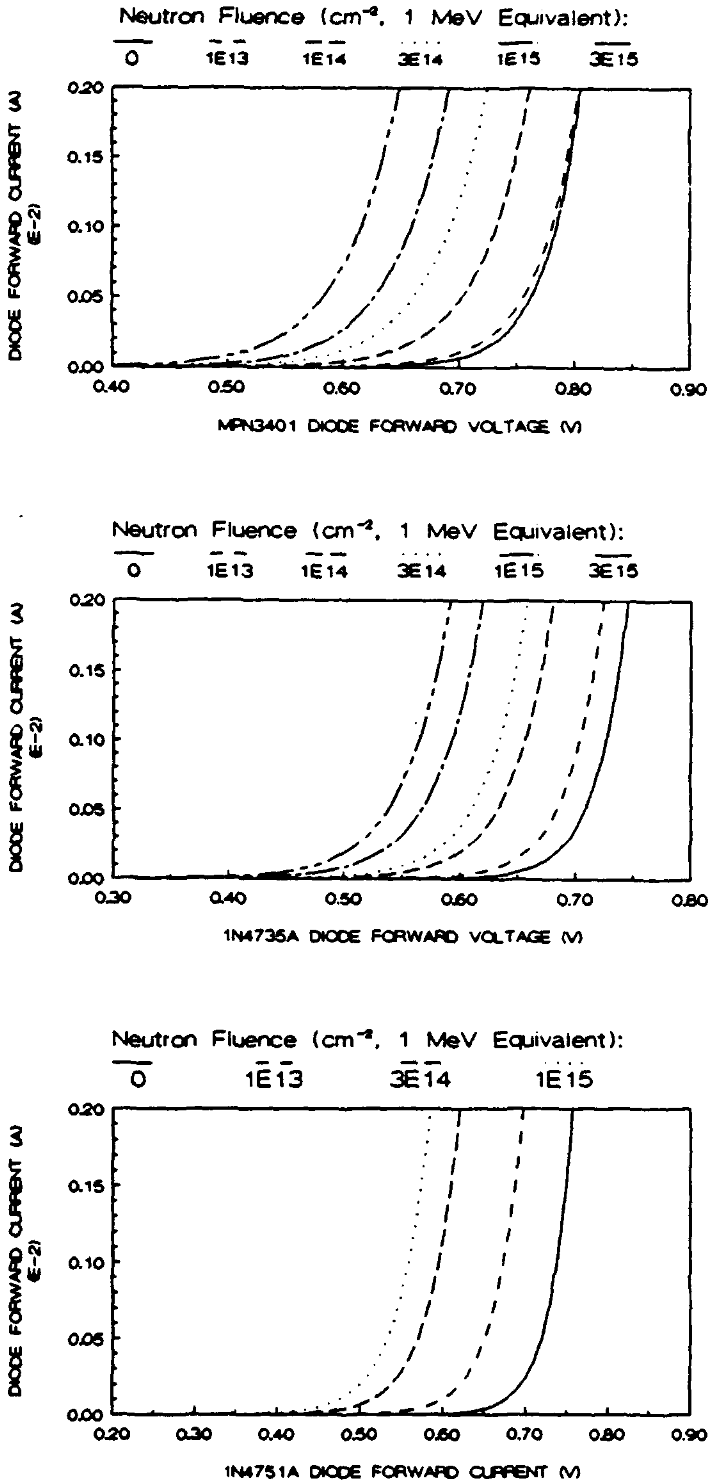


Fig. 6a Forward I-V characteristics of Type 3 diodes before and after neutron irradiation.

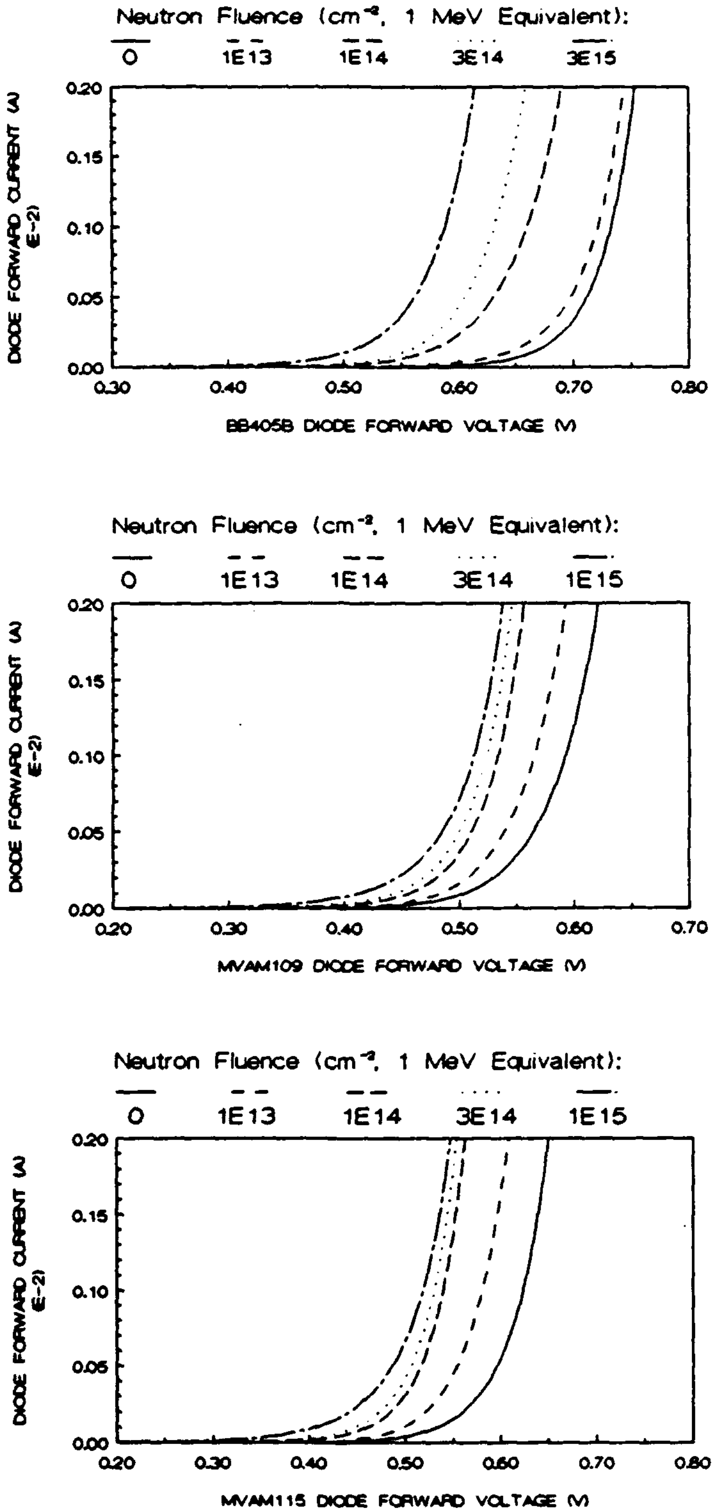


Fig. 6b Forward I-V characteristics of Type 3 diodes before and after neutron irradiation.

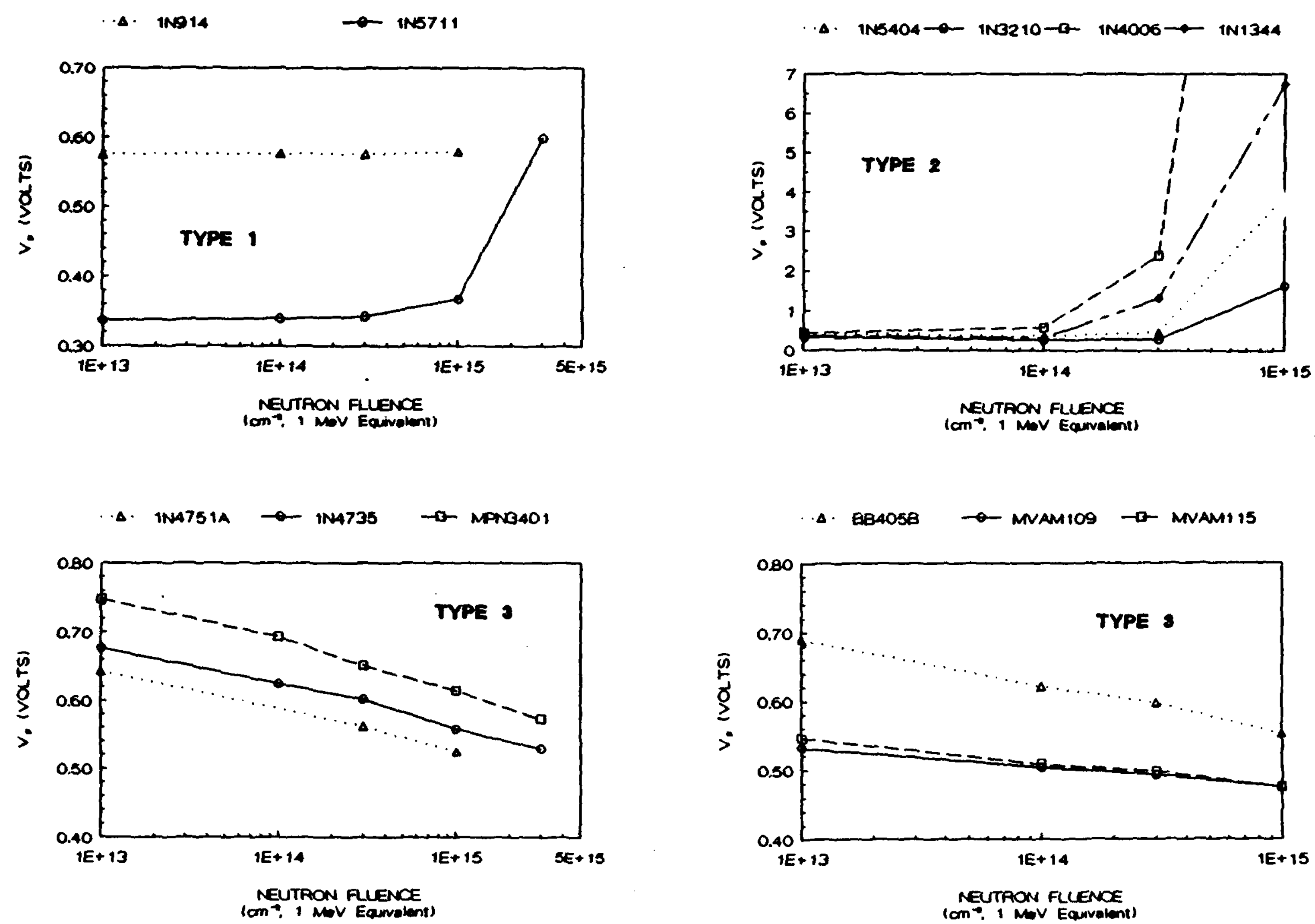


Fig. 7 Forward voltage V_F at constant current $I_F = 0.4$ mA vs. log Φ for neutron irradiated (a) Type 1, (b) Type 2 and (c) Type 3 diodes.

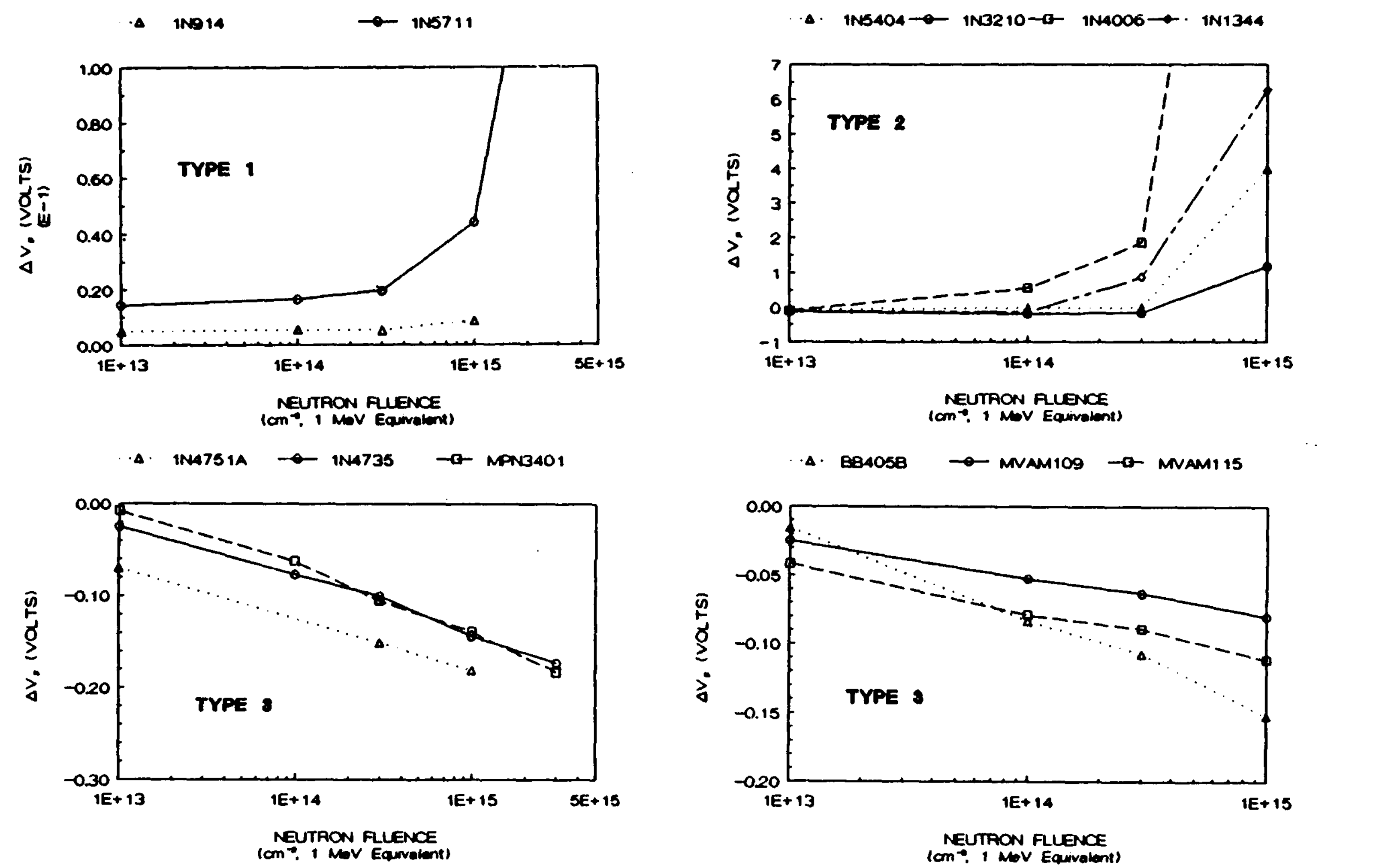
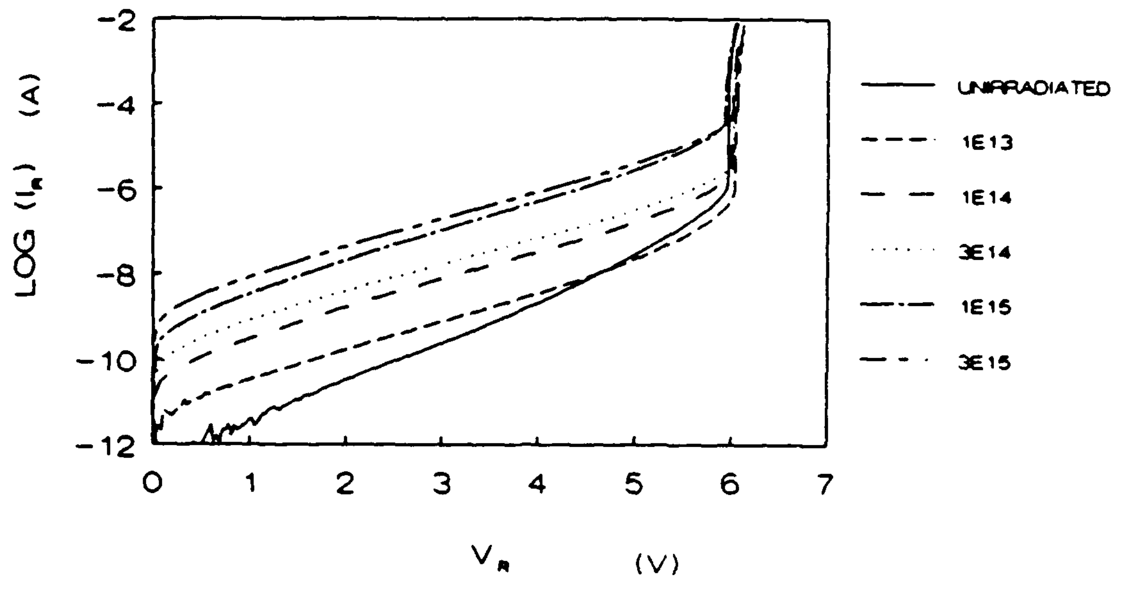


Fig. 8 Change in forward voltage ΔV_F at constant current I_F = 0.4 mA vs. log Φ for neutron irradiated (a) Type 1, (b) Type 2 and (c) Type 3 diodes.

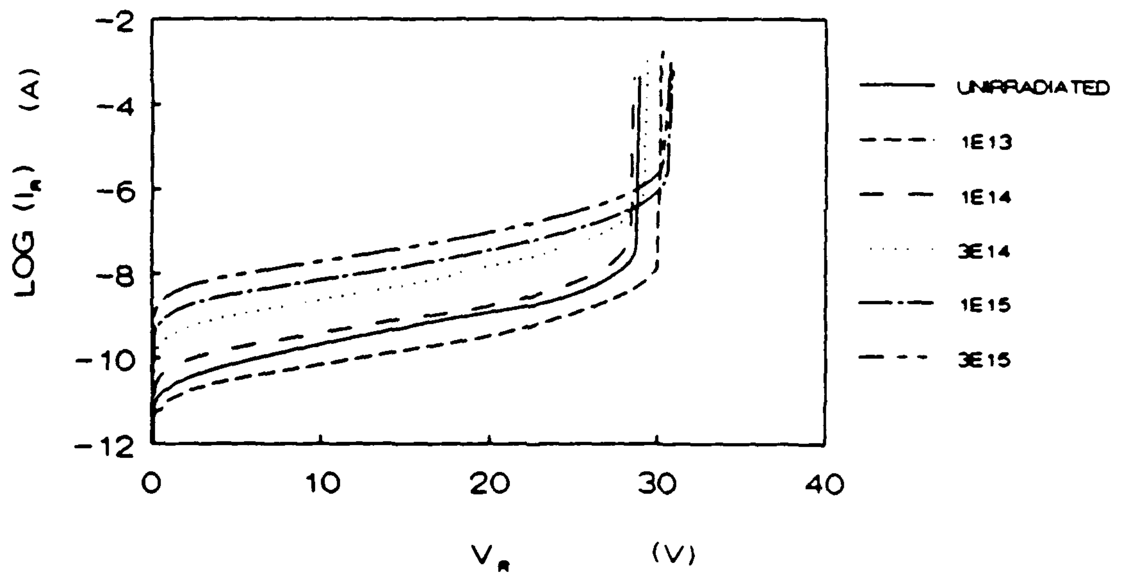
For Type 3 diodes, ΔV_F remains negative at all fluence levels used in this work and varies ~ linearly with log Φ up to the highest fluence level ($\approx 3x10^{15}$ n/cm^2) used here (see Figs. 7, 8 and 6).

3.3 REVERSE I-V CHARACTERISTICS

Reverse I-V characteristic measurements were limited to Zener diodes only. Figures 9a and 9b give log I_R vs. V_R for 1N4751A and 1N4735A Zener diodes respectively at different levels of neutron irradiation. The reverse current I_R at a fixed reverse voltage V_R increases with neutron fluence. Figures 10a and 10b give log I_R vs. log Φ at three values of reverse voltage V_R for these Zener diodes. This data shows that I_R increases by about 2 to 3 orders of magnitude in both types of Zener diodes. Further, the Zener voltage V_Z changes to more negative voltages with neutron fluence. At $3x10^{15}$ n/cm^2, the absolute increase in $|\Delta V_Z|$ is $\approx$ 100 mV for 1N4735A ($V_Z \approx 6.2$ V) and is $\approx$ 2 V for 1N4751A ($V_Z \approx 30$ V) Zener diodes. These results for the increase in reverse current and absolute value of Zener breakdown voltage confirm the trend of neutron radiation effects observed in other Zener diodes[1,2]. The radiation-induced changes in the reverse electrical characteristics of Zener diodes could be important and should be taken into account in circuit design.

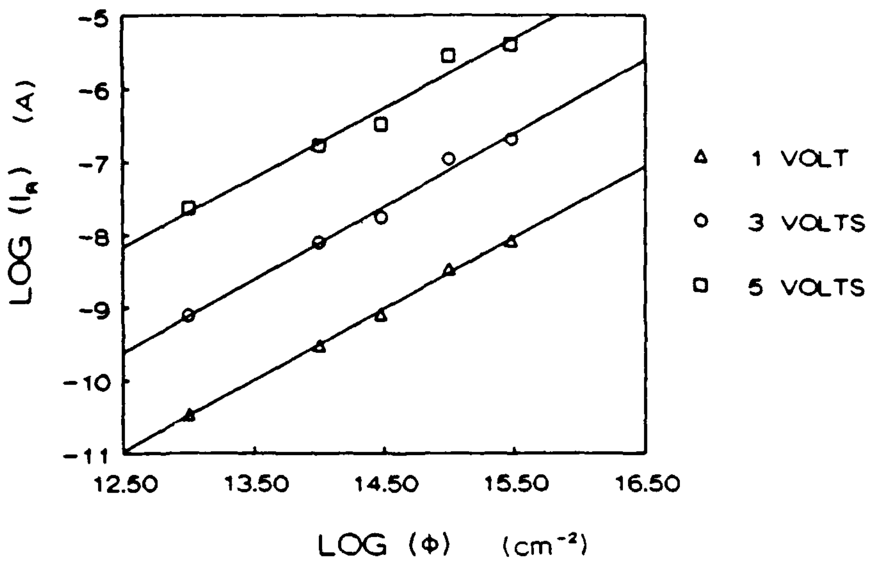


(a) 1N4735A

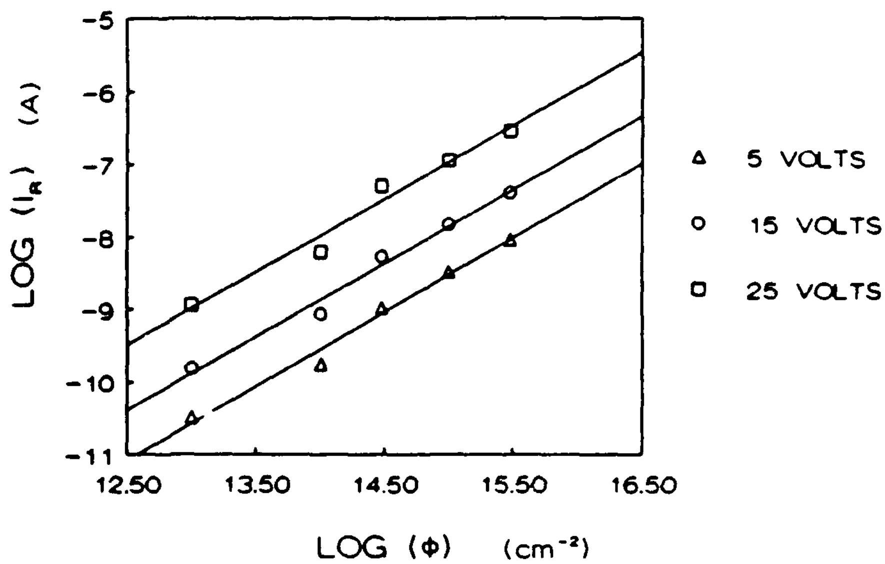


(b) 1N4751

Fig. 9 Reverse I-V characteristics for (a) 1N4735A and (b) 1N4751 Zener diodes irradiated at different neutron fluence levels.



(a) 1N4735A



(b) 1N4751

Fig. 10 Reverse current I_R at constant reverse voltage V_R vs. log Φ for (a) 1N4735A and (b) 1N4751 Zener diodes.

4.0 DISCUSSIONS

All of the results described in Section 3 can be explained qualitatively in terms of radiation damage to the junction and base region of the diode. Quantitative analysis of the data is not possible at present due to a lack of data for the electrical and physical parameters of the devices used in this work. Various physical phenomena which affect the diode characteristics on irradiation have been pointed out earlier in Sec. 1.

The applied voltage V_A across the diode is given by

$$V_A = V_B + V_J$$

$$= I \; (R_n + R_p) + V_J \tag{1}$$

where V_B represents the sum of ohmic voltage drops IR_n and IR_p across the neutral n and p regions of the diode respectively and V_J is the change in voltage across the junction due to an applied voltage V_A across the diode. In the case of a p-i-n diode, V_B would correspond to the voltage drop across the intrinsic (i) region. Normally V_B is small and can be ignored at low currents. However, both components of rhs of Eq. (1) should be taken into account for comparing the I-V characteristics of a diode before and after irradiation.

The change in V_A on neutron irradiation is thus the sum of changes in V_J and V_B. It will be shown in the following that $(dV_J/d\Phi)_I$ is always negative and $(dV_B/d\Phi)_I$ is always positive. The magnitudes of these two components depend on device dimensions and electrical properties of the materials making up the device. Thus, the change in V_A with fluence, $(dV_A/d\Phi)_I$, could be negative, positive or zero depending on the values of these respective components. The feasibility of $(dV_A/d\Phi)_I$ being equal to zero, at least in theory, is particularly attractive for developing rad-hard p-n junctions and p-i-n diodes.

The current through an ideal diode in the diffusion current regime is given by the Shockley equation:

$$I = I_s \left(e^{\frac{qV_J}{kT}} - 1 \right) \tag{2}$$

where I_S is the saturation current, I is the diode current, q is the electronic charge, k is Boltzmann constant and T is the device temperature. The saturation current I_S is given by

$$I_s = Aqn_i^2 \left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D} \right] \tag{3}$$

where N_D and N_A are the donor and acceptor densities, L_n and L_p are the diffusion lengths, D_n and D_p are the diffusion coefficients, n_i is the intrinsic carrier density and A is the cross-sectional area of the diode. For simplicity, let us consider an *abrupt junction* with say $N_D >> N_A$. This leads to

$$I \cong Aqn_i^2 \frac{D_n}{L_n N_A} \left(e^{\frac{qV_J}{kT}} - 1 \right) \tag{4}$$

Further,

$$L_n = \sqrt{D_n \tau_n}$$

where τ_n is the carrier life time. Substituting this in Eq. (4) and for $V_J >> kT/q$

$$I = \frac{Aqn_i^2 \sqrt{D_n}}{\sqrt{\tau_n} N_A} e^{\frac{qV_J}{kT}} \tag{5}$$

or

$$V_J = \left(\frac{kT}{q} \right) \ln \left(\frac{I\sqrt{\tau_n}\, N_A}{Aqn_i^2 \sqrt{D_n}} \right) \tag{6}$$

Substituting Eq.(6) in Eq.(1), we have

$$V_A = I\ (R_p + R_n) + \left(\frac{kT}{q} \right) \ln \left(\frac{IN_A\sqrt{\tau_n}}{Aqn_i^2 \sqrt{D_n}} \right) \tag{7}$$

Thus, the change in I-V characteristics of a diode on neutron irradiation is the sum of two components corresponding to the changes in each of the two rhs terms in Eq. (7). Neutron irradiation could lead to poor conductivity modulation and decrease in base conductivity which would result in an increase in V_B. On the other hand, the life time τ_n of the carriers decreases with neutron irradiation which leads to a decrease in the junction voltage. Thus neutron irradiation would always lead to a positive value for the change in the first rhs term in Eq. (7) and a negative value for the change in its second term.

Results for Type 1 diodes could be explained on the assumption that on irradiation, the change in the ohmic term in Eq.(7) corresponding to the conductivity change in the base or i region of the diode dominate the change in the voltage drop across the junction region. This would lead to an increase in the applied voltage across the diode at constant current with neutron irradiation as has been observed for Type 1 diodes in the present work (see Figs. 4, 7, and 8) and in other published diode results [1-5] (see Fig. 1).

The results corresponding to Type 3 diode (see Figs. 6-8) will be discussed next. These results are just opposite to that for Type 1. They can be explained if it is assumed that the base region (or the i region) is narrow such that the voltage drop across it is negligible in comparison to the voltage drop across the junction. In this case, the 2nd term in Eq. (7) controls neutron radiation effects of such diodes. This would result in a decrease in the applied diode voltage at constant current on neutron irradiation as observed here for Type 3 diodes.

It is possible that Type 3 diodes are merely a subset of Type 2 diodes. In this context, all Type 3 diodes may show Type 2 behaviour if they are subjected to sufficiently higher neutron fluence levels than used in this work.

The results for Type 2 diodes are more complex. In Type 2 diodes (see Figs. 5, 7 and 8), it would be expected that the base region is neither sufficiently narrow such that the voltage drop across it could be neglected nor it is dominant at lower irradiation levels. The change in voltage drop across the junction controls the total effect of neutron radiation on the diode at lower fluence levels. This leads to a net negative change in diode forward voltage at constant current at these radiation levels. However, at some radiation level, conductivity modulation effects are reduced due to a decrease in the minority carrier lifetime and diffusion length in the base region. In addition, there could be a decrease in the bulk conductivity of the base region due to neutron radiation effects. Thus, at some fluence level, the voltage drop over the base region begins to be significant. These effects will oppose increasingly the negative change in the diode voltage at constant current on irradiation. Eventually, at a certain fluence level, the decrease in diode voltage on irradiation attains a peak value. Beyond this fluence level, the reduction, $|\Delta V|$, in diode voltage on irradiation begins to decrease. It is recalled that Φ_{Rev} is that fluence level at which the shift in I-V characteristics with irradiation reverses its trend. For $\Phi > \Phi_{Rev}$, the voltage drop across the base plays an increasingly more significant role and the change in the diode voltage continues to become less negative. Eventually, it becomes zero at a higher fluence level. A further increase in radiation leads to a net positive change of the diode forward voltage at constant current. In this fluence regime, the increase in resistance of the base region and poor conductivity modulation control the net change of diode voltage with radiation.

The results for Type 2 diodes indicate that for a given device, $[(dV_B/D\Phi)_I + (dV_J/D\Phi)_I]$ could change with Φ. From the above discussion, it would appear that both $(dV_B/D\Phi)_I$ and $(dV_J/D\Phi)_I$ are not constant but may change with Φ. Creation of complex defects at higher neutron fluence level could lead to a reduction in the minority carrier lifetime, reduced diffusion length and possibly poorer conductivity modulation. This could be accompanied by reduced bulk conductivity in the base region. Further, the base width/diffusion length ratio would change with fluence and hence, the relative values of base width and diffusion length will be important in determining their effects on the diode characteristics. Thus, with irradiation, both poorer conductivity modulation and reduction in base conductivity could change with Φ and play increasingly important role in controlling the current through the diode at a fixed applied voltage. Further work with devices of known dimensions and parameters would be needed to understand the dependence of the two factors in the rhs of Eq. (7) on fluence.

5.0 APPLICATIONS

5.1 HIGH NEUTRON FLUENCE MONITOR

It is predicted from these results that a Type 3 diode could be developed as a high neutron fluence monitor in the range of 10^{11} - $3x10^{15}$ n/cm^2 and possibly to still higher levels. Type 3 diodes would offer a clear advantage over the Harshaw diode which is being studied at present for the measurements of high neutron fluence[(12)]. However, the Harshaw diode suffers from the problem of saturation at n $\approx$ $1x10^{12}$ n/cm^2 [(12)]. Thus, a Type 3 diode would be easily capable of measuring about three orders of magnitude higher neutron fluence than the present Harshaw diode. Type 2 diodes could also be used for this purpose up to Φ_{Rev} neutron fluence level. It may be recalled that Φ_{Rev} represents a quite high fluence levei in many diodes. Φ_{Rev} is equal to $\approx$ 10^{14} n/cm^2 for a number of diodes in the present work. However, a Type 2 diode cannot be used to measure fluence levels above Φ_{Rev} since the change in forward voltage is a multi-valued function of neutron fluence beyond that flunece level.

5.2 RAD-HARD P-N DIODE

It was pointed in the previous Section that $(dV_A/d\Phi)_I = 0$ in principle with a proper choice of device dimension and material properties. This possibility could be exploited to develop rad-hard p-n junctions and p-i-n diodes. However, further work would be necessary to fully understand the radiation-induced effects on such devices.

6.0 CONCLUSIONS

In summary, we have observed a variety of neutron radiation effects on the I-V characteristics of different types of commercial diodes. A new classification scheme consisting of three categories of these effects has been proposed in this work for the first time. All of our results and the prior results on neutron radiation effects on diodes could be classified in these three groups. The corresponding diodes are termed as Type 1, Type 2 and Type 3 diodes as defined earlier. The list of diodes studied in this work and their classification in the proposed scheme are shown in Appendix A.

It was noted that most of the previously reported results for neutron radiation effects on I-V characteristics of p-n junctions correspond to Type 1 diode results. Extensive results for Type 2 diodes are reported here. There have been only few references corresponding to such diodes in the past. Type 3 diode results are also reported for different types of diodes not reported previously. All of the results are explained qualitatively on the basis of the theories for a p-n junction and neutron radiation effects on semiconductors. Radiation effects on the diode characteristics are explained on the basis of radiation dependence of the minority carrier lifetime and bulk conductivity of the base. The variety of effects on diode characteristics obtained in this work indicate rather complex dependence of these diode parameters on neutron radiation.

This work points at the possibility of developing both rad-hard diodes as well as high neutron fluence monitors with vastly improved performance. The present results show that a Type 3 p-n junction or p-i-n diode could be used as an improved high neutron fluence monitor. Its upper limit for fluence measurement would be more than three orders of magnitude higher than that of a Harshaw p-i-n diode neutron fluence monitor --- a Type 1 diode in our classification --that has been evaluated recently for high neutron fluence measurements[12]. Further, it would appear that a Type 2 diode could also be developed to monitor high neutron fluence below a certain limit corresponding to Φ_{Rev} for that diode.

It is planned to study the dependence of I-V characteristics on electron and neutron fluence of different energies for selected Type 2 and Type 3 diodes of known device dimensions and material properties.

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SOME SPECIFICATIONS OF THE DIODES USED IN THIS STUDY   APPENDIX A

Part No.	Output Current	Breakdown Voltage	Reverse Current	Comments	Radiation Response
1N 914	75 mA	100V	25 nA dc @ 20V dc;	General purpose	Type 1
1N 5711	15 mA @a 410 mV	70V	40 nA @ 50V	Mixers, detectors	Type 1
1N 4006	1A	1000V	0.05 μA dc @ 800V	Diffused junction	Type 2
1N 1344	12A	350V	0.9 mA @ 200V	Diffused junction	Type 2
1N 3210	15A	200V	1.0 mA @ 200V	Diffused junction	Type 2
1N 5404	3A	400V	100 μA @ 400V	Medium power rectifier	Type 2
1N 4735A		V_z=6.2V	< 10 μA @ V_R = 3V	Reference voltage	Type 3
1N 4751		V_z=30V	< 5μA @V_R= 22.8V	Reference voltage	Type 3
MPN 3401		100V		PIN diode	Type 3
MVAM 115	50mA	18V		Varactor	Type 3
MVAM 109	50mA	15V		Varactor	Type 3
BB 405B	20mA	30V		Varactor	Type 3

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Neutron radiation effects on diode current-voltage characteristics have been studied for a variety of diodes over 1×10^{13} to 3×10^{15} n/cm^2 1 MeV equivalent neutron fluence range. A classification scheme consisting of three types of neutron effects on diode forward characteristics is proposed here for the first time. For constant forward current I_F higher than that in the generation-recombination regime, the diode voltage V_F either increases with fluence Φ (Type 1 diode), or V_F first decreases with Φ at lower fluence levels and then increases with Φ at higher fluence levels (Type 2 diode), or V_F decreases with Φ at all fluence levels used in this work (Type 3 diode). Most of the previous results on p-n junction diodes correspond to Type 1 diode results. Type 2 diode results are rather rare in the literature. Several examples of Type 2 diode results are presented here. Type 3 diode results are reported here for other types of diodes not reported earlier. These results are explained qualitatively in terms of the theories for a p-n junction and for radiation effects on semiconductors. It is shown here that a Type 3 diode could be developed as a high neutron fluence monitor with three orders of magnitude higher upper limit than the Harshaw p-i-n diode neutron fluence monitor under evaluation at the US Army Aberdeen Proving Grounds, Aberdeen, Md. The results also suggest a methodology for radiation hard diode development.

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Diode Characteristics
Neutron Fluence Monitor
Radiation Hardness