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Radiation Effects on Some Semiconductor
Materials & Devices

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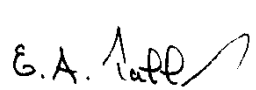
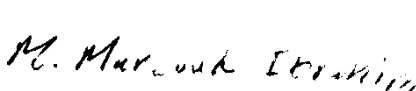
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ABSTRACT

The properties of some semiconductor materials (Si, Ge, Se, GaAs, InAs, CdS, GaP, Polyethylene and Quartz) and devices (CdS photoresistors, Si-Solar Cells and IMPATT's), where are used in radiation environment such as nuclear power plants, space satellites and radioisotopic-fueled thermoelectric generators, could be changed due to radiation exposure.

The study scanned how these materials and devices could be affected when exposed to various types of radiation namely: electrons -, neutrons -, γ -and solar radiation.

The author focused the investigation upon studying conductivity of semiconductor materials that is; energy gap calculations within an accuracy better than 93%, conductivity dependence on illumination level, where it is found that the relative change in conductivity (σ/σ_0) is function of both; the illumination level and the width of band gap. Values of 1.2, 11, 22.5 and 27 are obtained at 12 K.Lux for the InAs, GaAs, GaP and CdS respectively. Also, photovoltaic and photocurrent phenomena in GaAs and CdS specimens fabricated with gold electrodes are proved, and their maximum values for the open circuit voltage " V_{oc} " are 0.14V and 0.32 V, while the short circuit current " I_{sc} " density was found to be linear with illumination level.

On the other hand, it is found that the I_{sc} shows a linear dependence upon the illumination up to 10 sun level while V_{oc} varies exponentially. In addition to that I_{sc} shows a slight increase with temperature (within the range from -160°C up to 280°C) results in a temperature coefficient of ($\partial I_{sc} / \partial T$) = $+ 6.9 \times 10^{-6}$ A/ $^\circ\text{C}$, while that of " V_{oc} " is ($\partial V_{oc} / \partial T$) = $- 2.18 \times 10^{-3}$ V/ $^\circ\text{C}$.

Electron irradiation causes a pronounced decrease in both, the output characteristics and collection efficiency of the solar cell, also

the I_{sc} temperature coefficient is greatly increases with both; radiation fluence and energy, while V_{oc} temperature coefficient remains fairly unaffected.

Shelf annealing of the electron damaged solar cell at room temperature recovers (after 90 days) its I_{sc} & V_{oc} reduced by an amount of around 50%. Oven annealing was shown to have a significant effect, where heat treatment at 100 °C for one hour cause the sample to gain more than 95% of its initial characteristics.

No transient effects could be recorded with neutron flux up to value of 5×10^7 n/cm²/sec., while fluences up to 8.45×10^{15} n/cm² cause the solar cell to loose more than 60% of its output power. Moreover, IMPATT diode characteristics are interrupted: that is both the reverse saturation current and breakdown voltage increases with neutron fluence, while the depletion capacitance decreases for the same applied reverse voltage. Finally, the breakdown voltage temperature coefficient becomes negative due to irradiation.

Additional increase in neutron fluence, up to 1.872×10^{18} n/cm², causes all semiconductor devices to loose their main feature and to behave as linear resistors, besides affecting them to act as radioactive sources due to the presence of some trace elements such as: Fe, Ag, Co, Sb and Sn.

Optical properties are greatly influenced, in the direction of transparency increase, due to exposure with either neutrons - or γ -radiation.

On contrary, γ -radiation up to 4×10^8 rads does not show any significant permanent damage either in electrical, physical or chemical properties of semiconductor materials.

Transient γ -radiation affects conductivity modulation of semiconductor materials with a relative change in conductivity (σ/σ_0) at

γ -dose rate of 440 rads/sec. is 1.05, 7.15, 12.5, 25, 30 and 60 for InAs, GaAs, GaP, CdS, Polyethelene and Quartz. With respect to semiconductor devices it increases both the reverse saturation current of IMPATT diode and the current of CdS photoresistor where its sensitivity to γ -radiation is calculated to be 1.3567×10^{-7} A/V/rad/sec. Also it generates photocurrent in solar cells which is found to be function of cell size and γ -radiation dose rate where a sensitivity value of 0.3×10^{-6} A/cm²/rad/sec. results.

The author constructed and improved certain computer programs which actually will help other researchers in; calculation of the useful energy and efficiency of solar cell under various operating conditions (illumination, temperature and irradiation with protons, electrons, neutrons and γ -rays), semiconductor devices simulation and material parameters effect. Beside, well tested program were constructed which are designed for γ -dose rate distribution determination due to γ -emitters.

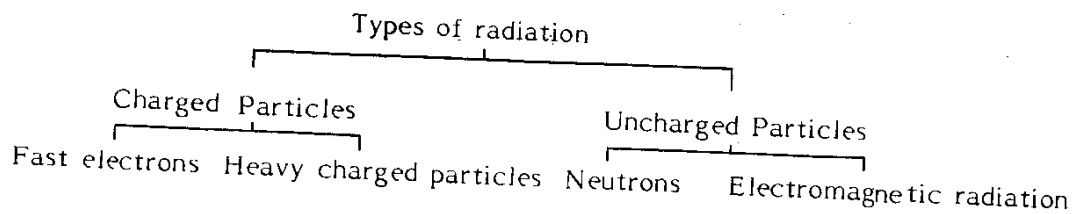
Several applications based on the results obtained through this study are achieved. One of which is the use of CdS photoresistor in low dose rate dosimetry down to millirads and silicon solar cell in high γ -dosimetry up to 440 rads/sec. Also, it become possible to make use of the linear response of the I_{sc} to measure high light intensities up to 10 sun levels.

SUMMARY

Some elements are characterized by possessing either surplus or deficiency of neutron in their atomic nucleus and hence, they are unstable. Such unstable elements are commonly known as radioactive isotopes. To attain stability, it emits ionizing radiations (particles or photons).

1- Radiation of Interest:

The radiation of primary concern in this thesis originates in nature and atomic or nuclear processes. They are conveniently categorized into four general types as follows:



Fast electrons include α -particles emitted in nuclear decay, as well as energetic electrons produced by any other process. **Heavy charged particles** denote a category that encompasses all energetic ions with one atomic mass unit or greater, such as β -particles, protons and fission products. **The electromagnetic radiation** of interest includes: X-ray emitted in the rearrangement of electron shells of atoms, γ -ray which originates from transition within the nucleus itself and solar radiation. **Neutrons** generated in various nuclear processes comprise the final major category, which is further divided into slow - and fast - neutrons.

The problem of predicting many different effects is greatly simplified through characterizing the radiation by its effect rather than by the radiation type, intensity or energy distribution. The reason of this simplification is due to the fact that the changes in the electrical behaviours of the semiconductors are due to two fundamental effects of radiation namely: displacements and ionizations. These two results from the interaction

of radiation and matter cause two common types of radiation damage in semiconductors namely: permanent and transient damages. The four types of radiation cannot be simply classified by the type of damage they cause, since each type of radiation can cause all the types of damage effects.

2- Importance of Radiation Damage:

Radiation effects study have grown in response to several needs. Some types of electronic systems must be capable for correctly operating during or after radiation exposure. The increasing number of earth satellites and interplanetary probes has created a need for electronic circuits which can withstand the space radiation environment, where high energy protons and electrons produce a fairly high radiation fluences. A second source of radiation is caused by the use of radioisotopic - fueled thermoelectric generators to produce electrical power energy.

3- Aim of the Work:

The study of the effect of radiation on semiconductors can help for construction of a system built up from devices less sensitive to radiation.

On the other hand, in the field of radiation research and its applications, one of the important parameters that need to be controlled is the absorbed dose. This implies the use of semiconductor materials as radiation detectors. In the present work interest has been given in studying the effect of radiation on some semiconductor materials and devices to obtain a device which is sensitive to γ -radiation.

4- Previous Work:

In 1965, it had been reported that for silicon solar cell the primary mechanism for power degradation is due to reduction in minority carriers lifetime in the bulk region resulting from particles fluence and energy [1]. It also observed that, crystal growth techniques and doping influence the

energy dependence of damage introduction rates in solar cell [2]. E. Stofel et al. [2] show that the resistance of the back contact of a solar cell is relatively unaffected when the cell is irradiated from the front face only. In 1971, some other researchers reported that due to long term nature of space mission simultaneous damage and annealing may occur [4-6]. In 1972, high efficiency silicon solar cells developed by J. Lindmayer [7] and R.A. Arndt et al. [8] were used for satellites. Also, in 1973, T. Faith [9] had reported that the damage due to radiation is probably a composite of several recombination centers which may dominate over different energy ranges.

J. Manning et al. [10] reported a computer codes (Known as E-DEP-1) to calculate the damage profile caused by 1 MeV heavy-ion irradiation. G.K. Hubler [11] had modified the E-DEP-1 code to include silicon displacement damage profile of high energy protons. In 1974, physical model for cell performance in long term space missions was preferable [12-14]. Also in 1975, the performance and radiation resistance of cell had been introduced [15-20].

C.J. Fischer et al. [21] reported that the irradiation produce a marked dependence of response on injection level. R.J. Stern [22] concluded that either surface recombination at face or majority carrier removal resulting from radiation damage are significant only when short circuit current degradation becomes 50% (at fluences well beyond 10^{12} proton / cm^2). A.H. Kalmia [23] had presented the basic degradation mechanisms in the solar cells which are; lifetime degradation and increase of the series resistance. Also photovoltaic parameters were measured by G.K. Hubler [24], with air - mass - zero (AMO) solar simulator, as a function of fluence and temperature before and after 1.0 MeV electron - and 5.0 MeV proton irradiations. Their maximum power degradation is 36% at 2×10^{15} e / cm^2 . W. Luft [25] reported the performance of set of 10 cell types from 3 different manufacturers (with efficiencies ranging from 10.3% to 13.6%) before and after exposure to irradiation. It was shown that efficiencies after irradiation by 1 MeV electrons to a fluence of 1×10^{15} e / cm^2 ranged from 8.0% to 9.0%, and the degradation in power output ranged from 31% to 32% for

cell with a $2\ \Omega$ -cm base resistivity and from 28% to 30% for cell with $10\ \Omega$ -cm resistivity.

In addition, several authors [26-34] have studied the effects of radiation on IMPATT oscillators. The critical parameters for IMPATT operation are the electric field distribution, the ionization coefficients, the reverse saturation current, the saturated drift velocity and the carriers lifetime. No data is available for radiation effects on the ionization coefficients or the saturated drift velocities, and these two parameters are assumed not to change for fast neutron fluences up to $10^{16}\ \text{n/cm}^2$. Wilson [26] points out that both the saturation drift velocity and the avalanche multiplication phenomenon are collision dominated, and the main path between collisions at room temperature is still short compared to the mean distance between defects even after $10^{16}\ \text{n/cm}^2$. The carrier lifetime degradation " $\Delta\tau$ " was found to follow the form:

$$\Delta\tau = (K\tau\ \phi)^{-1}$$

with $K\tau$ means lifetime degradation constant $\approx 7 \times 10^{-7}\ \text{cm}^2/\text{n/sec}$, and ϕ is the fluence in n/cm^2 .

After a fluence $\phi = 10^{16}\ \text{n/cm}^2$, the lifetime would be approximately $10^{-10}\ \text{sec}$, and consequently fraction of the transiting electrons may recombine at $10^{16}\ \text{n/cm}^2$. Ear - Nisse [31] have reported the results of a theoretical and experimental study on silicon P^+NN^+ devices. The study showed that the neutron irradiation causes carrier removal at the edges of the space - charge region leading to a widening of the depletion - region for the same applied voltage.

In 1968, Wilson and Lee [35] reported the effects resulting from fast neutrons with fluences $10^{16}\ \text{n/cm}^2$ on both dc - and microwave - characteristics of IMPATT Devices. Good forward dc characteristics are created up to $2 \times 10^{15}\ \text{n/cm}^2$. At higher doses, the forward characteristics are degraded by the formation of a thin intrinsic layer at the metallurgical PN-junction.

An IMPATT diode irradiated by neutron and γ -radiation pulses was studied and reported by Anderson [30]. The diode ceased to oscillate upon irradiation of each pulse and then recovered slowly. In 1972 transient ionizing radiation effects were reported by Borrego et al. [36]. The RF power is reduced at increasing dose rates. In 1976 R.J. Gutmann et al. [37] reported an evaluation of after effects in IMPATT oscillators with transient ionizing radiation. During pulse ($= 2 \times 10^9$ rads/sec) a leakage current is created, and its effect is a premature build up of the avalanche current, resulting in RF power reduction and an increase in frequency of oscillation. After the radiation pulse, the diode and oscillator return to preirradiation conditions.

In 1981, R.V. Konakova et al. [38] reported the results of experimental research of GaAs IMPATT's. Permanent damage appear in the (I-V) characteristics after absorbed doses around 2×10^9 rads.

Finally, in 1982, R.V. Konakova et al. [39] reported the effects of very high γ -radiation dose on diffusion length and consequently its effect on diode performance.

5- Scope of the Thesis

The goal of this study is to investigate the radiation effects on the characteristics of some semiconductor materials which covers a wide spread of different gap energies (InAs , Ge , Si , GaAs , Se , GaP , CdS , Polyethylene and Quartz), as well as some semiconductor devices which are of great interest in many practical applications (CdS photoresistors, silicon IMPATT diodes and solar cells).

To achieve this, the study covers the following topics:-

Chapter I, deals with the principles of semiconductor devices as well as the basic behaviours of the above mentioned materials. Also, the basic concepts and properties of radiation as well as its effects (either permanent or transient) on semiconductors are reviewed.

In Chapter II, we study the effects of solar radiation on the basic characteristics of semiconductor materials (e.g. conductivity, gap energy calculations and dependence of conductivity on illumination level). Also, the photovoltaic and photocurrent (produced by illumination) in laboratory fabricated specimens of GaAs and CdS are investigated. On the other hand, great interest is paid to the illumination effects on the electrical properties of both solar cells and IMPATT diodes. This is achieved through studying and measuring of:

Output characteristics, collection efficiency, (I-V) relationship, (C-V) dependence and temperature effects.

In Chapter III, the effects of electron irradiation (with different dose intensity and energy) on the solar cell output characteristics, collection efficiency and temperature coefficients are investigated.

Chapter IV, concerns with the neutron irradiation, where either transient or permanent damages are existing. The effect of permanent damage, which occur at high neutron fluence, on the electrical properties of semiconductors is analyzed, where some important aspects are concluded. Besides, neutron activation phenomenon is examined. Moreover, the optical properties of irradiated semiconductor materials are included.

Chapter V, covers the existence of γ -radiation permanent damage on semiconductor materials. This is achieved using different electronic techniques like: differential thermal-, thermal gravimetric - and X-ray diffraction-analysis. This damage may affect either optical, electrical, physical or chemical properties of the tested semiconductor materials. On the other hand, we study transient γ -radiation effects on the conductivity of semiconductor materials. Also, photocurrent generation in semiconductor devices as well as (I-V) relationships under exposure and dependence on γ -radiation dose rate are presented and discussed. Finally, speed of carriers generation and electrical properties of CdS photoresistors are included.

Chapter VI, we develop a computer program for the analysis of the effects of different radiation types (electrons, γ -rays, neutrons and protons) as well as the operating conditions (temperature, illumination, etc.) on the characteristics of silicon solar cells. This program is a powerful tool in the calculations of the output power and efficiency of solar cells under various operating conditions.

Also, another computer programs are developed which provides facilities for devices simulation as well as material parameters effects. In addition, a special program is developed for calculating the distribution of radioactive doeses for any γ -ray emitting source.

Several applications based on the results of this work are developed and reported in **chapter VII.** One of these applications is the use of CdS photoresistors in very low γ -radiation dose-rate dosimetry and the second is the use of silicon solar cell in high γ -radiation dose-rate dosimetry. Finally, by making use of the linear response of the short circuit current in solar cell, very high light intensity beams are found to be measurable.

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