Chapter 21

APPLICATION OF RADIATION TECHNOLOGIES FOR THE MODIFICATION OF ELECTRONIC DEVICES

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1. INTRODUCTION

Radiation can change the properties of semiconductor devices and electronic circuits used in different fields as both on the ground and in space. This may be due to specific influences of a radiation environment on certain parameters of electronic components as when used in nuclear power plants, from particle accelerators and other equipment based on nuclear technology as used in medicine, science and industry. A terrestrial radiation environment is present because of the existence of naturally occurring radioactive elements and cosmic rays. Current leakage can increase or a threshold voltage shifted after electronic devices are exposure to a radiation environment. In general, semiconductors and the insulation materials of electronic devices can degrade or even be damaged under certain exposure conditions. The reliability of semiconductor devices exposed to ionizing radiation can be significantly affected. This is more important now because electronic devices are now much smaller and more complex.

The principal consequence of irradiation on electronic materials is radiation-induced effects (damages) of materials, which can disturb the functioning of the electronic devices made from these materials. These effects are related both to the properties of the irradiated material and to the type of irradiation. Research has focused on the development of new methods related to the hardening of electronic devices and to the improvement of their operation in radiation environments. Radiation-induced effects can also be used in the manufacture of electronic devices for intended modification of semiconductor materials and the properties of the final product.

There are different sources for ionizing radiation. Some originate in nature, whereas others are man-made. Ionizing radiation can be photons (electromagnetic quanta of gamma rays and X-rays) or particle beams (electron, ion or neutron beams). Accelerated electrons and ions, X-ray beams and thermal neutrons are produced by different types of equipment and are used for the modification of semiconductor material properties on an industrial scale. The worldwide semiconductor market has been estimated at US$147 billion, of which about 45% was shared by the USA and Japan [1].

2. IONIZING RADIATION-INDUCED EFECTS IN ELECTRONIC DEVICES

Accelerated electrons, ion beams, X-rays, cosmic rays and gamma rays transfer their energy by ejecting atomic electrons, which can then ionize other atoms in the absorbing material. Radiation-induced effects depend primarily on the absorbed dose and type of semiconductor material, and are less dependent on type of radiation. The irradiation of silicon crystals with high energy particles or gamma rays or X-ray results in the generation of electron-hole pairs (ionization, which can be recognized as a transitory damage) and of a variety of defects in the crystal lattice (displacement damage, which can be considered as permanent).

Figure 1 illustrates the radiation paths for electron, ion and photon beams in an irradiated semiconductor material. Heavy charged particles (ion beams) lose energy in small steps. Their well-defined short penetration range depends on ion energy and the target material properties. Ion beams may cause frequent atomic displacements, whereas electrons can generate only some. Gamma rays

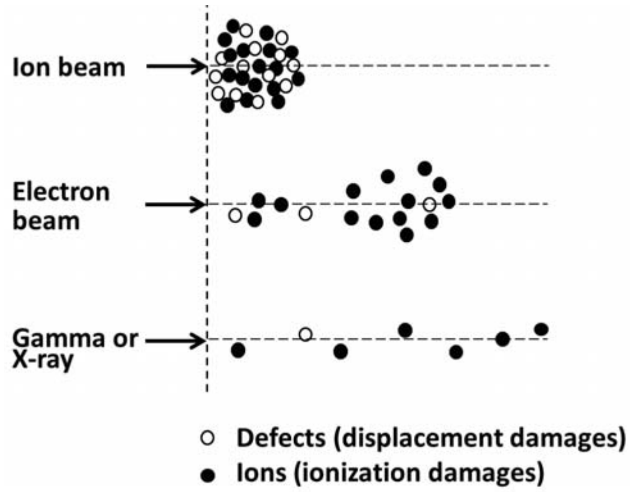

Fig.1. Radiation paths of electron and ion beams and gamma rays and X-rays in an irradiated semiconductor material.

and X-rays can generate rare atom displacements through the Compton effect. Ion beams can be also used to introduce impurities into the irradiated semiconductor material for certain electronic devices as well as to introduce dopants in substrates for state-of-art integrated circuit fabrication. The main advantages of ion implantation are: a low temperature process, precise dose, penetration depth control, possible implantation through thin layers of insulation, and a short process time.

The cumulative effects of semiconductor irradiation may occur during the entire lifetime exposure of the device or irradiation can be an intended step during the manufacturing process. In the first case, the irradiation may lead to damage of the semiconductor device if the radiation level has reached its tolerance limits. The sensitivity of such failure depends also on the type of semiconductor device and its construction. Several other parameters are also important: temperature, dose rate, device polarity, surface doping, and type of radiation. In some specific cases, a single event caused by the energy deposition of a single particle may also lead to catastrophic failure of device's operation. Dose effects can be evaluated in relation to the energy deposited in the irradiated material (dose level). The energy absorbed in an irradiated material liberates charge carriers which diffuse or drift to a place where they are trapped. In general, this leads to unintended concentrations of charge and consequently creates parasitic electronic fields.

Displacement damages are usually described in terms of the particle fluence (particles/cm^2). An elastic collision can be responsible for ejecting an atom from its normal lattice position. Displacement damages depend on the energy transferred to the lattice atoms. Displacements are specific for the types of particles and particle's kinetic energy. The primary knock-on atom may cause a cascade of atomic displacements before coming to rest. Certain levels of displacement energy are needed to overcome the semiconductor lattice forces and allow the atom to move for more than one atomic distance away from its original site. The threshold energy for an atom displacement in semiconductors is: 27.5 eV for Ge and 25 eV for Si. Displacement damages alter the electronic properties of the semiconductor crystals.

The crystalline structure of a semiconductor material can be modified by inelastic and elastic collisions which may occur during irradiation processing. Figure 2 shows the possible atom displacements from their original crystalline position. A displaced atom becomes an interstitial, thus its previous position is called a vacancy. Displaced atoms (interstitial) and vacancies are called a Frenkel pair. Vacancies and interstitials are mobile at sufficiently high temperatures and can be annealed by recombination. Damages may serve as charge--carrier donors and traps. Displacement defects play a major role in the reduction of the time interval needed for the transition between conduction and non-conduction states at semiconductor junctions. The presence of displacement effects in a semiconductor material is related to the reduction of a carrier lifetime. A carrier lifetime is defined as the average time it takes for a minority of the carriers to recombine.

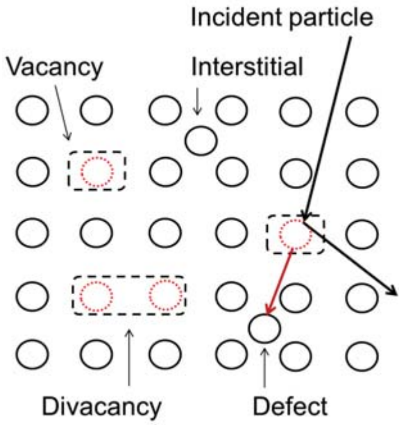

Fig.2. Defects created by atom displacement.

Displacement damages create trap levels, which help in transitioning electrons from valence to a conduction band. This leads to an increase of the reverse biased current. In the case of forward biased current, the trap level helps in the recombination of electrons and holes, which decreases the current. Traps that are close, either to the valence or conductive band, may capture charges (electrons and holes) and release them after a certain time. This leads to density variations of donors and acceptors. Ionization is a process that leads to the generation of ions by removing an electron from or adding an electron to a neutral atom. The principal result of ionization is the generation of electron-hole pairs within an irradiated material. Due to the specific configuration of energy levels, the radiation-induced effects in metals, semiconductors and insulators are quite different, as shown in Fig.3. Ionization-induced conductivity changes

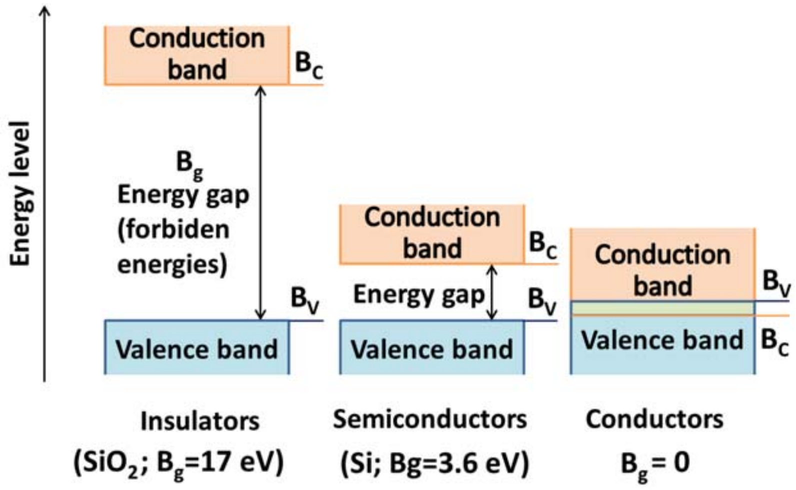

Fig.3. Energy band diagrams for insulators, semiconductors and conductors.

in metallic conductors are negligible. A quite different situation can be observed in irradiated semiconductors and insulators. The valence band in semiconductors and insulators is filled by electrons whereas conductive band is empty. A large number of electrons from the valence band can be excited to the conduction band because of irradiation. Time holes are produced in the valence band. Irradiation generates electron-hole pairs. Electron-hole pair generation energy amounts 2.8 eV for Ge and 3.6 eV for Si semiconductors. Since the direct recombination of electrons from conduction band with the vacancies in the valence band cannot happen, the electrons are free to drift through the irradiated material.

Electrons transferred to the conduction band can significantly increase the electrical conductivity of the semiconductor. Therefore ionizing radiation can modify certain electrical parameters of semiconductor devices, but also, in the extreme case, can ruin their performance and finally lead to the breakdown of the component or of a system.

Some semiconductor devices are more sensitive to radiation-induced ionization effects; some others are affected by a dominant radiation displacement damage. Permanent radiation damage can be observed only in the dielectric layers, like the gate oxide isolation in MOSFET (metal-oxide-semiconductor field-effect transistor) devices. When an electric field is present in the semiconductor material, part of the defect pairs do not recombine. Both electrons and holes start to drift in the electric field. Holes can be trapped in the defect centers inside the material, whereas electrons, having much higher mobility, can easily leave the material. In extreme cases, charges build up and defect activation may lead to degradation of the electronic device. If there is not an electric field, any unbalanced charges disappear due to recombination. The recombination process depends on the carrier lifetime and does not lead to material degradation.

Semiconductors of the n-type are characterized by electrical conduction made by the movement of electrons; whereas in p-type semiconductors, electrical conduction is mainly due to the movement of positive holes. In n-type semiconductors, the majority of carriers are electrons. In p-type semiconductors, the carriers are positively charged holes. A minority of carriers are responsible for carrying the lesser part of the current in a semiconductor.

In case of a p-n junction, the electric field separates electrons and holes. This leads to transient charging.

Semiconductor junctions are the basic components of diodes and more complex devices, as transistors and integrated circuits. They consist of p-type semiconductors where the majority of carriers are holes and n-type semiconductors where the majority of carriers are electrons, as show in Fig.4. A semiconductor junction is formed by direct contact between p- and n-type semiconductors which allows for the diffusion of charge carriers from one to another side of the contact. In this way, some of electrons are transferred from

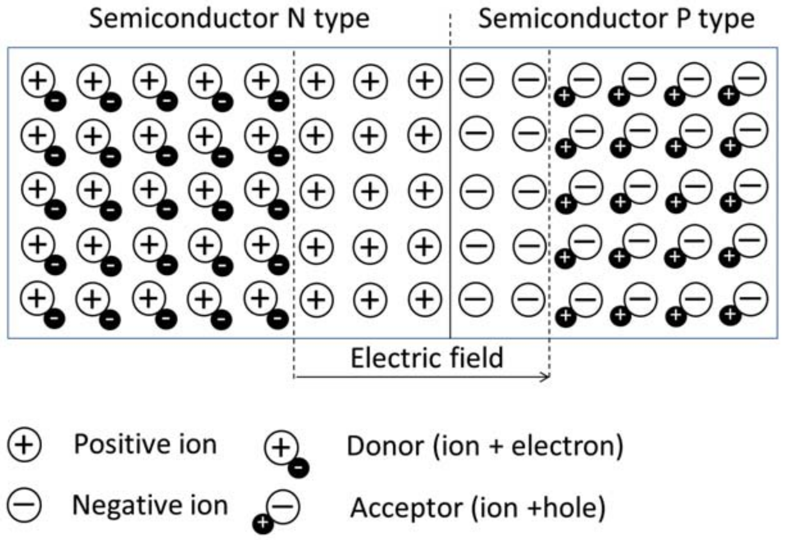

Fig.4. Semiconductor junction structure.

n- to p-type semiconductors; whereas holes in n-type semiconductors remain located on the same side of the junction. Thus narrow positive and negative charge barriers are formed indicating the appearance of an internal electrostatic electric field.

When the polarity of the battery is such that electrons are allowed to flow through the diode, the diode is said to be forward-biased. Conversely, when the battery is "backward" and the diode blocks current, the diode is said to be reverse-biased. A diode may be thought of as like a switch: "closed" when forward-biased and "open" when reverse-biased. A scheme of a diode is presented in Fig.5A. Different materials are used for the manufacture of p-n diodes: silicon, gallium-arsenide, silicon-carbide and others depending on how the device will be used.

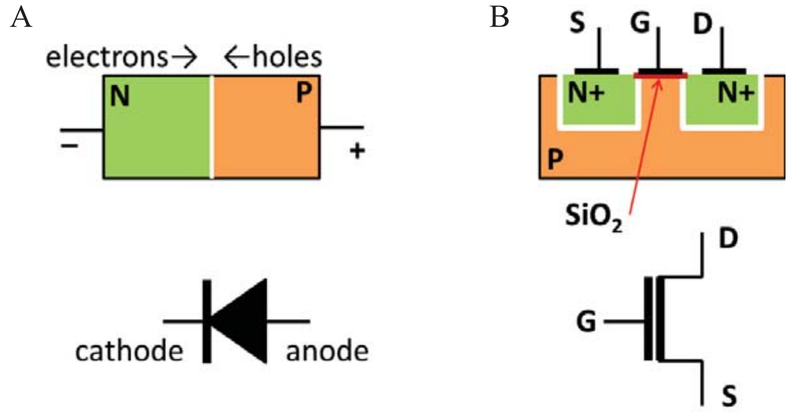

Fig.5. Schematic diagram of basic electronic devices: A – diode, B – MOSFET transistor (S – source, G – gate, D – drain, SiO_2 – gate insulator layer).

MOSFET transistors, as shown in Fig.5B, are also commonly used in electronic circuits. This device is very sensitive to the effects of the radiation environment because of the charge formation in the SiO_2 gate insulation layer. When the gate insulator is irradiated, free electrons and holes are created. These are then influenced by an applied electric field. Because of their mobility, electrons are able to move to the positive electrode. The holes move more slowly promoting the probability of getting trapped in the gate material. Trapped holes accumulate a charge which may significantly change a transistor's properties. A loss of drain control and transistor failure can be the result. Voltage-current properties of a transistor depend on the charge states in the gate insulator, which are determined by ionization damages. Discharging (a breakdown process) of a charged insulator is possible which may cause electrical damage of certain components of an electronic device.

3. RADIATION PROCESSING OF ELECTRONIC DEVICES

Semiconductors are used as a fundamental base for electronic components. Semiconductor devices are diodes, transistors, and integrated circuits and are used throughout computer and digital technology up to high power electronic devices, which are used to commutate high currents in power supply systems. There are a very broad range of uses for a variety of electronic devices with specific properties and technical specifications for each use. Some parameters for electronic devices, such as high switching speed (a reduction in the time interval between conduction and non-conduction states) or unified gain coefficient can be achieved by selective use of radiation processing. The semiconductor junction is usually described as a basic component of a diode. Diodes are the basic components of more complex devices, as transistors, FET (field effect transistors), thyristors and integrated circuits. A minority carrier's lifetime can be reduced by the introduction of efficient recombination centers. The recovery time for diodes and the switch off time for thyristors are directly proportional to the lifetime of minority carriers. Thus, all methods that lead to the shortening of the lifetime of minority carriers are used in the manufacturing of fast semiconductor devices. The generation of the recombination centers in the crystalline net of the silicon is the physical condition which shortens the lifetime of minority carriers. This may be achieved by introducing metallic impurities, like gold or platinum, into the silicon as a recombination centers of the semiconductor lattice. A similar effect can be obtained by the irradiation of the semiconductors with high energy elementary particles or photons. The irradiation process forms the primary and secondary defects in the crystalline net, and creates the effective recombination centers for minority carriers.

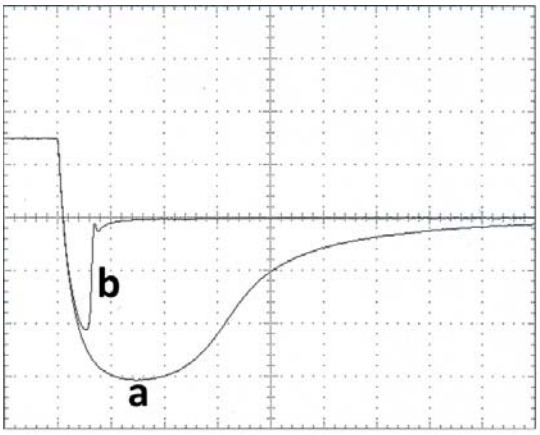

Fig.6. Current switching off characteristic of a diode: a – before irradiation, b – after electron beam treatment. Vertical scale: loading current – 2 A/div, horizontal scale: time – 1 μs/div.

The metal diffusion process is very sensitive to disturbances during fabrication procedure. High energy irradiation, in contrast, may be used for well controlled processing of high power diodes and of thyristors with known properties. The irradiation of semiconductor devices can also be performed in a final stage of the manufacturing process. An essential advantage of radiation processing is the ability to partially or totally remove the radiation effects by heating the samples. This can be very useful in the case of accidental overdosing. Electron beam (EB) irradiation was found to be the shortest, most useful and economic way for semiconductor processing.

Figures 6 and 7 show the loading current switching capabilities before and after electron beam irradiation for commercial semiconductor devices which were evaluated during experiment performed at the Institute of Nuclear Chem-

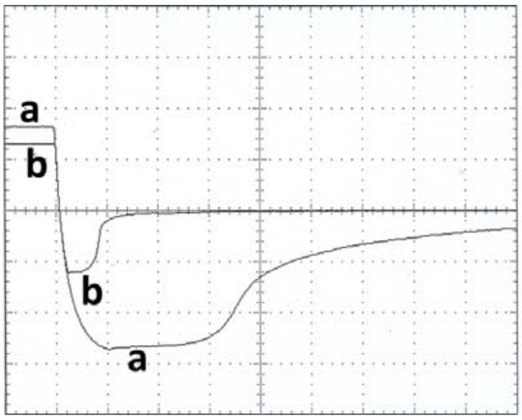

Fig.7. Thyristor current switching off characteristic: a – before irradiation, b – after electron beam treatment. Vertical scale: loading current – 2 A/div, horizontal scale: time – 1 μs/div.

A B

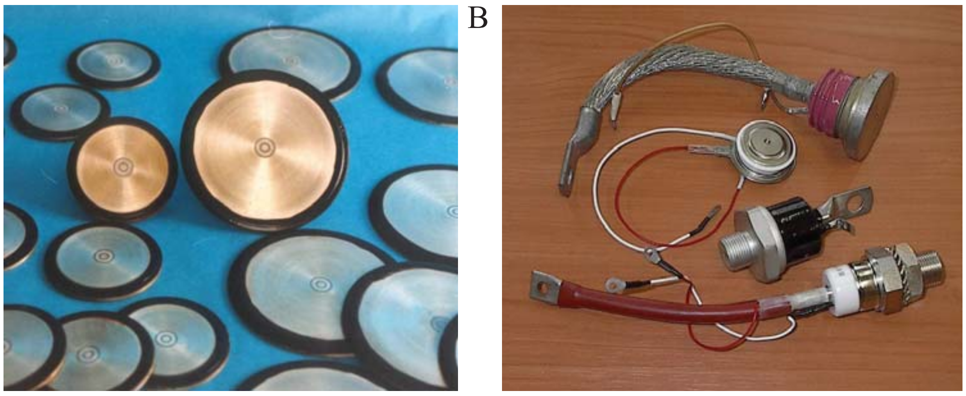

Fig.8. The general view of thyristor structures (A) and commercial power thyristors (B).

istry and Technology (INCT, Poland). Figure 8A shows the general view of a thyristor structure. Some commercial thyristors are shown in Fig.8B.

The dependence of the reverse recovery time (t_{rr}) as well as of the forward voltage drop (V_F) from a 10 MeV electron fluence (dose) on irradiated commercial diodes are presented in Fig.9 [2]. The minority carrier's lifetime and switching speed can be easily controlled by the fluence (dose) used in the irradiation process.

The major advantage of high energy electron irradiation is the depth of penetration of electrons in matter and the penetration into encapsulated semiconductor power devices. The possible high cost of radiation processing is compensated by a major improvement in semiconductor device performance and a simplification of the device manufacturing process. The following radiation-induced modifications of parameters of diodes and thyristor are possible:

- Shortening the recovery time of diodes and thyristors as a consequence of the shorter lifetime of minority carriers. This parameter depends on dose. Modifications are very effective but some saturation has been observed for

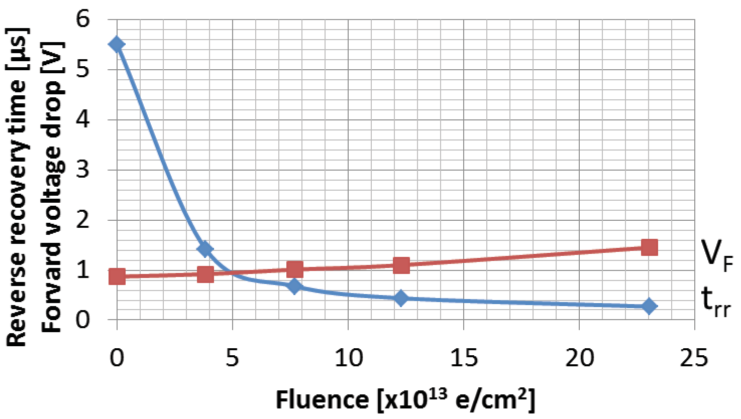

Fig.9. The relation between the fluence of 10 MeV electrons and reverse recovery time (t_{rr}) as well as forward voltage drop (V_F) of irradiated commercial diodes [2].

the high doses. It is quite common to reduce the switching-off time for thyristors by a factor of 3 and in parallel to reduce the diode's recovery time by approximately 10 times.

- An unfavorable fall of the load current has been observed (the increase of voltage in the conductive state) as a consequence of the decreasing lifetime and the average free diffusing distance of the carriers. This effect is much stronger if the voltage of the diode and silicon resistivity is higher after irradiation. A comparison of semiconductor devices properties after irradiation clearly shows advantages for the use of the radiation process for devices which can be used up to 1500 V.
- Radiation-induced defects in a silicon matrix are stable over a period of 40 years if the temperature of the semiconductor device does not exceed 125°C.

Figure 10 shows semiconductors packed for radiation processing at the INCT radiation facility that is equipped with an electron accelerator (beam energy – 10 MeV, beam power – 10 kW). The ratio between the price for a given performance level (higher unit price) and the unit cost of irradiation is, when using an electron beam, the highest for all radiation processing technologies used on a commercial scale. The price/cost ratio can be as much as 10 to 20 times of the irradiation cost.

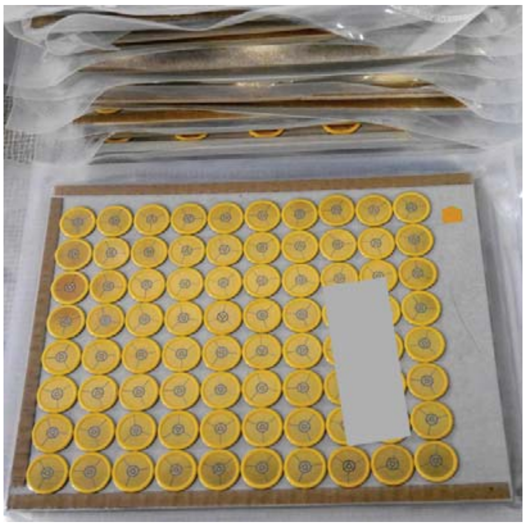

Fig.10. Semiconductors packed for radiation processing.

The large spread use of semiconductor devices containing doped gold or platinum impurities may lead to situation when a number of components do not meet required performance parameters. These components too can be improved by radiation processing.

Another important feature is related to the trimming process which is used after the radiation-induced modification of semiconductor devices. Significant reduction in the variations of certain semiconductor properties help to produce devices for parallel configurations. These devices require good matching of the reverse recovered charge or unification of the forward voltage drop [3].

The reduction of switching time of high power semiconductor devices may significantly reduce the thermal energy losses because in transit period the resistivity and the loading current are relatively high, capable of generating heat through resistance heating. Because of this effect, it was estimated that the Polish industry could save 32 GWh of power over a one year period. This would reduce the requirements for installed electrical power and generator plants by over 200 MW. The radiation modification of semiconductors on industrial scale was started in Poland over 40 years ago [4, 5].

Gamma irradiation gives similar effects as does electron beam processing but at significantly lower efficiency. Sometimes both electron and ion beam treatment methods are used to optimize certain properties (like switching characteristics). In such a case electron beam processing allows for the control of carrier lifetime in a material volume. Ion beam treatment, with limited penetration, can be used for precise changes of carrier lifetime in specific regions of the device. Electron doses ranging from 0.05 to 400 kGy and ion beam fluences (*e.g.* proton and helium) varying from 10^9 to 10^{13} ions/cm^2 are used. Exact irradiation conditions for certain types of semiconductor devices, like beam energy and dose rate, are confidential with each company.

4. DOSIMETRY BASED ON SEMICONDUCTOR SENSORS

Dosimetry plays an important role in nuclear research and in particular in radiation processing, where the absorbed dose should be established on a routine basis. The use of semiconductor devices, like Si diodes and MOSFET transistors, are recognized as one of innovative methods which can be used for dosimetry measurements as performed in the medical area at doses of 0.5 to 10 Gy and also in typical industrial irradiators where the absorbed dose can range from 10 Gy to 50 kGy [6]. One of the important features of the use of semiconductors in dosimetry measurements is simplicity and precise electrical readout.

The characterization of semiconductor devices as routine dosimeters revealed the possible influence of different environmental conditions on the final results [7]. A post-irradiation heat treatment protocol for stabilizing the dosimeter response is recommended. This is important in order to attain reliable dosimetry results and also to be able to read the dosimeter again at some future time. Semiconductor dosimetry is valid for both high activity gamma sources and for high energy, high power electron beam facilities.

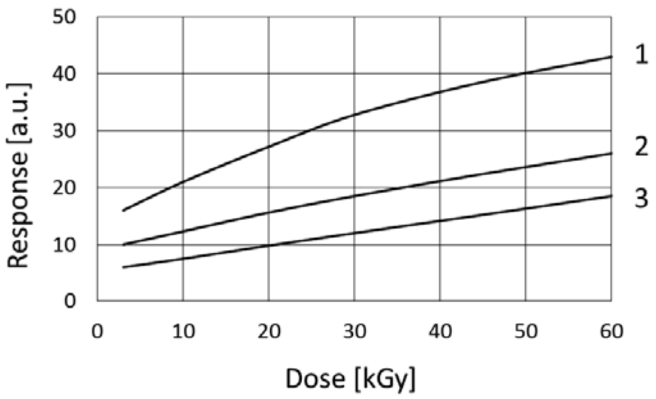

Fig.11. Calibration curves for transistor dosimetry system for cobalt-60 gamma rays: 1 – after irradiation; 2 – post-irradiated, after heating for 30 min at 100°C; 3 – post--irradiated, after heating for 30 min at 150°C [7].

The results presented in Figs.11 and 12 were obtained using commercially available, high voltage, fast switching n-p-n bipolar power transistors. A decrease in the charge carrier lifetime for these devices is proportional to the absorbed dose. The response of the transistor to irradiation was measured and compared with dose as absorbed in water according following reference dosimeter protocols.

Different dose responses of irradiated transistors were found for measurements performed just after irradiation, after heating for 30 min at 100°C and after heating for 30 min at 150°C. Significant differences between gamma and electron beam treatment were noted in the sensitivity of dose measurements and the ability to anneal irradiated semiconductor devices [8].

Experimental results obtained during the investigation of bipolar power transistors, which were tested as dosimeters, revealed that that they can be used

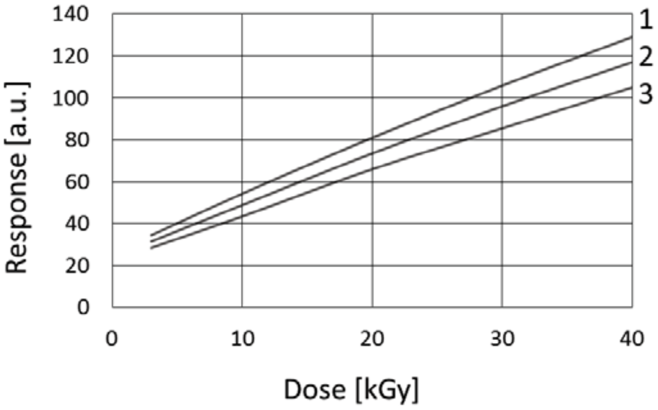

Fig.12. Calibration curves for transistor dosimetry system for 10 MeV electrons: 1 – after irradiation; 2 – post-irradiated, after heating for 30 min at 100°C; 3 – post-irradiated, after heating for 30 min at 150°C [7].

for routine dosimetry at gamma and accelerator facilities. However, each batch of transistors should be carefully evaluated because of variations in their response to irradiation. There is a limited dependence of transistor response to the temperature at which the measurements were made. A laboratory with a controlled temperature for ambient conditions should be used. The post-irradiation heat treatment protocol is recommended to stabilize the dosimeter response. This makes it possible to obtain reliable readouts of dosimeters in the future and were archived for months. The main advantages of using transistors for dosimetry are: low cost, a relatively inexpensive readout system, ease of use, and a very short time to perform dose measurements [9].

5. SUMMARY

Electron beam modification of semiconductor devices is based on the decrease of the lifetime of minority carriers after radiation treatment. To obtain suitable conditions for this process a number of defects are created in silicon crystals by high energy electrons. Certain irradiation conditions should be followed to obtain a compromise between decreasing carriers' lifetime, which leads to the faster switching properties, but at the same time reduces load current level. The major advantages of high energy electron beam use for the modification of the properties of electronic devices rely on the electron's depth of penetration into the matter and its generation of a uniform distribution of recombination centers. Because of this, a device's switching time can be tailored according to user needs even in finished or encapsulated power devices.

Electron beam processed fast switching power thyristors and diodes are used in a growing number of applications for which the long-term stability, the efficiency and energy savings semiconductor components are important and assured through competitive pricing. Power interruptions at data processing centers and at hospitals with life-support equipment are examples of the need for such power thyristors and diode devices, along with many other applications in metallurgy, mining, transportation, household uses and other areas. Electron beam technology does not require additional investment. The cost of using an existing electron beam facility can be melded into the total product cost. This can be quickly recovered because of the major improvement in devices and the simplification of the device manufacturing process.

The main factors (if not under control) that may cause the electronic component damage are: energy of the ionizing radiation, radiation flux and exposure time. Larger particles may cause higher damage due to their mass and cross section area. On the other hand, electromagnetic radiation (gamma rays, X-ray) requires a lot of energy to cause bulk damage in semiconductors. That is why X-ray inspection is rather safe for electronic devices.

The penetration of ionizing radiation through the silicon oxide layer formed on the semiconductor surface causes the buildup of a trapped charge in the insulator's layer. If the charge moves towards the SiO_2-Si interface, the basic characteristics of the semiconductor will be changed. Single radiation-induced effects are not recognized as permanent damage but have the potential to alter the microcode of certain devices and memory circuits.

The radiation processing technique, as compared to the introduction of metal impurities in semiconductors, offers: precision, reliability and reproducibility of required properties. Precise control of the concentration of defects that are generated provides more uniform electrical properties. Electron beam technology helps solve common diffusion problems present, when metal impurities are introduced into a semiconductor: non-uniform depth distribution of impurities and high leakage currents. The irradiation process is very flexible and can be used for the processing of raw semiconductor components and for final products as well as for the improvement of the device properties. The stability of radiation-induced defects is assured for over a period of 40 years, if the temperature of the semiconductor device does not exceed 125°C, which is close to upper limit of junction temperature during normal device operation. There is also the possibility to control and remove radiation-induced defects through a proper annealing process.

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