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Control of Switching Characteristics of Silicon-based Semiconductor Diode Using High Energy Linear Accelerator

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This paper reports control of switching characteristics of silicon-based semiconductor diode using electron beam produced using linear accelerator. Conventionally, p-n junction chips of diode are exposed to gamma rays from a radioactive source or electron beam from a microtron, depending upon the required level of correction. High energy linear accelerators featuring simultaneous exposure of multiple chips are recent advancements in radiation technology. The paper presents the results of the radiation process using a 10 MeV linear accelerator as applied in industrial manufacturing of a high voltage diode (2600 V). The achieved values of reverse recovery time were found to be within the design limits. The suitability of the new process was verified by constructing the trade-off curve between the switching and conduction parameters of the diode for the complete range using large number of experimental samples. The paper summarizes the advantages of the new process over the conventional methods specifically with reference to industrial requirements. The developed process has been successfully implemented in semiconductor manufacturing.

Keywords: Semiconductor diode, Reverse recovery characteristics, Electron irradiation, Linear accelerator.

PACS numbers: 85.30. – Z, 61.82.Fk

1. INTRODUCTION

Switching time is a critical parameter in power electronic applications especially where the speed of operation is a significant criterion for the circuit designer. Semiconductor diode, which is a bipolar device with electrons and holes as the two carriers establishing the current transport, switches alternately between conduction (ON) and blocking states (OFF) while operation. The switching speed is directly proportional to the rate of recombination of electrons and holes. Deep energy levels, which are formed within the forbidden band gap of Silicon during the fabrication of diode chip, aid the recombination process. Several methods are adopted in semiconductor manufacturing to create deep levels. Radiation, whereby the chips are exposed to gamma or electron rays, is the most effective method. This paper details the experiments and results of high energy (10 MeV) electron beam using linear accelerator as applied to a high voltage diode of 2600 V rating and 9 microseconds of reverse recovery time. The process was eventually established in industrial manufacturing for control of reverse recovery parameters of the diode.

2. STRUCTURE OF SEMICONDUCTOR DIODE

Semiconductor diode is basically a p-n junction having a four layer structure p^+-p-n-n^+. The p-n junction has a gradient profile of doping concentration that provides the high voltage capability to the diode, as in Ref. [1]. The widths of the p and n layers are so chosen as to accommodate the depletion regions on either side of the junction upon application of the rated reverse voltage. The n^+ and p^+ are heavily doped layers that promote injection of electrons and holes towards the junction and also improve ohmic contact with the respective cathode and anode electrodes.

3. FABRICATION

Fig. 1 shows the process flow chart for manufacture of semiconductor diode. Initially, the p-n is formed using a double diffusion process with Aluminium and Boron as p-type dopants. Further, n^+ layer is formed on the cathode side using a phosphorus-based dopant source. The silicon wafer is then attached to a molybdenum disc on the anode side using a high-vacuum (10^{-6} Torr) brazing process that employs an Aluminium-based solder alloy. This provides the final p^+-p-n-n^+ structure to the diode. Physical vapour deposition process is employed to deposit high purity metal electrode layers on anode and cathode sides. The circular periphery of the diode chip is then shaped at an angle using surface lapping and chemical-etching procedures that minimize the intensity of surface electric field during reverse blocking mode. A suitable rubber coating applied on the beveled edge neutralizes the surface charges present on the silicon surface. Further, the chip is encapsulated in a suitable package based on the specific application requirements. The structure of diode chip is shown in Fig. 2.

4. SWITCHING PARAMETERS

In a power electronic application, semiconductor diode periodically switches between ON and OFF states. The carriers flood the n and p layers of the diode during conduction. While switching to OFF state, these carriers take a finite time to clear these layers even after the reversal of bias, as in Ref. [2]. During this transient period, the diode current reverses the direction and passes through a peak, which is known as

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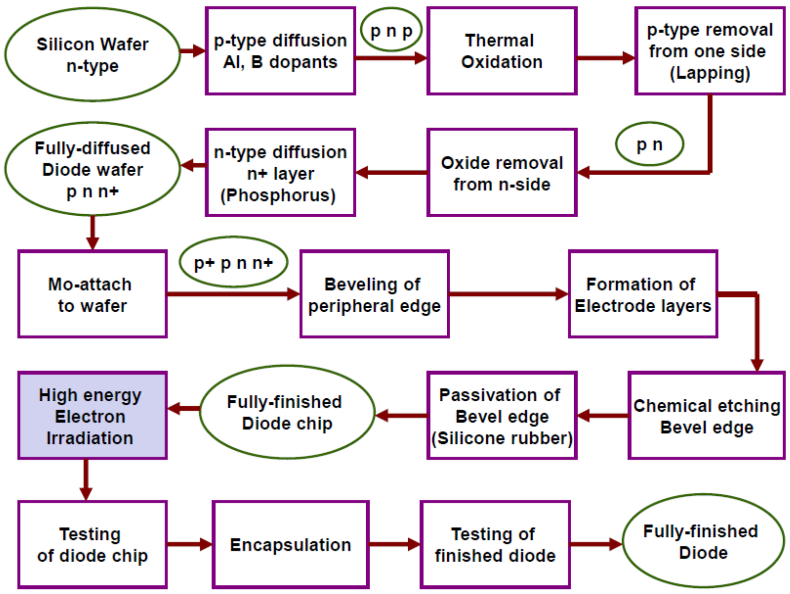

Fig. 1 – Process flow chart for manufacture of semiconductor diode

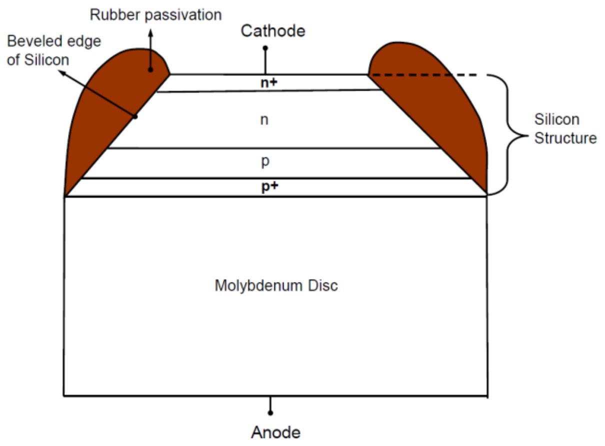

Fig. 2 – Structure of semiconductor diode

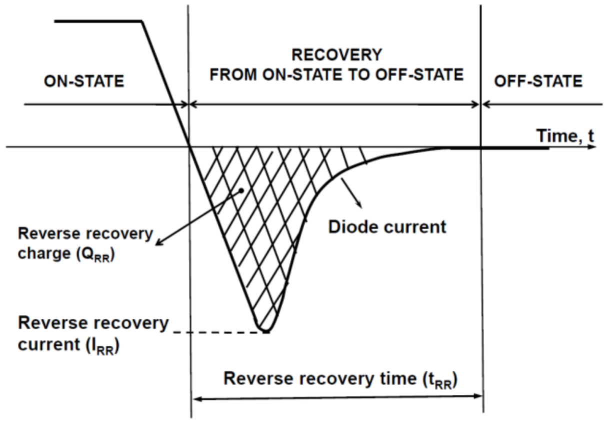

Fig. 3 – Semiconductor diode recovery from ON to OFF state

reverse recovery current (IRR). Further, the current decays at a pace determined by the rate of recombination of the carriers. As the current reaches certain minimum level, the diode is ready to support the reverse voltage. This instant defines the reverse recovery time (tRR). The charge that is cleared to facilitate the OFF condition is termed as reverse recovery charge (QRR). These recovery parameters are illustrated in Fig. 3.

5. CONTROL PROCESS

As explained above, the reverse recovery characteristic has a strong bearing on the speed with which the semiconductor diode turns off from its conduction state. Faster switching from ON to OFF stage is achieved by enhancing the recombination rate of electron-hole pairs. Energy levels created deep into the forbidden band gap of Silicon promote the recombination mechanism by way of capturing the carriers during their transition between valence and conduction bands. Diffusion of gold atoms into Silicon is one method to introduce such a deep energy level, as in Ref. [3]. However, this method is outdated in semiconductor manufacturing due to poor controllability of the associated high temperature process.

Exposure of diode chips to gamma rays or electron beam is adopted as an alternate process, as in Ref. [4]. Either a low energy radioactive chamber or a high energy microtron accelerator is conventionally adopted, depending upon the degree of correction required in the switching parameter. Unlike gold diffusion, radiation is a reversible process. If necessary, the effects of radiation can be nullified by means of a suitable heating process. Moreover, an irradiated diode chip exhibits considerably less reverse leakage current as compared to gold diffused chip. These meritorious aspects of radiation are critical to industrial manufacturing where rejection rate is a significant economic concern.

6. LINEAR ACCELERATOR

In recent times, the focus of radiation technology has been on developing high energy linear accelerators with features of simultaneous exposure of a large number of diode chips, as in Ref. [5]. For the present work, the 10 MeV linear accelerator (Linac) facility at Electron Beam Centre (EBC) of Bhabha Atomic Research Centre (BARC) located at Khargar, Navi Mumbai was used for adjusting the switching time of the high voltage diode of

2600 V rating to the specified application requirements. The accelerator system consists of LaB_6 based electron gun injecting into a standing wave on-axis coupled cavity Linac, which accelerates the beam to energy of 10 MeV level, as in Ref. [6-9]. A 2856 MHz, 3.5 MW Klystron based RF power source is used to establish the required electric field inside the Linac.

The electron gun produces electron beam of 50 keV, 10 microseconds, 100 Hz with maximum peak current ~ 1 A. The complete beam line is in high vacuum (10-7 torr) produced by turbo-molecular pump.

7. EXPERIMENTS AND RESULTS

In semiconductor manufacturing, it is necessary to maintain high level of purity of materials and cleanliness of surroundings in order to satisfy the inherent process requirements. As a consequence to this, the initial values of switching parameters of the fabricated diode are at a higher level than the specified upper limits, thereby necessitating suitable correction. Electron dose is selected based on the initial value. In order to prescribe the dose on a scientific basis, a diode response curve was constructed. For this, samples of diode chips were irradiated with different doses of electron. The ratio of the final to the initial values was used to evolve the relationship between the required correction and the dose. Fig. 4 shows the dosage curve for reverse recovery time, where t_{RR0} and t_{RRE} represent the initial and final values respectively.

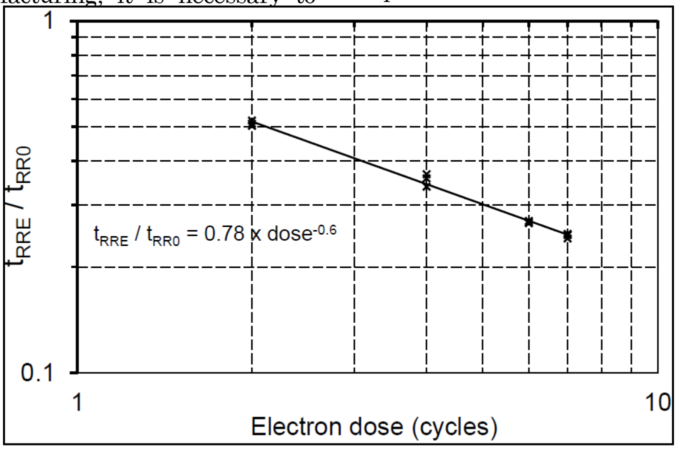

Fig. 4 – Diode response curve for selection of electron dose

While selecting the dose to bring down the reverse recovery time within the specified limit, care is also exercised to ensure that the forward conduction drop does not exceed its upper specification limit after radiation. This is due to the inherent trade-off relationship between the switching and conduction parameters. The diode is designed with an acceptance window confined by the limits of both the parameters. Fig. 5 and Fig. 6 show the trade-off curves that were constructed by irradiating a large number of samples to different doses within a wide range. These graphs are plotted using the parameters normalized to their limiting values. Q_{RRL}, t_{RRL} and U_{FL} denote the upper specification limits of reverse recovery charge, reverse recovery time and forward voltage drop respectively. The acceptance window is also marked on the graphs. It is to be noted that only those samples lying within the window meet the application requirements. Since radiation is a reversible process, the samples falling outside the window can also be corrected either by repeated radiation or by a suitable heating process, depending on whether the switching parameter is higher or lower than its limit. The curve obtained using conventional 8.6 MeV microtron accelerator at Department of studies in physics, Mangalore University is also plotted on the same graphs. The observation that both the curves compare well with each other validates the new 10 MeV linear accelerator process for the given semiconductor application.

8. SUITABILITY OF PROCESS TO INDUSTRIAL MANUFACTURING

The 10 MeV linear accelerator process has features of mass processing. Hundreds of semiconductor chips are placed on the radiation bed of the accelerator and the process takes a maximum of 30 seconds per run.

Such a mass production capability coupled with short cycle time makes the linear accelerator suitable to industrial manufacturing. Further, the reversibility of process, observed as similar to the Microtron accelerator, is an added merit to the industry, as it provides economic advantage by way of minimized rejection rate.

9. SUMMARY

High energy electron beam using 10 MeV linear accelerator was explored as a process in industrial manufacturing for control of switching parameters. The process capability was demonstrated using a Silicon-based high voltage diode (2600 V). Diode response curve was constructed to facilitate appropriate selection of electron dose based on the initial values of reverse recovery parameters. The complete trade-off curves depicting the relationship between switching and conduction parameters were experimentally established based on radiation carried out on a large number of samples. The new linear accelerator process was verified by comparing the trade-off curves with those of conventional mircrotron accelerator. The successful implementation of the new process in semiconductor manufacturing is attributed to its mass production and short cycle time features.

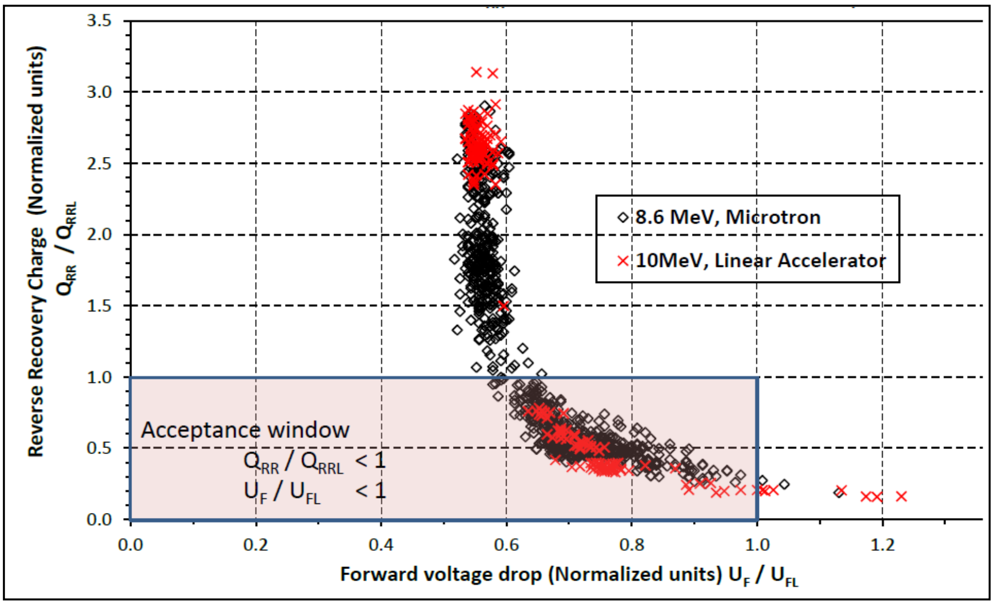

Fig. 5 – Trade-off chart of semiconductor diode: reverse recovery charge versus forward voltage drop

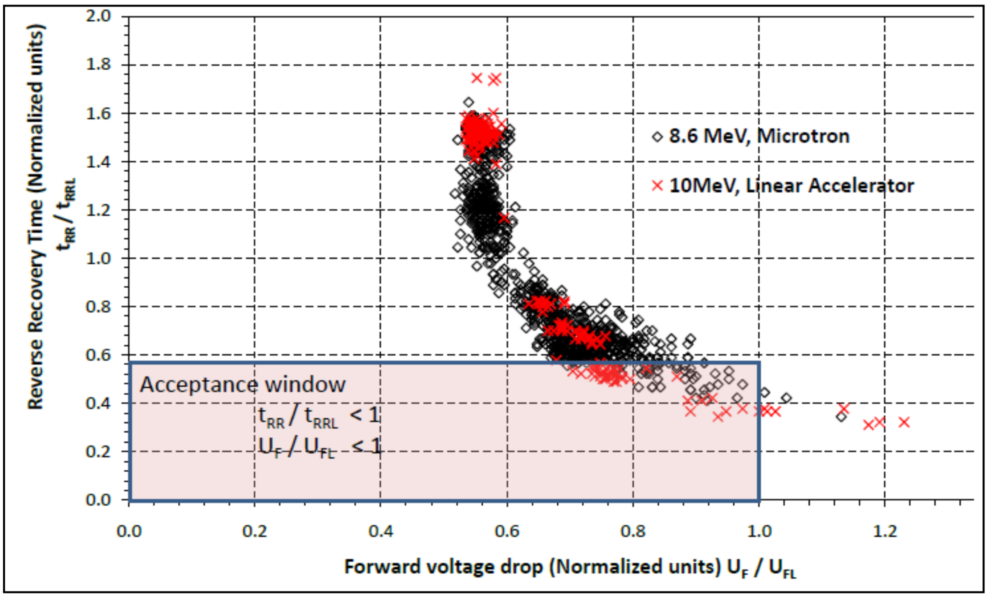

Fig. 6 – Trade-off chart of semiconductor diode: reverse recovery time versus forward voltage drop

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