CHAPTER I
INTRODUCTION

High performance semiconductor devices with better voltage and current handling capability are required in different fields like power electronics, computer and automation. Since the invention of the germanium point contact transistor in 1948[1], there has been all round progress in the science and technology of these devices. A number of new devices have been developed and old technologies have been optimized and modified by introducing better materials, designs and processes to meet the growing need for better characteristics. Besides, higher voltage and current ratings, higher switching frequency is also required for the compact design of Switch Mode Power Supplies (SMPS), for high power efficiency in variable speed motors and for better picture quality in TV deflection circuits. The power diode and transistor have been in use in such applications for a long time. The technology of these devices is quite mature. To meet the demand of still higher switching frequency, these devices are facing some inherent constraints. While operating these devices in the ON state, there is storage of minority charge carriers in various parts of the diode and transistor. These minority charges cause storage time delay and affect the voltage and current conduction processes during reverse recovery, (τ_{rr}). The dissipation in the ON state and during reverse recovery (τ_{rr}), constrain the operation of the diode and BJTs to a switching frequency of about 100 kHz. Large efforts have been made to decrease the losses in the ON state and during reverse recovery to improve the switching performance of these devices. In the present work, we study the effect of incorporation of “universal contact” (UC) [2] on the storage of minority carriers, reverse recovery process and other characteristics of diodes and transistors. Before focusing our attention on this important topic, the present state of art of the semiconductor devices with a particular emphasis on the diode and bipolar junction transistor (BJT) is presented.

1.1 STATE OF THE ART OF TWO TERMINAL DEVICES USED FOR SWITCHING

In power circuits, active devices may be classified into two categories i.e. the two terminal devices mostly for rectification and three terminal devices as control switch. In two terminal devices we may include PIN diode and Schottky diodes. Both have their own merits. The Schottky is a low ON state voltage uni-polar device. There is no minority charge storage and hence its switching speed is fast. However, silicon Schottky diodes are limited to less than 100 volts reverse blocking voltage because of higher reverse leakage and soft breakdown. The Schottky diodes made of other material like GaAs and SiC have high switching speeds, high operating voltage and wider temperature rating [3]. But, their technology is comparatively new and materials are costlier in comparison to silicon. In medium (500-2000) and high voltage (>2000 V) operation, silicon PIN diode is the only reliable and widely used device at present. However, it has a relatively high ON state voltage and large reverse recovery time. Both of these are responsible for larger heat dissipation. To tackle the issue of higher ON state voltage and larger reverse recovery of silicon PIN diodes, three modification of the basic PIN diode structure are suggested in literature. The first is the incorporation of “universal contact”

(UC) [2], which is the focus of the present study. The second is the junction barrier controlled schottky (JBS) [4] rectifier, which is a Schottky rectifier structure with a P-N junction grid integrated into the drift region. It has low ON state voltage and smaller reverse recovery. The experimental device capable of supporting 30 volts has been demonstrated. The third device is the merged PIN/Schottky (MPS) rectifier [5] to reduce the switching losses in high voltage power rectifiers without increasing the ON state voltage. A comparison of PIN and MPS rectifiers with IGBT has been carried out for variable speed motor drives. It is shown that the switching performance of the variable motor drive improves with MPS rectifier [6] with respect to PIN diode. Thus, there has been progress in the technology of the two terminal devices and the shortcomings of the basic PIN diode are slowly being removed.

1.2 STATE OF THE ART OF THREE TERMINAL DEVICES USED FOR SWITCHING

There has been steady progress in the technology of the three terminal power devices. While consistent efforts have been made to improve the old devices like Thyristor and BJT by introducing modifications and innovations, a few new device like power MOSFET, MCT and IGBT have been developed. The extensive progress in the design and technology has resulted in the development of thyristors with a rating of 4000-8000V and 3000A. A whole variety of devices like triac, reverse-conducting thyristor, GTO (gate turn-off thyristor) and light triggered thyristor have been also developed. For the thyristor used for phase control at line frequencies the turn-off time is normally in the range from one hundred to several hundred microseconds. When thyristors are designed and manufactured specifically to have short turn-off times, their turn-off time is several microseconds up to 50 μs [7]. In medium voltage (<1500V), BJT, MOSFET and IGBT are the desired devices. The BJT has been in use for more than 50 years. It is simple, easy to manufacture and easy to use. Millions of discrete bipolar transistors are manufactured every year. Continuous efforts have been made to understand the physics and to improve its characteristics by introducing new designs and innovations. Different models [8, 9, and 10] have been developed to enhance our understanding of this device and now are part of most simulation programs. Thousands of papers and application notes have appeared in literature dealing with all these aspects. In contrast to its low voltage counterpart, the high voltage BJT has two major limitations. One is the low gain (~10-20) and other is the large reverse recovery (1-20 μs) delay. The low gain requires large base drive and the large reverse recovery limits its operation at high switching frequency.

To overcome the problem of large base drive, larger reverse recovery delays and other constraints like current crowding etc. of BJT, two different kinds of developments have taken place. First, those who had the faith in the simplicity and ruggedness of BJT have tried to remove the shortcomings of the BJT structure and improve its characteristics. Some technological developments have taken place to improve the basic BJT structure. The doping profile of base, emitter and collector has been optimized to increase the current gain so as to reduce the base-drive, eliminate reach-through breakdown and increase the safe operating area. Connecting two BJT in monolithic Darlington configuration has, largely solved the low current gain problem of power BJT.

New emitter structures like hollow emitter, cellular emitter structure [11] and perforated emitter have been proposed. These structures basically deal with the problems of current crowding and reverse recovery. Second, there emerged a number of new kinds of devices, which showed better characteristics and solved some of the problems faced by the users of the BJT. Out of these, power MOSFET, IGBT and MCT are the important developments. Power MOSFET is different from its low voltage counterpart. The drain is made on the bottom side of the substrate instead of the same side of the source. This increases the area for current conduction and current conduction takes place through transport of majority carriers in the drift region. No delays are observed as a result of storage or recombination of minority carriers in power MOSFETs during turn off. Their inherent switching speed is orders of magnitude faster than the bipolar transistors. The transistor is controlled by voltage on gate electrode. No separate high current drive is required. Power MOSFETs have other advantages like higher safe operating area. However, these advantages are offset by high ON state resistance. As there is no injection of minority carriers to modulate the conductivity of drift region, the ON state resistance of the MOSFET is high. High on-resistance of MOSFETs limits its operating forward current density to relatively low values (typically in the range of 10 A/cm^2 for a 600 V device)[12]. Another competing device, IGBT is a hybrid of MOSFET and BJT. It incorporates the physics of bipolar current conduction with a voltage control gate of MOS. The injection of minority carriers into the bipolar drift region reduces the ON state voltage. Because of this, it is capable of operation at relatively high current densities (typically 200-300 A/cm^2), even when designed to support high voltage. These devices are being used in a number of applications.

The above two-technology i.e. of Metal-Oxide-Silicon (MOS) field effect transistor and Insulated Gate Bipolar Transistor (IGBT) have emerged as real contender of BJT power technology. There is no doubt that MOSFET and IGBT have better characteristics in certain respects in comparison to BJT. However, as yet these have not replaced BJT either due to higher cost consideration or due to complexity of design and manufacturing difficulties. The discrete PIN diodes and BJT are still reigning the market in medium voltage and current applications. Most important thing is that these devices still enjoy the confidence of users and manufacturers. Millions of discrete p-i-n diodes and bipolar transistors are still marketed by Motorola, Philips, Siemens and other big companies. Though, the research activity has dwindled in this area in recent times because of the maturity of bipolar technology and interest in other competing devices, it is felt that there is need to improve the switching speed of the p-i-n diodes and BJT transistors.

1.3 FOCUS OF THE PRESENT WORK

There have been developments to enhance the switching performance of diodes and transistors, such as, through Au doping and through use of Schottky clamp transistor. In 1982, Amemiya [2] introduced a concept known as universal contact to improve reverse recovery performance of diodes and transistors. Amemiya et al showed that the incorporation of n^+p^+ UC in a p^+nn^+ diode at the n^+ end resulted in significant improvement in reverse recovery and decrease in the forward ON voltage. In addition, the application of UC had an advantage when compared to the technique of Au doping to control the reverse recovery, that it did not lead to increase of leakage current or a soft breakdown.

The incorporation of universal contact in the n^+ region such that it adjoins the lightly doped n region, works well with diodes of low or moderate breakdown voltage, but degrades the reverse blocking capability of high voltage diodes due to the onset of reach-through. Kitagawa [13] proposed the incorporation of p^+n^+ universal contact inside the diffused region of the p^+nn^+ diode away from the lightly doped region; this avoided the reach-through and still improved the reverse recovery time. Besides diodes, the universal contact has also been applied to low voltage BJTs to obtain significant reduction in storage time, Narain [14].

In the work [2,13,14], although the usefulness of the universal contact has been demonstrated, its application however has been in a limited range of current, voltage and devices. It will be further desirable to explore the effects of incorporation of UC over a wider range of current and voltage in diodes and transistors and other devices. The application of UC in a diode or transistor involves creating new diffused regions in an otherwise conventional device. The presence of these new regions alters the distribution of minority carriers and the currents flowing within the device. It is necessary to have a suitable analysis and model, which can account for the various phenomena, taking place inside the device and their influence on various parameters of the device.

1.4 OBJECTIVE OF THE PRESENT WORK

Keeping in view of the above considerations, we define the following objectives of the thesis: -

(1) To study the reduction in reverse recovery due to incorporation of universal contact and its effects on other device characteristics using a combination of analytical modeling, numerical simulation, fabrication and characterization of low and high voltage PIN diodes with and without incorporating of universal contact.

(2) To suggest changes in the design of PIN diode to achieve better characteristics.

(3) To study and model the reduction in reverse recovery due to incorporation of UC and its effects on other device characteristics using a combination of analytical modeling, numerical simulation, fabrication and characterization of low and high voltage BJT with and without incorporating universal contact.

(4) To suggest changes in design of BJT to achieve better characteristics.

1.5 OUTLINE OF THE THESIS

The study is divided into five chapters.

The first chapter gives an introduction to the need for faster switching power devices and the position of PIN diode and BJT amongst other competing devices. The conventional methods of improving reverse recovery are discussed followed by a description of advantages of UC with respect to these methods and the review of the work already done in this area.

In the second chapter, a theoretical framework for investigating the switching characteristics of PIN diodes is developed through modeling of effective minority carrier lifetime in the device. The dependence of effective lifetime on important device parameters and its relationship with other device specifications such as reverse blocking voltage are discussed in detail. The results obtained from the analytical model are validated and elaborated through extensive 2D numerical simulation [15] and fabrication and characterization of diodes of different breakdown voltages. Based on this study a new improved structure for PIN diode is suggested.

In chapter three, the model developed for PIN diode is extended to discuss the switching characteristics of BJTs and the impact of insertion of universal contact within the extrinsic base region. The relationship between effective minority carrier lifetime in the transistor and parameters such as collector current density and breakdown voltage are discussed in detail. The effect of universal contact on the ON state voltage $V_{CE(sat)}$ of the transistor is analyzed in detail. The results from the analytical model are validated and elaborated using 2D numerical simulations of the device and fabrication and characterization of low and high voltage transistors.

In chapter four, the process flow developed for the fabrication of low and high voltage diodes and transistors and the incorporation of universal contact within them is described in detail.

In chapter five, the important results obtained in the thesis are summarized and further extensions of the work are discussed.