Thesis Title: **A STUDY INTO THE APPLICABILITY OF P^+N^+ (UNIVERSAL CONTACT) TO POWER SEMICONDUCTOR DIODES AND TRANSISTORS FOR FASTER REVERSE RECOVERY**

Name: **RAGHUBIR SINGH ANAND**

Roll Number: **9410474**

Thesis Supervisor **Dr. J. Narain**
Dr. B. Mazhari

Degree for which submitted **Ph.D.**

SYNOPSIS

PN junction diodes and Bipolar junction transistors (BJTs) are used in a wide variety of switching applications, such as, TV deflection circuits, motor drives, switched mode power supplies and others. In most of these applications, the diodes and transistors are used for operation at frequencies less than 100 kHz. The limiting mechanism for the speed of operation is the presence of stored minority charge during the ON state and the reverse recovery time required for removing these stored charges. The uni-polar devices like Schottky and MOS are inherently fast because of absence of minority charge storage but also have the disadvantage of lower reverse breakdown voltage and higher heat dissipation in comparison to bipolar devices. The Insulated Gate Bipolar Transistor (IGBT) has low on-state losses but due to its relatively involved technology, it is restricted to higher end devices. Even with the limitations as compared to Schottky,

MOSFET and IGBT, the PIN rectifiers and BJT are still used in various applications. There have been developments to enhance the switching performance of diodes and transistor, such as, through Au doping and through use of Schottky clamp transistor. In 1982, Amemiya [1] introduced a concept known as universal contact to improve reverse recovery performance of diodes and transistors. The present work is concerned with the various aspects of the application of the "universal contact" (UC) to 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 [2] 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 [3].

In the work [1-3], 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 phenomenon taking place inside the device and their influence on various parameters of the device.

Keeping in view 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.

The major contributions of this thesis are:

1. A theoretical framework is developed which shows that effective minority carrier lifetime (τ_{eff}) , defined as the ratio of total minority charge stored to the total current flowing through the diode, can be viewed as a function of three time constants: $t_{eff}^{-1} = t_L^{-1} + t_M^{-1} + t_R^{-1}$, where $\tau_L/\tau_M = I_M/I_L$, t_M is the recombination lifetime in the lightly doped middle region and $\tau_R/\tau_M = I_M/I_R$. I_L , I_R and I_M are the minority carrier currents injected into the left p^+, right n^+ and middle ν regions. Using this viewpoint, it is shown that effective minority carrier lifetime and therefore reverse recovery time which is closely related to it, can be reduced by redistributing current away from lightly doped v-region to n^+ and p^+ regions where effective minority carrier lifetime can be reduced by incorporating universal contact.

2. The analytical model developed in this work shows that the effective lifetime decreases with increase in current density and that the advantages of incorporating a universal contact decrease as the breakdown voltage of the diode increases. It is also shown that the incorporation of universal contact allows a new tradeoff between the switching speed and the reverse blocking voltage determined by the proximity of universal contact to the lightly doped region of the diode. The predictions of the model are verified through extensive 2-D [4] numerical simulation and fabrication and characterization of low (~150 V) and high (>1000 V) voltage diodes. [5]

3. A new diode structure incorporating universal contacts inside both n^+ and p^+ diffused regions is proposed. It is shown through analytical calculations and 2D numerical simulations that this diode structure results in large reduction in reverse recovery. The improvements in reverse recovery are 60% and 66% at 0.3 A/cm^2 and 50 A/cm^2 respectively with respect to the conventional diode structure.

4. The analytical model developed for PIN diodes is extended to model the effects of incorporating universal contact within the extrinsic base of BJTs. It is shown that the use of universal contact allows redistribution of base current in saturation from collector region where recombination lifetime is high to extrinsic base region where effective recombination lifetime is low. As for the diode case, the model predicts improvement in switching speed with increase in collector current density but degradation of switching characteristics with increase in transistor's reverse blocking voltage. These results are verified through 2-D numerical simulation

5. The improvement in switching characteristics as a result of incorporation of universal contact is accompanied with an increase in the ON state voltage, $V_{CE(sat)}$ of transistors. The increase in $V_{CE(sat)}$ in transistors with UC is attributed to decrease of β_R, the reverse current gain and early onset of quasi-saturation effects.

6. The usefulness of the universal contact in high voltage (BV_{CBO} >1000 V) transistors has been experimentally demonstrated for the first time. An improvement of 23% in reverse recovery has been obtained in experimental high voltage BJT [6]

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 simulations 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 device is described in detail.

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

Reference:

[1] Y. Amemiya, T. Sugeta, and Y. Mizushima, ‘Novel low-loss and high speed diode utilizing an ‘ideal’ ohmic contact”, IEEE Trans. Electron Devices, Vol. **ED-29**, pp. 236-243, 1982

[2] M.Kitagawa, K. Matsushita, A. Nakagawa; High-Voltage (4KV) Emitter Short Type Diode (ESD); Proceedings ISPSD 1992, Tokyo, pp. 60-65.

[3] Narain, J, "A Novel method of reducing the Storage Time of Transistors", IEEE Electron Devices letter, **EDL-6**, No.11, 578-579, 1985.

[4] Silvaco International Inc, ATLAS User Manual (1996), Device Simulation Software.

[5] Anand, R.S., Mazhari, B. and Narain, J, "A study into the Applicability of P^+N^+ (Universal Contact) to Power Semiconductor Diodes for Faster Reverse Recovery", IEEE Trans. Electron Devices (Submitted)

[6] Anand, R.S., Mazhari, B. and Narain, J, "A study of Improved Reverse Recovery in Power Transistor Incorporating Universal Contact", IEEE Trans. Electron Devices (Being Submitted)