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Transient Switch-on Collector Current Analysis in Punch-Through IGBT

Authors:
1. **Md. Akhirul Islam (12121114)**
2. **MD. Nazmul Hossain (12321066)**
3. **M. Mubaswir Altab (12321067)**
4. **Tonmoy Bhowmik (12321067)**

Supervisor:
Mr. Avijit Das
Lecturer
Dept. of EEE,
BRAC UNIVERSITY

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Department of Electrical and Electronics Engineering
BRAC University

Declaration of Authorship

This is to declare that this thesis named “Analysis of different characteristic curves of Punch through IGBT using Silvaco TCAD” is submitted by the authors listed for the degree of Bachelor of Science in Electrical and Electronics Engineering to the Department of Electrical of Electronics Engineering under the School of Engineering and Computer Science, BRAC University. We hereby affirm that the research work and result was conducted solely by us and no other. Materials of the study and work found by other researchers have been properly referred and acknowledged. This thesis paper, neither in whole nor in part, has been previously submitted elsewhere for appraisal.

Authors name and signature:

Serial no.	Name	ID	Signature
01.	Md. Akhirul Islam	12121114	
02.	MD. Nazmul Hossain	12321066	
03.	M.Mubaswir ALtab	12321067	
04.	Tonmoy Bhowmik	12321068	

____

Supervisor

Imagination is the highest form of research.

Albert Einstein

Abstract:

Analysis of switching power loss of IGBT is considered desirable. In our thesis, the switch on behavior is analyzed through investigation into transient anode collector current of Punch Through (PT) Insulated Gate Bipolar Transistor (IGBT). Changing the Doping concentration, gate voltage and collector to emitter voltage along with different temperature in punch through IGBT we compared different collector currents.

Acknowledgement:

This note is made to express our gratefulness to some people who really encouraged and supported us a lot in making this report.

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Abbreviations:

IGBT=Insulated Gate Bipolar transistor

Physical Constants

Ambipolar Diffusivities	D	$=$	18 cm^2/s
High level excess carrier lifetime	τ_{HL}	$=$	0.1 μs (τ_0)
		$=$	0.3 μs (τ_1)
		$=$	2.45 μs (τ_2)
		$=$	7.1 μs (τ_3)
Supply voltage	V_{bus}	$=$	400 V
Dielectric constant of Si	ε_{Si}	$=$	$11.7 \times 8.854 \times 10^{-14}$ F/cm
Charge of electron	q	$=$	1.6×10^{-19} C
Base doping concentration	N_B	$=$	2×10^{14} cm^{-3}
Hole Diffusivity	D_p	$=$	14 cm^2/s
Metallurgical base width	W_B	$=$	9.3×10^{-3} cm
Device active area	A	$=$	0.1 cm^2
Emitter electron saturation current	I_{sne}	$=$	6×10^{-14} A
Intrinsic carrier concentration	n_i	$=$	1.45×10^{10} cm^{-3}
Electron mobility	μ_n	$=$	1500 cm^2/Vs
Hole mobility	μ_p	$=$	450 cm^2/Vs
Ambipolar mobility ratio	b	$=$	3.3
Total current	I_T	$=$	10 A

Dedicated to

Our Parents

1. Introduction

The Insulated Gate Bipolar Transistor also called an IGBT for short, which is mainly used for extremely fast electronic switching in a variety of applications. The most important thing about IGBT is that it can deal with High Voltage and High Current. IGBT is created by the functional integration of MOS and Bipolar device technologies in monolithic form which combines the best attributes of the existing families of MOS and Bipolar Device. No integral Diode is present in it like MOSFET, so we can choose an external recovery diode suitable for a particular application. IGBT is something of a cross between a conventional Bipolar Junction Transistor (BJT) and a field effect Transistor (MOSFET), it essential to have a sound knowledge on BJT and MOSFET.

A Bipolar Junction Transistor or BJT has has a three doped semiconductor Regions (emitter, collector and base) separated by two p-n junction. The p-n junction between the base and the emitter has a barrier voltage about 0.6 V. BJT mainly preferred for low current applications.

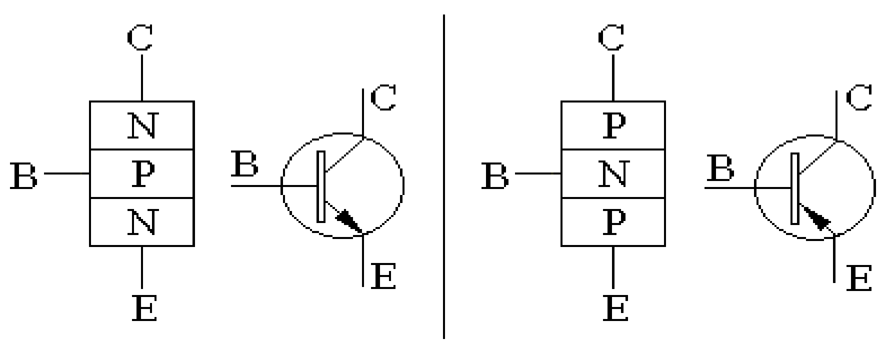


Figure 1: NPN and PNP Transistor

On the other hand, metal–oxide–semiconductor field-effect transistor is a field-effect transistor (FET) with four-terminal source (S), gate (G), drain (D), and body (B) terminals, the body or substrate of the MOSFET is often connected to the source terminal which make it three-terminal device like other field-effect transistors. MOSFET has a thin layer of silicon oxide between the gate and the channel. Noticeable advantage in MOSFET over a regular transistor is that it requires very little current to turn on less than 1mA, while delivering a much higher current to a load. P-channel MOSFET are known as PMOS while as N-channel MOSFET are known as NMOS. Two basic form of MOSFET are Depletion Type where the transistor requires the Gate-Source voltage, V_{GS} to switch the device "OFF". The depletion mode MOSFET is equivalent to a "Normally Closed" switch. The more common Enhancement mode MOSFET or eMOSFET is the reverse of the depletion-mode type. Diffusion current, i.e. sub-threshold leakage current exists in enhancement MOSFET while as depletion MOSFET do not have any diffusion current.

However, It is obvious that IGBT combination of the low on state resistance of power bipolar transistor and the high input impedance of power MOSFET provides a major advantage where the high impedance allows controlled turn-on and gate controlled turn off.

The IGBT has the output switching as well as conduction characteristics of a bipolar transistor. But it is like voltage-controlled, like a MOSFET which means it has the advantages of high-current handling capability of a bipolar with the ease of control of a MOSFET. However, IGBT has some disadvantages too; it has large current tail as well as no body drain diode.

The MOSFET and IGBT structures look very similar. The main difference is the addition of a p substrate beneath the n substrate. The IGBT technology is certainly the device of choice for breakdown voltages above 1000V. On the other hand, MOSFET is certainly the device of choice for device breakdown voltages below 250V. Choosing between IGBTs and MOSFETs, it is essential to be careful because it is very application-specific and cost, size, speed and thermal requirements should all be considered.

IGBT is a minority carrier device with high input impedance and large bipolar current-carrying capability which is a functional integration of Power MOSFET and BJT devices in monolithic form and combines the best attributes of both and thus achieve optimal device characteristics. The combination of the low on state resistance of power bipolar transistor and the high input impedance of power MOSFET is one of the advantages of this device where high input impedance of power MOSFET allows controlled turn-on and gate controlled turn-OFF.

The IGBT is suitable for many applications in power electronics, especially in Pulse Width Modulated (PWM) servo and three-phase drives requiring high dynamic range control and low noise. It also can be used in Uninterruptible Power Supplies (UPS), Switched-Mode Power Supplies (SMPS), and other power circuits requiring high switch repetition rates. IGBT improves dynamic performance and efficiency and reduced the level of audible noise. It is equally suitable in resonant-mode converter circuits. Optimized IGBT is available for both low conduction loss and low switching loss.

The main advantages of IGBT over a Power MOSFET and a BJT are:

- It has a very low on-state voltage drop due to conductivity modulation and has superior on-state current density. So smaller chip size is possible and the cost can be reduced.
- Low driving power and a simple drive circuit due to the input MOS gate structure. It can be easily controlled as compared to current controlled devices (thyristor, BJT) in high voltage and high current applications.
- Wide SOA. It has superior current conduction capability compared with the bipolar transistor. It also has excellent forward and reverse blocking capabilities.

However the main drawbacks are:

- A reduction in on-state voltage can cost the IGBT to experience slower switching speed at turn-off. The reason is that while electron flow can be abruptly halted simply by reducing the gate-emitter voltage below the gate threshold voltage (as is the case with the MOSFET), there's still the matter of the holes that are left in the drift and body regions (there's no terminal connection to remove them). The only way to get them out of there is by sweep-out, which is dependent upon voltage across the device and internal recombination. As a result, the device displays a tail current at turn-off until the recombination is complete. This has always been a big drawback for the IGBT.
- Switching speed is inferior to that of a Power MOSFET and superior to that of a BJT. The collector current tailing due to the minority carrier causes the turn-off speed to be slow.
- There is a possibility of latchup due to the internal PNPN thyristor structure.

IGBT is suitable for scaling up the blocking voltage capability. In case of Power MOSFET, the on-resistance increases sharply with the breakdown voltage due to an increase in the resistively and thickness of the drift region required to support the high operating voltage. For this reason, the development of high current Power MOSFET with

Chapter 2

2.1 Basic Structure

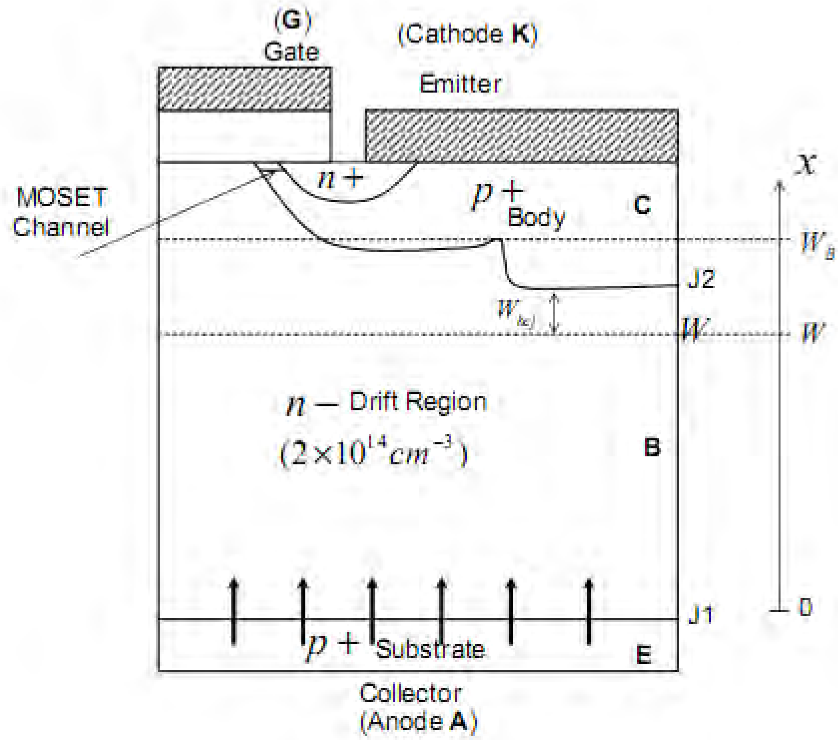
2.1.1 Cross Sectional Structure

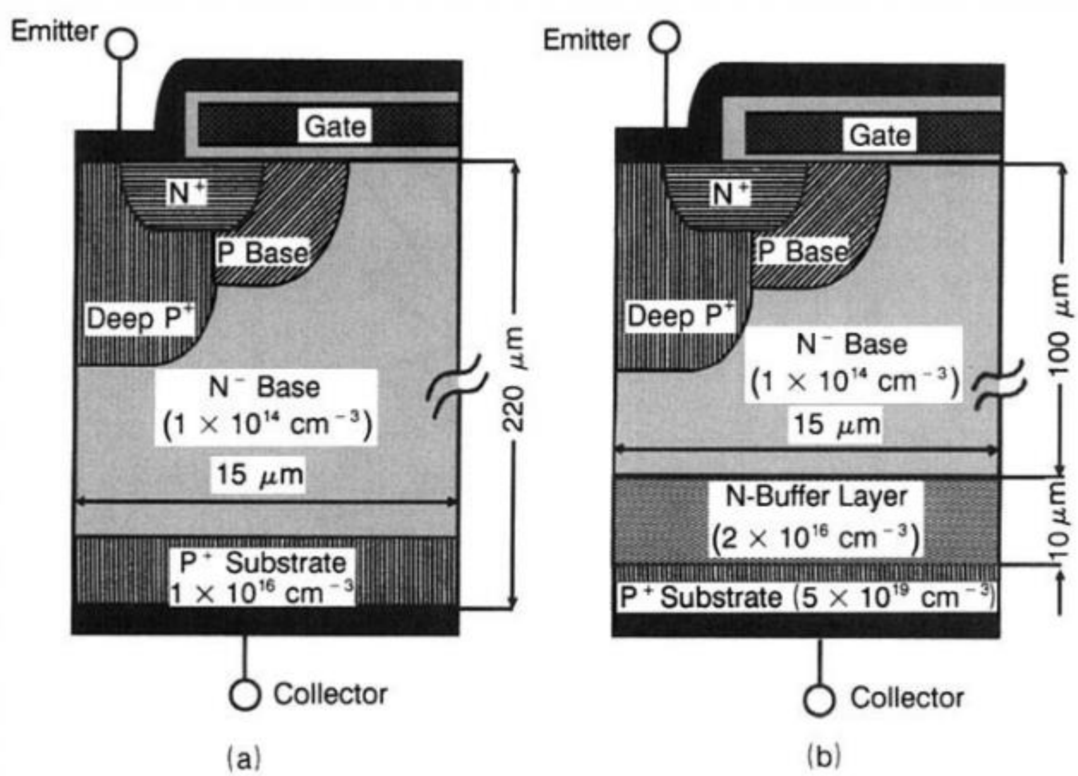
The cross section of a typical IGBT structure has been shown in Fig. 2.1.The structure of the device is similar to that of a Vertical Double di_used MOSFET (VDMOSFET) with the exception that a highly doped p-type substrate is used in lieu of a highly doped n-type drain contact in the VDMOSFET.A lightly doped thick n-type epitaxial layer (NB = 10^{14} cm^{3}) is grown on top of the p-type substrate to support the high blocking voltage in the reverse bias mode state. A highly doped p-type region (NA = 10^(19)cm^3) is added to the structure to prevent the activation of the PNPN thyristor during the device operation. The power MOSFET is a voltage-controlled device that can be manipulated with a small input gate current ow during the switching transient. This makes its gate control circuit simple and easy to use.

2.1.2 NPT & PT IGBT

A highly doped n+ bu_er layer could also be added on top of the highly doped p+ substrate. This layer helps in reducing the turn-OFF time of the IGBT during the transient operation. The IGBT with a bu_er layer is called a Punch-Through (PT) IGBT while the IGBT without a bu_er layer is named a Non-Punch Through (NPT)

Cross of schematic and NPT and PT structure of IGBT given in next page.


(G)
Gate
(Cathode K)
Emitter
MOSET
Channel
n+
p+
Body
C
x
W_B
J2
W_{bcj}
W
W
n − Drift Region
$(2\times10^{14}cm^{-3})$
B
J1
0
p + Substrate
E
Collector
(Anode A)


Emitter
Gate
N+
P Base
Deep P+
N− Base
(1 × 10¹⁴ cm⁻³)
15 μm
P+ Substrate
1 × 10¹⁶ cm⁻³
220 μm
Collector
(a)
Emitter
Gate
N+
P Base
Deep P+
N− Base
(1 × 10¹⁴ cm⁻³)
15 μm
100 μm
N-Buffer Layer
(2 × 10¹⁶ cm⁻³)
10 μm
P+ Substrate (5 × 10¹⁹ cm⁻³)
Collector
(b)

The PT structure with the advantage of an extra bu_er layer mainly performs two main functions:

-avoids failure by punch-through action.
-reduces the tail current during turn-o_ and shortens the fall time of the IGBT.
In the case of PT IGBT, the epitaxial layer is not as thick (less thick) as NPT IGBT because a n+ layer is placed over the p+ layer. It is very likely to have punched through the J2 junction to the J1 junction. This n+ layer can handle some of the punch through and act as a shield to the J1 junction. This n+ bu_er layer occupies some spaces in the base of IGBT, which leaves less space for the total charges in the base region during the IGBT on state (turn-on) operation. As a result, these charges are removed by the n+ layer more quickly when switching occurs. This n+ layer is a recombination center which helps holes get recombined with electrons before reaching the base region and fewer holes, as a result, will be injected into the base region (lower efficiency). As a result, the carrier lifetime is reduced and the switching frequency is increased. However, since fewer carriers are injected into the base region compared to the NPT IGBT, the conductivity modulation is reduced (higher base resistance) and the on-state voltage is increased. The trade OFF between the reduced turn-OFF time and the increased on-state voltage should be accounted for. For NPT IGBT considered in this thesis dissertation, the epilayer thickness is thick enough since no n+ layer is introduced on top of the highly doped p+ layer substrate. Because the thickness of the n□ layer is greater than PT IGBT, the resistance is high in this region and, as a result, a higher reversed voltage can be sustained when J2 is reversed biased. The punch through of the J2 to the J1 is less likely to occur, i.e. a non-punch through situation. If the punch through occurs, then the IGBT breakdown voltage will be degraded causing the device to break down. When the emitter base junction J1 is forward biased and the gate voltage is greater than the threshold voltage; injection of holes from the p+ substrate is increased. The resistance of the n- layer is reduced when the injected hole density becomes much greater than the background doping N_B. The turn-OFF time of the NPT IGBT is longer than the PT IGBT because the removal of so many stored charges in the base region is slow due to the absence of recombination centers. Carriers do not recombine as fast, which means they have longer lifetimes.

The NPT IGBT is more e_cient than the PT ones since more charges are injected from the p+ layer to the n□ . The injected holes do not get recombined as fast as in PT IGBT, which has an n+ bu_er layer on top of the p+ layer. The NPT IGBTs, which have equal forward and reverse breakdown voltage, are suitable for AC applications. The PT IGBTs, which have less reverse breakdown voltage than the forward breakdown voltage, are applicable for DC circuits where devices are not required to support voltage in the reverse direction. Fig. 2.3 shows the Doping Concentration & Electric Field distribution of NPT & PT IGBT.

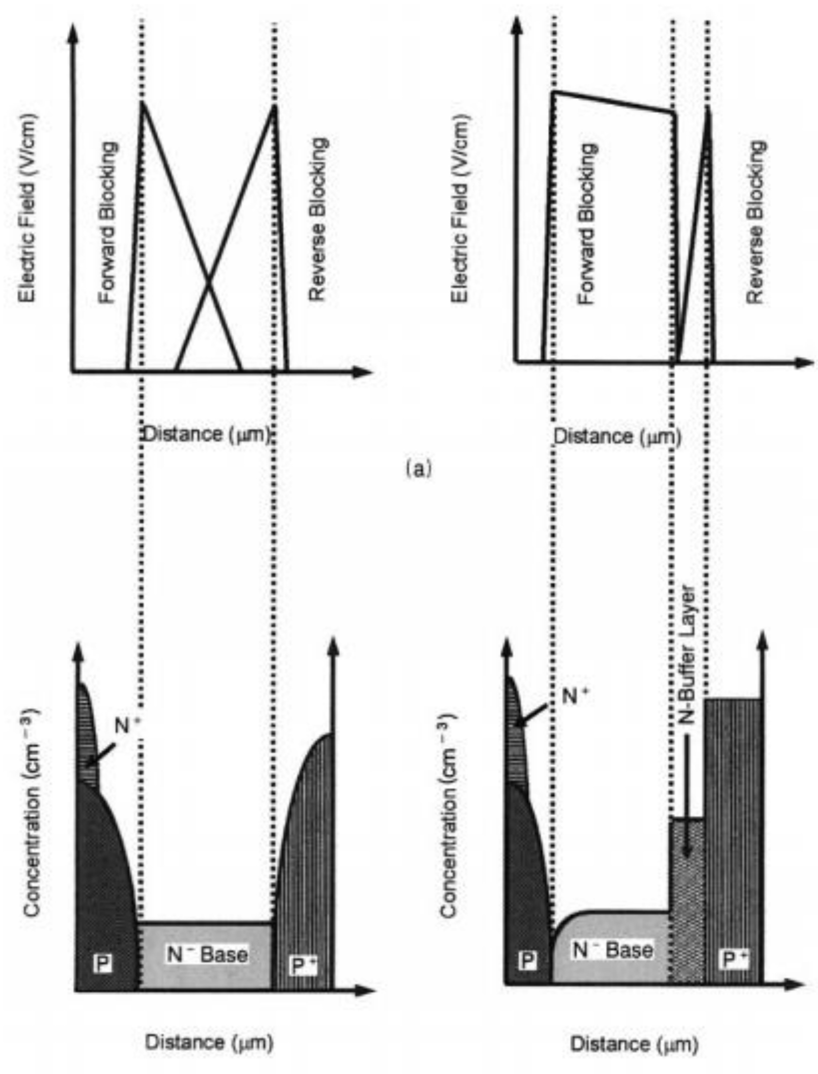
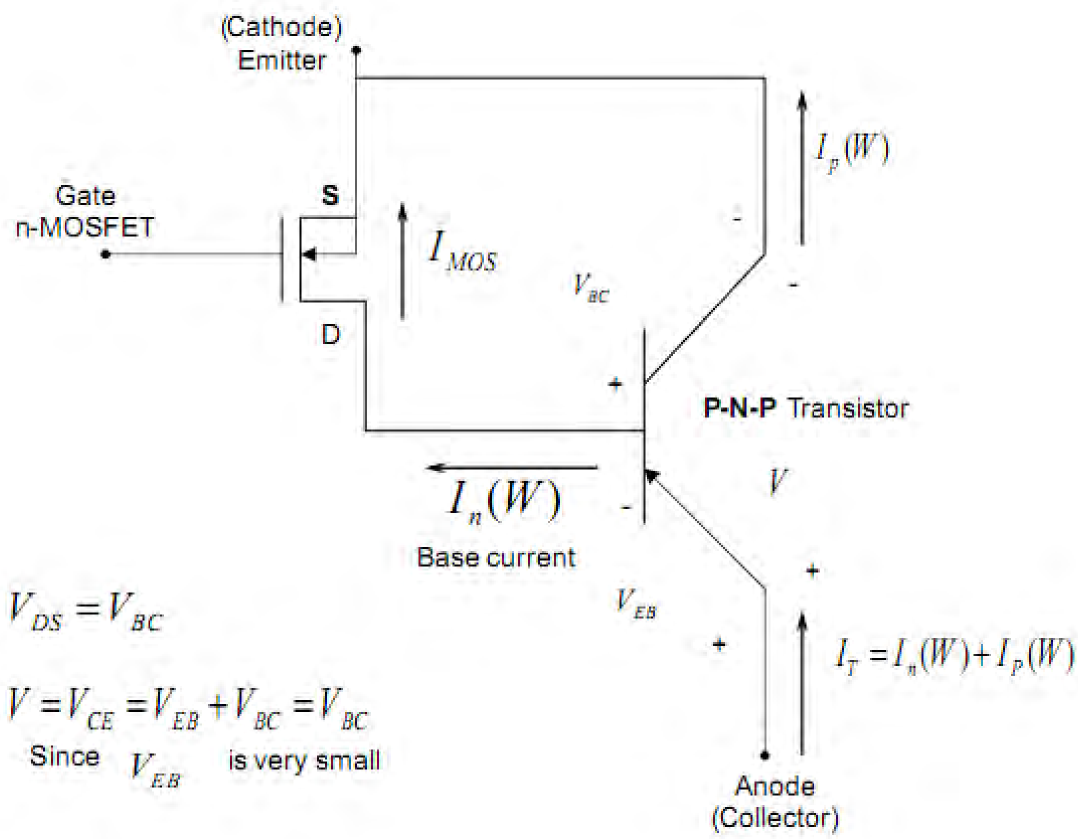


Figure above it is about Doping Concentration & Electric Field Distribution (a)NPT IGBT & (b)PT IGBT

Characteristic Comparison of NPT & PT IGBT:

Characteristics	NPT IGBT	PT IGBT
Switching Loss	Medium	Low
Conduction Loss	Medium	Low
Paralleling	Easy	Difficult
Tail Current	Long, low amplitude	Short
Short Circuit Rated	Yes	Limited (High Gain)

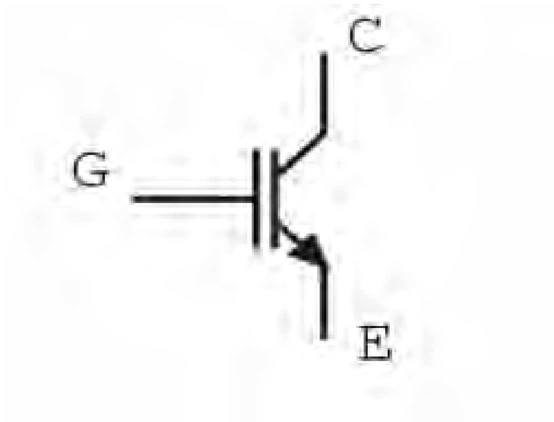
The equivalent circuit model of IGBT: Based on the structure, an equivalent circuit of IGBT can be shown in Figure below. It consists of a PNP transistor (BJT) & a n channel MOSFET.The p+ substrate, n+ epilayer & p+ body forms the PNP transistor. The p-type substrate is the emitter for BJT and is the anode terminal of the device. When the p substrate is forward biased (V_{EB}>0),the minority carrier injection causes transistor current IT , owing from the anode region. This current has two parts at the Base-



-Electron current (I_n(W)).
-Hole current (I_p(W)).

The Anode to Cathode voltage (VAC) can be represented by
$V_{AC} = V_{EB} + V_{BC}$

where,



(FIG: circuit symbol of IGBT)

V_{EB}=Bipolar Emitter to Base voltage.
V_{BC}=Base to Cathode voltage.

Basically VDS of MOSFET & VBC are same.Since V_{EB} is very small, we can write $V_{AC} = V_{BC.}$

From the equivalent circuit, a circuit symbol can be formed which is shown figure above, It has three parts-
-Collector (C) which is the anode terminal of IGBT.
-Gate (G) which is the Gate terminal of MOSFET.
-Emitter (E) which is the cathode terminal of IGBT

2.2 IGBT operation

When a positive gate voltage greater than the threshold voltage (V_T) is applied, electrons are attracted from the p+ body towards the surface under the gate. These attracted electrons will invert the p+ body region directly under the gate to form an n channel. A path is formed for charges between the n+ source and the n+ drift region.

When a positive voltage is applied to the anode terminal of the IGBT, the emitter of the IGBT section is at higher voltage than collector. Minority carriers (holes) are injected from the emitter (p+ region) into the base (n+ drift region). As the positive bias on the emitter of the BJT part of the IGBT increases, the concentration of the injected hole increases as well. The concentration of the injected holes will eventually exceed the background doping level of the n+ drift region; hence the conductivity modulation phenomenon. The injected carriers reduce the resistance of the n+ drift region and, as a result, the injected holes are recombined with the electrons owing from the source of the MOSFET to produce the anode current (on state).

2.3 Transient Operation of IGBT

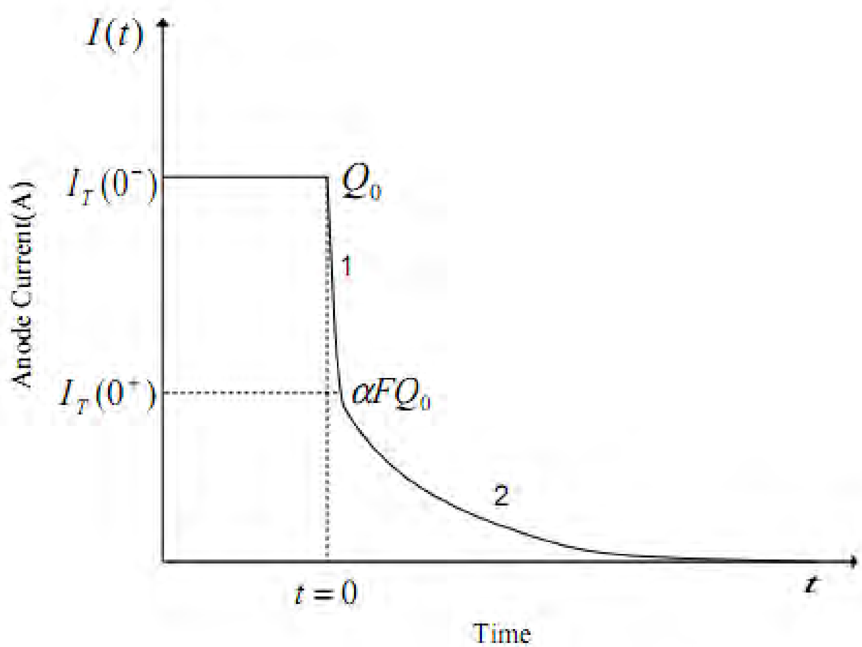
While the turn-on time of the IGBT is quite fast, the turn-on time can be slow because of the open base of the PNP transistor during the turn-on period. Figure below, it shows the typical IGBT turn-on transient where IT (0^+) is the current after the initial rapid fall. The initial rapid drop in the anode current is due to the sudden removal of the MOS channel. This is followed by a slower decay due to the removal of the carriers stored in the lightly doped layer(n+). The turn-on process is initiated when we lower the gate voltage to a value lower than threshold voltage(V_T) This removes the formed electron channel from under the gate and blocks the MOS component of the current IMOS. I_{MOS}=I_n(W)=0 in this case and the collector-base voltage V_{bc} increases resulting in a widening of the depletion region at the n- (base-collector side or source of MOSFET).

The relation between IT (0^-) and IT (0^+) is through β_{tr}. It is the ratio of the current immediately after the initial rapid fall to the magnitude of the fall and is shown along with the ratio of W(t) to L (W(t)/L) in the appendices. The switching losses of the IGBT are dominated by the losses, which occur during the much slower second phase of the turn-on period transient. This is because of the time required removing or extracting the injected carriers in this phase. This is a major disadvantage of the IGBT device as it suffers from high-switching losses. This can be overcome by reducing the lifetime of the carriers in the base through recombination of extraction processes s quickly as possible before the device reaches its blocking voltage state.

The collector-base junction is reversed biased and its depletion region widens during the turn-on of the IGBT. When the IGBT is on, the status of the base-collector junction is reversed biased as can be seen from Figure. When the IGBT is on, the status of the base-collector junction is reversed biased and V_{bc} is increased leading to the increment of the depletion region since the current decreases. The widened region supports the entire voltage drop across the device as mentioned previously based on. When a negative voltage is applied to the anode terminal, the emitter-base junction is reversed biased and the current is reduced to zero. A large voltage drop appears in the n+ drift region since the depletion layer extends mainly into that region.

The MOSFET gate voltage controls the IGBT switching action. The turn-OFF takes place when the gate voltage is less than the threshold voltage (V_T). The inversion layer at the surface of the p+ body under the gate cannot be kept and therefore no electron current is available in the MOSFET channel while the remaining minority carriers of holes, which were stored during the on state of the IGBT, require some time in order to be removed or extracted. The switching speed of the IGBT device depends upon the time it takes for the removal of the stored charges in the n+ drift region which were built up during the on state current conduction (IGBT turn-on case).

This is the figure for Typical IGBT turn-off transient showing turn-on phases



Chapter 3

Literature review of some Transient analysis of some transient modeling of IGBT

Several models have been Parabolic in the literature to describe both the DC and the transient behaviors of the IGBT. In this section, we have reviewed the most popular model Parabolic by Allen R. Hefner.

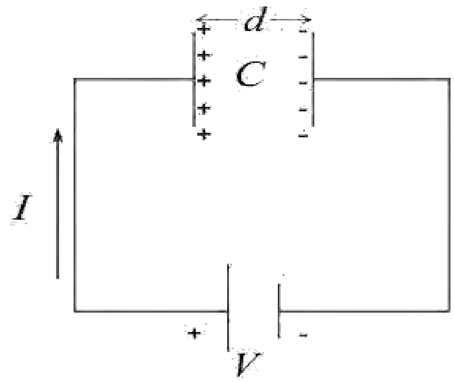
3.1 Approaches Taken By Allen R. Hefner

In Hefner's, transient modeling approach, the general ambipolar trans-port electron current expression

$I_n(W(t)) = I\boldsymbol{\tau}(t)/\ 1+1/\ b + qAD(\partial n(x,t)/\ \partial x)$

Which was used to find an expression for the voltage rise (dV(t)/dt*)*. $I_n(W\ (t))=I_{MOS}$ as shown in Figure and it is important since it controls the operation of IGBT.

Since the reverse bias on junction J_2 in Figure does not increase rapidly and the depletion in capacitance of junction $J_2$is partially charged a short period of time, I_{MOS} current is instantaneous. An expression for I_{MOS} can be obtained if we consider the collection-base junction depletion capacitance as in Figure below.



Here d is distance between the plates and the rate of q change is

$dq/dt = I(current)$

As we know $q(t) = C_{bcj}(t)V(t)$, so

$dq/dt = d/dt[C_{bcjt}V(t)]$

$= V(t)\,[C_{bcj}(t)/dt] + C_{bcj}(t)[dV(t)/dt]$

and in terms of the junction capacitance of the reverse biased junction, the displacement current $I_n(W(t))$ is, (3.1)

$$I_n(W) = V(t)\frac{dC_{bcj}(t)}{dt} + C_{bcj}(t)\frac{dV(t)}{dt}$$

The first term on the right hand side of the equation (3.1) was ignored by Hefner. The rate of change of $C_{bcj}(t)$ should be included in calculating the displacement current since the capacitance varies with time as the depletion width changes with voltage. From equation (2.6) and the fact that J = I/A, where A is the device active area,

$$In\ (W(t)) = [I\boldsymbol{\tau}(t)/\ 1{+}1\ b] + qAD[\partial p(x{,}t)/\ \partial x]$$

And from Hefner's approach

$$I_n(W(t)) = C\mathrm{bcj}(t)[dV(t)\ /dt]$$

$$= 2qADp/[\ 1{+}1\ /b][\partial p(x{,}t)\ /\partial x] \qquad (3.2)$$

Hefner used equation (3.2) to obtain V(t) for the transient operation of IGBT. He implemented the concept of moving the redistribution current. In his transient approach, he neither used the steady state expression for p(x) nor did he linearize the steady state expression for p(x). Moreover he assumed $C_{bcj}(t)$ to be constant with time, which is not so in reality.

His p(x) expression consists of two parts,

$$p(x)= P\mathrm{o}[\ 1-\ x/W(t)]–P\mathrm{o}/W(t)D[[x2/\ 2]-\ W(t)x/\ 6\ –[x3/\ 3W(t)]$$

$$[dW(t)/dt] \qquad (3.3)$$

From equation (2.6) & (3.3)

$$I_n(W(t)) = b/\tau(t) /1+b+ qAD[\partial p(x)/\partial x]$$

Or, $$In(W(t))=IT(t)/[1+1/b] +2qADP/[1+1/b][\partial p(x)/\partial x] \qquad (3.4)$$

And instead of equation (3.1), Hefner applied $I_n(W(\overline{t})) = C_{bcj}(t)$ in his approach. Integrating equation (3.3) in the base and multiplying by qA, the total charge Q,

$Q = qA \int p(x\} dx$

$= qA\ [x–[x\text{^}2/ 2W(t)]–[Po/W(t)D]\ [[x\text{^}3/ 6]−[W(t)x\text{^}2/ 12]$

$−\ [x\text{^}4 /12(t)]]\ [dW(t)/dt]$

$=qA[[\ o(W(t)–[W(t)/ 2] –[x\text{^}2/ 2W(t)]] –[Po/W(t)D]$

$[[\text{^}3 /6]\ −\ [W(t)x\text{^}2/ 12] –[x\text{^}4 /12W(t)]]\ [dW(t) /dt]$

$= [qAPo(t)/ 2] –[qA/PoWD]\times 0$

$=qAPo(t) /2 \qquad (3.5)$

as can be seen $dW(t)\ /dt$ has no effect on Q calculation. We can find $\partial(x)\ /\partial x$ from equation (3.3) as when x=W(t) $\partial p(x)\ /\partial\ = [Po/W(t)]$ –$[Po/W(t)D]$ $[2x/$ $2-W(t)/$ $6-$ $3x^2/W(t)]$ $[dW\ (t)/dt]$

When x=W(t)

$\partial p(x)/\partial x{=}{-}P$o $[W(t)$ –Po $/W(t)D]$ $[W(t)-$ $[W(t)/$ 6$]$ $-W(t)]$
$[dW(t)/dt]$

$\partial px/\partial{=}$ $[-P$o$/W(t)]$ –$[P$o$/$ $6D]$ $[dW(t)/dt]$

The hole current is -qA$\partial(x)\ /\partial x$ and from the above equation
$-\ qA[\partial p(x)/\partial x]{=}$ $[qADP$o$/W(t)]$–$[qAP$o$D/$ $6D]$ $[dW(t)/dt]$
= $[qADP$o$/$ $(t)]$ –$[qAP$o$D/6D]$ p$dW(t)\ /dt]$

As Q=$qAP0(t)/$ 2 ,from above equation
$-$ qAD $[\partial p(x)/\partial x]{=}$ $2QD/W$^2 (t)–$Q/$ $3W(t)$ $[dW(t)/dt]$ (3.6)

The first term on the right hand side of equation (3.6) is categorized by Hefner asthe charge control component and the second term is categorized as the moving boundary redistribution component of the hole current.

From equation (3.4) and (3.6)
In(W(t))= C $[dV(t)/dt]$ = $I\boldsymbol{\tau}(t)$ /[1+1/b]– [4QDP/(1+1 /b)$W^2(t)$]
+ $Q/$ $3(t)$ $[dW(t)\ /dt]$

This equation can be expressed in a different way if in $-qA\partial(x)/\partial x$ equation (3.6) is modified as

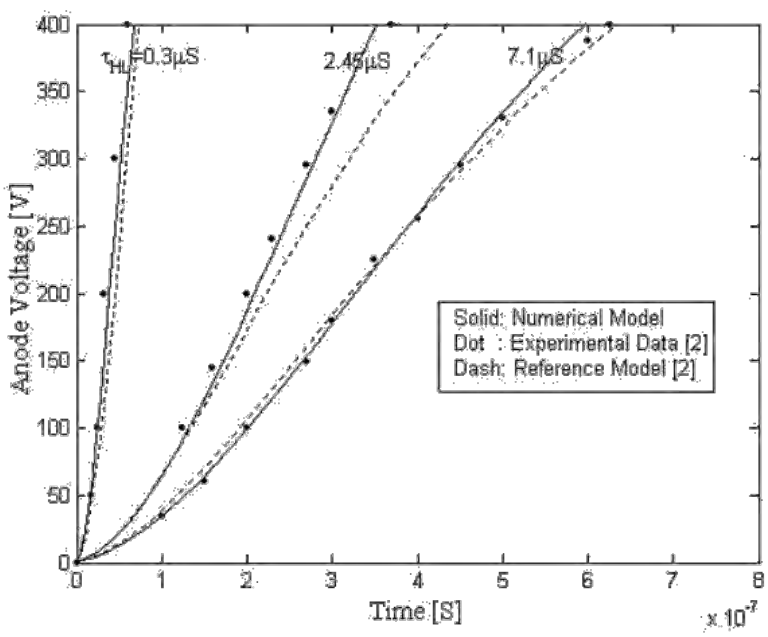


FIGURE 3.2: A comparison of the theoretical and measured 10A infinite inductive load switching voltage waveforms for devices with different base lifetimes

$-2qAD[\partial p(x)/\partial x]= 4DpQ/W^2 (t)–Q/ 3W(t) (1+ 1/b)[dW(t)/dt]$

….. (3.7)

From equation (3.4), we have

$In(W(t))=C\ [dV/dt]$

$= I(t)/(1+1/b) + [2qADP/(1+1 /b)]\partial p(x)/\partial x$

Now using equation (3.7), and the fact that

$dV(t)/dt$ = [$\mathbf{\tau}(t) - 4DpQ/W\text{^}2\ (t)$] / [$Cbcj\ (t)$ (1+1 /b) [1+ $Q/\ 3qAW(t)NB$]]

…. (3.8)

Where I(t)=I$\mathbf{\tau}$ (0−) for large inductive loads and $I\mathbf{\tau}(t)$ = $4DpQ(t)/W\text{^}2\ (t)$ [Appendix A] forthe constant anode voltage in which$d(t)\ dt$ = 0 indicating that the voltage W(t) are constants

Equation (3.8) is Hefner's transient $d(t)\ dt$ model for IGBT and Q(t)is expressed by solving the following non-linear differential equation Parabolic by Hefner

$d\ (t)\ /dt$= $-Q(t)/\tau HL$ –[$4Q2(t)Isne/W\text{^}2\ (t)A\text{^}2q\text{^}2ni\text{^}2$] …. (3.9)

Where n is emitter electron saturation current (A) and $ni$is the intrinsic carrier concentration (cm−3.) In Hefner's approach, the negative of the collected hole current I(W(t)) consists of a charged control current (Icc) and redistribution current (Ip), which make this model more complex. The expression (3.9) is not simple and Qo cannot be easily determined since there is no expression for P_o which can be substituted for in Qo equation to evaluate Q_o for magnitude. Also, this model

did not consider the rate of change of C(t) in the calculation of the displacement current I(W(t)).

3.1.2 Redistribution time and Charge Control Current

Representative excess carrier distributions in the wide-base bipolar transient at various moments during a constant anode voltage turn-off transient are showing Fig. 3.3

When the base current is removed (constant anode voltage case) or the anode clamp voltage is reached (inductive load case), the carrier distribution in the base changes rapidly to one for which the total current at the emitter is equal to the hole current at the collector (from distribution (a) to (b) in Fig. 3.3), so that quasi-neutrality is maintained in the bipolar base. This reduction in the total device current is responsible for the initial rapid fall in current observed in the switching transient current waveform. The initial rapid fall consists principally of the steady-state net electron current at the collector (base current for the constant anode voltage case)and the component of hole drift current associated with the net electron current there. The remaining slowly decaying excess majority carrier store is responsible for the slowly decaying portion of the switching transient current wave form.

The boundary conditions on the electron and hole currents are different between the steady-state condition and the slowly decaying current phase. As a result, the electrons & holes that recombine can no longer be supplied be the divergence of their current densities as they are in steady-state, but are only supplied by (and thus reduce)the local excess carrier concentration. The curvature in the carrier distributions and the corresponding divergence of the current densities that remains after the initial rapid fall in emitter current acts to redistribute the excess carriers in the base from distribution (b) & (c) in Fig. 3.3.After the redistribution is complete, the excess carrier distribution and the terminal current are given in terms of the total excess carrier charge in the base, so the remainder of the waveform can be described using a charge control model. The redistribution time and the relation between the charge and current after the redistribution is complete are found from the time-dependent ambipolar diffusion equation with

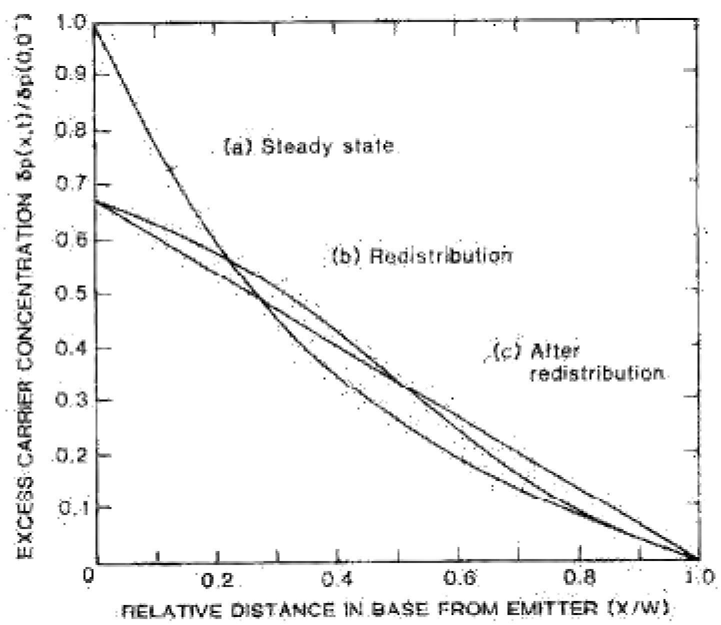


Figure 3.3: The Excess carrier distribution in the base before (a), during (b), and after (c) the redistribution phase of a constant anode voltage switching transient, for W/L=2.5 and for (x= 0) << (*x*= 0). The effect of the decay of the total excess carrier has been left out to illustrate the redistribution process. [3]

(W)=0 and the total current equal to emitter edge of the base for negligible electron current atthe injected into the emitter to the collector current gives:

$$\partial(x,t)/\partial t = \partial P(x,t)/\partial t \qquad (3.10)$$

The general solution to equation,

$$\partial^2\delta p/\partial x^2 = \partial p/L^2 + 1/D\,[\partial\delta p/\partial t]$$

With the conditions of:

$$\delta(x=0, t=0) = P\text{o} \qquad (3.11)$$

$$\delta pW, = 0 \qquad (3.12)$$

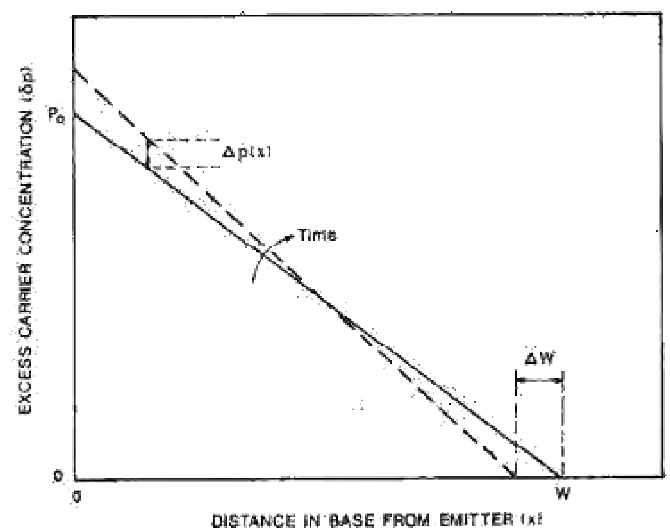


Figure 3.4: The carrier distribution in the base indicating the charge in excess carrier concentration with time dueto the moving collector-base depletion edge boundary

and equation (3.10) foe W independent of time is

$$\delta p(x,t) = P\text{o,o}\,(1 - x/W)e(-t/\tau HL) + \Sigma Am\,\sin(2\pi mt)e(-t/\tau m) \quad \ldots(3.13)$$

Where

$$1/\tau m = 1/\tau H + (2m\pi)^{\wedge} 2Dp/W^{\wedge}2 \qquad \ldots\ldots (3.14)$$

The first term of equation (3.13) is the linear charge control component of the distribution and the sine terms are the redistribution components which decay in time. For the base width $WB = 93\times10-6m$ and other parameters, $m = 0.1/m2us$.For times much larger than this, the redistribution terms become negligible and the current is determined by linear charge control component of the distribution

The redistribution terms are independent of the total base charge and the integrated charge of the charge control term is equal to the total excess base charge:

$$Q(t) = qAP0{,}0W/2\ e^{\wedge}(-t/\tau HL) \qquad \ldots\ldots (3.16)$$

Therefore, the current can only be described by a charge control model after their distribution is complete. Using equations (3.13) & (3.15) for (W) = 0, the charge control current is

$$I(t) = [4Dp/W^{\wedge}2]Q(t) \qquad \ldots\ldots (3.17)$$

Because the integrated charge of each of the redistribution terms is zero, the value of current obtained by extrapolating the current decay waveforms back to the time of the initial rapid fall in current corresponds to the value of current obtained from equation (3.16) evaluated for the initial charge.

Hefner assumed the depletion capacitance ($C_{bcj}(t)$) to be constant throughout

the whole process. But in reality, the depletion capacitance ($C_{bcj}(t)$) is a function of base depletion width (W(t)) as because

$$C_{bcj}(t)=A\varepsilon Si\,/\,Wbcj\,(t)$$

The depletion capacitance is inversely proportional to the depletion width. So when the depletion width increases, capacitance decreases as well as effective base width (W(t)). This was not included in Hefner's approach which is the main limitation of the model.

Chapter 4

Transient Analysis through parabolic approximation:

The main foundation of the Parabolic model by Linear was based on the assumption that effective base width must be much less than the carrier diffusion length (W << L). But in case of base width greater than or equal to the diffusion length, the Parabolic models would give much variation than the experimental result. We have taken this limitation into account and have tried to propose a model that would give consistent result in all cases (W > L and W < L).

4.1 Approximation of minority carrier concentration:

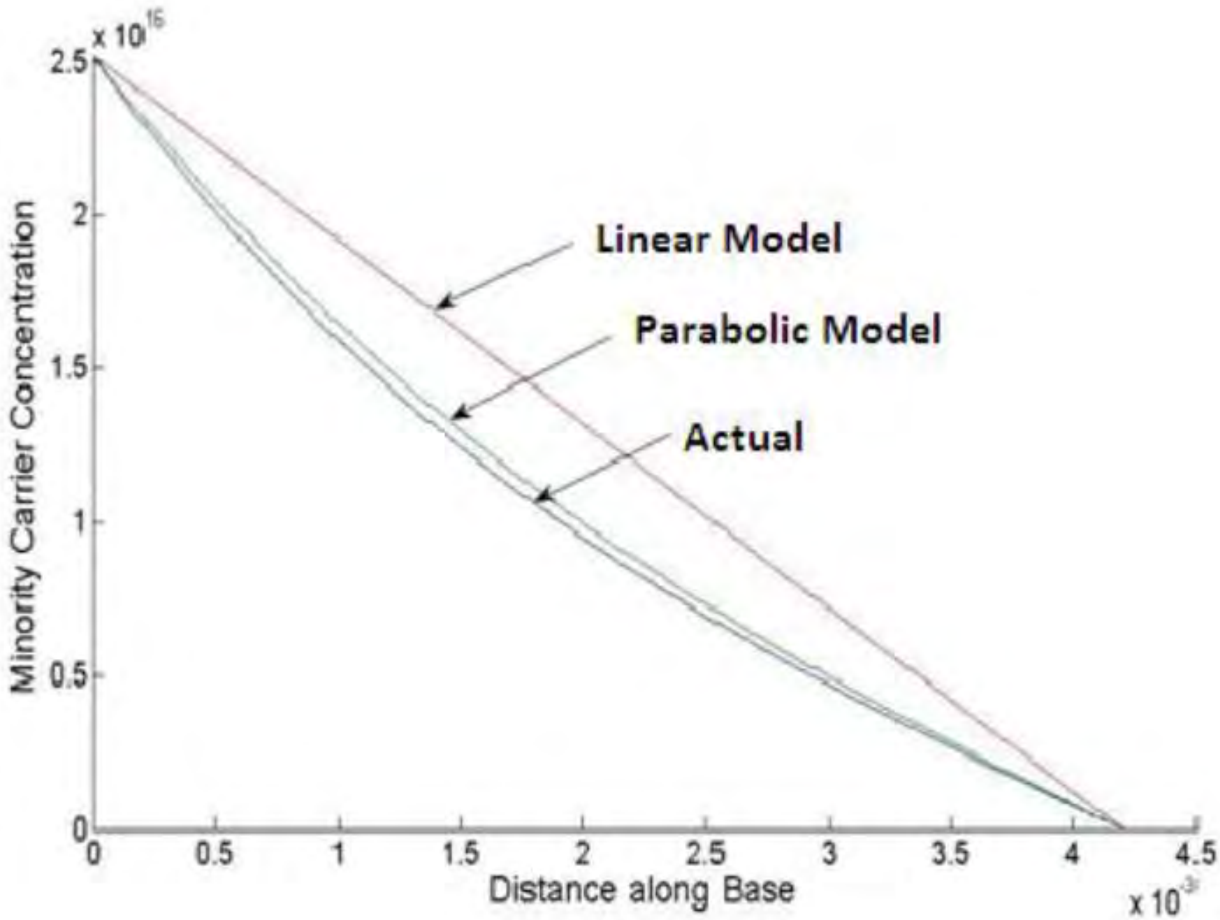
For linear approximation, assuming that W<<L , we obtain,

$$p(x,t) = P_o \frac{\sinh(\frac{W-x}{L})}{\sinh(\frac{W}{L})}$$

Which turns into,

$$p(x,t) = P_o[1 - \frac{x}{W}] \tag{4.1}$$

But when W = L or, W > L ,is assumed, the two curves show large deviation.



In the figure above (using MATLAB), carrier distribution in the base indicated the change in excess carrier concentration with distance in base for (W > L). Thus we can assume parabolic approximation,

$$\sinh(\frac{W-x}{L}) = \frac{W-x}{L} + \frac{1}{6}(\frac{W-x}{L})^3$$

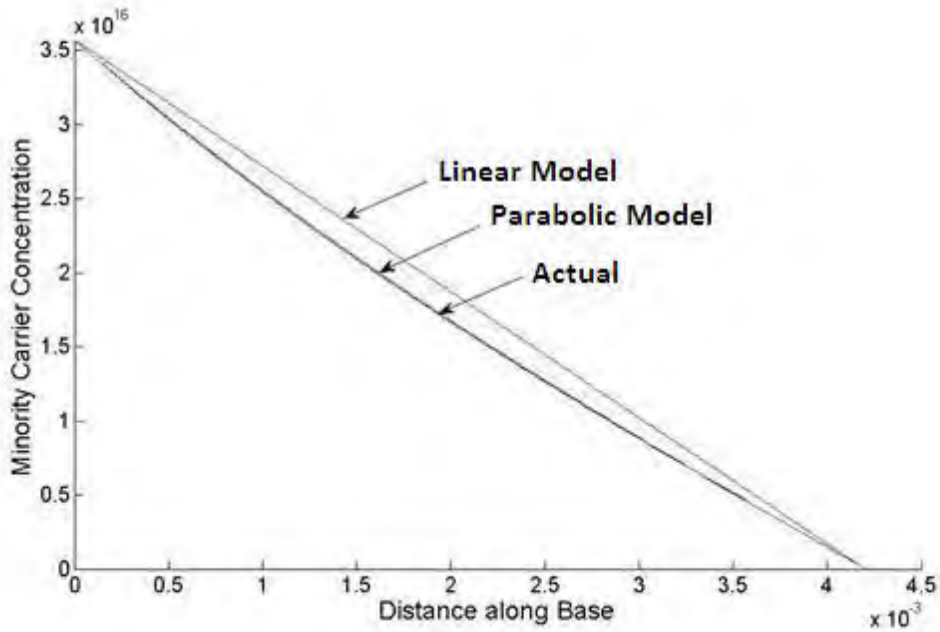
$$\sinh(\frac{W}{L}) = \frac{W}{L} + \frac{1}{6}(\frac{W}{L})^3$$

Our initial approximation for carrier concentration,

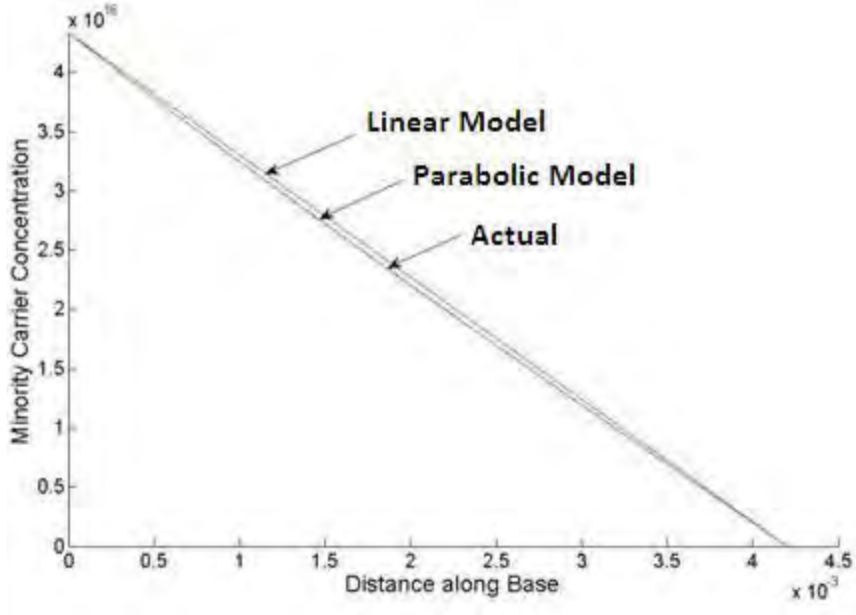
$$p(x,t) = P_o \frac{\frac{W(t)-x}{L} + \frac{1}{6}\left[\frac{W(t)-x}{L}\right]^3}{\frac{W(t)}{L} + \frac{1}{6}\left[\frac{W(t)}{L}\right]^3} \tag{4.2}$$

This closely corresponds to the sinh curve for all values of W unlike the linear approximation.

Figure below is for the carrier distribution in the base indicating the change in excess carrier concentration with distance in base for W = L.



This figure is for carrier distribution in the base indicating the change in excess carrier concentration with distance in base for W < L.



Now,

$$p(x) = P_o \frac{\frac{W-x}{L} + \frac{1}{6}\left(\frac{W-x}{L}\right)^3}{\frac{W}{L} + \frac{1}{6}\left(\frac{W}{L}\right)^3}$$

$$= P_o \frac{\frac{6(W-x)L^2 + (W-x)^3}{L^3}}{\frac{6WL^2 + W^3}{L^3}}$$

$$= P_o \frac{(W-x)[6L^2 + (W-x)^2]}{W(6L^2 + W^2)}$$

$$= P_o (1 - \frac{x}{W})[\frac{6L^2 + (W-x)^2}{6L^2 + W^2}]$$

$$= P_o [\frac{1 + \frac{1}{6}\left(\frac{W-x}{L}\right)^2}{1 + \frac{1}{6}\left(\frac{W}{L}\right)^2}]$$

Hence,

$$p(x,t) = P_o[\frac{1+\frac{1}{6}[\frac{W(t)-x}{L}]^2}{1+\frac{1}{6}[\frac{W(t)}{L}]^2}] \tag{4.3}$$

And,

$$\frac{\partial P(x,t)}{\delta t} = \frac{\partial P_o(t)}{\partial t}[1-\frac{x}{W(t)}]S + P_o(t)S(-x)(-1)\frac{1}{[W(t)]^2}\frac{\partial y}{\partial x} + P_o(t)[1-\frac{x}{W(t)}]\frac{\partial S}{\partial t}$$

In tis equation 4.4 ,

$$S = [\frac{1+\frac{1}{6}[\frac{W(t)-x}{L}]^2}{1+\frac{1}{6}[\frac{W(t)}{L}]^2}]$$

Now,

$$\begin{aligned}
\frac{\partial S}{\partial t} &= \frac{[1+\frac{1}{6}(\frac{W}{L})^2]\frac{2}{6}(\frac{W-x}{L})\frac{1}{L}\frac{\partial W}{\partial t} - [1+\frac{1}{6}(\frac{W-x}{L})^2]\frac{2}{6}\frac{W}{L}\frac{1}{L}\frac{\partial W}{\partial t}}{[1+\frac{1}{6}(\frac{W}{L})^2]^2} \\
&= \frac{[1+\frac{1}{6}(\frac{W}{L})^2]\frac{1}{3L^2}(W-x)\frac{\partial W}{\partial t} - [1+\frac{1}{6}(\frac{W-x}{L})^2]\frac{1}{3L^2}W\frac{\partial W}{\partial t}}{[1+\frac{1}{6}(\frac{W}{L})^2]^2} \\
&= \frac{\frac{1}{3L^2}\frac{\partial W}{\partial t}[W-x+\frac{W^2}{6L^2}(W-x) - W - \frac{W}{6}(\frac{W-x}{L})^2]}{[1+\frac{1}{6}(\frac{W}{L})^2]^2} \\
&= \frac{\frac{1}{3L^2}\frac{\partial W}{\partial t}[-x+\frac{W^3-W^2x}{6L^2} - \frac{W^3-2W^2x+Wx^2}{6L^2}]}{[1+\frac{1}{6}(\frac{W}{L})^2]^2} \\
&= \frac{\frac{1}{3L^2}\frac{\partial W}{\partial t}\frac{1}{6L^2}[-6L^2x+W^3-W^2x-W^3+2W^2x-Wx^2]}{\frac{(6L^2+W^2)^2}{36L^4}} \\
\frac{\partial S}{\partial t} &= \frac{2\frac{\partial W}{\partial t}[x(W^2-6L^2)-Wx^2]}{(6L^2+W^2)^2} \qquad (4.5)
\end{aligned}$$

In linear approximation, the charge was found to be,

$$Q_o = qAP_o\frac{W}{2} \qquad (4.6)$$

and the actual value was,

$$Q_o = qAP_oL\tanh(\frac{W}{2L}) \qquad (4.7)$$

Taking the parabolic approximation,

$$tanh(\frac{W}{2L}) = \frac{W}{2L} - \frac{1}{3}(\frac{W}{2L})^3$$

So, we take steady state excess base charge as

$$\begin{aligned}
Q_o &= qAP_oL[\frac{W}{2L} - \frac{1}{3}(\frac{W}{2L})^3] \\
&= qAP_oL[\frac{W}{2L} - \frac{1}{24}\frac{W^3}{L^3}] \\
&= qAP_o[\frac{W}{2} - \frac{1}{24}\frac{W^3}{L^2}] \\
\Rightarrow P_o &= \frac{Q_o}{qA[\frac{W}{2} - \frac{1}{24}\frac{W^3}{L^2}]} \qquad (4.8)
\end{aligned}$$

Now,

$$\begin{aligned}
\frac{\partial P_o}{\partial t} &= \frac{Q_o}{qA}(-1)[\frac{1}{2}\frac{\partial W}{\partial t} - \frac{1}{24L^2}3W^2\frac{\partial W}{\partial t}] \\
&= -\frac{P_o}{(\frac{W}{2} - \frac{1}{24}\frac{W^3}{L^2})}[\frac{1}{2} - \frac{W^2}{8L^2}]\frac{\partial W}{\partial t} \\
&= -\frac{P_o}{W}\frac{24L^2}{(12L^2 - W^2)}[\frac{1}{2} - \frac{W^2}{8L^2}]\frac{\partial W}{\partial t} \qquad (4.9)
\end{aligned}$$

Now assuming, W << L,

$$\begin{aligned}
\frac{\partial P_o}{\partial t} &= -\frac{P_o}{W}\frac{24L^2}{12L^2}\frac{1}{2}\frac{\partial W}{\partial t} \\
\frac{\partial P_o}{\partial t} &= -\frac{P_o}{W}\frac{\partial W}{\partial t} \qquad (4.10)
\end{aligned}$$

This is the expression deduced by Henfer and Haji.

4.1.1 Ambipolar diffusion coefficient:

$$\frac{\partial^2 p(x,t)}{\partial x^2} = \frac{p(x,t)}{L^2} + \frac{1}{D}\frac{\partial p(x,t)}{\partial t} \tag{4.11}$$

Integrating once,

$$\frac{\partial p(x,t)}{\partial x} = \frac{1}{L^2}\int p(x,t)\partial x + \frac{1}{D}\int \frac{\partial p(x,t)}{\partial t}\partial x$$

Hence,

$$\begin{aligned}
\int p dx &= \frac{P_o}{\frac{W}{L}+\frac{1}{6}\frac{W^3}{L^3}}[(-\frac{1}{L})\frac{(W-x)^2}{2} - \frac{1}{6L^3}\frac{(W-x)^4}{4}] \\
&= \frac{P_o}{\frac{6L^2W+W^3}{6L^3}}(-\frac{1}{24L^3})[12L^2(W-x)^2 + (W-x)^4] \\
&= -\frac{P_o}{4W(6L^2+W^2)}[12L^2(W-x)^2 + (W-x)^4]
\end{aligned}$$

$$\frac{1}{L^2}\int p dx = -\frac{P_o}{4WL^2(6L^2+W^2)}[12L^2(W-x)^2 + (W-x)^4] \tag{4.12}$$

Now,

$$
\begin{aligned}
\frac{\partial p}{\partial t} &= \frac{\partial P_o}{\partial t}(1-\frac{x}{W})S + P_o S \frac{x}{W^2}\frac{\partial W}{\partial t} + P_o(1-\frac{x}{W})\frac{\partial S}{\partial t} \\
&= \frac{\partial P_o}{\partial t}(1-\frac{x}{W})[\frac{1+\frac{1}{6}(\frac{W-x}{L})^2}{1+\frac{1}{6}(\frac{W}{L})^2}] + P_o[\frac{1+\frac{1}{6}(\frac{W-x}{L})^2}{1+\frac{1}{6}(\frac{W}{L})^2}]\frac{x}{W^2}\frac{\partial W}{\partial t} \\
&\quad + P_o(1-\frac{x}{W})\frac{2\frac{\partial W}{\partial t}[x(W^2-6L^2)-x^2W]}{(6L^2+W^2)^2} \\
&= A+B+C
\end{aligned}
$$

Here,

$$A = \frac{\partial P_o}{\partial t}(1-\frac{x}{W})[\frac{1+\frac{1}{6}(\frac{W-x}{L})^2}{1+\frac{1}{6}(\frac{W}{L})^2}] \tag{4.13}$$

$$B = P_o[\frac{1+\frac{1}{6}(\frac{W-x}{L})^2}{1+\frac{1}{6}(\frac{W}{L})^2}]\frac{x}{W^2}\frac{\partial W}{\partial t} \tag{4.14}$$

$$C = P_o(1-\frac{x}{W})\frac{2\frac{\partial W}{\partial t}[x(W^2-6L^2)-x^2W]}{(6L^2+W^2)^2} \tag{4.15}$$

Now,

$$
\begin{aligned}
A &= \frac{\partial P_o}{\partial t}(\frac{W-x}{W})\frac{6L^2+(W-x)^2}{6L^2+W^2} \\
&= \frac{\partial P_o}{\partial t}\frac{6L^2(W-x)+(W-x)^3}{6L^2W+W^3} \\
\int A dx &= \frac{\partial P_o}{\partial t}\frac{1}{W(6L^2+W^2)}[\frac{6L^2(W-x)^2}{-2} - \frac{(W-x)^4}{-4}] \\
&= \frac{P_o}{W}\frac{\partial W}{\partial t}\frac{1}{4W(6L^2+W^2)}\frac{(12L^2-3W^2)}{(12L^2-W^2)}[12L^2(W-x)^2+(W-x)^4]
\end{aligned} \tag{4.16}
$$

And,

$$
\begin{aligned}
B &= P_o \frac{x}{W^2} \frac{\partial W}{\partial t} \frac{6L^2 + (W - x)^2}{6L^2 + W^2} \\
&= P_o \frac{1}{W^2(6L^2 + W^2)} \frac{\partial W}{\partial t} [6L^2 x + x(W - x)^2] \\
&= P_o \frac{1}{W^2(6L^2 + W^2)} \frac{\partial W}{\partial t} [6L^2 x + W^2 x - 2Wx^2 + x^3] \\
&= P_o \frac{1}{W^2(6L^2 + W^2)} \frac{\partial W}{\partial t} [x(6L^2 + W^2) - 2Wx^2 + x^3] \\
\int B dx &= P_o \frac{1}{W^2(6L^2 + W^2)} \frac{\partial W}{\partial t} [(6L^2 + W^2)\frac{x^2}{2} - 2W\frac{x^3}{3} + \frac{x^4}{4}] \qquad (4.17)
\end{aligned}
$$

Also for C,

$$
\begin{aligned}
C &= P_o(1 - \frac{x}{W}) \frac{2\frac{\partial W}{\partial t}[x(W^2 - 6L^2) - x^2 W]}{(6L^2 + W^2)^2} \\
&= \frac{2P_o}{W(6L^2 + W^2)} \frac{\partial W}{\partial t} [x(W^2 - 6L^2)W - x^2(W^2 - 6L^2) - x^2 W^2 + x^3 W] \\
&= \frac{2P_o}{W(6L^2 + W^2)} \frac{\partial W}{\partial t} [xW(W^2 - 6L^2) - x^2(2W^2 - 6L^2) + x^3 W] \\
\int C dx &= \frac{2P_o}{W(6L^2 + W^2)^2} \frac{\partial W}{\partial t} [W(W^2 - 6L^2)\frac{x^2}{2} - (2W^2 - 6L^2)\frac{x^3}{3} + W\frac{x^4}{4}] \qquad (4.18)
\end{aligned}
$$

So,from equations (4.12),(4.16),(4.17) & (4.18),

$$\begin{aligned}\frac{\partial p(x,t)}{\partial x} &= \frac{1}{L^2}\int p dx + \frac{1}{D}\int \frac{\partial p}{\partial t}dx \\ &= -\frac{P_o}{4L^2W(6L^2+W^2)}[12(W-x)^2L^2 + (W-x)^4] \\ &\quad + \frac{1}{D}\frac{P_o}{W}\frac{\partial W}{\partial t}\frac{1}{4W(6L^2+W^2)}\frac{(12L^2-3W^2)}{(12L^2-W^2)}[12L^2(W-x)^2+(W-x)^4] \\ &\quad + \frac{1}{D}P_o\frac{1}{W^2(6L^2+W^2)}\frac{\partial W}{\partial t}[(6L^2+W^2)\frac{x^2}{2} - 2W\frac{x^3}{3} + \frac{x^4}{4}] \\ &\quad + \frac{1}{D}\frac{2P_o}{W(6L^2+W^2)^2}\frac{\partial W}{\partial t}[W(W^2-6L^2)\frac{x^2}{2} - (2W^2-6L^2)\frac{x^3}{3} + W\frac{x^4}{4}] + C_1\end{aligned} \tag{4.19}$$

Integrating equation (4.19), we get,

$$\begin{aligned}p(x,t) &= -\frac{P_o}{4L^2W(6L^2+W^2)}[\frac{12L^2(W-x)^3}{-3} + \frac{(W-x)^5}{-5}] \\ &\quad + \frac{1}{D}\frac{P_o}{W}\frac{\partial W}{\partial t}\frac{1}{4W(6L^2+W^2)}\frac{(12L^2-3W^2)}{(12L^2-W^2)}[\frac{12L^2(W-x)^3}{-3} + \frac{(W-x)^5}{-5}] \\ &\quad + \frac{1}{D}P_o\frac{1}{W^2(6L^2+W^2)}\frac{\partial W}{\partial t}[(6L^2+W^2)\frac{x^3}{6} - 2W\frac{x^4}{12} + \frac{x^5}{20}] \\ &\quad + \frac{1}{D}\frac{2P_o}{W(6L^2+W^2)^2}\frac{\partial W}{\partial t}[W(W^2-6L^2)\frac{x^3}{6} - (2W^2-6L^2)\frac{x^4}{12} + W\frac{x^5}{20}] \\ &\quad + C_1x + C_2\end{aligned} \tag{4.20}$$

That is the expression for excess carrier concentration which is a function of x and t. Boundary conditions:

$$x = 0, p = P_0 \tag{4.21}$$

$$x = W, p = 0 \tag{4.22}$$

Now at x= 0 and p=P_0 ,

$$\begin{aligned} P_0 &= \frac{P_0}{4L^2W(6L^2+W^2)}[\frac{20L^2W^3+W^5}{5}] \\ &\quad - \frac{1}{D}.\frac{P_0}{W}.\frac{\partial W}{\partial t}.\frac{1}{4W(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}.[\frac{20L^2W^3+W^5}{5}] + C_2 \\ &= \frac{P_0W^2}{20L^2}.\frac{20L^2+W^2}{(6L^2+W^2)} - \frac{1}{D}.\frac{P_0}{20W^2}.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}.\frac{W^3(20L^2+W^2)}{(6L^2+W^2)} + C_2 \end{aligned}$$

$$C_2 = P_0 - \frac{P_0W^2}{20L^2}.\frac{20L^2+W^2}{(6L^2+W^2)} + \frac{1}{D}.\frac{P_0W}{20}.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}.\frac{(20L^2+W^2)}{(6L^2+W^2)}$$

$$C_2 = P_0 - \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2} - \frac{1}{D}.W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}] \tag{4.23}$$

And x= W and P=0,

$$\begin{aligned} 0 &= \frac{1}{D}.\frac{P_0}{W^2}.\frac{1}{(6L^2+W^2)}.\frac{\partial W}{\partial t}[(6L^2+W^2)\frac{W^3}{6} - \frac{W^5}{6} + \frac{W^5}{20}] \\ &\quad + \frac{1}{D}.\frac{2P_0}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[(W^2-6L^2)\frac{W^3}{6} - (2W^2-6L^2)\frac{W^3}{12} + \frac{W^5}{20}] + C_1W + C_2 \end{aligned}$$

$$
\begin{aligned}
\Rightarrow -C_1W &= \frac{1}{D}.\frac{P_0}{W^2}.\frac{1}{(6L^2+W^2)}.\frac{\partial W}{\partial t}[(W^3L^2+\frac{W^5}{6}-\frac{W^5}{6}+\frac{W^5}{20}] \\
&+\frac{1}{D}.\frac{2P_0}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^5}{6}-L^2W^3-\frac{W^5}{6}+\frac{W^3L^2}{2}+\frac{W^5}{20}] \\
&+P_0-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2}-\frac{1}{D}.W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}] \\
&= \frac{1}{D}.\frac{P_0}{W^2}.\frac{1}{(6L^2+W^2)}.\frac{\partial W}{\partial t}[(W^3L^2+\frac{W^5}{20}]+\frac{1}{D}.\frac{2P_0}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[-\frac{L^2W^3}{2}+\frac{W^5}{20}] \\
&+P_0-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2}-\frac{1}{D}.W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}] \\
&= \frac{1}{D}.\frac{P_0}{(6L^2+W^2)}.\frac{\partial W}{\partial t}.\frac{W}{20}[20L^2+W^2]+\frac{1}{D}.\frac{P_0}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[-L^2W^3+\frac{W^5}{10}] \\
&+P_0-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W^2}{L^2}+\frac{1}{D}.\frac{P_0}{20}.W.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2} \\
&= \frac{1}{D}.\frac{P_0W}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}+\frac{1}{D}.\frac{P_0W^3}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}] \\
&+P_0-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W^2}{L^2}+\frac{1}{D}.\frac{P_0}{20}.W.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow -C_1 &= \frac{1}{D}.\frac{P_0}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}+\frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}] \\
&+\frac{P_0}{W}-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2}+\frac{1}{D}.\frac{P_0}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2} \\
&= \frac{1}{D}.\frac{P_0}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[1+\frac{12L^2-3W^2}{12L^2-W^2}]+\frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}] \\
&+\frac{P_0}{W}-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2} \\
&= \frac{1}{D}.\frac{P_0}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{24L^2-4W^2}{12L^2-W^2}]+\frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}] \\
&+\frac{P_0}{W}-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2}
\end{aligned}
$$

$$\Rightarrow C_1 = -\frac{1}{D}.\frac{P_0}{20}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{24L^2-4W^2}{12L^2-W^2}] - \frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}]$$
$$-\frac{P_0}{W} + \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2} \qquad (4.24)$$

$$P(x,t) = \frac{P_0}{4L^2W(6L^2+W^2)}[4L^2(W-x)^3 + \frac{(W-x)^5}{5}]$$
$$-\frac{1}{D}.\frac{P_0}{W}.\frac{\partial W}{\partial t}.\frac{1}{4W(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}[4L^2(W-x)^3 + \frac{(W-x)^5}{5}]$$
$$+\frac{1}{D}.\frac{P_0}{W^2(6L^2+W^2)}.\frac{\partial W}{\partial t}.[(6L^2+W^2)\frac{x^3}{6} - W\frac{x^4}{6} + \frac{x^5}{20}]$$
$$+\frac{1}{D}.\frac{2P_0}{W(6L^2+W^2)^2}.\frac{\partial W}{\partial t}.[W(W^2-6L^2)\frac{x^3}{6} - (2W^2-6L^2)\frac{x^4}{12} + W\frac{x^5}{20}]$$
$$-\frac{1}{D}.\frac{P_0x}{5}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{6L^2-W^2}{12L^2-W^2}] - \frac{1}{D}.\frac{P_0xW^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}]$$
$$-\frac{P_0x}{W} + \frac{P_0x}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2} + P_0 - \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2} - \frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}]$$
$$(4.25)$$

This is actual the excess carrier concentration P(x,t) for base n-drift region.

Now we know, the excess base charge can be calculated by the following equation

$$Q(t) = qA\int_0^W p(x)dx \qquad (4.26)$$

Integrating the excess carrier concentration, we get

$$\int P(x,t)dx = \frac{P_0}{20L^2W(6L^2+W^2)}[\frac{20L^2(W-x)^4}{-4} - \frac{(W-x)^6}{6}]$$
$$- \frac{1}{D}.\frac{P_0}{20W^2}.\frac{\partial W}{\partial t}.\frac{1}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}[\frac{20L^2(W-x)^4}{-4} - \frac{(W-x)^6}{6}]$$
$$+ \frac{1}{D}.\frac{P_0}{W^2(6L^2+W^2)}.\frac{\partial W}{\partial t}.[(6L^2+W^2)\frac{x^4}{24} - W\frac{x^5}{30} + \frac{x^6}{120}]$$
$$+ \frac{1}{D}.\frac{2P_0}{W(6L^2+W^2)^2}.\frac{\partial W}{\partial t}.[W(W^2-6L^2)\frac{x^4}{24} - (W^2-3L^2)\frac{x^5}{30} + W\frac{x^6}{120}]$$
$$- \frac{1}{D}.\frac{P_0}{5}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{6L^2-W^2}{12L^2-W^2}].\frac{x^2}{2} - \frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}].\frac{x^2}{2}$$
$$- \frac{P_0}{W}.\frac{x^2}{2} + \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2}.\frac{x^2}{2}$$
$$+ P_0x - \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2} - \frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}]x \qquad (4.27)$$

Now, putting x=W (Upper limit),

$$\left[\int P(x,t)dx\right]^W = \frac{1}{D}\frac{P_0}{W^2(6L^2+W^2)}\frac{\partial W}{\partial t}\left[(6L^2+W^2)\frac{W^4}{24} - \frac{W^6}{30} + \frac{W^6}{120}\right]$$
$$+ \frac{1}{D}\frac{2P_0}{W(6L^2+W^2)^2}\frac{\partial W}{\partial t}\left[W(W^2-6L^2)\frac{W^4}{24} - (W^2-3L^2)\frac{W^5}{30} + \frac{W^7}{120}\right]$$
$$- \frac{1}{D}\frac{P_0}{5}\frac{\partial W}{\partial t}\frac{20L^2+W^2}{6L^2+W^2}\frac{6L^2-W^2}{12L^2-W^2}\frac{W^2}{2}$$
$$- \frac{1}{D}\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}\frac{(W^2-10L^2)}{10}\frac{W^2}{2}$$
$$- \frac{P_0}{W}\frac{W^2}{2} + \frac{P_0}{20}\frac{W}{L^2}\frac{20L^2+W^2}{6L^2+W^2}\frac{W^2}{2}$$
$$+ P_0W - \frac{P_0}{20}.\frac{20L^2+W^2}{6L^2+W^2}\left[\frac{W^2}{L^2} - \frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}\right]W$$

$$
\begin{aligned}
\left[\int P(x,t)dx\right]^{W} &= \frac{1}{D}\frac{P_0}{W^2(6L^2+W^2)}\frac{\partial W}{\partial t}\left[\frac{W^4L^2}{4}+\frac{W^6}{24}-\frac{W^6}{30}+\frac{W^6}{120}\right] \\
&+\frac{1}{D}\frac{2P_0}{W(6L^2+W^2)^2}\frac{\partial W}{\partial t}\left[\frac{W^7}{24}-\frac{W^5L^2}{4}-\frac{W^7}{30}+\frac{W^5L^2}{10}+\frac{W^7}{120}\right] \\
&-\frac{1}{D}\frac{P_0}{5}\frac{\partial W}{\partial t}\frac{20L^2+W^2}{6L^2+W^2}\frac{6L^2-W^2}{12L^2-W^2}\frac{W^2}{2} \\
&-\frac{1}{D}\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}\frac{\left(W^2-10L^2\right)}{10}\frac{W^2}{2} \\
&-\frac{P_0W}{2}+\frac{P_0}{20}\frac{W}{L^2}\frac{20L^2+W^2}{6L^2+W^2}\frac{W^2}{2} \\
&+P_0W-\frac{P_0}{20}\frac{20L^2+W^2}{6L^2+W^2}\left[\frac{W^2}{L^2}-\frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}\right]W
\end{aligned}
$$

$$
\begin{aligned}
\left[\int P(x,t)dx\right]^{W} &= \frac{1}{D}.\frac{P_0}{(6L^2+W^2)}.\frac{\partial W}{\partial t}.[\frac{W^2L^2}{4}+\frac{W^4}{60}] \\
&+\frac{1}{D}\frac{P_0}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}.[\frac{W^6}{30}-\frac{3W^4L^2}{10}] \\
&-\frac{1}{D}.\frac{P_0}{5}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{6L^2-W^2}{12L^2-W^2}].\frac{W^2}{2} \\
&-\frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}].\frac{W^2}{2} \\
&-\frac{P_0W}{2}+\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2}.\frac{W^2}{2} \\
&+P_0W-\frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2}-\frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}]W \quad (4.28)
\end{aligned}
$$

Now, putting x=0 (lower limit),

$$
\begin{aligned}
\left[\int P(x,t)dx\right]_0 &= -\frac{P_0}{20L^2W(6L^2+W^2)}\left[5L^2W^4+\frac{W^6}{6}\right] \\
&+\frac{1}{D}\frac{P_0}{20W^2}\frac{\partial W}{\partial t}\frac{1}{6L^2+W^2}\frac{12L^2-3W^2}{12L^2-W^2}\left[5L^2W^4+\frac{W^6}{6}\right]
\end{aligned}
$$

$$\left[\int P(x,t)dx\right]_0 = -\frac{P_0W^3}{20L^2(6L^2+W^2)}.\frac{30L^2+W^2}{6} + \frac{1}{D}.\frac{P_0W^2}{20}.\frac{\partial W}{\partial t}.\frac{1}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}[30L^2+W^2] \quad (4.29)$$

Subtracting 4.21 from 4.20,

$$\begin{aligned}\int_0^W Pdx =& \frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)}.\frac{\partial W}{\partial t}.\frac{15L^2+W^2}{60} + \frac{1}{D}\frac{P_0W^4}{(6L^2+W^2)^2}\frac{\partial W}{\partial t}.\frac{W^2-9L^2}{30}\\ &- \frac{1}{D}.\frac{P_0W^2}{10}.\frac{\partial W}{\partial t}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{6L^2-W^2}{12L^2-W^2}] - \frac{1}{D}.\frac{P_0W^2}{(6L^2+W^2)^2}.\frac{W^2}{2}\frac{\partial W}{\partial t}[\frac{W^2-10L^2}{10}]\\ &+ \frac{P_0W}{2} + \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}.\frac{W}{L^2}.\frac{W^2}{2} - \frac{P_0}{20}.\frac{20L^2+W^2}{(6L^2+W^2)}[\frac{W^2}{L^2}\\ &- \frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2-3W^2}{12L^2-W^2}]W + \frac{P_0W^3}{20L^2(6L^2+W^2)}.\frac{30L^2+W^2}{6}\\ &- \frac{1}{D}.\frac{P_0W^2}{20}.\frac{\partial W}{\partial t}.\frac{1}{(6L^2+W^2)}.\frac{12L^2-3W^2}{12L^2-W^2}[30L^2+W^2] \quad (4.30)\end{aligned}$$

If we assume W is much much smaller than L (W << L),

$$\begin{aligned}\int_0^W Pdx =& \frac{1}{D}.\frac{P_0W^2}{6L^2}.\frac{\partial W}{\partial t}.\frac{15L^2}{60} + \frac{1}{D}\frac{P_0W^4}{36L^4}\frac{\partial W}{\partial t}.\frac{-9L^2}{30} - \frac{1}{D}.\frac{P_0W^2}{10}.\frac{\partial W}{\partial t}.\frac{20L^2}{6L^2}.\frac{6L^2}{12L^2}\\ &- \frac{1}{D}.\frac{P_0W^2}{36L^4}.\frac{W^2}{2}\frac{\partial W}{\partial t}.\frac{-10L^2}{10} + \frac{P_0W}{2} + \frac{P_0}{20}.\frac{20L^2}{6L^2}.\frac{W^3}{2L^2} - \frac{P_0}{20}.\frac{20L^2}{6L^2}[\frac{W^2}{L^2}\\ &- \frac{1}{D}W.\frac{\partial W}{\partial t}.\frac{12L^2}{12L^2}]W + \frac{P_0W^3}{20L^2(6L^2+W^2)}.\frac{30L^2+W^2}{6}\\ &- \frac{1}{D}.\frac{P_0W^2}{20}.\frac{\partial W}{\partial t}.\frac{1}{6L^2}.\frac{12L^2}{12L^2}.30L^2\end{aligned}$$

$$\int_0^W Pdx = \frac{1}{D}.\frac{P_0W^2}{24}.\frac{\partial W}{\partial t} - \frac{1}{D}\frac{P_0W^4}{4L^2}\frac{\partial W}{\partial t}.\frac{1}{30} - \frac{1}{D}.\frac{P_0W^2}{6}.\frac{\partial W}{\partial t} - \frac{1}{D}.\frac{P_0W^4}{72L^2}.\frac{\partial W}{\partial t} + \frac{P_0W}{2}$$
$$+ \frac{P_0W^3}{12L^2} - \frac{P_0W^3}{6L^2} + \frac{1}{D}\frac{P_0W^2}{6L^2}\frac{\partial W}{\partial t} + \frac{P_0W^3}{24L^2} - \frac{1}{D}.\frac{P_0W^2}{4}.\frac{\partial W}{\partial t}$$

$$\int_0^W Pdx = \frac{P_0W}{2} - \frac{P_0W^3}{24L^2} - \frac{3}{8}.\frac{1}{D}.P_0W^2.\frac{\partial W}{\partial t} \tag{4.31}$$

Now the excess base charge will be,

$$\begin{aligned} Q(t) &= qA\int_0^W Pdx \\ &= qA\frac{P_0W}{2} - qA\frac{P_0W^3}{24L^2} - qA\frac{3P_0W^2}{8D}.\frac{\partial W}{\partial t} \\ &= qA[\frac{W}{2} - \frac{W^3}{24L^2}] - qA.\frac{3}{8}.\frac{1}{D}.P_0W^2.\frac{\partial W}{\partial t} \end{aligned} \tag{4.32}$$

As we know,

$$\begin{aligned} L &= \sqrt{D\tau_{H_L}} \\ \Rightarrow L^2 &= D\tau_{H_L} \\ so, D &= \frac{L^2}{\tau_{H_L}} \end{aligned}$$

Hence,

$$qA.\frac{3}{8}.\frac{1}{D}.P_0W^2.\frac{\partial W}{\partial t} = qA.\frac{3}{8}.\frac{W^2}{L^2}.P_0.\frac{\partial W}{\partial t}.\tau_{H_L} \approx 0$$

As (W/L) << 1,

$$Q(t) = qAP_0[\frac{W}{2} - \frac{W^3}{24L^2}] \tag{4.33}$$

Which is the exact expression found in the thesis paper of Mohsen A. Hajji.

Since,

$$\frac{W^3}{L^2} \approx 0,$$

So we get,

$$Q(t) = qAP_0\frac{W(t)}{2} \tag{4.34}$$

This is exact expression found by Hefner in his journal paper.

Again we know exact expression for Q(t)

$$Q(t) = qAP_0L\tanh(\frac{W}{2L}) \tag{4.35}$$

if we take binomial expansion of tanh(W/2L),

$$\begin{aligned}\tanh(\frac{W}{2L}) &= \frac{W}{2L} - \frac{1}{3}.(\frac{W}{2L})^3 + ... \\ &\approx \frac{W}{2L} - \frac{W^3}{24L^3}\end{aligned}$$

$$Q(t) = qAP_0L[\frac{W}{2L} - \frac{W^3}{24L^3}] \tag{4.36}$$

$$= qAP_0[\frac{W}{2} - \frac{W^3}{24L^2}] \tag{4.37}$$

This is the exact expression as seen in equation (4.25).

However now, assuming,

$$\frac{W}{L} << 1, \frac{W^3}{L^2} \approx 0$$

$$Q(t) = qAP_0\frac{W(t)}{2} \tag{4.38}$$

Chapter: 5

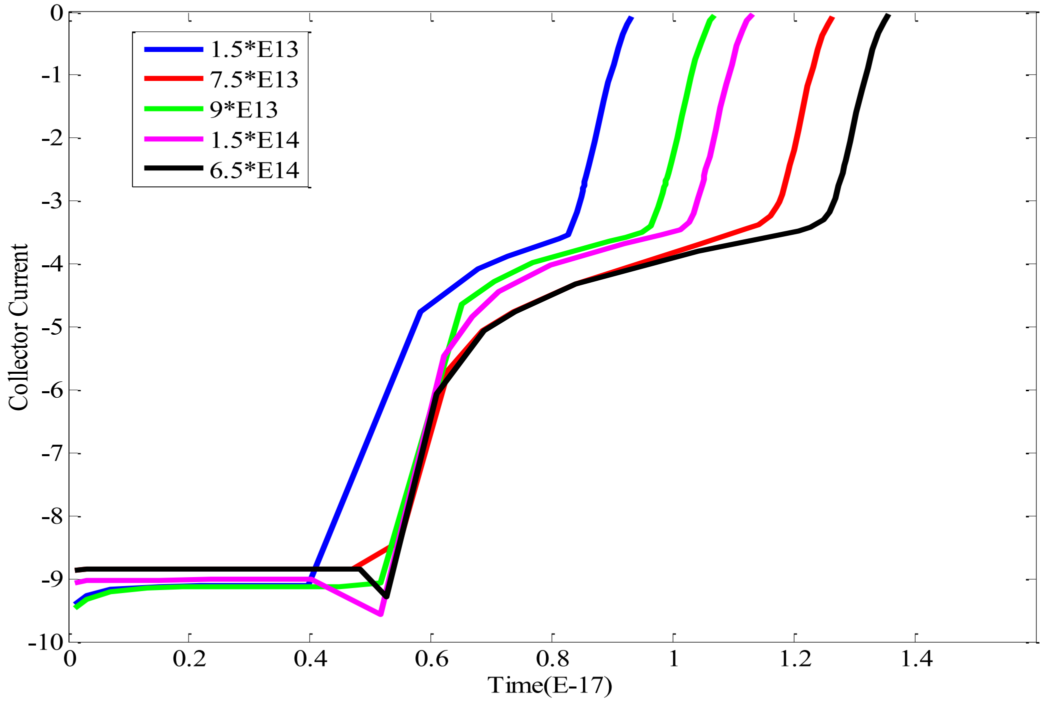
Result and Discussion:

In this part we have analyzed about the different region concentration variation effect on collector current, effect of variation of the gate voltage and collector current. Finally we will discuss about the Temperature (K) effect on the collector current of a Punch through Insulated Gate Bipolar Transistor (IGBT).

The drift region doping concentration effect on collector current:

First of all, the doping concentration of drift region of a PTIGBT create a lot of effect on the anode current because if we increase the doping concentration on the drift region then the collector current of a PTIGBT current will start to flow. The drift region is the n type region so there are electrons. Normally we taka a light doping in the drift region because when we inject the hole in the p+ substrate then the holes of the p+ subtract region holes and the drift region electrons recombined with each other. But if we increase the doping gradually then the recombination time between the hole and electron will increase so the collector current will take more time to increase and the switching on time will increase. From the following graph we can easily see the difference between the switch on time of a PTIGBT in different doping.

Graph:



From the graph we can say that after injected the hole in the p substrate when we apply the gate voltage and the collector emitter voltage then the electron start to move and in the base region they start to recombined and after the recombination the collector current rise very quickly because the n+ buffer layer punches this electron through the emitter.

Table5.1:

Doping concentration of drift region(cm^-3)	Recombination start time(micro sec)	Recombination end time(micro sec)	Switch on time(micro sec)
1.5x10^13	0.58	0.8	0.90
7.5x10^13	0.60	0.93	1.02
9.0x10^13	0.62	1.0	1.10
1.5x10^14	0.60	1.2	1.22
6.5x10^14	0.66	1.25	1.30

Table5. 1: Different values for different type of doping concentration in the drift region.

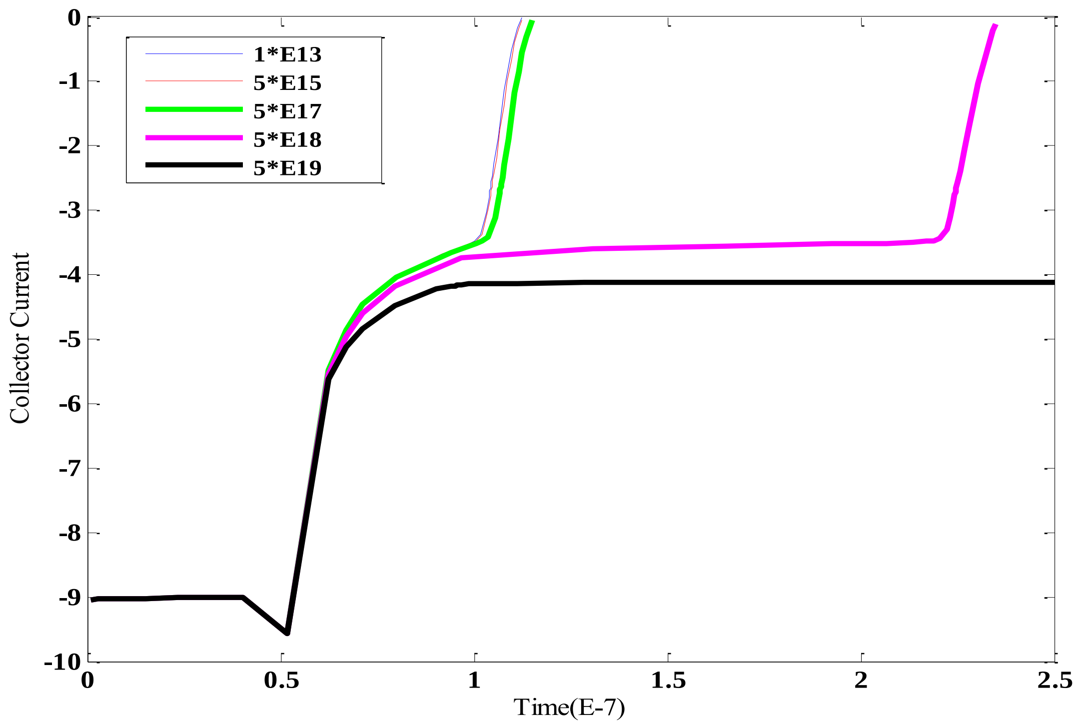
Change in buffer layer doping concentration:

Further developed/improved device can be achieved by adding a few more buffer layers which will tends to more perfect switching because the power loss will be less and hence the IGBT wont burnt out so the devices which connected via IGBT will remain safe.

With the buffer layer we can speed up the switching of an IGBT and it also helps to reduce the trail current during the turn of the IGBT. So it is very important to select the sweet able buffer layer doping for which we will get the comparatively first switching. If we increase the buffer layer doping too much then the power loss will be more and the electron will not get too much energy to move towards the gate channel so the IGBT will not on in that situation. But if we keep the buffer layer concentration less than the p+ substrate concentration then the collector current curve will rise smoothly and the IGBT will on a bit quicker. So we select the buffer layer doping more than the drift region concentration but less than the p+ substrate concentration. It may can be select as 10^(16) or 10^(17)

where the p+ substrate doping is 10^(19) and the n drift region concentration is 10^(13).

Graph:



From the above diagram we can see that when the buffer layer concentration is 5x10^(19) then the collector current is not rising because there is more power losses and more recombination rate but when the doping concentration is decreasing then the power losses is also decreasing and the switch on time is increasing. The recombination time also increase with the increasing of bopping concentration in the buffer layer which decreasing the switch on time or the collector current rising time. The recombination time and the switch-on time values with different buffer layer concentration are given the bellow table.

Table5.2:

Doping concentration of buffer layer region(cm^-3)	Recombination start time(micro sec)	Recombination start time(micro sec)	Switch on time(micro sec)
1x10^13	0.5	0.8	0.7
5x10^15	0.5	0.7	0.8
5x10^17	1	1.0	1.0
5x10^18	1	2.25	2.35
5x10^19	1	Very large	Switch will not on

Figure 5.2: For the different doping concentration in buffer layer.

Effect of changing gate voltage:

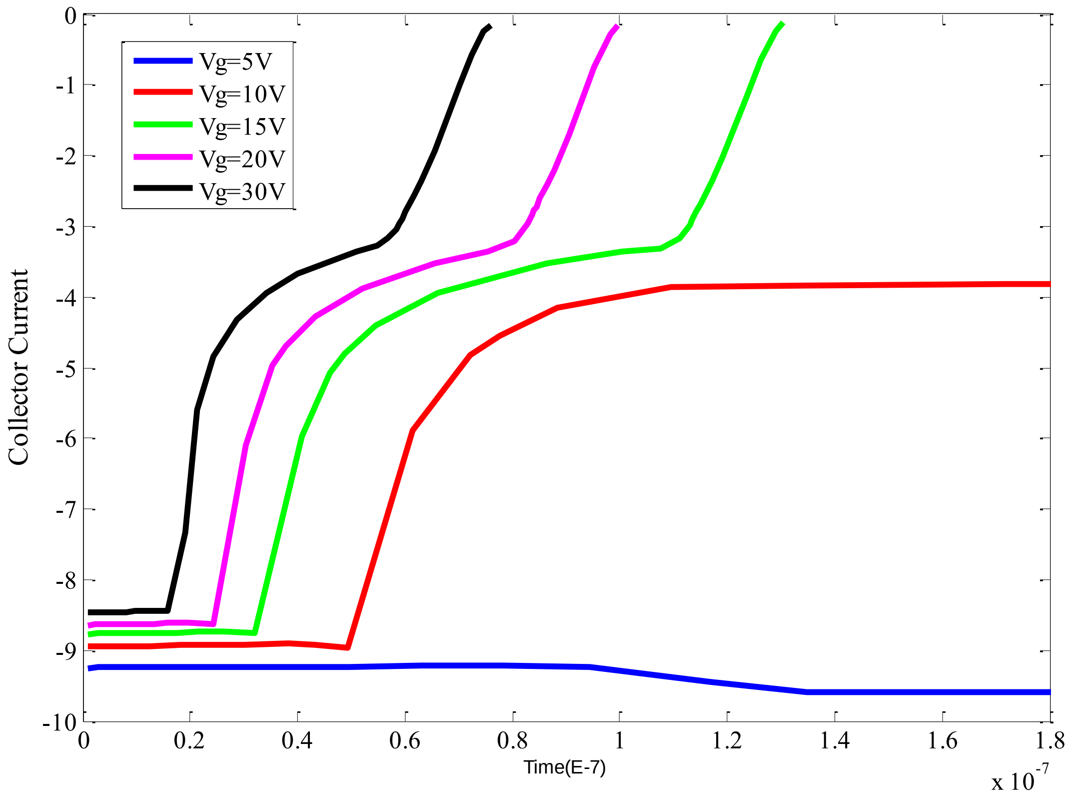
Firstly when we supply the collector voltage but there will be no supply to the gate then the junction (J2) will be in the reverse base situation because there is a p base region under the n base region and there do not make any channel any more. But when we will short the gate with the emitter then there will create an electron layer under the gate oxide which is known as channel. So there come a breakdown in the p base and electron start to flow and the current start to flow through the emitter. Now if we increase the temperature gradually then the channel length will also increase gradually and then more current start to flow. But when the gate voltage in about 30v then the collector current rise very quickly which can be harmful for our IGBT because we are using the silicon oxide and at 30v silicon break down comes and the current increase rapidly. On the other hand if we make the gate voltage very low then the switch will never on because the channel which will be created by the gate voltage that will be too much small to flow the current through the emitter. If we see the following curve then it will be clearer to us. From the curve we can say that when the gate voltage is 5v then the collector current is going down which will never goes up word and so the switch will never be on. For the gate voltage 30v then the collector current is rising very quickly. It is also not too good for our IGBT because it can make some hotspots inside the IGBT for which the IGBT can burn out. So we need to select the gate voltage between 10v to20v for a very sweet able switching.

Table5.3:

Gate voltage (v)	Switch on time(micro second)
5v	never
10v	Very large
15v	1.2
20v	0.95
30v	0.7

Table5.4:for voltage and switch on time

Graph:



Temperature effect:

In this section we provide details about the impact of temperature on the Punch through IGBT. If we increase the temperature then which parameters will change in a punch through IGBT we will discuss that parameters and how they changes here also.

The temperature dependence parameters are electron and holes mobility, intrinsic carrier concentration and the carrier life time. If we increase or decrease the temperature all those parameters will also be change. How all those parameters are changing will be describe in bellow.

Parameter	Temperature Dependence Equation
Carrier lifetime	$\tau_{HL} = 5\times10^{-7}\left(\frac{T}{300}\right)^{1.5}$
Electron mobility	$\mu_n = 1400\left(\frac{300}{T}\right)^{2.5}$
Hole mobility	$\mu_p = 450\left(\frac{300}{T}\right)^{2.5}$
Intrinsic concentration	$n_i = {3.88\times10^{16}(T)^{1.5}} \Big/ {\exp\left(\frac{7000}{T}\right)}$

Effects of Temperature and Doping on Mobility of a punch through IGBT:

Conductivity of a material is determined by two factors: the concentration of free carriers available to conduct current and their mobility. In a semiconductor, both mobility and carrier concentration are temperature dependent. There are two basic types of scattering mechanisms that influence the mobility of electrons and holes:

lattice scattering and impurity scattering. We know that lattice vibrations cause the mobility to decrease with increasing temperature.

However, the mobility of the carriers in a semiconductor is also influenced by the presence of *charged impurities*. Impurity scattering is caused by crystal defects such as ionized impurities. At lower temperatures carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering increases and the mobility decreases. This is just the opposite of the effect of lattice scattering. The total mobility then is the sum of the lattice-scattering mobility and the impurity-scattering mobility. Total mobility has a temperature at which it is a maximum. The approximate temperature dependence of mobility due to lattice scattering is T-3/2, while the temperature dependence of mobility due to impurity scattering is T+3/2. In practice, impurity scattering is typically only seen at very low temperatures. In the temperature range we will measure, only the influence of lattice scattering will be expected.

Temperature Dependence of Carrier Concentration:

The carrier concentration in a power semiconductor is also affected by the temperature. At very low temperatures (large 1/*T*), negligible intrinsic electron-hole-pairs (EHPs) exist, and the donor electrons are bound to the donor atoms. This is known as the ionization(or freeze -out*)* region. As the temperature is raised, increased ionization occurs and at about 100K all of the donor atoms are ionized, at which point the carrier concentration is determined by doping. The region where every available dopant has been ionized is called the extrinsicregion. In this region, an increase in temperature produces no increase in carrier concentration. On the other hand for a doped semiconductor, the temperature dependence of electron concentration. At very low temperatures (large 1/ T), negligible intrinsic electron-hole-pairs (EHPs) exist and the donor electrons are bound to the donor atoms. This is known as the ionization (or freeze-out) region. As the temperature is raised, increased ionization occurs andat about 100K all of the donor atoms are ionized, at which point the carrier concentration is
Determined by doping. The region where every available dopant has been ionized is called the extrinsic (or saturation) region. In this region, an increase in

temperature produces no increase in carrier concentration. Referring the Equation of intrinsic carrier concentration is

$$n_i(T) = 2\left[\frac{2\pi kT}{h^2}\right]^{\frac{3}{2}}\left(m_n^* m_p^*\right)^{\frac{3}{4}} \exp\left[\frac{-E_g}{2kT}\right]$$

Form the above equation we can say that if we increase the temperature then the energy band gap will increase and the intrinsic carrier concentration will also increase which is responsible for increasing the switching on time decreases.

Temperature Dependence of Conductivity for a Semiconductor:

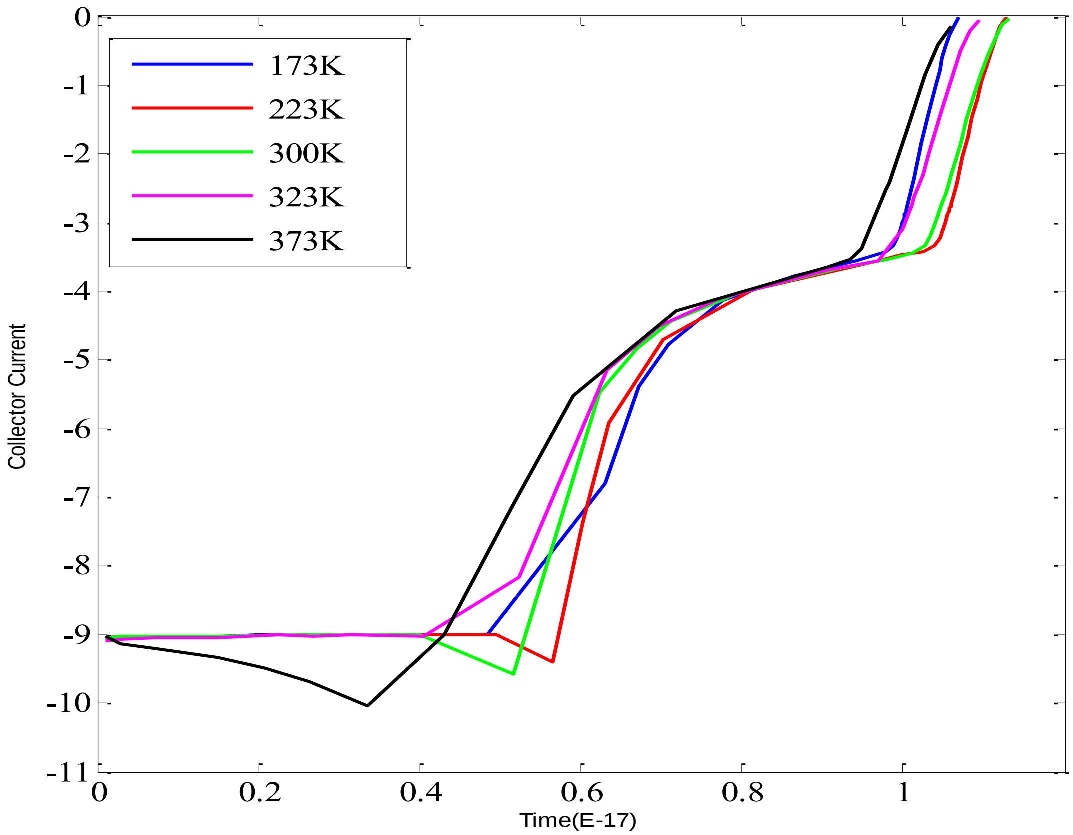
At fairly low temperatures (less than 200K), the dominant scattering mechanism might be impurity scattering (T3/2) while the carrier concentration is determined by extrinsic doping (n = ND+), therefore conductivity would be seen to increase with temperature(T3/2)

Other possibilities, depending on the material, doping, and temperature will show different temperaturedependence of conductivity. One particularly interesting case occurs at high temperatures (above 400K or higher) when carrier concentration is intrinsic (Equation 4) and mobility is dominated by lattice scattering (μαT-3/2). In such cases, the conductivity can easily be shown to vary with temperature as:

σαexp(-Eg/ 2kT)

In this case, conductivity depends only on the semiconductor band gap and the temperature. In this temperature range, measured conductivity data can be used to determine the semiconductor band gap energy, Eg.

Graph:



173K
223K
300K
323K
373K
Collector Current
Time(E-17)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
0
0.2
0.4
0.6
0.8
1

Table5.5:

Temperature (K)	Electron Mobility (Cm^2)/v-sec	Hole Mobility (Cm^2)/v-sec	Lifetime	Intrinsic carrier concentration
123	13935.79	4180.73	1.39*10^(-7)	1.02*10^(-5)
173	5939.90	1781.97	2.18*10^(-7)	0.24*10^(-3)
223	3148.70	944.61	3.20*10^(-7)	3.10*10^(6)
273	1898.83	569.65	4.34*10^(-7)	1.28*10^(9)
300	1500	450	5*10^(-7)	1*10^(10)
323	1247.06	374.11	5.58*10^(-7)	5.24*10^(11)
373	870.39	261.06	6.93*10^(-7)	7.79*10^(12)
423	635.39	190.61	8.37*10^(-7)	6.5*10^(13)

Table 5.5:Different values of different parameters in different temperatures.

Conclusion:

A previously developed physics-based IGBT model is implemented into the IC-SPICE circuit simulator. The IC-SPICE circuit simulator was chosen for this study because it provides the user with programming capability. This programming capability is essential for implementing the complex model equations that are necessary to describe the behavior of the ICBT. When implementing physics-based models into IC-SPICE: 1) the model must before emulated as an interconnection of controlled sources, 2) the variables used to formulate the model must be normalized so that each variable has a comparable absolute error tolerance, and 3) the partialderivatives of the controlled source functions with respect to each controlling variable must be evaluated. The IG-SPICE IGBT model developed in this paper is verified by comparing the results of the model with experimental results for various circuit operating conditions. The model performs well and describes experimental results accurately for the range of static and dynamic conditions in which the device is intended to be operated. The effectiveness of theIC-SPICE IGBT model is demonstrated by examining the effects of the normal process variation of the model parameters upon the static and dynamic sharing of paralleled IGBTs. The results indicate that the threshold voltage and trans conductance variations tend to result in dynamic current spikes, whereas lifetime variations tend to result in uneven current tails. Both lifetime and trans conductance variations result in uneven staticsharing.

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Appendix A

Effective Depletion width from Poisson's Equation

When an electric field is created in the depletion region by the separation of positive and negative space charge densities. Fig below shows the volume charge density distribution in the p-n junction assuming uniform doping and assuming an abrupt junction approximation. We will assume that the space charge region abruptly ends in the n region at x = $+x_n$, and abruptly ends in the p region at x =-x_p, (x_p is a positive quantity).

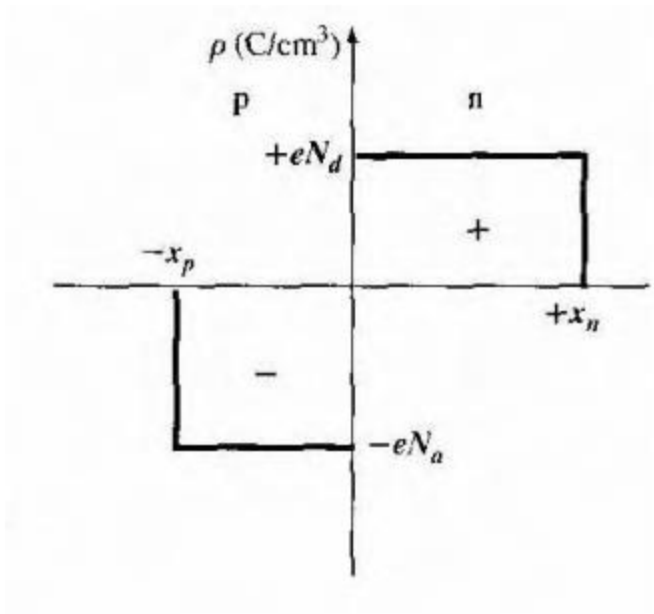


Figure D1: The space charge density in a uniformly doped pn junction assuming the abrupt junction approximation

The electric field is determined from Poisson's equation which, for a one-dimensional
analysis, is

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\varepsilon_s} = -\frac{dE(x)}{dx}$$

Where Ø(x) is the electric potential and E(x) is the electric field, ρ (x) is the volume charge density and charge densities from the figure above,

$$\rho(x) = -eN_a \qquad\qquad -x_p < x < 0$$

And

$$\rho(x) = eN_d \qquad\qquad 0 < x < x_n$$

The electric field in the p region is found by Poisson's equation

$$E = \int \frac{\rho(x)}{\varepsilon_s} dx = -\int \frac{eN_a}{\varepsilon_s} dx = -\frac{eN_a}{\varepsilon_s} x + C_1$$

Where C1 is a constant of integration, electric field is assumed to be zero in the neutral p region for $x < x_p$, since the currents are zero in thermal equilibrium. As there are no surface charge densities within the p-n junction structure, the electric field is a continuous function. The constant of integration is determined by setting $E = 0$ at $x = x_p$. The electric field in the p region is then given by,

$$E = -\frac{eN_a}{\varepsilon_s}(x + x_p) \qquad\qquad -x_p \leq x \leq 0$$

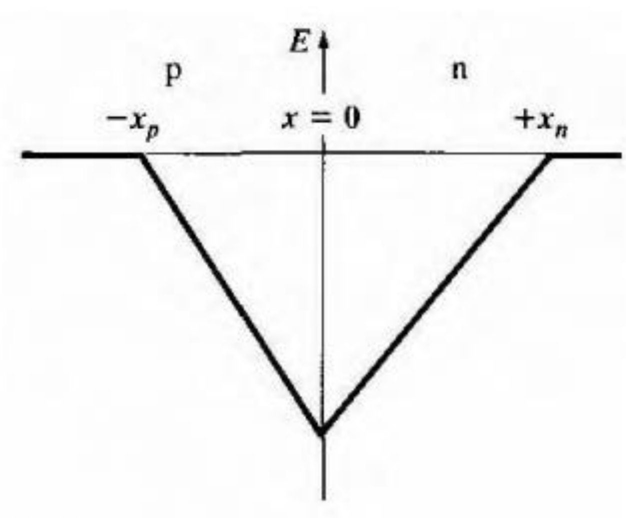
The electric field is determined from,

$$E = \int \frac{eN_d}{\varepsilon_s} dx = \frac{eN_d}{\varepsilon_s} x + C_2$$

Where C2 is again a constant of integration and this constant is determined by setting E = 0 at x = x_n, since the electric field is assumed to be zero in the n region and is a continuous function. Then

$$E = -\frac{eN_a}{\varepsilon_s}(x_n - x) \qquad\qquad 0 \leq x \leq x_n$$

Now, from this Electric field in the space charge region of a uniformly doped pn junction,



The electric field is also continuous at the metallurgical junction, or at x = 0.Setting electric field in p and n region equal to each other at x = 0 gives,

$$N_a x_p = N_d x_n$$

Equation (D.8) states that the number of negative charges per unit area in the p region is equal to the number of positive charges per unit area in the n region.
In the last plot of the electric field in the depletion region the electric field direction is from the n to the p region, or in the negative x direction for this geometry. For the uniformly doped p-n junction, the E-field is a linear function of distance through the junction, and the maximum (magnitude) electric field occurs at the metallurgical junction. An electric field exists in the depletion region even when no voltage is applied between the p and n regions.

The potential in the junction is found by integrating the electric field. In the p region then, we have

$$\phi(x) = -\int E dx = \int \frac{eN_a}{\varepsilon_s}(x + x_p)dx$$
$$\phi(x) = \frac{eN_a}{\varepsilon_s}\left(\frac{x^2}{2} + x_p x\right) + C_1{}'$$

Where the last part is again a constant of integration. The potential difference through the pn junction is the important parameter, rather than the absolute potential, so we may arbitrarily set the potential equal to zero at x = - x_p . The constant of integration is then found as,

$$C_1{}' = \frac{eN_a}{2\varepsilon_s}x_p{}^2$$

So that the potential in the p region can now be written as

$$\phi(x) = \frac{eN_a}{2\varepsilon_s}(x + x_p)^2 \qquad\qquad -x_p \leq x \leq 0$$

The potential in the n region is determined by integrating the electric field in the n region, or

$$\phi(x) = -\int E dx = \int \frac{eN_d}{\varepsilon_s}(x_n - x)dx$$

Then

$$\phi(x) = \frac{eN_d}{\varepsilon_s}\left(x_n x - \frac{x^2}{2}\right) + C_2{}'$$

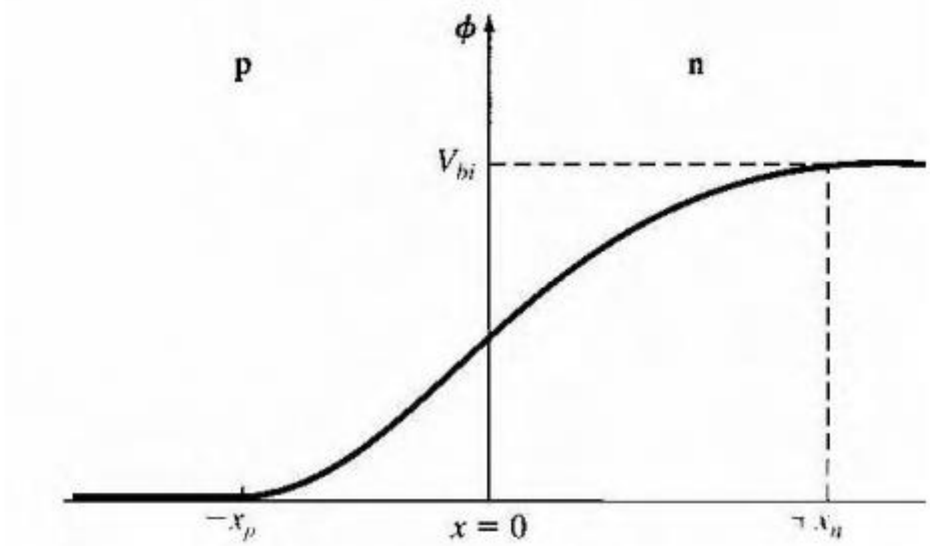
Where the last part is another constant of integration. The potential is a continuous function, hence we get,

$$C_2{}' = \frac{eN_a}{2\varepsilon_s}{x_p}^2$$

The potential in then region can thus be written as,

$$\phi(x) = \frac{eN_d}{\varepsilon_s}\left(x_n x - \frac{x^2}{2}\right) + \frac{eN_a}{2\varepsilon_s}{x_p}^2 \qquad 0 \leq x \leq x_n$$

Figure showed below is a plot of the potential through the junction and shows the



quadratic dependence on distance .The magnitude of the potential at x = xn is equal to the built-in potential barrier. Then we get,

$$V_{bi} = [\phi(x = x_n)] = \frac{e}{2\varepsilon_s}\left(N_a {x_p}^2 + N_d {x_n}^2\right)$$

We can determine the distance that the space charge region extends into the p and n regions from the metallurgical junction. This distance is known as the space charge width or Depletion Width. Now may write, for example,

$$x_p = \frac{N_d x_n}{N_a}$$

Then, solving for x_n, we obtain,

$$x_n = \left\{ \frac{2\varepsilon_s V_{bi}}{e} \left[\frac{N_a}{N_d}\right] \left[\frac{1}{N_a + N_d}\right] \right\}^{\frac{1}{2}}$$

However now, similarly we can solve for x_p. After finding total depletion width we can say $N_d << N_a$ and $x_n >> x_p$ and also x_n almost equal to W_{bcj}. If the metallurgical base width is W_B, then the effective depletion width can be written as,

$$W(t) = W_B - W_{bcj}(t)$$

$$W(t) = W_B - \sqrt{\frac{2\varepsilon_s V_{CE}(t)}{qN_B}}$$

Appendix B

Ambipolar diffuision coefficient

Electrons and holes transport cannot be treated separately at high injection level because the electrons move in a cloud of holes and conversely. Combination of continuity equation for electrons with that for holes, and introduction of a new parameter, namely, Ambipolar Diffiusion Coefficient, which is an algebraic function of electron and hole diffusivities and concentrations. The dening equation for the ambipolar diffiusion coefficient is

$$D = \frac{nq\mu_n D_p + pq\mu_p D_n}{nq\mu_n + pq\mu_p}$$

D_n = Electron Diffusion Coeffcient
μ_p = Hole Diffusion Coefficient
μ_n = Electron mobility
n = Hole mobility
p = hole concentration
q =charge of an electron

The advantage gained from this approach is that the resulting single equation allows focusing our attention on the minority carrier concentration, while the presence of majority carrier concentration is automatically accounted for by the ambipolar diffusion coeffcient.

Hence we can determine,

$$\frac{D_n}{\mu_n} = \frac{kT}{q}$$

$$\frac{D_p}{\mu_p} = \frac{kT}{q}$$

$$\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p} = b$$

Assuming n = p, we will get,

$$
\begin{aligned}
D &= \frac{nq(\mu_n D_p + \mu_p D_n)}{nq(\mu_n + \mu_p)} \\
&= \frac{\mu_n D_p + \mu_p D_n}{\mu_n + \mu_p} \\
&= \frac{\frac{\mu_n}{\mu_p} D_p + D_n}{\frac{\mu_n}{\mu_p} + 1} \\
&= \frac{b D_p + D_n}{b + 1} \\
&= \frac{D_p + \frac{D_n}{b}}{1 + \frac{1}{b}} \\
&= \frac{D_p + D_n \frac{D_p}{D_n}}{1 + \frac{1}{b}} \\
&= \frac{2D_p}{1 + \frac{1}{b}}
\end{aligned}
$$

Hence,

$$2D_p = D(1 + \frac{1}{b})$$

Appendix C

Silvaco Sample Code:

```
# (c) Silvaco Inc., 2015
go atlas

TITLE : IGBT LATCHUP SIMULATION
# IGBT steady state output characteristics
# Save the solution at Vce=300 V

mesh

x.mesh loc=0.0 spac=1.3
x.mesh loc=13.0 spac=0.75
x.mesh loc=25.0 spac=1.4

y.mesh loc=-0.08 spac=0.04
y.mesh loc=0.0 spac=0.04
y.mesh loc=0.6 spac=0.2
y.mesh loc=8.0 spac=1.0
y.mesh loc=70.0 spac=20.0
y.mesh loc=100.0 spac=10.0

region num=1 y.max=0.0 oxide
region num=2 y.min=0.0 silicon

# electrodes #1 - gate; #2 - emitter #3 - collector

elec num=1 left y.min=-0.08 length=13.0 name=gate
elec num=2 right y.min=0.0 y.max=0.0 length=6.8 name=emitter
elec num=3 bottom name=collector

# impurity profile
doping uniform conc=1.5e14 n.type
doping uniform conc=1.0e19 p.type y.t=81.4 y.b=100
doping uniform conc=1.0e17 n.type y.t=65.0 y.b=81.4
```

```
doping gauss conc=2.7e17 p.type junc=5.8 x.l=13 ratio=0.8
doping gauss conc=9.3e19 n.type junc=0.4 x.l=13 x.r=20 ratio=0.8

save outf=powerex03_0.str

tonyplot powerex03_0.str -set powerex03_0.set

mater region=2 taup0=1e-6 taun0=1e-6
contact num=1 n.poly

models analytic srh auger fldmob surfmob

solve init

method newton trap

# Vce increased from 0.0
solve vcollector=0.1
solve vcollector=0.5
solve vcollector=1
solve vcollector=2
solve vcollector=5
solve vcollector=10 vstep=10.0 vfinal=50 name=collector
solve vcollector=75 vstep=25.0 vfinal=300 name=collector
save outf=powerex03_1.str


go atlas

mesh

x.mesh loc=0.0 spac=1.3
x.mesh loc=13.0 spac=0.75
x.mesh loc=25.0 spac=1.4

y.mesh loc=-0.08 spac=0.04
y.mesh loc=0.0 spac=0.04
y.mesh loc=0.6 spac=0.2
y.mesh loc=8.0 spac=1.0
```

```
y.mesh loc=70.0 spac=20.0
y.mesh loc=100.0 spac=10.0

region num=1 y.max=0.0 oxide
region num=2 y.min=0.0 silicon

# electrodes #1 - gate; #2 - emitter #3 - collector

elec num=1 left y.min=-0.08 length=13.0 name=gate
elec num=2 right y.min=0.0 y.max=0.0 length=6.8 name=emitter
elec num=3 bottom name=collector



# impurity profile
doping uniform conc=1.5e14 n.type
doping uniform conc=1.0e19 p.type y.t=81.4 y.b=100
doping uniform conc=1.0e17 n.type y.t=65.0 y.b=81.4
doping gauss conc=2.7e17 p.type junc=5.8 x.l=13 ratio=0.8
doping gauss conc=9.3e19 n.type junc=0.4 x.l=13 x.r=20 ratio=0.8


mater region=2 taup0=1e-6 taun0=1e-6
contact num=1 n.poly


thermcontact num=1 elec.num=3 temp=300


models analytic srh auger fldmob surfmob lat.temp
impact selb


method newton trap
```

```
# Solution at Vge=0 and Vce= 300.0 V is loaded
load inf=powerex03_1.str master

solve prev

output flowlines jx.e jy.e jx.h jy.h

log outf=powerex03.log
solve v1=10.0 ramptime=100.e-9 tstep=1e-9 tstop=1.e-6 t.compl=1000

save outf=powerex03_2.str

tonyplot powerex03.log -set powerex03_log.set

quit
```