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Base Doping Profile Investigation in to Transient base Charge Modeling of IGBT

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Abstract

The study of doping concentration in the carrier storage region of IGBT is considered desirable in many power converter applications. This Letter presents base doping profile estimation through investigation into transient base charge modeling of Non-punch through (NPT) Insulated Gate Bipolar Transistor (IGBT). Parabolic profile has been used for base carrier concentration which consequently leads to an analytical model for transient base charge decay of IGBT. The proposed model shows better consistency compared to the previously used linear model in all doping profiles. Finally, the implications of doping dependence on the base charge decay are explained, including implementation of doping profile estimation technique.

***Index terms*—** base doping profile, transient base charge, parabolic approximation, effective base width, ambipolar diffusion length.

1 I. Introduction

ince its invention in 1979 [1], IGBT has been considered a preferred switching device in power electronic systems and significantly improved the quality of life of people. Specially 90% of low voltage products (600V to 1700V) are being occupied by IGBTs. Compared to the first and second generation of NPT IGBTs, the device performance using latest thin film technology has been improved by introducing various doping concentrations in the Carrier Storage Region (CSR), specially known as SPT technology [2] or field stop concept [3]. The advantages of the first two generations have been combined by this technology, resulting in evolution of further generations [4][5][6]. Different doping profiles have significant effects on the base charge distribution of NPT IGBTs, which can be thoroughly studied by proper estimation of doping concentration in the effective base region (CSR) of IGBT. In recent times, high doping profile has been considered as a matter of concern in the steady-state and transient operation of IGBT. However, with the modern IGBT structure having highly doped CSR, a MOSFET-like behaviour has been seen at low collector-emitter voltage when the gate is fully turned on [7]. Actually increasing the base doping concentration can reduce the on-state loss while maintaining the desirable blocking voltage. But too high doping may affect the injection efficiency of p-emitter and result in some undesirable effects [8], which need to be avoided. This has caused considerable interest in modeling of base doping profile in DC linked type circuits [9] as well as motor drive applications [10]. However, the accurate and effective study of IGBT requires proper modeling of doping profiles in the CSR with systematic estimation technique. This paper introduces the idea of doping profile modeling in the base through investigation into the transient characteristics of IGBTs. The steady state minority carrier concentration is proposed through a parabolic profile [11]. Using this profile, an analytical model is derived for explaining transient base charge decay during turn-off. Fourth order Runge-Kutta (RK4) method is used to validate the model over a wide range of doping concentration. Finally being consistent with the practical results, base doping profile is investigated through turn-off base charge distribution on different time instances.

2 II. Turning of Operation of Igbt

During the turn-off operation of IGBT the gate voltage is kept less than the threshold voltage. It is assumed that the anode voltage is kept constant during the current decay, but it may be different from the anode voltage of the steady state. Fig. **??** shows the cross section schematic of IGBT half cell and Fig. **??** shows the schematic diagram of excess minority carrier distribution for two doping profiles, Low-doped Base (LDB) and High-doped Base (HDB). The figure shows charge distribution for immediately before (steady state) and after the channel current has been removed. It can be seen that the minority carrier holes decreases quickly to zero after switching in case of LDB, resulting in a large depletion region. This causes the effective base width (W) smaller than the ambipolar diffusion length (L). On the other hand, the HDB causes the carrier reduction much slower after turn-off, causing a smaller depletion region. In this case the effective base width is not very small compared to the total base width (WB), resulting in W being comparable or even larger than L. So the transient operation is very much dependent on the base doping profile.

3 III. Expression for Transient base Charge

The main foundation of the previously established models was based on the assumption that W must be much smaller than L, which corresponds to LDB. But these models are inefficient in case of other doping profiles and thus fail to optimize power in NPT and PT IGBTs. The proposed model takes this into account and provides consistent results in all base doping concentrations.

The initial expression for time independent minority carrier concentration is assumed by taking parabolic approximation in the hyperbolic function W x L p x P W L ? ? ? + ? ? ? ? ? = ? ? + ? ? ? ? ?

where P 0 is minority carrier concentration at the collector-base junction, W is effective base width, L is ambipolar diffusion length and x is the distance from emitter to collector region. Using this assumption in the ambipolar diffusion equation and integrating the equation with boundary conditions x=0;p= P 0 and x=W;p=0, a time dependent expression for minority carrier concentration is found in the previous work [11].5 2 3 0 2 2 2 ( ) (,)**4 ( ) 5 4**

(6) 6) 12P W x P x t L W x L W L W ? ? ? = ? + ? ? + ? ? 2 2 0 2 2 2 2 1 1 12 3 4 (P W L W D W t W L W L W ? ? ? ? + ? 5 2 3 ( ) 4 ( )**5**W x L W x ? ? ? ? + ? ? ? ? ? 3 4 5 2 2 0 2 2 2 1 (6) 6

6 20 (6)P W x x x L W W D t W L W ? ? ? + + ? + ? ? ? + ? ? 0 2 2 2 2 1 (**6**) P W D t W L W ? + ? + 3 4 5 2 2 2 2 (6) (2 6) 6 12 20 x x x W W L W L W ? ? ? ? ? + ? ? ? ? ? 2 2 2 2 0 2 2 2 2

1 20 6 5 6 12P x W L W L W D t L W L W ? + ? ? ? + ? 2 2 2 0 2 2 2

1 10 10 (6)P xW W W L D t L W ? ? ? ? + 2 2 0 0 0 2 2 2

20 20 6P x P x L W W P W L W L ? ? + ? + + ? ? + ? ? 2 2 2 2 2 0 2 2 2 2 2 2 20 1 12 3 .....(**2**) 20 6 12P L W W W L W W D t L W L L W ? ? ? ? + ? ? ? ? ? ? ? ? ? ? + ? ? ? ? ?

where D is ambipolar diffusivity.

Integrating the excess carrier concentration with respect to x having limit of zero to W and then multiplying by charge (q) and area (A), an expression for stored base charge is found W t W t Q t qAP L ? ? = ? ? ? ? ?

The charge decay rate relates to the electron current at emitter -base junction through the following expression ???? Using the quasi-equilibrium simplification and assuming high-level injection of the holes into the base, an expression for transient base charge decay is found ??.. .... (5) where I sne is the emitter electron saturation current and ? HL is high level excess carrier lifetime.

For W«L, the equation is reduced to the exact form reported in [12]. Fourth order Runge-Kutta (RK4) method is later used to plot Q vs t graph to validate the IV. Result and Discussion for Transient Modeling Fig. **??**, Fig. **??** and Fig. **??** show the simulation results of the parabolic approximation taken in this proposal. Here effective base width (W) is considered to be 4.2 * 10 ?3 cm. The results are compared to those of experimental data and linear forms used in [12]. Simulations are shown for three cases: The case of N ?? =0.7x10 14 cm ?3 is shown in Fig. **??**, which explains the case of high carrier lifetime as well as low doping profile. Both the proposed model and linear model are in good agreement with the experimental data. This follows from the fact that during turn-off operation, a large number of charges fail to recombine resulting lower rate of charge decay in the base. Both the parabolic and linear expression depict this buildup correctly.

4 b) Case: Moderate Doping Profile

In case of N ?? =2x10 14 cm ?3 , the doping concentration is neither high nor low. From Fig. **??**, it is seen that the traditional model shows some deviation with the experimental data, while the proposed model shows better consistency. This is due to the fact that when doping in base is neither high nor low, only some of the charge carriers are able to reach the collector base junction due to significant recombination during turn-off. This results in comparatively higher rate of decay in the transient base charge. The proposed model is able to account for this effect correctly but the linear model fails to do so.

5 c) Case: High Doping Profile

Fig. **??** shows the case of high doping profile, where ?? ?? is considered to be ??. ð ??"ð ??"?????? ???? ???? ??? . The parabolic model maintains good consistency with the practical data, while the linear model continues to show deviation as the assumption it is based upon, no longer holds true in case of high doping profile. Base doping being high causes higher rate of charge recombination during turn-off, resulting in conduction of charge approximately to zero. Once again, the proposed model is able to predict this phenomenon, while the linear model falls short.

Different doping profiles considered in Fig. ??, Fig. ??

6 V. Investigation in to base Doping Profile

From the following discussion, it is evident that the proposed model shows better consistency with the experimental observations than the traditional linear model. Through this, an opportunity has been created for investigating doping profiles in the Carrier Storage Region (CSR) using dQ/dt dependence of IGBT. Base doping concentrations can be thoroughly estimated through investigation into transient base charge profile on specific time instance. Here the model is analyzed for two time instances; 0.1 µs and 0.8 µs.

Fig. 6 and Fig. 7 show the modeled dependence of base charge decay on base doping profiles at time instance of 0.1 µs and 0.8 µs accordingly. It can be clearly seen that the proposed model predicts nearly same as the linear one in case of low transient charge, but deviates significantly when charge decays from a higher value. In case of LDB, emitter-base junction current (In) depends on the variation of W compared to L. But when doping is considerably high, W becomes insignificant respective to L which causes the prediction of the two models nearly same, which has been shown in Table II [1] [2]

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Figure 1: Fig. 1 :Fig. 2 :

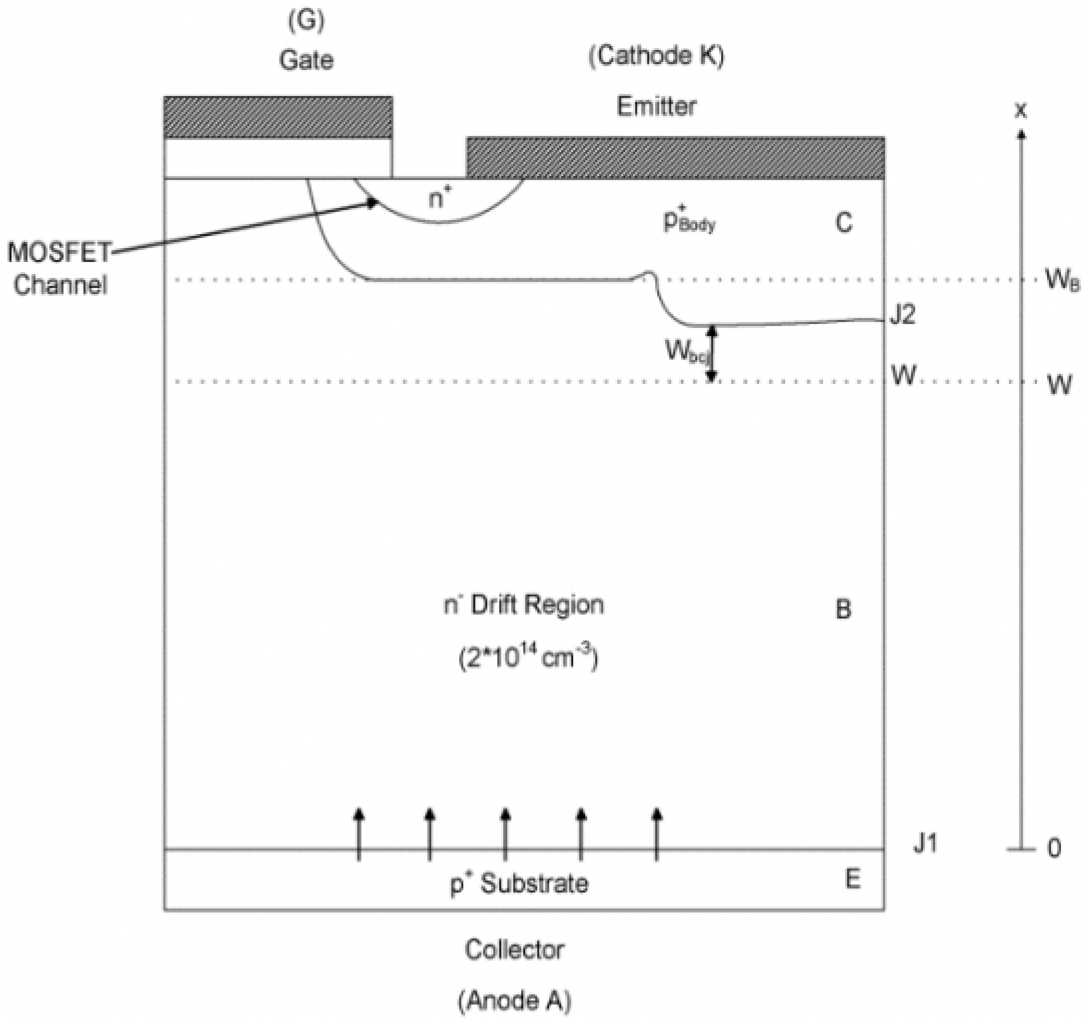
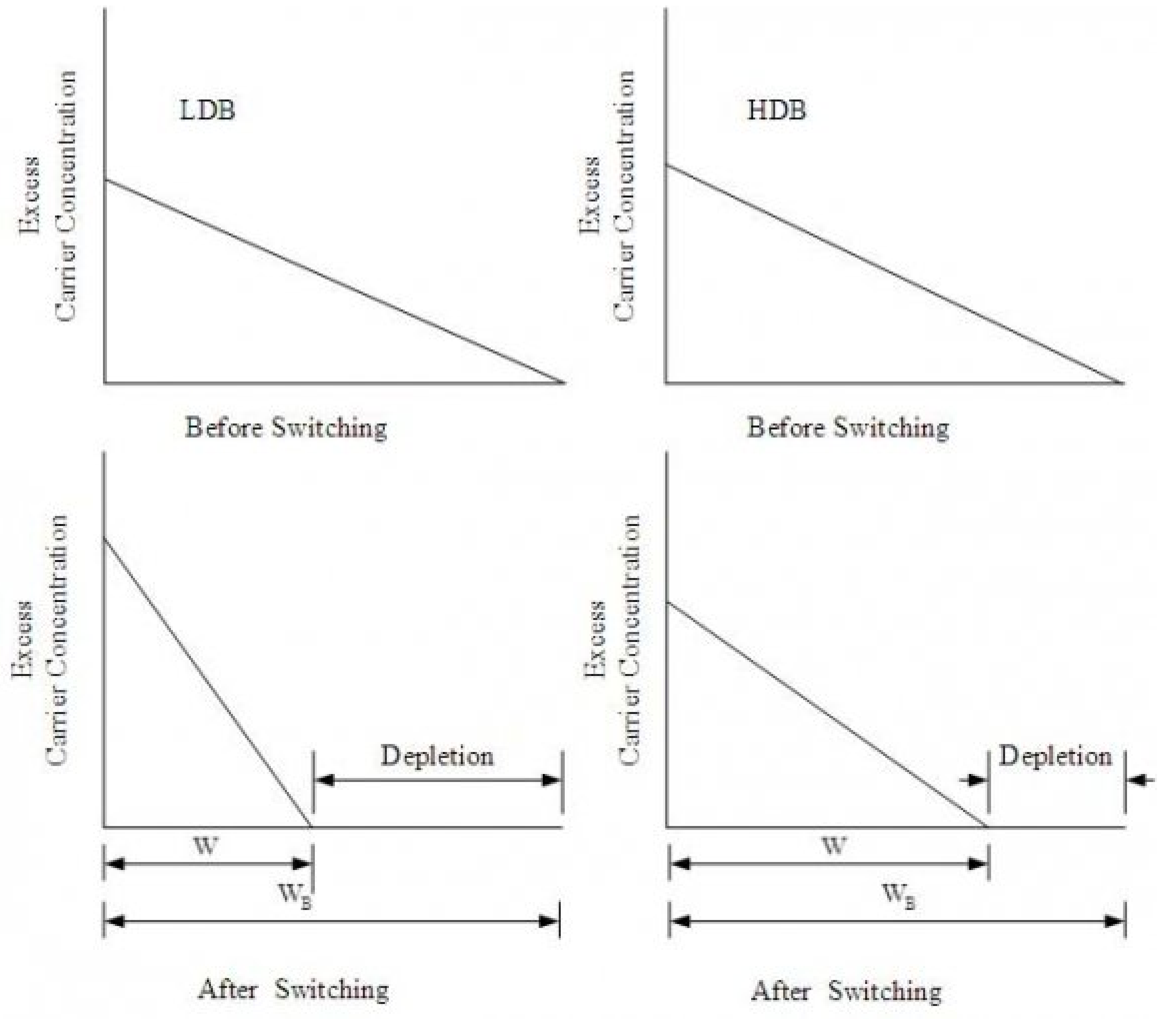

(G)
Gate
(Cathode K)
Emitter
x
n+
p+Body
C
MOSFET
Channel
WB
J2
Wbcj
W
W
n- Drift Region
(2*10^14 cm^-3)
B
J1
0
p+ Substrate
E
Collector
(Anode A)

Figure 2:



LDB
Excess
Carrier Concentration
Before Switching
HDB
Excess
Carrier Concentration
Before Switching
Excess
Carrier Concentration
Depletion
W
W_B
After Switching
Excess
Carrier Concentration
Depletion
W
W_B
After Switching

Figure 3:

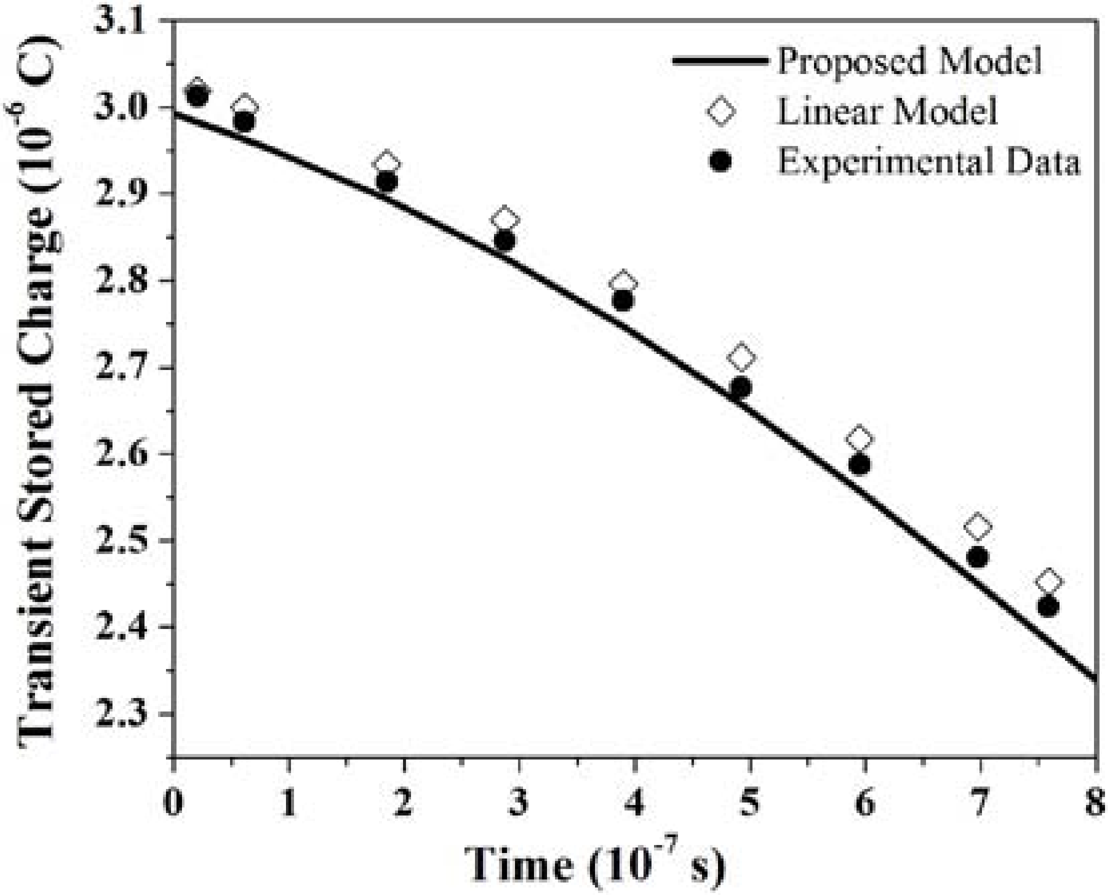


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Figure 4: Fig 3 :Fig. 4 :Fig. 5 :

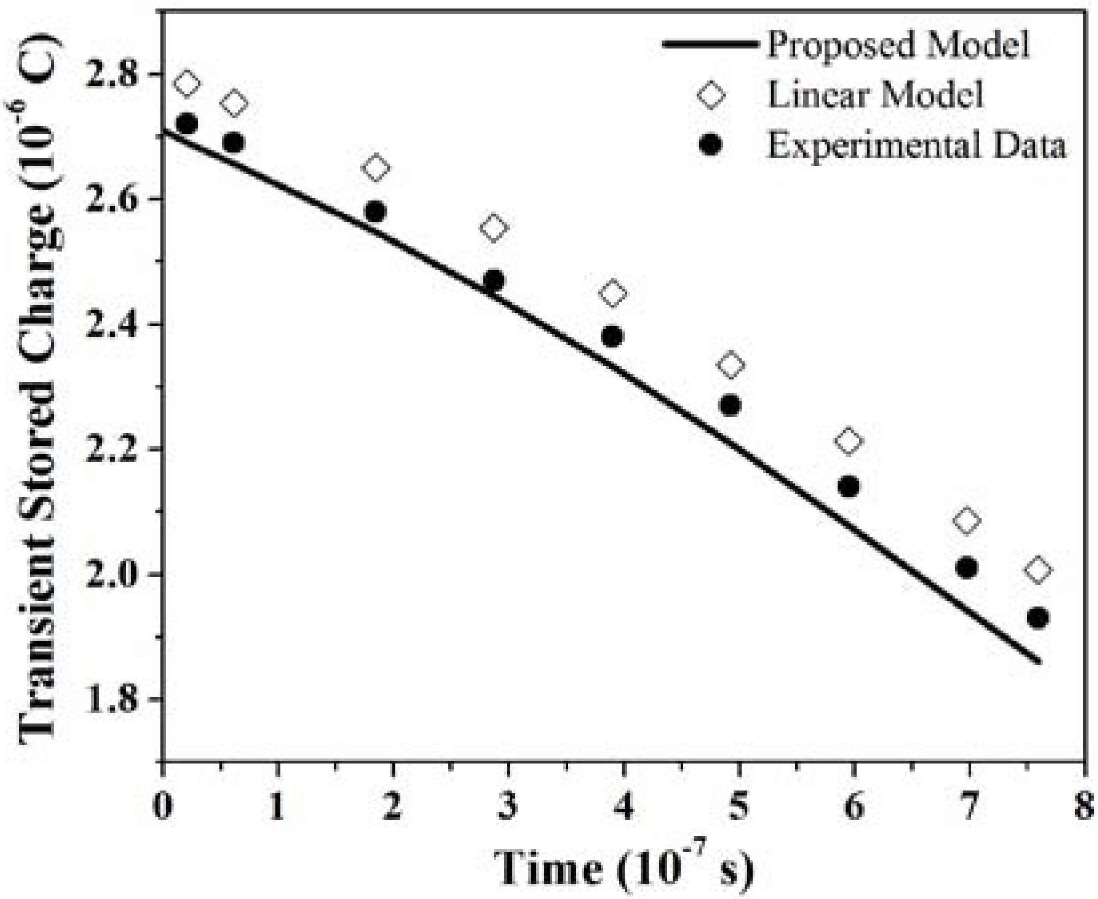

Figure 5:

$$\frac{dQ(t)}{dt} = -\frac{Q(t)}{\tau_{HL}} - I_n(0)$$

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Figure 6: Fig. 7 :

$$\frac{dQ(t)}{dt} = -\frac{Q(t)}{\tau_{HL}} - \frac{Q(t)^2}{q^2 A^2 \left(\frac{W(t)}{2} - \frac{W(t)^3}{24L^2}\right)^2} \frac{I_{sne}}{n_i^2}$$

6

Figure 7: Fig 6 :

Figure 8: .

I

Base Doping Concentration (???? ???? ???? ???)	Time (7 10 ? s)	Transient Base Charge Experimental	(6 10 ? C) Proposed	Linear
	0.2	3.01	2.99	3.02
	2.0	2.91	2.89	2.93
Low (0.7)	4.0	2.78	2.75	2.80
	6.0	2.59	2.56	2.62
	7.5	2.42	2.34	2.45
	0.2	2.72	2.69	2.79
	2.0	2.58	2.55	2.65
Moderate (2)	4.0	2.38	2.33	2.45
	6.0	2.14	2.08	2.21
	7.5	1.93	1.86	2.01
	0.2	1.24	1.20	1.66
High (3.5)	2.0	0.81	0.69	1.25
	4.0	0.59	0.42	0.82
	6.0	0.34	0.24	0.48
	7.5	0.19	0.14	0.30

Figure 9: Table I :

II

Time Instance (µs)	Transient Charge (???? ?ð ??"ð ??" C)	Base Doping Concentration (???? ???? ???? ???) Proposed	Linear
	2.5	2.8099	2.0853
	2	3.3783	2.4973
0.1	1.5	4.0035	3.1936
	1	4.8845	3.9609
	0.5	6.6892	6.3108
	2	2.5950	2.0113
	1.5	3.1901	2.3644
0.8	1	3.8562	2.9737
	0.75	4.3103	3.4420
	0.5	4.9495	4.4095

Figure 10: Table II :

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