Transient Analysis of PT-IGBTs at High Temperature

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ABSTRACT- In this paper, excess minority carrier distribution in drift and buffer layers and accumulated charges for PT IGBT have been, for the first time, analytically expressed with different transient times, lifetimes and temperatures. Furthermore those parameters are also expressed with temperature to predict the transient response which are critical to the real operation. Active base region has been chosen to extract the temperature dependency of the device by including the buffer layer which is important but neglected due to the complexity up to now.

1. Introduction

Recently IGBT has been used in controller for inductive loads such as motors and UPS. It has characteristics of high-impedance of MOSFET and high current of BJT as a switching device in power electronic field[1].

IGBT has operation region of higher level of power than power MOSFET and GTO but lower frequency. Tail current caused by taking long time to remove excess minority carrier injected to base region.

Analytical models[2][3] for PT IGBT have been proposed to predict the transient characteristics for switching analysis. PT IGBT having buffer layer is more faster than NPT IGBT during turn-off but has lower forward voltage.

One of analytical models for PT-IGBT[2] interpreted Hefner's models[4][5] which is numerical due to the complexity of equations so that the model didn't consider buffer layer for simplifying equation.

In this paper, buffer layer has been taken into consideration to derive the analytical expression. Excess minority carrier distribution was simulated with different lifetimes and temperatures for solving boundary conditions at drift and buffer layers under the assumption of quasi-equilibrium simplification. Accumulated charges in drift and buffer layers were also expected with different lifetimes and temperatures respectively.

2. Physics of PT-IGBT

Concentration of excess minority carrier injected from emitter to base is greater than doping concentration of base because IGBT has wide and low concentration of base region. Therefore we considered ambipolar transport equation to represent the behaviors of the carriers.

In buffer layer, ambipolar transport equation is shown by

$$\frac{d^2\delta p}{dx^2}=\frac{\delta p}{L_{pB}^2}-\frac{1}{D_{pB}}\frac{d\delta p}{dt} \qquad (1)$$

and in drift layer,

$$\frac{d^2\delta p}{dx^2}=\frac{\delta p}{L_{pD}^2}-\frac{1}{D_{pD}}\frac{d\delta p}{dt} \qquad (2)$$

where is δp excess carrier concentration, L_{pB}, L_{pD} are diffusion length. D_{pB} and D_{pD} represent diffusivities in buffer and drift layers respectively.

Intrinsic concentration, effective masses, energy gap and mobility are a function of temperature [6][7] and can be represented as follows;

$$n_i=4\times10^{15}\left(\frac{m_n*}{m_0}\cdot\frac{m_p*}{m_0}\right)\times\left(\frac{T}{300}\right)^{3/2}e^{-\frac{Eg}{2kT}} \qquad (3)$$

$$\frac{m_n*}{m_0}=1.028+(6.11\times10^{-4})T-(3.09\times10^{-7})T^2 \qquad (4a)$$

$$\frac{m_p*}{m_0}=0.610+(7.83\times10^{-4})T-(4.46\times10^{-7})T^2 \qquad (4b)$$

$$E_g=1.17-\frac{4.73\times10^{-4}\cdot T^2}{T+636} \qquad (5)$$

and

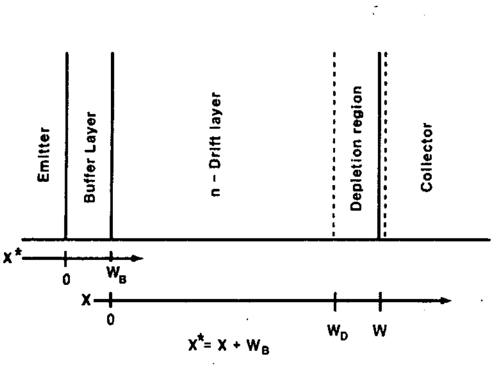

Fig. 1 Coordinate system used in developing the model for buffer layer device.

$$\mu = \mu_{\min} + \frac{\mu_0}{1+(N/N_{ref})^{\alpha}} \qquad (6)$$

where n_i is intrinsic carrier concentration m_n^*, m_p^* represent effective masses of electron and hole respectively. E_g and μ are energy gap and mobility respectively and N is the doping concentration, N_{ref}, $\mu_{\min}$, μ_0, α are the values at 300K.

3. PT IGBT Model

As MOSFET in the device is only concerned with on/off control, active operation happens mainly in the BJT area. Therefore a model proposed in this work mainly focuses on BJT portion of the device. In this model, steady state condition has been assumed to be QS(Quasi Static) and only the transient condition must be assumed as NQS(Non-Quasi Static) condition because boundary condition changes by the variation of depletion layer thickness with applied voltages[8]. It is, therefore, needed to consider a time term in the derivation of excess minority carrier due to the different boundary conditions. It is important to notice that the charge is affected by the boundary condition and has direct relation to the tail current which causes loss of power at turn-off period.

3.1 Steady state Condition

Fig. 1 represents a 1-dimensional coordinate system used to develop a BJT model in IGBT. Interface between base and emitter has been defined as zero. W_B is width of buffer layer, w_D is the total drift width, W_D is the width of active drift region. w_{bcj} is the junction depth between collector and base can be obtained from equation (7).

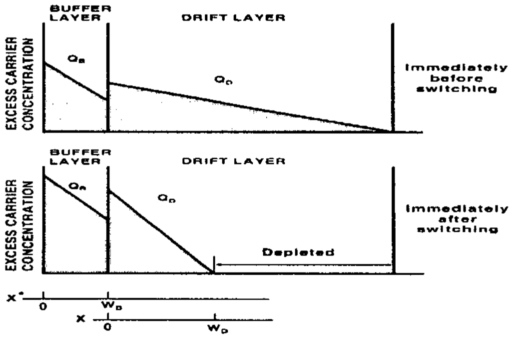

Fig. 2 Excess minority carrier distribution in buffer layer and drift layer for transient and steady conditions.

$$w_{bcj} = \sqrt{\frac{2\varepsilon_{si}(V_{bc}+V_{bi})}{qN_D}} \qquad (7)$$

$$W_D = w_D - w_{bcj} \qquad (8)$$

$$W = W_B + W_D \qquad (9)$$

where W is active base width, q electronic charge, N_D drift doping concentration, V_{bc} base-collector voltage drop, V_{bi} built-in voltage. Excess minority carrier concentration can be obtained from the equation (1),(2) at the steady state by defining $\frac{\partial \delta p}{\partial t} = 0$. Equations (10), (11) represent excess minority carrier concentrations in drift and buffer layers respectively.

$$\delta p(x) = P_{D0}\frac{\sinh[(W_D - x)/L_D]}{\sinh(W_D/L_D)} \qquad (10)$$

and

$$\delta p(x^*) = \frac{P_{B0}\sinh\left(\frac{W_B - x^*}{L_{pB}}\right) + P_{BW}\sinh\left(\frac{x^*}{L_{pB}}\right)}{\sinh\left(\frac{W_B}{L_{pB}}\right)} \qquad (11)$$

where P_{D0}, P_{B0} are initial excess minority carrier concentration in drift and buffer layer respectively. P_{BW} is excess minority carrier in the boundary bewteen drift and buffer layer and L_D represents ambipolar diffusion length.

Total charge in steady state is obtained as

$$Q_S = q(P_{B0}+P_{BW})L_{pB}\tanh\left(\frac{W_B}{2L_{pB}}\right) + qP_{D0}L_D\tanh\left(\frac{W_D}{2L_D}\right) \qquad (12)$$

and will be uesd as an initial condition for total charge in transient condition.

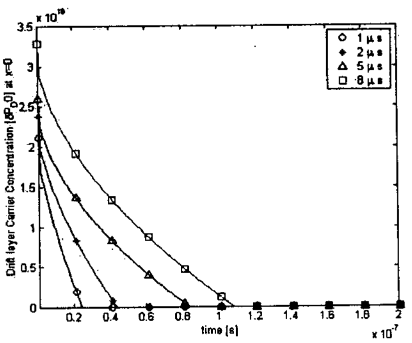

Fig. 3 Excess minority carrier distribution in drift layer with lifetimes.

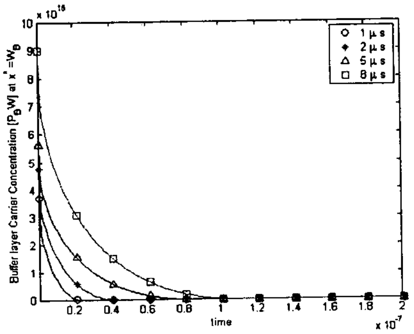

Fig. 4 Excess minority carrier distribution at buffer layer with lifetimes

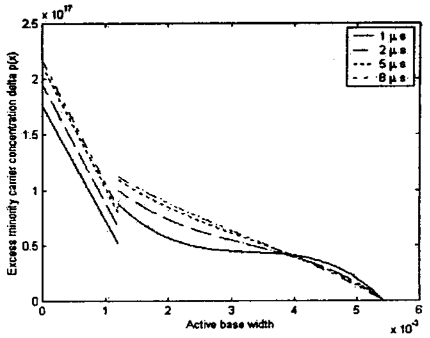

Fig. 5 Excess minority carrier distribution at buffer layer and drift layer at anode voltage 10 [V] with lifetimes

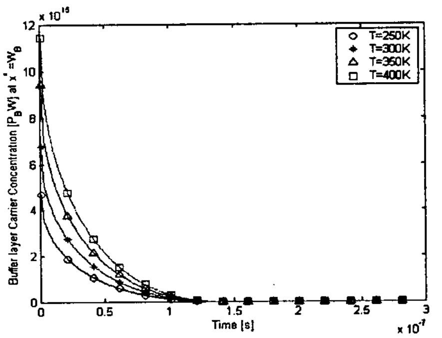

Fig. 6 Excess minority carrier distribution in buffer layer with temperatures.

3.2 Transient Condition

Variation of depletion width has been counted to trace the excess carrier concentration at transient state. Base region is therefore divided into two regions, buffer and drift layers, to obtain excess minority carrier concentration.

Depletion region increases as anode voltage drop increases in transient condition. Equation (7) can be expressed as

$$w_{bcj} \approx \sqrt{\frac{2\varepsilon_{si} V_A(t)}{qN_D}} \tag{13}$$

Fig. 2 represents excess carrier concentration ditributions both in buffer and drift layers for steady state and transient condition. Excess carrier concentration in buffer layer can then be expressed as

$$\delta p(x^*) = P_{B0}\left[1-\frac{x^*}{W_B}\right]+P_{BW}\frac{x^*}{W_B} \tag{14}$$

and that in drift layer to be

$$\delta p(x) = P_{D0}\left[1-\frac{x}{W_D}\right]-\frac{J_T}{2D_D V_A(t)}\left[\frac{x^2}{2}-\frac{W_D x}{6}-\frac{x^3}{3W_D}\right] \tag{15}$$

where D_D is ambipolar diffusivity. Total base charge can then be obtained by adding the charges both at drift and buffer layers leading to equation (16).

$$Q_t(t) = (Q_S+\tau_D\alpha)e^{-\frac{t}{\tau_D}}\tau_D\alpha \tag{16}$$

where

$$\alpha = -\frac{Q_B}{\tau_D}+\frac{Q_B}{\tau_B}+\frac{P_{B0}N_B}{n_i^2}J_{sne} \tag{17}$$

where τ_D and τ_B are lifetimes in drift and buffer layer respectively, Q_B and N_B are accumulated charge and doping concentration in buffer layer. J_{sne} represents saturation current density.

Anode voltage drop is very important because it causes switching loss. Grandient of anode voltage with time is obtained as [4]

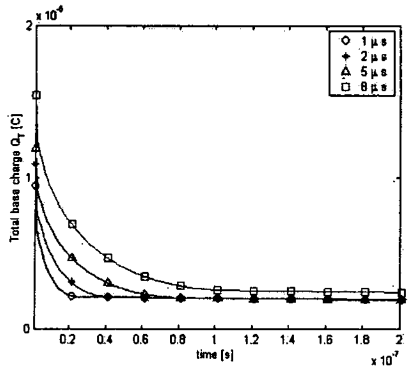

Fig. 7 Total base charge distribution with lifetimes for trasient condition

$$\frac{dV_A}{dt}=\frac{I_T-\left(\frac{4D_{pB}}{W_B^2}Q_B+\frac{4D_{pD}}{W_D^2}Q_D\right)}{\frac{A\varepsilon_{si}}{W_{bcj}}\left(1+\frac{1}{b}\right)\left[1+\frac{Q_D}{3qN_DAW_D}\right]} \tag{18}$$

Numerical approach could only be applied to solve equation (18). However the above equation can be analytically solved by assuming $Q_D >> 3qAN_DW_D$. Anode voltage $V_A(t)$ is then expressed as

$$V_A(t)=\frac{R_B^2-2\cdot t\cdot R_A\cdot R_C-R_B\sqrt{R_B^2-4\cdot R_A\cdot R_C\cdot t}}{2R_A^2} \tag{19}$$

where

$$R_B=W\cdot\left(R_r\cdot Q_D+2I_T\cdot R\cdot t+8\frac{D_{pB}}{W_B}Q_B\cdot R\cdot t\right) \tag{20}$$

$$R_A=R\cdot\left(R_r\cdot Q_D+I_T\cdot R\cdot t-4\frac{D_{pB}}{W_B}Q_B\cdot R\cdot t\right) \tag{21}$$

$$R_C=I_T\cdot W^2-4D_{pD}\cdot Q_D-4\frac{D_{pB}}{W_B}Q_B\cdot W^2 \tag{22}$$

$$R_r=\frac{A\cdot\varepsilon_{si}(1+1/b)}{R\cdot 3qAN_D} \tag{23}$$

4. Results and Discussions

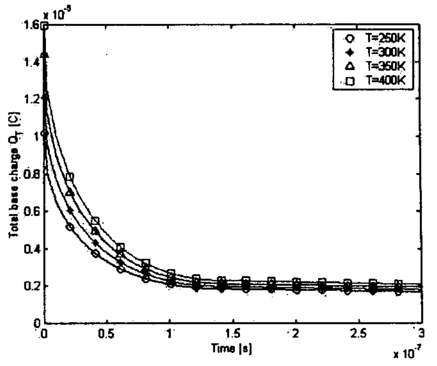

Fig. 8 Total base charge distribution in transient with temperatures

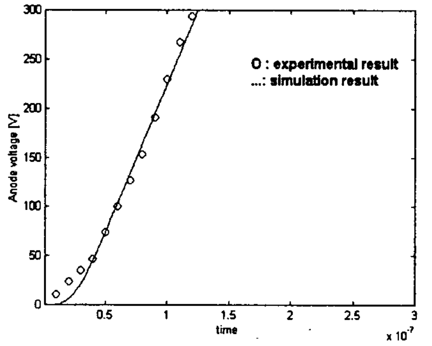

Fig. 9 Comparison of modeled data with experiment of anode voltage in lifetime 5 [μs]

Excess minority carrier concentrations in buffer and drift regions have been plotted with different lifetimes in Fig. 3, Fig. 4. Different lifetimes of 1μs, 2μs, 5μs and 8μs are used to obtain the profile. From the figures, excess carrier concentration increases as the lifetime increases and decreases with time. Fig. 5 depicts excess minority carrier distribution with active base widths in buffer and drift layers at anode voltage of 10 [V] with different lifetimes. Fig. 6 represents distribution of excess minority carrier concentration with different temperatures in buffer layer. From the results, excess carrier concentration increases as temperature increases. Fig. 7 shows distribution of total base charge with different lifetimes in active base region. Fig. 8 shows total base charge with times at four different temperatures .

Fig. 9 depicts theoretical prediction of anode voltage with experimental data at lifetime of 5μs.

5. Conclusion

In this paper, excess minority carrier distribution in drift and buffer layers and accumulated charges for PT IGBT have been, for the first time, analytically expressed with different transient times, lifetimes and temperatures. All the parameters having temperature dependency are taken into calculation to predict the transient analysis which is critical to the real application. Anode voltage is also expressed analytically. From the results, power loss which is the key to the design of PT IGBT could be described analytically for the fast prediction of the electrical parameters of a device.

References

[1]. Allen R. Hefner, David L. Blackburn, "An Analytical Model for the Steady-State and Transient Characteristic of the Power Insulated-Gate Bipolar Transistor," *Solid-State Electronics*, Vol. 31, No. 10, pp.1513-1532, 1988

[2]. A. Ramamurthy, S. Sawant, and B, J, Baliga, " Modeling the [dV/dt] of the IGBT During Inductive Turn Off," *IEEE Transacions on power Electronics*, Vol. 14, No.4, July 1999

[3]. Kuang Sheng, Stephen J. Finney, and Barry W. Williams "A New analytical IGBT Model with Improved Electrical Characteristics" *IEEE Transactions on Power Electronics*, Vol. 14, No 1, January 1999

[4]. Allen R. Hefner, Jr. "Performance Trade-off The Insulated Gate Bipolar Transistor: Buffer Layer Versus Base Lifetime Reduction" *IEEE Transaction Power Electron Dev.*, PE-2, p. 194, 1987; also in IEEE PESC Conf. Rec., p. 27, 1986

[5]. Allen R. Hefner, Jr. "Modeling Buffer Layer IGBT's for Circuit Simulation", *IEEE Transactions on Power Electronics*, Vol. 10, No 2, Mar. 1995

[6]. S. M. Sze, *Physics of Semiconductor Device 2nd Edition*, Wiley-Interscience, p16～p35

[7]. Robert F. *Pierret, Semiconductor Device Fundamentals*, Addison-Wesley conpany, Inc, p53～p57,pp.79～85, 1996.

[8]. Allen R. Hefner, JR, "Analytical Modeling of Device-Circuit Interaction for the Power Insulated Gate Bipolar Transistor(IGBT)," *IEEE Transaction on Indus. Applications*, Vol. 26, No. 6, November/december 1990