An Analytical Transient Model for NPT IGBT

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ABSTRACT - In this paper, transient characteristics of IGBT has been analytically solved to express the excess minority carrier distribution in active base region and the output voltage. Non-Punch Through(NPT) structure has been selected to prove the validity of the model. It is based on the equivalent circuit of MOSFET which supplies a low gain and a high level injection to the base of BJT. None of the quasi static conditions have been assumed to trace the transient characteristics. The basic elements of the model have been derived from the ambipolar transport theory.

Theoretical predictions of the output voltages have been obtained with different lifetimes and compared with experimental and theoretical results available in the literature. From the analytical approach, good agreement has been obtained to provide reliable and fast output of the device.

1. Introduction

In recent years, IGBT(Insulated Gate Bipolar Transistor) is one of the promising high speed and high power devices which provide a power MOSFET with simple gate drive circuit and a BJT with low resistance in the on-state.[1] Two categories are shown in the transient analysis of the device. One is based on the analysis of carrier transport inside a device. The other focuses on the external circuit to drive it under the optimal condition by using basic concept of the device. The latter can be a compensation for the transient characteristics based on the Zero-Voltage and/or Zero-Current switching for the use of switching devices such as an inverter or a converter.[2]

Analytical models for NPT IGBT have been proposed to predict the turn-off characteristics for the transient analysis. NPT IGBT which has no buffer layer is less faster than PT IGBT during turn-off and has high switching power losses generated inside the device. NPT IGBT, however, has lower on state voltage drop and higher forward voltage drop[3]. Short circuit performance for IGBT was presented by Trivedi *et al.*[4] to obtain the SOA(Safe Operation Area) fully depending on a simulator itself. An analytical model as introduced by Yue *el al.*[5] which limits the operating range to be low voltages.

Hefner[6] proposed physically based models which should be solved numerically in some way to obtain the voltage, current, charge and excess minority carrier concentration which are essential to tail current and thus power losses at turn-off period. However the expressions consist of complicate functions with variable capacitance and redistribution of capacitance which are hard to apply for analytical calculation. A model proposed by Ramamurthy *et al.*[7] uses analytical expression for the voltage variation with time when the device is turned off. It is, however, needed to exclude the nonlinear expression to consider the simple expression for the variation of internal charges and the boundary conditions with voltages. Therefore anode voltage shows 1st order dependence on time which leads an error especially at low transient time. The voltage variation with switching time has been analyzed by considering the dependence of the internal carrier concentration and base region on the applied voltages and the time.

To prove the validity of the model, excess carrier concentration has been compared with the results in the literature obtained from the numerical calculation with different lifetimes and show good agreement. Anode voltage drop has also been analytically derived and compared with experimental data with different lifetimes. From the results, an analytical model can predict the transient characteristics of the device accurately and extends its applicability for theoretical predictions to the devices regardless of IGBT structures.

2. 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 with applied voltages. 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

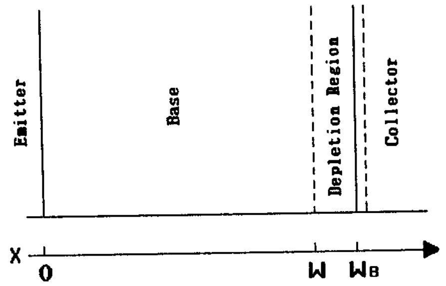

Fig. 1. Coordinate system used to develop a BJT model in IGBT.

the charge is affected by the boundary condition and has direct relation to the tail current which causes a problem at turn-off period.

Due to the supplement of base current from MOSFET, electron current comes from collector edge. Electron current is therefore identical to the MOSFET current and hole current is expressed as collector current of the bipolar transistor. Because the current in the base flows under a high-level injection condition, i.e. carrier concentration n ~p and very low current gain, transport equations for hole and electron should be expressed as ambipolar transport equations.

Ambipolar diffusion equation depending on time can be written as

$$\frac{\partial^2 \delta p}{\partial x^2} = \frac{\delta p}{L^2} + \frac{1}{D}\frac{\partial \delta p}{\partial t} \tag{1}$$

where L is ambipolar diffusion length defined by $\sqrt{D\tau_{HL}}$ with τ_{HL} representing lifetime at high level injection. D is ambipolar diffusion coefficient given by $D{=}2D_nD_p/(D_n{+}D_p)$ where D_n and D_p are diffusion coefficients of electron and hole, respectively.

2.1 Steady state condition

Fig. 1 and Fig. 2 represents a cross sectional view of IGBT and a 1-dimensional coordinate system used to develop a BJT model in IGBT. Interface of base and emitter has been define as zero. W is an active base width and W_B is total base width. Junction depth W_{bcj} between collector and base can be obtained from equation(2) and the quasi neutral base width W which is active base width by equation(3) as

$$W_{bcj} = R\sqrt{V_{bc} + V_{bi}} \tag{2}$$

where

$$R = \sqrt{2\varepsilon_{si} / qN_B}$$

and

$$W = W_B - W_{bcj} \tag{3}$$

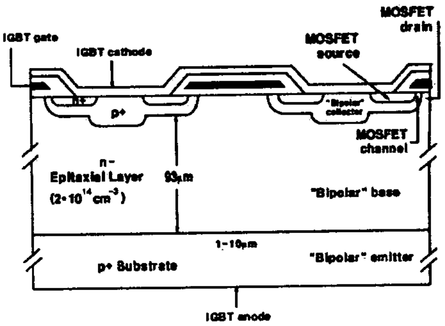

Fig. 2. A cross sectional view of IGBT

where W_{bcj} is a depletion width at the base-collector junction and ε_{si} is the dielectric constant of silicon. N_B, V_{bc} and V_{bi} are base doping concentration, collector-base voltage drop and built-in potential, respectively.

Quasi-neutral base width decreases by an increase of the base-collector depletion width. It is because V_{bc} increases abruptly during the turn-off period shown in equation(2). Two boundary conditions of excess minority carrier concentration should be given at x=0 and x=W to solve the diffusion equation represented in equation(1). By defining x=0 as the emitter edge of the base and x=W as the collector edge of the quasi-neutral base, steady-state boundary conditions for the excess carrier distribution can be expressed as

$$\delta p(W) = 0 \tag{4}$$

$$\delta p(0) = P_0 \tag{5}$$

Excess minority carrier concentration can be obtained from the equation(1) at the steady state by defining $\frac{\partial \delta p}{\partial t} = 0$ and by using two boundary conditions from equations (4) and (5), i.e[8].

$$\delta p(x) = P_0 \frac{\sinh[(W-x)/L]}{\sinh(W/L)} \tag{6}$$

where P_0 is an initial carrier concentration at the emitter edge of the base and can be derived from the total diffusion current density J_T as

$$J_T = J_p + J_n \tag{7}$$

$$J_p(x) = q\mu_p p(x)E(x) - qD_p \frac{\partial \delta p(x)}{\partial x} \tag{8}$$

$$J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{\partial \delta n(x)}{\partial x} \tag{9}$$

where J_n and J_p are hole and electron current densities, respectively. Increments of minority carriers for holes and electrons are approximately identical for high level injection so that J_T can be expressed as

$$J_T = \frac{2qD_p P_0}{L}\tanh\left(\frac{W}{L}\right) \quad (10)$$

where boundary conditions at x=0 are $J_p = J_T$ and $J_n = 0$ [9]. Therefore, P_0 can be expressed as

$$P_0 = \frac{LJ_T}{2qD_p}\tanh\left(\frac{W}{L}\right) \quad (11)$$

When current density is constant, P_0 is functions of the length of the quasi-static region *W*, and ambipolar diffusion length *L* which is sensitive to the applied voltage. Initial carrier concentration is therefore changeable with different lifetimes and voltages. Initial carrier concentration of equation(11) is therefore a function of *W* and/or voltage drop between base and collector during transient condition. Total carrier charge *Q* in base region is obtained by integrating excess minority carrier concentration through active base region *W* and expressed as

$$Q = \frac{L^2 I_T}{2D_p}\left(1 - \frac{1}{\cosh(W/L)}\right) \quad (12)$$

Total carrier charge obtained under the steady state condition, equation(12), will be used as an initial condition for the transient analysis. Base and collector currents are obtained from the electron and hole currents under the assumptions of *QS* condition and high level injection in the base. Electron current I_n injected into the emitter is given by zero.

2.2 Transient Condition

Gate potential should be applied below threshold voltage to turn off the device. In this condition, channel and base current of MOSFET and BJT should be rapidly removed. However, the collector current slowly decays because the stored excess carriers spend time in the base, which provides a tail current leading to power losses during turn-off period.

Because the boundary conditions of electron and hole currents are different at the steady-state and transient conditions, the shape of the excess carrier distribution and the relationship between the current and the total excess carrier charge in the base are different during the transient.

The difference exists for two reasons, the first is that the transport equations of electron and hole are coupled with ambipolar transport theory so that the hole current at the collector changes with the removal of the electron current of MOSFET which is high because of the low current gain. The second reason is that the depletion width at the collector-base varies faster with different anode voltages than the excess carriers transit in the base region. Therefore, it is required to redistribute the carrier into the changing base width during the transition of anode voltages. The depletion width increases with the increase of V_{bc}, V_A can then be represented as V_{bc} because V_{bc} is comparatively larger than V_{eb}. Equation(4) can be expressed as

$$W_{bcj} \approx R\sqrt{V_A} = R\sqrt{a_{\max}(\tau_{HL})\cdot t} \quad (13)$$

where $a_{\max}$ represents maximum available gradient of voltage with time which differs from the structures and life time. Therefore $a_{\max}$ has been expressed analytically as a function of lifetime as

$$a_{\max} = \frac{c_{NPT}}{\tau_{HL}} + \alpha_{NPT} \quad (14)$$

where c_{NPT} and α_{NPT} are given to be 1.17×10^9 [V] and 1.1×10^8 [V/sec] respectively in this NPT structure.

Excess carrier concentration at the transient condition can be obtained from the solution of diffusion equation by including time term, and it is given by

$$\delta p = P_0\left(1 - \frac{x}{W}\right) - \sqrt{\frac{N_B}{2q\varepsilon_{si}V_A(t)}}\frac{J_T}{D}\left(\frac{x^2}{2} - \frac{Wx}{6} - \frac{x^3}{3W}\right) \quad (15)$$

Equation(15) has been used to predict the variation of excess minority carrier concentration during transient condition. It is important to mention that the stored base charge Q_t should be removed rapidly because power losses is caused by tail current resulting from Q_t. To possible ways can be applied to meet this requirement. One would be a control of lifetimes and the other could be an insertion of highly doped buffer layer between base and emitter.

Stored base charge Q_t for transient condition can be related with the following equation as [1]

$$\frac{dQ_t}{dt} = -\frac{Q_t}{\tau_{HL}} - I_n \quad (16)$$

where I_n is defined by zero. Q_t can then be obtained from the differential equation (16) as

$$Q_t(t) = \left[qP_0AL\tanh(W/2L)\right]\cdot e^{-t/\tau_{HL}} \quad (17)$$

and *Q* from equation(12) has been used for the initial condition of Q_t. Voltage drop through collector-base junction during turn-off is very important because it causes power losses when switched. This voltage

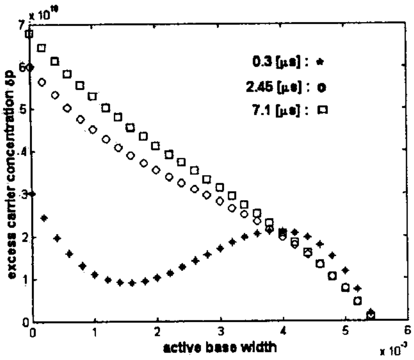

Fig. 3. Comparison of excess carrier concentration with different lifetimes

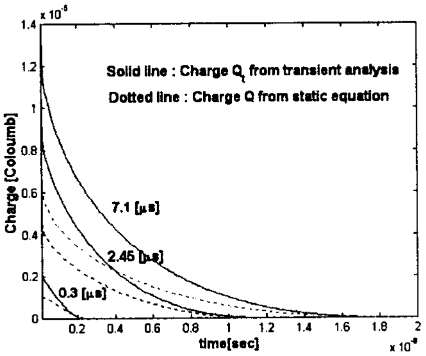

Fig. 4. Comparison of the charges at static and transient conditions with different lifetimes.

increases as supplied voltage and power losses increase with time. Gradient of anode voltage with time is then obtained as [6]

$$\frac{dV_A}{dt}=\frac{I_T}{C_{bcj}(1+(1/b))(Q_t/3qAN_BW)}-\frac{12qD_pAN_B}{C_{bcj}W(1+(1/b))} \qquad (18)$$

Voltage drop can then be obtained during turn-off by integrating equation(18) with transient time. In the calculation, emitter-base voltage drop is ignored because the voltage drop at collector-base junction is much bigger than that at the emitter-base during the transient state. It is because emitter-base voltage changes with different P_0 and increases up to 1[V] during transient condition. However, base-collector voltage reaches almost up to voltage $V_A(t)$ can be obtained as functions of time t and anode voltage.

In equation(18), C_{bcj} and Q_t are a function of W. Therefore they can be a function of V_A. After some algebraic manipulation of equation(18), the anode volatage V_A as

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

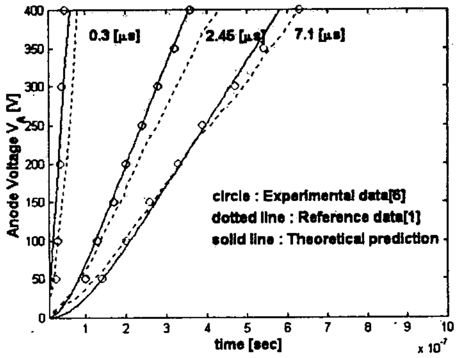

Fig. 5. Comparisonof anode voltage with different lifetimes 0.3 [μs], 2.45[μs], 7.1[μs].

where

$$R_A=R(R\cdot t\cdot I_T+R_r\cdot Q_t)$$
$$R_B=W_B(2R\cdot t\cdot I_T+R_r\cdot Q_t)$$
$$R_C=W_B^2\cdot I_T-4D_p\cdot Q_t$$

and

$$R_r=\frac{A\varepsilon_{si}(1+1/b)}{3qAN_BR}$$

It is instructive to notice that even the transient charge Q_t in equation(17) is used in solving equation(18).

3. Results and Discussions

In this paper, excess minority carrier concentration, transient charge Q_t, and anode voltage have been analytically expressed with voltages, times, active base widths and different lifetimes.

Excess carrier concentration has been plotted with different lifetimes under constant anode voltage of 200[V] in fig. 3. From the figure, excess carrier concentration increases as the lifetime increases. It is shown that excess carrier concentration was simulated when each lifetime is 0.3μs, 2.45μs, 7.1μs.

Fig. 4 shows the charges resulting from equation (17) and equation (12) for transient condition. Equation(12) expressed for the static condition could be used by applying time dependent depletion width in the calculation. From the results, the difference between newly introduced transient charge Q_t and the results obtained from equation (12) increases as the lifetime and transient time increase.

Time dependent anode voltages with different lifetimes have been plotted in fig. 5. Theoretical prediction has been compared with the experimental data and also with the numerical simulation of the reference and shows quite good agreement over the wide range of times and lifetimes.

4. Conclusion

An analytical model for NPT IGBT's, based on a non quasi-static BJT model, has been presented in this paper. Excess carrier concentration and base charge have been proposed analytically and theoretical predictions of the anode voltages have been compared with the experimental data and obtained good agreement.

Futuer work will be devoted to analyzing current model and power losses and temperature characteristics for IGBT circuit's.

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