An Excess Carrier Lifetime Extraction Method for Physics-based IGBT Models

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Abstract

An excess carrier lifetime extraction method is derived for physics-based insulated gate bipolar transistor (IGBT) models considering the latest development of the IGBT modeling. Based on the two-dimensional (2-D) mixed mode Sentaurus simulation, the clamp turn-off test is simulated to obtain the tail current. Then the proposed excess carrier lifetime extraction methods are performed using the simulated data. The comparison between the extracted results and actual lifetime directly obtained from the numerical device model directly demonstrates the accuracy of the proposed method.

Key words: IGBT, parameter extraction, excess carrier lifetime, 2-D Sentaurus simulation

I. INTRODUCTION

In recent years, the characterization and modeling of IGBT have been greatly improved [1]-[6]. The physics-based models for non-punch-through (NPT), punch-through (PT) and field-stop (FS) IGBTs become more and more accurate. However, precise IGBT models are not enough. It is necessary to include a parameter extraction method that can accurately extracted the parameters needed for the models.

Excess carrier lifetime is one of the most important parameters for physics-based IGBT models, which characterize the tail current during the turn-off transient and on-state voltage drop. Although many works are published on lifetime extraction [7]-[19], most of them use the extraction theory in [7] to extract excess carrier lifetime for NPT IGBT models, and the extraction theory in [17] to extract the excess carrier lifetime for PT or FS IGBT models. Since the great development of IGBT transient modeling theory, especially the availability of the newly proposed expression for the transient dynamics of excess carrier distribution in N-base [4] and the improved understanding of transient modeling of FS layer [5], the extraction method should be modified to meet the latest developments. Moreover, in all these papers, the extraction method is validated by comparing the experimental and simulated characteristics of IGBT at static and transient states. The validation is not adequate enough. Since the simulation accuracy is dependent on so many factors, the accuracy of the simulation results cannot guarantee the accuracy of the extraction method.

In this paper, based on the latest development of IGBT modeling theory [4], [5], an excess carrier lifetime extraction method is proposed for physics-based IGBT models. The sentaurus simulation is used to validate the proposed method. In the validation, the sentaurus 2-D mixed mode simulation is used to simulate the clamp voltage turn-off test. Using the simulated data, the proposed extraction method is performed. Finally, the comparison between the extracted results and the actual lifetime obtained from the numerical device model straightforward validates the proposed method.

II. EXCESS CARRIER LIFETIME EXTRACTION METHOD

The excess carrier lifetime is extracted by the tail current at constant voltage supply, which is obtained from the clamp voltage turn-off test. For NPT IGBT, the extraction of N-base lifetime \( \tau_L \) is independent of the clamp voltage. For PT and FS IGBT, a low clamp voltage extraction is needed to get the N-base lifetime \( \tau_L \), and a high clamp voltage extraction is also needed to obtain the buffer layer lifetime \( \tau_H \).

A. Extraction of \( \tau_L \) for NPT IGBT Models

According to the Hefner IGBT modeling theory [7], during the turn-off transient, the base charge decay rate is

\[
\frac{dQ_n}{dt} = \frac{Q_n}{\tau_L} - I_{n0}
\]

where \( Q_n \) is the excess carrier charge in N-base. \( \tau_L \) is the excess carrier lifetime in N-base. \( I_{n0} \) is electron current.
injected into the emitter.

\[ Q_L = I_2 \cdot \frac{W_L^2}{4D_p} \]  
(2)

where \( W_L \) is the undepleted N-base width. \( D_p \) is the hole diffusivity in N-base. \( I_2 \) is the total current.

\[ I_{e0} \] in (1) is expressed as [7]

\[ I_{e0} = \frac{I}{n_i} \]  
(3)

where \( n_i \) is the intrinsic carrier concentration. \( I_{e0} \) is the emitter electron saturation current. \( P_h \) is the excess carrier concentration at emitter edge of N-base.

At turn-off transient, if the anode voltage rise time is prolonged, fewer electrons can arrive to the P emitter to provide the electrons needed for recombination. The local electrons and holes thereby have to recombine, which results in the decrement of \( P_h \). Since \( I_{e0} \) is proportional to the square of the \( P_h \), \( I_{e0} \) reduces to zero when \( P_h \) decreases. Therefore, prolong the anode voltage rise time, \( I_{e0} \) in (1) can be neglected. Substitute (2) into (1) yields

\[ \tau_L = \left[ \frac{dlnI_L}{dt} \right]^{-1} \]  
(4)

The current decay rate \( [-dlnI_L/dt]^{-1} \) decreases at low current because N-base leaves high-level injection condition, and low-level lifetime is smaller than the high-level lifetime. At high current, the current decay rate also decreases due to the increased rate of emitter electron current injection [7]. In the range where current decay rate is maximum, the N-base is in high-level injection and the electron current injection is negligible, (4) is valid. \( \tau_L \) equals to the maximum value of current decay rate.

**B. Extraction of \( \tau_L \) and \( \tau_H \) for PT IGBT Models**

In PT IGBT, the N-base is in high-level injection condition. Therefore, the hole current transmission equation takes the form of bipolar transport, which is given by [20]

\[ I_{pl} = I_2 \cdot \frac{1}{1+b_L} - qAD_L \frac{d(\delta p)}{dx} \]  
(5)

where \( D_L = 2D_{sL}D_{pL}/(D_{sL} + D_{pL}) \). \( D_{sL} \) and \( D_{pL} \) are electron and hole diffusivity in N-base, respectively. \( b_L = \mu_{sL}/\mu_{pL} \). \( \mu_{sL} \) and \( \mu_{pL} \) are electron and hole mobility in N-base. \( \delta p \) is the excess hole concentration and \( A \) is the device active area.

At turn-off transient, the N-base excess hole distribution is [4], [5]

\[ \delta p(x,t) = P_{h0} 1 - \frac{x}{W_L} \left[ \frac{P_{h0}}{W_L} \frac{dW_L}{dt} + \frac{x^2}{2L_c} \right] \]  
(6)

where \( W_L \) is the width of undepleted N-base. \( P_{h0} \) is the excess carrier concentration at \( x = 0 \), as shown in Fig. 1.

\[ L_c \] is the base diffusion length, \( L_c = \sqrt{D_c \tau_c} \).

**Fig. 1. Coordinate diagram for PT and FS IGBT.**

In the clamp voltage turn-off test, after the anode voltage reaches to the clamp voltage, the anode voltage remains constant. Therefore, \( dW_L/dt \) in (6) is zero. Combining (5) and (6) with second term of (6) neglected, the hole current \( I_{pl} \) and \( I_{p2} \) in Fig. 1 can be obtained.

\[ I_{pl} = I_{pl}(x = 0) = I_2 \cdot \frac{1}{1+b_L} - qAD_L \frac{d(\delta p)}{dx} + \frac{2Q_{e0}}{3L_c} \]  
(7)

\[ I_{p2} = I_{p2}(x = W_L) = I_2 \cdot \frac{1}{1+b_L} - qAD_L \frac{d(\delta p)}{dx} + \frac{Q_{e2}}{3L_c} \]  
(8)

where \( \tau_{ab} \) is ambipolar base transit time, \( \tau_{ab} = W_L^2/2D_c \).

The N-base excess charge \( Q_L \) is proportional to the base diffusion length, \( N_I \) is the buffer layer doping concentration. \( P_{h0} \) and \( P_{j0} \) are the excess carrier concentration at \( x' = 0 \) and \( x' = W_H \). \( Q_{e0} \) is the excess charge in Buffer layer. \( Q_{h0} = qAW_H(P_{h0} + P_{j0})/2 \). \( Q_b \) is the base charge. \( Q_b = qAW_LN_L \cdot \tau_{b} \) is Buffer layer base transit time. \( \tau_{ab} = W_L^2/2D_c \).

Notice \( N_L << N_I \), the second term on the right side of (9) is much smaller than the first term [5]. Equating (7) and (9) with the second term of (9) neglected, the base charge \( Q_L \) is expressed as

\[ Q_L = \frac{Q_{e0}}{1 + b_L} + \tau_{b} \]  
(10)

where \( Q_{e0} \) is the total excess charge in the N-base and Buffer layer. \( Q_b = Q_{h0} + Q_{e0} \). Substitute (10) into (8), the hole current \( I_{p2} \) at \( x = W_L \) which is now the total current, is given by
The total charge decay rate is [20]
\[
\frac{dQ}{dt} = \left( \frac{W_e}{4D_i N_i} + \frac{W_n}{2D_i N_i} + \frac{W_p N_t}{D_i n_p^2 A} \right) I_t - \left( \frac{qW_{Hb}}{\tau_{Hb} N_i} + \frac{I_{mb}}{n_p^2} \right)^2 I_t^2
\] (12)
where \( \tau_{Hb} \) is the excess carrier lifetime in high-doped buffer layer.

For the high clamp voltage extraction, \( W_t \approx 0 \), (11) is simplified as
\[
I_t = \frac{Q_t}{\tau_{Hb}}
\] (13)
Substituting (13) into (12) with \( W_t = 0 \), (14) is obtained.
\[
\frac{d\ln(I_t)}{dt} = -\frac{1}{\tau_{Hb}} + \frac{2N_t I_{mb}}{qW_{Hb} n_p^2}
\] (14)
the first term on the right side of (14) corresponds to the excess charge recombination in the buffer layer, while the second term denotes the emitter electron current injection. Since \( \tau_{Hb} \) is very short, the excess charge recombination rate in buffer layer is much larger than the electron injection rate. The second term on the right of (14) can be neglected, then (15) is obtained.
\[
\tau_{Hb} = \left[ \frac{d\ln(I_t)}{dt} \right]^{-1}
\] (15)

At high current, the buffer layer leaves the low-level injection condition. The current decay rate thereby increases because the high-level lifetime is larger than the low-level lifetime. At low current, the excess charge in buffer layer is almost exhausted, the current decay is dominated by the electron current injection. The current decay rate increases due to the decreased rate of emitter electron current injection. In the minimum current range where buffer layer is in low-level injection condition and electron current injection is negligible, (15) is valid. The \( \tau_{Hb} \) equals to the minimum value of current decay rate.

For the low clamp voltage extraction, notice \( \tau_{ab} \ll \tau_{L} \), (11) is simplified as
\[
I_t = \frac{Q_t}{\tau_{Hb} + \frac{b_1 + (2b_1 - 1)\tau_{Hb}}{1 + b_1} + \frac{3(1 + b_1)\tau_e}{2qAD_i}}
\] (16)
Prolong the anode voltage rise time. Fewer electrons can arrive to the \( J_0 \) junction to provide the electrons needed for recombination. Therefore, the local electrons and holes are recombined, and \( P_{Hb} \) decreases. Since the excess carrier lifetime in buffer layer is very short, the excess carrier recombination rate is very large. Thus \( P_{Hb} \) reduces greatly as a result of the recombination. In PT IGBT, the electron current injected into emitter is [17]
\[
I_{net} = \frac{I_{net} P_{Hb} n_p}{n_p^2}
\] (17)
The electron current \( I_{net} \) injected into emitter is thereby negligible due to the great decrement of \( P_{Hb} \).

Prolong the anode voltage rise time to eliminate electron current injection. Notice the terms contain \( I_{net} \) in (12) correspond to the electron current injection. Neglecting the terms contain \( I_{net} \) in (12), substitute (16) into (12) yields
\[
\frac{d\ln(I_t)}{dt} = -\frac{1}{\tau_{Hb}^*} \left( 1 + \frac{I_t}{I_t^*} \right)
\] (18)
where
\[
\frac{1}{\tau_{Hb}^*} = \frac{1}{\tau_{Hb}} + \frac{b_1 + (2b_1 - 1)\tau_{Hb}}{1 + b_1} + \frac{3(1 + b_1)\tau_e}{2qAD_i}
\] (19)
and
\[
\frac{1}{I_t^*\tau_{Hb}^*} = \frac{1}{\tau_{Hb}^*} + \frac{\frac{qW_{Hb}}{\tau_{Hb}^*} N_t I_{mb}}{W_t}
\] (20)
As what has been discussed for (4), (18) only validate in the range where current decay rate is maximum. In this range, \( I_t \) is much smaller than \( I_t^* \). Therefore, \( \tau_{Hb}^* \) approximately equals to the maximum current decay rate. The maximum current decay rate can be used in (19) to calculate \( \tau_{Hb} \).

C. Extraction of \( \tau_L \) and \( \tau_{Hb} \) for FS IGBT Models
In FS IGBT, The N-base is also in high level injection condition, so the equations (5)-(8) still validate. However, unlike the PT buffer layer, the FS layer is in high-level injection condition [5], thus (9) should be modified as
\[
I_{pet} = \frac{I_t}{1 + b_1} + \frac{4 W_{pet} (P_{Hb} - P_{Hb}^t)}{W_t}
\] (21)
Notice the doping concentration in FS layer is about \( 1 \times 10^{18} \text{cm}^{-3} \), thus \( b_1 \approx b_1 \), since \( N_L \ll N_t \), the third term of (21) can be neglected [5]. Equating (7) and (21), the base charge \( Q_b \) is expressed as
\[
Q_b = \frac{Q_t}{1 + \frac{b_1 + 2\tau_{Hb}}{3\tau_e}}
\] (22)
Substitute (22) into (8), the collector current, which is now the total current, is given by
\[
I_t = \frac{I_t}{1 + \frac{b_1}{b_2} \left( \frac{Q_t}{Q_b} \right) \frac{1 + 2\tau_{Hb}}{3\tau_e}}
\] (23)
For the high clamp voltage extraction, since \( W_t \approx 0 \), (23)
is simplified as

\[ I_f = \frac{1 + b_l}{b_l} \frac{Q_f}{\tau_{Fth}} \]

(24)

\[ \frac{1}{I_f'} \tau_{off}' = \frac{1 + b_l}{b_l} \frac{1}{\tau_{th}} \frac{1}{N_{hi}} \left( \frac{W_e}{2qD_{th}} \right)^2 \]

(29)

As what has been discussed for (4), (27) is also valid in the range where current decay rate is maximum. In this range, \( I_f \) is much smaller than \( I_f' \). Therefore, \( \tau_{off}' \) equals to the maximum current decay rate. The maximum current decay rate can be used in (28) to calculate \( \tau_e \).

III. NUMERICAL SIMULATION

In order to validate the proposed extraction method, the 2-D Sentaurus numerical simulation is performed to obtain the tail current. In the simulation, the test circuits in Fig. 2 are used to simulate the clamp voltage turn-off test. Thanks to the Sentaurus mixed-mode simulation, all the diodes, resistors and inductors used in the test are implemented by built-in Sentaurus compact models. The NPT, PT and FS IGBT under test are implemented by 2-D numerical device models. Table 2 shows the parameters used in the 2-D numerical device model.

![Fig. 3. Typical waveforms of IGBT turn-off process.](image)

Based on the mixed-mode simulation, the clamp voltage turn-off waveforms can be obtained. The typical and simulated turn-off waveforms are shown in Fig. 3 and Fig. 4, respectively. As shown in Fig. 3, the IGBT turn-off transient can be divided into four phases. In the phase 1, the gate-side capacitance discharges and the gate voltage \( V_g \) decreases accordingly. In phase 2, due to the Miller effect, \( V_g \) approximately remains constant. \( V_{ce} \) starts to rise slowly, while the collector current \( I_c \) still remains unchanged. As the collector-emitter voltage \( V_{ce} \) increases about 10 V or so, the phase 3 starts. The \( V_{ce} \) begins to increase rapidly towards \( V_{dc} \). In this phase, the collector-emitter voltage \( V_{ce} \) starts to rise slowly, while the collector current \( I_c \) still remains unchanged. As the collector-emitter voltage \( V_{ce} \) increases about 10 V or so, the phase 3 starts. The \( V_{ce} \) begins to increase rapidly towards \( V_{dc} \). In this phase, the collector emitter depletion capacitance begins to charge. The charging current greatly compensates the collector current reduction due to the shrinking of the MOS-side electron current. The collector current \( I_c \) then undertakes a slow decreasing. Once \( V_{ce} \) reaches \( V_{clamp} \), the phase 4 starts. The diode begins to conduct, the IGBT’s collector current then starts to transfer into the diode. Since \( V_{ge} \) is under the threshold voltage \( V_{th} \), the MOS-side electron current and the hole drift current associated with it are removed. This results an initial rapid fall of collector current \( I_c \). After that, the collector current \( I_c \) undertakes a slowly decaying due to the remaining excess carrier.
recombination in the N-base and buffer layer.

As shown in Fig. 3, the duration of phase 3 and phase 4 are defined as \( \tau_r \) and \( \tau_L \), respectively. During \( \tau_L \), the excess carrier in N-base and buffer layer undergo slow recombination. The current decay rate during \( \tau_L \) can be used to extract the excess carrier lifetime. \( \tau_r \) is the anode voltage rise time. In order to eliminate the excess carrier concentration \( P_0 \) at emitter edge of N-base, \( \tau_r \) should be enough long. In the range the extracted carrier lifetime is independent of \( \tau_r \), the extracted results equal to the real carrier lifetime.

![Fig. 4. Simulated clamp voltage turn-off waveforms of NPT IGBT using \( R_g = 5 \Omega \) at 150V/50A.](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NPT IGBT</th>
<th>PT IGBT</th>
<th>FS IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-base doping concentration (cm(^{-3}))</td>
<td>(5 \times 10^{12})</td>
<td>(5 \times 10^{15})</td>
<td>(5 \times 10^{15})</td>
</tr>
<tr>
<td>N-base width ((\mu)m)</td>
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<td>70</td>
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<tr>
<td>Trench gate depth ((\mu)m)</td>
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<tr>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>PT buffer layer/FS layer width ((\mu)m)</td>
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<td>4</td>
</tr>
<tr>
<td>PT buffer layer/FS layer doping concentration (cm(^{-3}))</td>
<td>-</td>
<td>(1 \times 10^{17})</td>
<td>(5 \times 10^{15})</td>
</tr>
<tr>
<td>P emitter width ((\mu)m)</td>
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<td>10</td>
<td>4</td>
</tr>
<tr>
<td>P emitter doping concentration (cm(^{-3}))</td>
<td>(5 \times 10^{16})</td>
<td>(5 \times 10^{18})</td>
<td>(1 \times 10^{17})</td>
</tr>
</tbody>
</table>

**IV. EXTRACTION METHOD VALIDATION**

Based on the simulated tail current, the proposed lifetime extraction methods are performed to extract excess carrier lifetime. The extraction method is directly validated by comparing with the actual excess carrier lifetime obtained from the 2-D numerical device model.

**A. Excess lifetime extraction for NPT IGBT models**

The circuit in Fig. 2a is used to simulate turn-off test. In the circuit, the clamp voltage \( V_{\text{clamp}} \) is 150V. The inductor \( L \) is 2 mH. The source voltage \( V_{cc} \) is 500V. The capacitance \( C_1 \) is 50mF. The load resistor \( R_L \) is 5 \(\Omega\). The gate resistor \( R_g \) is varied to change the anode voltage rise time.

Simulate the turn-off tests with six different anode voltage rise time at 150V/50A. Based on the simulated tail current, the current decay rate is calculated by (4), as shown in Fig. 5. In the range where the maximum current decay rate is independent of anode voltage rise time, \( \tau_L \) is extracted to be \(6.01 \mu s\). The actual lifetime \( \tau_L \) obtained from the NPT IGBT device model is \(6.2 \mu s\), which is very close to the extracted value.

![Fig. 5. The current decay rate versus total current for NPT IGBT.](image)

**B. Excess lifetime extraction for PT IGBT models**

For the high clamp voltage extraction of PT IGBT, the test circuit in Fig. 2a is used to extract \( \tau_H \). In the circuit, the inductor \( L \) is 2 mH. The gate resistor \( R_g \) is set to zero. The voltage of \( V_{cc} \) is 600V. The capacitance \( C_1 \) is 50mF. The load resistor \( R_L \) is 5 \(\Omega\). The clamp voltage \( V_{\text{clamp}} \) ranges from 300V to 550V. This is done to verify that the given extraction method can provide reasonable extraction result at different clamp voltages.

Simulate the turn-off test at 50A. Then the current decay rate is calculated by (15). Then \( \tau_H \) is extracted by finding the minimum value of the current decay rate. Fig. 6 shows the extracted \( \tau_H \) at different clamp voltages.

For the low clamp voltage extraction, the test circuit in Fig. 2b is used to extract \( \tau_L \). In the circuit, the clamp voltage \( V_{\text{clamp}} \) is 5V. The capacitance \( C_2 \) is 100mF. The gate resistor \( R_g \) is varied to change the anode voltage rise time.
Simulate the turn-off test at 5V/50A. Based on the simulated tail current, the current decay rate is calculated, as shown in Fig. 7. In the range where maximum current decay rate is approximately independent of anode voltage rise time, the \( \tau_{\text{eff}} \) is extracted to be 4.26 \( \mu s \). Substitute the extracted \( \tau_{\text{eff}} \) into (19), \( \tau_{\text{L}} \) is calculated to be 62.3 \( \mu s \).

The actual \( \tau_{\text{L}} \) and \( \tau_{\text{H}} \) of the PT IGBT device model are 63 \( \mu s \) and 28 ns, respectively. The extracted \( \tau_{\text{L}} \) and \( \tau_{\text{H}} \) show great accuracy.

Fig. 6. The extracted \( \tau_{\text{H}} \) versus clamp voltage for PT IGBT.

Fig. 7. Current decay rate versus total current for PT IGBT.

C. Extraction Methods for FS IGBT models

For the high clamp voltage extraction of FS IGBT, the circuit in Fig. 2a is used to extract \( \tau_{\text{H}} \). All the parameters in the circuit are the same as the high clamp voltage extraction for PT IGBT. Finding the maximum current decay rate, then \( \tau_{\text{H}} \) is extracted by (25). The extracted \( \tau_{\text{H}} \) is plotted versus various clamped voltages in Fig. 8.

For the low clamp voltage extraction, with the circuit in Fig. 2b, the turn-off test is simulated at 5V/50A. In the circuit, the capacitance \( C_2 \) is 100mF. The gate resistor \( R_2 \) is varied to change the anode voltage rise time. Based on the simulated tail current, the current decay rate is extracted, as shown in Fig. 9. In the range where the maximum current decay rate is independent of anode voltage rise time, \( \tau_{\text{eff}}' \) equals to the maximum current decay rate (4.35 \( \mu s \)). Substitute the \( \tau_{\text{eff}}' \) to (28), \( \tau_{\text{L}} \) is extracted to be 5.6 \( \mu s \).

The actual \( \tau_{\text{L}} \) and \( \tau_{\text{H}} \) obtained from the FS IGBT device model are 62 \( \mu s \) and 1 \( \mu s \), respectively. The extracted \( \tau_{\text{L}} \) and \( \tau_{\text{H}} \) are very close to the actual value.

It should be pointed out that the extracted \( \tau_{\text{H}} \) will greatly overestimated when the extraction method for PT IGBT is used to extract the lifetime, as shown in Fig. 9. This is because FS layer is in high-level injection condition [5] while PT buffer layer is in low-level injection condition, and the high-level injection lifetime is larger than low-level injection lifetime.

V. CONCLUSION

A novel excess carrier lifetime extraction method is presented in this paper. Compared with the published extraction methods, the novelty of the proposed method is presented in the following aspects.

1). The newly proposed IGBT modeling method are used to derive a new excess lifetime extraction theory.

2). The 2-D Sentaurus numerical simulation is used to validate the proposed method. In the validation, the actual
excess carrier lifetime of the 2-D numerical device model is obtained. Then the proposed method is directly verified by the comparison of the extracted and actual lifetime.

In the end, the good agreement of the actual carrier lifetime and the extracted value demonstrate the accuracy of the proposed extraction method.

REFERENCES


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