

Automated Parameter Extraction Software For Advanced IGBT Modeling

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Abstract—A software package for extracting parameters to be used in advanced IGBT models is presented. In addition, new model equations and extraction procedures are introduced that more accurately describe a wide range of IGBT types including the recently developed Warp-Speed IGBTs. The parameter extraction software package consists of five programs that extract the 20 physical and structural parameters needed in the most recent version of the Hefner IGBT model. Each program has a graphical user interface and uses the IEEE 488 bus to control the measurement instruments. Various algorithms are employed for fitting the IGBT model equations to measured data. The new software package enables users of the simulation software products to extract model parameters themselves and thus permits the simulation of new IGBT part numbers as soon as they are introduced.

I. INTRODUCTION

The IGBT (Insulated Gate Bipolar Transistor) is becoming the power switch of choice for many power applications because it offers a good compromise between on-state loss, switching loss, and ease of use. To develop circuits and systems using these devices, models are needed for use in circuit simulators. The Hefner IGBT model is used extensively by the industry and is provided as part of several commercial circuit simulation programs [1, 2]. Typically, the IGBT model is used in a circuit simulator by selecting a pre-characterized component from the software vendor's component library or by extracting the necessary model parameters from terminal electrical measurements. Previous publications described the basic IGBT model parameter extraction sequence [3, 4]. As the parameter extraction algorithm is very complicated, only a few laboratories throughout the world have the capability to accurately extract the IGBT model parameters.

The purpose of this paper is to introduce a new software package that enables end users of simulation software products to extract model parameters themselves.

In addition, new model equations and extraction procedures are introduced that more accurately describe a wide range of IGBT types including the recently developed Warp-Speed[†] IGBTs. The new IMPACT (IGBT Model Parameter extrACTION) software package consists of five programs: LFTMSR, BTAMSR, SATMSR, LINMSR and CAPMSR that extract the 20 physical and structural parameters for the most recent version of the Hefner IGBT model. The programs have a graphical user interface and use the IEEE 488 bus to control the measurement instruments. Each program has a help menu that explains the operation and procedure for extracting the IGBT model parameters. In this paper, the new model and extraction equations, the detailed operation of each extraction program, and parameter extraction examples are described. The software package is available through <http://ray.eeel.nist.gov/impact/>.

II. IGBT EXTRACTION SEQUENCE

To model a particular IGBT part number, an extraction sequence is needed to determine the values of all of the model parameters from electrical measurements. The extraction process is divided into a sequence of steps where only a few unknown parameters are obtained at each step. This is done by selecting electrical characteristics that isolate a few unknown parameters at a time and fitting the measured data to the corresponding model equation. The parameters obtained at each step are then used as known values in subsequent steps. In general, dynamic measurements are used first to access the internal bipolar transistor. The internal MOSFET characteristics are then calculated using the bipolar current gain characterized in previous extraction steps.

Table 1 is a list of IGBT model parameters, the electrical characteristics that are used to extract each parameter, and the name of the automated extraction program that implements the extraction step. The

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Table 1. Parameters, Extraction Programs, and Characteristics

Parameter symbol	Parameter name	Program	Extraction characteristic
A	Device active area		Chip size
τ_{HL}	Lifetime	LFTMSR	Low V_A tail decay rate
t_{buf}	Buffer layer lifetime		High V_A tail decay rate
I_{sne}	Emitter electron saturation current	BTAMSR	Tail size vs. current
W_b	Metallurgical base width		Tail size vs. V_A
N_b	Base doping concentration		Tail size vs. V_A
W_{buf}	Buffer layer width		Tail size vs. V_A
V_T	Threshold voltage	SATMSR	Saturation current vs. V_{gs}
K_{psat}	Saturation region transconductance		Saturation current vs. V_{gs}
θ	Transverse field transconductance factor		High Saturation current vs. V_{gs}
K_{fl}	Low current transconductance factor		Low Saturation current vs. V_{gs}
dV_{Tl}	Low current threshold voltage differential		Low Saturation current vs. V_{gs}
K_{plin}	Linear region transconductance	LINMSR	On-state voltage vs. V_{gs}
R_s	Anode series resistance		On-state voltage vs. V_{gs}
τ_{rat}	Low-level injection lifetime ratio		On-state voltage vs. current
τ_{mod}	Carrier modulation uniformity factor		On-state voltage vs. current
C_{gs}	Gate-source capacitance	CAPMSR	Gate charge
C_{oxd}	Gate-drain overlap oxide capacitance		Gate charge
A_{gd}	Gate-drain area		Gate-drain charge
V_{Td}	Gate-drain overlap depletion threshold		Gate-drain charge
N_{buf}	Buffer doping concentration		Reverse Capacitance

parameters are listed in the order that they are extracted. In the first step, the device active area is extracted by visual inspection of the chip size. Five basic types of electrical measurements are used to extract the remaining model parameters: 1) The turn-off current tail decay rate versus anode current and voltage is used to extract the base lifetime and the buffer layer lifetime (LFTMSR). 2) The relative size of the turn-off current tail versus anode current and voltage is used to extract the emitter injection parameter, the base width, the base doping concentration, and the buffer layer width (BTAMSR). 3) The saturation current versus gate voltage is used to extract the MOSFET channel transconductance and threshold voltage parameters including high and low current effects (SATMSR). 4) The on-state voltage versus gate-source voltage characteristic is used to extract the linear region transconductance and anode series resistance, and the on-state voltage versus anode current is used to extract the low-level injection lifetime parameters (LINMSR). 5) The gate charge, gate-drain charge, and reverse capacitance characteristics are used to extract the gate-source capacitance, the gate-drain overlap oxide capacitance, the gate-drain overlap area and buffer layer doping concentration (CAPMSR).

III. LABWINDOWS/CVI* INSTRUMENTATION SOFTWARE

The parameter extraction measurements require high precision and the ability to make calculations on waveforms obtained from computer-controlled instruments. The basic measurement system used to do this

consists of a computer that controls power supplies, a waveform digitizer, a temperature controller, a capacitance-voltage meter, and a curve tracer. A typical extraction procedure sets parameters of the electronic instruments, initiates the measurement, and transfers the data to the computer where it is analyzed using model equations. The extraction software must have the features and options necessary to extract parameters for a wide range of device types and requires a user interface with controls and displays necessary for user interaction. Therefore, the tools used for the parameter extraction software development must provide the capability to control instruments, retrieve data from the instruments, perform curve fitting and interpolation, calculate model equations, and provide a method for developing a user-friendly graphical interface.

Labwindows/CVI is an integrated C programming environment for the development of laboratory instrumentation software. It provides integrated I/O libraries, analysis routines, and user-interface development tools. The Labwindows/CVI software package includes a large set of instrument drivers that simplify communication with electronic instruments. Because the programming environment is based on the C programming language, the model equations required for parameter extraction can be readily implemented. A wide array of controls such as knobs, meters, gauges, dials, and graphs are provided. This facilitates the user control of the program operation, features selection, and visualization of the extraction process.

To develop a parameter extraction program using the Labwindows/CVI programming environment, the programmer 1) defines a Graphical User Interface (GUI) specific to the project, 2) uses instrument libraries to

* LabWindows/CVI™ is a trademark of National Instruments Inc.

program the commands for measurement instrument control, and 3) implements model equations to analyze data with the numerous standard C/C++ and CVI functions. After the programmer designs the user interface, Labwindows/CVI automatically generates the structure of the code and associates functions that respond to the controls on the GUI. The programmer then implements the C program code to be executed for each of these functions. This process is facilitated using the built-in code generation tools for various functions such as instrument control, curve fitting, graphing, printing, and file management.

To illustrate the use of a Labwindows/CVI generated GUI, Fig. 1 shows the Physical Constants sub-panel used within all of the IGBT extraction programs. This sub-panel is used to initialize the physical constants according to the measurement temperature, enabling extraction for the electro-thermal version of the IGBT models [5]. It is important that the extraction tools use the exact same equations for the temperature dependence of the physical constants that are used in the model template.

To operate this sub-panel, the user would click one of the buttons on the window using the mouse-pointing device, or enter numerical values into the numeric entry/display boxes. For example, the temperature numeric value can be changed from 300 K shown in Fig. 1 using the increment/decrement arrows to the left of the value or by clicking the numeric entry/display box and typing in the new temperature. Clicking the CALCULATE button executes the function that calculates the physical constants corresponding to the new temperature and displays the new values for each of the physical constants. When the user clicks the "Quit" button, the program stores the values, closes the sub-panel, and uses the new values in subsequent calculations in the extraction process.

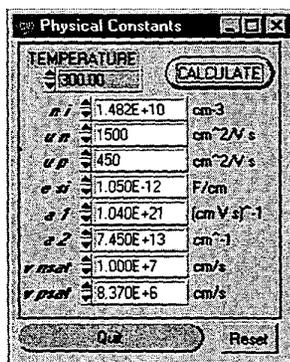


Fig. 1: Physical constants panel

IV. ORGANIZATION OF IMPACT SOFTWARE PACKAGE

In this section, the organization and structure of the IMPACT software package is described. The software package is organized into five programs, each performing the extractions for the five different types of measurements

described in Table 1. For best coherence, the front panel user interface of each program is designed to have a similar layout and function. In addition to the front panel, the five extraction programs include pop-up panels for selecting fitting algorithms, calculating the temperature-dependent physical properties of silicon, plotting intermediate calculated functions such as current gain, and verifying the accuracy of the extraction. Where multi-level extraction is required, each level of the extraction is split into a different sub-panel window, as described below in subsection V-A for the voltage dependence of lifetime, and in V-B for the voltage dependence of neutral base width.

As an example, Fig. 2 shows the front panel user interface for the LFTMSR program described in subsection V-A below. The upper graph on each front panel displays the measured data and enables the detection of any problems that might have occurred during the experimentation. The lower graph shows the transformed data that is fitted to the model equations, the fitted line, and other calculated quantities of interest such as internal voltages or currents. The full set of IGBT model parameters is listed on the right-hand side of each front panel, where the parameters in the yellow box are associated with the buffer-layer version of the IGBT model. The device type switch is used to define whether the buffer-layer or non-buffer-layer model extraction equations are to be used. Each program updates several of these parameters (highlighted in blue) as the extraction functions on the panel are executed.

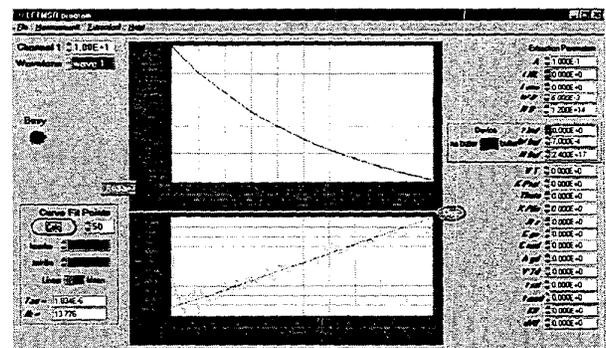


Fig. 2: Lifetime extraction front panel.

Each front panel includes four pull-down menus: File, Measurement, Extraction, and Help. The File menu allows the user to load, save, and print measurement and extraction results. The contents of the Measurement, Extraction, and Help menus vary with the software program. The Measurement menu includes functions to set up instruments and to direct the desired measurements to be made. Various measurement methods are provided to facilitate the measurement conditions that may be required for different IGBT technologies and current ratings. The Extraction menus include pop-up panels to set up physical constants, extraction parameters, and curve fitting parameters as well as functions that perform and refine the

extraction. The user can interact with the software to set up new extraction ranges and parameter values in algorithms. The help menu guides the user through the extraction process from the very beginning and describes the basic steps as well as more elaborate functions.

V. OPERATION OF IMPACT SOFTWARE PROGRAMS

In this section, the operation and extraction of the five IMPACT software programs are described. The programs are described in the order that they would be used in a typical extraction procedure.

A. τ_{HL} and τ_{buf} extraction (LFTMSR)

The decay rate of the turn-off current tail versus anode current and voltage is used to extract the base lifetime τ_{HL} and buffer layer lifetime τ_{buf} . The constant anode voltage turn-off current tail decay rate can be measured using either the clamped large inductive load (1mH) test circuit or the constant anode supply voltage test circuit [4]. The clamped inductive load technique is most suitable for small base lifetimes because it results in a larger tail size.

The LFTMSR program is divided into two distinct panels: the base lifetime is extracted from the front panel (Fig. 2) using multiple current tail waveforms with different initial current values and the same anode or clamp supply voltage, and the buffer layer lifetime is extracted using a sub-panel (Fig. 3) that plots lifetime versus voltage where each lifetime voltage data point is obtained from the front panel.

To perform the extraction, the tail current for a constant voltage condition is first measured and transferred to the program as shown in the upper graph of Fig. 2. The exponential current decay rate versus current of the data is then fitted to the model equation for constant voltage current decay:

$$-\frac{d \ln I_T}{dt} \equiv \frac{1}{\tau_{HL}} \left(1 + \frac{I_T}{I_{k,\tau}} \right). \quad (1)$$

This is done using the CALC button where the number to the right of the button is the number of points to be used in the numerical derivative calculation. The resulting current decay rate data (calculated using the left hand side of eq 1) versus current is shown as the green curve in the lower graph of Fig. 2. The red curve shows the least square fit of the data to the equation on the right hand side of eq 1 where the values of τ_{HL} and $I_{k,\tau}$ calculated from the fit are displayed in the numerical display boxes.

It is necessary to limit the range over which the data are fitted using the values of I_{maxlim} and I_{minlim} to eliminate the high and low current effects not described in the simplified model equation of eq 1. In many instances, it is necessary to calculate the decay rate versus current using multiple measured current tail waveforms with different initial current values. In this case, the waveform number near the upper left-hand corner corresponds to the

one displayed in the upper graph, and the decay rate for all of the waveforms is shown in the lower graph.

For buffer-layer devices, the sub-panel shown in Fig. 3 is used to extract the buffer layer lifetime by performing the above procedure for different voltages and fitting the data to the model equation for effective lifetime versus voltage [2]. To do this, the effective lifetime is calculated at a given supply voltage (as described above for Fig. 2) and is added to the list of lifetime versus voltage data points using the "Add to total points" button inside the orange box on the right-hand side of Fig. 3. The other buttons inside the orange box are used for file management and data management. For example, extraneous data points can be excluded from the fitting algorithms. When the "Calculate Lifetimes" button is pressed, the data are fitted to the effective lifetime versus voltage model equation and the extracted values of τ_{HL} and τ_{buf} are updated in the parameter list. When the "Calculate I_{sne} " button is pressed, the value is calculated using the value of $I_{k,\tau}$ presently displayed on the front panel of Fig. 2.

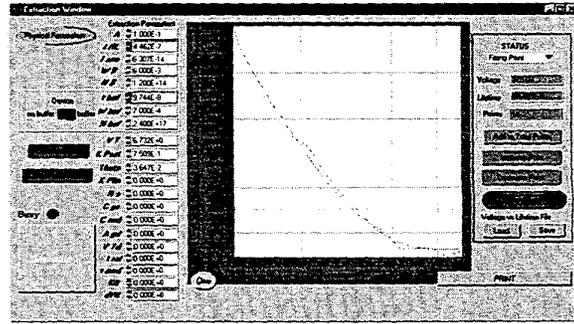


Fig. 3: Sub-panel for calculating buffer layer lifetime parameters.

B. I_{sne} , W_b , W_{buf} and N_b extraction (BTAMSR)

The relative size of the turn-off current tail versus anode current and anode voltage is used to extract the emitter electron saturation current I_{sne} , the metallurgical base width W_b , the base doping concentration N_b , and the buffer layer width W_{buf} . To simplify the extraction, the program automatically detects the two phases of the current decay waveform (the rapid fall in current followed by the slowly decaying current tail) and determines the relative size of the tail, β_{tr} . This process is performed for several values of current and the measured values of β_{tr} versus current are fitted to the simplified model equation to determine the value of β_{tr}^{max} and I_{sne} . The value of β_{tr}^{max} is used to calculate the quasi-neutral base width W using the value of lifetime obtained from the previous extraction step described in section V-A. The entire process is then repeated for several values of supply voltage and the values of W versus voltage are then used to extract the base width and doping density information.

The BTAMSR program is divided into two distinct panels. The main panel (Fig. 4) builds the curve β_{tr} versus tail current using automatic detection of the tail size,

performs the extrapolation to obtain the values of I_{sne} or β_{tr}^{max} , and calculates the value of W using a simplified model equation for the constant voltage or clamped inductive load condition. The sub-panel (Fig. 5) is then used to build the values of W used to extract the base width and doping density information. The parameters used in the automatic tail current detection and extrapolation process can be adjusted using the extrapolation parameters pop-up window (Fig. 6) accessible through the extraction pull-down menu. Other pop-up windows available from the extraction pull-down menu are used to view statistical information in intermediate quantities in the extrapolation process.

The upper graph in Fig. 4 shows the measured current waveform (red curve) extrapolated with the tail of a higher current turn-off waveform (green curve). The vertical lines indicate the time points determined by the program to be the beginning and end of the initial rapid fall in current and the end of the redistribution phase.

To begin the extraction process, measured turn-off current waveforms are transferred to the computer and the tail is automatically detected. The tail is then extrapolated back to the time of the initial rapid fall in current to obtain the initial value of tail current tail $I_T(0^+)$. The slide-ring switch on the right-hand side of Fig. 6 provides several options for extrapolation method.

After each extrapolation of the current versus time curves, the measured values of $I_T(0^+)$ and the relative tail size:

$$\beta_{tr} \equiv \frac{I_T(0^+)}{I_T(0^-) - I_T(0^+)} \Big|_{V_A=const} \quad (2)$$

are displayed in the numeric boxes to the right of the graph where $I_T(0^-)$ is the average value of current before the initial rapid fall in current. The user is given the choice of including these results in the lower graph $1/\beta_{tr}$ versus tail current $I_T(0^+)$ using the "Add to total points" button. This process is continued using waveforms with different initial current values until enough data are accumulated in the lower graph on Fig. 4.

From the IGBT model equations, the measured values of $1/\beta_{tr}$ versus $I_T(0^+)$ are expected fall on a line with a slope of $1/(\beta_{tr}^{max} I_k)$ and a zero current intercept of $1/\beta_{tr}^{max}$:

$$\beta_{tr} = \beta_{tr}^{max} \left(1 + \frac{I_T(0^+)}{I_k} \right)^{-1} \quad (3)$$

where the expressions for β_{tr}^{max} and I_k are given in ref. [4] for the non-buffer-layer model and in ref. [2] for the buffer layer model. The solid curve in the lower graph of Fig. 4 is obtained from a least-squares linear fit to the $1/\beta_{tr}$ data and the calculated values of I_k and β_{tr}^{max} are listed below the graph. The value of I_k is used to extract the parameter I_{sne} and the value of β_{tr} is used to obtain the value of the quasi-neutral base width W as described for the sub-panel (Fig. 5). The extracted values of W versus $V^{1/2}$ are then used to extract W_b , W_{buf} , and N_b as described below.

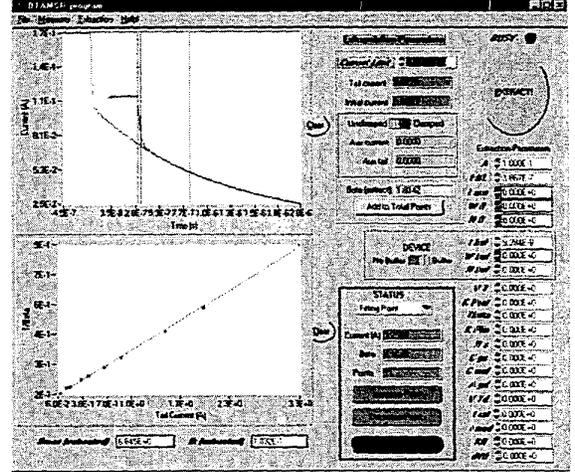


Fig. 4: I_{sne} , W_b , W_{buf} , and N_b extraction front panel.

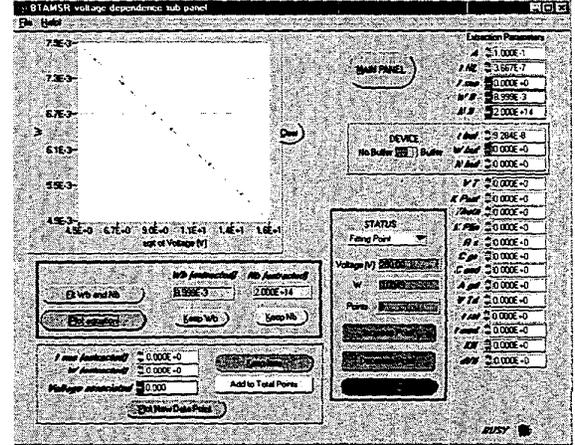


Fig. 5: I_{sne} , W_b , W_{buf} , and N_b extraction sub-panel.

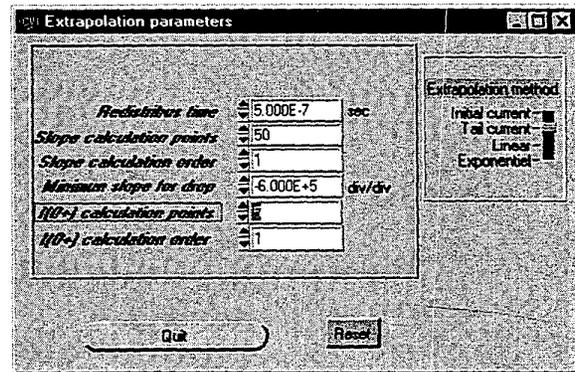


Fig. 6: Extrapolation parameters pop-up window.

The extraction procedure continues by switching to the sub-panel (Fig. 5) using the button "Extract" on the top right-hand corner of the front panel of Fig. 4. The extracted values of I_{sne} and W are displayed within the green box at the bottom of the sub-panel of Fig. 5. By

clicking the “Keep Isne” button within the green box, the value of I_{sne} is added to the parameter list on the right. By clicking the “Add to total point” button, the values of W and V are added to the data array. This entire process is repeated using the “Main Panel” button to build the W versus $V^{1/2}$ array plotted on the sub-panel on Fig. 5. The buttons inside the orange box are used to manage this data array.

The buttons inside the blue box are used to manage the extraction of the values of W_b and N_b . For the non-buffer layer IGBT model, W is expected to be given in terms of anode voltage by:

$$W \approx W_B - \sqrt{\frac{2\epsilon_{si} V_A}{q N_B}} \quad (4)$$

The “Fit W_b and N_b ” button is used to obtain a least squares fit to this equation. The “Keep W_b ” and “Keep N_b ” buttons are used to add the extracted values to the parameter list. The “Plot equation” button uses values in the parameter list to plot eq 4, enabling the user to see the results for manually entered parameter values. The extraction for the buffer layer case will be the topic of a future publication.

C. K_{psat} , V_T , θ , K_{β} and dV_{T1} extraction (SATMSR)

The saturation current versus gate voltage is used to extract the internal MOSFET transconductance parameters for the saturation region K_{psat} , the high current region θ , the low current region K_{β} and dV_{T1} , and the threshold voltage V_T . To perform the extraction, the IGBT saturation current is measured versus gate voltage and divided by the current gain of the internal bipolar transistor (calculated using the parameters obtained by the previous two extraction programs) to obtain the internal MOSFET saturation current I_{mos}^{sat} . The value of the square root of I_{mos}^{sat} versus gate voltage is then used to extract the parameters of the internal MOSFET.

The SATMSR program consists of the front panel (Fig. 7) and several pop-up panels for verifying the quality of the final fit (Figs. 8 and 9) and viewing the bipolar current gain that is used as an intermediate quantity in the extraction. The pop-up panels of Figs. 8 and 9 are accessed using the Extraction pull down menu.

To perform the extraction, the saturation current is measured using the Measure pull-down menu. The red curve in the upper graph of Fig. 7 shows the measured results. The Measure pull-down menu offers different measurement functions according the IGBT device characteristics and the curve tracer required for the current range of interest, e.g., Sony/Tektronix 370 or 371. The user also specifies the collector voltage and the maximum current for the measurement using the numeric input boxes in the blue box to the right of the upper graph in Fig. 7. Because the curve tracers use the collector voltage as the sweep variable and the gate voltage as the step variable, the program uses the gate voltage offset voltage and the

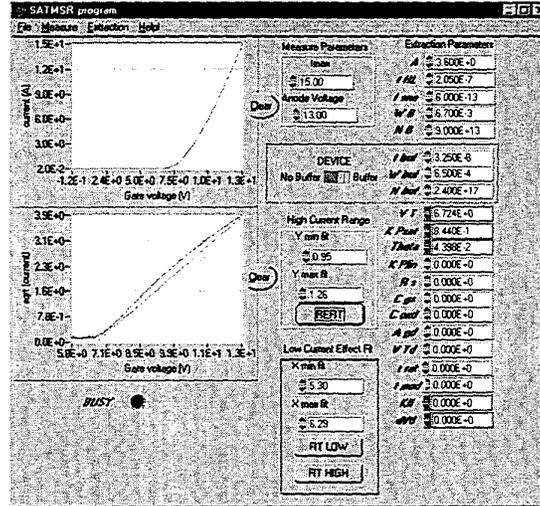


Fig. 7: K_{psat} , V_T , θ , K_{β} , and dV_{T1} extraction front panel.

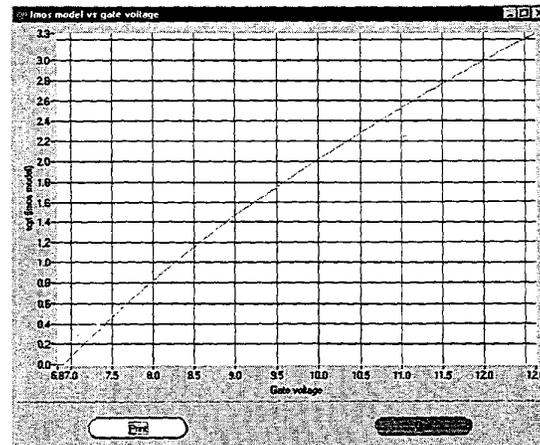


Fig. 8: Final fit of high current model (blue) to data (green)

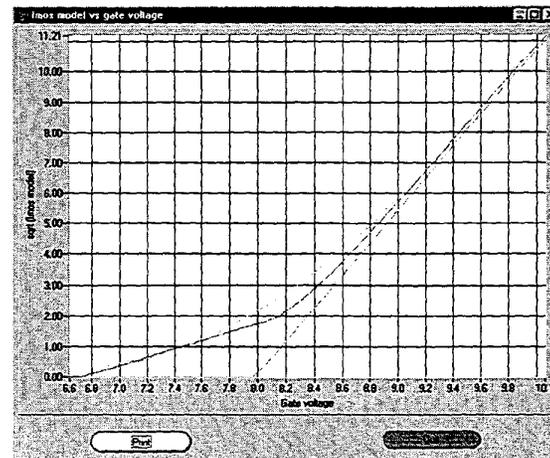


Fig. 9: Final fit of low current model (blue) to data (green)

cursor readout to generate the continuous graph of current versus gate voltage.

After the measurement is performed, the model parameters are extracted using the function "Calculate model parameter" in the Extraction pull-down menu. This function first calculates the bipolar current gain versus current, and then uses this to calculate the internal MOSFET saturation current versus gate voltage using the relationship:

$$I_{mos}^{sat} = I_T^{sat} / (1 + \beta_{SS}). \quad (5)$$

This "Calculate model parameter" function then plots the square root of both I_{mos}^{sat} and I_T^{sat} in the lower graph in Fig. 7 (green curve and blue curve respectively). The function also performs a least-squares fit to the simplified model equation:

$$\sqrt{I_{mos}^{sat}} = \sqrt{\frac{K_{psat}}{2}} (V_{gs} - V_T), \quad (6)$$

plots the least-squares fit (grey line in the lower graph of Fig. 7), and displays the computed values of V_T and K_{psat} in the parameter list on the right-hand side of Fig. 7.

Because the simplified model equation (eq. 6) is only valid for the intermediate current range, the "Calculate model parameter" function also calculates and displays default values for the limits of the least squares fit range and displays them in the blue box to the right of the graph (Yminfit and Ymaxfit). The user can modify these values and re-perform the extraction using the "Refit" button inside the blue box. After the parameters are extracted for the intermediate current range, the parameters for the high and low current ranges are extracted.

The model for the high current effects is described in ref. [1]. The high current parameters are obtained by selecting the "Refine K_{psat} and θ " button from the Extraction pull-down menu and the low current parameters are extracted using the buttons in the orange box to the right of the lower graph in Fig. 7. This "Refine K_{psat} and θ " button recalculates these values while keeping V_T constant to fit the high current range as well as the intermediate current range and displays the parameter list in the list on the right-hand side of Fig. 7. Figure 8 shows the final fit including the high current effect where the curvature is due to the parameter θ .

Although the model for the low current effects has been implemented by Hefner and provided as part of Saber since 1998 in version 5.0, the low current equations have not been described in a previous publication and are given below. The low current effect or "soft threshold effect" is due to conduction at the corners of the DMOS cells. The corners have a lower threshold voltage and a lower transconductance than the main MOSFET channel.

The soft threshold effect model basically consists of a parallel combination of the main MOSFET channel with another MOSFET representing the conduction at the corners of the MOSFET cells:

$$I_{mos} = I_{mosh} + I_{mosl} \quad (7)$$

where

$$I_{mosh} = \frac{(1 - K_{\beta}) K_{psat} (V_{gs} - V_{Th})^2}{2(1 + \theta(V_{gs} - V_{Th}))} \quad \text{for } V_{gs} - V_{Th} > 0 \quad (8)$$

$$I_{mosl} = \frac{K_{\beta} K_{psat} (V_{gs} - V_{Tl})^2}{2(1 + \theta(V_{gs} - V_{Tl}))} \quad \text{for } V_{gs} - V_{Tl} > 0 \quad (9)$$

This model is formulated such that the equations as well as the extraction procedure reduce to the model described in ref [1] that does not include the soft threshold effect. The threshold voltages for the two internal MOSFETs are described in terms of the extraction parameters using:

$$V_{Th} = V_T + \frac{K_{\beta}}{1 - K_{\beta}} dV_{Tl} \quad (10)$$

$$V_{Tl} = V_T - dV_{Tl} \quad (11)$$

where V_T is the threshold extracted as described above and the values of dV_{Tl} and K_{β} are extracted from the low current region.

To complete the extraction, the user alternates between the "Fit Low" and "Fit High" buttons to refine the fits to the low and intermediate ranges. During this process, the values for the limits of the least-squares fits in the low and intermediate range can be adjusted. However, the software provides robust automatic algorithms for performing the extractions that usually do not require adjustment of the calculated default parameters. At any point during the extraction, the user can select the "Display Final Fit" button from within the Extraction pull-down menu to view the progress of fitting the I_T^{sat} measurements. Figure 9 shows the final fit including the low current effect where the current below the inflection point in the model (blue curve) is fitted by the low current equations.

D. K_{plim} , R_s , τ_{mod} and τ_{rat} extraction (LINMSR)

The linear region on-state voltage versus gate voltage for a constant anode current is used to extract the linear region transconductance K_{plim} , and the anode series resistance R_s . The current versus on-state voltage at the low current level is then used to extract the electron/hole mobility ratio τ_{rat} , and the carrier modulation uniformity factor τ_{mod} .

The LINMSR program consists of one main panel shown in Fig. 10 with two graphs. The top graph plots the anode voltage versus $1/(V_g - V_T)$ for a constant anode current, and the bottom graph plots the current versus on-state voltage. The Measure pull-down menu is used to initiate the measurement where the test parameters are defined in the lower blue box. The test parameters include the anode test current I_{test} , the maximum gate voltage V_{gmax} , and the maximum anode voltage V_{amax} . Because the Sony/Tektronix 370 and 371 curve tracers apply voltage and measure current, the LINMSR program uses an

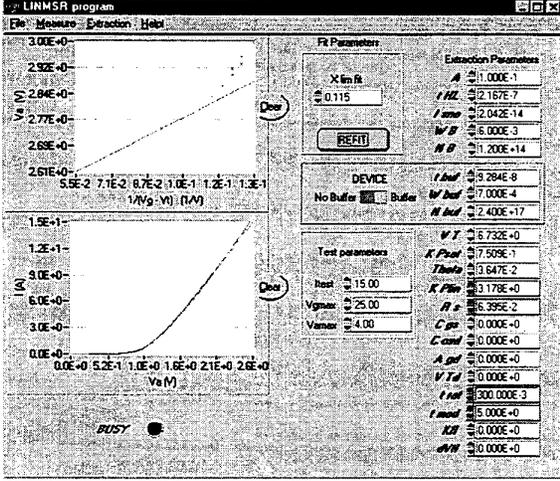


Fig. 10: K_{plin} , R_s , τ_{mod} , and τ_{rat} extraction front panel.

iteration algorithm to establish the constant anode test current as described below.

When the measurement sequence is initiated, the gate voltage is set to the maximum gate voltage specified in the lower blue box and the anode voltage is set to zero. Then, the anode voltage is stepped up with the minimum increment size available on the curve tracer. During this process, the anode current and Kelvin-contact anode voltage are measured and transferred to form the red curve (measured curve) in the lower graph of Fig. 10. This process continues until the measured current is greater than the anode test current.

After the measured current reaches the test current, the process transitions to accumulating data for the upper curve of Fig. 10. This curve requires the anode voltage versus gate voltage pairs that result in a constant current. These data pairs are obtained by decreasing the gate voltage if the measured current is greater than I_{test} and increasing the anode voltage if the measured current is less than I_{test} . Because the minimum voltage increment for the anode voltage is more coarse than for the gate voltage for the Sony/Tektronix 370 and 371 curve tracers, each increment of anode voltage results in a data point in the lower graph of Fig. 10. The gate voltage for each anode voltage step is determined by bisection of the gate voltages that produce a current above and below I_{test} . The data collection is completed when the maximum anode voltage is reached.

After the measurement is performed, the model parameters are extracted using the function "Calculate model parameter" in the Extraction pull-down menu. This performs a least-squares linear fit (extrapolation line in the top graph of Fig. 10) to the extraction equation that is valid for the MOSFET linear region of operation [4]:

$$V_{on} = V_r + \frac{I_T}{(1 + \beta_{ss})K_{plin}} \left(\frac{1}{V_{gs} - V_T} \right), \quad (12)$$

where

$$V_r \equiv V_{eb} + R_s I_T + \frac{I_T \theta}{(1 + \beta_{ss})K_{plin}}. \quad (13)$$

The values of K_{plin} and R_s are thus obtained from this extraction step using the values of V_T , β_{ss} , V_{eb} , K_{plin} and θ calculated from the model parameter obtained in previous extraction steps. The IGBT model equations including the transition between the linear and saturation regions is plotted in the data in the upper graph of Fig. 10 by selecting "Replot Calculated Parameters" from within the Extraction pull-down menu.

At this step, the user extracts the effects of τ_{mod} and τ_{rat} by selecting "Display Final Fit" from within the Extraction pull-down menu. These parameters describe the transition from low-level to high-level injection lifetimes. For very fast IGBTs where the electron and hole lifetimes differ substantially, this transition results in a larger on-state voltage (sometimes forming a snap back region called a trigger finger) in the low current range of the lower graph of Fig. 9. Although the model for the low injection lifetime effects has been implemented by Hefner and provided as part of Saber since 1998 in version 5.0, the model equation has not been published elsewhere and is given here:

$$\tau_{HL}' = \tau_{HL} \left[1 - \frac{(1 - \tau_{rat}) Q_b \tau_{mod}}{Q_l + Q_b \tau_{mod}} \right]. \quad (14)$$

The lower graph on Fig. 10 shows that the measured and simulated on-state characteristics are nearly identical after completing this extraction procedure. As an aid in extracting the model parameters, the user can display the internal components of on-state voltages by selecting "Display Internal Voltages" from within the Extraction pull-down menu.

E. C_{gs} , C_{oxd} , A_{gd} , V_{Td} and N_{buf} extraction (CAPMSR)

The gate- and gate-drain charge characteristics are used to extract the gate-source capacitance C_{gs} , the gate-drain overlap oxide capacitance C_{oxd} , the gate-drain overlap area A_{gd} , and the gate-drain overlap depletion threshold V_{Td} . The reverse capacitance voltage characteristics are used to extract the buffer layer doping concentration N_{buf} .

The CAPMSR program consists of one main panel (Fig. 11) with two graphs. The upper graph contains the measured waveforms necessary for the calculation, and the lower graph contains curves calculated from the data and the fitted lines used for the extraction. The particular curves that appear in each graph depend on the type of extraction being performed. The example shown in Fig. 11 uses the gate-charge characteristic to extract the gate-source capacitance C_{gs} and the gate-drain overlap oxide capacitance C_{oxd} . In this paper, only the program operation for the gate-charge characteristic is described because the program is operated similarly for extractions using the gate-drain charge or reverse capacitance voltage characteristics.

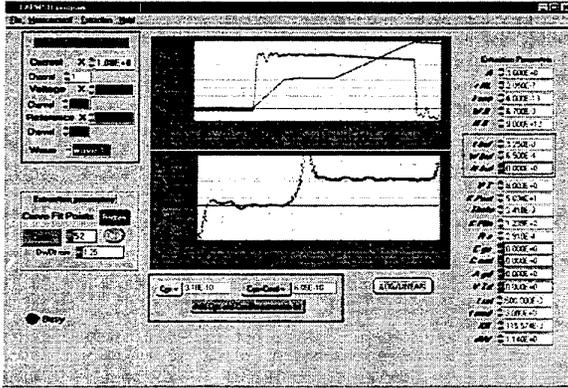


Fig. 11: Cgs, Coxd, Agd, VTd, and Nbuf extraction front panel.

To begin the extraction, the Meaure pull-down menu is used to initiate the measurement and acquire the waveforms from the oscilloscope, where the waveform parameters are defined in the red box to the left of the graph. The “Calc” Button within the blue box is used to calculate the capacitance curve in the lower graph using:

$$C(V) = \frac{I}{dV/dt} \quad (15)$$

This capacitance versus voltage curve is then displayed on the lower graph. The minimum curve value of dV/dt and the number of derivative points for the calculation can be specified in the blue box, although the default values are usually sufficient. These values primarily control smoothing and scaling. To extract the model parameters, the horizontal blue and green lines are aligned with the

plateau regions. The button “Add Cgs and Coxd to parameter list” then updates the parameter list.

VI. CONCLUSIONS

A software package called IMPACT is presented for extracting parameters of advanced IGBT models. The software package consists of five programs that extract the 20 physical and structural parameters of the most recent version of the Hefner IGBT model. Each program provides robust automatic algorithms for performing the extractions that usually do not require adjustment of the calculated default parameters. The availability of this new software package will enable users of the simulation software products containing the Hefner IGBT model to extract model parameters themselves and thus permits the simulation of new IGBT part numbers as soon as they are introduced.

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