Simulation Standard

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IGBT Switching Simulation Based on the Double-Pulse Method

1. Introduction

Minimizing switching losses remains a significant challenge for power devices. The standard method for measuring switching parameters and evaluating the dynamic behavior of Si, SiC, and GaN MOSFETs and IGBTs is the Double Pulse Test (DPT) [1]. DPT helps determine switching times, switching losses, and ensures proper switching behavior. Figure 1 shows a typical circuit diagram for the DPT. The device under test (DUT) consists of two devices: the lower IGBT and the upper Diode. Inductor load L is used to replicate real circuit conditions. Leakage inductance Lσ and stray capacity Cσ are also included in the circuit. Figure 2 represents the standards to measure switching time and switching loss for an IGBT. Further information can be found in the datasheet of a power device.

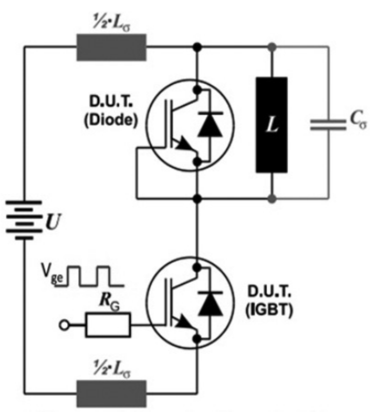

Figure 1. Dynamic test circuit [2].

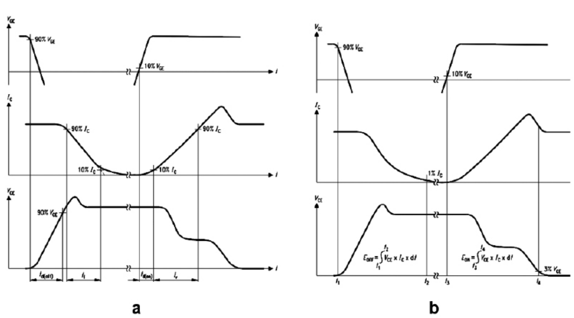

Figure 2 Definition of switching characteristics: a. switcing time; b. switching loss [1].

This article introduces a DPT-based simulation method to perform the transient switching characteristics of an IGBT device. It also provides standard templates for power device switching characteristics and performance assessment using Silvaco TCAD simulation tools. The deck used for this article can be found in Silicon_Power_ex17 of the 2024 Baseline.

2. Simulation Setup and Results

The simulation flow is performed by Victory DoE, a UI-driven software solution to automate TCAD simulation projects, run experiments, and perform data analysis. The process starts with Victory Process, which simulates the process steps required for a trench-gate field-stop-based IGBT device. The generated structure is then imported into Victory Mesh, which rebuilds the mesh using a Delaunay meshing scheme. The switching characteristics of the device is performed using Victory Device. Key parameters from the simulation results are extracted using the Extraction module. For each tool used in the flow, the associated input parameters and the extracted parameters are presented in Victory DoE.

2.1 Victory Process

In this step, the process simulation of the TG-FS-IGBT is performed. Various process modules are integrated into one flow. Figure 3 shows the final structure of the IGBT process simulation. A typical set of major design rules are assumed: a cell pitch of 3µm, a substrate thickness of 100µm, a trench gate depth of 6µm, and a gate oxide thickness of 100nm.

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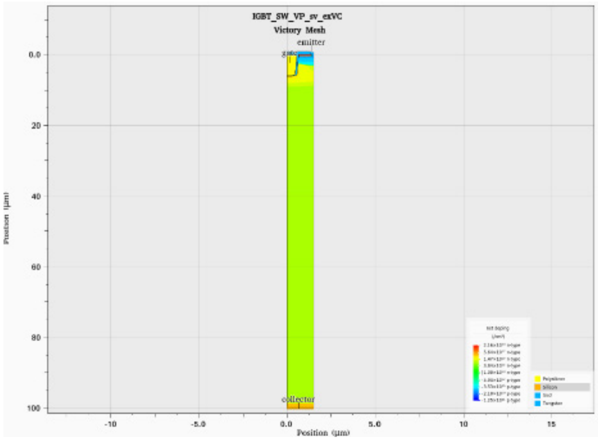
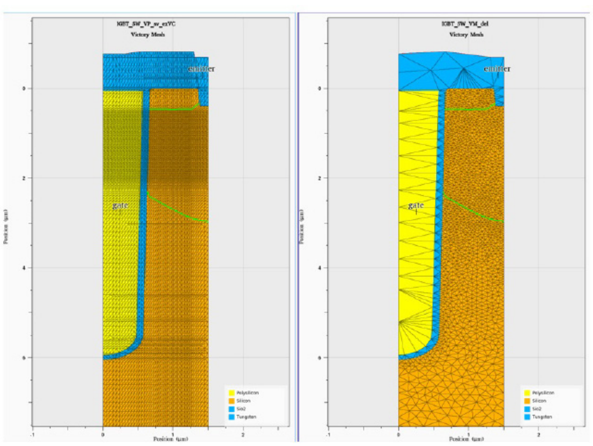


Figure 3. Final structure of the process simulation.

2.2 Victory Mesh

Victory Mesh is used to build the device simulation mesh on the structure. There are two meshing schemes: conformal mesh and Delaunay mesh, as shown in Figure 4. The Delaunay meshing scheme is highly flexible, giving the user near-unlimited control over how their mesh is built [3]. In this project, the Delaunay mesh is built for device simulation due to fewer mesh nodes (3598) compared with the conformal mesh (12441).



a b

Figure 4. Remeshed structure: a. conformal mesh; b. Delaunay mesh.

2.3 Victory Device

The dashboard for the dual pulse switching simulation is shown in Figure 5. Several parameters can be set in Victory DoE for transient mixed-mode simulation:

DC link voltage (vc)
Load inductance (lc)
Stray inductance (ls)
Gate resistance (rg)
Gate pulse maximum value (vg)
Turn-on and turn-off time (ton and tof)
Gate voltage rise time and fall time (trg and tfg)

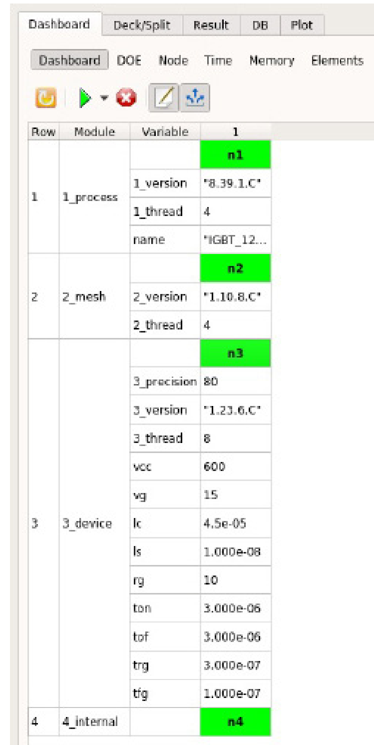


Figure 5. Dashboard for switching simulation

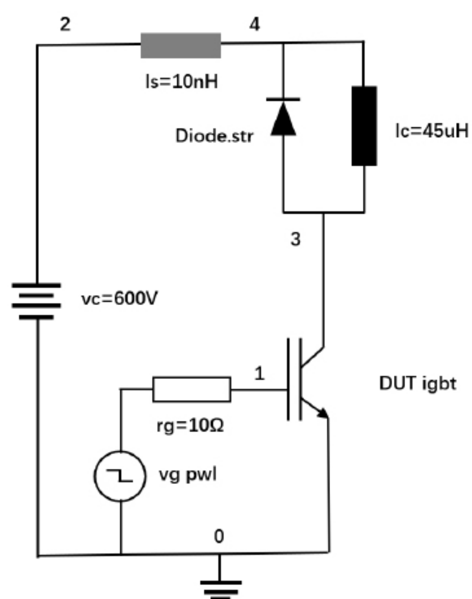


Figure 6. Switching measurement circuit

Figure 6 shows the switching measurement circuit used to simulate the switching behavior of the IGBT. A constant voltage power supply of 600V is applied between the collector and emitter, and a pulse of 15V is applied to the gate with 3µs turn-on and turn-off switching times. The inductor load is 45µH. The diode, derived from an external structure file, is connected to a stray inductor of 10nH and in parallel with a load inductor of 45µH.

To simulate the switching behavior, Victory Device takes the following physical models into account: (1) low-field mobility dependent on doping and temperature; (2) parallel-electric-field dependent mobility (velocity saturation); (3) Shockley-Read-Hall and Auger recombination; (4) impact ionization; and (5) band gap narrowing effects.

Figure 7(a) shows the simulated switching waveforms based on the dual pulse test. Figures 7(b) and 7(c) show the simulated turn-off and turn-on waveforms of the switching system, respectively. In the figures, the V[collector] is scaled down by a factor of 15 to match the V[gate] curve in the waveforms.

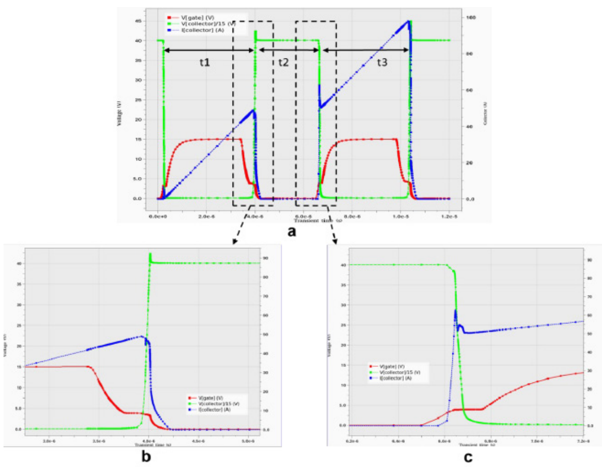


Figure 7. a. simulated switching waveforms; b. simulated turn-off waveforms; c. simulated turn-on waveforms.

The simulated switching waveforms consist of three phases as seen in Figure 7. The phases are as follows[4].

1. First pulse with duration t1
2. Pulse break with duration t2
3. Second pulse with duration t3

During the first pulse (duration t1), the DUT (IGBT) is turned on and a closed-loop circuit consisting of a voltage source (vc), a load inductance (lc), and the DUT (IGBT) is formed. The pulse length should ensure that the required current (DC collector current) is reached. The duration of the first pulse is defined by:

$$Vc = lc \cdot di/dt$$

where Vc is the voltage source, lc is the load inductance, ic is the desired test current, and t is the duration of the first pulse.

The pulse break t2 turns off the DUT and forms the current flows through the freewheeling diode. At the beginning of the pulse break t2, the Vce peak is caused by stray inductance and can be calculated by:

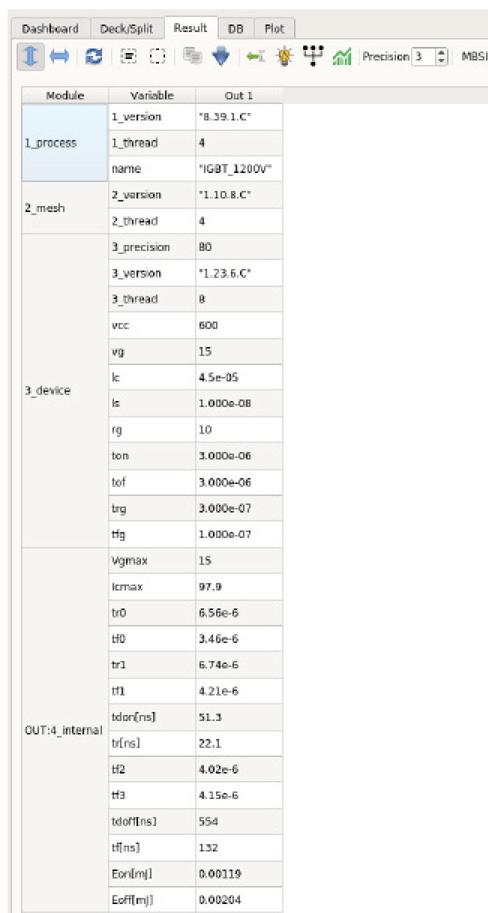
$$Us = ls \cdot di/dt$$

where Us is the peak voltage of the collector, ls is the stray inductance, and di/dt is the collector current slope during the rise of the collector peak voltage. The length of the pulse break should ensure that the DUT is completely turned off before the second pulse.

During the second pulse t3, the DUT is turned on again. The voltage drops, and the current continues to rise. The peak overshoot in the current observed in Figure 3(c) is caused by the reverse recovery of the freewheeling diode. Thus, the turn-on loss should be calculated during the second pulse to account for the additional current of the freewheeling diode. The duration of the second pulse can be equal to the duration of the first pulse and ensure that the current through the DUT does not reach an impermissibly high value.

2.4 Extraction

Switching parameters of the IGBT waveforms shown in Figure 8 are extracted by Victory DoE according to the definition summarized in Figure 2. The turn-on parameters and the turn-off parameters are extracted from Figures 7(c) and 7(b), respectively. The extraction methodology for all switching parameters is implemented in the deck, and the parameters are extracted automatically after the switching simulation is finished.



Module	Variable	Out 1
1_process	1_version	"8.39.1.C"
	1_thread	4
	name	"IGBT_1200V"
2_mesh	2_version	"1.10.8.C"
	2_thread	4
3_device	3_precision	80
	3_version	"1.23.6.C"
	3_thread	8
	vcc	600
	vg	15
	lc	4.5e-05
	ls	1.000e-08
	rg	10
	ton	3.000e-06
	tof	3.000e-06
	trg	3.000e-07
	tfg	1.000e-07
OUT:4_internal	Vgmax	15
	Icmax	97.9
	tr0	6.56e-6
	tf0	3.46e-6
	tr1	6.74e-6
	tf1	4.21e-6
	tdon[ns]	51.3
	tr[ns]	22.1
	tf2	4.02e-6
	tf3	4.15e-6
	tdoff[ns]	554
	tf[ns]	132
	Eon[mJ]	0.00119
	Eoff[mJ]	0.00204

Figure 8. Extracted switching parameters

3. Conclusion

In this article, IGBT switching simulation based on the double-pulse method is carried out. In particular, the setup and process of the double-pulse simulation are discussed in the Victory Device section. Agreement with experimental data demonstrates that Silvaco TCAD software can be used to model the switching behavior of power devices and help customers design and improve device switching performance effectively.

Reference

[1] Tektronix application note. Double Pulse Testing for Power Semiconductor Devices with an Oscilloscope and Arbitrary Function Generator.

[2] Infineon application note. IGW60T120. Low Loss IGBT in TrenchStop and Fieldstop technology.

[3] Simulation Standard. Volume 30, Number 1, January, February, March 2020. The Victory TCAD Suite: From process simulation and emulation to re-meshing, to electrical and Mixed Mode simulation.

[4] Jens Schweickhardt. ROHDE & SCHWARZ application note. TIPS & TRICKS ON DOUBLE PULSE TESTING.