International Journal of Hybrid Information Technology
Vol.9, No.1 (2016), pp. 141-152
http://dx.doi.org/10.14257/ijhit.2016.9.1.13

Modeling of the New Transient Behavioral Spice Model of IGBTs Including Temperature Effect

Messaadi Lotfi[1] and Dibi Zohir[1]

[1]Department of Electronics, Advanced Electronic Laboratory (LEA), Batna University, Avenue Mohamed El-hadi Boukhlouf, 05000, Batna, Algeria
lotfi.messaadi@gmail.com,zohirdibi@yahoo.fr

Abstract

This paper presents an Analog behavioral model (ABM) of the Insulated Gate Bipolar Transistor (IGBT) with Orcad Pspice 16.5. The Spice model was built using device parameters extracted through experiment. A full study of switching behavior of IGBT during turn-off and turn-on for inductive load with freewheeling diode is presented and simulated. All simulation results presented in this paper are validated, compared and showed good agreement with the measured data. The temperature dependent behavior is simulated and analyzed.

Keywords: *IGBT, Behavioral modeling, Switching losses, Transient characteristics, Modeling and Simulation, Pspice, Power Electronics, Temperature effect*

1. Introduction

Power electronics is the technology of converting electric power from one form to another using electronic power device. It has undergone intensive developments in recent years with the advances and innovations in power semiconductor devices, power conversion techniques, microprocessors, DSP, application specific ICs, personal computers, CAD tools, control and estimation techniques [1].

The key element in a power conversion system is the power semiconductor device that operates as power switch. By some estimates, more than 60% of all the power utilized in U.S. A flows through at least one power device and more often through multiple devices [2]. The improvement in power semiconductor devices is the driving force behind the improved performance, efficiency, size and weight of power conversion systems. The requirement for ideal power semiconductor device is the ability to control the power flow to the load with zero power dissipation. In the conducting mode, the device should have infinite current conduction capacity, while in the blocking mode, it should have infinite blocking voltage capacity. Furthermore the switching speed between the different modes should be very fast.

Commercially available since 1988, the Insulated Gate Bipolar Transistors (IGBT's) are widely used in today's power conversion systems for high switching frequency and medium power ranges. The IGBTs combine the advantage of the high current density in bipolar operation with the advantage of the fast switching and low drive power of MOS gated devices. Other advantages include low steady-state losses, very low switching losses, high short-circuit capability and easy to make parallel connection.

2. Self-Heating in IGBT Transistor

We know that the parameters of a semiconductor are temperature dependent. Specifically, for power semiconductor devices, with its high ambient temperature application environment and high power rating, the temperature dependence is even more critical. Generally, the power devices' properties and performance in circuits will degrade

ISSN: 1738-9968 IJHIT

with increased temperatures. This can be attributed to the reduction of the carrier mobility with increased temperature according to the following relation.

In order to avoid destruction and permanent damage of the device, the junction temperature Tj must be kept under a safe operating value T_{jmax} that is normally specified by the manufacturer. For a silicon device, the temperature rating is usually 150 °C and can be as high as 600 °C for silicon carbide which has higher temperature capacity [6]. Keeping the junction temperature in the safe operating range is not enough for the devices long-term reliability. Due to loading in the circuit, power losses vary and the temperatures of the power devices fluctuate while operating. This fluctuation causes mechanical stress due to the different thermal expansion coefficients of the layers inside a device. The stress affects the solder and wire bond connections.

Thermal analysis is therefore a fundamental issue in the design of power conversion systems. It provides us with information that can be used for the analysis of the device long-term reliability, maximum ratings characterization, package design optimization, correct choice of heatsink [9]. So through self-heating effect, there is a connection between the electrical and thermal performances of the semiconductor device as shown in Figure 1 [10]. The voltage across the device U_{CE} and the current through the device I_E will determine the power dissipated. This in turn will generate heat and thus changes the junction temperature of the device. This new junction temperature will affect the parameters U_{CE} and I_E for they are temperature-dependent.

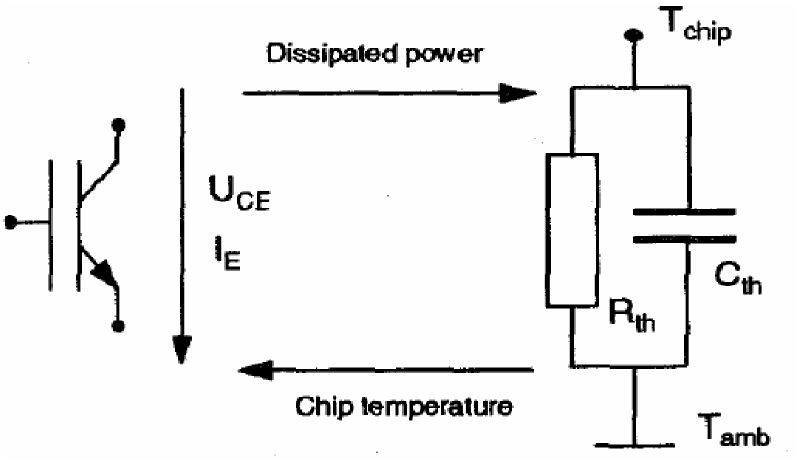

Figure 1. Coupling between Thermal and Electrical Model of a Power Device

An electro-thermal analysis, which accounts for the coupling, will provide more realistic and accurate information for a device in operation. For some applications, only an electrothermal model can give reasonable results. An example is the case for predicting the output characteristics of a semiconductor device under short-circuit condition [3].

3. IGBT Structure

Figure 2.1 shows a cross section schematic of a typical IGBT. Figure 2.2 shows the discrete equivalent circuit model of the device, which consists of a wide base P-N-P bipolar transistor (BJT) in cascade with a MOSFET. The structure of the device is similar to that of a vertical double diffused MOSFET with the exception that a highly doped p-type substrate is used in lieu of a highly doped type drain contact in the vertical double diffused MOSFET. A lightly doped thick n-type epitaxial layer ($N \approx 10^{14}$ cm^{-3} B) is grown on top of the p-type substrate to support the high blocking voltage in the reverse bias mode state. A highly doped p-type region ($N \approx 10^{19}$ cm^{-3} A) is added to the structure to prevent the activation of the PNPN thyristor during the device operation. The power

MOSFET is a voltage-controlled device that can be manipulated with a small input gate current flow during the switching transient. This makes its gate control circuit simple and easy to use.

A highly doped n+ buffer layer could also be added on top of the highly doped p + substrate. This layer helps in reducing the turn-Off time of the IGBT during the transient operation. The IGBT with a buffer layer is called a punch through PT IGBT while the IGBT without a buffer layer is named a non-punch through NPT IGBT.

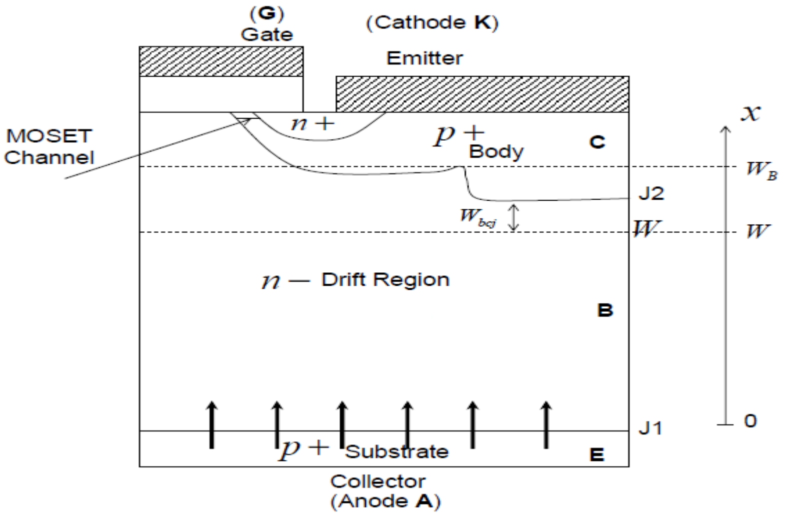

Figure 2.1. Cross Section Schematic of the IGBT Half-cell

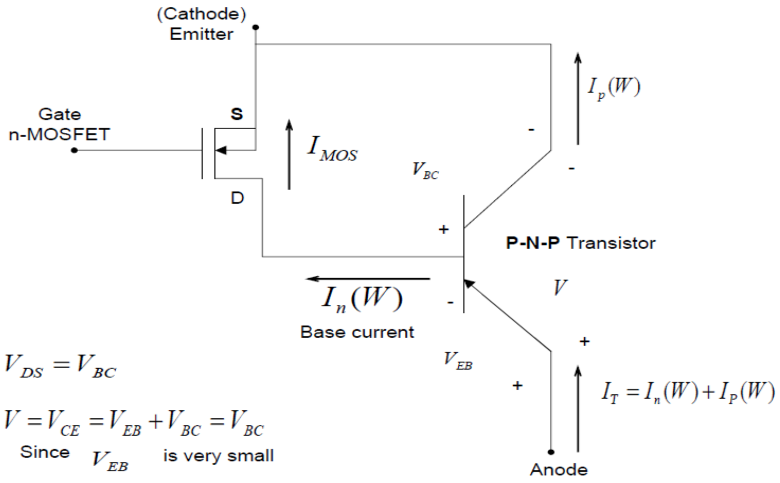

Figure 2.2. Equivalent Circuit Model of the IGBT

3.1 Physics of IGBT

From the cross-section of the IGBT (Figure 2.1), we can see that the IGBT is a four-layer power semiconductor device having a MOS gate.

When a negative voltage is applied to the collector with respect to the emitter, there will be no current flow through the device for the lower junction (J1) is reverse biased. This provides the reverse blocking capacity of the IGBT.

When the gate is attached to the emitter (V_{GE}= 0 volt), and a positive voltage is applied to the collector with respect to the emitter (the same voltage as gate), the upper junction (J2) is reverse biased and the device operates in the forward blocking mode.

If a positive voltage higher than the threshold voltage is now applied between the gate and the emitter (V_{GE}> Vth), the surface of the P base region is inverted and an N channel will appear. The electrons will then flow from the N+ emitter to the N drift region forming the base current for the vertical P-N-P transistor of the IGBT. An increase in the positive voltage between the collector and emitter leads to an increase in the injected holes concentration until it exceeds the background doping level of the N drift region. In this region of operation, the device behaves like a P-I-N device and this explains the IGBT's ability to handle high current densities. If we further increase the voltage between the collector and the emitter, the N-channel will get pinched-off. The base current for the P-N-P transistor will be limited and so will the hole current through the path. The collector to emitter current reaches the saturation point and the IGBT operates in the active region. The output characteristics of the IGBT are similar to that of the MOS and the output current is controlled by the gate voltage V_{GE}. The I-V characteristics of IGBT are shown in Figure 2.2. From the above, one concludes that IGBT integrates the physics of MOS and bipolar junction transistors. The P-I-N behavior of the BJT part provides high forward conduction density, and the MOS gate structure determines the low drive power and fully gate-controlled output characteristics.

a. Switching characteristics

3.2.1 Turn-On

The turn-on switching characteristics for an IGBT transistor are similar to that of a MOSFET. The whole process is indicated in the Figure3.1.

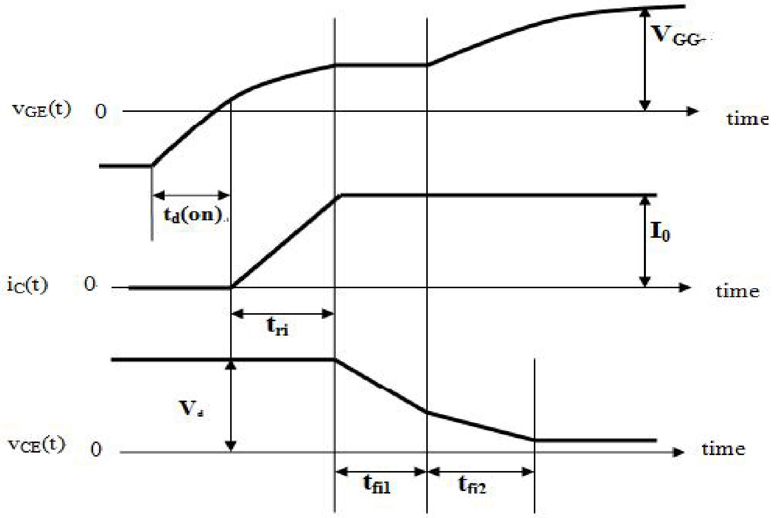

Figure 3.1. IGBT Turn-on Switching Characteristics [3]

As shown in the Figure 3.1, during the delay time t_d(on) the gate-emitter voltage increases to the threshold voltage $V_{GE(th)}$ of the device. This is caused by the gate resistance R_g and the input capacitances (C_{GC} and C_{GE}). But the miller effect capacitance, C_{GC} is very small that its affect can be neglected. Beyond this time the collector current starts to increase linearly until it reaches to the full load current. During the time when $i_C=I_0$ the voltage V_{GE} is first kept constant and at this moment the collector current flows through C_{GC} only, that causes that the voltage V_{CE} decreases to the zero on-state. After this moment the voltage V_{GE} starts to increase until it reaches to V_{GG} [6].

Turn-on switching losses: Turn-on switching losses are the amount of total energy losses during turn on under inductive load. It is normally measured from the point where the collector current starts to flow to the point where the collector-emitter voltage drops completely to zero. The turn on energy losses calculation is given by the equation below.

3.2.2 Turn-Off

The whole turn-off process is indicated in the Figure 3.2.

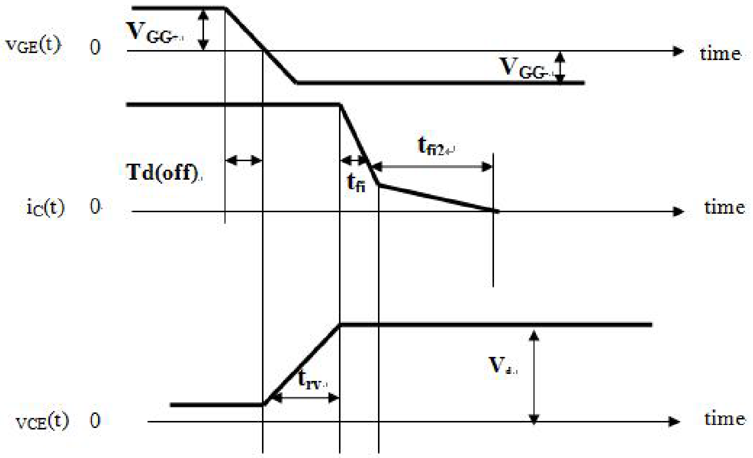

Figure 3.2. IGBT Turn-off Switching Characteristics [3]

The transistor is turned off by removing the gate voltage, V_{GE}. As shown in the figure, both the voltage V_{CE} (t) and the current $i_C(t)$ are kept constant until the gate voltage reaches the voltage V_{GE}(Ion) which is used to keep the current $i_C(t)$ in steady on state. This moment is called the delay off time. After this the collector voltage V_{CE} starts to increase. The rate of rise for the collector voltage is determined by the gate resistance. When the collector voltage reaches the input voltage the collector current starts to decrease and the free-wheeling diode starts to conduct.

The major difference between the IGBT turn-off and the MOSFET turn-off is observed in the collector current waveform where there are two distinct time intervals. The rapid drop that occurs during the t_{fi1} interval corresponds to the turn-off of the MOSFET section of the IGBT. The 'tailing' of the collector current during the second interval t_{fi2} is due to the stored charge in the n-drift region.

Turn-off switching losses: Turn-off switching are the amount of total energy losses during the turn off under inductive load. It is measured from the point where the collector-emitter voltage begins to rise to the point where the collector current falls completely to zero. The turn off energy losses calculation is given by the equation below.

4. Results and Discussion

In this section we obtained experimental results and the energy losses calculated from them are presented. Factors which affect the switching losses including: turn-on and turn-off transient times, voltage and current levels, gate resistances and temperatures are investigated. All the data both measured and simulated are from Figure 4.1 and 4.2, due to the range of measurement equipments. To measure the transient characteristics of the IGBT while conducting currents of some Amperes, we built the circuit from Figure 4.1.

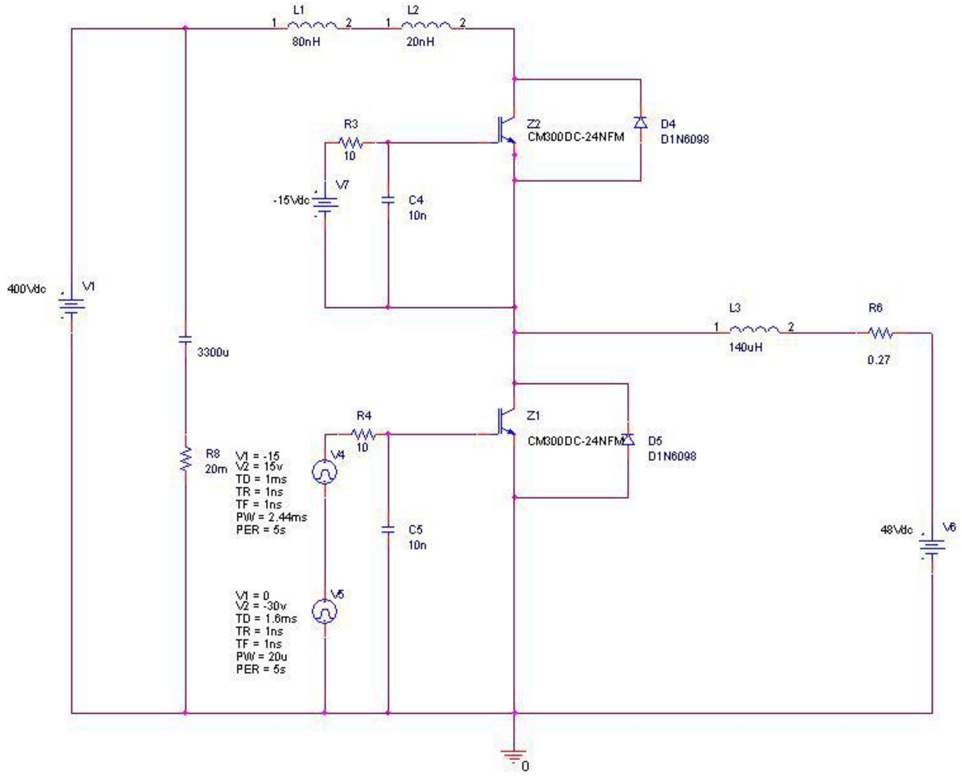

Figure 4.1. Circuit Simulation of IGBT [8]

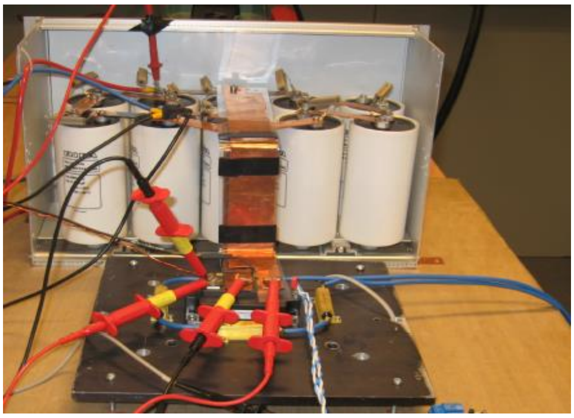

Figure 4.2. Experiment Set Up Design for IGBT [7]

5. IGBT Control Circuit Design

The digital control circuit in this paper is represented in Figure 5.

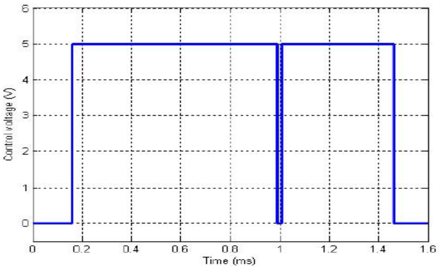

Figure 5.1. Control Waveform

5.1 Turn on

a. IGBT

It can be seen from Figure 5.2 and 5.3 that the simulated turn-on transient of the IGBT is consistent with the measured one. However, the measured turn-on durations for 36V V_{CC} (Figure 4.1) are much longer compared with the 400V ones from Figure 5.3. This is because of the V_{CE}-tail characteristics of the IGBT modules. This voltage tail effect decreases with the increasing of the V_{CE}. A slow discharging of C_{GC} (gate collector capacitance) causes the long V_{CE}-tail.

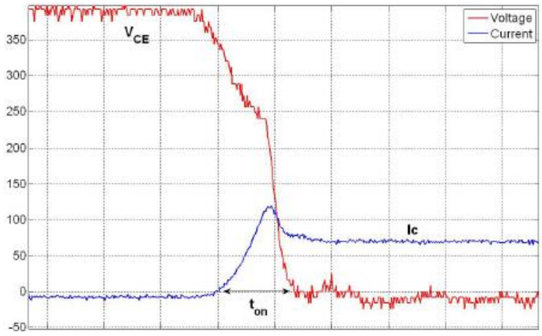

Figure 5.3. Measured Turn-on Transient, 0.2μs/div

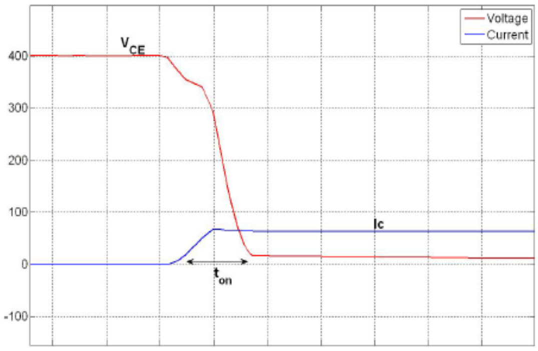

Figure 5.2. Simulated Turn-on Transient, 0.2μs/div

a. Free-Wheeling Diode

At the moment of the IGBT turn-on, the free-wheeling diode in the other IGBT stops conducting, as shown in Figure 5.5 and 5.6. There are no reverse recovery characteristics in the simulated turn-off transient of the free-wheeling diode; this is due to that the free-wheeling diode is not integrated into the IGBT module in the Pspice. The separate Schottky diode, which is used in the simulation, is not the same model as the one in the hardware.

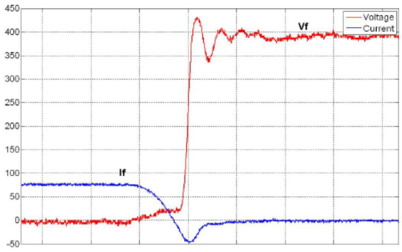

Figure 5.5. Measured Diode Voltage and Current, 0.2μs/div

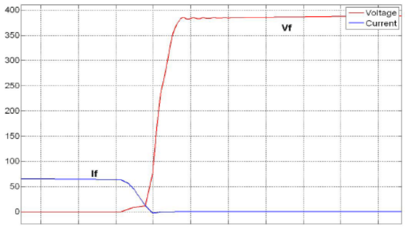

Figure 5.6. Simulated Diode Voltage and Current, 0.2μs/div

5.2 Turn off

b. IGBT

The simulated and the measured collector-emitter voltage V_{CE} oscillate at the turn-off duration, as shown in Figure 5.7 and 5.8. This can be caused by the reverse recovery characteristics of the free-wheeling diode in the other IGBT. The difference of the free-wheeling diode in the simulation and hardware setup make the oscillation frequency inconsistent. The voltage spike in the simulation is not coinciding with the one in the hardware measurement; the reason is that the values of the stray inductances in the simulation and the hardware are not exactly the same.

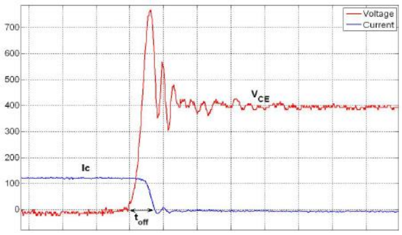

Figure 5.7. Measured Turn-off Transient, 0.2μs/div

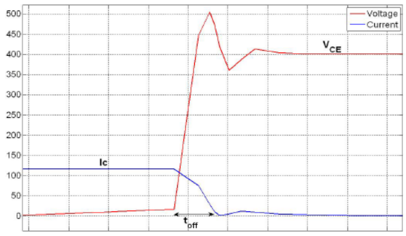

Figure 5.8. Simulated Turn-off Transient, 0.2μs/div

c. Free-wheeling diode

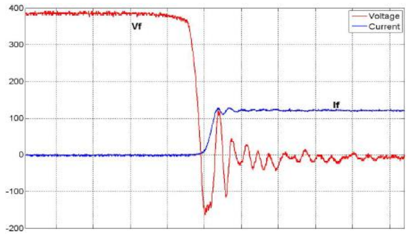

Figure 5.10. Measured Diode Voltage and Current, 0.2μs/div

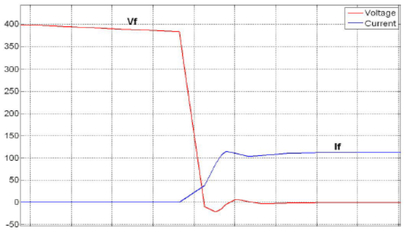

Figure 5.9. Simulated Diode Voltage and Current, 0.2μs/div

From Figure 5.10, it can be seen that there are almost no losses during the diode turn on. According to this, only the free-wheeling diode reverse recovery losses are investigated in the following analysis.

6. Effect of Gate Resistance

A small gate resistance charges and discharges the IGBT input capacitance faster which reduces the switching times and switching losses and improves immunity to dv/dt during turn-on. However, a small gate resistance can lead to oscillations between the IGBT input capacitance and the parasitic lead inductance.

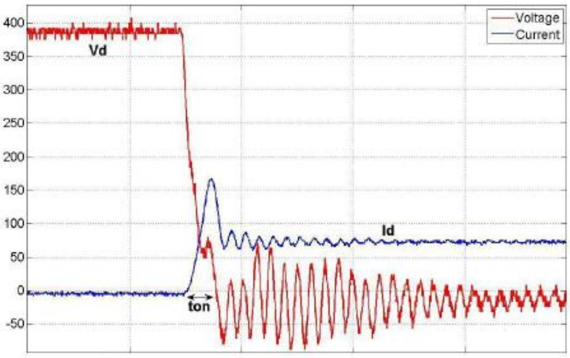

Figure 6. Measured Turn-on Transient, Rg=40, 0.5μs/div

7. Effect of Temperature

From Figure 7.1 and 7.2, it can be seen that both the turn-on and turn-off losses are constant with the temperature changes. That is because for this non-punch through IGBT, the turn-off duration remains constant in its working temperature range. For the free-wheeling diode, however, the reverse recovery losses, shown in Figure 7.3, increase with the temperature. That is due to the reverse recovery current which will increase with the temperature.

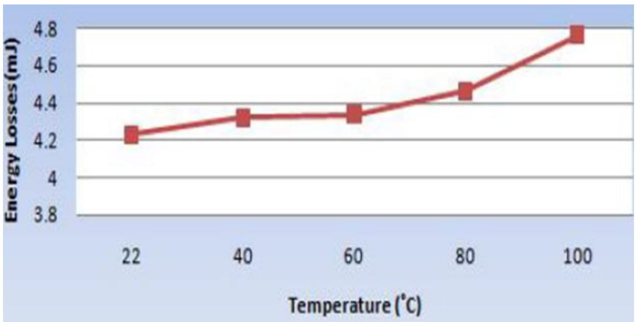

Figure 7.1. Turn-On Losses for Different Temperatures

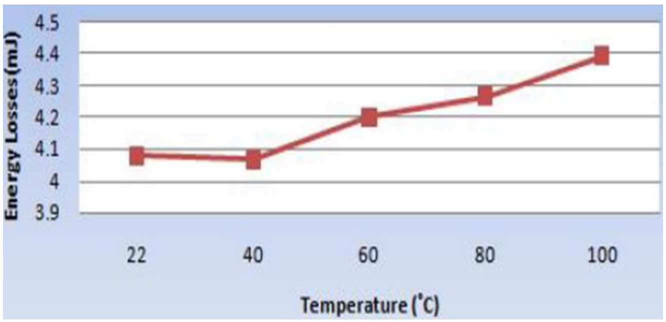

Figure 7.2. Turn-Off Losses for Different Temperatures

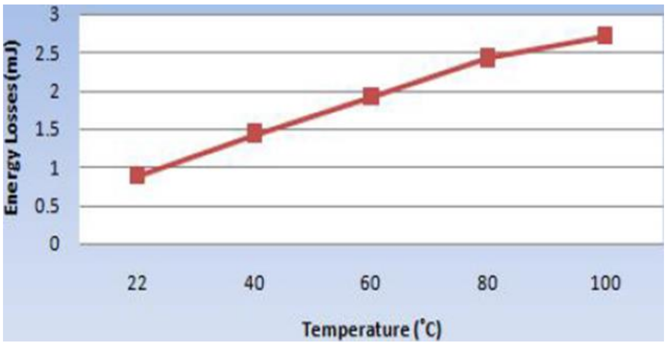

Figure 7.3. Free-wheeling Diode Reverse Recovery Losses

8. Conclusion

An IGBT Spice behavioral Model is designed and simulated to investigate the switching characteristics and losses of a new IGBT module. The switching characteristics and switching losses are explored under different parameters both in the hardware and simulation. It can be seen that the switching losses both for the IGBT and the free-wheeling diode are increasing with the voltage and current levels. The gate resistance also affects the losses greatly: the IGBT switching losses increase with the increase of the gate resistance; on the other hand, the reverse recovery losses decrease with the gate resistance. In addition, the switching losses of this new IGBT module is not affected so apparently by the temperature variation, however, the reverse recovery losses increase significantly with the temperature. The stray inductance affects the switching characteristics remarkably, so it should be as low as possible. Finally we can see that all simulation results presented in this paper are validated, compared and showed good agreement with the measured data.

References

[1] L. Benbahouche, *et al.,* “New numerical power IGBT model and simulation of its electrical characteristics”, IEEE Conference, ISBN: 0-7803-726-X, Smolenice Castle Slovakia, **(2002)**, pp. 211-214.

[2] “Mitsubishi Electric, “Mitsubishi semiconductors power modules MOSFET introduction”, **(1998)**.

[3] U. Mohan and Robbins, “Power Electronics Converters, Applications and Design”, Wiley, **(2003)**.

[4] F. Mihalich, et al., “IGBT SPICE model” IEEE Transactions on Industrial Electronics, vol. 42, no. 1, **(1995)** February, pp. 98-105.

[5] B. Baliga, “Fundamentals of Power Semiconductor Devices”, Springer, **(2008)**.

[6] D. W. Berning and A. R. Hefner, “IGBT model validation for soft-switching applications”, Industry Applications, IEEE Transactions on, vol. 37, **(2001)** April, pp. 650 -660.

[7] T. Grigorova and K. Asparuhova, “An Improved IGBT Behavioral PSpice Macromodel” ICEST’2007, Bitola, vol. 2, **(2007)**, pp. 785-788, Macedonia.

[8] A. R. Hefner, “An improved understanding for the transient operation of the power insulated gate bipolar transistor (IGBT)”, Power Electronics, IEEE Transactions on, vol. 5, **(1990)** October, pp. 459 - 468.

[9] B. J. Baliga, “The Insulated Gate Transistor - A New Switching Power Device”, IEEE Ind. Appl. Soc. Meet., **(1983)**, pp. 794 - 803.

[10] H. S. Oh and M. El Nokali, “A new IGBT behavioral model” Solid State Electron., vol. 45, **(2001)** November, pp. 2069–2075.

[11] W. Kang, *et al.*, “A Parameter Extraction Algorithm for an IGBT Behavioral Mode”, IEEE Transactions on Power Electronics, vol. 19, no. 6, **(2004)** November.

[12] U. Drofenik and J. W. Kolar, “A General Scheme for Calculating Switching and Conduction-Losses of Power Semiconductors in Numerical Circuit Simulations of Power Electronic Systems”, Proc. of the 5th International Power Electronics Conference (IPEC), Niigata, Japan, **(2005)** April 4–8.

[13] P. Antognetti and G. Massobrio, “Semiconductor Device Modeling with SPICE”, New York, McGraw-Hill Book Company, **(1988)**.

[14] S. M. Sze, “Semiconductor Devices, Physics and Technology”, New York, Wiley & Sons, **(1985)**.

[15] K. Asparuhova and T. Grigorova, “IGBT High Accuracy Behavioral Macromodel”, 26th Int. Conference on Microelectronics, MIEL 2008, Nis, Serbia, vol. 1, **(2008)** May, pp. 185-188, ISBN 987-1-4244-1881-7.