IGBT Failure mechanism and boundary analysis under large current and high temperature turn-off

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Abstract. Considering overload working conditions in electromagnetic emission, the paper presents a simulation of IGBT turn-off under large current and high temperature. Numerous simulation result is received under a specific test circuit. Boundary conditions for temperature, current and starry inductance are obtained under a set of temperature criterion. Further analysis proves that after temperature reaches the criterion, high current density path swiftly extends from local area to a vertical current path throughout the cells. This method for IGBT theoretical boundary is useful for similar projects or working conditions.

1. Introduction

The Trench Insulated Gate Bipolar Transistor (TIGBT) is widely used in power electronic circuits for its high power-density, fast switching speed and low conduction loss. Usually, the device is strictly limited by its SOA (Safe Operation Area). However, in some projects like electromagnetic launch system (EMALS) and high-speed railways, IGBT is evitable to operate under large current and high temperature mainly because of aperiodic and transient overload conditions and strict volume limits. It’s important to understand the device failure mechanism under the overcurrent and high temperature conditions.

According to the previous study, the IGBT failure mechanism can be categorized as overvoltage failure, overcurrent failure, thermal failure and others. High inductive loads or starry inductance will induce peak voltage during the turn-off process. The breaking down voltage depends on cell structures and doping designs. Latter two kinds of failure mechanisms are more common in the EMALS. Usually, factors like inductance, packages, peak current, gate waveform can all be the potential reasons.

Nevertheless, temperature can be a main factor in the failure process the device will finally turn down under by localized breakdown or melting[1].Local high temperature is more likely to exceeds instinct temperature and IGBT will failed because of thermal breakdown. Local electro-thermal feedback between current and temperature increase produces a stable current filamentation due to the injection of the N–N+ junction ,as reported in[2]. However, the failure process is still unclear.

For engineering practice, when IGBT turns off under overcurrent conditions (over than twice the rated current) or in a large junction temperature (larger than max temperature 150℃) the junction temperature has a 700K instinct temperature limits. However, the boundary is an experimental value for all kinds of IGBT and it’s difficult to measure the real junction temperature from the experiment, which makes it difficult to consider design margin for these overload conditions. So, it’s essential to find a new way to establish current and temperature boundary.
The aim of this work is to find the failure mechanism and the theoretical boundary for turning off under overcurrent and high temperature conditions. In this work, a 1.7kV/3.6KA Trench-IGBT has been inverted by TCAD to simulate the turning off transient process. The simulation result can be effective reference for engineering design under overcurrent conditions and high temperature conditions.

2. Device description and parameters verification

The cross section of 1700-V/3600-A trench gate IGBT is shown in Figure 1 and the main parameter is described in Table I.

| Main parameters     | value       |
|---------------------|-------------|
| N-drift thickness, um | 175         |
| Cell pitch, um      | 27          |
| Trench-gate depth, um | 4.5        |
| p-body doping concentration, cm^{-3} | 2.45*10^{17} |
| N-drift doping concentration, cm^{-3} | 7*10^{13} |

In this section, a half-cell IGBT structure is shown in Figure 1. A short Dummy-cell structure is used in the emitter side. The including emitter is shorted to the 4 Dummy cells and they are laterally insulated by floating p region. Virtual gate in the right part is the gate without n-source doping nearby. The structure can adjust the capacitance ability as well as improve the short-circuit ability. [3]

Figure 1. half-cell structure for IGBT device

The physical input parameters for the simulations have been adjusted to match the realistic static characteristics in Figure 2. The breakdown voltage is approximately 1900V in (a) under thermal dynamic mode with initial temperature 125°C and Vg=0V. The Ic-Vce curve is shown in (b).

Figure 2 the breakdown curve and Ic-Vce curve for device simulation
The gate voltage is set as 15V. The simulation results are basically constant with datasheet value for Infineon FZ3600R17HE4.

3. IGBT overcurrent and high temperature boundary conditions

3.1. Theoretical analysis

In the previous works and experiments, UIS (unclamped inductive switching) conditions is widely discussed and performed. The failure mode is simply divided into energy limitation and current limitation. For the former kind, it can be expressed as equation (1):

$$E_{c\alpha} = \alpha \cdot I_{\text{peak}} \cdot (B V - V_{\text{dc}}) \cdot T_{\text{off}}$$  \hspace{1cm} (1)

Where $\alpha$, $I_{\text{peak}}$, $T_{\text{off}}$ are the proportionality constant, max switching current and turn off time. $B V$ is breakdown voltage. when $E > E_{c\alpha}$, the temperature exceeds the critical value and leads to the device failure. Another way that leads to failure is the latch-up process caused by large current. [4] The parasitic thyristor is conducted because of the build-in potential $V_{\text{bi}}$, shown in equation (2)

$$I_{\text{crit}} = \frac{V_{\text{bi}}}{R_{\text{body}}}$$  \hspace{1cm} (2)

$R_{\text{body}}$ is the emitter-to-body resistance, $V_{\text{bi}}$ is about 0.7V, and $I_{\text{crit}}$ is the critical current. However, the $R_{\text{body}}$ is optimized to a small value and the latch-up current is too large compared with experiment results.

Simulations by TCAD have proven that during turn-off process, current filaments contribute to the catastrophic failure. In [5], inhomogeneous carrier density before the onset of dynamic avalanche results in the filament formation. The dynamic avalanche leads to the increase of peak electric field as well as the max temperature. With the temperature or current increasing, there is an increase of the impact ionization rate leading to an elevation of temperature, but no failure occurs, the device is in “non-destructive failure”. For further increasing of these conditions, the device failed destructively by a thermal runaway mechanism and local area can exceed 750K. [6, 7]

Instinct temperature plays an important role in the process from “non-destructive failure” to “thermal runaway”. $T_{\text{int}}$ is strongly decided by the free carriers, so the $T_{\text{int}}$ differs widely in various devices. In the previous work, the instinct temperature is set at 700K or 850K for silicon and SiC MOSFET which is an experimental value [8]. For modern IGBT under thermal equilibrium, initial temperature $T$ and the background doping concentration $n_i$ have a theoretic relationship shows as equation (3)

$$n_i = 3.87 \times 10^{16} T^{3/2} \exp \left( -7020 / T \right)$$  \hspace{1cm} (3)

When temperature exceeds $T_{\text{int}}$, heat generated carrier will cover the background carriers. Considering that the real carrier density is larger than the background carrier density in the static state, the typical temperature and carrier density distribution are shown in Figure 3.
So, there exist two carrier density in the p+ n junction: p+ side carrier density $N_{p+}$ and n side density $N_n$ with $N_n < N_{p+}$. When carrier density $n_i$ reaches $N_n = 3.5 \times 10^{14}$ (for average), temperature reaches $T_1 = 530K$, according to the equation (3). The device can still work because the p-n junction still has the concentration difference and the space charge region can still withstand voltage. When carrier density $n_i$ reaches $N_{p+} = 5 \times 10^{15}$, the temperature reaches $T_2 = 600K$, the p-n junction disappears, and the device cannot withstand the blocking voltage.

So, during the turn off, the max temperature can decide the failure as follows:

a) $T_{\text{max}} < T_1 = 530K$, the device safely turns off
b) $T_1 < T_{\text{max}} < T_2 = 600K$, the device is in a “non-failure mode”, the device does not necessarily fail. But it’s very dangerous.
c) $T_{\text{max}} > T_2$, the device is bound to fail and its catastrophic.

3.2. Test Circuit setting in TCAD

To test the current and temperature boundary, Dual-cell IGBT is connected to the circuit in Figure 4 by using Sentaurus Device. Other elements like diode or capacitance are default spice model to reduce calculating time. The circuit is shown in Figure 4. $L_s$ and $L_c$ is the starry inductance and load inductance. The thermal surface resistance for electrode is set as $5 \times 10^{-4} \text{cm}^2 \cdot \text{K/W}$. Unibo model is used to describe the avalanche behavior and self-heating has been considered.

![Figure 4 Test circuit for IGBT turn-off](image)

3.3. Current and starry inductance boundary conditions

Figure 5 shows the max current turn-off ability under different initial temperature and gate resistance. In the simulations, increasing the conducting time for IGBT to rise the max turn-off current until the max temperature reaches $T_2 = 530K$ and the max temperature is recorded. With the increasing of $R_g$ or initial temperature, the max current is decreasing. When initial temperature is higher than 500K, device will exceed $T_{\text{int}}$ in static states and the simulation does not converge.

![Figure 5 Current boundary in different initial temperature and gate resistance](image)
Starry inductance exists in connections like bond wires and bars, which will induce peak voltage and increase the loss. The influence of starry inductance is shown in Figure 6. Initial temperature and max turn-off current is set at 150°C and 11000A, respectively. From the temperature boundary conditions above, The IGBT will turn off safely with \( L_s = 10 \text{nH} \) while be in “non-failure mode” with \( L_s = 50 \text{nH} \). It also can be illustrated in fig b). The current density and the impact ionizations alone “c1-c2” (in Figure 3) are compared in figure b). Compared with 10nH starry inductance, 50nH starry inductance has a 3600A/cm² max current density and the electric field is higher and steeper, which leads to 10 times higher impact ionization.

Lower starry inductance can improve the \( \frac{dV_{ce}}{dt} \) performance and reduce the turn-off loss, when the starry inductance reduce from 50nH to 13nH, IGBT4 Highspeed switching loss can reduced by 40%.[9]

In the EMALS, IGBT chips have to endure repetitive stress and the fatigue damage is accelerated by larger junction fluctuation. Starry inductance and the package thermal resistance are increasing. Therefore, dynamic degeneration is also noteworthy in the establishment of theoretical boundary.[10]

4. Catastrophic Failure analysis

For further study on the transient process from non-failure mode to failure mode, a contrast test is set under different turn-off current, marked on the Figure 5. Simulations results are illustrated in Figure 7. In stage I, the igbt firstly turns on with max avalanche generation increasing and then turns down because of the current declining. In stage II, the starry inductance induces an over voltage and the curve climbs up to a peak value. The avalanche generation is limited by the negative temperature effect limits and other recombination effects. They are generally the same expect the absolute value.
However, in stage III (leakage current stage), the non-failure curve can turn off the gate in 2 us but the failure curve cannot turn off the gate, with a large leakage current and swiftly increased temperature. Later in t=94us, the voltage goes down abnormally like in short-circuit. The avalanche generation rebounds sharply at 103us which shows the avalanche is extrema severe and the result is destructive.

To analysis the failure process, the details at 2us and 4us after gate signal for success and failure curve is shown in Figure 8 and they are divided into 2 lines, respectively. The current density, lattice temperature and impact ionization distributions, (a) to (c) respectively. High current-density path spread in (a) from success to failure and the peak value increase from 4000 to 90000A/cm², which performs like a localized short-cut path forms through the device and the outer voltage decreases. That’s mainly because the silicon exceeds its instinct temperature and the silicon lose its semiconductor characterises. The breakdown voltage decreases, and the local silicon breaks down. Meanwhile, the impact ionizations multiplies by 10 times at the same DC voltage (fig(c)), which helps increases the carrier density and the turn off loss, and worse the turning off conditions.

![Figure 8 non-failure mode and failure mode contract](image)

Therefore, from non-failure mode to failure mode, the severe avalanche generation increase the local loss and induce a higher temperature in few microseconds. Max Temperature climbs up from T1 to T2. Then a thermal feedback set up and the device shows like in a short-circuit inevitably. The whole process for the failure can be illustrated in Figure 9. With the increase of $T_{\text{max}}$, IGBT gradually transforms from successful mode to failure turn-off mode.

![Figure 9 IGBT failure process under large current and high temperature conditions](image)
5 Conclusion
The application of IGBT modules used in electromagnetic emission will inevitably make the IGBT under electric and thermal pressure. The failure mechanism is explained as localized high temperature in the current filaments exceeding its instinct temperature. Severe avalanche generation promotes the max temperature and makes the current filaments wider. A distinct current path will finally form through the vertical structure and performs like short circuit. The process is short in few microseconds and the result is catastrophic. The boundary conditions for the IGBT working in overcurrent and high temperature conditions are obtained by a set of simulations, which provides some meaningful and valuable suggestions for the IGBT device selections and design margin.

Acknowledgments
This work was supported by the JCJQ Program (2020-JCJQ-ZD-105,2020-JCJQ-JJ-139).

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