Online IGBT Temperature Measurement via Leakage Current in HTRB Test

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Abstract. To evaluate the reliability of endure high voltage when IGBT is turned off and eliminate the defective devices, HTRB (High Temperature Reverse Bias) test is one of the necessary tests for IGBT before it’s produced. According to the IEC standard, DUTs (Device Under Test) are usually blocked, and bear forward bias voltage, which is preferably 80% of \( V_{CES\text{max}} \). During the HTRB test, DUT junction temperature should be set at maximum virtual junction temperature \( T_{vj(max)} \) which is usually between 125°C to 150°C. Due to high voltage, even though the leakage current is very low, high-power semiconductor devices generate dissipated power during HTRB test, which lead to junction temperature increase. And to access the reliability accurately, the rise of temperature cannot be neglected. To insure the test is carry out at standard temperature, this paper monitors DUTs junction temperature by using leakage current as a TSEP (Temperature Sensitive Electrical Parameter). The experiment proofs that higher the junction temperature is, the more accurate the measure results will be, in the operating temperature range. In this paper, thermal resistance measurement is used to evaluate the validity of this method.

1. Introduction
Insulated-Gate bipolar transistors (IGBTs) are widely used in power semiconductor, which serves on new energy vehicles, wind power generation, aerospace power supplies and high-speed railway. IGBTs are expensive and fragile transistors, the damage of one unit may destroy the whole system and cause huge economic losses. Thus, the reliability of IGBTs always draws wide attention from the field [1].

To prevent device failure amid operation, the same batch of production should be sampled for HTRB (High Temperature Reverse Bias) test. The major objective of the test is to check the device’s endurance of high voltage when it is turned off. HTRB test also helps to assess the reliability of device before the subject batch is put in use. HTRB test is a kind of aging test, one of the necessary tests for IGBT before it’s produced, which can eliminate the defective devices effectively. This assessment is mainly aimed at checking the reliability of endure high voltage between collector and emitter, which belongs to the comprehensive performance assessment of chip.

According to the IEC standard [2], during the HTRB test, DUTs junction temperature \( T_j \) should be set at maximum virtual junction temperature \( T_{vj(max)} \) which is usually between 125°C to 150°C. For high-power semiconductor devices, leakage current and high forward voltage will generate power...
consumption in HTRB test. The power consumption will cause junction temperature rise of devices. Junction temperature which exceeding the specified range would cause failure of normal IGBT and bring economic loss to the manufacturer. And if the temperature is too low, it neither can remove the defective device nor have an accurate assessment of the device reliability. According to the Arrhenius model, 10°C of temperature rise will lead to half lifetime expectancy reducing. Therefore, it is important to measure and control the DUT (Device Under Test) junction temperature in reliability test.

At present, most manufacturers control the junction temperature by calculating the thermal resistance, or measuring temperature via the thermocouple or NTC which is built-in DCB (Direct Copper Bonding). However, the thermal resistance, not always constant, changes with device temperature and degradation [3][4]. Furthermore, the thermal resistance test bench isn’t the same one that used in HTRB test, so the value of thermal resistance maybe difference. Moreover, because of the junction temperature rise, the DCB temperature measured by thermocouple or NTC is also different from the temperature of chip.

For these difficulties in temperature control in HTRB tests, this paper presents an IGBT junction temperature measurement via leakage current, which can be used as a TSEP (Temperature Sensitive Electrical Parameter) in HTRB test. With this measurement, temperature can be monitored accurately online. The advantage of this test method is that temperature measurement can be implemented in HTRB test without modifying the test circuit, and DUT junction temperature can be controlled by calculating the leakage current.

2. Calibration Model

When the IGBT turned off, the MOS channel is pinched off, collector current $I_c$ is nearly zero. At the moment, IGBT leakage is made up of two parts, one is from IGBT chip, which mainly is diffusion current of parasitic thyristor; the other is from antiparallel diode.

While the IGBT is blocked, the leakage current from both parasitic thyristor and anti-parallel diode is decided by PN Junction, so the leakage current satisfies the Shockley equation.

$$I_R = \frac{q n_i^2 D_p}{N_D \tau_p} + \frac{q n_i W_D}{\tau_p}$$  \hspace{1cm} (1)

Hole lifetime $\tau_p$, hole diffusion coefficient $D_p$ and $n_i$ are all temperature dependence. When the IGBT is turned off, the reverse PN junction is an abrupt junction, so that the second term in equation (1) is negligible [5]. As it is shown in equation (2).

$$I_R = \frac{q n_i^2 \sqrt{D_p}}{N_D \tau_p} + \frac{q \sqrt{D_p}}{\sqrt{\tau_p}} p_n \exp\left(\frac{E_g}{kT}\right)$$  \hspace{1cm} (2)

Among them, according to [5][6].

$$q \frac{\sqrt{D_p}}{\tau_p} \propto \tau_p^\gamma$$  \hspace{1cm} (3)

$$p_n = N_e \exp\left(\frac{E_g}{kT}\right)$$  \hspace{1cm} (4)

$\gamma$ is constant, $p_n$ is hole concentration of N region. Therefore, IGBT leakage current varies with temperature can be expressed as equation (5).

$$I_R(T_j) \propto T^{3+\gamma/2} \exp\left(\frac{E_g}{kT}\right)$$  \hspace{1cm} (5)

Among them, energy gap $E_g$ satisfies the formula (6) [6].

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$  \hspace{1cm} (6)

When the temperature is high, compared with exponential term, the varies of $T^{3+\gamma/2}$ can be neglect. Therefore, as temperature rises, the leakage current from parasitic thyristor and that from antiparallel diode are growing exponentially. Thus, it is appropriate to fit the DUTs’ calibration with equation (7).
Using IGBT leakage current as a TSEP, the test results have high precision, due to their more temperature sensitivity in a high-temperature region. Moreover, the leakage current is determined by the chip in DUTs, so the measure result will not change with variation of other factors like thermal resistance. To calibrate IGBT leakage current ($I_{CES}$), the DUT is placed in a thermostat, in which temperature is set up from 80°C to 130°C. After the DUT’s temperature stays stable, the $I_{CES}$ is measured with Tek 370, which can generate continuous and single voltage pulse, while concurrently measure the DUT current. To prevent the temperature rising caused by dissipated power, single voltage pulse is used during the calibration.

To eliminate the effect brought by instability forward bias voltage in HTRB test, we set $V_{GE}$ as 0V, and collect-emitter voltage ($V_{CE}$) as 1100V, 1150V, 1200V respectively. The calibration curves of IGBT (Module: FF100R12KS4) is shown in figure 1.

\[ y = ae^{bx} \]  
(7)

In figure 1, it can be observed that compared with $T_j$, the forward bias voltage has little effect on $I_{CES}$ in HTRB tests, so the influence of minor voltage fluctuation during the HTRB test can be ignored when measure the $T_j$. The $I_{CES}$ is more sensitive to the junction temperature and exponentially grows with the rising of the junction temperature. This is characteristic of the chip. Therefore, the calibration curves would not alter with the change of test bench.

3. HTRB junction temperature measurement

3.1 Calibration

In this experiment, 8 DUT were divided into two groups for HTRB testing. Since each DUTs has slight differences in their calibration, DUTs’ calibration is tested separately. Calibration curves for the eight DUTs, are shown in figure 2. Fit the calibration curves with equation (7). The curves fit is shown in Table 1.

![Figure 1. FF100R12KS4 Calibration curves](image1)

![Figure 2. Calibration curves](image2)
In order to verify the accuracy of the fitting formula, the fitting calibration curves are compared with the actual calibration curves. The result is exhibited in figure 3, when the temperature is higher than 115°C, the fitting error of equation (7) is no more than ±0.2°C. It is obvious that the fitting curve provides sufficiently accurate results.

### 3.2 Thermal Resistance Calculation

To verify the accuracy of TSEP temperature measurement, this paper makes a contrast with the test method of thermal resistance calculation. Temperature calculation model is shown as figure 4.

![Temperature calculation model](image)

**Figure 4. Temperature calculation model**

Junction temperature control is needed in HTRB test. During the test, junction temperature is calculated by adding heatsink temperature and the temperature rise caused by dissipated power. Calculation formula is as follow:

$$ T_j = T_{th.couple} + P \times R_{th} $$  \hspace{1cm} (8)
Where $T_{th, couple}$ is the temperature measured by thermal couple, $P$ is dissipated power, $R_{th}$ is the thermal resistance between IGBT chip and heatsink.

During the test, DUT junction temperature is set as 125°C, forward bias voltage $V_{CE}$ is set as 2640V, 80% of breakdown voltage $V_{CES,max}$, which is 3300V. At 125°C, the DUT $I_{ces}$ is about 40mA; $R_{th}$ is 30K/KW, so the dissipated power bring about a rise of 3.1°C junction temperature. Use formula (8) to calculate heatsink temperature and set it at an appropriate value.

3.3 Temperature measurement in HTRB tests

The 8 DUTs were divided into two groups for 8-hour HTRB test. For real-time monitoring the health status of DUTs, leakage current is collected once per 6s, so the junction temperature of DUTs can be calculated easily. The leakage current of each DUT is brought into the corresponding calibration curve, the test results are shown in follows.

![Temperature measure result in 8-hour HTRB test](image)

In figure 5, the temperature result calculated by $I_{ces}$ fluctuating between 123.5°C-125.5°C, is similar to that calculated by thermal resistance. Although the temperature curve of each device is slightly different, most of the wave patterns of the same group of devices can be observed from the figure, indicating that the leakage current temperature measurement method has a higher accuracy.

4. Summary

This paper presents a method that DUT’s leakage current is used as a TSEP to monitor DUT’s junction temperature. The instability of forward voltage is also considered. Temperature measurement is made in HTRB test and the result is compared with that of thermal resistance measurement. The results obtained by the two methods are similar, which can prove the validity of leakage current method.

The advantage of using leakage current as temperature sensitive parameter to measure the junction temperature of devices in HTRB test is that this temperature measurement method does not need to change the test circuit. Besides, leakage current only influenced by junction temperature, not other external environment. Therefore, this method is more advantageous when the device thermal resistance is difficult to measure.

Future work will continue to improve the accuracy of the leakage current temperature measurement method, and it will be studied further whether the voltage pulse will produce temperature rise in the process of measuring the calculation curve, which will influence the temperature measure results.

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