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ISPSD, May 2007, Jeju_Island, Korea

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1200V IGBTs operating at 200°C? An investigation on the potentials and the design constraints

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Abstract

The targeted 175°C junction temperature limit for the next generation of 1200V IGBT requires safe and reliable operation of the devices at a temperature of 200°C. Due to the exponential scaling of several IGBT parameters, such high temperatures will subject the IGBT to new levels of stress, guiding chip designers and application people onto completely new grounds whose firmness is largely unknown. In this paper, we take some first steps by investigating the operation of 1200V IGBTs at temperatures up to 200°C, looking at their characteristics, trying to understand potentials and possible threats, and drawing initial conclusions how such devices must be dimensioned in order to operate safely.

Introduction

Over the past years, the main development trend for power semiconductors was aimed at increasing the power density for a given targeted application. From the device viewpoint, the limitations are three fold; first is the total losses in the device, second the safe operating area boundaries, and finally the maximum allowable junction temperature during operation. On the other hand, another limitation exists for the removal of the power dissipated in the device. However, this challenge remains a focus of package and system cooling developments.

As state-of-the-art IGBTs slowly approach the limits in terms of losses reduction, the maximum junction temperature moves more and more into the limelight of the interest. The fact that the most important enabler, namely the power handling capability (SOA) of devices, has risen to a level where IGBTs can theoretically be operated at currents that greatly exceed the ratings of modern systems, has further increased the pressure towards expanding the temperature range [1]. Depending on the rated voltage, IGBTs have so far been limited to 150°C (for 1200V and 1700V) or 125°C (2500 V and higher). Since the heat flux is proportional to the temperature difference (ΔT), a higher allowable junction temperature operation of the semiconductor offers better conduction of the generated heat and hence, an increase in the power density for a given device area. Hence, an increase by 25°C enhances the rated power by 25 – 35%, depending on the cooling conditions [2]. Our analysis started with the thorough characterization of state-of-art 1200V IGBTs over a wide temperature range of up to 200°C. Investigated parameters included many static characteristics as well as switching performance and losses tradeoffs. From the results obtained, the apparent conclusion is that the IGBTs can still operate well at 200°C. Unfortunately, this does not yet permit the conclusion that the devices can be rated for this temperature. In order to draw such a conclusion, one must ensure that the IGBTs do not destabilize as a result of non-uniformities and parameter variations. The stronger emphasis when operating at elevated temperatures will be put on

stability issues: the fact that most 1200V IGBTs are run in parallel operation, raises the danger of current mis-sharing, which may under unfavourable conditions lead to thermal runaway and failure of the devices. Whether or not this happens depends on the temperature-dependent characteristics of the IGBT. Hence, a complete assessment requires that stability criterions are formulated, and that device characteristics are tailored to support stability.

In addition, we will discuss a proposed characterization method for IGBTs at very high temperatures. The conducted work represents a fundamental contribution to the discussion of raising the maximum operation temperature for potentially increasing the power density of IGBTs.

Static Performance of 1200V IGBTs up to 200°C

All measurements were carried out on a 6.5mm x 6.5mm 1200V Soft-Punch-Through (SPT) IGBT rated at 25A. By implementing a reliable and effective guard ring junction termination and passivation, the IGBT exhibits stable blocking characteristics and suitable leakage currents for operation at higher temperatures. The reverse blocking characteristics were the first to be measured due to their critical dependence on the device operating temperature. Figure (1) shows the IGBT leakage current values at reverse voltages up to 1300V and for temperatures ranging from 25°C up to 200°C.

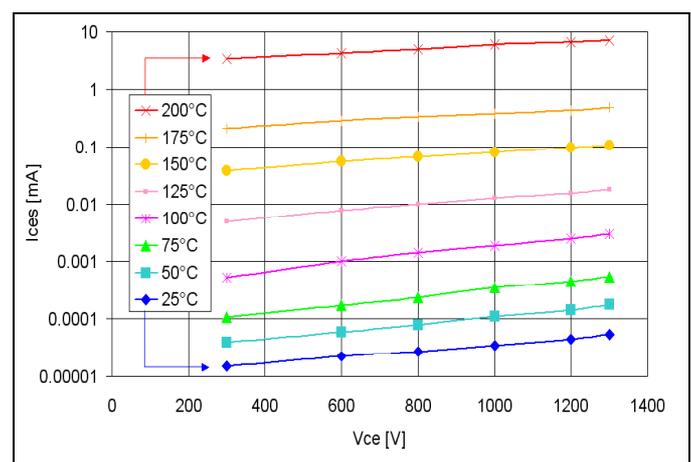


Fig. 1: 25A/1200V IGBT leakage current measurements.

Under static reverse bias conditions, the main critical parameter is given by the leakage current. It is clear, that thermal runaway sets upper limits for the operating temperature. Results show that the leakage current maintains a value below 1mA up to 175°C. Nevertheless, a clear increase to above 5mA is obtained at 200°C.

From basic cooling calculations of thermal stability during blocking [3], for the given chip size mounted on a standard DCB substrate, base-plate and heat-sink, a stable reverse blocking condition at 900V can be maintained if the leakage current does not exceed 4mA. This is clearly not the case at 200°C since the leakage current exceeds 5mA. These results provide the first most important criteria for stable device operation. Maintaining low and uniform leakage currents becomes an even more important target when designing for very high temperature operation. The IGBT breakdown voltage for same temperature range was measured at a leakage current of 5mA as shown in figure (2). The curve exhibits a normal trend with increased breakdown voltage at higher temperatures. The breakdown voltage at 200°C does not appear in this graph since the leakage current at this temperature is above 5mA. However, the IGBTs maintained stable reverse avalanche behaviour for the whole temperature range.

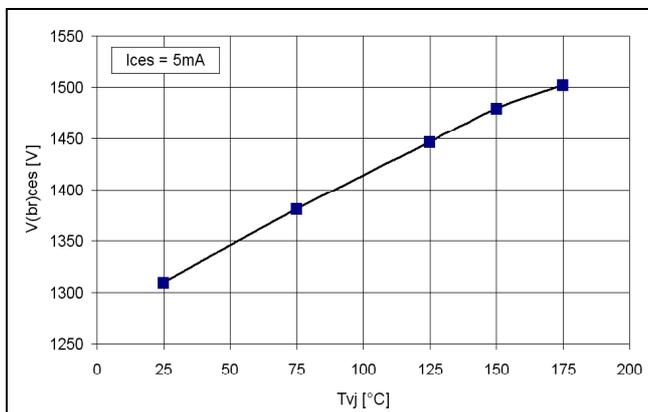


Fig. 2: 25A/1200V IGBT breakdown voltage vs. temperature.

Figure (3) shows the IGBT on-state characteristics up to 200°C. Due to the thin wafer SPT design, the 25A/1200V IGBT achieves low conduction losses with a typical on-state voltage of 2.0V at 25°C and 2.4V at 200°C at 25A. The curves clearly exhibit a positive temperature coefficient for the whole temperature range. This is decisive factor for safe parallel operation especially at high operating temperatures in order to get a minimal current de-rating. As it turns out in this case, a temperature-independent current of 8A guaranties for a positive temperature coefficient under all operating temperatures up to 200°C.

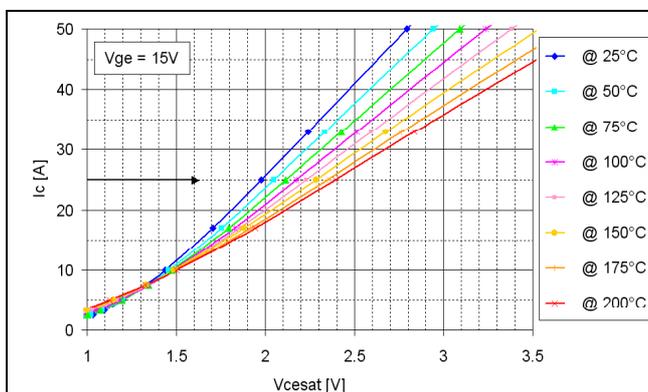
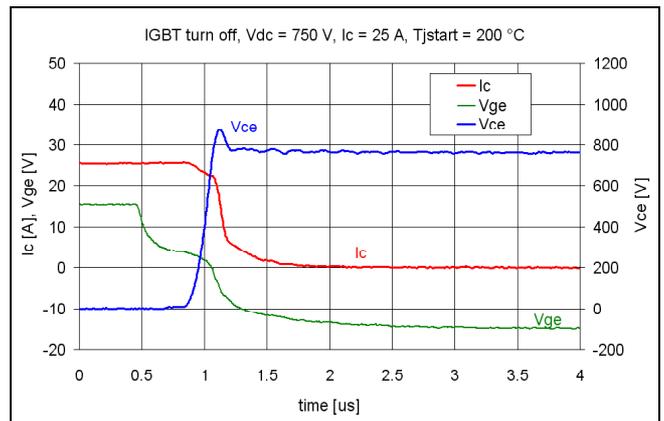
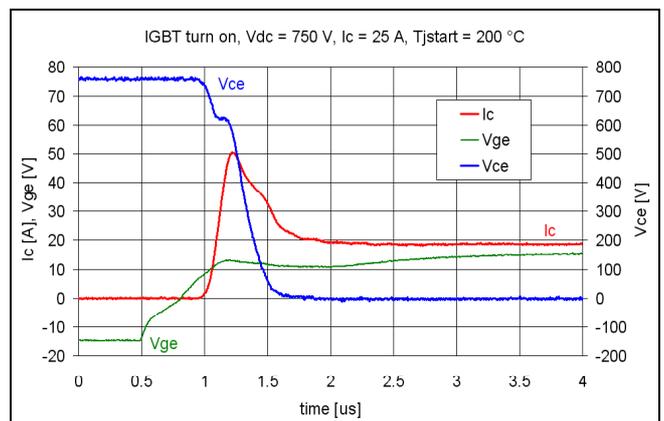


Fig. 3: 25A/1200V IGBT Vcesat measurements up to 200°C. Dynamic Performance of 1200V IGBTs up to 200°C

The dynamic performance of the 25A/1200V IGBT was evaluated in a standard inductive load circuit. Figure (4) shows the nominal switching characteristics of the SPT-IGBT during turn-off (a) and turn-on (b) at 200°C. The tests were carried out at a nominal current of 25A and a DC link voltage of 750V. The losses calculations reveal that the switching losses are practically doubling when increasing the temperature from 25°C up to 200°C. The turn-on losses increase from 4.5mJ at 25°C up to 9mJ at 200°C, while the turn-off losses increase from 2mJ 25°C up to 4mJ at 200°C. From the losses obtained, the output current was calculated for a wide range of frequencies as shown in figure (5).



(a) Turn-off waveforms.



(a) Turn-on waveforms.

Fig. 4: 25A/1200V IGBT switching waveforms at 200°C.

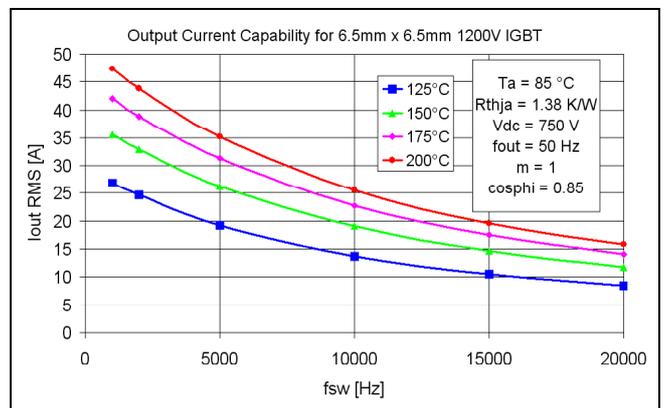


Fig. 5: 1200V IGBT output rms current capability vs. frequency.

The graphs reveal the potential to increase the total output current at higher temperatures despite the high static and dynamic losses obtained. A 50% increase in capability is clear when increasing the temperature from 125°C to 200°C.

RBSOA and Avalanche Capability up to 200°C

Figure (6) shows the RBSOA switching characteristics of the SPT-IGBT during turn-off with a collector current of 100A and a DC link voltage of 1000V at 200°C. Rugged performance is demonstrated for the IGBT while employing a large stray inductance value of 800nH. The turn-off capability is remarkably high around four times nominal current, which corresponds to the de-saturation current with 15V applied to the gate.

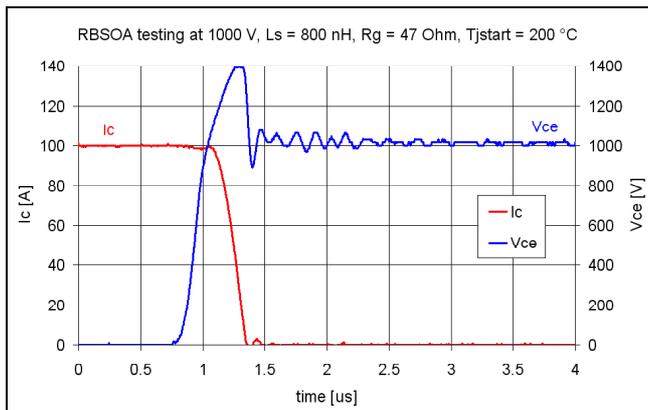


Fig. 6: 25A/1200V IGBT RBSOA at 200°C.

To further investigate the ruggedness of the 1200V IGBT, unclamped inductive tests were carried out to evaluate the device avalanche capability at high temperatures. The dynamic tests forces the IGBTs into self-clamp mode during turn-off and measures the device ruggedness and such conditions [4]. Figure (7) shows the voltage and current waveforms obtained from avalanche testing at 200°C.

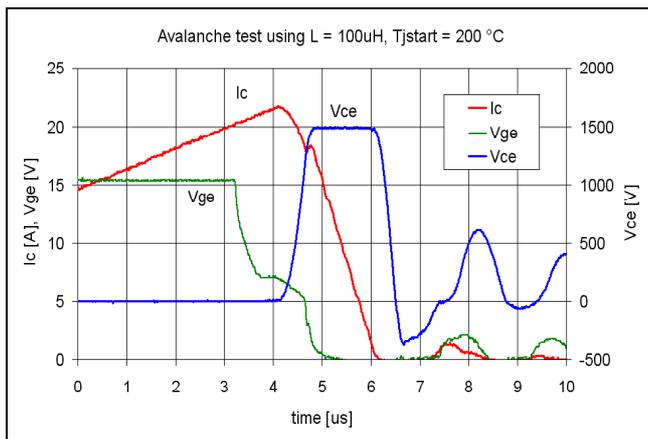


Fig. 7: 25A/1200V IGBT Avalanche Test at 200°C.

Although the device exhibits a maximum current turn-off potential under avalanche conditions in excess of 100A, this capability is strongly reduced with increased temperatures as shown in figure (8). However, the IGBT maintains at 200°C a certain nominal current level withstand capability.

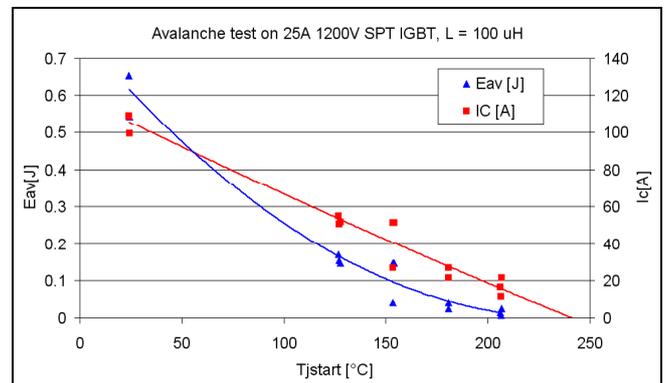


Fig. 8: 25A/1200V IGBT maximum avalanche energy and current vs. temperature.

Short Circuit Capability up to 200°C

The short circuit performance is a very important issue when operating at higher temperatures. First, it is important to note that the short circuit current decreases significantly with higher temperatures. The short circuit current level at high temperatures should at all times maintain a given value above the normal operating currents, which are typically equal to twice the rated current. This is vital for ensuring controllable turn-on behaviour and low switching losses. Normally, short circuit operation raises three major concerns: (i) short circuit turn-on failures due to field distortion, (ii) short circuit turn-off failures because of latch-up, and (iii) thermal runaway due to excess energy during short circuit [5][6]. The first concern is normally associated with higher currents and lower temperatures. Thus, operation at a higher temperature will not have a negative impact. The second concern relates to the device ruggedness, which was addressed earlier. Therefore, the main focus here is with regard to concern (iii). Figure (9) shows the results obtained from short circuit tests carried out at 25°C and 200°C for two different pulse widths respectively. The junction temperature was plotted using adiabatic thermal calculations for T_j of the chip silicon volume heated up by the short circuit pulse, and confirmed by the temperature dependence of the short circuit current.

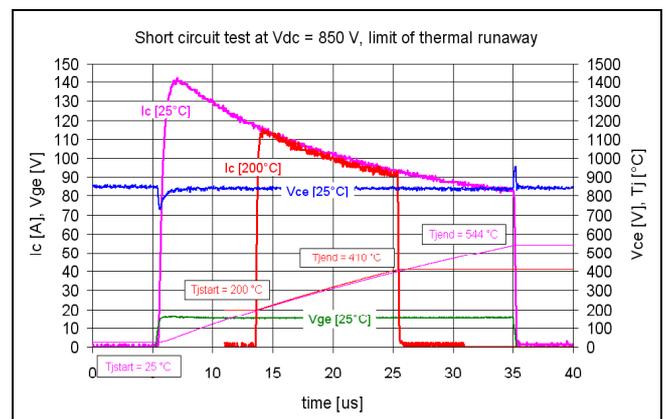


Fig. 9: 25A/1200V IGBT short circuit waveforms at 25°C and overlaid short circuit current at 200°C.

It was observed that thermal runaway occurs for devices starting at a higher temperature, however failing with a lower peak junction temperature at the end of the short circuit pulse. This is due to reduced transient cooling at high ambient temperatures. From destructive measurements due to excess energy at a wide temperature range, two plots were generated

for the short circuit energy and corresponding pulse width versus temperature as shown in figure (10). As can be seen clearly, the maximum allowable energy and pulse width has dropped considerably at higher temperatures. This approach could be overcome either by reducing the short circuit current with limitations regarding controllable switching behaviour as mentioned earlier, or by shortening the short circuit withstand duration as is currently widely discussed.

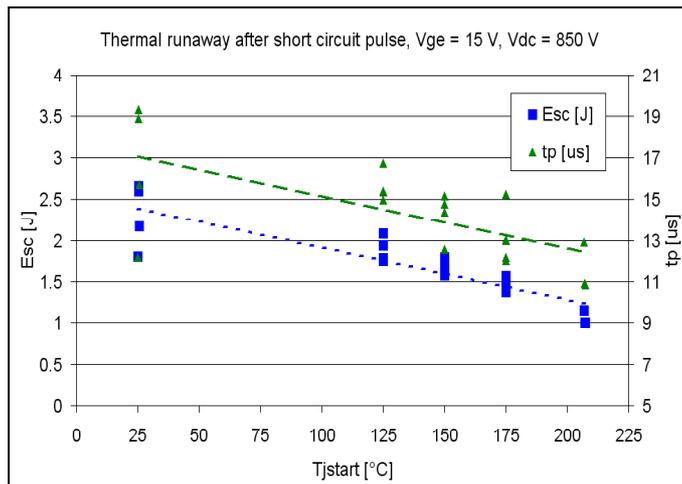


Fig. 10: Short circuit energy and pulse width versus temperature.

Proposed Test Method at Elevated Temperatures

A further subject here is to discuss a proposed high temperature characterization method of IGBTs for elevation beyond 200°C. Measurements and characterisation at such high temperatures will impose many challenges on the materials of a test-setup. In addition, the classical approach, which is based on the standard external heat contact to increase the temperature of the entire set-up to a targeted level, often does not work because static stability criterions might be violated. Hence, results can be erroneous, and failure modes may occur that are not relevant in practice. To solve this conflict, we propose a measurement method based on a preheating of the device to the desired temperature using a variable short-circuit pulse as shown in figure (11).

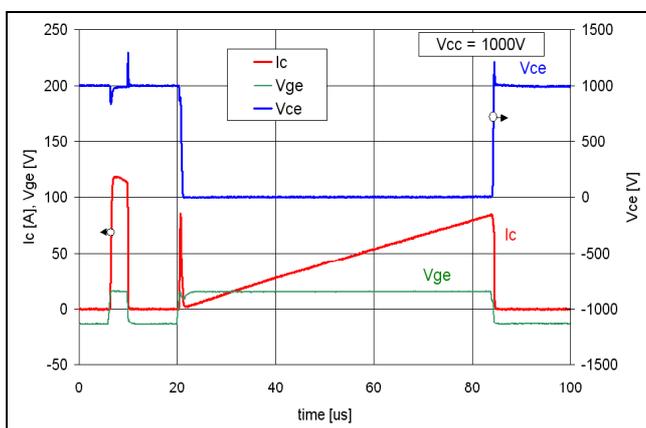


Fig. 11: IGBT turn-off test after preheating using a short circuit pulse.

The principle is based on enabling the chip to self-heat with a number of short-circuit pulses prior to the intended measurement.

The energy is dissipated in a short time compared to the time constant of heat conduction.

Hence the temperature in the chip can be chosen by the number and/or conditions of the short-circuit pulses. A reasonable estimation of the chip temperature can be obtained through the measured short circuit current level.

Conclusion

Modern advancements of power semiconductor devices in terms of loss reductions and higher SOA limits have enabled a tremendous increase of power density due to carefully designed and optimised devices. Nevertheless, with modern device designs approaching their silicon limits in terms of loss reductions, a new trend for increasing the device power density has emerged targeting higher temperature operation of power devices. The results presented in this paper for a 1200V SPT-IGBT bring forth important data with regard to the device behaviour for future applications that aim for a permanent higher temperature operation. The main conclusion points out to stable behaviour for the device at higher temperatures with clear limitations in terms of leakage current, avalanche capability and short circuit performance. Moreover, today's applications with requirements for an intermittent operation lifetime and safe operation limits will also benefit from a better knowledge of the margins in order to estimate the effects of transient or exceptional high temperature conditions. Further work will focus on the reliability aspects of high temperature operations, which is strongly linked to the packaging technology.

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