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Reliability aspects of copper metallization and interconnect technology for power devices

Frank Hille [a,*], Roman Roth [b], Carsten Schäffer [b], Holger Schulze [b], Nicolas Heuck [c], Daniel Bolowski [c], Karsten Guth [c], Alexander Ciliox [c], Karina Rott [a], Frank Umbach [a], Martin Kerber [a,1]

[a] Infineon Technologies AG, Am Campeon 1-12, D-85579 Neubiberg, Germany
[b] Infineon Technologies Austria AG, Siemensstr. 2, A-9500 Villach, Austria
[c] Infineon Technologies AG, Max-Planck-Str. 5, D-59581 Warstein, Germany

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ABSTRACT

The introduction of thick copper metallization and topside interconnects as well as a superior die attach technology is improving the performance and reliability of IGBT power transistor technologies significantly.
The much higher specific heat capacity and higher thermal conductivity increases the short circuit capability of IGBTs, which is especially important for inverters for drives applications. This opens the potential to further optimize the electrical performance of IGBTs for higher energy efficiency.
The change in metallization requires the introduction of a reliable barrier against copper diffusion and copper silicide formation. This requires the development of an efficient test method and reliability assessment according to a robustness validation approach.
In addition, the new metallization enables interconnects with copper bond wires, which yield, together with an improved die attach technology, a major improvement in the power cycling capability.

1. Introduction

The introduction of .XT technology [1] in silicon based insulated gate bipolar transistors (IGBTs) together with suitable free wheeling diodes (FWDs) is boosting the potential for higher energy efficiency and reliability of power modules. This technology comprises a copper front side metallization on a tungsten-based diffusion barrier introduced in the IGBT and the diode (cf. Fig. 1), copper wedge bonding as front side interconnect, and an advanced die attach by silver sintering.

Higher energy efficiency of new inverter generations by increasing the power density is the key driver for technology development, being enabled mainly by two measures: First, by the reduction of power losses in the IGBT and the diode and therefore directly increasing the usable output power for a fixed maximum junction temperature. And second, by the increase of maximum junction temperature itself, allowing for even higher power losses and therefore also output power at identical cooling conditions. Both measures can be combined. They require however significant improvement in short circuit capability of the IGBTs as well as the reliability of interconnects.

Part I of this work reviews how an improved thermal setup by employing a new die attach technology as well as a copper metallization serving as heat sink does improve the thermal short circuit capability significantly. This opens the potential for further electrical device optimization.

Part II of this work focuses on the implementation of the copper metallization as well as the reliability aspects arising from it. The dynamics of copper silicide formation and the consequence for device operation are investigated. As a result, a highly reliable separation of copper from silicon by a diffusion barrier is required, since otherwise device destruction occurs. The failure mechanisms, the methodology for testing and the methodology for reliability assessment according to a robustness validation approach are discussed.

Thick copper metallization enables the replacement of aluminum wedge bonds by much harder copper wedge bonds. Together with the improved die attach technology, the overall interconnect reliability with respect to power cycling is tremendously improved. Results for various module setups and explanations for the failure modes are discussed in part III.

2. Improvement of short circuit ruggedness

Short circuit ruggedness is a requirement for many electrical drives. Due to a failure in operation – especially during commissioning or maintenance work – a shorting of the inductive load driven by the inverter can happen. As a consequence the output terminals of the IGBT are more or less directly connected to the DC link bus with high voltage.

* Corresponding author.
E-mail address: frank.hille@infineon.com (F. Hille).
[1] Present address: Dr. Martin Kerber, Schnann 65, A-6574 Pettneu am Arlberg.

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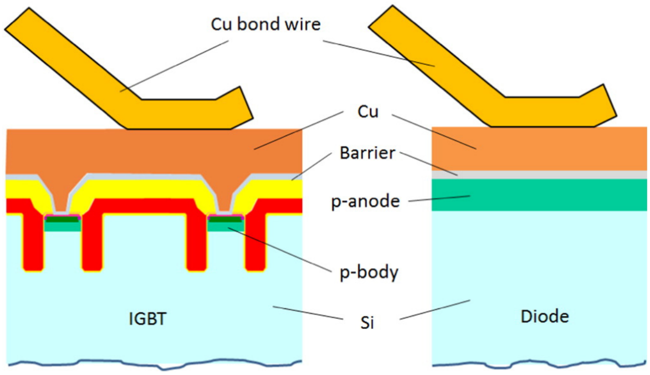

Fig. 1. Schematic cross section of a) IGBT and b) FWD with .XT power copper metallization (picture from [6]).

The missing inductive load can no longer limit the current increase with time once the IGBT is turned on. Therefore, the IGBT has to limit its current under short circuit operation itself. Furthermore, the IGBT should be able to withstand this operation for a few to ten microseconds until this faulty operation mode is detected by the control circuit and to safely turn off afterwards.

Short circuit operation means a considerable stress in terms of high currents and dissipated energy, hence a number of short destruction mechanisms are reported. An up to date review is found in [2]. In the present case, the thermal short circuit destruction mechanism is the relevant one [3,4]. In this destruction mode, the IGBT is able to withstand the short circuit operation and even safely turns off the load current after the gate is turned off. However, the device is destructed some hundreds of microseconds up to milliseconds after the short circuit pulse.

A study including electro-thermal device simulation (cf. Fig. 2), taking into account the electrical and thermal setup, explains the failure mechanism and how an improved thermal setup can help [5]. The predictions for the improvements have been experimentally validated within this study for a 1200 V IGBT technology. During the short circuit pulse of only a few microseconds, heat dissipation takes place mainly in the drift region of the transistor. The temperature distribution is basically confined to the silicon volume of the chip, with a maximum temperature in the middle of the drift region. The front side MOS structure with its n-source and also the back side p-emitter are still close to the starting temperature before the short circuit pulse. The short circuit pulse is too short for considerable heat transport.

After the short circuit pulse heat diffusion takes place into the region of n-source at the front side and p-emitter at the back side. As temperature increases at these junctions, thermally induced leakage currents occur: electron current from the n-source, hole current from the p-emitter. Electron and hole current are coupled to each other by pnp-amplification in case of an IGBT. Suppressing the temperature rise at one of the junctions helps to lower the self-heating after the short circuit pulse and delays thermal runaway.

For the front side, the thin aluminum metallization is replaced by thick copper metallization, which needs to have considerable amount of the heat capacity of the silicon volume to act as temporary heat sink. Introducing this measure alone increases the critical short circuit energy by 20%–25% (cf. Fig. 3).

For the back side, the heat transport out of the silicon into the copper coating of the ceramic substrate is limited by the low thermal conductivity of the soft solder die attach. Just by replacing it by a layer of much higher heat conductivity, as Ag sintering or diffusion soldering, the critical energy can also be increased by 20%–25%.

The highest improvement is obtained if both measures, a thick copper metallization and a novel die attach, are employed simultaneously. Both junctions are kept as cool as possible, avoiding that a thermally induced electron/hole current from one side is leading to an increase of the respective hole/electron current from the other side by pnp-amplification, which is compromising the effectiveness of the single sided measures. As a consequence, the increase of 85% in critical short circuit energy well exceeds the sum of improvements of the single sided measures (cf. Fig. 3).

Levers for increasing the power density can then be employed, all requiring an increase in short circuit ruggedness. First, the MOS cells may be designed for higher electron currents, leading to a better plasma distribution suitable for switching with lower electrical losses but increasing the short circuit current. Second, the drift region, which needs to be flooded with excess carriers and is therefore determining the electrical losses to a wide extent, may be reduced in thickness. This however simultaneously reduces the heat capacity of the silicon volume. Third, the maximum junction temperature may rise. This usually means a reduction of short circuit capability since the condition at which self-heating exceeds the cooling capability is reached sooner.

2.1. Novel copper metallization and its reliabilty aspects

Copper is a very suitable heat sink for improved short circuit ruggedness due to its high thermal capacitance and conductivity. For the required copper thickness, electrochemical deposition is a very capable method. A wafer-metallization process benefits from the cost-efficient, stable and precise methods of a wafer fabrication at a very low defect density level. It is crucial that the thick metallization covers all cells of the IGBT or the complete anode area of the diode. The wafer metallization process enables a perfect alignment of the metallization on the chip, and provides a high degree of freedom concerning the layout of the metallization. The process is even suitable to fabricate the IGBTs

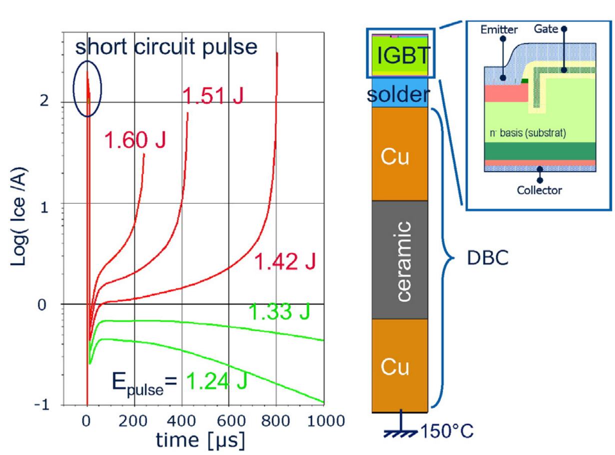

Fig. 2. Electro-thermal device model. Left picture: the collector emitter current (log scale) initially increases after the short circuit pulse and leads to device destruction if a critical energy is exceeded. Right picture: IGBT cell and mounting setup (picture from [5]).

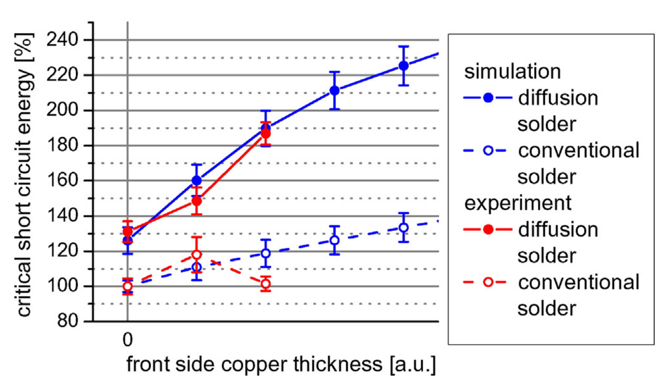

Fig. 3. Improvement potential of critical short circuit energy on a relative scale. The aluminum front side is represented as 0 µm copper. Error bars for the simulation results are caused by the discretization of gate voltages (picture from [5]).

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