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State of the art and Future Prospective of Si-IGBT Technologies

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Abstract

An overview about state of the art Insulated Gate Bipolar Transistors (IGBT) as a key component in power electronics is given, the underlying device concepts are explained as well as an outlook about next development steps. They will result in ongoing power density and efficiency increase and will contribute to the worldwide energy saving efforts. In this context Si IGBT technology will still play an important role also for the next years - despite the upcoming wide band gap switches.

1. Introduction

The Insulated gate bipolar transistor (IGBT) represents a power MOSFET-bipolar transistor integration by combining the physics of MOSFET operation and bipolar transistor's one. It serves as a key component in nearly all high power electronic systems. As IGBTs meanwhile have already a quite long history of more than 25y [1] and as wide bandgap successor candidates like GaN and SiC power transistors catching up in the power semiconductor market, it is worth to have a closer look on today's state of the art IGBT device concepts and technologies and what are options in Si IGBT technology for the future.

2. State of the art Si-IGBT

Today's state-of-the-art IGBTs use similar approaches [1]. The most relevant device elements are the transistor cell concept on the front side of the device and the vertical structure consisting of drift region, optionally buffer or field stop region and back emitter (see Fig. 1).

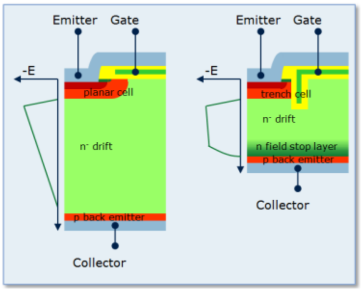

Fig.1 Evolution from an IGBT with planar cell / vertical non punch through structure to an IGBT with a trench cell / vertical field stop concept.

2.a Transistor Cell Concept

As cell concept the trench cell technology is widely introduced, meanwhile over the whole available voltage class range from 400V up to 6.5kV, whether it is the trench cell based IEGT [2], a structure with defined distances between the trench cells [3] or a structure with more narrow and differing gate and/or source trenches, whether with or without an additional n doped charge storage layer below the p body [4, 5]. They all have in common the basic principle of enhancing the amount of carriers (both holes and electrons) in the upper region of the chip during the on state condition resulting in a low on state voltage [6]. Latest trends to further increase the carrier amount on the front side are reducing cell size and cell pitch to micro or even sub-micron sizes [7]. However, the carrier engineering has to be carefully balanced to stay with reasonable turn off losses.

2.b Concepts for Vertical Structures

The second important device element besides the cell is the vertical IGBT structure. The thinner the vertical structure (for a given blocking voltage), the lower are the achievable on state and switching losses. State of the art is a punch through construction with a medium n doped layer between drift zone and low efficient back emitter without any carrier life time reduction needs [8], later often called as field stop structure (see also a right picture in Fig. 1). The concept was first introduced in the voltage class of 1200V [9] and then stepwise above up to 6.5kV as well as in the lower voltage arena of 600V and even below to 400V with chip thicknesses of only 45µm.

2.c Increasing Power Density

Improvements in the cell and vertical structure from the very first until to today's IGBTs with its successively reduced on state and switching losses, combined with increased junction temperatures (T_j) from 125°C up to now even 175°C, combined with adequate improvements in the module technology [10, 11], result in shrunken chip and module sizes for a given power over the years as shown in Fig. 2.

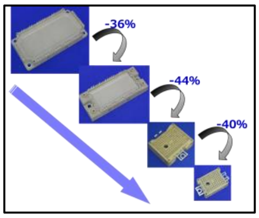

Fig.2 Footprint reduction of a 35A/1200V module by ongoing improvement in Si IGBT and module technology within 4 IGBT generations [1].

3. Future Prospective of Si-IGBT

As the Si IGBTs are driven closer to their limits the more important it gets to clarify what requirements from application point of view are really needed. Examples are the short circuit duration time and voltage slopes (dV/dt) at turn on and turn off. These aspects define the further path of Si IGBT development but also for wide band gap materials, as especially their advantages of low switching losses only hold as long as they are allowed to switch fast. This has to be taken into account when discussing further development steps for Si and SiC/GaN.

3.a *Next Gen. Cell Concepts and Gate Driving schemes*

To approach the theoretical limit of IGBT on state performance [12] lot of activities with deep sub-µ mesas between adjacent deep trenches [13, 14] are running, as shown e.g. in Fig. 3. An on state voltage of about 1V for a 1200V device may become feasible, however, drawbacks like quite high switching losses because of the high amount of carrier plasma still have to be solved, and short circuit robustness topics because of the high transconductance of such cell concepts, too.

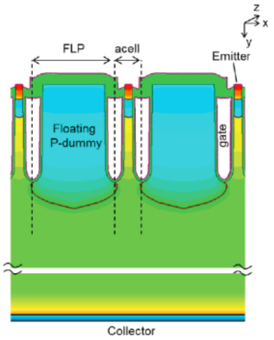

Fig. 3 IGBT cell structure with very small mesas [14].

With respect to short circuit requirements, the trade-off between withstand time and forward voltage drop can be solved by use of IGBT chips in intelligent power modules (IPM) with current sensing and a dedicated gate driver reducing the gate voltage in a short circuit case within the very first µs. This method is not new but may get standard also for standard IGBT modules, as it enables additional overall performance improvement [15]. Another aspect of sophisticated gate driving schemes can be useful for reverse conducting (RC) IGBTs with also narrow trench cell mesas: Changing the plasma concentration during freewheeling mode from a higher level and shortly before the commutation event to a lower level could help to make use of the full potential of such RC devices [16].

3.b Next Gen. Vertical Structure Concepts

Also the vertical IGBT structure still can be improved. 1200V IGBTs with a thickness about 110µm [17] and 750V IGBTs with 70µm are common today. From theory for a 1200V blocking capability chip thicknesses of 80…90µm should seem feasible (100µm already demonstrated [18]), for 600V about 45…50µm should be possible. Ultrathin wafer technology is able to serve these needs, meanwhile in first 300mm power semiconductor production facilities [19]. However with thinner IGBT chips, switching softness, cosmic ray robustness and thermal short circuit capability will become more critical. The softness topic can be mitigated by low inductive module and inverter setups, also by more sophisticated field stop engineering as well as the right choice of back emitter efficiency. For cosmic ray robustness, the drift zone resistivity can be reduced.

3.c New Thermal Management and Interconnect techniques

A sufficient high level of thermal short circuit capability can be achieved – despite reduced chip thickness and cells with high transconductance - by implementing a thick Cu layer on top of the chip in combination with alternative chip back interconnect techniques, as shown in fig. 4. Several realization options for this increased thermal short circuit robustness were already described [10, 20, 21].

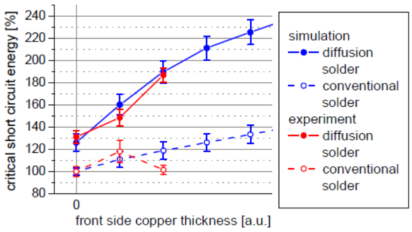

Fig. 4 Critical short circuit energy of a 1200V IGBT as a function of different interconnect technologies and Cu chip metal thickness [20].

A second aspect of such new interconnect techniques is a significantly increased power cycling capability by a factor of more than 10 [10], what may result after a T_j enhancement above 175°C still in sufficient cycle numbers before end of life.

Maybe such combined chip / module solutions will open the path to enhanced T_j up to 200°C in future, resulting once again together with the described innovations in cell and vertical structure as well as gate driving in a much higher power density than today's products. Of course the measures of advanced thermal management will also be of importance for the wide bandgap semiconductors with their potential for even higher temperatures above 200°C.

4. Conclusion

Also after nearly 30y of innovation the Si IGBT is still not at its end and further steps in the race in power density and efficiency are in progress. However the gap between Si and wide bandgap with respect to a parameter like "costs/power" within the overall power electronic system will get closer, as cost down measures on the wide bandgap technologies accelerate. But on the same time, also the Si IGBT technology will still improve and make use of large scale wafer diameter production. So, as a guess, also for several next years there will stay a co-existence between Si and wide bandgap power devices.

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