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Progress and Challenge in High to Ultra-High Voltage SiC Power Devices

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Global warming is an urgent matter, and measures must be taken to realize a low-carbon society at an early stage. For this purpose, there is a need for the sophistication of energy management technology in a smart linkage inside and outside the smart grid, accompanied by the large-scale introduction of renewable energy and energy storage technology. Further, for a safer and more secure society, we must improve the resilience of the electric power system. To achieve a super smart society, by the fusion of energy and information, the role of power electronics becomes increasingly important in the energy value chain.

Power electronics and power devices are the two sides of evolution. Thus far, power electronics has been supported by the evolution of Si-IGBTs. Since the performance improvement of Si-IGBTs has reached the physical limit, expectations for wide-bandgap semiconductor devices are increasing. With the same device structure, SiC devices can achieve 10 times higher breakdown voltages than those of Si. Especially, by replacing bipolar Si-IGBTs with unipolar 600 V–3.3 kV SiC-MOSFETs, the size of power electronics components is expected to be reduced significantly with low switching loss [1].

Further, a method of omitting a Schottky barrier diode (SBD) using the body diode of the MOSFET has been developed. When a body diode is used, since it is a bipolar operation, countermeasures against forward degradation are required. Particularly, when surge enters, there is a possibility that the basal plane dislocation (BPD) in the substrate expands. Using the recombination enhancement layer, we succeeded in preventing this by suppressing the number of holes reaching the substrate [2].

For high-voltage devices, 6.5–13 kV SiC-MOSFETs have been developed [3-4]. A 6.5 kV SBD-embedded SiC-MOSFET is also reported [5]. By incorporating the built-in SBD, turn-on of the body diode can be suppressed. As for a next-generation MOSFET, we are studying a 6.5 kV class super junction (SJ) structure. The SJ structure enables us to obtain less than half the on-resistance compared to a normal SiC-MOS, expected to be applied to the traction systems of high speed trains.

By applying the IGBT structure to SiC, it is possible to realize over 10 kV MOS-controlled switching devices, which cannot be reached by Si. Considering 13–33 kV bipolar device, the drift layer doping needs to be in the range of $1–4 \times 10^{14}$ cm^{-3}, and the thickness of 150–300 μm [6]. When the conductivity modulation occurs, their lifetimes are suppressed by direct and Auger recombination. To obtain sufficient conductivity modulation, approximately 30 μs is required as SRH (Shockley-Read-Hall). On the other hand, in bipolar device simulation, parameters such as the lifetimes at a particularly high carrier doping are not maintained, and we have tackled the setting of the TCAD parameters.

Thus far, there have been reports of 4.5–27 kV for PiN diodes and 6.5–27 kV with IGBTs [7-12]. Bidirectional switches with MOS gates on both sides have also been proposed [13]. Regarding PiN diodes, those close to the limit value of the differential on-resistance have been reported. As for the IGBT, the differential on-resistance is 3 to 5 times the theoretical value presently. Moreover, in the IGBT, improving the trade-off between the conduction loss and switching loss is a challenge. Similar to the history of Si, optimizations of device design and structure are needed, considering such as injection enhancement effect, lifetime control and injection control on the collector side. In the actual wafer-level process, problems such as interface dislocation generation and substrate cracking during the process arise due to the difference in lattice constants between the drift layer and p^{++} layers. It is also necessary to develop epi-substrate processing and process technology to solve these problems.

With ultra-high-voltage SiC devices, it will be possible to change the design concept of the current power transmission and distribution systems drastically. For example, a solid state transformer (SST) and intelligent power switch used in smart grids [14], miniaturization of static var compensator (SVC), reduction of the stages of modular multilevel converters (MMC) in HVDC, and highly reliable high-speed circuit breakers are expected. In addition, it can contribute to the intelligence of next-generation power systems, such as power system tidal current control, system voltage boosting, and DC power supply for realizing the loop system.

The use of SiC devices promotes the downsizing of the power electronics component, and the total cost including running cost is expected to be much lower than that of the Si base. However, SiC devices still have high initial costs, which is obstructing the expansion of the SiC market. Significant cost reduction of SiC substrates and the epi-process are required, with further improvement in quality and low dislocation to improve the yields. On the other hand, to fully utilize the high current density obtained with ultra-high-voltage bipolar devices, the development of heat removal technology and insulation technology in the ultra-high-voltage modules is also desired. Innovation is necessary not only in device technology but also in peripheral technology.

We hope that SiC technology will contribute further to the super smart society that adopts efficient energy usage, including energy storage, rather than the expansion of energy creation.

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