Challenge of Adopting TCAD in the Development of Power Semiconductor Devices for Automotive Applications

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***Abstract*—Due to the mass consumption of fossil fuels since the 20th century, the automotive industry is facing various issues, such as the depletion of fuel resources and worsening air quality. Power semiconductor devices can help to resolve these issues by facilitating the development of technologies to save energy and diversify fuel usage. This paper describes the requirements and outlook for power semiconductor devices. It also introduces an example of the adoption of technology computer aided design (TCAD) in power semiconductor device development.**

Keywords— TCAD, automotive, HV, EV, PHV, vehicle, power device, reliability, SiC, GaN

I. Introduction

The automotive industry is facing various issues, such as the depletion of fossil fuel resources and worsening air quality caused by congestion. Automakers are working to help improve the environment by developing technologies to save energy and diversify fuel usage, and by encouraging the widespread adoption of environmentally friendly vehicles. Toyota Motor Corporation regards hybrid vehicles (HVs) as currently the most practical and effective means of improving fuel efficiency. This paper describes the reliability requirements for power semiconductor devices used in HVs and an example of the adoption of technology computer aided design (TCAD) to help enhance reliability and quality in device development.

II. Actions for Sustainable Mobility

Fig. 1 shows a future roadmap for the adoption of next-generation environmentally friendly vehicles such as HVs, plug-in hybrid (PHV), full electric (EV), and fuel cell (FCV) vehicles. The roadmap is divided into various mobility categories in accordance with the size of the vehicle and the travel distance. The normal passenger vehicles of today may well be replaced by more environmentally friendly HVs and PHVs. The adoption of full EVs is restricted by the range and charging time of the battery, which means that EVs are more suitable for shorter distances, such as commuting within cities. FCVs have a longer range and shorter refueling time than EVs, which makes them suitable for longer distance transportation and emissions reduction. Toyota is developing HV systems and power semiconductor devices for these systems as core technologies that can be adopted in all next-generation environmentally friendly vehicles.

III. Power Semiconductor Devices for HVs

Toyota has concentrated on the development of silicon insulated gate bipolar transistors (Si-IGBTs) for HV systems. The key point for improving the performance of Si-IGBTs is to reduce loss. However, with the performance of IGBTs approaching the theoretical limits, activities seeking to achieve a breakthrough in the development of the next generation of power semiconductor devices for HVs have begun to focus on silicon carbide (SiC). TCAD has also been incorporated into the development of SiC power semiconductor devices.

IV. Reliability of Automotive Semiconductors

As shown in Fig. 2, a vehicle is exposed to various internal and external stresses. Table 1 shows that automotive semiconductors must function in a wide range of operating temperatures, and be resistant against both strong vibrations and large fluctuations in power voltage. Some of the requirements for automotive semiconductors are more stringent than those for semiconductors used in consumer electronics and aircraft. The role of TCAD in power semiconductor device development is to help ensure high reliability.

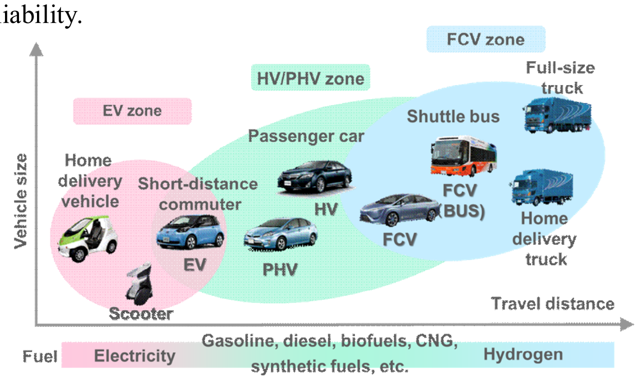

Fig. 1. Roadmap of future mobility categories

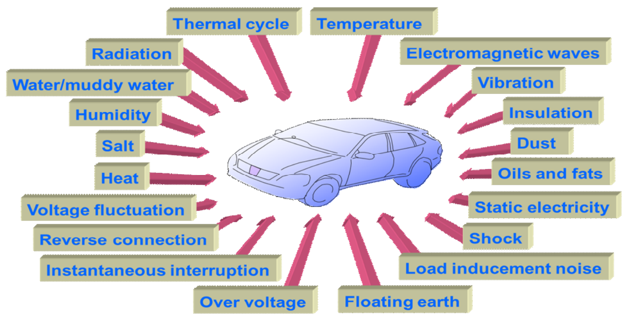

Fig. 2. Stress from ambient surroundings

TABLE I. REQUIREMENTS FOR AUTOMOTIVE SEMICONDUCTORS

	Measuring instrument	Consumer electronic	Automobile	Aircraft
Demand accuracy : [%]	0.1～1	Several	Several	0.1～1
Operating temperature:[℃]	0～40	-10～70	-40～150	-65～350
Vibration[G]	～1	5	25	20
Power voltage variation[%]	±10	±10	±50	±10
Electromagnetic environment	Good	Good	Bad	Good
Other tolerances	-	Moisture	Salt water, Exhaust gas	Salt water

V. SIMULATION CASES FOR POWER DEVICES

A. UIS Simulation

The diagram on the left of Fig. 3. shows the unclamped inductive switching (UIS) test circuit, which is used to evaluate power device reliability (i.e., the L load avalanche withstand capability of the device). The waveform shown in the graph on the right demonstrates that the collector current (Ic) increases linearly when the device gate switches ON, and that the collector voltage (Vc) increases dramatically as soon as the gate switches OFF due to counter electromotive force from the inductor. In a power device, this is called the avalanche phenomenon.

Fig. 4. shows the surface temperature of an IGBT measured by an infrared (IR) camera at timings t1 to t4 using a system installed into the UIS test circuit. The thermal maps show that the temperature distribution is not uniform over the surface of the IGBT. High temperatures appear to move across the surface in short time units of several tens of µs. Although the total current decreases in a linear fashion, this result implies that the location of the avalanche current moves inside the IGBT.

The diagram on the left of Fig. 5. shows an outline of a device capable of measuring individual currents flowing in the wire bonds of an IGBT by monitoring the current in a Rogowski coil using a tester. The diagram on the right shows an actually measured waveform in a device avalanche state. At 30 µs, the current flowing in emitter pad B is higher than the other pads. However, at 60 µs, the current flowing in emitter pad C is the highest. These measurements confirmed that the avalanche current moves as predicted (this is referred to as the hopping phenomenon).

This phenomenon was analyzed using TCAD. The images on the left and right of Fig. 6. show examples of two- and three-dimensional analysis results, respectively. The analysis identified current hopping in the order of 1 µs. According to these results, localized high current densities occur inside an IGBT during a UIS test, causing localized heat generation. This phenomenon reduces the UIS performance of IGBTs [1], [3].

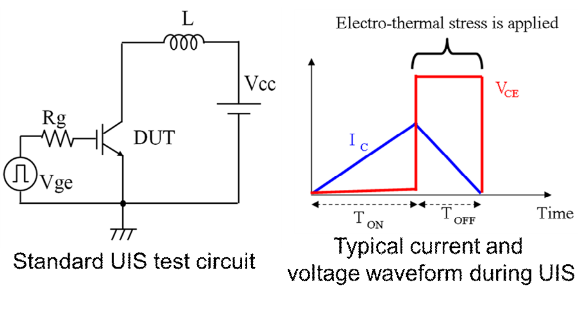

Fig. 3. UIS circuit and waveform

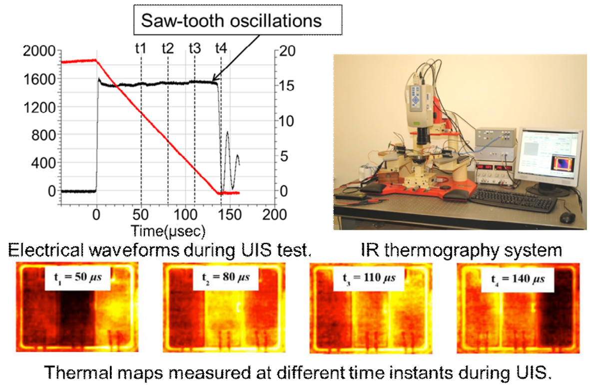

Fig. 4. Measured electrical waveforms during UIS test [1]

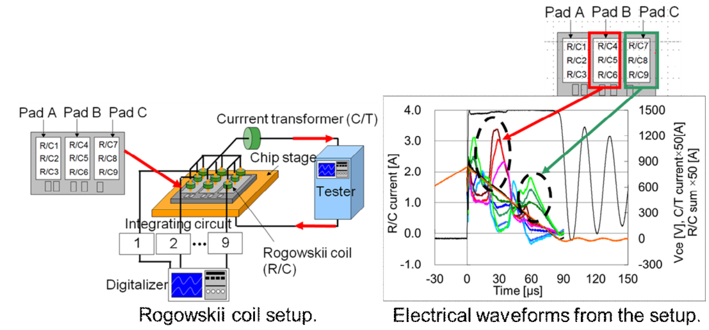

Fig. 5. Rogowskii coil setup.and waveform [2]

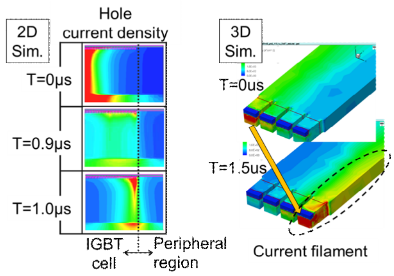

Fig. 6. TCAD Simulation analysis [1],[3]

B. Simulation-Based Study of CosmicRay Iinduced Single-Event Burnouts in Power Devices

Cosmic ray induced single-event burnouts (SEBs) of power devices in HVs have been studied as part of effort to achieve highly reliable design against chance failures [4-6]. There is general agreement that the flux of these particles contains 97% neutrons at sea level. High-energy neutrons are strongly penetrating radiation, and these neutron fluxes consist of about 10 particles cm^{-2} h^{-1} at sea level [7]. Therefore research has focused on the neutrons in terrestrial cosmic rays that cause SEBs in power devices. Strong high-energy neutrons with a broad energy spectrum were provided by the Research Center for Nuclear Physics (RCNP) at Osaka University.

The triggering process of SEBs in SiC power diodes has been investigated by white neutron-irradiation experiments and transient device simulations. Recoil ions created by nuclear spallation reactions between single incident neutrons and the constituent nuclei of the device generate electron-hole pairs along the recoil ion tracks. Transient device simulations have described the initial generated charge along the recoil ion track shown in Fig. 7. During a SEB. a DC voltage is applied between the cathode and the anode.

Fig. 8. shows a simulated SEB current, and the maximum lattice temperature, SiC surface temperature, and aluminum surface temperature of a SiC power diode. The maximum lattice temperature of SiC eventually reaches the sublimation temperature. In contrast, the aluminum surface remains at room temperature. Fig. 9. shows the electric field distributions along recoil ion tracks at the various times shown in Fig. 8. At time 1, the peak electric field is located at the p^+/n^- junction. The electron-hole pairs generated by the incident recoil ions subsequently travel through the n^- region in the device. The density of electrons traveling to the cathode side increases in the vicinity of the n^-/n^+ interface. Therefore, the peak electric field shifts from the vicinity of the p^+/n^- junction to the n^-/n^+ interface owing to the space charge effect. Moreover, punch-through of the electric field occurs at the anode contact. The double-sided electric field distribution corresponds to the diode secondary breakdown [5]. Therefore, the diode behaves locally like a resistor. The displacement current caused by the discharging current from the depletion layer capacitance leads to negative SEB current, at time 4 shown in Fig. 8. SEB current due to impact ionization at the n^-/n^+ interface subsequently flows at time 5. The impact ionization rate has a negative temperature coefficient. Therefore, the SEB current caused by impact ionization decreases in accordance with the increasing lattice temperature at time 6. Finally, the maximum lattice temperature reaches the sublimation temperature of SiC. The simulated peak lattice temperature located in the vicinity of the n^-/n^+ interface and anode contact, and the locations of the peak lattice temperature correspond to the destruction traces shown in Fig. 10.

It was concluded that impact ionization at the n^-/n^+ interface is a key point of the mechanism that triggers SEBs in power devices. An efficient way to suppress double-sided impact ionization is to design a diode with a thicker n^- region. The SEB threshold voltage can be designed by optimizing the device parameters.

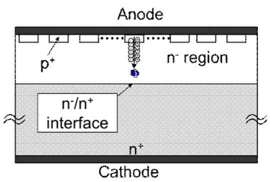

Fig. 7. Cross-sectional view of simulated SiC power diode [6].

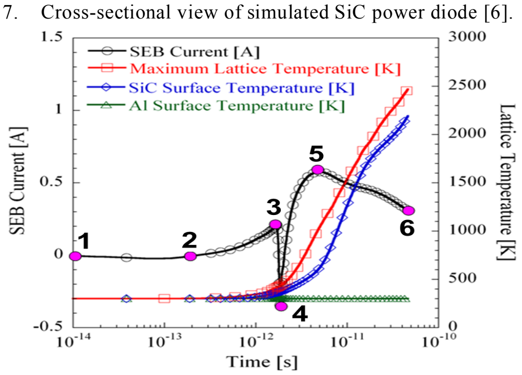

Fig. 8. Simulated SEB current, maximum lattice temperature, SiC surface temperature, and Al surface temperature of SiC power diode [6].

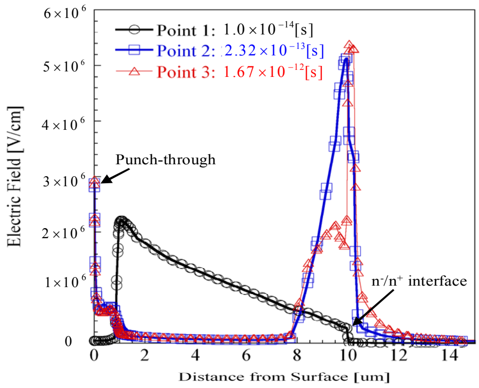

Fig. 9. Electric field distributions along recoil ion tracks at various times shown in Fig. 8 [6].

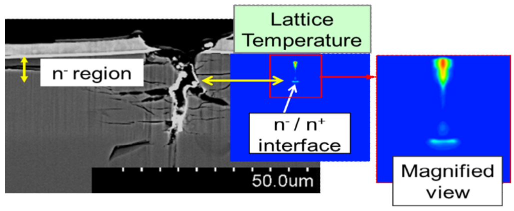

Fig. 10. Cross sectional scanning electron microscope (SEM) view of SEB destruction trace and simulated lattice temperature at time 6 shown in Fig. 8.

C. SiC nano-scale pit simulation

Recent requirements for power devices for EVs, HVs, FCVs, and power conversion include the capability to handle larger currents and an increased active area. However, commercial silicon carbide (SiC) diodes only have a rated current of between 6 and 50 A, and a small size of 1.0-12mm2. In contrast, SiC diodes used in hybrid systems have a rated current of several hundred A and an active area size of at least 25mm2. As a result, as the active area size increases, product yield deteriorates dramatically due to greater leakage current and decreasing breakdown voltage in reverse current voltage (I-V) characteristics.

It is widely known that several types of crystal defects in epitaxial wafers cause reverse I-V characteristics to deteriorate. The risk of these crystal defects occurring increases in accordance with the size of the active area, resulting in lower product yield. Although the impact of threading dislocations on device characteristics has been studied, there is little agreement on the relationship between I-V characteristics and threading dislocation density. As described in the previous report, a positive correlation was identified between leakage current density and threading dislocation density in junction barrier Schottky diodes (JBSDs) in very small leakage current regions when the diode is reverse-biased. However, the impact of threading dislocations on leakage current has not been identified for each of the different types of diodes such as Schottky barrier diodes (SBDs), JBSDs, and PN junction diodes (PNDs). Furthermore, the impact of threading dislocations on leakage current has not been identified for each of the different types of dislocations such as spiral, edge, and basal plane. Therefore it is necessary to identify the mechanism by which dislocations cause diode leakage current to increase.

This study used TCAD to analyze the impact of threading dislocation density on leakage current in SBDs. Fig. 11. shows the simulation model. The impact of nano-scale pits on the leakage current was analyzed by device simulation (Fig. 12). Without nano-scale pits, it was found that the leakage current density increased linearly with respect to the reverse voltage. However, with nano-scale pits, an electric field concentration several times larger than that generated with a flat Schottky interface occurred at the nano-scale pit peaks (Fig. 12, Sample A). Therefore the leakage current density at -200 V suddenly increased, forming a clearly convex-shaped IV characteristic. The magnitude of the leakage current at -1,200 V was also found to be greater for samples with nano-scale pits. Accordingly, it was concluded that nano-scale pits have a major impact on leakage current in SBDs.

Next, JBS diodes with and without nano-pits were fabricated to verify the impact of nano-pits on the leakage current. The diodes with nano-pits are referred to as sample A and those without pits are referred to as sample B. Fig. 14. shows typical reverse I-V characteristics of sample A and sample B 200 A-class JBS diodes. The leakage current in sample A increased suddenly to 10-6 A/cm2 at 100 V. Current fluctuated from 10-5 A/cm2 to 10-4 A/cm2. The leakage current waveform has a convex-shape, which is similar to the simulation results for a diode with nano-pits (Fig. 12). In contrast, the leakage current in sample B is extremely low, from 2×10-7 A/cm2 to 3×10-6A/cm2 at 1,200 V. The leakage current waveform of sample B was a theoretical straight line (Fig. 12). Finally, TCAD was applied to analyze the mechanism of the increasing leakage current and to find an essential solution for this issue.

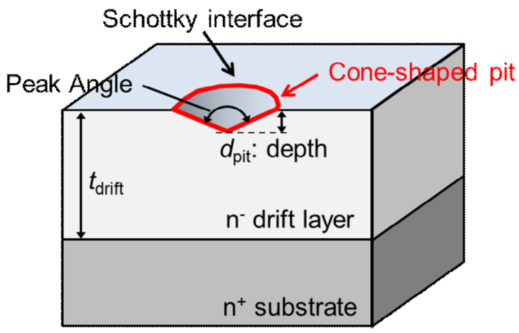

Fig. 11. SiC nano-pit simulation model

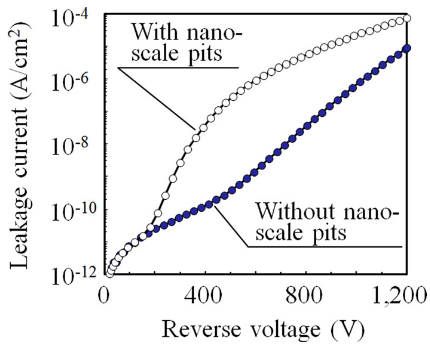

Fig. 12. Reverse I-V characteristics of device simulation

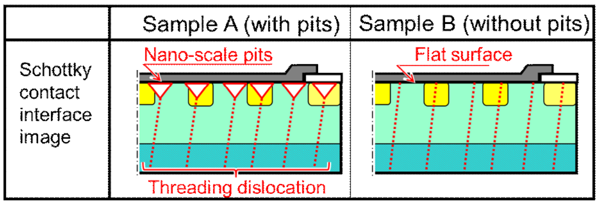

Fig. 13. Mechanizm of leak current with pits and without pits

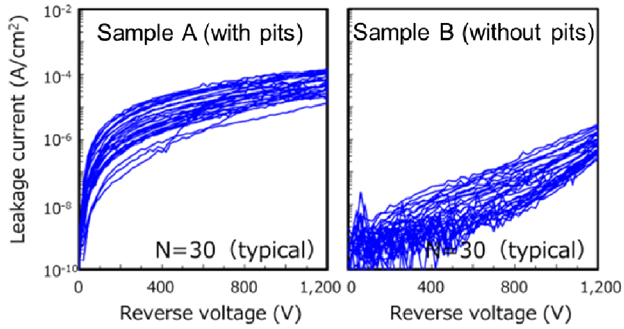

Fig. 14. Reverse I-V characteristics of experimental

VI. Summary

Automotive semiconductors are used in various environments and require high reliability. In addition to helping to design power semiconductor device structures with lower loss, TCAD is also being utilized to analyze physical phenomena inside devices. For this reason, TCAD is an extremely useful tool for improving the reliability and ruggedness of power semiconductor devices.

TCAD is also expected to play a major role in the future development of wide bandgap semiconductors such as SiC.

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