Opening windows for silicon carbide junction termination extensions

Companies keen to commercialize SiC for high-voltage power applications need production flows that are robust against process variation. Mike Cooke reports on attempts to improve the effectiveness of junction termination extensions across a range of parameters.

Power devices fabricated using silicon carbide (SiC) technology benefit from a high critical electric field of 3MV/cm due to the wide energy bandgap of 3.26eV. Also attractive for power applications is high thermal conductivity in the range 3–3.8W/cm-K. Despite the difficulties in working and processing the material, a range of companies is developing SiC for a range of high-voltage power applications.

Market analysis firm Yole Développement says that there are more than 30 companies worldwide that have established dedicated SiC device manufacturing. According to Yole, Infineon and Cree lead the way, with Rohm, STMicroelectronics and Mitsubishi Electric also in the running. In Japan, there are also Fuji Electric, Panasonic, Toshiba, and Hitachi.

China has Global Power Technology commercializing SiC power devices with a capacity of 1000 wafers per year. The big State Grid Corporation of China and China South Locomotive & Rolling Stock Corporation Ltd are developing SiC devices for grid and rail applications, respectively. In addition, automobile and electronics company BYD Co Ltd has tested Cree SiC devices for electric and hybrid electric vehicles.

In other parts of Asia, Taiwan's Hestia Power is a fabless developer that has begun commercializing SiC diodes, and in Korea Maple Semiconductor and

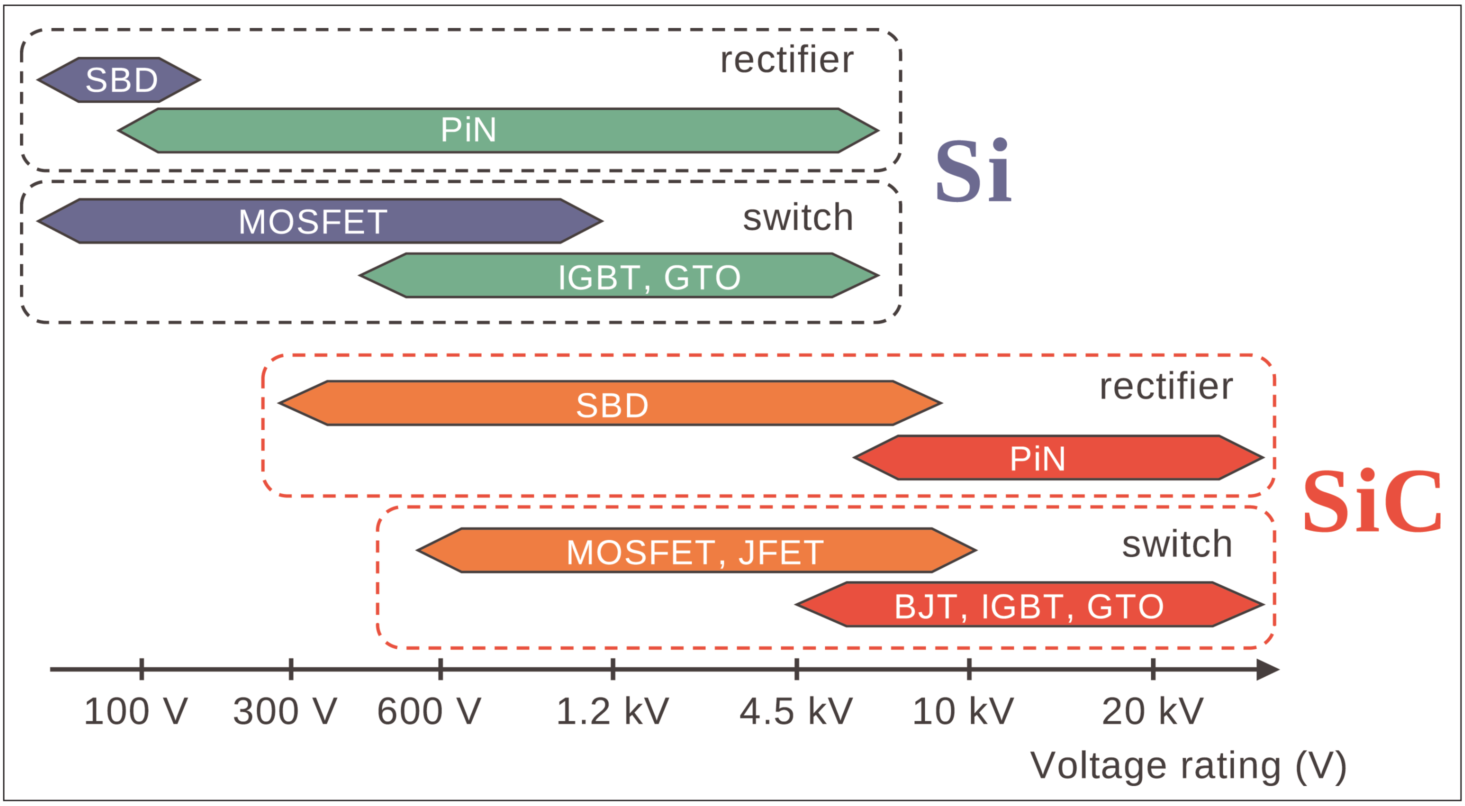

Figure 1. Major territories of individual unipolar and bipolar power devices for Si and SiC in terms of rated blocking voltage, according to a recent review [Tsunenobu Kimoto, Jpn. J. Appl. Phys., vol54, p040103, 2015].

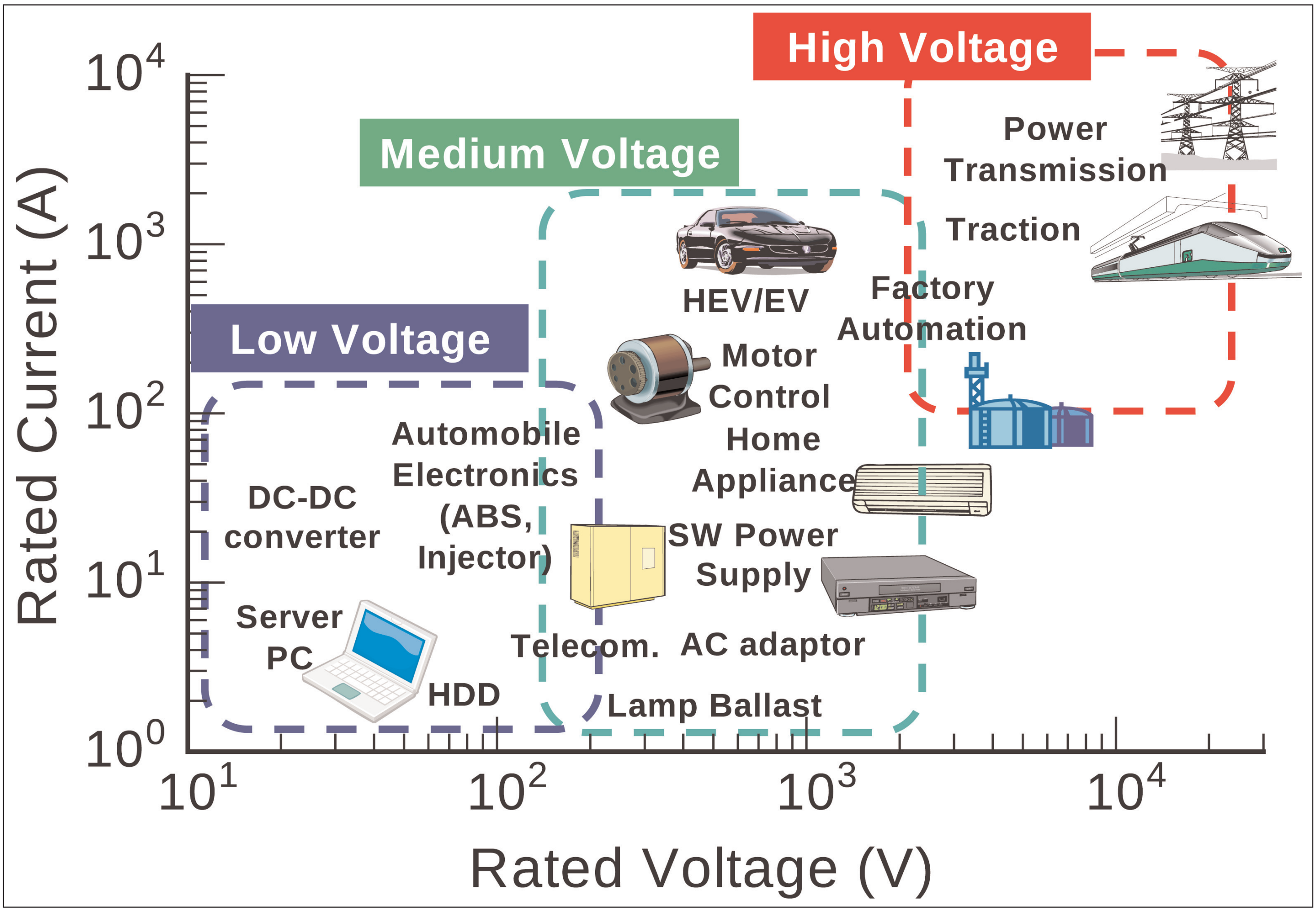

Figure 2. Major application areas of power devices plotted as a function of rated voltage [Tsunenobu Kimoto, Jpn. J. Appl. Phys., vol54, p040103, 2015].

Hyundai have agreed to jointly develop SiC technology.

Market analysts and developers see potential applications for SiC's high voltage (up to 1.7kV, according to Yole, although higher ratings of more than 25kV have been achieved in the laboratory — see Figure 1), frequency and temperature capabilities in rail, electric vehicle and hybrid electric vehicle (EV/HEV), electricity grid and renewable energy, such as wind and solar power (Figure 2). Typical subsystems that could benefit include power factor correction (PFC) circuits and inverters for DC to AC conversion. Meanwhile gallium nitride — another wide-bandgap material with high critical field that can be grown on large-area silicon, reducing production costs — is being developed for power switching at relatively low voltages, compared with SiC.

Electric power is growing in importance — comprising 22.3% of total final energy consumption in 2012, according to the International Energy Agency. SiC has the potential to improve delivery at low cost through more efficient power conditioning and conversion. Presently, power conversion steps lose between 5% and 15% of energy throughput to heat.

Although problems with SiC crystal growth and device processing have been largely overcome, there continue to be concerns related to defects and reliability.

Edge terminations are designed to avoid field crowding effects that cause premature breakdown. Various groups have developed a number of techniques such as floating field rings, junction termination extension (JTE), and multi-step etched JTE. The aim of these methods is to shift and reduce the peak field to where it can do least harm to device performance and reliability.

Unfortunately, these techniques can take up a large amount of space on the chip (about three times the drift layer thickness) — an economic concern, given the high price of silicon carbide substrates. Added process complexity also increases production costs. The techniques also suffer from a narrow window for process variations such as critical dimensions and doping implant dosage, which naturally hits the yield of devices working to spec.

The nature of silicon carbide makes standard isolation techniques such as trench etching difficult. For SiC, this would need deep reactive ion etch, which can be prohibitively time consuming given the hardness of the material.

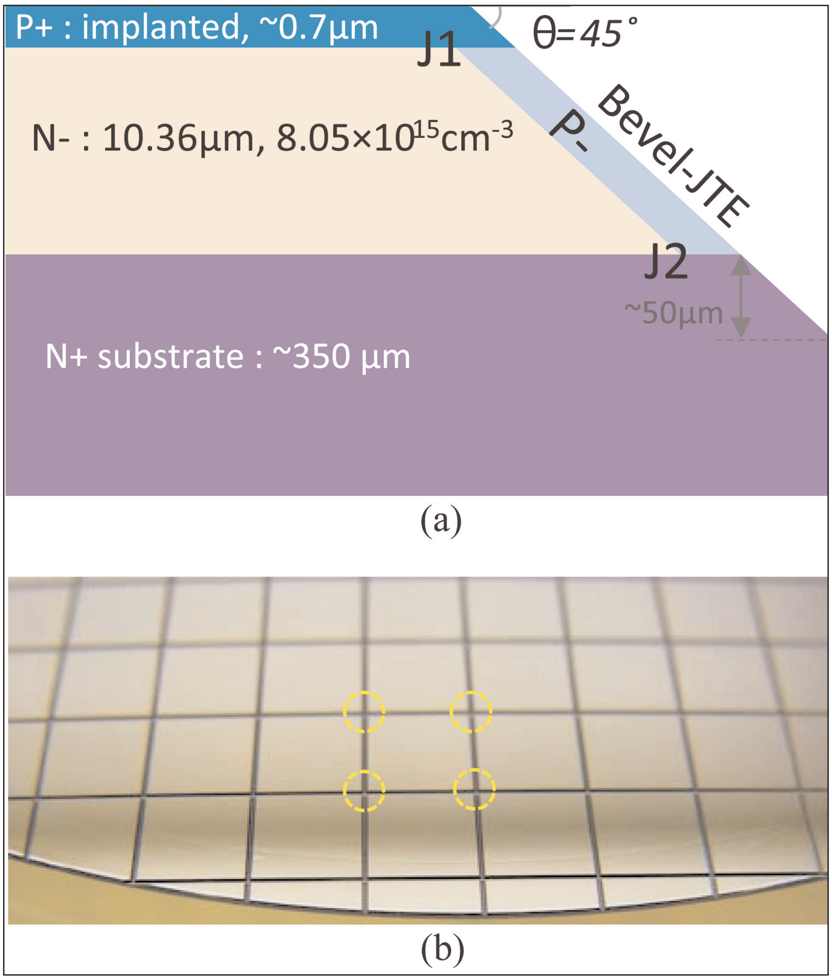

Figure 3. (a) Schematic cross section of a PiN rectifier with the Bevel-JTE. Over-diced area into the substrate is used for the final dicing, (b) wafer image after bevel dicing. Corners of the Bevel-JTE are indicated by dashed circles.

Bevel JTE

North Carolina State University (NCSU) in the USA has developed a new edge termination technique for 4H-SiC high-voltage devices [Woongje Sung et al, IEEE Electron Device Letters, published online 29 April 2015]. The technique involves beveling the device and creating a JTE with implanted aluminium doping (Figure 3).

The researchers used an angled dicing blade to create the bevel. Angles between 30º and 90º could be achieved easily. The angle and feed speed were chosen to reduce surface roughness and chipping.

The doping of the JTE needs to be adjusted to avoid locating the high field at either the bottom of the pn junction (high doping) or at the main junction (low doping). Both extremes result in lowered breakdown voltage. The high doping condition also increases leakage currents.

A range of 4H-SiC PiN rectifiers was fabricated with a chip size of 4mmx4mm. The top p^+ layer was doped with aluminium implantation of total

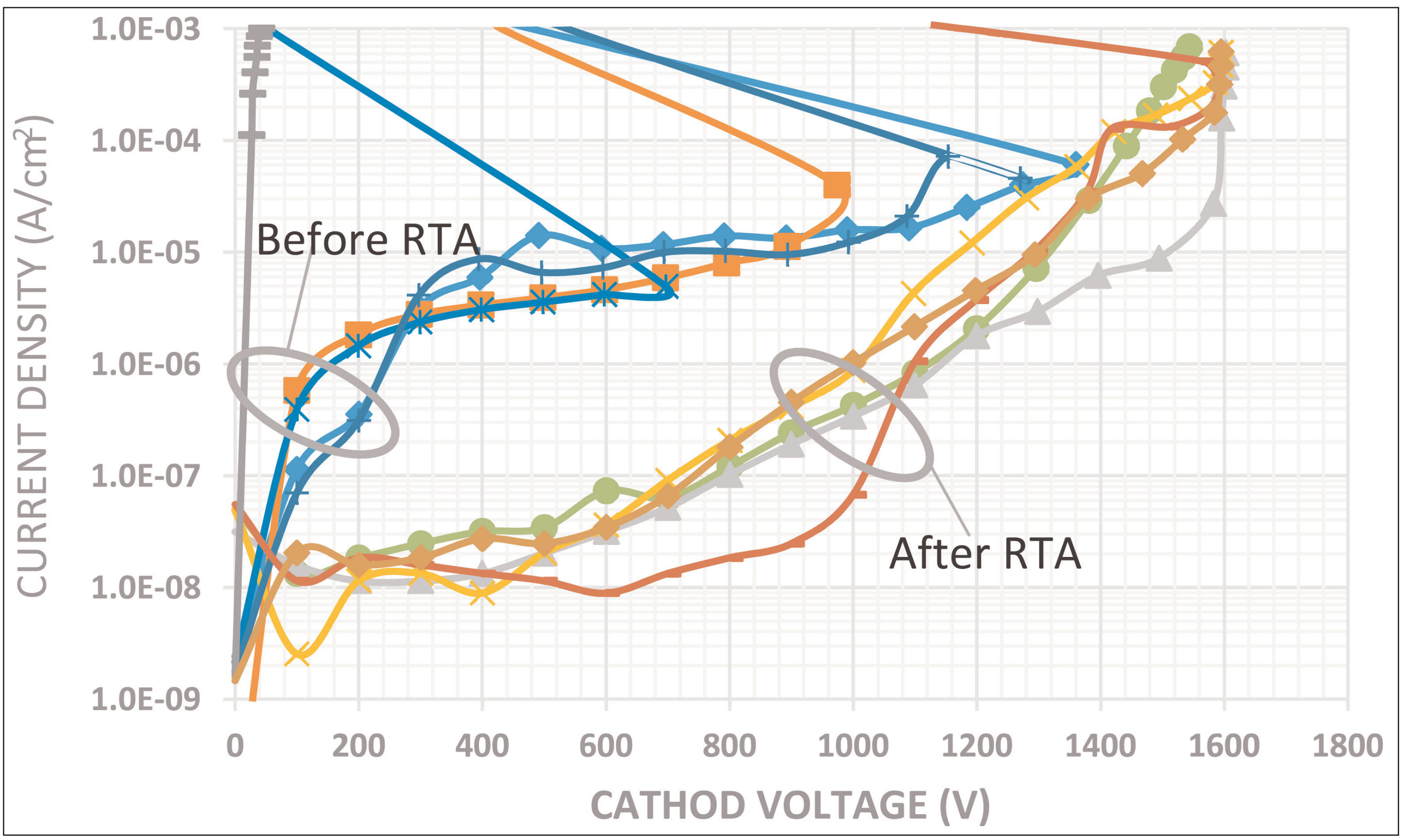

Figure 4. Effect of RTA on reducing leakage current. Reverse blocking characteristics before and after the RTA process on same dies implanted at $2x10^{13}/cm^2$.

dose $2x10^{15}/cm^2$ at 300keV.

The bevel-JTE was formed using orthogonal bevel dicing and ion implantation. The dicing blade was V-shaped with a 45º angle. Damage from the sawing step was removed with a 0.3µm reactive ion etch. Doping activation was achieved with annealing at 1800ºC for 5 minutes. Leakage current could be reduced by rapid thermal annealing (RTA) at 1000ºC for 1 minute in laughing gas, more soberly known as nitrous oxide (N_2O).

The researchers achieved a maximum breakdown voltage of 1600V with an anode current density of $1mA/cm^2$. The breakdown was 95% of the maximum theoretical value for a one-dimensional model. Bevel implant doses in the range $1–2x10^{13}/cm^2$ gave the maximum breakdown. The breakdown was reduced to ~$800V$ for $3x10^{13}/cm^2$ dosage due to current leakage.

Comparison with simulation results suggests incomplete activation of the doping (~50%). The researchers suggest that the annealing may evaporate some of the dopant and create unintentional doping elsewhere in the structure. "This results in higher measured breakdown voltages than shown by simulation," the team adds.

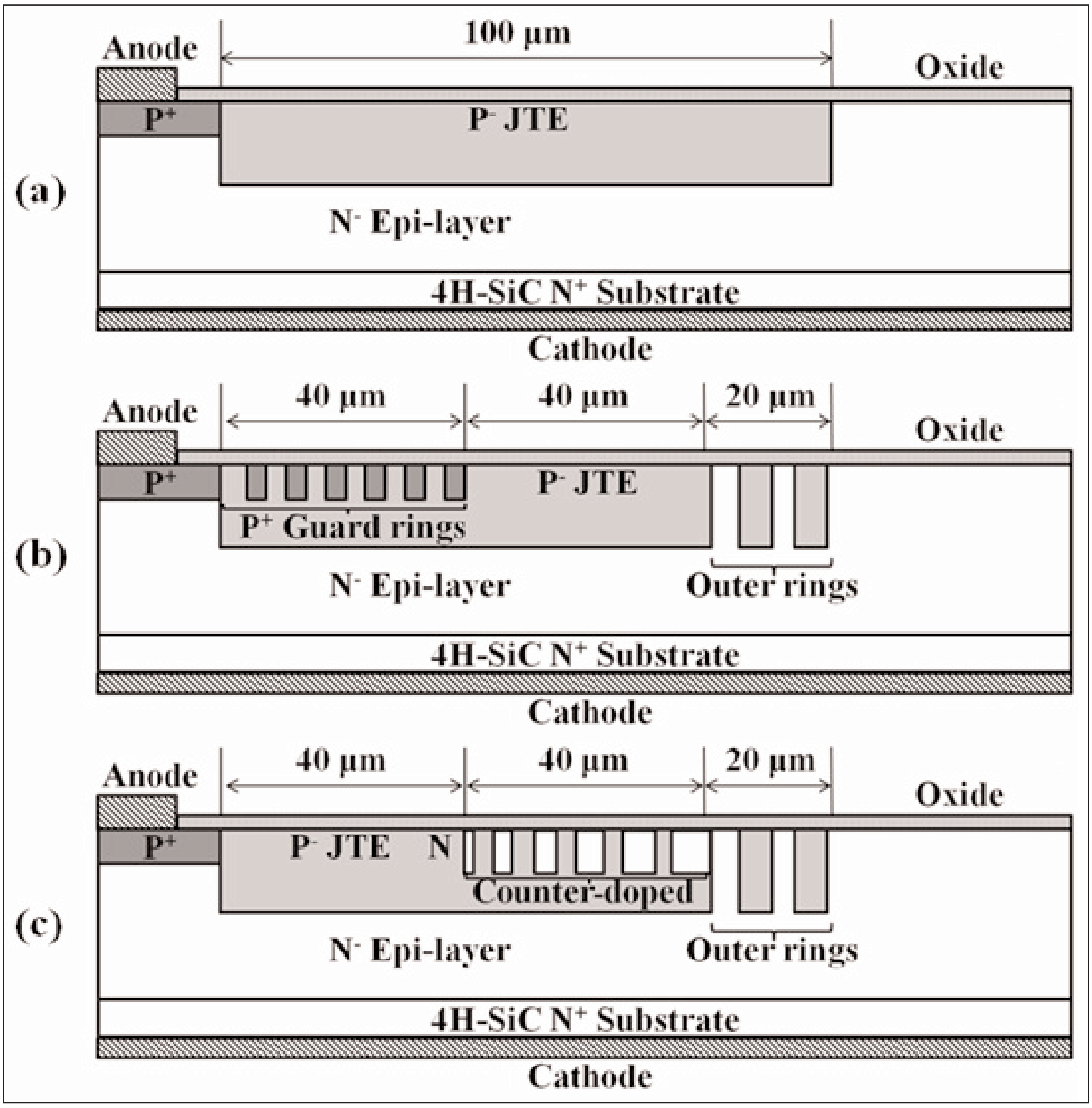

Figure 5. Cross-sectional schematics of three termination structures: (a) single-zone (SZ) JTE, (b) GAJ plus ORs, and (c) CD-JTE plus ORs.

Since the Bevel-JTE is fabricated with a dicing blade, it can be simply applied to any vertical device in SiC that has a drift layer of different thickness by adjusting the dicing depth. It is more attractive to use the Bevel-JTE structure for higher-voltage devices because a significantly large area of the wafer is occupied by edge termination structures using conventional approaches

The RTA process reduced current leakage significantly (Figure 4). The researchers attribute the improvement to curing of implant-induced defects and damage, reducing the concentration of active carrier trapping centers.

The researchers comment: "Since the Bevel-JTE is fabricated with a dicing blade, it can be simply applied to any vertical device in SiC that has a drift layer of different thickness by adjusting the dicing depth. In fact, it is more attractive to use the Bevel-JTE structure for higher-voltage devices because a significantly large area of the wafer is occupied by edge termination structures using the conventional approaches."

The team estimates that the bevel-JTE is three times narrower than conventional approaches to edge termination. Also, the complexity and implant dose sensitivity is reduced. The researchers believe that the technique can be used for other devices with different ranges of breakdown voltage.

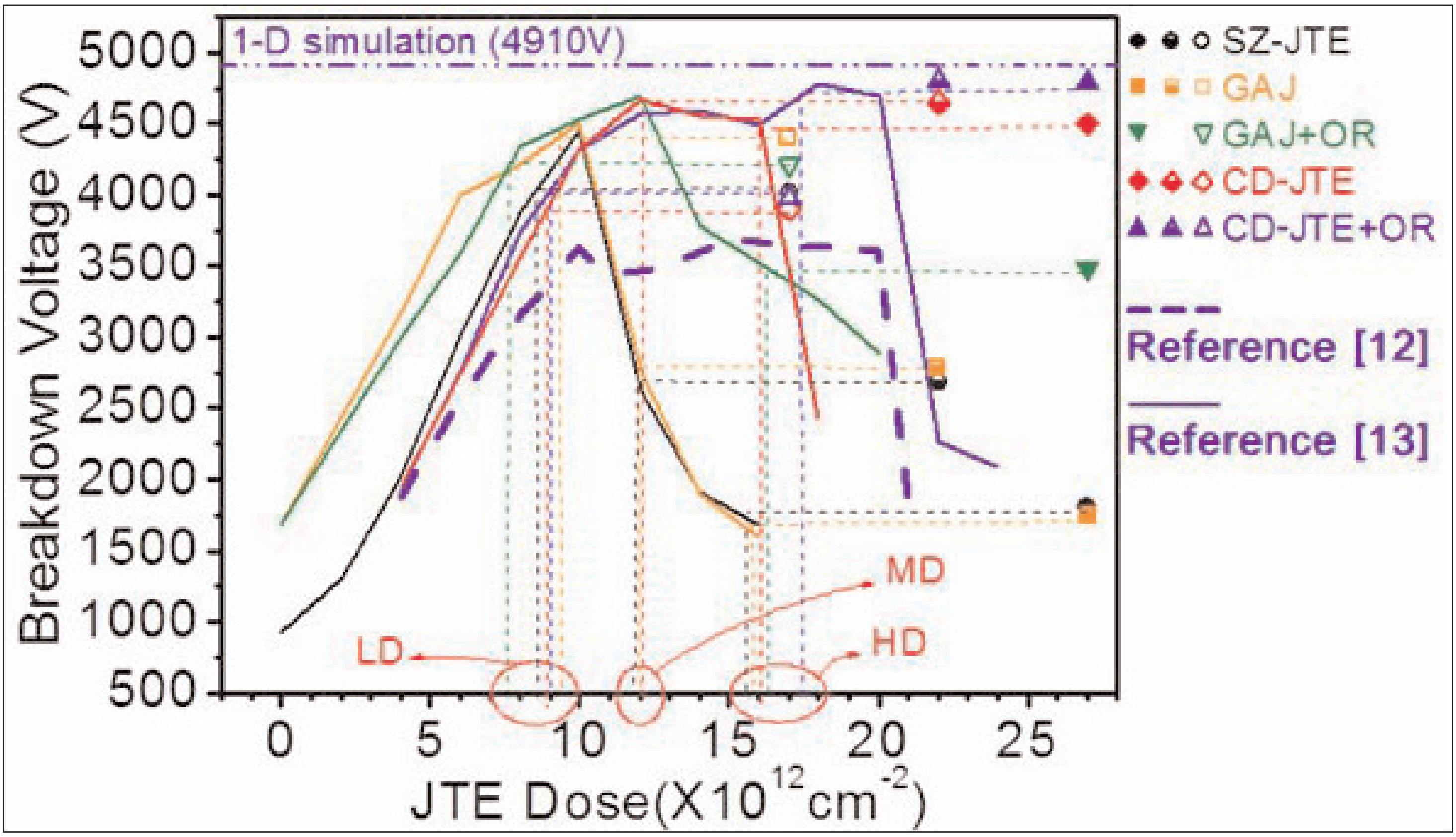

Figure 6. Reverse breakdown voltages (BVs) measured on 30μm PiN diodes with all termination structures and high (HD), medium (MD), and low (LD) JTE doses. Also shown are simulation results using two different impact ionization models (dashed and solid line).

Counter doping

Another approach to improving JTEs has been developed by Taiwan's National Tsing Hua University and Washington State University in the USA [Jheng-Yi Jiang et al, IEEE Electron Device Letters, published online 30 April 2015], based on theoretical work carried out in conjunction with Taiwan's Industrial Technology Research Institute [Chih-Fang Huang et al, IEEE Transactions on Electron Devices, vol.62, p.354, 2015].

The researchers were keen to produce JTEs with larger process windows in terms of giving a wider implant dose range. In particular, the theoretical work suggested that suitable counter-doping (CD) could increase the dose range for JTEs. Alternative JTE strategies, involving guard-ring assisted junctions (GAJs) around the anode or outer rings (OR), were produced for comparison and combination with counter-doping (Figure 5). The theoretical simulations also suggest reduced sensitivity of performance to the presence of surface charges for the CD strategy.

Table 1. Breakdown voltages for different device structures with 30μm drift layer.

Structure	Breakdown
SZ-JTE	~2000V
GAJ	~2000V
GAJ+OR	3500V
CD-JTE	4420V
CD-JTE+OR	4720V

PiN devices were produced using N^- epitaxial layers and P^+ main junction implants of aluminium at up to 180keV. The JTE P^- doping was achieved with implants up to 360keV. The N-type counter-doping used phosphorus implants at up to 200keV. The implants were activated with annealing at 1650ºC for 10 minutes in argon, where the surface was protected with a carbon cap layer. The researchers believe that the activation was around 60% for the JTE and 70% for the counter doping.

The annealed ohmic contacts were titanium/aluminium/nickel for the anode and titanium/nickel for the cathode. The active area of the devices was $7.85 \times 10^{-3} cm^2$.

The measured specific on-resistance for devices with 30μm n-type epilayers ranged between 7.75mΩ-cm^2 and 8.57mΩ-cm^2 with diode ideality of about 1.6. The reverse leakage current was of the order of nanoamps — the accuracy of the measurements was limited by the noise floor of the equipment (~10^{-7}A/cm^2).

A series of different device structures was tested for breakdown in Fluorinert liquid (Figure 6, Table 1). The highest breakdown of 4720V occurred for CD-JTE with outer rings (OR). A thinner n-type epitaxial layer of 11μm gave a breakdown of 1850V for the CD-JTE+OR structure with medium and high doping. ■

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