

Wide load potential for electric vehicles

The enhanced material properties of wide-bandgap materials beckon for developers of electric vehicles.

Mike Cooke reports.

Environmental concerns have fallen off the agenda somewhat in recent months with the focus on economic recovery. However, the basic long-term concerns remain in building efficient systems capable of harnessing existing and future energy creation and conversion technologies. For transportation, hybrid electric vehicles (HV or HEV), pure electric (EV), and fuel cell hybrids (FCHV) are being considered to reduce the reliance on gasoline, and to reduce exhaust and global warming gas pollution.

These systems require greater control over high-power electricity compared with traditional fossil fuel vehicles. Power inverters are used to convert from the direct-current battery or fuel cell to the kilohertz currents needed to drive high power motors (>10kW). Hybrids also want to conserve excess energy generated during braking and convert the power back to storage. Such demands require switches that can handle high power, current and voltage. One also wants to develop intelligent power systems for response and efficiency — that means producing power semiconductor systems that have extreme capabilities.

The US Department of Energy has set a number of targets for HEVs for 2020: the power electronics should have a power density better than 14.1kW/kg and 13.4kW/liter as well as efficiency better than 98%, all at a price of less than \$3.3/kW.

Existing silicon IGBTs

Commercial HEVs/EVs presently use silicon-based insulated gate bipolar transistors (IGBTs), combined with suitable diodes, as the main driving switch. For hybrids particularly, where the electric power is running in tandem with a high-temperature fossil fuel engine, silicon is not the ideal semiconductor material (see Table). These devices require a secondary cooling system to maintain suitable junction temperatures (e.g. ~85°C). Also, materials with higher breakdown voltages are desired to enable the use of higher-power motors and to protect against surge voltages.

The wide-bandgap semiconductor silicon carbide (SiC) has the potential to operate up to 600°C, so interfacing with standard engine coolant systems aiming at 105°C should be easy. Jettisoning special cooling would cut cost. Also, SiC's breakdown voltage is ten times that of silicon. Since the devices are smaller, the capacitance is lower and switching can be faster. Losses can be lower during both turn-on and turn-off. SiC also has much better thermal conductivity, allowing fast heat transfer out of the device. However, SiC is a difficult material to grow and work — developments are still needed in terms of wafer quality and size, gate isolation and packaging to handle the higher-temperature environment. Once mature, the technology could enable significant reductions in weight and size, and increases in efficiency.

Gallium nitride (GaN) is another wide-bandgap semiconductor with potential that is being explored. This option also has a high breakdown field and high carrier saturation velocity, along with better carrier mobility. Longer term, diamond films may be developed for such applications, but we will not consider this possibility here.

Table 1. Sample of material properties for application to high-power electronics. Source: Tolbert et al, Oak Ridge National Laboratory report on 'Power electronics for distributed energy systems and transmission and distribution applications', 2005.

Property	Unit	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Band gap	eV	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant		11.9	13.1	9.66	10.1	9	5.5
Electric breakdown field	kV/cm	300	455	2500	2200	2000	10000
Electron mobility	cm ² /Vs	1500	8500	500	1000	1250	2200
Hole mobility	cm ² /Vs	600	400	101	115	850	850
Thermal conductivity	W/cmK	1.5	0.46	4.9	4.9	1.3	22
Saturated electron drift velocity	10 ⁷ cm/s	1	1	2	2	2.2	2.7

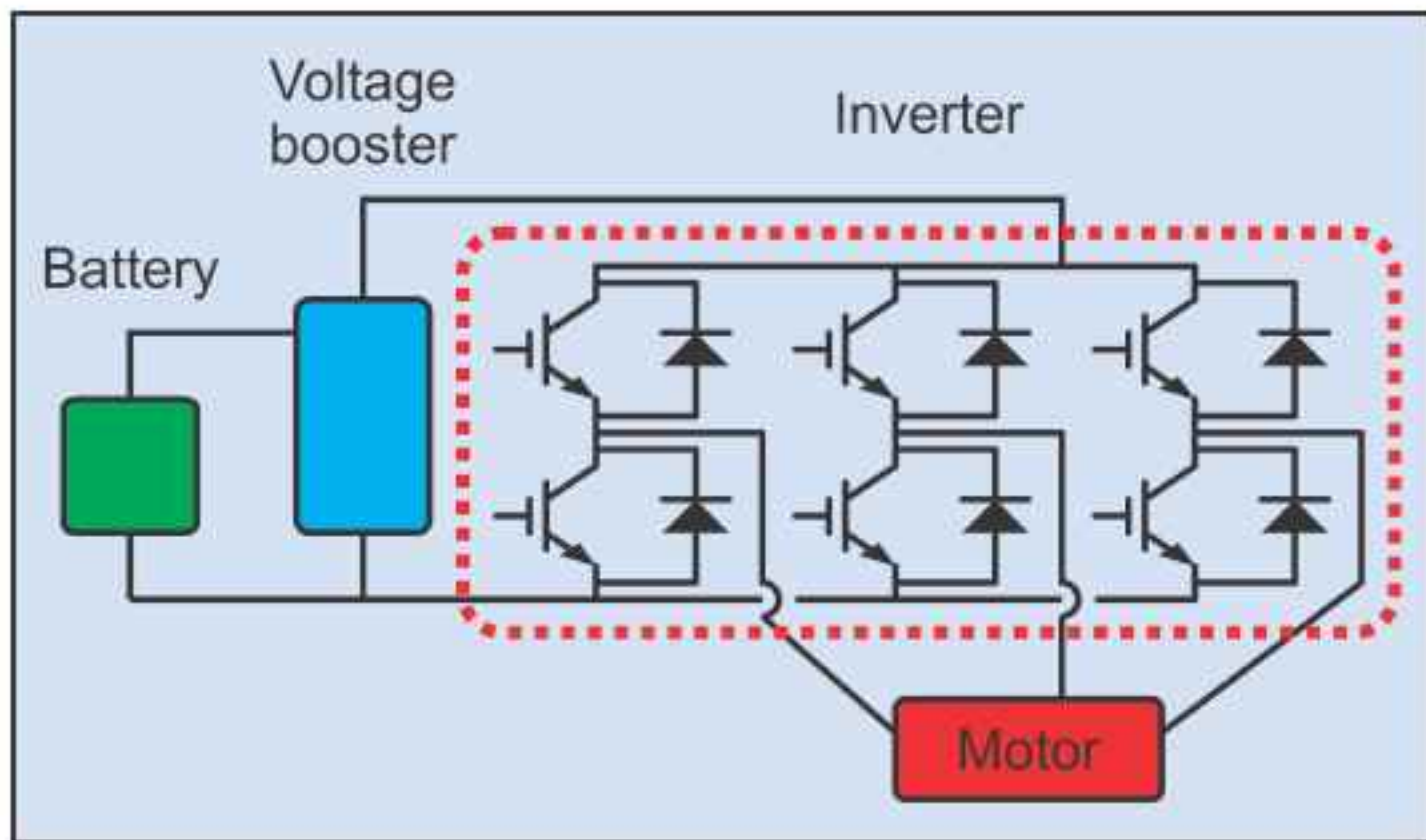


Figure 1. Typical set-up for powering electric motor from battery supply, as used in Toyota Prius.

Automobile traction

The first successful hybrid electric vehicles for the general automotive market came out of Japan in the 1990s with the Toyota Prius and the Honda Insight. While the Prius is a parallel-series hybrid, meaning that the electric motor can operate the car on its own, the Insight's electric power is used to 'assist' the main engine. The difference is seen in the amount of power that the electric motors need to deliver: 60kW for a recent model of the Prius; 10kW for the Insight. Both vehicles have gasoline engines capable of around 70kW. These vehicles, along with the ranges coming from US and European competitors, are based on silicon IGBT technology.

However, these companies are not blind to the advantages that would accrue to successful implementation of wide-bandgap alternatives. Toyota recently presented some of its GaN power device research [Tutomu Uesugi and Tetsu Kachi, 'GaN Power Switching Devices for Automotive Applications', CS MANTECH Conference, 2009].

Toyota has produced a range of HVs since the first Prius in 1997. While the first Prius used a 277V battery

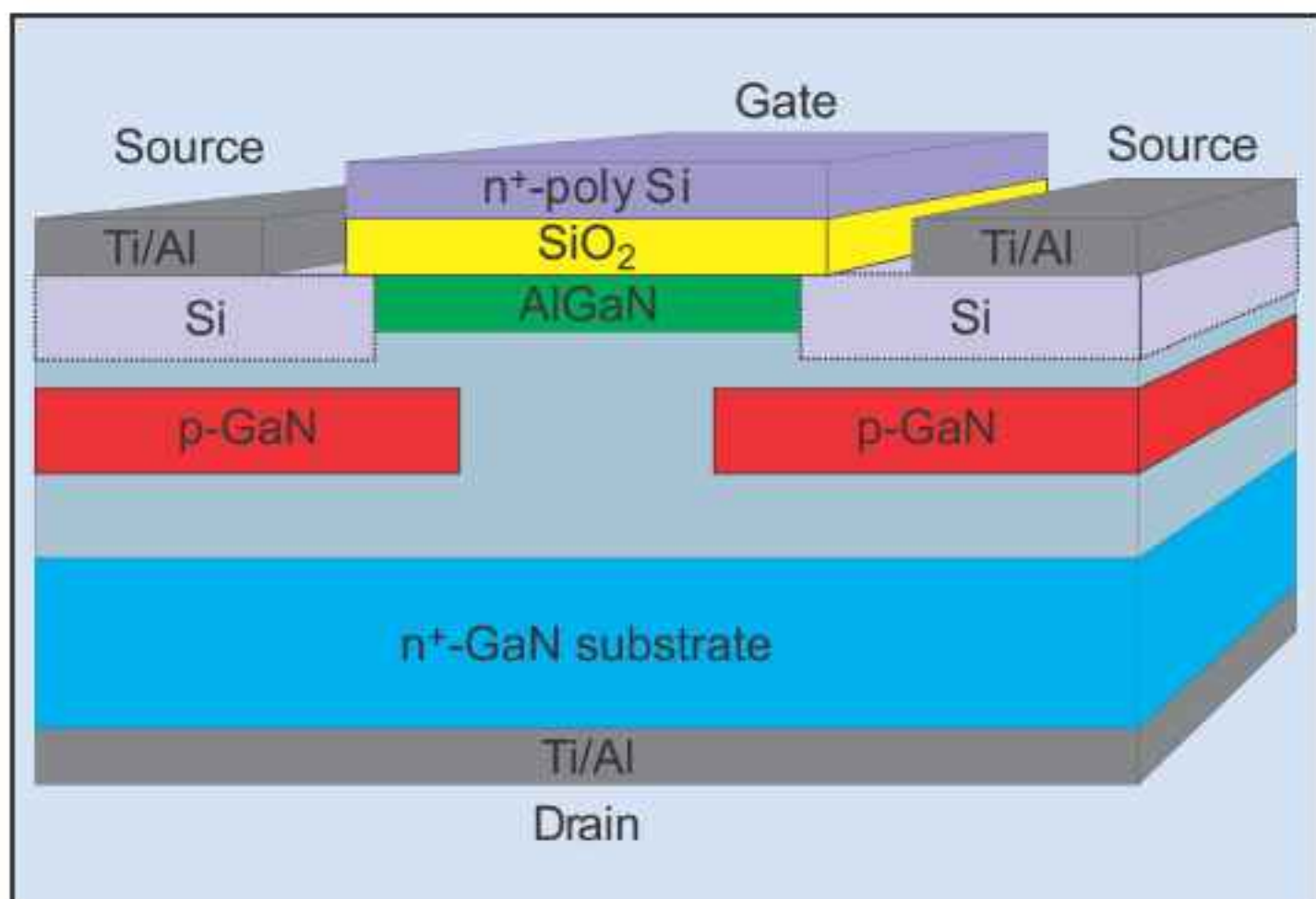


Figure 3. Schematic of Toyota GaN-based heterojunction field-effect transistor (HFET), which is targeted at vehicle applications.

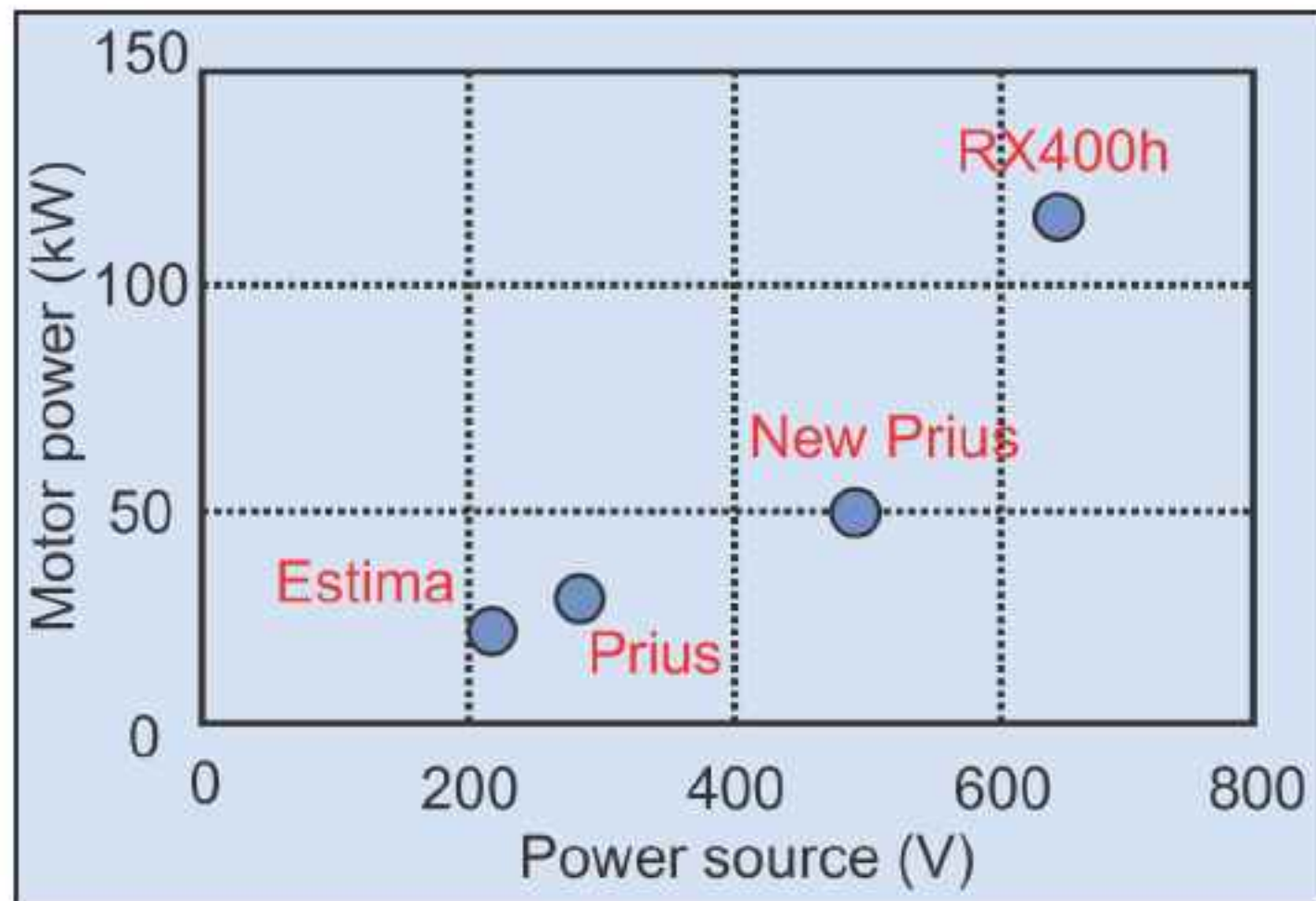


Figure 2. Toyota has been increasing the voltage level to enable higher-power motors in its electric vehicles.

directly connected to the inverter stage, later versions (from 2003) have used a voltage booster from 202V to 500V before linking into inverter and motor (Figure 1). Some newer HV systems have increased the voltage boost beyond 600V (Figure 2). The present silicon-based component used in HV inverters has a breakdown voltage of about 1kV.

For HV applications, Toyota is attracted to gallium nitride due to its wide bandgap, high breakdown electric field and high saturation velocity. AlGaN/GaN field-effect transistors have been developed mostly in the lateral direction, aiming at relatively low power (of the order of Watts) and high frequency (of the order of gigahertz) for applications such as RF power amplification. For high power (defined in the paper as 20–30kW) and the lower frequencies of electric motors, a vertical structure is most suitable for small chip sizes, simple wiring, and high breakdown. 'Current collapse', which is a feature of lateral devices, is not expected to be a problem in the new format. The current collapse phenomenon is associated with

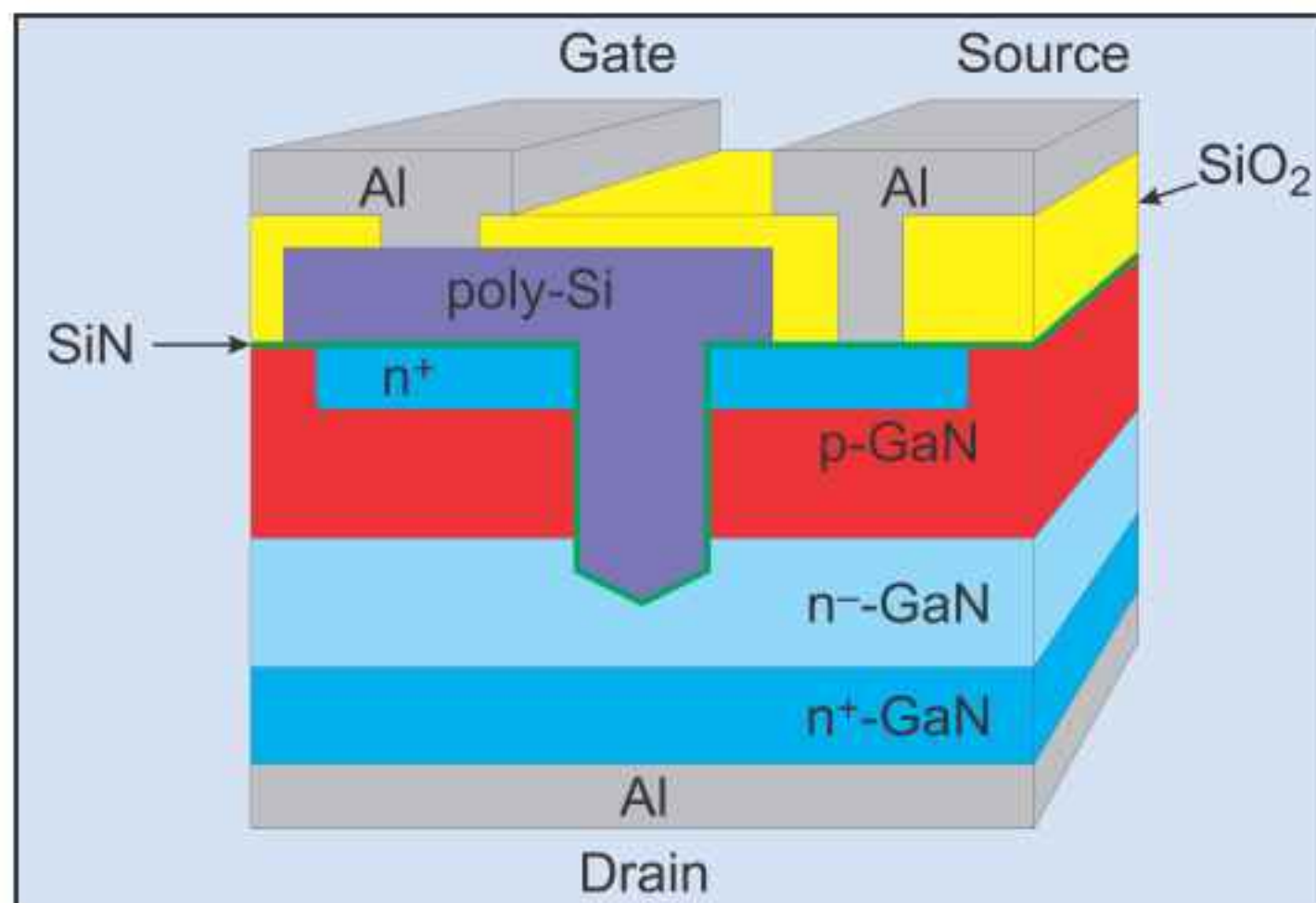


Figure 4. Schematic of Toyota GaN-based metal-oxide field-effect transistor using U-shape trench structure (UMOSFET).

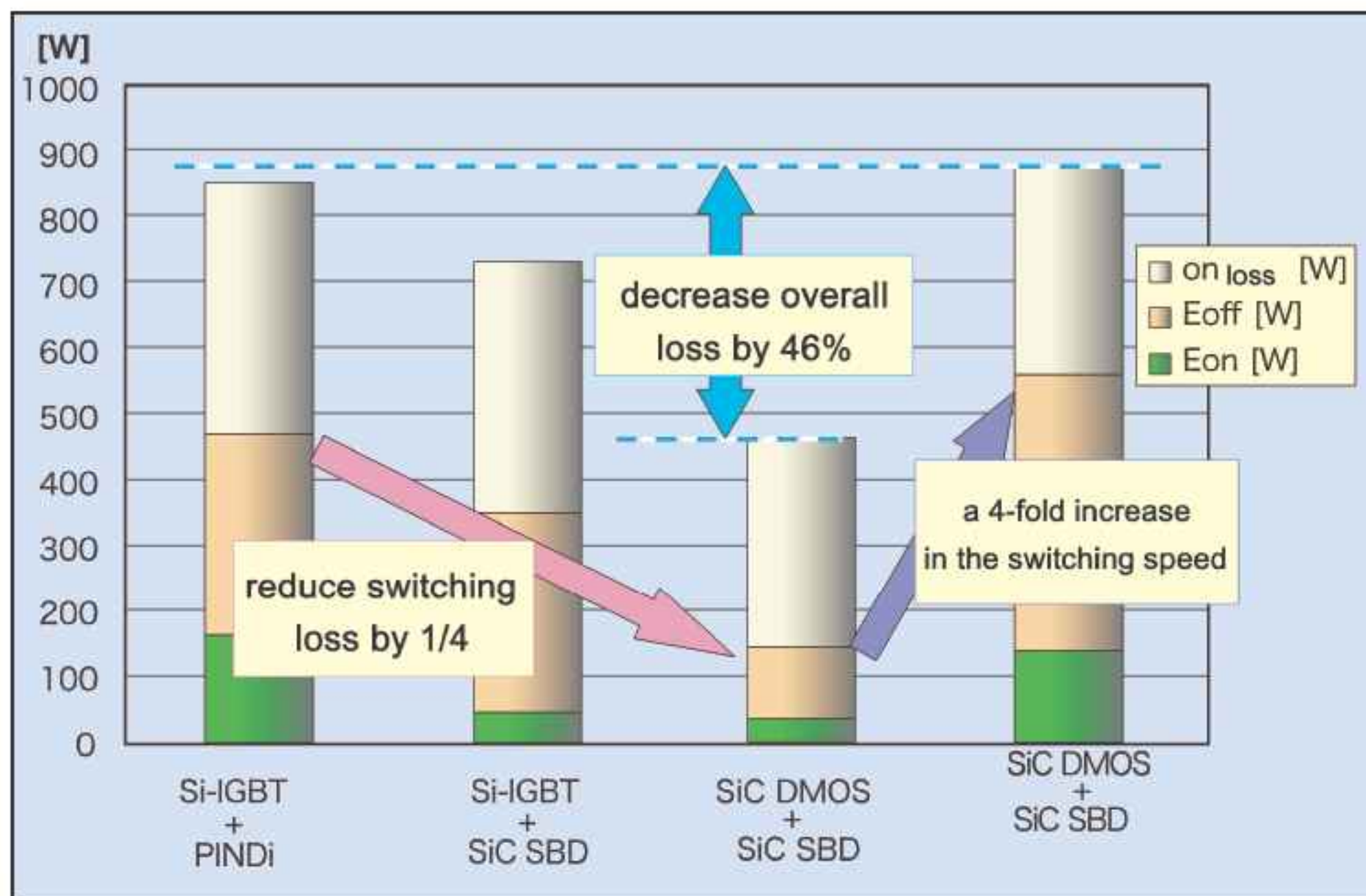


Figure 5. Comparison by Rohm and Honda of losses for various configurations of SiC implementation to replace silicon diodes and IGBTs.

the effect of surface states on current flow. The vertical structure current flow is through the bulk of the material, not just a thin layer near the surface, and hence surface effects are much less significant.

However, running current through the bulk, one may worry that other breakdown mechanisms may come into play from the relatively high dislocation density in such materials, favoring the use of higher-quality free-standing material. Recently, 2-inch substrates of such material have become available from several suppliers.

Toyota has explored two GaN MOSFET types: an AlGa_N/GaN heterostructure FET similar to the double-diffused Si MOSFET (Figure 3), and a device with a U-shape trench (Figure 4).

The HFET used a polysilicon gate with high-temperature silicon dioxide (HTO) insulation. The source/drain electrodes were titanium/aluminum stacks. The current is blocked using a magnesium-doped p-GaN blocking layer. The gate channel consists of the AlGa_N/GaN interface, which enables flow through an



Figure 6. Nissan's X-TRAIL fuel cell vehicle.

aperture in the center of the blocking layer. Metal-organic chemical vapor deposition (MOCVD) was used, along with inductively coupled plasma (ICP) etching of the aperture in the blocking layer. Silicon ion implants were made to form the source regions. Isolation came from nitrogen ion implantation. The gate stack growth was by low-pressure chemical vapor deposition (CVD).

Unfortunately, the resulting device broke down at a mere 50V. The researchers attributed this to the floating nature of the p-GaN blocking layer. This means that the bulk of the drain voltage is applied across the gate oxide, where the failure occurs. Suggested improvements include ohmic contacts on

the p-GaN layer, along with thicker p-GaN and n-GaN (drift) regions.

For the trench gate structure, the problem is obtaining smooth side walls enabling a suitable gate channel current flow. Dry-etch (plasma) trenches are not smooth enough, so the Toyota team developed a dry-wet combination: ICP was used to form a V-groove that was then continued to a U-groove using a tetramethyl-ammonium hydride (TMAH) wet process. TMAH is commonly used to develop photoresists and for anisotropic etching of silicon. In the GaN structure developed by Toyota, the TMAH created smooth m-plane side-walls. Again, polysilicon and HTO were used for the gate structure for an accumulation-mode device. For enhancement-mode, the HTO was replaced with silicon nitride due to its higher dielectric constant and hence better breakdown voltage. In the event, the breakdown occurred at 180V, higher than the SiN breakdown, suggesting that the depletion layer extended beyond the region of the insulator. However, the breakdown site was in the insulator. Hence there is a need to reduce the electric field around the trench.

Silicon carbide switch boost

On the SiC side, Japanese electronic component firm Rohm has worked with both Honda and Nissan on applying the material to the electric vehicle sector.

Rohm's work with Honda has resulted in a full SiC inverter module containing a one-phase converter circuit and a three-phase inverter. The device contains both SiC MOSFETs (4.8mm x 2.4mm) and Schottky barrier diodes (SBDs, 5.14mm x 5.14mm). Rohm says that SiC devices have one-seventh of the switching loss of Si IGBTs (Figure 5). In the power modules built using

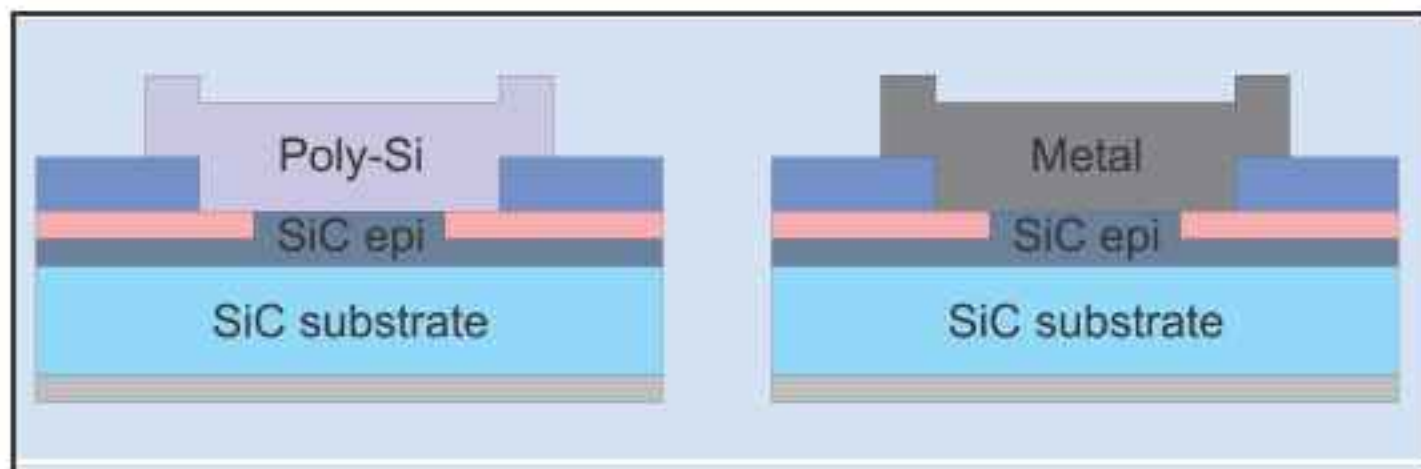


Figure 7. Schematic for Rohm and Nissan's heterojunction diode (left), compared with SBD.

its technology, the switching loss is a quarter that of IGBT-based set-ups. The use of SiC also enables a faster switching speed to be used — 80kHz rather than 20kHz for Si IGBTs for the same power loss.

In 2008, Nissan launched tests of an inverter containing SiC diodes. The tests were carried out on the company's X-TRAIL fuel cell vehicle (Figure 6). Nissan developed a special heterojunction diode (HJD) structure combining SiC and polysilicon for use in the application (Figure 7). The surface of the diode was reduced by 70% (the chip measures 5mm x 5mm), while giving 20% better power efficiency. Simplifications in the inverter design resulting from SiC application reduced the size/weight of the device by 15–20%. More general use in EVs and HEVs is hoped for. Use of further diodes on the transistor is expected to reduce the size of the unit further. The on-resistance is $0.85\text{m}\Omega\text{cm}^2$ with a voltage resistance of 900V. The on-resistance of Si SBDs is usually in the range 5–10 $\text{m}\Omega\text{cm}^2$.

Hitting the gas pedal

In 2008, Mitsubishi announced plans to accelerate its R&D into SiC modules for application in the 2011 time-frame. Initial targets include in-room and industrial air conditioners, PV inverters, elevators and other products. The company also sees possibilities later for application to EVs and HEVs.

Earlier Mitsubishi work [Shin-ichi Kinouchi and Masayuki Imaizumi, Mitsubishi Electric Advance, p.17, March 2006] involved producing an inverter consisting of SiC-based MOSFETs (Figure 8) and Schottky barrier diodes (SBDs) packaged in a non-optimal module designed for use with silicon IGBTs. The device was used to power a 100W three-phase geared motor on a 200V supply with no change in characteristics after 80 hours of operation. Also in 2006, the company increased the motor power to 3.7kW with a 400V supply (a rating commonly used for industrial purposes), claiming a 50% reduction in power loss compared with a silicon-based system. The system was also about a quarter of the volume of the traditional set-up. The most recent announcement from the company is of an 11kW motor being driven by an inverter containing six SiC MOSFETs and six SiC SBDs, reducing losses by around 70% (Figure 9).

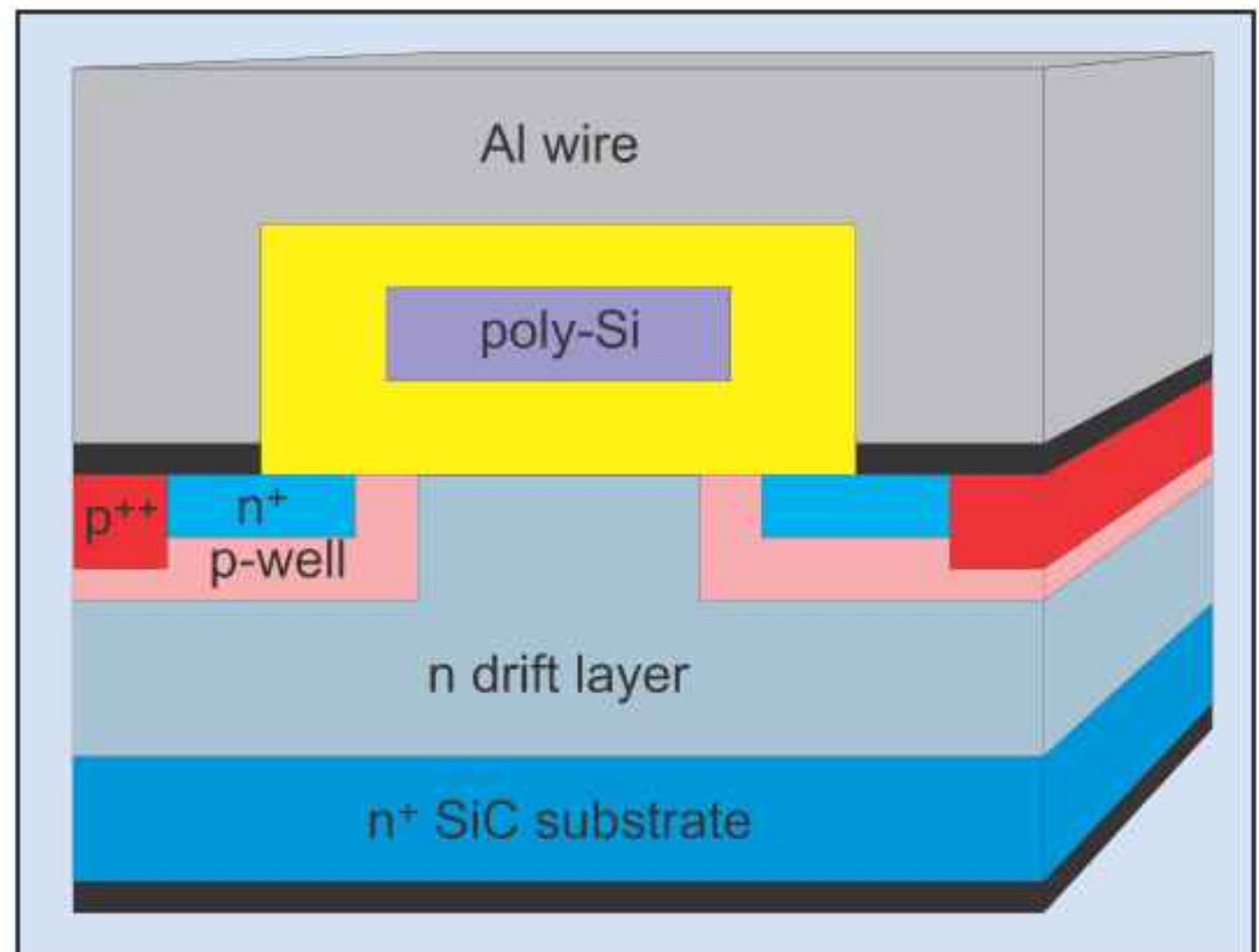


Figure 8. Schematic of Mitsubishi SiC-based MOSFET. Source: Naruhisa Miura et al, 'Successful development of 1.2kV 4H-SiC MOSFETs with the very low on-resistance of $5\text{m}\Omega\text{cm}^2$ ', ISPSD, 2006.

Mitsubishi has not yet decided on when to commercialize this technology — the company says that it needs to make improvements in the SiC MOSFET and SBD to reduce power loss and that it will work to make devices that can handle power in larger volumes. Aiming at the year ending March 2011, Mitsubishi hopes to use this technology in its room and package air conditioners, photovoltaic inverters, elevators and other electric equipment.

Moving technology investments

Another motor vehicle producer, Sweden's Volvo, is interested in wide-bandgap components. Last year (2008), it invested through its Volvo Technology Transfer arm into SiC developer TranSiC, along with other funds

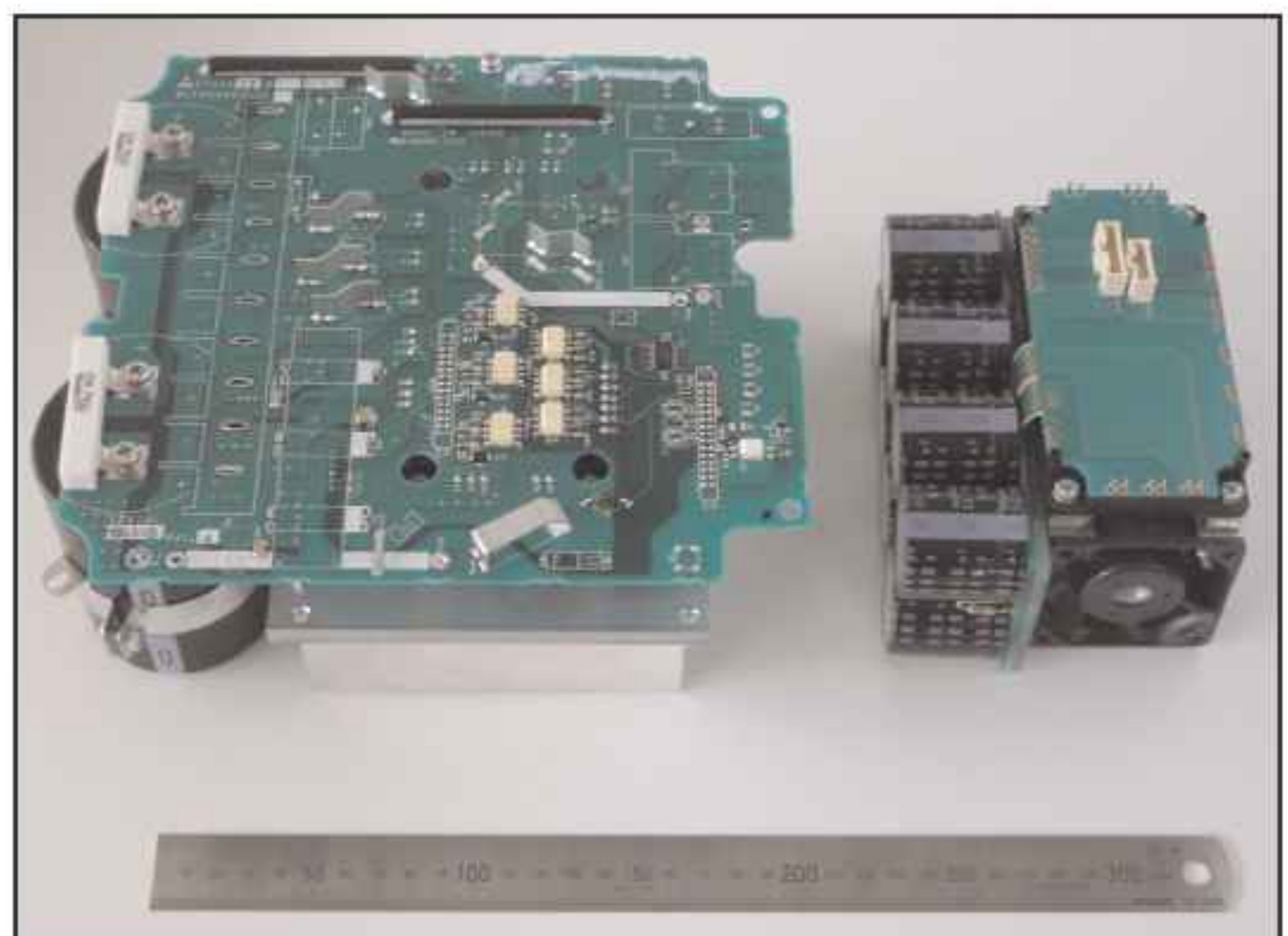


Figure 9. Size comparison of Mitsubishi 11kW SiC-based inverter (right) with Si-based component. SiC enables a volume reduction to a quarter of the size, giving a power density of $10\text{W}/\text{cm}^3$.

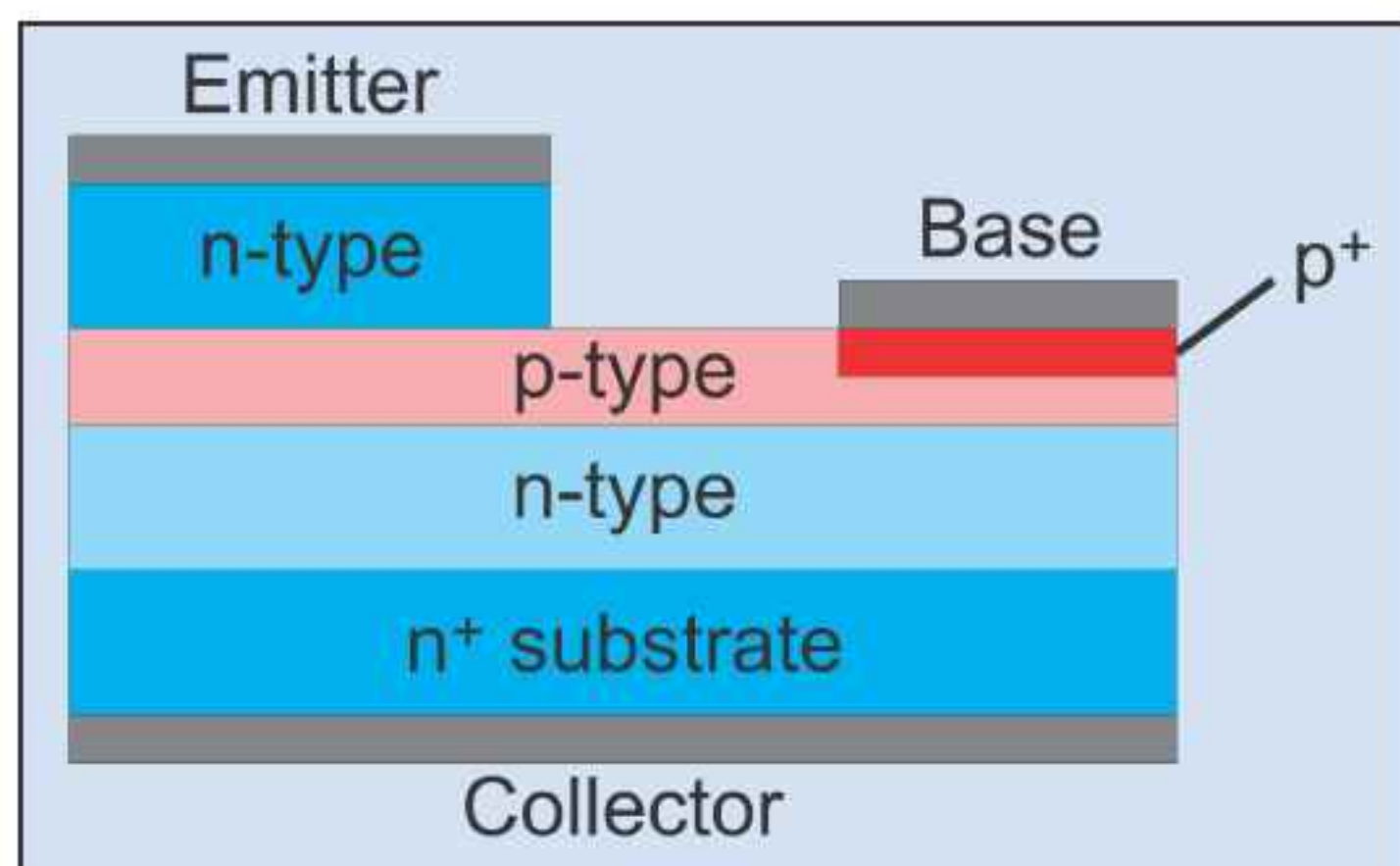


Figure 10. Schematic of TransSiC's BitSiC SiC-based bipolar junction transistor.

such as Industrifonden and Midroc New Technology. Volvo also made an investment in the same company in December 2006, when the motor company specifically mentioned HEVs as its target for SiC technology, citing the material's high-temperature and voltage performance. The company is hoping that heating due to electrical losses could be reduced so much that separate cooling systems will not be required. Smaller and more compact systems could also produce lighter and less expensive vehicles. Volvo seems to be aiming its main hybrid efforts at the public transport and industrial sectors such as buses, logging and refuse collection.

TransSiC was founded in 2005 to develop a normally-off SiC bipolar junction transistor (BJT), based on Swedish SiC research. The company claims an operating temperature range for its BitSiC product (Figure 10) from as low as -80°C up to an impressive $+550^{\circ}\text{C}$. The current density is about $140\text{A}/\text{cm}^2$, but TransSiC hopes to achieve $400\text{A}/\text{cm}^2$ for reduced per Ampere costs. The devices are sold bare or packaged, with or without an anti-parallel Schottky diode, in TO-258 (high temperature), TO-220 or TO-247 formats. The devices are rated up to 1200V and 20A. In October 2008, TransSiC announced a new prototype SiC six-pack of 1200V 6A transistors and 1200V 10A SiC Schottky diodes all in an aluminum nitride (AlN) direct copper bond (DCB) module, aiming at $+225^{\circ}\text{C}$ operation. TransSiC's present production is small-scale, using the 4-inch line at the Electrum Laboratory owned by Sweden's Royal Institute of Technology (KTH).

Also in Europe, Infineon and Siemens jointly own SiCED, a company that develops technology and systems based on silicon carbide power devices. The firm also has production facilities for small-scale prototyping, along with developing high temperature packaging and other supporting technologies. SiCED is involved in a German funding project for hybrid cars together with Volkswagen and others. However, these are very preliminary studies.

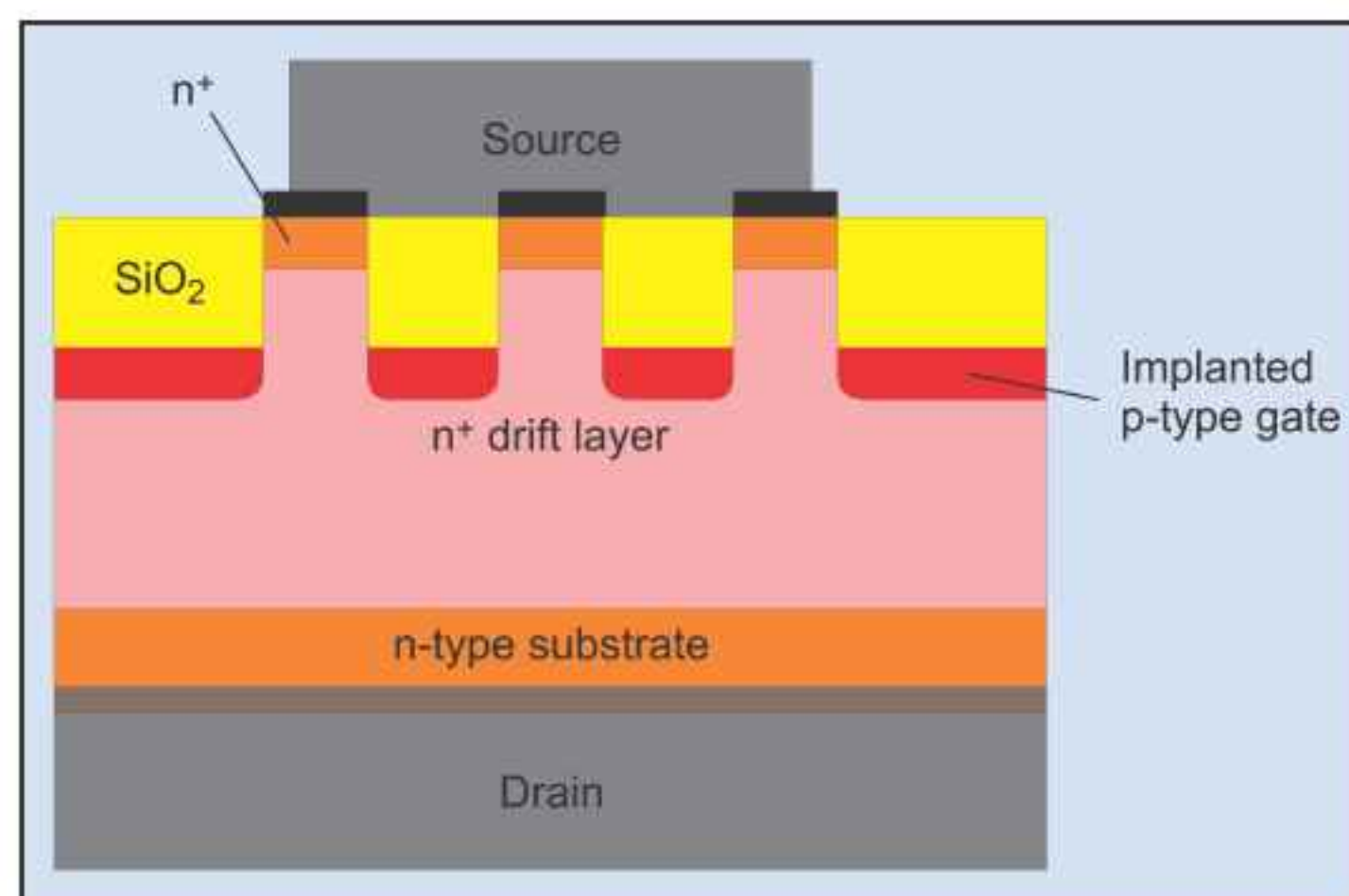


Figure 11. SemiSouth's VJFET.

Military interest

Much of the US development of wide-bandgap semiconductors has emanated from defense research contracts, and the high-power sector has had its share of such funding. For example, SiC device producer Cree has worked with power module developer Powerex to produce an all-SiC dual-switch 1200V, 100A power module demonstrator for the US Air Force Research Laboratory (ARFL). Part of the aim is to produce components that can operate at higher temperatures, in this case a junction temperature of 200°C . The module uses both SiC MOSFETs and diodes to achieve its purpose. The MOSFETs are normally-off. The companies hope to be able to develop drop-in replacements for existing IGBT-based components along with smaller, lighter-weight systems with reduced cooling requirements, but with increased reliability and overload capacity due to SiC's high-temperature operation capability.

Operating the SiC MOSFET-based module at a junction temperature of 150°C and at a frequency of 20kHz gave 38% lower conduction losses and 60% lower switching losses, compared with a silicon IGBT module of equal rating. The total power-loss reduction came to 54%. Low conduction and switching losses give high efficiency with applications seen in solar energy power inverters and electric drives, and power conversion for hybrid and electric vehicles. The all-SiC module uses common materials and assembly processes. The module is scalable to higher currents and the layout can be modified for other switch configurations.

Conversion focus

SemiSouth has looked at the 200–500V DC-DC converter stage rather than the inverter [for example, in work with Mississippi State University, Kelly et al, 'A Scalable SiC Device for DC/DC Converters in Future Hybrid Electric Vehicles', APEC, 2006]. The stage is designed to create a 500V bus voltage for the

motor/generator system. It is believed that a 100°C increase in junction temperature over silicon IGBTs can be achieved.

SemiSouth has worked on scaled prototypes using SiC junction field effect transistors (JFETs) and SiC Schottky diodes. Again, a vertical structure was used for the JFET (VJFET, Figure 11). Silicon JFETs are normally-on devices, meaning that a gate bias is needed to shut off the current. This is not the preferred arrangement for the boost-type converter application. However, in SiC it can be arranged to shift the threshold of the JFET to be less negative or even positive, allowing the preferred normally-off behavior. JFETs also enable the use of bias-enhanced blocking effects and lower on-resistance.

SemiSouth believes that SiC VJFET 'drop-in' replacements could be produced for existing silicon IGBTs, but with higher junction temperature handling. It is hoped that both the average and surge current ratings would be comparable to those of Si IGBTs, while the switching properties would be higher speed, more like those of MOSFETs.

Further application of SiC could come in motor drive power electronics, similar to that envisaged in Toyota's GaN work.

Hot packaging

SiC is also being explored for HEV application at the US Oak Ridge National Laboratory (ORNL), which sees higher power density coming from the reduced thermal management demands and smaller passive components. ORNL has worked to characterize the new SiC and other wide-bandgap devices becoming available with a view to HEV application. Further simulation work has been carried out to assess potential impacts on HEV performance.

ORNL has also collaborated with Cree and Semikron to build a prototype 55kW inverter that, while using Si IGBTs, uses Cree's SiC Schottky diodes instead of Si pn diodes. The efficiencies of the SiC Schottky based devices delivered higher efficiencies under all operating conditions (up to 33% loss reduction). The laboratory has also worked with University of Arkansas to create suitable packaging for the higher-temperature operation envisaged for such devices, compared with the IC packaging designed for use with Si operation (<150°C). The research has demonstrated new packaging technology operating at ~200°C ambient without a heatsink. One TO-220-packaged 75A-rated SiC Schottky device operated at a case temperature of 361°C at 20A for more than an hour without failure. Increasing the current to 25A produced failure after a short time. ■

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