Fundamental and Advanced Technologies

Fundamental Technology
Advanced Technology

Outlook

Energy-related fields including power electronics are raising expectations as areas that will grow in the future. For this reason, large-scale projects involving collaboration between industry, government and academia are being continuously carried out. These projects are facilitating the establishment of an environment that makes it possible to develop wide-band gap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN). These are next-generation power semiconductors that follow Si power semiconductors, in which Japan has maintained its competitiveness. The environment also allows for research and development relating to power electronics equipment using such materials.

Commercialization of power semiconductors and power electronics equipment requires specialized elemental technologies and coordinating technologies that integrate them. Elemental technologies of power semiconductors include technology to produce high-quality semiconductors that provide the base and technology to form an epitaxial layer on the substrate. They also include technology for p/n control by ion implantation to dope impurities, photo-etching technology, trench forming technology, insulating film forming technology, semiconductor-metal junction technologies to form Schottky and ohmic junctions and other process-related technologies. Further, they include common fundamental technologies for the individual processes. Power semiconductor devices can be completed by integrating these elemental technologies to design and build devices and processes that satisfy the intended performance and cost requirements. In research and development of wide-band gap semiconductors, improving the level of the respective elemental technologies is required to develop advanced technologies, a task that is important and difficult. In order to ultimately make power semiconductor devices into competitive products, coordinating the elemental technologies to improve competitiveness in terms of cost and performance is essential. Technologies required include technology to electrically connect power semiconductor devices to terminals and package technology to give them an insulation property and durability. Various types of power electronics equipment that use the completed power semiconductor modules and power systems that use them as key components are also necessary to meet similar demand, as device performance is improved.

Fuji Electric has positioned power semiconductors and power electronics at the center of our core technologies to move forward with research and development of fundamental and advanced technologies required. And we have systematized these core technologies through measurement and control technologies to reinforce our efforts in electrical and thermal energy-related solutions. To acquire advanced technologies we do not own ourselves, we actively take part in industry-government-academia collaboration projects and joint research.

Regarding SiC, we have developed a simulation technology that makes it possible to estimate the epitaxial film growth rate in a vertical CVD furnace capable of high growth rate, which is used by the R&D Partnership for Future Power Electronics Technology. In addition, we have developed an SiC trench metal-oxide semiconductor field-effect transistor (MOSFET) jointly with the National Institute of Advanced Industrial Science and Technology and achieved on-resistance that is 20% lower than the conventional planar type in the 3.3-kV class. We have also developed an SiC-Schottky barrier diode (SiC-SBD) and made use of its characteristic small reverse-recovery loss to realize a 25% reduction in inverter generated loss. To develop these semiconductor devices, we have made the most use of various analysis technologies including synchrotron radiation topography and spectroscopic analysis. We have also conducted follow-up evaluations on the types and locations of defects, substrate stress and deformation for each process, and this contributes to the building of process technologies that generate fewer stacking faults.

For power electronics equipment, we have achieved miniaturization and a density increase while also establishing an analysis technique that makes it possible to predict temperature with higher accuracy than the conventional method. We have done this by linking electromagnetic field analysis with thermo-fluid analysis to apply the loss distribution as a heat generation condition. In addition, as many international standards are established by the International Electrotechnical Commission (IEC), Fuji Electric actively engages in committee activities, and has received recognition for this.

We have also worked on various development activities for improving the performance and safety of electrical and thermal systems and the components that support them. Concerning technologies for protecting photovoltaic power generation systems, we have developed power system protection equipment and its installation technology for estimating an overcurrent due to lightning strikes. In the field of high-temperature-resistant solder bonding materials, we have developed a lead-free solder alloy featuring a continuous operation lifetime that is about 2.6 times longer than the previous products. The aim is to realize smaller power converters with a higher output by improving their power density. Regarding the arc interaction analysis technology anticipating short-circuit faults inside switchboards, we have developed analysis tools for implementing thermo-fluid analysis utilizing a three-dimensional simple finite volume method as well as arc interaction analysis. This allows designers to consider the shape and pressure discharge structure for the switchboard and significantly reduce the analysis time (about 1/100 of the conventional method).

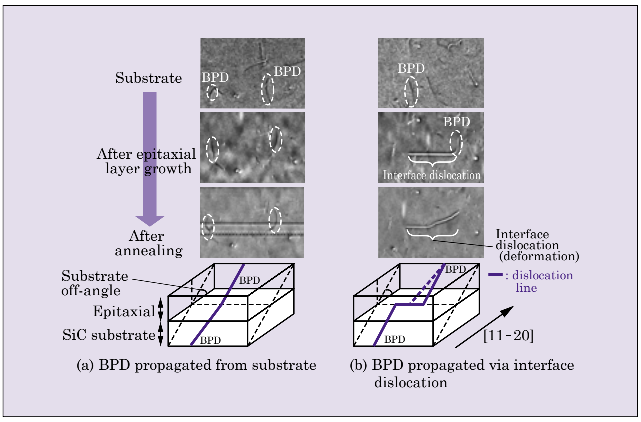
Fuji Electric will continue working to improve the quality of research and development. It will do this by striving to develop advanced technologies leading to innovation of electrical and thermal energy technologies, and making the most of fundamental technologies that support these development activities.

Fundamental Technology

1 Analysis Technology Supporting the Development of Next-Generation Power Devices

To improve the reliability of SiC-metal-oxide semiconductor field-effect transistor (SiC-MOSFET), it is essential to control crystal defects in the device structure. In particular, the key is to use technology for transforming crystal dislocations inherent in a substrate into a harmless form, eventually eliminating stacking faults generated in the epitaxial layer. Crystal dislocations are transformed by thermal and mechanical stress generated in the respective stages of the process but the course of transformation has been unknown up to now. Fuji Electric has made the most use of various analysis technologies including synchrotron radiation topography and spectroscopic analysis for analytical study. It has also conducted follow-up evaluations on the types and locations of defects, substrate stress and deformation for each process for a range of items from a substrate to a device. Based on this, we have successfully suppressed the generation of defects in the device manufacturing process to realize a high-reliability SiC-MOSFET that features characteristic changes of the MOSFET during operation that are less than one-fifth, compared with that of conventional devices.

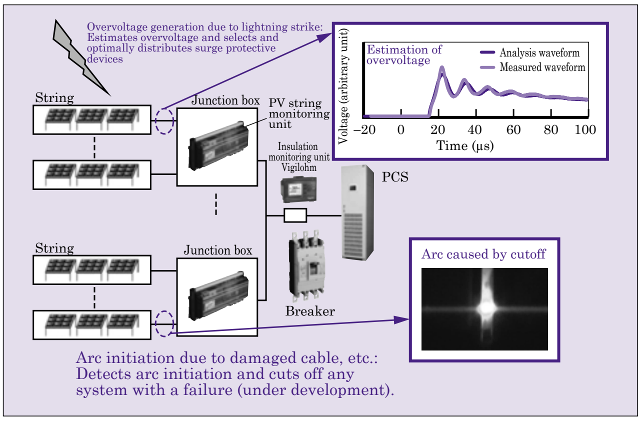
Fig. 1 Synchrotron radiation topograph of SiC basal plane dislocations (BPD)



2 Protection Technologies of Photovoltaic Power Generation Systems

As photovoltaic power generation systems become increasingly widespread, the need is also increasing for safe operation of distributed power generation facilities. In addition to the development of equipment required to protect power systems, Fuji Electric is working on the development of technologies for appropriate selection and installation of these facilities. We have developed technology to analyze the system voltage and current behavior associated with short circuits, which is required for selecting circuit breakers, and analysis technology for estimating an overvoltage due to lightning strikes, which is required for selecting surge protective devices (SPDs). At present, we are engaged in the development of technology for quickly detecting arc faults resulting from incomplete circuit connections or dameged cables. In the future, we intend to propose even safer systems by combining a string monitoring unit, insulation monitoring unit, etc.

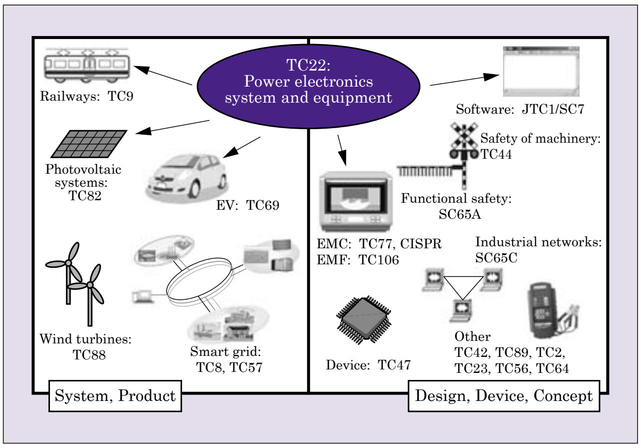
Fig. 2 Products and technologies relating to safe operation of photovoltaic power generation systems



3 Conformance to International Standards Related to Power Electronics

In the field of power electronics, a number of international standards are established by the International Electrotechnical Commission (IEC). Recently, the number of deliberations on standards has been increasing. This makes it necessary for manufacturers to participate in the deliberations and develop conforming technologies in order to expand into the global market, and Fuji Electric has been actively engaged in these activities. Regarding the drive efficiency standard, we have submitted a measuring method and sequence from Japan to international deliberations based on the results of testing jointly conducted with the Japan Electrical Manufacturers' Association (JEMA). We have also acted as the leader to reflect this standard in a draft of the IEC standard. Fuji Electric received recognition for its revision activities for Edition 5.1 of CISPR 11, an international standard for radio frequency emission, and won an IEC 1906 Award. In addition, our achievement of the inclusion in CISPR 11 of EMC requirements for system interconnection power converters for photovoltaic power generation equipment was acknowledged. This led to us winning an award at the Electrical Industry Technology Achievement Awards as a member of the JEMA Distributed Power Supply EMC Study Committee team.

Fig. 3 International standards surrounding power electronics



Fundamental Technology

4 Gas Analysis Technology Conforming to MARPOL Annex VI "Regulations for Prevention of Air Pollution from Ships"

In order to prevent air pollution from ships, exhaust gas regulations are gradually being reinforced based on the International Convention (MARPOL Annex VI). To meet the requirement for continuous monitoring of exhaust gas from ship engines, Fuji Electric has developed a gas analysis technology that conforms to the "Regulations for the Prevention of Air Pollution from Ships." The main features are as follows:

(1) A laser-based method allows wet basis measurement that reduces the effect of moisture interference. This has eliminated the need for a moisture-removing device, leading to the successful miniaturization of the entire equipment.
(2) One unit incorporates two laser elements to allow simultaneous measurement of SO_2 (sulfur dioxide) and CO_2.
(3) Sensitivity of SO_2 measurement is improved by applying a quantum cascade laser.

Fig. 4 Laser-based SO_2/CO_2 gas analyzer

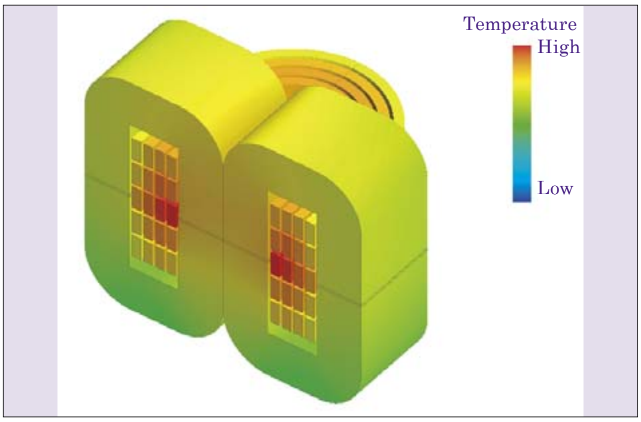
5 Thermal Simulation Technology in Reactor Design

Recently, power electronics devices have been getting increasingly smaller in size and higher in density and, in terms of thermal design of equipment, improved temperature prediction accuracy is required for magnetic components such as reactors and transformers.

To determine the temperature with high accuracy, it is key to be able to perform accurate loss calculations. Accordingly, we have attempted to improve accuracy in electromagnetic field analysis by modeling that gives consideration to magnetic characteristics and eddy current loss due to leakage flux. Furthermore, we have established an analysis technique capable of predicting temperature with higher accuracy than the conventional method by linking electromagnetic field analysis with thermo-fluid analysis to apply the loss distribution as a heat generation condition. This provides detailed temperature distribution including hot spots by analysis and improves the design accuracy of a reactor cooling structure.

In the future, we intend to apply this technique to equipment design so as to reduce the number of prototyping cycles and development period.

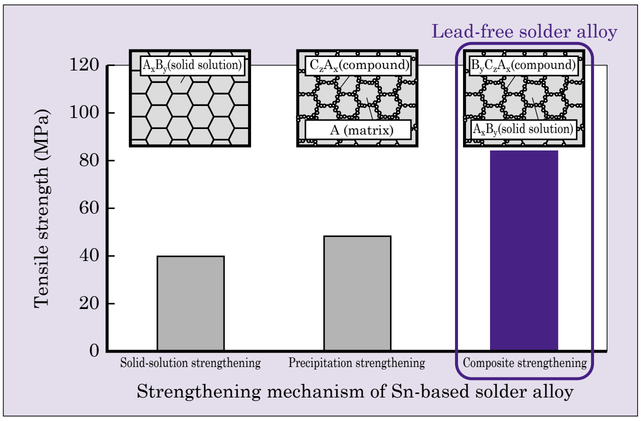
Fig. 5 Example of reactor temperature analysis by linking electromagnetic field analysis with thermo-fluid analysis



6 Solder Joining Materials with High-Temperature Operations

Solder joining materials for power semiconductors are required to offer characteristics of high thermal resistance and fatigue lifetime resistant in order to achieve the high-temperature operation and improved reliability demanded. Fuji Electric has been working independently on the development of solder joining materials since 1990 and making contributions to society by realizing environmentally friendly and highly reliable power converters. To meet the need for power converters with better performances, we have developed a new lead-free solder alloy that withstands high-temperature operation. This lead-free solder alloy is a result of identifying the degradation mechanism by conducting detailed failure analysis of materials respectively from solid-solution strengthening and precipitation strengthening, which are strengthening mechanisms for metal materials, and compensating for their weaknesses to achieve composite strengthening. This has enabled us to accomplish a high-temperature continuous operation lifetime (T_{jmax} = 175°C) improved by approximately 2.6 times compared with that of conventional solders. This makes it possible to achieve a higher output and reduce the size of power converters by having an improved power density.

Fig. 6 Relationship between solder alloy strengthening mechanism and mechanical characteristic

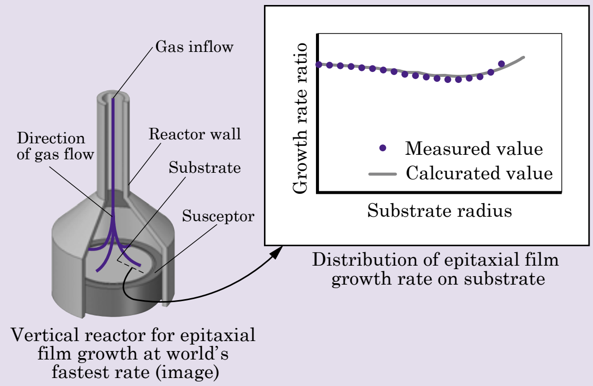


Advanced Technology

1 SiC Epitaxial Film Growth Simulation Technology

In an epitaxial film growth process by using chemical vapor deposition (CVD), high growth rate and uniformity film thickness are required in order to improve productivity. In this research, we have developed a simulation technology that makes it possible to estimate the growth rate of epitaxial film in a vertical CVD reactor which can provide high growth rate used in the R&D Partnership for Future Power Electronics Technology. In the simulation, the epitaxial film growth rate in a substrate can be estimated under the various kind of process conditions, such as temperature and gas flow rate. This research is a result of the "Novel Semiconductor Power Electronics Project Realizing Low Carbon Emission Society" entrusted by the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO).

Fig. 7 Distribution of epitaxial film growth rate on substrate

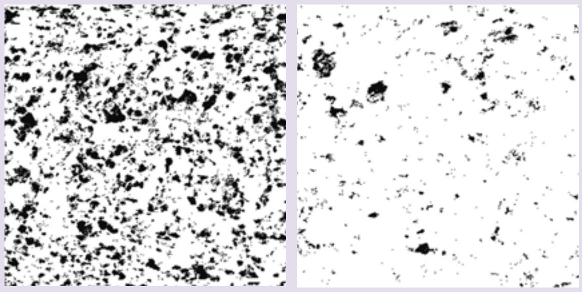


2 Crystal Orientation Control Technology for Heat-Assisted Magnetic Recording

For the magnetic layer of heat-assisted magnetic recording media, ordered FePt alloy with high magnetic anisotropy energy is used. A magnetic film of FePt, which is a cubical crystalline system, is more prone to crystal orientation defects than a magnetic film of CoPt, which is a hexagonal-crystal used in the magnetic layer of the current perpendicular magnetic recording media. As a result, low-frequency noise at reading will be large.

In order to reduce crystal orientation defects, Fuji Electric worked on developing the seed layer directly beneath the magnetic layer. By introducing the newly developed seed layer, we have successfully reduced orientation defects of magnetic grains that grow directly on the layer by 25% as compared with the current seed layer. We now plan to verify the effectiveness of the medium with this seed layer.

Fig. 8 Crystal orientation mapping of FePt film formed on seed layer



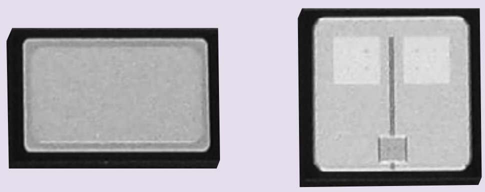
(a) Current seed layer (b) Newly developed seed layer

*White: Perpendicular orientation (non-defective orientation),
Black: In-plane or oblique orientation (defective orientation)

3 3,300-V SiC-SBD and SiC-MOSFET

An SiC-Schottky barrier diode (SiC-SBD) is characterized by the extremely small reverse recovery loss. By replacing the silicon diode used in a 3,300-V insulated-gate bipolar transistor (IGBT) module with an SiC-SBD to make a hybrid module, the inverter generated loss can be reduced by 25%. In addition, an SiC-metal-oxide semiconductor field-effect transistor (SiC-MOSFET) can be combined with an SiC-SBD for use in an inverter circuit as an All-SiC module, which makes it possible to further reduce generated loss. For the SiC-MOSFET, an implantation and epitaxial metal oxide semiconductor (IEMOS) structure has been used to achieve the characteristic on-resistance at room temperature of 14 mΩcm^2. These 3,300-V SiC modules are expected to be applied to electrical rolling stock and transmission and distribution devices. This research or part of this research has been conducted as a project of the "Tsukuba Power-Electronics Constellations (TPEC)," a joint research entity.

Fig. 9 Chip external appearance



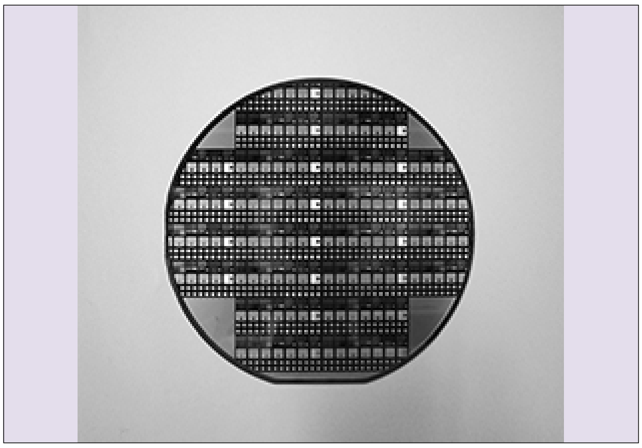
(a) SiC-SBD (b) SiC-MOSFET

Advanced Technology

4 SiC Trench MOSFET

Recently, practical application of SiC-metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs), which are capable of dissipating less power, has been progressing in order to meet the demand for efficiency improvement and miniaturization of power converters. Because of the planar structure, there is a limit to the amount that on-resistance can be reduced by having smaller design rules. Accordingly, to further reduce on-resistance, Fuji Electric is engaged in the development of a trench MOSFET, which is advantageous for smaller design rules, jointly with the National Institute of Advanced Industrial Science and Technology. The trench MOSFET under development is not only aimed at achieving low on-resistance but also intended for mitigation of an electric field in the gate oxide film at the trench bottom. It achieves this by using the p-well structure deeper than a trench gate in order to ensure high reliability. The trench MOSFET of 3.3-kV class experimentally produced with this structure has achieved 20% lower on-resistance than a planar type.

Fig. 10 Wafer after processing of 3.3-kV SiC trench MOSFETs

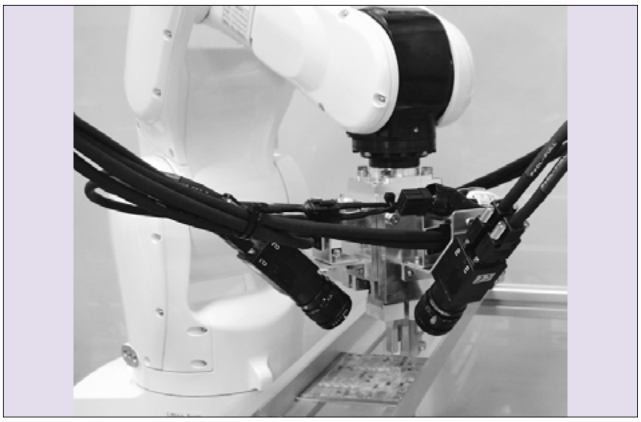


5 Visual Feedback Control in Robot Operation

Recently, automation by using robots has been advanced but operations dependent on human perception (vision, kinesthetic sense, tactile sense, etc.) have not reached a level of practical use. To realize robot behavior that fits the situation in the same way as a human, we are moving ahead with the development of autonomous control technology of robots. Our system gives real-time feedback of visual and kinesthetic sense information to control the arm trajectory and force of operational movements.

We have recently developed a technology for automatic mounting of electronic components that uses visual information for feedback control of a robot. When an electronic component is inserted in the printed circuit board, two cameras are used to capture the lead end and the center of the through-hole. Then, the arm trajectory is successively adjusted so that the two coincide on each camera image, and this has made it possible to insert a component with high accuracy and without any insertion failure due to displacement.

Fig. 11 Electronic component mounting using visual feedback control



Fuji Electric

Innovating Energy Technology