Development of Compound Semiconductor Devices — In Search of Immense Possibilities —

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Many different compound semiconductors can be formed by changing the combination of constituent elements. Properties of alloy semiconductors, mixture of multiple compound semiconductors, can be changed in a continuous fashion by changing the mixing ratio. Very thin alloy semiconductor multilayers, which show interesting properties, can be formed by sophisticated epitaxial growth method such as MOVPE (metalorganic vapor phase epitaxy) or MBE (molecular beam epitaxy). Based on these matters, uncounted numbers of compound semiconductor devices with a wide variety of functions and characteristics have been developed. This is a magnificent feature and great magnetism unique to compound semiconductors and not found in silicon semiconductors.
Sumitomo Electric Industries, Ltd. has been developing various kinds of compound semiconductors for about half a century and is the world's biggest company on compound semiconductors. GaAs and InP substrates and their epitaxial wafers for consumer and communication markets have been the lead products. Recently, GaN substrates for blue-violet lasers have been developed for the new generation optical disk market.
This paper describes the past quarter century's history of developing various kinds of compound semiconductor optical and electron devices, focusing mainly on Sumitomo Electric's research and development activities.

Keywords: compound semiconductor, MOVPE, MBE, wide-bandgap semiconductor, power semiconductor device

1. Introduction

Many different compound semiconductors can be formed by changing the combination of constituent elements. Properties of alloy semiconductors composed of a plurality of compound semiconductors can be changed in a continuous fashion by changing the composition ratio. A very thin alloy semiconductor multilayer showing interesting properties can be formed by sophisticated epitaxial growth methods such as MOVPE (metal organic vapor phase epitaxy) or MBE (molecular beam epitaxy). Based on these matters, innumerable compound semiconductor devices with a variety of functions and characteristics have been developed. This is a magnificent feature and great magnetism unique to compound semiconductors and not found in silicon semiconductors.

Sumitomo Electric Industries, Ltd. has been developing various kinds of compound semiconductor materials for about half a century, and is the world's largest manufacturer of compound semiconductors. The Company has been supplying GaAs and InP substrates and their epitaxial wafers to the consumer and communications markets as its leading compound semiconductor products, and recently succeeded in developing GaN substrates for blue-violet lasers that are being used in new optical disk systems. As to compound semiconductor devices, a large number of optical and electron devices have been developed and commercialized for power and communications markets.

This paper describes the past quarter century's history of developing various kinds of optical and electron devices, focusing mainly on Sumitomo Electric's research and development activities.

2. Compound Semiconductors

2-1 Elemental semiconductors and compound semiconductors

During the last half of 20th century, the revolutionary progress of electronics has greatly changed our life and society. The leading player of this progress is definitely the integrated circuit (IC), whose main material is silicon (Si). Si together with Ge, which played a warm-up act of Si as the first transistor material, are called element semiconductors, which are made up of single element.

On the other hand, semiconductors which are formed by ionic bond of multiple kinds of semiconductors are called compound semiconductors. Generally speaking, materials formed by ionic bonds become insulators because of their strong electrostatic force of attraction. In some cases, they become semiconductors because of their weak electrostatic force of attraction with particular combination of anions and cations. Before now, many kinds of compound semiconductors and compound semiconductor devices have been developed and commercialized. These compound semiconductors are classified by the group number in periodical table (**Table 1**) of the constituent elements such as III-V, II-VI, or IV-IV. Widely known III-V

Table 1. Periodical table of major elements of compound semiconductors

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

compound semiconductors are GaAs, InP, GaN, and AlN. Well-known II-VI and IV-IV semiconductors are ZnSe, ZnS, CaTe, and SiC, SiGe, respectively. Sumitomo Electric has been developing various kinds of compound semiconductor materials for about half a century. The Company has been supplying mainly III-V compound semiconductors, such as GaAs, InP, GaP substrates and epitaxial wafers (**Photo 1**), for consumer and communication markets, and recently supplies GaN substrates for blue-violet lasers of Blu-ray discs.

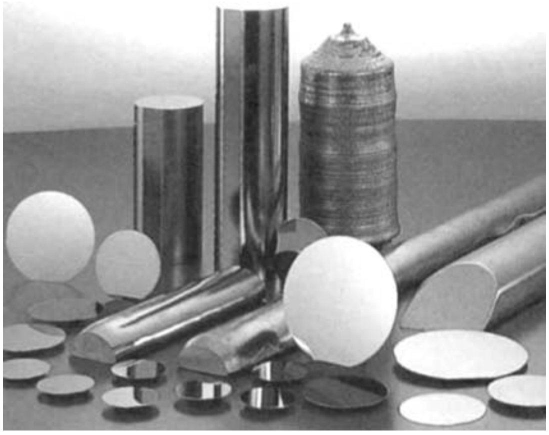

Photo 1. Compound semiconductors such as GaAs and InP

2-2 Compound semiconductors and alloy semiconductors

Many different compound semiconductors can be formed by changing the combination of constituent elements. In addition, multiple compound semiconductors can form alloy semiconductors. For example, Ga$_x$In$_{1-x}$As ($0<x<1$) ternary alloy or Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ quaternary alloy semiconductors can be formed intentionally by mixing multiple elements. Properties of these alloy semiconductors, such as lattice constant and energy bandgap, can be changed in a continuous fashion by changing composition ratio. This is a magnificent feature and great magnetism unique to compound semiconductors and not found in silicon semiconductors. Energy bandgaps and lattice constants of various compound semiconductors and ternary alloys are shown in **Fig. 1**.

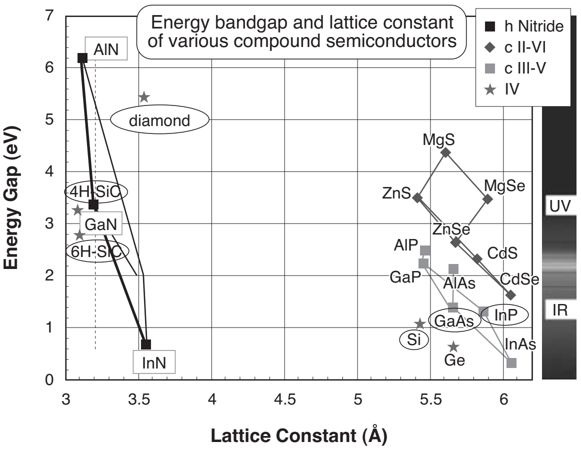

Fig. 1. Energy bandgap and lattice constant of various compound semiconductors

Different from alloy semiconductors, concept of superlattice semiconductors which consist of two kinds of compound semiconductors with a thickness of a few atomic layers and show different properties from original semiconductors was proposed. The authors grew the multilayer structure of InAs and GaAs with each thickness of a few atomic layers by MBE(1)-(4) and fabricated a hetero-junction transistor with InAs/GaAs superlattice semiconductor as a channel layer(5)-(7). However, the characteristics of the device were similar with those of transistors with alloy semiconductor.

2-3 Epitaxial growth

Very thin multiple compound or alloy semiconductors should be grown successively in order to form semiconductor devices with various characteristics. These structures with two different semiconductors are called a hetero-junction, and the method of crystal growth of semiconductor with very few defects is called epitaxial growth method (epitaxy). The origin of the word "epitaxy" is Greek; "epi-" means "on" and "taxis" means "lining-up." Therefore epitaxy means lining-up crystal growth with right crystallographic axes direction. Epitaxial growth process is a most important one to fabricate high performance semiconductor devices. Generally speaking, in order to grow a semiconductor layer with low defect density, the lattice constant of the growth layer should be very close to that of substrate. Lattice matched hetero-junction can be obtained in the growth of an alloy semiconductor, whose lattice constant can be changed in a continuous fashion by changing composition ratio.

Several kinds of epitaxial growth methods have been developed such as LPE (liquid phase epitaxy), MBE (molecular beam epitaxy), and MOVPE (metal-organic vapor phase epitaxy). In order to fabricate high performance devices, very thin multiple semiconductor layers, such as a few nanometers, are essential, and for that purpose, MOVPE and MBE are well-suited. For the mass production of devices, MOVPE is most suited and widely utilized for the production of lasers for optical disk systems and optical fiber communication applications.

2-4 Hetero-junction and quantum well

A hetero-junction with a steep interface, which means semiconductor composition changes abruptly at the interface, is essential for the fabrication of high performance compound semiconductor devices. For example, for the fabrication of QWs (quantum well structures), in which semiconductor layer with a narrow bandgap is wedged between semiconductor layers with wide bandgaps, steep hetero-junctions are essential to obtain good QW structures. The authors developed a MOVPE machine in the early 1980s by precisely optimizing the gas pipe arrangement and the reactor shape with exercising their ingenuity. The quality of QWs can be evaluated by optical measurements such as photoluminescence. The photoluminescence data of GaInAs ternary QWs and GaInAsP quaternary QWs using the MOVPE are shown in **Fig. 2**. Clear luminescence from the QW even with the well thickess of 6 angstroms was observed, which verified the high quality of QWs grown by the MOVPE(8)-(10). These data were the best ones at the time it measured.

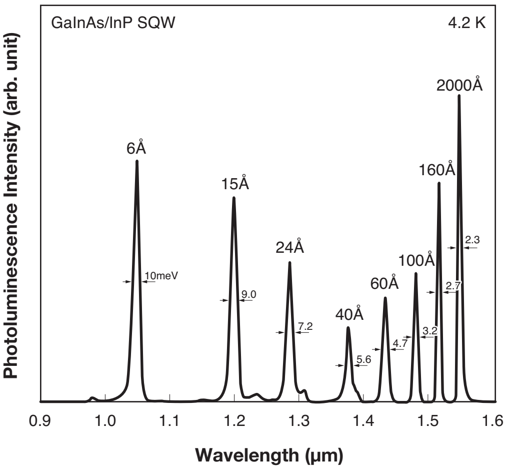

Fig. 2. PL spectra at 4.2K of a stack of GaInAs/InP SQWs and a GaInAs bulk layer

3. Photonic Devices

3-1 MQW lasers for optical fiber communications

Characteristics of semiconductor lasers can be greatly improved by using QW structures as active layers. The authors fabricated a 1.3 μm laser diode for optical fiber communication applications utilizing GaInAsP quaternary MQW (multiple quantum well) structure and verified that the characteristics of this laser, such as threshold current, slope efficiency and temperature characteristics, were superior to those of the conventional lasers(11). All MOVPE process, that is, buried growth and cladding growth together with MQW growth are done by MOVPE, was first realized on a two-inch diameter InP wafer, and high uniformity of the laser characteristics was obtained. This drastic change in the production process of semiconductor laser improved laser performance by the use of MQW structure and reduction of production cost by using two-inch diameter wafer, and contributed to the commercialization of high performance QW lasers.

These quantum well lasers have been widely used in optical modules of Sumitomo Electric and other optical fiber communication systems all over the world. This production technology was also developed to produce other kinds of lasers, such as uncooled coaxial analog distributed feedback lasers for optical CATV systems(12), 1.48 μm and 0.98 μm optical pumping lasers for fiber amplifiers(13)-(18), and red MQW lasers for DVD systems(19)-(28) (**Photo 2**).

3-2 Receiver OEIC for optical communication

Various kinds of photonic devices, such as laser diodes and photo diodes, can be fabricated on compound semiconductor substrates. Various kinds of electron devices, such as transistors and diodes, can be also fabricated on compound semiconductor substrates. Therefore photonic devices and electron devices can be integrated into a single chip called an OEIC (opto-electronic integrated circuit). In 1990s, numbers of research on OEICs for optical fiber communications were conducted. The device structures of light emitting devices, such as laser diodes, are very complicated and making optical cavity structure is also difficult. On the other hand, the structures of photonic receiver devices are comparatively simple, and it is desirable that the first stage amplifier circuit is placed near to the receiver for high speed operation. Thereby researches on OEICs were done mainly on receivers.

It was expected that the performance, reliability, size, and production cost of OEICs were superior to those of conventional hybrid integrated circuits. The authors fabricated receiver OEICs in which a PIN photodiode and a receiver amplifier circuit were integrated on an InP substrate(29)-(31). Low noise receiver OEICs which integrated an equalizer(32),(33), eight channel receiver OEIC arrays by which eight channel signals could be received in parallel(34),(35), and super high speed receiver OEICs(36),(37), were also successfully fabricated. In these OEICs, HEMTs (high electron mobility transistors) were used as electron devices. In order to improve the performance, HBTs (hetero-junction bipolar tran-

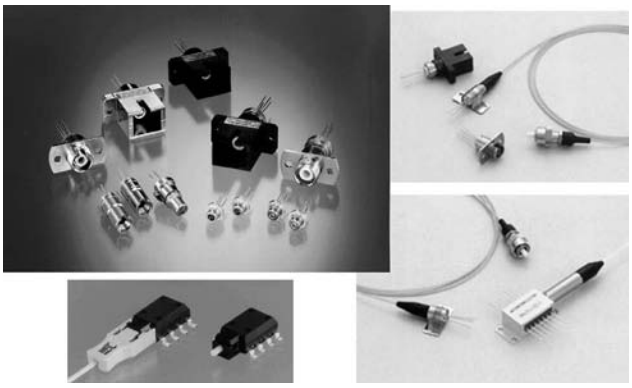

Photo 2. Various kinds of semiconductor laser modules

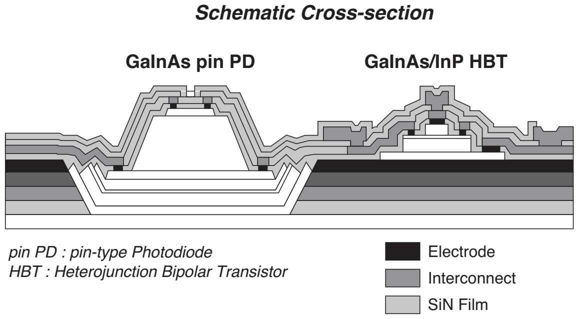

Fig. 3. Schematic cross-section of receiver OEIC(77)

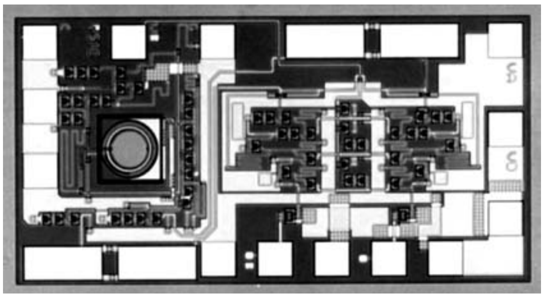

Photo 3. PIN-HBT receiver OEIC with an integrated equalizer(77)

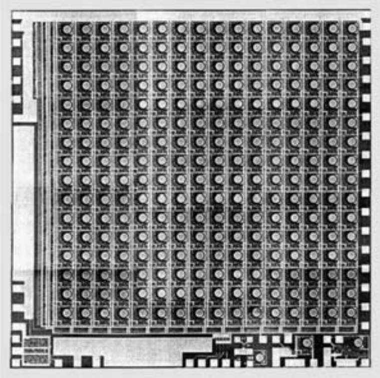

Photo 4. 16 x 16 receiver OEIC array(78)

sistors) were also used as electron devices(77) (**Fig. 3**, **Photo 3**). For parallel interconnection(78), 16 x 16 OEIC arrays were also fabricated (**Photo 4**). In the viewpoint of cost reduction, simple OEICs in which a photodiode and several passive components were integrated were used for optical data link products of Sumitomo Electric.

3-3 Blue-violet laser for optical disk

The market of laser diodes for optical disks is the major application field of compound semiconductor devices. Near infrared AlGaAs lasers were firstly used for CD players. Then DVD systems came on stage, and red laser diodes utilizing quaternary AlGaInP as active layers were used. In these laser diodes for CD and DVD, lattice-matched AlGaAs and AlGaInP epitaxial active layers can be grown on GaAs substrates. Sumitomo Electric has supplied huge quantities of GaAs wafers to the customers all over the world.

Generally speaking, in order to increase the amount of information recorded on a single disk, the wavelength of the laser for writing and reading should be shortened. In Blu-ray disks, blue-violet laser with the wavelength of about 400 nm are used. As it is impossible to fabricate a laser diode emitting blue-violet light on a GaAs substrate, active layers of the blue-violet laser should be InGaN and AlGaN alloys.

As for the LEDs of the blue-violet wavelength region, LEDs using InGaN/AlGaN multiple layers grown on sapphire substrates came into practical use by the famous technical developments of Shuji Nakamura. These LEDs have been widely used in white LEDs for many applications such as backlights of mobile telephones. In the case of the production of high power blue-violet lasers, different from the case of LEDs, high quality lattice-matched epitaxial layers are required for the device reliability. For that purpose, GaN substrates were desired. However, high quality GaN substrates were not available because of the difficulty of the growth of GaN. Sumitomo Electric first succeeded in the production of GaN substrates by developing a unique technology on the growth of GaN onto a different semiconductor, utilizing all of their accumulating crystal growth technology(38)-(42) (**Photo 5**). The blue-violet lasers are now widely used for various kinds of Blu-ray disk systems.

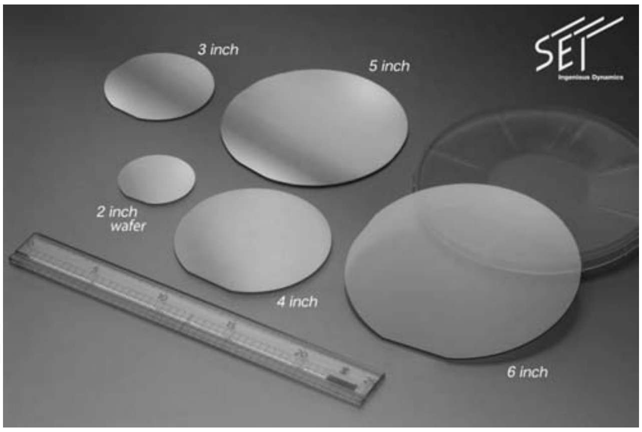

Photo 5. GaN single crystal wafers

3-4 White LED

GaN LEDs on sapphire substrates currently hold a dominant share of the market as light sources of white LEDs. Before the successful development of GaN LEDs, LEDs and laser diodes of ZnSe, II-VI compound semiconductors, were studied for a long time. ZnSe is so called a wide bandgap semiconductor, whose energy bandgap is wider than those of GaAs and InP. It had been quite difficult to grow high-quality large-diameter ZnSe crystals. By using sublimation technique, Sumitomo Electric first developed a two-inch diameter, high-quality ZnSe substrate with the dislocation density of less than 1 x 10^4 cm^{-2} (43)-(45). In order to obtain low resistivity for photonic devices, technology of aluminum diffusion into ZnSe crystals was developed(46).

Sumitomo Electric developed white LEDs using the ZnSe substrates described previously(47). This device was a unique single solid device that combined the blue-violet light with the wavelength of around 485 nm emitted from a ZnSe LED and the broad band excited light around 585 nm (**Fig. 4**). The features of this ZnSe-based LED were (1) simple fabrication process without fluorescence material, (2) low operation voltage of 2.5V comparing with GaN LEDs, (3) capability of wavelength control and small fluctuation of color tone, and (4) tolerance to the electrostatic breakdown due to the conductive substrate. By adopting the double-layer clad structure, the device life time became comparable with that of a GaN LED(48). Although the ZnSe-based white LED was promising for light sources of mobile equipment, it did not come to practical use because of the significant technology advancement of GaN LEDs on sapphire or SiC substrates.

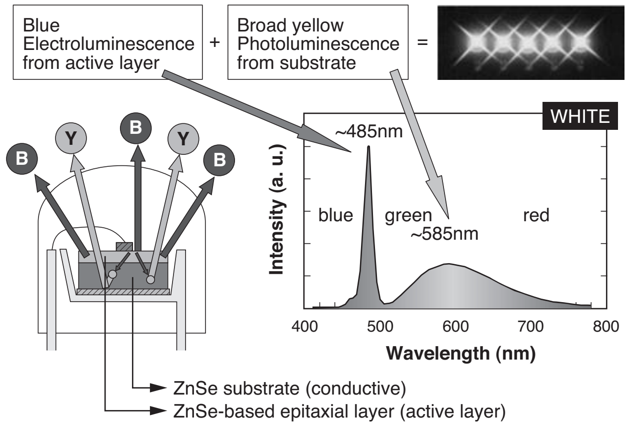

Fig. 4. Fundamental principle of ZnSe-based white LED

4. Electron Devices

Almost all the photonic devices described in Section 3 can not be made without compound semiconductors. On the other hand, most commercial electron devices, such as transistors, are produced by using Si, not compound semiconductors. However, by using compound semiconductors, electron devices with higher performance, such as high frequency operation or low noise, can be obtained. High speed and high frequency operation can be possible with GaAs or InP, and low-loss and high-voltage operation can be possible with SiC or GaN. In this section, various compound semiconductor electron devices developed so far is described.

4-1 High frequency electron device

From 1970s to 1990s, GaAs was a very promising material for the applications of high speed transistors or integrated circuits because of its high electron mobility compared with Si, and a large number of research projects were conducted all over the world. Concerning Si electron devices, MOSFETs (metal-oxide-semiconductor field effect transistors), which utilize electric channels formed at the interface between Si and the oxide, are widely used because of the low interface state density at Si/SiO2 interfaces. In comparison with Si, good quality interfaces between GaAs and its oxide or dielectric materials cannot be obtained. For that reason, GaAs MOSFETs were not realized. The authors also studied GaAs MOS structures by using several fabrication processes. Interface state density could be greatly reduced by the anodization of deposited aluminum on GaAs or by using Ga-doped SiO_2 film to prevent out-diffusion of Ga into SiO_2 film(49)-(51), but commercial GaAs MOSFETs could not be developed.

As the GaAs MOSFETs were not obtained, GaAs MESFETs (metal-semiconductor field effect transistors), which utilized Schottky barrier junction as gate electrodes, were used as element transistors in ICs(52)-(54). Although GaAs ICs were expected as the displacement of Si ICs because of their high-speed and low-power dissipation characteristics, they did not enter the market of LSIs due to the rapid improvement in performance of Si ICs. However, small size ICs are widely used as switching ICs and amplifier ICs for wireless communication systems, and amplifier ICs and driver ICs for optical fiber communication systems(55) (**Photo 6**).

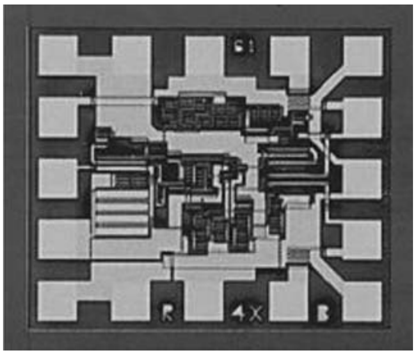

Photo 6. Photomicrograph of GaAs amplifier IC

In the case of discrete devices, GaAs-based transistors have been widely used mainly in wireless communication systems. An HEMT (high electron mobility transistor), in which two dimensional electron gas at the hetero-interface between GaAs and AlGaAs is used as a channel, is a well known transistor invented by T. Mimura and his coworkers(82). GaAs-based HEMTs are now produced in Sumitomo Electric Device Innovations. These GaAs-based HEMTs have been multiplied out to other material systems such as InP, GaN, and SiGe. The authors developed a unique high-performance transistor, "pulse-doped FET," without using a hetero-junction(56),(57) (**Fig. 5**). A very thin (several nanometers) highly-doped GaAs layer grown by MOVPE is used as a channel layer in the pulse-doped FET. The puls-doped FET was proposed for the application of low noise MMICs (mono-

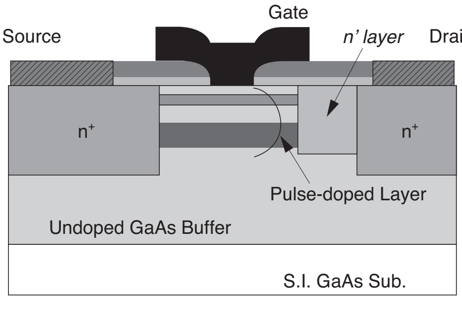

Fig. 5. Schematic cross-section of a GaAs pulse-doped FET

lithic microwave integrated circuits) in a down converter of satellite communication systems because of the low noise, high radiation resistivity and good distortion characteristics(62)-(68). The pulse-doped FETs have been widely used in base stations of wireless communication systems.

Regarding InP-based transistors, lattice-matched $In_xGa_{1-x}As/Al_yIn_{1-y}As$ systems or slightly lattice-mismatched systems to InP substrates are used. InP-based transistors show the best high frequency performance among all the electron devices. The authors developed various kinds of InP-based transistors as the element device in InP-based receiver OEICs described in 3-2.

4-2 Power devices

Power devices represent semiconductor devices, such as diodes, transistors and thyristors to convert or to control electric power, and the core elements of power electronics. Before the invention of the transistor in 1947, mercury-arc rectifiers were used for power conversion from direct current to alternate current or vice versa. As the mercury-arc rectifiers utilized the discharge phenomenon of mercury in vacuum, there were some reliability issues. Si diodes having rectification function were commercialized in 1960s and began to be used in high-capacity electric power conversion.

As Si device technologies progress, the rated current and voltage of diodes, transistors and thyristors have been increased and their characteristics have been much improved. Power devices are now widely used in various kinds of power equipment and systems, such as electric power transmission and distribution systems, electric railways, hybrid and electric vehicles, fuel-cell electric vehicles, electrical power supplies, such as UPSs (uninterruptible power supplies), AC servo systems for industrial robots, home electric appliances, such as air conditioners, or various kinds of office automation equipment. The global market size of power devices is now a few trillion yen.

It is desirable that energy loss at the conversion of electric power is minimized and conversion efficiency is 100%. As several percent of all the energy consumed throughout the world are consumed in power devices, the reduction of power dissipation in power devices is essential for the realization of the energy-saving society. Regarding the control of electric power, it is desirable that electric power is controlled precisely, without delay, with the control power as small as possible.

In order to satisfy the demands described above, Si power device technologies for higher switching speed have been developed. However, it is an actual state that the improvement seems to approach the limits due to the solid state properties of Si.

The loss in power devices at switching consists of the loss by on-resistance during on-time, the loss by leakage current during off-time, and the switching loss during switching time. In order to reduce these losses, small on-resistance and fast switching are desirable. To satisfy these conditions, wide bandgap semiconductors, such as SiC or GaN, are promising for the constituent materials of next generation power devices. By using wide bandgap semiconductors, higher breakdown voltage, lower power dissipation, faster switching and higher temperature operation can be possible due to the wide energy bandgap compared with Si.

4-3 Wide bandgap semiconductor power devices

4-3-1 Wide bandgap semiconductors

The energy bandgap of wide bandgap semiconductors is wider than that of Si (**Table 2**). For example, energy bandgaps of SiC and GaN are about three times as wide as that of Si. Breakdown voltage of SiC and GaN is about ten times as large as that of Si due to the wider bandgap. Besides, high breakdown voltage wide bandgap semiconductors have the properties of fast saturation drift velocity and high thermal conductivity. As described in Section 4-2, on-resistance should be reduced in order to reduce the power dissipation of power devices. On-resistance of power devices consists mostly of resistance of the drift layer. By using SiC as device material, the thickness of drift layer can be ten times as thin as that of Si device because breakdown voltage of SiC is ten times as large as that of Si. The doping concentration of SiC can be 100 times as large as that of Si because the electric field in the semiconductor is proportional to square root of doping concentrations. Therefore the resistance of SiC can be 1/1000 times as small as that of Si. Although on-resistance includes resistance other than the drift layer resistance, the use of SiC as the device material can greatly reduce the on-resistance of power devices, and hence power devices with high breakdown voltage and low dissipation power can be realized.

Table 2. Solid state properties of various semiconductors

	Si	4H-SiC	GaN	AlN	Diamond
Energy Bandgap (eV)	1.1	3.3	3.4	6.2	5.5
Electron Mobility (cm^2/Vs)	1,400	1,020	2,000	1,090	2,000
Breakdown Field (MV/cm)	0.3	3.0	3.3	12.0	8.0
Saturation Velocity (cm/s)	1.0×10^7	2.0×10^7	2.7×10^7	2.2×10^7	2.5×10^7
Thermal Conductivity (W/cmK)	2	5	1	3	20

4-3-2 SiC power devices

In 1950s, numbers of researches on SiC materials were carried out because of their high temperature application capability. Since then, researches on SiC decayed as it was quite difficult to grow high quality SiC crystal. However, in late 70s, two key technologies were developed, that is, "crystal growth technique" in Russia and "step-flow epitaxy" in Japan(83). Thereby in 1990s, development of SiC power devices gathered momentum.

SiC Shottky barrier diodes were firstly developed and put on the market in 2001. At the present time, the main research and development target is transistors for switching. Sumitomo Electric is developing two types of SiC transistors, that is, RESURF (reduced surface field)-type JFETs (junction-gate field effect transistors)(84)-(88) and MOSFETs(89).

A JFET is a device which takes advantage of the solid state properties of SiC because it can apply the inherent electron mobility of SiC to channel mobility because the current path is inside the crystal in comparison with a MOSFET. A unique device with high-speed, low-loss and high-temperature operation can be obtained to optimize the device structure. Microphotographs of a RESURF JFET are shown in **Photo 7** and a schematic cross-section of a RESURF JFET is shown in **Fig. 6**.

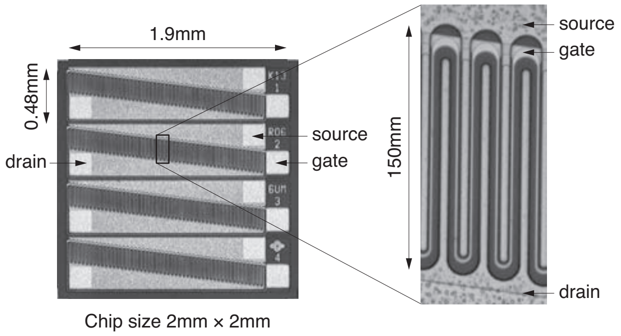

Photo 7. Microphotos of a RESURF JFET

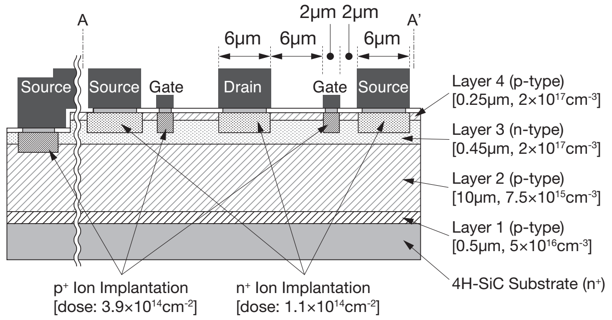

Fig. 6. Schematic cross-section of a RESURF JFET

In **Fig. 6**, current in the n-type channel between the source and the drain is controlled by the potential of the gate, and the n-channel is wedged between p-type layers. By using this structure, low resistance can be compatible with high breakdown voltage because the peak electric field between the gate and the drain can be suppressed, and carrier concentration of the n-channel layer can be increased. Fast switching characteristics with the rise and fall time of 3ns are obtained for a 1 μm channel device. This device is promising for electric power supply in a base station of wireless communication systems due to the fast switching characteristics with the breakdown voltage of several hundreds.

Meanwhile, regarding SiC MOSFETs, it is an actual condition that electron mobility in a MOS channel is not sufficiently high due to the imperfectness of the MOS interface. Sumitomo Electric showed high electron mobility in the MOS structure by forming a flat surface with the level of atomic layers by utilizing a unique process(89). As this SiC MOSFET is expected to show high breakdown voltage, low loss and high current operation, it is quite promising for power equipment and automobile applications as a substitution of a high-capacity Si IGBT.

4-3-3 GaN power devices

Although material properties of GaN are similar to those of SiC with almost the same energy bandgap, on-resistance of a GaN device is several times as small as that of SiC one. Therefore, GaN power devices are promising for energy saving devices.

Regarding GaN devices, photonic devices, such as white LEDs or blue-violet laser diodes, first came on the market. For the fabrication of power devices, lattice-mismatched SiC or Si substrates have been used because large diameter GaN substrates for power devices are not yet available. Sumitomo Electric Devices Innovations, Inc. first developed and commercialized a GaN electron device on SiC substrates for wireless communication systems. As for GaN power devices, GaN devices on Si substrates are widely developed because of the low cost of Si substrates. However, GaN devices on Si are not suited for high capacity devices because of the low thermal conductivity of Si compared with GaN, and impossibility of a vertical current flow device. They are expected as substitutes for low-capacity Si power MOSFETs.

Sumitomo Electric is developing GaN power devices using high quality GaN substrates produced in the company. GaN Schottky barrier diodes and pn-junction diodes were first fabricated on GaN substrates. For the Schottky barrier diode characteristic, on-resistance of 0.71 mΩcm^2 and breakdown voltage of 1100 V are obtained by using a high quality n-type GaN layer with the electron mobility of 930 cm^2/Vs(90). Meanwhile, for the pn-junction diode characteristic, on-resistance of 6.3 mΩcm^2 and breakdown voltage of 925 V are obtained by reducing the doping of Mg in the p-type GaN layer(91).

As for the GaN power devices on GaN substrates, Sumitomo Electric demonstrated novel vertical hetero-junction transistors with a re-grown AlGaN/GaN two-demensional electron gas channel(92). A schematic cross-section of this device is shown in **Fig. 7**. Fabrication process of this device is shown as follows. A n$^+$-GaN/p$^-$-GaN/n$^-$-GaN structure was grown on a free-standing GaN substrate by MOVPE. A mesa-structure of the n$^+$-GaN/p$^-$-GaN/n$^-$-GaN layer with a slope angel of about 16 degrees was formed by ICP-RIE (induc-

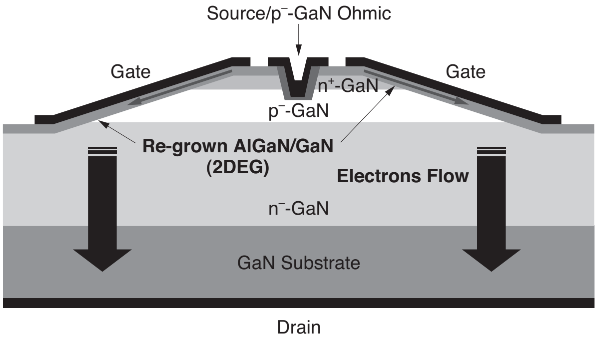

Fig. 7. Schematic cross-section of vertical hetero-junction field effect transistor

tively coupled plasma reactive ion etching). Undoped-GaN and AlGaN layers were re-grown on the mesa-structure by MOVPE to create 2DEG channels. Then electrodes were fabricated. This device exhibited a specific on-resistance of 7.6 mΩcm^2 at a threshold voltage of -1.1 V and a breakdown voltage of 672 V. The breakdown voltage and the figure of merit are the highest among those of the GaN-based vertical transistors ever reported. It was demonstrated that the threshold voltage can be controlled by changing the thickness of AlGaN layers, and a normally-off operation was achieved with a 10-nm-thick $Al_{0.2}Ga_{0.8}N$ layer.

4-3-4 AlN power devices

As the energy bandgap of AlN is very wide (6.2 eV) as shown in **Table 1**, AlN is promising for the applications of the substrates of ultraviolet light sources as photonic devices. As for electron devices, AlN is expected to be the substrate of robust power devices with higher temperature operation compared with SiC and GaN. However, as the crystal growth of AlN is more difficult than that of SiC or GaN, AlN single crystals, which can be called wafers, have not been obtained (**Photo 8**).

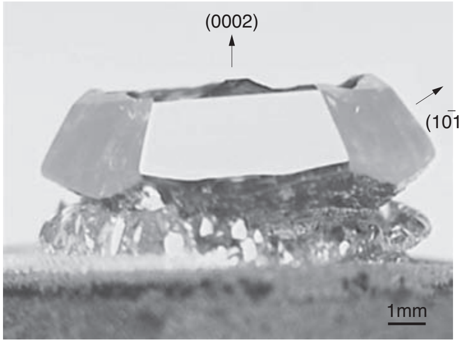

Photo 8. AlN single crystal

Sumitomo Electric started the research and development of substrate technologies and epitaxial growth technologies of AlN in the last half of 1990s(93),(94). In the project of NEDO (the New Energy and Industrial Technology Development Organization) started in 2007, our co-researchers fabricated and evaluated HEMTs by using epitaxial wafers grown on AlN substrates by Sumitomo Electric(95). These devices are the first transistors fabricated on free-standing AlN substrates. A maximum saturation current of 0.13 A/mm at Vgs = 2 V and a maximum transconductance of 25 mS/mm were obtained. DC characteristics of an AlGaN-channel HEMT on AlN substrate and a conventional GaN-channel HEMT were comparatively examined at the temperature range from RT to 300°C. The drain I-V characteristics of these devices are shown in **Fig. 8**. The temperature-dependence of the drain current of the AlGaN channel HEMT on AlN substrate is about as half as that of a GaN channel HEMT, which shows that devices on AlN substrates have better high-temperature characteristics than those of devices on GaN.

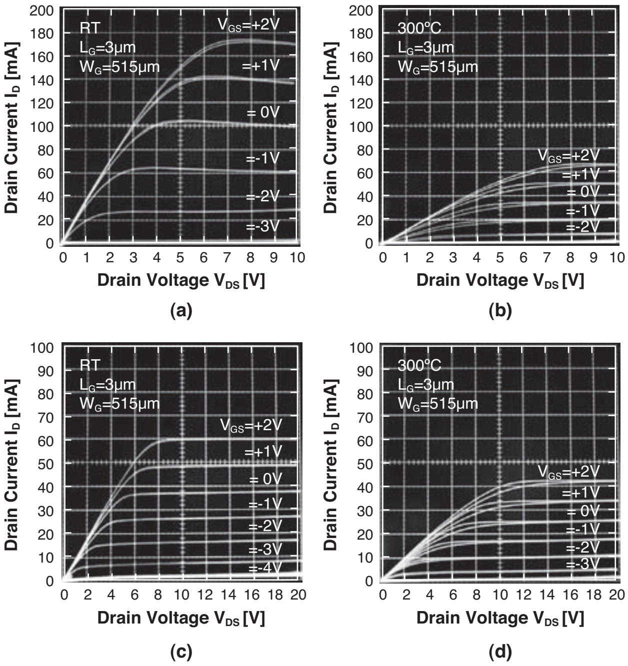

Fig. 8. Drain I-V characteristics for GaN-channel HEMT (a, b) and AlGaN-channel HEMT (c,d)

4-3-5 Diamond power devices

Although diamond is an elemental semiconductor, not a compound semiconductor, it is promising as a material for power devices because of its wide energy bandgap, and therefore it is included in this paper. Diamond has been widely used for heatsinks or cutting tools such as dice for wire drawing or precision turning. There has been no applications of diamond as wide bandgap semiconductor materials.

Most significant features of diamond as a semiconductor material are the high electric breakdown field and high thermal conductivity derived from its wide energy bandgap. As the figure of merit of diamond as a power device is far beyond those of other materials, diamond is quite promising for power device applications.

The biggest issue for the practical realization of diamond power devices is the development of crystal growth technologies and device process technologies. In the first case, it is essential to develop crystal growth technology of high-quality and big size single crystal diamonds with low density of impurities and defects. Regarding crystal formation methods of diamond, ultra-high pressure formation and gas phase formation are commonly used. Gas phase formation, such as plasma-enhanced CVD (chemical vapor deposition), is suitable for the growth of the substrates for semiconductor devices. AIST (the National Institute of Advanced Industrial Science and Technology) has been carrying out the research on crystal growth of diamond by CVD. Recently AIST has developed the technology for synthesizing large single crystals of diamond by the "Direct Wafer-making technique," by which laminar single crystals and seed crystals of diamond can be separated. AIST has produced several laminae of diamond single crystals with uniform properties by adopting the Direct Wafer-making

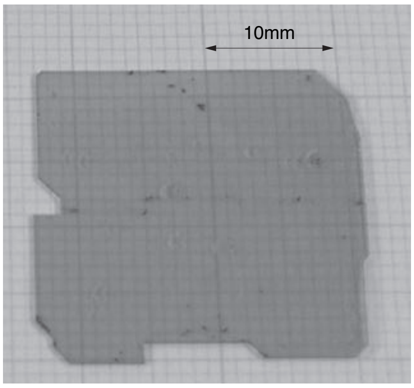

Photo 9. Diamond wafer

technique, and bonded these laminae together to obtain a large-area wafer(96),(97) (**Photo 9**). This technology is expected to enable low-cost production of large diamond single crystals.

Regarding devices using diamond crystal SAW (surface acoustic wave) devices, electron emitters, ultraviolet LEDs, Schottky barrier diodes, and MOSFETs have been reported.

Sumitomo Electric developed diamond SAW devices, which are not so called semiconductor devices, for high frequency applications. Diamond SAW devices were used for optical data link products of Sumitomo Electric(98),(99). Due to the easy electron emission properties of diamond, it is promising to be used for electron guns of electron beam equipment, such as electron microscopes, electron beam radiation machines, or electron beam lithography equipment. Sumitomo Electric successfully found out excellent electron emission capability by using n-type diamond highly-doped with phosphor, and succeeded in high current electron emission of 1103 mA from a 1 mm^2 diamond device(100) (**Photo 10**). In the collaborative development of the NEDO Project, Sumitomo Electric, Elionix Inc. and AIST successfully demonstrated the drawing of 4-nm-width line pattern, the narrowest line width ever reported. An electron gun module for an SEM (scanning electron microscope) was made (**Photo 11**), and a secondary electron image of gold particle was successfully taken with the magnification ratio of 100,000 (**Photo 12**).

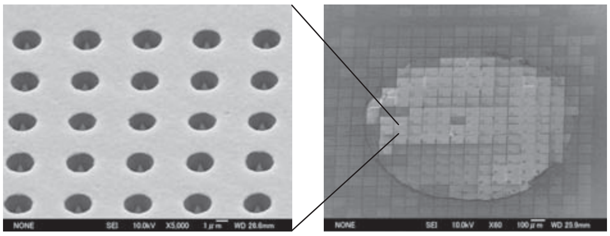

Photo 10. Diamond electron emitter array (5 µm pitch array)

Photo 11. Electron gun module

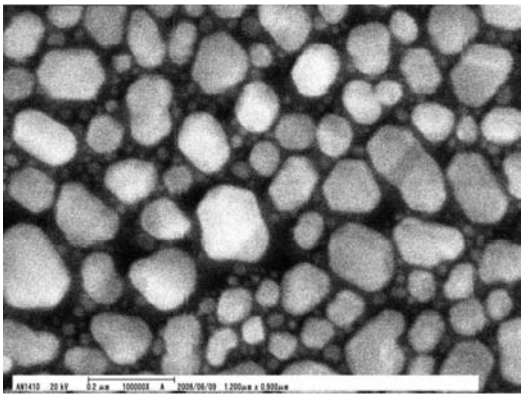

Photo 12. Secondary electron image of gold particle taken by using a diamond electron gun

Regarding the main discussion on power devices, research on Schottky barrier diodes and transistors have been conducted by using diamond devices. In the collaborative research of Sumitomo Electric and AIST on diamond Schottky barrier diodes, the electric breakdown field of 3.1 MV/cm, which is higher than that of SiC, was obtained(102). Diamond is a quite promising material for high temperature operation due to its wide bandgap, and AIST demonstrated that a diamond Schottky barrier diode can be operated at 400 or 500˚C by using Ru (ruthenium) as a Schottky gate material(103). High speed switching characteristics of this diode was also reported(104).

The research on diamond transistors began in 1990s. Several transistors which utilize the channel of hole accumulation layers formed at the surface of diamond terminated by hydrogen have been reported. The cutoff frequency of 45 GHz on a transistor with the gate length of 0.15 µm was reported(105).

As the figure of merit of diamond transistors is quite high compared with that of other semiconductor materials, diamond transistors are very promising for power devices with high breakdown voltage, low power dissipation, and high temperature operation. However, it is expected that it will take considerable time for the commercialization of diamond power devices because of the difficulties of obtaining high-quality, large-diameter and low-cost diamond wafers.

5. Conclusion

This paper describes the past quarter century's history of developing various kinds of compound semiconductor substrates, epitaxial growth technologies, and optical and electron devices, focusing mainly on Sumitomo Electric's research and development activities. Semiconductor structures with desirable properties can be obtained by distributing multiple compound semiconductors three-dimensionally according to the design, and innumerable compound semiconductor devices with a variety of functions and characteristics can be achieved. This is a magnificent feature and great magnetism unique to compound semiconductors and not found in silicon semiconductors. It is an issue, engineering issue, that the three-dimensional distribution of compound semiconductors can be formed according precisely to the design.

The advancement of this semiconductor engineering is indispensable to achieve future semiconductor devices. If semiconductor structures are formed according precisely to the design, it is expected that semiconductor devices with higher performances (high frequency, high output, low power dissipation, etc.) and with lower production cost compared with the conventional ones can be obtained. Semiconductor devices with completely new functions or with wider operation regions (for example, expanding the wavelength region of semiconductor lasers) can also be expected.

Another big issue of semiconductor engineering is to achieve low-cost, high-performance, and large-size compound semiconductor substrates. The largest issue for the commercialization of compound semiconductor power devices is its high production cost resulting from the substrate matters. The one who can solve this issue will become the first to commercialize compound semiconductor power transistors. Sumitomo Electric is trying hard to solve this Chinese puzzle.

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