White Paper

Compound Semiconductor Electronic Devices for Communications and Measuring Instruments

Contents

1 Introduction

Data communications traffic is increasing explosively due to the spread of 5G mobile and cloud services. As a consequence, the optical communications market is pushing ahead with introduction of fast and high-capacity next-generation standards. such as 400 gigabit Ethernet (400 GbE). Additionally, investigation of the next-generation 800GbE standard has already started. The modulation rates used for these signals are extremely high speed at 53 Gbaud for 400GbE, and 112 Gbaud for 800GbE. With the start of commercial 5G mobile communications, investigation of next-generation 6G standards is starting. It seems likely that future frequency bands will expand from the microwave band (1 to 30 GHz) into the millimeter waveband (30 to 300 GHz). Achieving these high-speed communications will require electronic devices for communications and such devices will play a key role in supporting future communications infrastructure.

Materials for communications electronic devices commonly use compound semiconductors fabricated from more elements than generally used silicon. A compound semiconductor is fabricated from at least two chemical elements each of which has unique properties facilitating high-speed operation due to fast electron mobility and saturation velocity. Moreover, materials with a wide bandgap offer excellent insulation and withstand-voltage characteristics. High-performance transistors can be fabricated by using heterojunction layers of these different compositions compound semiconductors; two examples of these transistors are the High Electron Mobility Transistor (HEMT) and the Heterojunction Bipolar Transistor (HBT).

In 1999, Anritsu Laboratories (name at that time) of Anritsu Corporation started research into semiconductor process technology for fabricating HBT using gallium arsenide (GaAs). The aim was to use our high-speed IC to increase the uniqueness of Anritsu measuring instruments. Several years of research were required, but in 2003 we successfully incorporated an MMIC using GaAs HBTs in a measuring instrument targeted at optical communications. In 2008, we successfully further increased the speed of measuring instruments using an MMIC fabricated from higher- speed indium-phosphide (InP) HBTs. The number of products has increased over subsequent years and now Anritsu measuring instruments for optical communications use many of our MMICs. More recently, we have started supplying electronic devices for communications, such as amplifier and digital ICs using our MMIC technology, to customers outside Anritsu.

2 High-speed Transistors using Compound Semiconductors

2.1 What is a Compound Semiconductor?

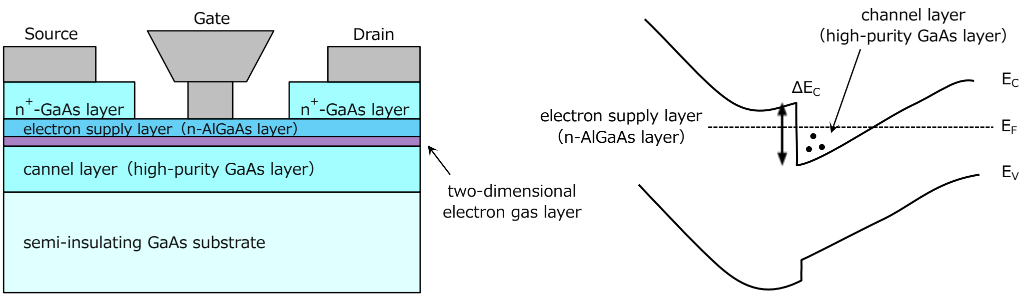
Table 1 lists the elements used as materials for fabricating semiconductors. Silicon (Si), the most commonly used semiconductor material is classified as Group IV in the periodic table of chemical elements; it is a stable semiconductor material using one element. Silicon is commonly used in the world of semiconductor fabrications due to its excellent workability and low cost. On the other hand, compound semiconductors can also be formed by mixing different materials such as elements from Group III and V, and II and VI. Typical compound semiconductors are formed from GaAs (gallium arsenide), InP (indium phosphide), SiGe (silicon germanium), and GaN (gallium nitride). Although the compound-semiconductor process is difficult and expensive, the resulting characteristics of the materials are much better than silicon in terms of higher speeds and withstand voltage. Moreover, high-speed transistors, such as HEMT and HBT, can be fabricated using heterojunction layers of the different compound semiconductors[1).

Table 1 Semiconductor Materials

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

2.2 Principles and Structure of High Electron Mobility Transistor (HEMT)

Figure 1 shows the basic structure of the HEMT[2). The HEMT is a Field Effect Transistor (FET) constructed of a separate electron-supply layer for supplying carriers, and a channel layer through which carriers travel. The GaAs HEMT uses GaAs for the base substrate and channel layer as well as aluminum gallium arsenide (AlGaAs) for the electron-supply layer. Doping the



(a) Cross-section (b) Energy Bands

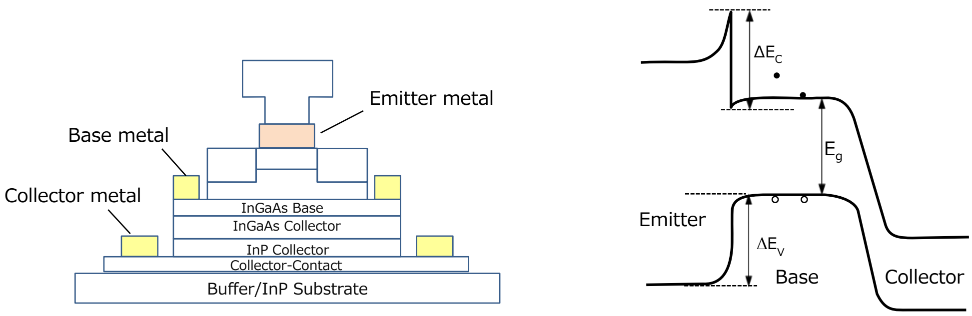
Fig. 1 HEMT Basic Structure

AlGaAs electron-supply layer with impurities results in accumulation of conductive electrons emitted from the donor with a triangular potential well formed at the GaAs boundary formed by a high-density 2D electron gas layer. The HEMT has excellent low-noise and high-speed characteristics due to the reduced Coulomb scattering of the 2D electron gas layer when electrons are travelling, as well as high electron mobility. The InP HEMT uses an InP substrate with an InAlAs electron-supply layer and an InGaAs channel layer. InGaAs has high electron mobility, offering faster operating speeds than the GaAs HEMT. The GaN HEMT uses a GaN substrate with an aluminum gallium nitride (AlGaN) electron-supply layer and GaN channel layer to offer a high withstand voltage of several hundred volts plus high operation speed.

2.3 Principles and Structure of Heterojunction Bipolar Transistor (HBT)

Figure 2 shows the basic structure of the HBT, which uses a wide-bandgap semiconductor at the emitter layer. Using this structure, at a forward bias, the current from the base to emitter is extremely low due to the high-potential barrier (ΔE_V) resulting from the holes facing the emitter from the base. Consequently, most of the emitter current flows to the base, allowing the base density to be increased and the base resistance Rb can be lowered (higher-frequency operation possible at lower base resistance). In addition, current gain can be larger with a thinner base layer. The HBT compound semiconductor materials may be either GaAs or InP for even faster operation. With regard to the HBT layer structure, this White Paper explains an example of our HBT process.

The GaAs HBT uses GaAs as the substrate, InGaP as the emitter layer, and GaAs as the base layer. The InP HBT uses InP as the substrate and InGaAs as the base layer. Like the HEMT, the HBT has excellent high-speed operation but the double-heterojunction structure offers higher withstand voltage than the HEMT as well as featuring high gain as transconductance (gm) increases. In SiGe HBT systems, the substrate is Si while the emitter is n-Si and the base layer is SiGe. Although the SiGe HBT has lower withstand voltage than GaAs HBT and InP HBT systems, low-cost fabrication is possible using general silicon semiconductor processes.



(a) Cross-section (b) Energy bands

Fig. 2 HBT Basic Structure

Moreover, large-scale integrated circuits can be implemented using BiCMOS technology combining CMOS.

2.4 Comparison of Transistor Types

The typical functions and performance required by high-speed transistors are high withstand voltage, low noise characteristics, good linearity, and high integration. Table 2 compares these features.

Table 2 Relative Comparison of Transistors

Transistor Type	Withstand Voltage	Low-frequency Noise	High-frequency Noise	Linearity	Integration
HEMT	A	B	S	S	B
HBT	S	S	A	S	A
SiGe HBT	B	S	A	A	S

B: Poor; A: Good; S: Excellent

The HEMT has excellent high-frequency noise characteristics due to the low Coulomb scattering effect when electrons are traveling. The HBT features high withstand voltage due to adoption of the double-heterojunction structure. The SiGe HBT can be highly integrated using BiCMOS technology. By making use of each of these features, electronic devices with each of these transistor types are used widely, especially in the communications field.

3 High-speed Transistor Application Fields using Compound Semiconductors

3.1 Application Examples in Communications Market

Compound semiconductors have excellent high speed and high withstand voltages, so they are used in high-frequency amplifiers for communications applications. Figure 3 shows a typical communications-infrastructure network using compound semiconductor high-frequency amplifiers in various fields, such as optical communications, wireless communications, satellite communications, automobile radar. The GaAs HEMT is used in microwave wireless communications with a frequency range of 1 to 30 GHz. For example, high-output and low-noise amplifiers are used for both mobile and satellite communication systems. The InP HEMT is used as high-output amplifiers in optical communications as well as in 76-GHz band automobile radar. The GaN HEMT is used as high-output amplifiers in 1 to 30-Hz band cellular-telephone base stations and satellite broadcasting[3)]. Like the GaAs HEMT, the GaAs HBT is used in high-output amplifiers for mobile communications. The InP HBT is used in high-output amplifiers for 28 and 56-Gbaud signal rates used by optical communications. The SiGe HBT with BiCMOS technology is used as LSIs for wireless and optical communications equipment. Compound semiconductor application fields are expected to expand in future centered on both communications and radar.

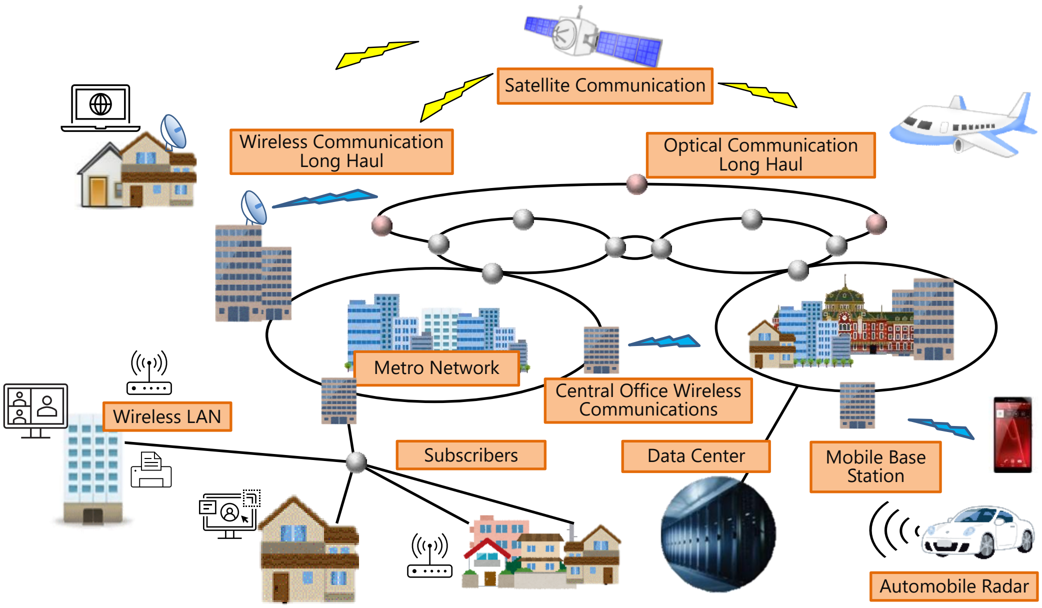


Fig. 3 Communications Infrastructure Network

3.2 Measuring Instrument Application Examples

In addition to high-quality, high-frequency performance, measuring instruments also require customized specifications to implement various functions. Due to the relatively low development costs and excellent high-speed operation, compound semiconductors can be used to implement custom ICs for communications measuring-instrument applications. In particular, due to the more uniform characteristics and fast current rise time of HBTs compared to HEMTs, HBTs are better suited for use in relatively large scale high-speed digital ICs. As a result, they are ideal devices for high-speed communications measuring instruments. Anritsu's MP1900A and MP2110A (Fig. 4) are typical optical measuring instruments using many ICs developed using our in-house InP HBT process technology. These popular high-

MP1900A

MP2110A

Fig. 4 Anritsu Optical Communications Measuring Instruments performance and high-function instruments have excellent market support due to the wide line of expansion modules (Table 3) using ICs developed with our process technologies[4].

Table 3 Function Module Product Line

Function	Operating Frequency
2:1 Multiplexer	DC to 64 Gbps
1:2 De-multiplexer	DC to 64 Gbps
Differential 2-way Amplifier	30 kHz to 40 GHz
T Flip-Flop	DC to 60 GHz

3.3 Optical Modulator Driver Application

Figure 5 shows a typical block diagram of the optical-signal transmitter section used in optical communications. The signal-free CW optical signal output from the semiconductor laser has an electrical signal output from the driver amplifier superimposed upon it by the optical modulator. Since the optical modulator must be driven using a high-voltage electrical signal, a high-output driver amplifier is used. Either an EA modulator or an InP MZ (indium phosphide Mach-Zehnder modulator) is used as the optical modulator. The former is operated by a single-ended signal so the drive voltage must be about 1 to 2.0 Vpp. The latter is operated by a differential signal, so the drive voltage must be about 1.5 to 4 Vpp (differential). The new 400GbE optical communications standard uses a 53-Gbaud signal rate, requiring a driver amplifier band of at least 40 GHz to obtain a good modulation signal at 53 Gbaud. In addition, the new 800GbE standard currently under investigation uses a signal rate of 112 Gbaud, requiring a driver amplifier band of at least 70 GHz. The segregation graph in Fig. 6 shows an example of the operation frequency (horizontal axis) of semiconductor materials used in amplifiers versus output power (vertical axis). The GaAs, InP, and SiGe semiconductor materials used in driver amplifiers for 400GbE and 800GbE are enclosed in the red circle at the bottom right of the graph. The highest operation frequency is supported by InP, which is the best semiconductor material for market-leading optical communications driver amplifiers.

Figure 7 shows the Eye diagram for a 53-Gbaud PAM4 optical waveform driven by an EA modulator using a developed differential linear amplifier[5]. This amplifier uses the InP HBT process to achieve a band exceeding 40 GHz. TDECQ is a typical index for measuring the waveform quality of optical PAM4 signals; waveform quality is better at a smaller TDECQ. Furthermore, a higher extinction ratio (Outer ExR), which is the light ON/OFF ratio, is best for optical signal transmissions. The IEEE standard for optical transceiver optical waveforms specifies a maximum TDECQ of 3.4 dB and a minimum extinction ratio of 3.5 dB. This amplifier produces an excellent optical waveform satisfying this standard.

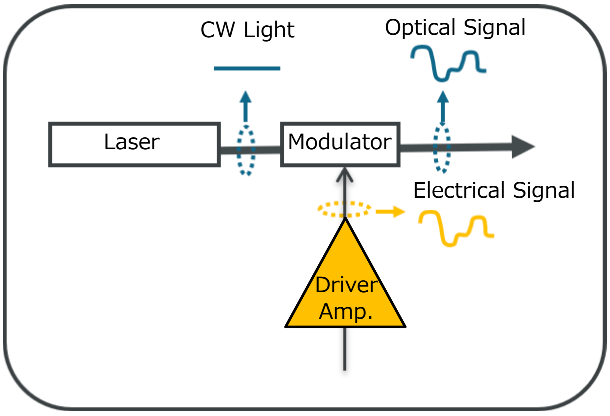


Fig. 5 Optical Signal Transmitter Block Diagram

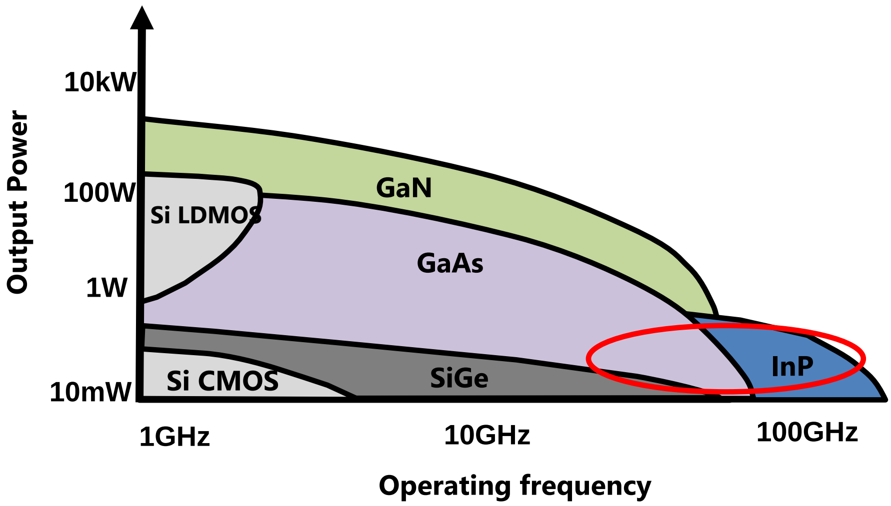
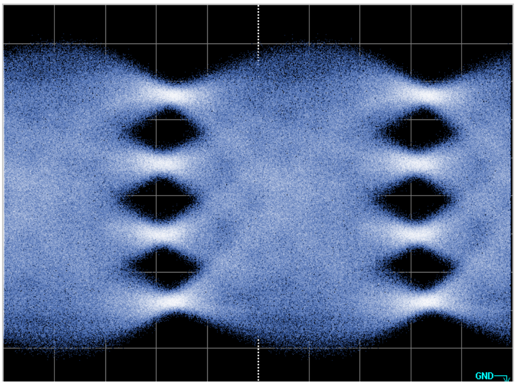


Fig. 6 Semiconductor Material Segregation and Relationship with Operating Frequency and Output Power



TDECQ: 1.66 dB
Outer ExR.: 4.37 dB

Fig. 7 53-Gbaud PAM4 Optical Waveform

4 Conclusions

Electronic devices using compound semiconductors leverage the excellent properties of these materials to support today's communications technologies. Anritsu uses its in-house-developed InP HBT process technologies to offer customers high-speed and high-performance amplifier modules and functional modules based on the high-speed, high-withstand voltage and high-transconductance properties of these materials.
Anritsu's continuing development of leading-edge electronic devices for communication applications will play a key role in future growth of communications technologies.

5 References

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