4 Millimeter Wave Devices

4-1 Research Project on Millimeter-wave Semiconductor Devices

Toshiaki MATSUI, Keisuke SHINOHARA, Masataka HIGASHIWAKI, and Nobumitsu HIROSE

In order to put millimeter-wave communications systems to use, it is crucial to improve the efficiency of communications devices and to minimize their size. In our institute, we focus on millimeter-wave semiconductor devices in order to develop millimeter-wave communication technology which can be adapted to various applications. Among our results is the attainment of a cutoff frequency of 472 GHz, the world's highest figure to date*1. In the following manuscript, we shall introduce our research project including InP and nitride compound semiconductor devices, SiGe semiconductor devices, Si-CMOS integrated circuit and SiN passivation film using hot-wire CVD process.

Keywords
Wireless communications, Semiconductor devices, Millimeter-wave, HEMT, InGaAs, InP, GaN, InN, SiGe, HotWire, SiN

1 Research Background

Faced with dramatic changes in industry structures, virtually all industries will continue to grow ever more dependent on IT (information technology) to survive in the global marketplace. Success will depend heavily on the overall development of content, software, and hardware. As a public research institute, one of our primary roles is to find seeds for hardware, which represents one of the most fundamental technology areas and to develop such seeds into practical applications.

Silicon (Si) devices, particularly Si-CMOS, have continued to make remarkable progress in performance in recent years. Such devices function as essential parts of electronic hardware. With 2 GHz already attained, clock speeds of common MPUs are expected to reach 20 GHz by 2007.

In the field of communications, as represented by the Internet, strong demand still exists for semiconductor devices operating at ever higher frequencies. For example, the frequencies used by mobile phones, which are predicted to evolve into the most commonly used type of Internet terminals, outstripping PCs, will move from the 2-GHz to the 5-GHz bands as data processing volumes continue to increase. Even for low-cost-available wireless LANs such as Bluetooth and IEEE802.11, the 2.4-GHz band is being employed[1]. Even millimeter wave and sub-millimeter wave bands may be used in years to come for applications such as 60-GHz band wireless LANs, which are expected to answer the problems posed by the last-mile leg to office and home LANs. The cutoff frequency (f_T) required for semiconductor devices used in those bands can be as high as 40 GHz for the 2.4-GHz band, 80 GHz for the 5-GHz band, and 150 GHz for the 60-GHz band[2].

The performance of a communications system is determined by the capabilities of its component electronic devices, particularly the transistors that function as active devices. There are two approaches to improving transistor operating speeds:

(A) Improve carrier mobility in the semiconductor material;

(B) Downsize the gate (base) structure (make the film thinner).

Approach (B) has been used to boost the operating speeds of Si devices, while approach (A) has been applied to compound semiconductors (for example, GaAs, InP, GaN and InN - described in greater detail further below), which offer higher mobility. With structure in which the channel layer is separate from the carrier supply layer, HEMTs[3] have helped reduce the size and weight of satellite broadcast receiver antennas and mobile phones. This structure can maximize the advantage of compound semiconductors, enabling a degree of mobility an order of magnitude greater than that of Si.

On the other hand, the frequency band employed for mobile phones is around 1 GHz. Even for satellite broadcasts, frequency bands are about 12 GHz at most. The problem posed by rapidly diminishing frequency space, resulting from explosive growth in communications terminals and ever-higher transfer rates required for data communications, makes it especially urgent to develop practical electronic devices capable of performing amplification at practical levels in the millimeter wave band. We have been attempting to improve the performance of InP-based HEMTs that offer mobility (in the InGaAs layer, a channel layer, where electrons flow) twice that of GaAs. We have also begun investigating nitride-based compound semiconductors and SiGe HEMTs, which are expected to serve as next-generation semiconductor materials. The wide band gaps and high electron saturation velocities of nitride-based compound semiconductors offer the potential for use not only in base stations for ground-based communications terminals, but in communications satellites. Integrating SiGe with Si -currently the most-common semiconductor material- will help reduce the overall cost of communications systems, while also improving security, an issue whose significance is certain to become even more prominent in the near future.

In addition to core devices for communications applications, our research has investigated base band (BB) units, which are deeply related to high-frequency front ends, as well as issues related to the deposition of SiN films employing the HotWire CVD method. SiN offers considerable promise as passivation films (protection films).

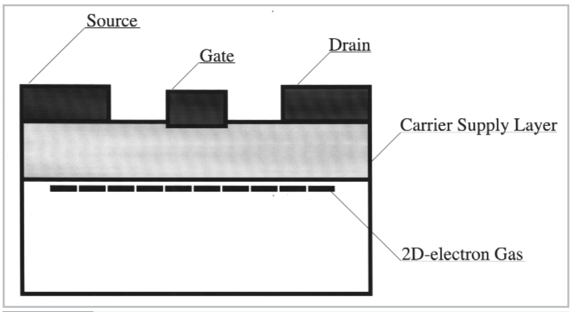

Fig. 1 Schematic structure of HEMTs

2 InP-based Semiconductor Device

Lying between the visible light and microwave bands, the frequencies ranging from millimeter to sub-millimeter waves remain relatively underutilized especially for public communication or broadcasting areas. Nevertheless, this band region will be critically important for future ultra high-speed communications systems. Transistors capable of running at high speed and providing good performance in the millimeter wave region of high frequencies will play a key role in making the most efficient possible use of this frequency band. Transistors that can run at high frequencies provide significant gains with single-step amplification and lower noise when employed as amplifiers. Their superb conversion gain in high frequencies greatly enhance the performance of millimeter wave communications systems.

Compared to conventional GaAs-based HEMTs, InP-based HEMTs offer advantages of high electron mobility, high electron saturation velocity, and high electron density, opening up the possibility of operations at higher speeds[4]. They can also be combined with optical devices, since the same semiconductor materials are used in lasers and photodiodes for fiber optic communications. Research on the InP-based HEMTs was initiated about 20 years ago[5], and it was reported that its cutoff frequency (the upper limit frequency at which the transistor can perform amplification), which is the major index representing device performance, reached approximately 350 GHz in 1992[6].

We have optimized the epitaxial structure and process conditions of InP based HEMTs and achieved the shortest gate length 25 nm and world-record figure of f_T = 472 GHz, with stable operation[7][8][9]. This value significantly exceeds conventional records, suggesting that an unknown phenomenon may be responsible for electronic transport in the device. One of our challenges is to clarify this physical phenomenon and eventually to attain even higher operation speeds.

Transistors used in real-world systems require circuits that perform tasks such as amplification, mixing, and oscillation. One of our next challenges will be to fabricate elemental units of communication systems such as amplifiers, mixers and oscillators using our original HEMTs. We have pushed ahead with investigations of the commercialization of HEMTs in order to make full use of their potential. For example, a single stage amplifier employing our HEMTs is expected to provide power gain of 10-12 dB at 100 GHx. Our HEMTs have the potential to change system architectures. We plan to develop techniques to integrate this transistor with peripheral circuits.

Noise levels can be further reduced by cooling HEMT devices, which may allow use of the device in receivers for sub-millimeter wave bands beyond 300 GHz - for example, for radio astronomy. In anticipation of operations at higher frequencies and lower noise levels, we will establish a low-temperature measurement system to determine their low-temperature properties.

3 Nitride-based Compound Semiconductor Device

Currently, most transistors operating at frequencies above the millimeter wave band (>30 GHz) use compound semiconductors. This is because compound semiconductors provide physical properties superior to Si, and because of the difficulty in fabricating Si devices that provide adequate performance at frequencies beyond the millimeter wave band. However, compound semiconductors have inherent drawbacks and limitations that have become increasingly clear. The challenge is to develop new compound semiconductor materials capable of overcoming such limitations.

Nitride-based compound semiconductors represent one of the most promising candidates. We have been focusing on gallium nitride (GaN) and indium nitride (InN) as major nitride materials that meet the above requirements. GaN is a semiconductor material that received considerable attention in a brief period during the late 1990s as a material suitable for blue-light LEDs and laser diodes. At first, the primary motive for research on this material was its potential application to blue light-emitting devices. However, in recent years, the applicability of this material to high-frequency high-power devices (in particular, GaN/AIGaN field-effect transistors)[10] has also been studied. This is because the wide band gap of this material-3.39 eV-creates high tolerance in gate voltage, as demonstrated in Table 1. The resulting transistors may be used as power devices in high-speed wireless communications systems for final-mile connections between base stations and residences. Wide band gaps offer the potential for “tough devices” capable of operating under harsh environments such as space radiation or high temperature above 300℃. In such environments, Si or other compound semiconductor devices, due to their intrinsic characteristics, are unable to function. In addition, calculations predict that electrons will propagate rapidly in InN. Thus, the ability to use a single-crystal InN of high quality as a transistor material would provide an innovative transistor with excellent high-frequency characteristics[11]. Among the physical properties listed in Table 1, saturation electron velocity in particular can be used as an index of the velocity of electrons flowing under the gate electrode. Theoretically, the saturation velocity of InN is at least 1.5 times that of InGaAs, the material that currently holds the highest value. To oversimplify somewhat, this suggests that f_T will increase by a factor of 1.5. Moreover, the band structure of InN allows for the possibility that the velocity of electrons flowing beneath the gate electrode will increase by a factor of 1.5 times or more if used in short gate-length high frequency transistors. Theory suggests that the f_T of an InN-HEMT with a gate length of 100 nm will exceed 1 THz while that of InGaAs-HEMTs formed on the InP substrate with the same structure will be 250-300 GHz. In addition, in contrast to GaAs, which contains toxic materials such as As (arsenic), nitride-based compound semiconductor materials are ecologically-friendly.

Table 1 *Physical properties of major semiconductor materials*

	Band gap (eV)	Electron mobility(cm^2/Vs)	Saturation electron velocity(cm/s)
GaN	3.39	2000	2.9×10^7
InN	1.89	4000	4.2×10^7
GaAs	1.43	6000	1.8×10^7
InGaAs	0.86	12000	2.7×10^7
Si	1.10	1200	1.0×10^7

We have a research plan to investigate crystal growth as a first step toward obtaining high-quality GaN and InN crystals. With regard to GaN, a number of research institutes have already presented papers that describe how to grow high quality crystals. Thus, we simply need to find the conditions for optimal crystal growth, based on the reports already available. On the other hand, apart from a handful involving crystal growth, there have been few studies of InN. In the limited number of reports presented so far, it has not yet been possible to develop high-quality crystals with the performance that theory would predict, in part due to the difficulty of growing good crystals. Thus, our primary goal is to grow high-quality InN crystals as yet unattained. We will then develop prototype short gate-length high-frequency transistors using GaN and InN in the channel layer to allow evaluation of their high-frequency characteristics.

4 SiGe HEMTs

The upper limit of the operating frequency of Si-CMOS integrated circuits is currently increasing rapidly, as the scale of design rules continues to grow finer. For NMOS transistors, the cutoff frequency has reached 60-70 GHz when gate length is 0.18 μm, high enough for use even in 5-GHz applications. As design rules grow even finer in the years ahead, some predict that f_T = 200-300 GHz will be possible if gate length is reduced to 50 nm or less. Since Si-CMOS can operate at higher clock speeds, there has been a growing interest in forming RF units with Si-CMOS*2 to integrate RF units with BB (base band) units in low-end products (for example, for Bluetooth applications). If realized, this would lead to significant cost reductions. However, there are inherent difficulties in providing a fast PMOS transistor that will be used as a pair with an NMOS transistor, due to its low carrier (hole) mobility. Meanwhile, as is typical of the so-called new business model that apples to such services that provide devices free, communications terminals, represented by mobile phones, belong to a highly cost-sensitive market in which wide marketplace penetration is crucial. Due to the difficulty of reducing the cost of compound devices, there is a strong demand for replacing compound devices with Si-based semiconductor devices and integrating all required functions onto a single chip[12].

The industry currently awaits the development of SiGe semiconductor devices capable of solving the above problems. Since SiGe is a mixed crystal of Si and Ge, both of which belong to the IV family of semiconductors, the accumulated techniques for manufacturing Si semiconductors can be adopted, and cost reductions should be relatively easy. Although their performance is inferior to that of compound semiconductor devices, SiGe semiconductor devices can function satisfactorily at the frequency of the above applications. In fact, an integrated circuit has been devised in which part of the RF unit is made of Si or SiGe-BiCMOS (a combination of BJT and CMOS) and integrated with the BB unit.

Si-based semiconductor devices using SiGe are broadly classified into SiGe bipolar and SiGe-FET devices. SiGe-HBT, a bipolar device, is already commercially available, while strained Si-MOSFETs and Si-based HEMTs, both FET devices, are the subject of intensive developmental efforts. While each of these materials have their own distinctive features, FET devices are more promising, given the trend toward circuit integration. In contrast, it has become increasingly clear that the possible margin of performance improvements in strained Si-MOSFETs will be limited to a few tens of percent, compared to conventional Si-MOSFETs[13]. Si-based HEMTs operate in the same manner as GaAs-HEMTs, which have served as leading high-frequency compound semiconductors in receivers for satellite broadcasting, and are suitable for high frequency operations.

Given the above, we have been developing SiGe-HEMTs. Our research efforts have focused on wafer evaluations, device fabrication processes, and related device performance evaluation technologies for HEMT device fabrication.

5 Si-based Integrated Circuit for Communications

The most significant part of the Si-CMOS integrated circuit for wireless communications systems is the BB unit that receives intermediate frequency (IF) signals from analog high-frequency (RF) units and performs digital processing. As HEMTs such as InP-, InN- and SiGe-based devices raise operating frequencies of high-end wireless communication devices to the millimeter wave band, the operating frequencies of the IF unit will also increase. This trend will eventually require digital integrated circuits of BB units receiving output from the IF unit to run even faster (Fig.1). Since the role of Si-CMOS integrated circuits in wireless communications is expected to grow in coming years[14], it is critical for even the Communications Research Laboratory to push ahead with research in this field.

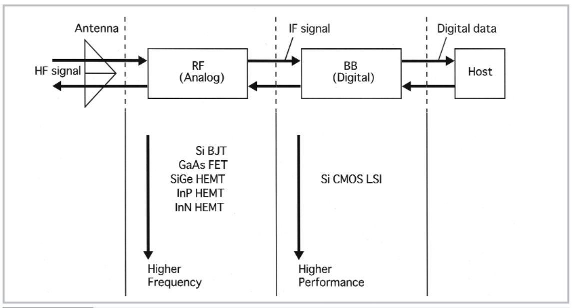

Fig.2 *Schematic diagram of configuration of communications gear*

Although operating frequencies have been successfully boosted, a number of challenges remain. At the moment, BJT exhibits better performance than CMOS in terms of operating frequency per unit current. This is because, compared to BJT, MOS transistors are characterized by smaller mutual conductance and require high-capacity passive devices for impedance-matching. Additionally, the matching property of the pair transistor degrades as design rules become finer. Additionally, paralleling shrinking design rules, power supply voltages must be reduced to maintain voltage tolerances, which in turn makes it necessary to guard against deteriorating SN (signal-to-noise) ratios during low-voltage operations.

Two approaches have been proposed to solve these problems. One is a physical approach[15] represented by finer design rules and the development of low-k/high-k dielectric materials. The other focuses on improving device structures and circuit configurations. Our emphasis is on the latter approach. For example, we may downsize the passive components by adopting three-dimensional device structure via micromachining to create compact, high-performance devices, employing self-contained circuits using neural network technologies in analog/digital (A/D) conversion for signal transport from the RF to BB unit and for digital signal processing in the BB unit. In particular, the BB unit requires high-efficiency hardware (dedicated circuits). High-efficiency hardware offers advantages in both speed and cost, while low-efficiency hardware provides performance inferior to that of firmware (combination of CPU and software). We need to develop high-efficiency hardware suited to specific goals.

We plan to build small-scale equipment on our premises that will allow us to carry out the cycle of design, fabrication, and evaluation efficiently, with quick turn-around times, in order to investigate crucial circuit elements (cells) consisting of a few thousand gates. In cooperation with independent foundries, we will evaluate performance at LSI levels based on the design, fabrication, and evaluation expertise accumulated through research and development on prototype cells (Fig.3).

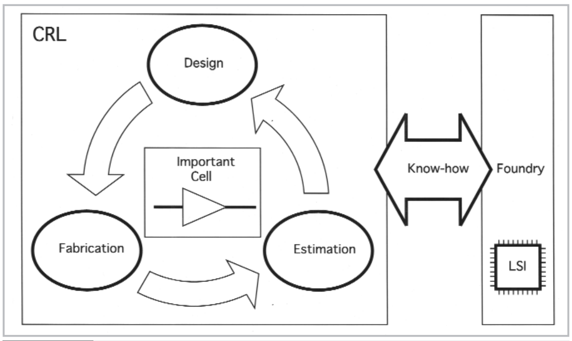

Fig.3 Relations between CRL and cooperative independent foundries

6 HotWire CVD

HotWire CVD (Cat CVD) was proposed by Matsumura and Tachibana in 1985[16] as an amorphous silicon thin-film deposition process. Fig.4 is a schematic diagram illustrating this process. It offers advantages such as low hydrogen content in the film, efficient use of the primary material gas (silane), and easy development into a large area process. As a result, this process has been investigated intensively. Part of the process technology has been incorporated into volume manufacturing processes. We focus on the application of compound semiconductors to passivation films, for which it is essential to clarify the reaction process to improve the quality of passivation films. The primary material gas is a mixture of silane and ammonia. The decomposition process of silane has been investigated in depth[17][18], while that of ammonia is currently not well-understood. Another concern is that compound semiconductors may be damaged by high temperatures generated by the proximity of the filament to the substrate. InP, in particular, has very low thermal conductivity, and its surface temperature increases even when the back of the InP substrate is chilled.

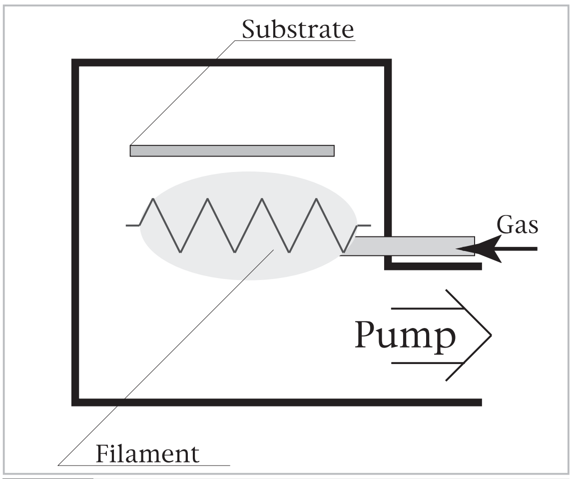

Fig.4 Schematic structure of HotWire CVD system

Fig.5 demonstrates the mass peak intensity (m/e = 2:H2, = 16:NH2, = 17:NH3, = 28:N2) corresponding to reactions affecting filament temperature (measure with a pyrometer) during ammonia decomposition. The chamber pressure was 4 Pa and the ammonia gas flow rate was 100 SCCM. The chamber pressure was adjusted by controlling the rotation of the turbo molecular pump serving as the major vacuum pump. The ammonia

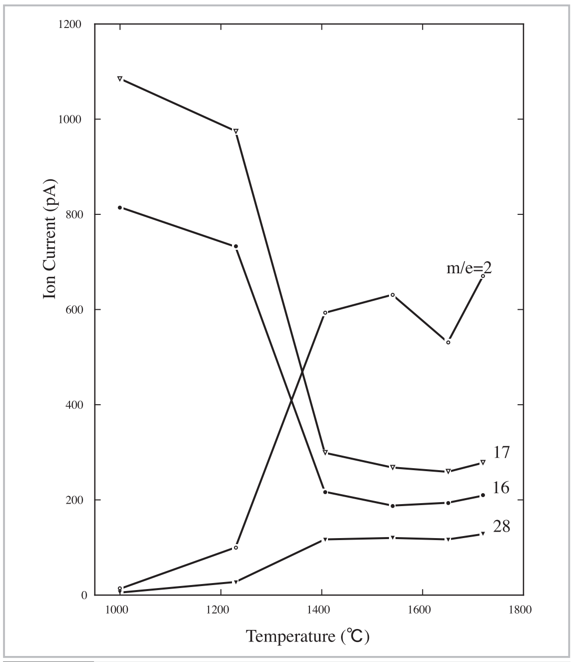

Fig.5 Ammonia decomposition spectra versus filament temperature

abruptly decomposed when filament temperatures rose over 1250℃. Peak intensity did not change much when heated to temperatures exceeding 1400℃, despite the remaining ammonia gas that had not reacted.

We plan to gather relevant data and to measure the surface temperature of the substrate in order to clarify the reaction mechanism for lower process temperatures.

7 Conclusions

The capabilities of a newly-developed communications system hinge on that of the component devices, which in turn depend on their constituent semiconductor devices. Studies of semiconductor device technologies will play a fundamental role in tapping frequency bands not yet utilized and in the implementation of ultra high-speed communications systems. The goals of our research plan include the realization of THz-class transistors, high-output millimeter wave transistors, and high-speed signal processing devices. Such devices are expected to contribute significantly to the evolution of diverse communications technologies related to ground-based wireless communications systems, stratospheric platform systems, space communications systems, and encryption technologies for ensuring data security during wireless communications. The Communications Research Laboratory has undertaken research into such devices with the close cooperation of private enterprises, universities, and public research institutes. Since we plan to work jointly with a number of external organizations in research on innovative devices and studies of potential commercialization, we cordially request aid in any form from other institutions. In addition, to accelerate the implementation of a new millimeter wave communications system, we are currently developing applications technologies for functional parts and high-performance communications gear.

Acknowledgments

We wish to acknowledge the suggestions and information contributed by Dr. Kasai and Dr. Kasamatsu at the Fujitsu Laboratories.

Note:

＊1 As of the end of September in 2001.

＊2 To date, Si-CMOS has commonly been used in the base band (BB) unit, while compound devices such as GaAs or bipolar junction transistors (BJTs) are deployed in the radio frequency (RF) unit.

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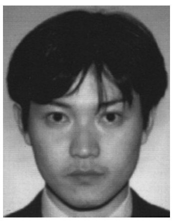
Precision Measurement in High Frequency Region



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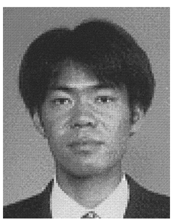
High-Frequency Semiconductor Devices



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Semiconductor Crystal Growth, Semiconductor Device Process

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Semiconductor Process, Fine Process