The Dawn of the New RF-HySIC Semiconductor Integrated Circuits: An Initiative for Hybrid ICs Consisting of Si and Compound Semiconductors

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SUMMARY Abstract The concept, state of the art, and future development directions of hybrid semiconductor integrated circuits (HySICs), which combine RF-CMOS ICs with compound semiconductor monolithic microwave integrated circuits (MMICs) are described in this paper, taking up recent wireless technologies as example applications. It is shown that ICs with superior function can be designed by mixing the optimal characteristics from the different semiconductors. To realize new semiconductor ICs, several component technologies for RF-HySIC are introduced in terms of chip/MMIC design, measurement, and breadboard fabrication. A prototype RF-HySIC is described for the combination of a GaN Schottky barrier diode with a Si RF-IC matching network developed at 5.8 GHz. A GaN diode structure, measurement and characterization of nonlinear devices, a GaN amplifier, and a GaAs MMIC are introduced as component technologies. In addition, the design for using an RF-CMOS matching network circuit with a size of 1.2 mm × 2.3 mm and room-temperature chip/wafer direct bonding under high-pressure conditions are explained. For advanced and autonomous ICs, HySIC and chip/MMIC topologies combined with a processor are proposed for application of HySIC to wireless sensor systems.

key words: hybrid semiconductor IC, RF-IC, GaN amplifier, rectifier

1. Introduction

Recently, wireless technology has produced a society where communication is becoming ubiquitous. The advantages of wireless communication technology have been extended to wireless sensor systems, and further, to wireless powering of electrical circuits by nano-electronics technology. Intelligent communication systems employing 5G have attracted attention as promising technologies for life amenities in the near future. Furthermore, an Internet of Things (IoT) powered by 5G has been proposed, and is expected to contribute to realizing a sustainable society [1], [2]. Wireless sensor systems play an important role in the IoT. Among the key technologies in these systems are integrated circuits (ICs) such as RF-CMOS ICs and compound semiconductor monolithic microwave integrated circuits (MMICs) [3], [4]. In addition, planar antennas are needed for compact modules in potentially low-cost systems.

Si CMOS technology was originally developed for digital processors and memory in information signal processing systems. In addition, due to super-fine processes and nano-electronics technology, analog CMOS chips are able to operate in the microwave and millimeter-wave regions. As a result, RF-CMOS ICs have recently been used as a low-power, low-cost ICs in compact high-speed personal communication systems [5], [6]. Si CMOS fabricated using silicon-on-insulator is attractive as a candidate for ecologically friendly green devices for safety and life amenities in a sustainable society. However, in terms of performance, Si devices suffer from large loss characteristics in circuits. To avoid this problem, circuit size needs to be sufficiently small.

Compound semiconductors such as GaAs, GaN, and InP have been developed that offer high performance such as high-power, low-noise, and high-speed operation even at millimeter-wave and terahertz frequencies [7]–[10]. However, these materials contain rare metals and rare earths. Further, in terms of the process technology, there are fabrication difficulties that lead to high cost. When these devices are used in wireless systems, much attention is paid to the trade-off between green technologies and use of rare material resources that are not abundant on Earth.

To overcome these problems, in particular to realize low-cost RF MMICs, the use of different types of semiconductor devices has been studied and good results have already been published. These mainly result from bonding technology between different types of semiconductor substrates [11]. In this paper, a solution for high-performance, low-cost, compact ICs in wireless systems is proposed by mixing the semiconductor from the design stage. It is believed that green wireless ICs offering good features could be produced by combining Si RF-ICs with high-performance chips/MMICs consisting of compound semiconductor devices such as GaN or GaAs. We call this a hybrid semiconductor integrated circuit (HySIC) and denote such devices that operate at radio and microwave frequencies as RF-HySIC.

2. The Design Approach to HySIC

As described in the previous chapter, communication systems, wireless sensors, and microwave power transmission require high performance, low cost, small size. To satisfy these requirements, we recognize that Si RF-CMOS IC technology and compound semiconductor chips and MMICs play important roles as the components of HySIC. Further-
more, ICs with superior function are expected through the optimal mixing. We believe that the uniqueness of our approach is to mix compact circuit topology due to the low-cost Si RF-IC with high-performance characteristics due to the compound semiconductor devices and circuits when the proposed RF-HySIC is designed and fabricated.

The approaches when designing and fabricating HySICs take account of implementation, replacement, and scalability. To maintain stable operation, heat problems need to be avoided. When a substrate with a low heat conduction rate is used instead of a metal substrate, it is inevitable that diode chips and FETs for high-power amplifiers (HPAs) will operate unstably or breakdown easily. In this case, the device and the passive circuit need to be implemented on a good heat-sink substrate (typically a metal plate). Next, let us consider a low-cost, small HySIC by scaling. This is achieved by replacing one part of the monolithic microwave integrated circuit (MMIC) with that from another type of semiconductor. In this case, the HySIC should be designed using the same device parameters and one semiconductor circuit can be mounted on the other circuit substrate. If the designer wants a more compact configuration of the HySIC, it is possible to use RF-CMOS technology in the circuit topology.

The designer needs to have good skills for measuring the characteristics of compound semiconductor device chips and designing Si RF-CMOS ICs and compound semiconductor MMICs using commercially available CAD tools. To obtain good agreement between the theoretical characteristics and experimental results, reliable experimental data from device chips such as I-V characteristics and S-parameters are needed. To minimize the uncertainty from experimental tools, accurate collimation and tuning are needed during measurement. Using fundamental measurement data and CAD by carrying out nonlinear simulations, the designer can establish the device model through nonlinear parameter extraction after a suitable nonlinear model is selected (such as an Angelov device model).

In the design of the IC, both small-signal S-parameters and large-signal S-parameters are utilized. First, small-signal S-parameters enable us to determine the circuit topology. Second, by using a nonlinear device model, the steady-state operation of the circuit can be investigated by harmonic balance simulation. Finally, after the compound semiconductor amplifier MMIC (e.g., GaAs) and Si RF-CMOS amplifier IC have been designed to operate at the same frequency with the same performance, the amplifier HySIC can be created by replacing part of the GaAs amplifier MMIC with part of the Si RF-CMOS amplifier IC with the same functional circuit. Examples of this kind of combination are a HySIC amplifier with a Si RF-CMOS gate matching circuit and gate bias circuit, and a GaAs drain matching circuit with a drain bias circuit and a GaN FET chip. Using this configuration, thin lightweight intelligent active integrated antenna arrays are feasible. This is a promising approach not only for minimizing performance degradation due to large loss tangents and high cost by super-fine Si processes, but also for performing sophisticated processes resulting in high value added to GaAs and related compound semiconductors.

3. State-of-the-Art HySIC Components at 5.8 GHz

After the RF-HySIC design has been determined, the choice of fabrication processes, selection of measurement equipment, and method of implementation are considered. This challenge requires high-quality design, fabrication and evaluation of the ICs. In this study, a Si RF-CMOS IC and a compound semiconductor chip/MMIC using GaN and GaAs were selected. These IC technologies include the RF-IC process, chip/wafer bonding, and chip/MMIC topologies. It is useful to introduce the component technologies of the RF-HySIC in terms of chip/MMIC design, measurement, and breadboard model fabrication [12], [13].

3.1 The Si/GaN Schottky Barrier Diode Characterization

3.1.1 Diode Structure

In fabricating the HySIC by the Si RF-IC process, the nano-process equipment in the super cleanroom at the ISAS/JAXA is used for the Si Schottky barrier diode (SBD), the RF-CMOS, and the fine microwave circuit topology. For instance, fabrication of the Si SBD with a p-well in a Si n-type semi-insulating substrate by the process is investigated.

(a) Si SBD and probe measurement.

(b) The SBD DC curve

Fig. 1 SBD test pattern and characteristics
using a probe station. The SBD with a probe and the I-V characteristic are shown in Fig. 1. The fabricated RF-IC matching network is shown in Fig. 2.

To take advantage of GaN and design a rectifier using a GaN SBD with high RF-DC conversion efficiency, it is essential to characterize the properties. We report the impedance measurement of a GaN SBD at a frequency of 5.8 GHz as shown in Fig. 3.

Although properties are generally estimated from measurement results or theoretical analysis, theoretical device characterization without measurement does not lead to successful circuit operation. This is because device physical models are not perfect, the calculation process is not simply limited to the actual diode, and the amount of calculation may become large in many cases. We therefore carried out parameter extraction from the nonlinear device model based on measurement data.

When diode characteristics are measured, it is important to determine the reference plane for evaluating the device under test (DUT). Figure 4 shows the case of 1-port device measurement. The data obtained from collimation are shown in Fig. 5. The reflection coefficient of the diode is included in the bonding wire impedance. To estimate the diode impedance precisely, the wire bonding impedance needs to be eliminated as shown in Fig. 6(a). After collimation, the reliable impedance is measured as shown in Fig. 6(b).

3.1.2 Nonlinear Device Measurement

An auto-tuning system is an S-parameter measurement system that has various impedance conditions at the input and output ports. The characteristics of the active device such as a transistor depend on the input power and the output load. To develop a high-efficiency amplifier, we need to measure the efficiency under various input power and output load conditions and find the best among them. In the auto-tuning system, control of the input power is equivalent to impedance control at the input port and control of the output load is equivalent to impedance control at the output port. As a result, we can find the optimal impedance conditions by using the auto-tuning system.

In Fig. 7, a schematic drawing of the auto-tuning system is shown. The two tuners in front of and behind the device under test (DUT) produce a variety of different impedance conditions. The S-parameters of the tuners are measured in advance for all impedance states and a datasheet is made. For the DUT, such as a transistor, the scattering parameters and efficiency are measured under various input and output impedance conditions. Based on the datasheet of the tuners, the effects of both tuners are removed and the optimal efficiency conditions are measured.

An example of a block diagram and measurement results for a diode is indicated in Fig. 8. The dashed line indicates the reference plane of the boundary between the source impedance $Z_{sg}$ and the diode input impedance $Z_{in}$. The maximum input power is $-18$ dB which occurs at the point indicated by the red diamond. When the rectifier is
3.1.3 Diode Modeling

In this study, an SBD is used as a device for RF-to-DC conversion in nonlinear operation. The nonlinear capacitance is denoted as follows:

\[ C = \varepsilon \frac{S}{w} \]
\[ w = \sqrt{\frac{2\varepsilon (\phi_{bi} - V)}{qN_d}} = \sqrt{\frac{2\varepsilon \phi_{bi}}{qN_d} \left( 1 - \frac{V}{\phi_{bi}} \right)} \]

Here, \( \varepsilon \) is the dielectric constant, \( S \) is the area of the diode, \( w \) is the depletion layer width, \( \phi_{bi} \) is the built-in-potential, \( q \) is the electron charge, and \( N_d \) is the impurity density. The nonlinear behavior of the rectifier circuit is investigated by using these formulae. The equivalent circuit model shown in Fig. 9 is used in order to simplify the analysis.

From the measurement of reflection coefficient of the rectifier circuit, the characteristics of the nonlinear capacitance of \( C_j \) and \( R_s \) are evaluated from the following equations:

\[ Z = 50 \frac{1 + \Gamma}{1 - \Gamma} \]
\[ Y = \frac{1}{Z} = \frac{1}{R} + j\omega C = \frac{1 + j\omega RC}{R} \]
\[ Z = \frac{R}{1 + j\omega RC} = \frac{R(1 - j\omega RC)}{1 + \omega^2 R^2 C^2} \]

3.2 GaN and GaAs MMIC Power Amplifiers

3.2.1 The GaN Amplifier

When an HPA is considered, a multi-stage HySIC amplifier
consisting of an MMIC using a nano RF IC is very attractive in terms of compactness and potentially low cost. These conditions are strongly demanded by the RF components in the communication systems of satellites. The GaN HPA shown in Fig. 10 was developed by our research group for the deep space communication system in a cubic satellite, Procyon, which launched in 2015 from Tanegashima Space Center. This GaN HPA does not operate at 5.8 GHz but at 8.4 GHz. However, we would like to examine the GaN HPA as a promising component for high-power HySIC.

In this HPA, a GaN chip (by TriQuint) is used (see Fig. 11) that was designed by commercially available software (Keysight ADS). In order to investigate the characteristics, a nonlinear simulation was carried out in order to obtain high power and high RF-to-DC conversion efficiency. In addition, a Cu metal plate is used as an effective heat sink which is one of the key points of the HPA module. These are shown in Fig. 12. The small-signal S-parameters of the fabricated HPA circuit are shown in Fig. 13 (a) for \( V_d = 28 \) V and \( I_d = 0.5 \) A. Figure 13 (b) shows the input–output characteristics at 8.4 GHz for \( V_d = 28 \) V and \( V_g = -3.5 \) V. In each figure, solid lines indicate measurement data and dotted lines indicate data simulated using the constructed nonlinear model. Figure 13 (a) shows that the measured \( S_{11} \) is smaller than \(-10 \) dB at frequencies of 8.4 to 8.8 GHz. The measured \( S_{21} \) exceeds 10 dB at frequencies of 8.35 to 8.75 GHz. Figure 13 (b) confirms that the measured maximum output power is 42.6 dBm and the measured maximum drain efficiency is 55.8% at 8.4 GHz.

### 3.2.2 The C-Band GaAs MMIC

Among the various compound semiconductors, GaAs is popular for high-frequency ICs. GaAs MMIC amplifiers are also a good candidate for power amplifier HySICs and low-noise amplifier HySICs. A C-band GaAs high-power high-electron-mobility transducer (HEMT) MMIC was fabricated using the pseudomorphic HEMT process by a foundry service (UMS Co. Ltd.). The configuration is shown in Fig. 14. The GaAs PA MMIC operates at 5.8 GHz with \( V_{gs} = 0.5 \) V, \( V_{ds} = 4.0 \) V and produces an output power
of 30.6 dBm, gain of 23.6 dB, and power added efficiency (PAE) of 39.1% at the 1 dB compression point. The measurement data are shown in Fig. 15.

3.3 The RF-HySIC Rectifier with the Si Matching Network and the GaN Diode

3.3.1 The Hybrid IC on a PC Board

The 5.8 GHz band GaN diode rectifier was developed as a fundamental circuit for Si and GaN rectifier HySICs. The matching network part was fabricated using a PC circuit board, and the GaN diode chip was directly mounted on the Cu heat sink plate. The circuit substrate is held by screws to enhance adhesiveness between the circuit substrate and the Cu heat sink plate. As can be seen in Fig. 16, the measured RF–DC conversion efficiency and output DC power of 10 W at 5.9 GHz are 32.6% and 3.04 W, respectively. The frequency shift in the optimal peak operation is attributed to the wire bonding.

3.3.2 Design of RF-CMOS HySIC

In terms of the applications of HySICs, active integrated antennas employing a HySIC rectifier/harvester consisting of a Si RF-IC and GaN SBD are good candidates. By using the merits of Si and GaAs circuits to obtain the optimal performance, low-cost compact RF-ICs can be realized by sharing MMIC geometry. A rectifier consisting of a Si RF-CMOS and GaN SBD is introduced here as an example of HySIC design [14]. A novel hybrid rectifier design method using a standard 0.18 μm CMOS MMIC and a GaN diode is proposed as shown in Fig. 17. The target RF input power is around 10 W at 5.8 GHz and the output DC power is set to 2 to 3 W. To achieve this kind of high input/output power from a small CMOS chip as shown in Fig. 18, low-impedance and wide thin-film microstrip lines are used as impedance matching circuits. To protect the capacitors from high voltage generation, series capacitor pairs are used for DC blocking and RF short circuit. A high-linearity 3-stage
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n-MOS single-pole, single-throw (SPST) switch is also employed for the impedance matching tuning. The GaN diode is modeled by measurement, and designed to be connected via eight bonding wires. The chip size is only 1.2 mm \times 2.3 mm (Fig. 18). The simulation results show that input return loss is lower than \(-14\) dB (Fig. 19), and power efficiency is around 30\% at 10 W RF input (Fig. 20).

3.3.3 The Si RF-IC and Chip/Wafer Bonding

This chapter shows a prototype RF-Hysic that combines a GaN SBD with a Si RF-IC matching network developed at 5.8 GHz. The circuit characteristics are almost the same as the fundamental circuit introduced in the previous section. Replacement of the PC circuit board for the matching net-

work into the Si substrate is the first step for future miniaturization of the HySIC technology which utilizes different types of semiconductor devices. The circuit pattern of the Si RF-IC matching network was created by nano-process technology as shown in Fig. 21. The advantages of this method are that the RF circuit part can be made with only one mask process. This is an advantage of HySICs using this method. However, there may be a penalty that it requires a relatively large area.

Although this produces a compact IC, the diode chip made from a different semiconductor must be mounted in the rectifier HySIC. For this purpose, chip/wafer direct bonding of the GaN chip onto the Si substrate using Au ground metal was carried out by high-pressure bonding at room temperature. Three types of wafers are needed for room-temperature chip/wafer direct bonding: the chip-holding/alignment adapter, the circuit-patterned wafer, and the high-pressure-loading wafer. To achieve successful bonding, it is important to satisfy the roughness and pressure conditions. The surfaces of both materials were activated by Ar fast ion beam, and the roughness of the surfaces was kept less than 1 nm under a high pressure of 50 MPa. Figure 21 shows the attempt to align the rectifier HySIC using the high pressure bonder (BOND MEISTER, MHI Machine Tool Co. Ltd.). Since the backside of GaN has Au backing conductor as a common ground, the two semiconductors became adhered via the Au metal under the ultrahigh pressure. The loaded pressure was more than 10 MPa at room temperature. In addition, an attempt at MMIC/wafer bonding was made between the GaAs MMIC and the Si analog IC as shown in Fig. 22. Good adhesion was achieved.

4. Directions of HySIC Development

The fundamental technologies described in the previous chapter for HySIC can be applied to 5G communication
A promising application for an SoC using a HySIC is in a phased array radar. The concept of a self-consistent wireless harvester sensor chip using HySIC with dimensions of about 20 mm square is shown in Fig. 23 [15]. Recently, high-speed logic ICs have become available at low price that operate with low-power consumption in compact packages. When used in an array antenna (see Fig. 24) with high performance such as retro-directive function, the wireless sensor system in a vehicle can be taken advantage of in autonomous navigation in cars, airplanes, and satellites [16]–[18].

5. Conclusion

In this paper, the concept, state of the art, and future development directions for HySICs consisting of RF-CMOS ICs and compound semiconductor MMICs were described. These can be designed to provide ICs with superior function by mixing the optimal characteristics of each semiconductor. The component technologies of RF-HySICs needed in order to realize the HySIC were introduced in terms of chip/MMIC design, measurement, and breadboard model fabrication.

As a prototype RF-HySIC, a combination of a GaN SBD with a Si RF-IC matching network developed at 5.8 GHz was demonstrated. The component technologies described include the structure, measurement, and characterization of GaN diode, the GaN amplifier, GaAs MMIC fabrication, design using RF-CMOS, and chip/wafer bonding. For advanced and autonomous ICs, HySIC and chip/MMIC topologies combined with a processor were proposed for application of HySIC to wireless sensor systems.

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References


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