Millimeter-Wave RFIC Technologies For 5G Systems

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This paper describes semiconductor technologies for millimeter-wave radio frequency integrated circuits (RFICs) used in the fifth generation mobile communication systems (5G). Specifically, this paper explains bulk complementary metal oxide semiconductor (CMOS) technology, the mainstream semiconductor fabrication process, silicon on insulator (SOI) CMOS technology that improves the high-frequency characteristics of bulk CMOS, and silicon germanium (SiGe) bipolar-CMOS (BiCMOS) technology that enhances the high-frequency characteristics based on bipolar technology. This paper also discusses millimeter-wave RFICs developed using each technology.

1. Introduction

Fifth generation (5G) mobile communication systems have become widespread around the world since 2019. The first-generation mobile communication service was started in 1979 by Nippon Telegraph and Telephone Public Corporation (now Nippon Telegraph and Telephone Corporation, NTT) as the first private-use cellular car phone service in the world. In April 1991, ultra-compact analog mobile phones were released, and the era of genuine and authentic mobile phones began. In 1993, a digital service was started as a second-generation mobile communication service, and in 2001, a third-generation mobile communication service standardized by the International Telecommunication Union (ITU) was launched as IMT-2000.

As mentioned above, a generation of mobile communication systems gives way to another approximately every 10 years, with the 1980s as the first generation, the 1990s as the second generation, the 2000s as the third generation, and the 2010s as the fourth generation. Details of the generation change show that progress has been made gradually in more stages. For example, a service called cdmaOne, which used third-generation technology, was launched in 1998. In addition, standards such as High Speed Packet Access (HSPA) called the 3.5 generation, Long Term Evolution (LTE) called the 3.9 generation, and LTE-Advanced were formulated by the Third Generation Partnership Project (3GPP) in 2003, 2009 and 2012, respectively.

It is thought that 5G mobile communication systems will also progress step by step. As an example, Table 1 shows the frequencies specified at the World Radiocommunication Conference (WRC) held in Egypt from October 28 to November 22, 2019. The global identification of 24.25-27.5 GHz, 37-43.5 GHz, 66-71 GHz, and the specific identification of 45.5-47 GHz and 47.2-48.2 GHz were decided at the conference [1)]. In addition, other frequencies, outside of those already specified by the WRC are also being considered at the next and later conferences.

This paper focuses on the millimeter-wave radio frequency integrated circuit (RFIC) technology among the technologies related to 5G, and describes their basic semiconductor technologies, and examples of RFICs for 5G.

Table 1. Details of frequencies identified for IMT at WRC-19 [1)].

	Region 1 (Europe, Russia, Arabia, Africa) 122 countries	Region 2 (North and South America) 35 countries	Region 3 (Asia, Pacific) 36 countries
24.25 to 27.5 GHz	Identified globally		
37 to 43.5 GHz	Identified globally		
45.5 to 47 GHz	Identified for 50 countries (Europe (some countries), Russia, Arabia, Africa)	Identified for 1 country (Brazil)	Identified for 2 countries (Iran, Korea)
47.2 to 48.2 GHz	Identified for 62 countries (Europe (some countries), Russia, Arabia, Africa)	Identified for all regions	Identified for 7 countries (Australia, Korea, India, Iran, Japan, Malaysia, Singa-pore)
66 to71 GHz	Identified globally		

2. Millimeter-wave semiconductor technologies

In the early stage, GaAs ICs, which are III-V compound semiconductors, were commonly used in millimeter-wave RFICs. Since they have excellent high-frequency characteristics and high breakdown voltages, they can deliver good performance for low-noise amplifiers and power amplifiers. However, they have a significant disadvantage that it is difficult to fabricate digital circuits using GaAs IC technology. On the other hand, complementary metal oxide semiconductor (CMOS) ICs, which are representatives of Si semiconductors, are

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Panel 1. Abbreviations, Acronyms, and Terms.

5G—Fifth Generation Mobile Communication System
ITU—International Telecommunication Union
3GPP—Third Generation Partnership Project
WRC—World Radiocommunication Conference
HSPA—High Speed Packet Access
LTE—Long Term Evolution
LTE-Advanced—Long Term Evolution Advanced
RFIC—Radio Frequency Integrated Circuit
CMOS—Complementary Metal Oxide Semiconductor
SOI—Silicon On Insulator
SIMOX—Separation by IMplanted Oxygen
FD-SOI—Fully Depleted SOI
PD-SOI—Partially Depleted SOI
BiCMOS—Bipolar-CMOS
IF—Intermediate Frequency
TRX—Transceiver

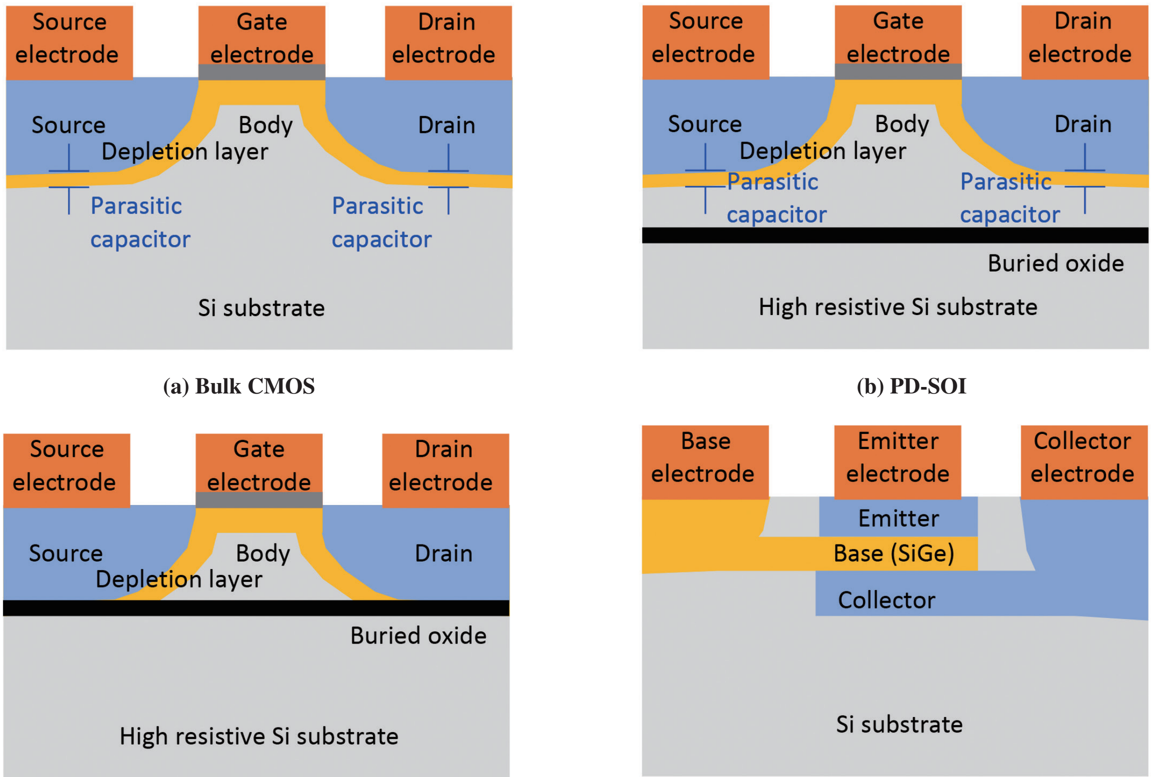

Fig.1. Simplified Si transistor structures.

suitable for digital circuit applications and have high-frequency characteristics improved with the progress of semiconductor miniaturization technologies. Therefore, the development of millimeter-wave RFICs has made a great step forward. Other technologies have also been tried to improve the high-frequency characteristics of Si semiconductors because miniaturization decreases breakdown voltage.

One of them is silicon on insulator (SOI) technology to improve high-frequency performance and reduce power consumption by creating insulating layers with oxide films under transistors to isolate them from a highly conductive Si substrate. There are several types of manufacturing methods for SOI. One of them, separation by implanted oxygen (SIMOX), is a technology that injects oxygen ions into a Si wafer to create an insulating layer (oxide film) inside. The development of this technology has been conducted by NTT, International Business Machines Corporation (IBM) and others [2)3)].

The SOI technologies are categorized into fully depleted (FD) SOI and partially depleted (PD) SOI. Figure 1 shows simplified Si transistor structures. Figure 1 (a) is a conventional CMOS (bulk CMOS) transistor, which has parasitic capacitance created between the transistor and the highly conductive Si substrate. The capacitance causes a leakage of high-frequency current and degrades high-frequency performance and increases power consumption. Figure 1 (b) shows a PD-SOI transistor, which can improve the high-frequency characteristics because it can reduce its parasitic capacitance with an insulating layer under the transistor. Unfortunately, the remained parasitic capacitance limits the improvement. Figure 1 (c) shows an FD-SOI transistor, which can further improve its high-frequency characteristics by the use of insulating layers directly under the transistors. This is because the insulation completely separates transistors and Si substrate, and the parasitic capacitance can be almost eliminated. However, it is difficult to create such insulating layers directly under the very thin layer in which transistors are integrated. It increases the wafer cost. The SOI technology is being focused by GlobalFoundries (GF), which acquired IBM's microelectronic business. Their foundry services use PD-SOI technology for 45 nm SOI and FD-SOI technology for 22 nm SOI.

SiGe bipolar technologies can also improve the high frequency characteristics of Si semiconductors. The mobility of electrons in a Si crystal is improved by injecting Ge into the crystal to create a crystal lattice strain, which improves high-frequency characteristics. Figure 1 (d) shows the simplified SiGe transistor structure. MOS transistors are usually designed so that the components are arranged in the horizontal direction, but bipolar transistors in the vertical direction. Bipolar transistors inherently have lower noise and higher gain characteristics than the MOS transistors, and the high frequency characteristics of SiGe bipolar transistors is further improved by Ge injection into their base layers. However, bipolar transistors are not suitable for digital circuit applications. For this reason, it is usually manufactured by Bipolar-CMOS (BiCMOS) technology, which is a combination of bipolar and CMOS technologies. In general, the number of BiCMOS manufacturing steps is greater and its manufacturing cost becomes higher than that of bulk CMOS. However, since the high frequency characteristics are improved, millimeter-wave RFICs can be manufactured using the less fine Si technology, which decreases the manufacturing cost of the photomask. Table 2 summarizes the characteristics of each Si semiconductor technology.

Table 2. Features of Si technologies.

	Bulk CMOS	SOI CMOS	SiGe BiCMOS
Merit	• Low manufacturing cost due to manufacturing only CMOS. • Digital circuits are small because miniaturized generations are used.	• Small parasitic capacitance • Manufacturing cost is about the same as bulk CMOS.	• Good high-frequency characteristics • Since the mask cost is low, the initial investment is small.
Demerit	• Large initial investment due to use of miniaturized generation • Output power is small because miniaturized generation is used.	• Large initial investment due to use of miniaturized generation • Wafer cost is high.	• Manufacturing costs are high due to manufacturing both bipolar and CMOS.

3. Millimeter-wave RFICs for 5G

A configuration of an antenna module for 5G [4] is shown in Fig. 2. The signals received by the array antenna at the Subarray Panel shown on the far right of the figure are amplified by the low noise amplifiers at the Front-Ends. Then, their signal phases are adjusted and combined inside the RF Beamformer. The combined signals are converted from radio frequency to intermediate frequency (IF) at the IF-RF Conversion. These signals are converted to digital signals by analog-digital converters (A/D) and signal processed. On the other hand, the signals generated by the digital section are converted to analog signals by digital-analog converters (D/A) and converted to a radio frequency at the IF-RF Conversion. Then, they are divided into phase-adjusted signals by the RF Beamformer. The divided signals are amplified by the power amplifiers at the Front-Ends and transmitted from the array antenna at the Subarray Panel.

As mentioned in Section 2, there are various semiconductor technologies for manufacturing millimeter-wave RFICs. Figure 2 describes the semiconductor technology corresponding to each functional block, as an example. There are many other methods of dividing the blocks and applying the semiconductor technologies.

The actual application examples are described in the following paragraph. Tokyo Institute of Technology and NEC Corporation are developing an RFIC composed of 4 transmission/reception circuits (TRX) using 65 nm bulk CMOS technology [5]. This RFIC has functions from the IF-RF Conversion to the Front-Ends, and modifies the RF signal phases by changing the phase of locally oscillated signals to miniaturize the IC. Samsung is developing an RFIC that has 16 parallel transmission parts of the functions from IF-RF Conversion to Front-Ends using 28 nm bulk CMOS technology [6]. MixComm is developing an 8 TRX RFIC, which has functions of the RF Beamformer and Front-Ends using 45 nm PD-SOI technology [7]. Regarding SOI technology, studies have been conducted to increase the output of power amplifiers on SOI by stacking them vertically to compensate for the decrease in output power due to micronizing transistor gate size [8]. millimeter-wave RFICs for 5G have also been developed using GaAs IC and GaN IC technologies, which have excellent high-frequency characteristics. However, only power amplifiers, low noise amplifiers, or both of them with switches are available because digital circuits cannot be created with these technologies.

IBM and Ericsson had jointly developed an RFIC with the functions from the IF-RF Conversion to the Front-Ends in Fig. 2 using SiGe BiCMOS technology [9]. This RFIC employs a true-time delay circuit as a phase shifter and is excellent in beam shaping. It has 32 TRX and excellent performance, and its paper has won the IEEE Paper Award. Based on it, Fujikura is co-developing an RFIC with IBM that reduces the chip area and power consumption by half when it is used for a 64-element antenna module while maintaining the same high-frequency characteristics.

4. Conclusions

Among 5G technologies, we have focused on the millimeter-wave RFIC technologies. We have introduced bulk CMOS, SOI CMOS, and SiGe BiCMOS technologies as the basic semiconductor technologies. We have also introduced the millimeter-wave RFICs for 5G. Each semiconductor technology has its own characteristics, and it is necessary to select it appropriately depending on the application. High-frequency characteristics are

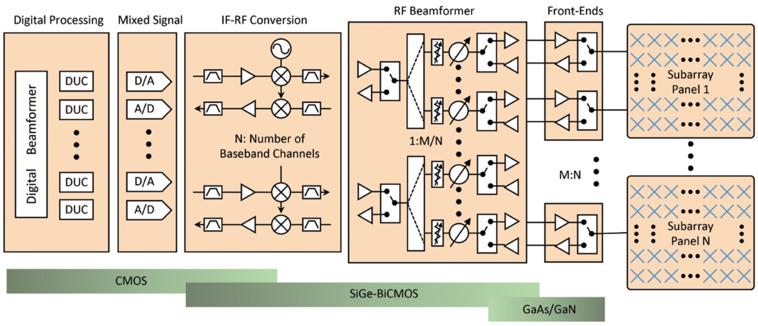

Fig.2. Simplified block diagram of mmWave phased array using hybrid beamforming [4].

particularly important when applied to millimeter-wave analog signals. In addition, whether the initial investment can be small or not is also an important factor since 5G frequencies are added continuously and it is necessary to prepare various lineups. From these points of view, we believe SiGe BiCMOS technology is suitable for 5G millimeter-wave RFIC currently.

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