Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp619-620

N-1-01 (Invited)

THz Circuitry Designs Based on InP and CMOS Devices

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Abstract

THz circuitry design techniques in the frequency regions close to Maximum Oscillation Frequency (F_{max}) of transistor are discussed. To realize the amplifiers in such high frequency regions, positive feedback architectures of a transistor to neutralize a negative feedback due to C_{gd}, and a precise device de-embedding method are necessary. Neutralization techniques and On-wafer calibration method for those purposes are adopted in THz amplifier designs. The amplifiers based on both technologies of InP and CMOS are also demonstrated.

1. Introduction

Recent sub-millimeter wave monolithic integrated circuits (MMICs) based on both of compound semiconductor high electron mobility transistor (HEMT) and CMOS are opening attractive applications for wireless communications and sensors [1-4]. As well-known, a key component in sub-millimeter waveband MMICs is an amplifier.

In this paper, we describe the RF circuitry designs based on InP HEMT and CMOS. The operational frequency of 300GHz on InP HEMT and 270GHz on CMOS are demonstrated in fabricated amplifier MMICs.

2. Technology comparisons

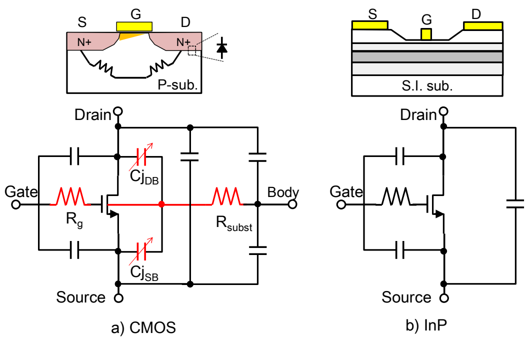

Fig.1 A cross-sectional views of transistors and equivalent circuitry of (a) CMOS and (b) InP.

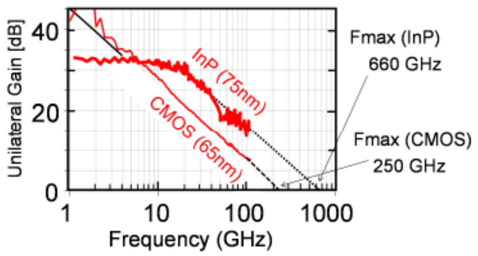

Fig.2 Measured unilateral gains.

First, we discuss the differences of RF characteristics of transistors and passive elements between CMOS and InP-HEMT.

Transistors

Fig.1 shows the cross-sectional views of the transistors and the equivalent circuits of (a) CMOS and (b) InP-HEMT. Since the CMOS transistor has a silicide gate electrode, the gate series resistance becomes higher than that of the InP-HEMT. The output capacitance at drain terminal is also large because of large PN junction capacitances between the drain/source and substrate. Those result in the large signal loss in sub-millimeter wave band. To reduce the large gate resistance and output capacitance, the multi-finger configuration with short gate width of unit transistor (~1μm) and small area for drain electrode are used for CMOS layout. On the other hand, thanks to Au gate electrode and semi-insulating substrate, InP-HEMT has small gate resistance and output capacitance compared with those of CMOS. Therefore, the gate width of unit transistor is quite larger than that of CMOS by several ten times. That results in the large capability of the output power for amplifiers. Fig.2 shows the measured unilateral gains of InP-HEMT and CMOS which have relatively same gate length. As shown in the results, the F_{max} of InP-HEMT is so much higher than that of CMOS.

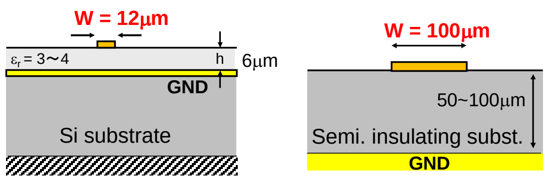

Fig.3 A cross-sectional views of transmission lines.

Transmission lines

Fig.3 shows the cross-sectional views of the transmission lines in (a) CMOS, and (b) InP-HEMT, respectively. As well known, since CMOS has the lossy substrate, the Micro-Strip Line (MSL) comprised of top and bottom metal layers is chosen to shield the signal leakage to substrate. Therefore, the narrow signal line is needed to obtain the characteristic impedance of 50 ohm, and causes large signal loss due to the series resistance of the signal line. On the other hand, in InP-HEMT with semi-insulating substrate, the backside metal of the MMIC can be employed for GND metal, and the wider signal line for 50 ohm is available. That is a great advantage to obtain the low loss impedance matching networks.

3. Design techniques

To realize the THz amplifiers, two design techniques are necessary. One is the unilateralization of the transistor. As

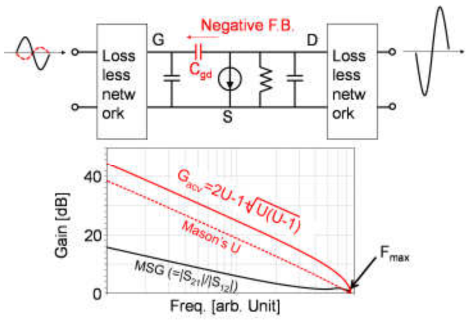

Fig.4 Small signal equivalent circuit and gain curves.

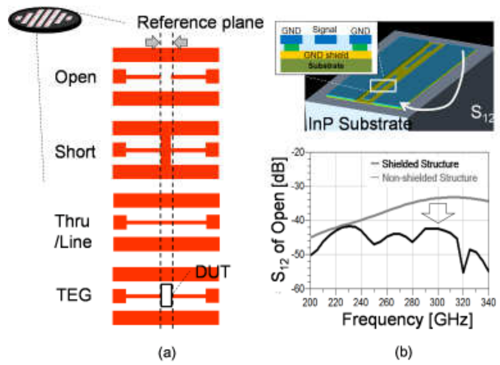

Fig.5 On-wafer calibration.

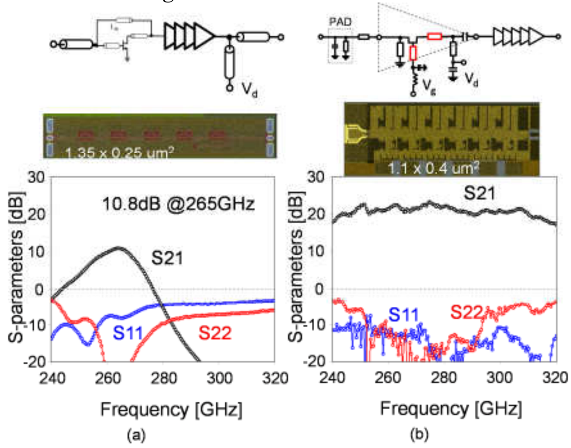

Fig.6 MMICs in (a) CMOS and (b) InP.

shown in Fig.4, the transistor has the feedback capacitance (C_{gd}), and it causes the negative feedback in common source topology. To enhance the gain, the positive feedback for canceling out the negative feedback is employed. Fig.4(b) shows the gain curves of transistor. When we successfully obtain the unilateralization of the transistor, the maximum achievable gain G_{acv} given by the equation in the graph can be expected. Therefore, the unilateralization techniques are required to realize the amplifier in the frequency region close to F_{max}.

The other technique is precise de-embedding method, because the PADs and lead lines included in the device TEST patterns has a serious impact on the high frequency characteristics of the devices. The de-embedding error of 1 fF of the capacitance and 10 μm of the line cannot be ignored in sub-millimeter waveband. For the precise extraction of the devices from the TEST patterns, we employ the On-wafer TRL (Through/Reflect/Line) calibration method. In On-wafer TRL, the calibration standard patterns are formed on the same wafer for the DUT (Device Under Test), as shown in Fig.5, and the reference planes can be set at the input/output of the DUT. Therefore, after the calibration process, the de-embedding for the PADs and the lines is not needed. This is the great advantage for the sub-millimeter waveband amplifier designs. However, in On-wafer TRL, the port isolation between port 1 and 2 are necessary. We design the ground shielded co-planer line for the TEG to avoid the signal leakage through the substrate, as shown in Fig.5 (b). In the electro-magnetic simulation, the isolation of less than 40dB can be obtained.

3. Measurement results

Finally, we describe the measurement results of the amplifier MMIC in both of CMOS and InP-HEMT. Fig.6 shows the circuit schematics, chip photos, and S-parameters in (a) CMOS and (b) InP-HEMT, respectively. As we know, CMOS is normally ON device, and the gate bias for the peak transconductance is close to the power supply voltage (0.8V). Therefore, the gate terminals can be directly coupled to drain through the transmission line designed for cancelling out the negative feedback [5]. The small signal gain of 10.5dB at 265GHz can be successfully obtained in 65nm CMOS [2]. On the other hand, InP-HEMT uses the common gate topology to enhance the gain. By tuning the length of the gate and drain bias feed line, the extremely wideband amplifier can be realized. Those results demonstrate the effectiveness of our design techniques. Finally, we also demonstrated the On/Off keying wireless transmission with data rate of 20Gbps in InP-HEMT [1]. Fig.7 shows the schematic diagram and photo of receiver MMIC, and its measurement results. The high sensitivity of the receiver with broadband can be obtained. It results in the clear eye opening waveforms with data rate of 20GBps. The receiver module using flip-chip assembly technique was also employed for KIOSK downloader system, and successfully demonstrated the video file downloading of 2GB/s [4].

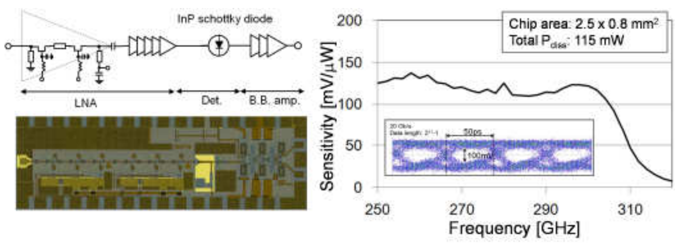

Fig.7 Receiver MMIC.

Acknowledgements

The authors would like to thank the device processing group in Fujitsu Laboratories Ltd. This work was supported in part by the research and development program on Multi-tens gigabit wireless communication technology at subterahertz frequencies of the Ministry of Internal Affairs and Communications, Japan.

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