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Wireless Interconnection by Electromagnetic Coupling of Open-Ring Resonators and Its Application to System Integration

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1. Introduction

Due to the advance of device miniaturization, the device speed on chips has increased. In addition, as the application of electronic systems spread, functional integration has enhanced. Therefore, broad-bandwidth interconnections among different types of IC chips are required.

The conventional I/O interconnection structures, such as bonding wires, flip-chip bonding and pin connections, however, have drawbacks on the performance and reliability issues. Several new approaches have been proposed, including wireless interconnection between dipole antennas, and capacitive or inductive coupling through circuits.

We proposed a resonator coupling with open-ring type λ/2 resonators. Although the transmission distance is limited to less than the order of wavelength, the structure has high transmission efficiency and wide bandwidth. Also it is free of rigid mechanical connection and precise alignment. So the open-ring resonator coupling could solve the chip interconnection problems.

2. Combination of CMOS and AlGaN/GaN HFETs

The scaling rule requires that the supply voltage should be reduced as MOSFET sizes are scaled down. Otherwise the devices will malfunction and the power consumption increases. However, there exist so-called "voltage limit" [1], which comes from the Maxwell-Boltzmann distribution for carriers. It says that $4kT/q$ is the minimum supply voltage for amplifiers with the voltage gain of unity. For practical applications, supply voltage of $10kT/q$ or 250mV will be the minimum at room temperature for any semiconductor devices regardless of their materials [2].

If the supply voltage is fixed, the minimum channel length is determined by the material breakdown filed strength E_C. Since the maximum operation frequencies for FETs will inversely proportional to their channel lengths,

Table 1 Estimated ultimate FET performances at V_{DD} of 0.25V.

	(unit)	silicon	GaAs	GaN
v_{SAT}	km/s	100	200	130
E_{CRIT}	V/μm	29	38	330
Ultimate L	nm	8.6	6.7	0.76
Ultimate f_T	THz	1.9	4.8	27.3

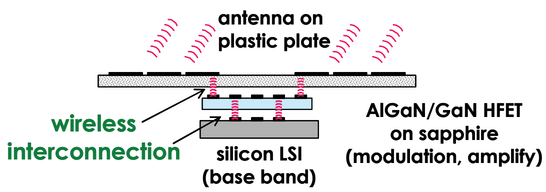

Fig. 1. Schematic model of microwave system using the wireless interconnections for signal transmission among silicon CMOS, AlGaN/GaN HFET RF amplifier and plastic antenna plate.

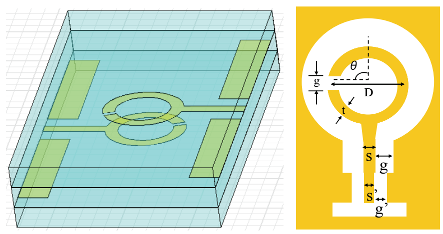

Fig. 2. Interconnection structure with a set of open-ring resonators and the open-ring pattern.

the ultimate FET speed at room temperature will be determined by their breakdown filed (Table 1). So, the wide bandgap semiconductors, such as GaN, will take the high frequency and high power parts of integrated systems. An AlGaN/GaN HFET with the channel length less than 100nm can handle the voltage over 10V even at 60GHz range [3], or maybe the power of 1W. Figure 1 shows an example of millimeter wave communication system where silicon CMOS takes the part from base band to 60GHz carrier signal generation. An AlGaN/GaN HFET on sapphire will amplify the signal and it is emitted from the antenna on the low cost plastic plate. The open-ring wireless interconnection will be used to transfer the signal among the chips and the antenna plate.

3. Interconnection with Open-Ring Resonator Coupling

For such applications, high transmission efficiency and wide bandwidth are required. Electromagnetic coupling of resonators will be suited for such applications. The resonator used in this structure is an open-ring type λ/2 resonator. Since both end of the resonator is close, undesirable radiation is minimized. When two resonators are placed within a wavelength range, they couple electromagnetically and exchange energy over the separation space. The structure forms a two-stage bandpass filter (BPF), where the transmission bandwidth increases as the coupling of the resonators becomes stronger [4]. To enhance the coupling, they are placed in anti-symmetric direction.

Figure 3 shows HFSS simulation results for 60GHz range signals through 0.2mm thick sapphire substrate. The ring diameter is $\lambda/2\pi$, or 240μm on sapphire substrates. The estimated bandwidth is 5.6GHz and the transmission loss is 0.23dB in the case with rings of perfect electrical conductor and 0.94dB for 1μm thick gold. Experiments are carried out at 15GHz range [5]. For substrate thickness of 0.2mm, S_{21} of -1.54dB (70%) and the bandwidth of 4.8GHz are obtained as shown in Fig.4. The results are consistent to the simulation results for this frequency range.

In this experiment, sapphire is used as the substrates, but CMOS is made on conductive silicon substrates. The effects of substrate conductivity are investigated by numerical simulation (Fig. 5). For 60GHz range, substrate resistivity more than 1k Ωcm will be enough to avoid the loss due to the eddy current. Though such substrates are not common in the present CMOS processes, they are technically available using high purity FZ substrates and twin-tub configuration.

4. Conclusion

Open-ring resonator coupling is investigated for the use of wireless interconnection. From numerical simulations, more than 5GHz bandwidth and -1dB transmission were obtained at 60GHz range even through 0.2mm insulating substrate. The performance of the interconnection with open-ring resonators are confirmed experimentally at 15GHz range.

For the use on silicon, substrate resistivity larger than 1k Ωcm is required, but this will not be the obstacle. The diameter of the ring is $\lambda/2\pi$ or 0.24mm at 60GHz on silicon and sapphire wafers. The size is comparable to the conventional bonding pad size. In addition, no rigorous alignment is required between the rings. Especially, they can be formed on any kind of devices with insulating substrates, because only metal wiring process is required.

Since silicon VLSI can handle the 60GHz signals [6], open-ring can be used as the interconnection between chips and printed boards if all the signals are modulated into 60GHz carrier signals. Then, RF devices, laser diodes and any other devices can be integrated on a printed board together with silicon CMOS devices through the open-ring resonator interconnection with 60GHz carrier signals.

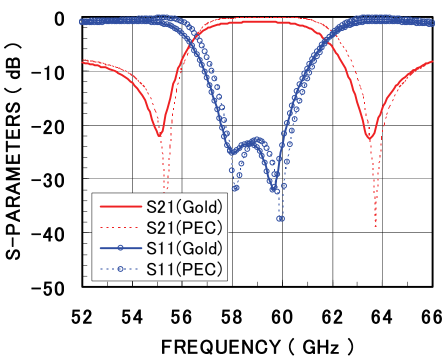

Fig. 3. Simulated transmission and reflection characteristics of the wireless interconnection. Sapphire thickness for the inserted layer is 0.2mm.

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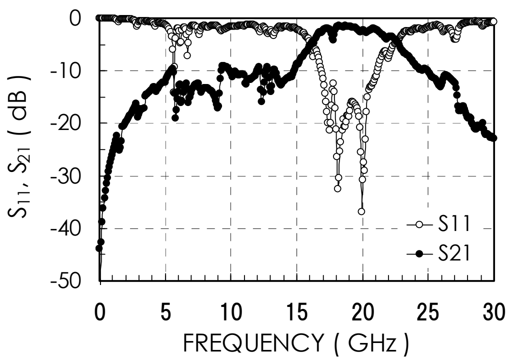

Fig.4 Measured transmission and reflection characteristics. The ring diameter is 0.96 mm and the substrate thickness is 0.2 mm.

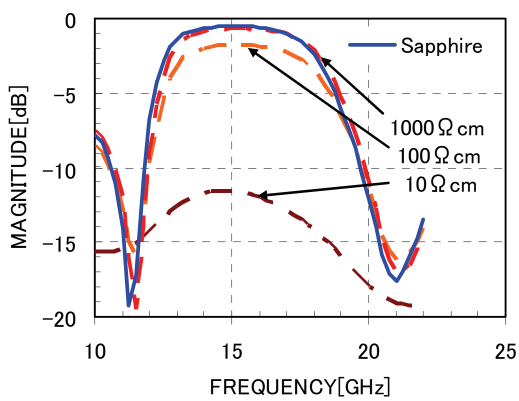

Fig. 5 Effect of conductivity for one of the two substrates by HFSS simulation. The lower ring is placed on the conductive substrates. The top and middle substrates are assumed as sapphire.