Wafer Level Integration of a 24 GHz and 34 GHz Differential SiGe-MMIC Oscillator with a Loop Antenna on a BCB Membrane

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Abstract — **The wafer level integration of a 24 GHz and 34 GHz SiGe-MMIC oscillator with buffer amplifier and a loop antenna on a BCB (Benzo Cyclo Butene) membrane is demonstrated. The phase noise of the not integrated 24 GHz and 34 GHz oscillator is -104 dBc/Hz and -88 dBc/Hz at an offset frequency of 1 MHz and the output power was measured to be +1 dBm and -3 dBm, respectively. The radiated power of both integrated systems is determined based on measurements with a horn antenna and discussed.**

I. INTRODUCTION

With increasing frequency of operation, and increasing complexity of systems, packaging becomes a main concern. Wafer Level Packaging (WLP) is getting an interesting alternative to more conventional techniques as it allows the combination of chips from various processing techniques, and high quality passive structures, on a small area (comparable to monolithic implementation), with low interconnect parasitics and at low cost [1, 2].

The reduction of interconnect parasitics becomes a prime concern in the upper microwave and millimeter wave region. The small wavelength imposes stringent geometric tolerance requirements to avoid increased reflections at discontinuities and possible resonance effects [3].

On the other hand with increasing frequency the size of antennas shrink and the realization of on chip antennas becomes feasible.

This paper demonstrates the successful wafer level integration of loop antennas on thin membranes with 24 GHz and 34 GHz MMIC SiGe oscillators, embedded into a Si host substrate.

II. OSCILLATOR AND ANTENNA DESIGN

For the realization of the oscillators with integrated buffer amplifier the commercial SiGe1 process from ATMEL was used. The substrate is a standard 20 Ωcm silicon wafer. The transistors have a selectively implanted collector resulting in an f_t and f_{max} of 50 GHz. For the passive components three metalization layers are available to realize inductors and interconnect lines. Three different resistor layers are available for low, medium, and high ohmic resistors. The capacitors are built by the first metalization and the base poly with a nitride dielectric in between [4].

The differential topology of both MMIC oscillators with buffer amplifier is identical and the schematic is shown in Fig. 1.

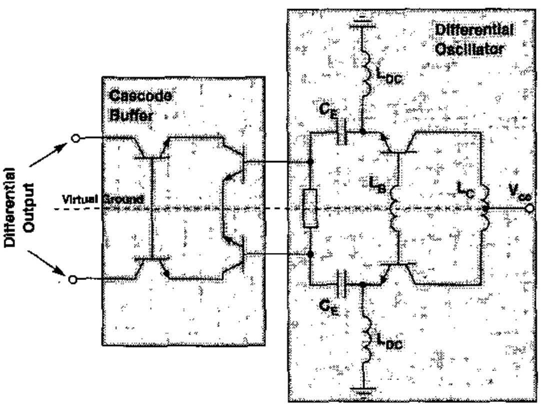

Fig. 1: Schematic of the differential MMIC oscillator with integrated cascode buffer amplifier.

Inductors are important passive components for the oscillator as they are used for both DC feed (L_{DC}) and as part of the resonator (L_B and L_C). While the inductors L_{DC} are conventional spiral coils L_B and L_C are center tapped coils using the top metalization layer with a thickness of 2.5 μm aluminum, to reduce capacitive coupling to the lossy substrate.

Center tapped coils are common in differential designs as they are compact and have high quality factors. The inductors were realized as test structures and measured separately. The extracted values at the corresponding frequency of the used coils are listed in Table 1.

Table 1: Properties of the used inductors for the oscillators.

Inductor	Frequency	Inductance	Q
L_B	34 GHz	317 pH	16.3
L_C	34 GHz	418 pH	15.3
L_B	24 GHz	401 pH	13.8
L_C	24 GHz	1053 pH	7.2

The capacitors C_E have values of 0.13 pF and 0.07 pF for the 24 GHz and 34 GHz oscillators, respectively. All transistors have one emitter finger with a length of 20 μm and a width of 1.2 μm.

The oscillator is connected to a differential cascode amplifier. The cascode amplifier has open collector outputs. That way a load with DC feed can directly be connected. The characteristics of a cascode amplifier with a low Miller capacitance and high backward isolation predestinate it for the use as buffer amplifier in an oscillator. The high backward isolation reduces the influence of the load (here the antenna) on the oscillator.

The antenna is a simple circular full-wave loop, resulting in diameters D_L=3.3 mm and 2.4 mm at 24 GHz and 34 GHz, respectively. Both structures were simulated using the Agilent Momentum software.

As the loop antenna is driven differentially it has a virtual ground opposite to the feed point. At this virtual ground the DC feed can be connected, see Fig 4. That way the loop antenna can directly be connected to the open collector outputs of the buffer amplifier.

III. TECHNOLOGY

A cross section of the MMIC oscillator integrated with the loop antenna on the BCB membrane on a standard silicon substrate (6-12 Ωcm) is shown in Fig. 2.

For etching the windows to integrate the MMIC oscillator and to remove the silicon underneath the BCB membrane the time multiplexed deep etching (TMDE)

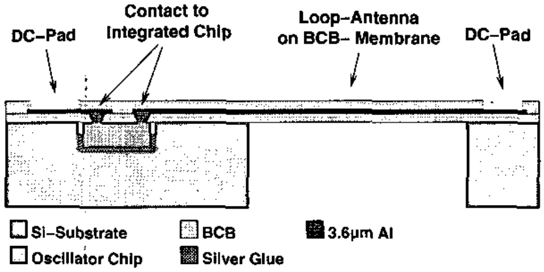

Fig. 2: Cross section of the integrated oscillator chip with the loop antenna on a membrane.

technique developed by Robert Bosch GmbH [5] is used. This plasma etching technique switches between an SF_6 flow for etching the silicon and a C_4F_8 flow for passivation of the side walls. This results in a high aspect ratio.

For the planarization of the inserted chip to the substrate photosensitive BCB[1] is used. BCB has good planarization characteristics compared to other polyimides [6]. Further properties of BCB are its low ε_r of 2.7 and its low dielectric loss factor of $\tan(\delta)$=0.0008 [7].

After curing BCB on the silicon substrate it has tensile stress due to its high coefficient of thermal expansion (52 ppm) compared to silicon (2.6 ppm). Therefor free standing membranes can be realized with BCB.

The process starts with etching 180 μm deep windows for placing the MMIC chips in the silicon substrate. The chips are inserted and fixed using two component silver filled epoxy. During the adhesive cure, the chips are held in place using an auxiliary plate pressed onto the wafer. BCB is then span onto the wafer with the chips in-place, for a thickness of 10 μm. After exposure and developing the vias to the contact pads of the chip the BCB is cured at 235 °C for 30 min. To remove residuals of BCB at the opened pads the wafer is dry chemically etched in an O_2/SF_6 plasma for 1 min. 100 nmWTi/3.6 μmAl is sputtered onto the wafer and wet chemically etched building the loop antenna and DC connections to the chip. A photography of the processed chip up to this step is shown in Fig 3.

To stabilize the BCB membrane a second layer of 20 μm BCB is spun on the wafer and cured. In a last step the silicon underneath the loop antenna is etched from the back side. It takes about 3 hours to etch through the 525 μm thick silicon substrate. For this etching the TMDE process was optimized regarding etching speed and homogeneity [8].

Fig. 4 shows a photography of the 34 GHz loop antenna with integrated chip. The membrane is

[1]CYCLOTENE 4026-46

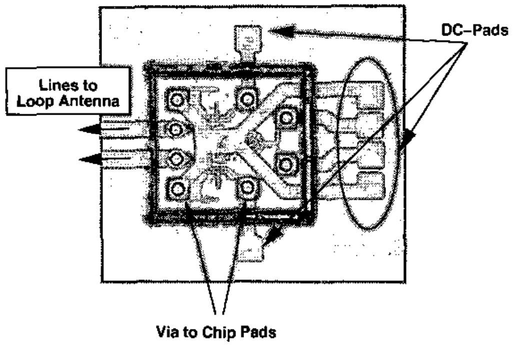

Fig. 3: Photography of the inserted oscillator chip with metal connections.

elliptically shaped with the diameters 5.6 mm and 4.5 mm (D_M). The diameter of the loop antenna is D_L=2.4 mm.

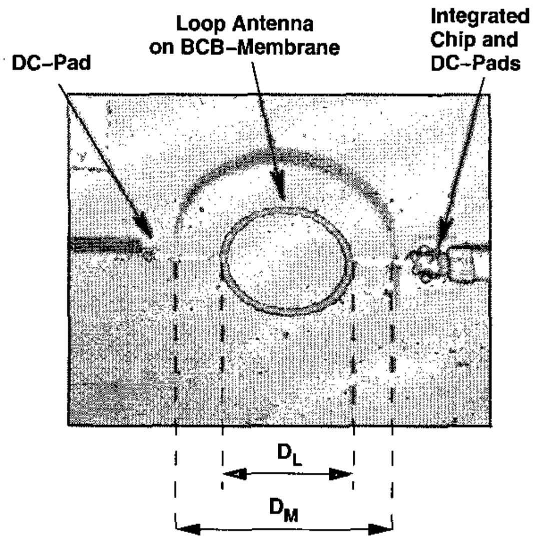

Fig. 4: Photography of the 34 GHz loop antenna on a BCB membrane with integrated oscillator chip.

IV. MEASUREMENTS

The loop antennas were also realized and characterized as stand alone test structures. For the measurements the backside of the antennas was covered with absorber material. This avoids reflections from the backside chuck.

The S-parameters were measured up to 40 GHz. The return loss is shown in Fig. 5.

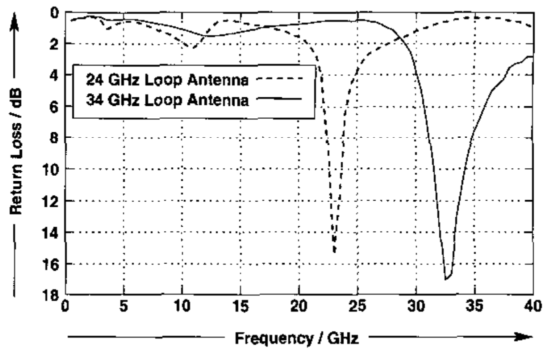

Fig. 5: Measured return loss of the 24 GHz and 34 GHz antenna.

The return loss of both antennas is better than 15 dB at resonance on a 50 Ω measurement system.

Before integrating the MMIC oscillators with the loop antenna they were measured and characterized on wafer. The power consumption of both oscillators is about 300 mW at a supply voltage of 5 V. The differential output ports of the cascode are connected to a 50 Ω measurement system with bias-Tees. The measured output power for the 24 GHz oscillator is 1 dBm and has a phase noise of -104 dBc/Hz at an offset frequency of 1 MHz. The 34 GHz oscillator has an output power of -3 dBm and a phase noise of -88 dBc/Hz at an offset frequency of 1 MHz.

To estimate the radiated power of both loop antennas with integrated MMIC oscillator the radiated signal was measured with a pyramidal horn antenna. The aperture of the horn antennas for 24 GHz and 34 GHz is $A_p = 5 \times 6\,\text{cm}^2$ and $A_p = 3 \times 4\,\text{cm}^2$, respectively. For this measurement the backside is also covered with absorber material.

To suffice the far field condition the power was measured at a distance of 60 cm above the loop antenna.

The received power of the 24 GHz system was measured to be -39 dBm at 24.58 GHz. The power of the 34 GHz system was measured to be -33 dBm at 34.11 GHz. This spectrum is shown in Fig. 6.

To calculate the radiated power, the Friis transmission formula is used:

$$P_{rx} = \frac{P_{tx} \cdot G_{tx} \cdot G_{rx} \cdot \lambda^2}{(4 \cdot \pi \cdot R)^2}, \qquad (1)$$

with P_{rx} the received power, P_{tx} the radiated power, R the distance between both antennas, and G_{tx} and G_{rx} the antenna gain of the transmitting and receiving antenna, respectively. The gain of the pyramidal horn antennas was calculated with the following approxi-

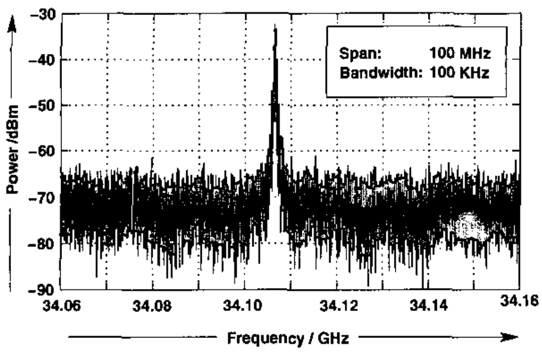

Fig. 6: Power measured with a horn antenna (A_p = $3 \times 4\,cm^2$) at a distance of 60 cm of the 34 GHz system.

mation:

$$G_{horn} \approx 10 \cdot \left[1.008 + \log_{10}\left(\frac{A_p}{\lambda^2}\right)\right] - (L_e + L_h), \quad (2)$$

with A_p being the aperture of the horn antenna and L_e and L_h the losses due to phase errors in the E- and H-plane [9]. The gain for the horn antennas was calculated to 19.9 dBi and 20.1 dBi for the 24 GHz and 34 GHz antenna, respectively. For the gain of the loop antenna 1.8 dBi is used.

The calculation of the radiated power for the 24 GHz system results in -5.1 dBm and for the 34 GHz system in +3.7 dBm. The higher calculated radiation power of the 34 GHz system compared to the 24 GHz system is in contrast to the on wafer measurements presented above.

An explanation is that the BCB membranes holding the loop antennas have the same size for both antennas. As the 24 GHz loop has a larger radius, it is closer to the lossy silicon substrate compared to the 34 GHz loop antenna. Therefor the antenna efficiency is lower. Also a better power matching for the 34 GHz system compared to the 50 Ω measurement system is possible. A further uncertainty is beam forming by the DC needles and probes around the systems during the measurements. This might increase the gain of the measured system.

V. Summary

The successful wafer level integration of a 24 GHz and 34 GHz MMIC SiGe oscillator with integrated buffer amplifier with a loop antenna on a BCB membrane is demonstrated. The design of the MMIC is described and measurements are presented. The radiation power of both systems is calculated from measurements and the results are discussed.

VI. Acknowledgment

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