Design and Performance Comparison of Various Terahertz Microstrip Antennas on GaN-on-Low Resistivity Silicon Substrates for TMIC

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***Abstract*- In this paper we demonstrate various configurations of THz microstrip antenna on GaN-on low resistivity silicon substrates (ρ < 40 Ω.cm). To reduce the losses caused by the substrate and to enhance the antenna performance, the driven patch is shielded by a ground plane and silicon nitride, with BCB as the inset layer between them. Second patch (elevated patch) is suspended in air using gold posts, which makes the design stack configuration. Here, study of various design performances has been represented by changing the shape of the antenna between rectangular and circular, optimising the BCB and stack height and evaluating performance of stack using air and BCB as dielectric. Better fabricated performance was obtained when the patch was elevated in air and by using rectangular-circular stack configuration with BCB and elevation height of 5 µm. 3D EM model showed directivity, gain, and radiation efficiency as high as 8.3 dB, 3.4 dB, and 32 % respectively, a significant improvement over single or stack configuration antenna. Better simulated gain (6.7 dB) was obtained with the BCB height of 30 µm using a single antenna and highest gain and directivity (7.5 dB and 8.8 dB respectively) for stack antenna of height 15 µm .To the authors' knowledge this is the first time such a study has been carried out at Terahertz frequency and this developed technology is suitable for high performance III-V material on low resistivity/ high dielectric substrates.**

I. INTRODUCTION

Recent years THz technology has found many applications in sensing, imaging, communication systems, and spectroscopy [1] [2]. These frequencies can show different spectral interactions for different materials and can achieve high image resolution [3]. For these applications, Terahertz Monolithic Integrated IC (TMIC) is emerging as a new technology due to advancement in high-speed semiconductor devices and nanotechnology [4]. III-Nitride based materials such as GaN are more suitable for TMIC technology over materials for instance, GaAs or InP due to higher power density and power efficiency [5]. Unwanted mode effects and reduced signal loss which occurs in the substrate itself while operating at these frequencies can be suppressed by adopting TMIC technology. With this, TMIC also has an advantage of smaller chip size, lower system cost, and higher performance. Recent research shows that a 450 GHz cutoff frequency (f_T) has been achieved

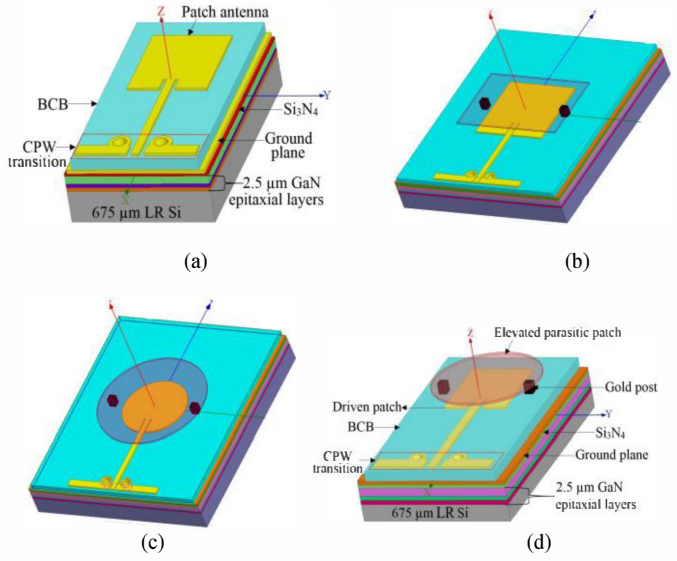

Fig. 1 Schematic of microstrip patch antenna
(a) Single-rectangular [15] (b) Double-rectangular (c) Double-Circular (d) Rectangular-circular antenna [16]

using GaN high-electron-mobility-transistors (HEMTs) on semi-insulating (SI) SiC through the intensive progress in GaN HEMTs scaling technologies toward THz operation. Multiple frequencies of their f_T can be obtained by implementing such devices using TMIC technology [6]. However. SiC substrates are expensive to produce currently and not readily available in large wafer sizes for low cost production.

The disadvantage of cost and large wafer size production is overcome by growing GaN on low resistivity (LR) Si for TMIC circuits, making the production costs of GaN-on-LR Si competitive with existing high-resistivity (HR) Si and SiC technologies. Nevertheless, performance degradation due to RF substrate coupling proves challenging for developing high-quality interconnects and passives circuits in GaN-on-LR Si technology [7].

Passive antenna circuits used in communication systems require high antenna gain and efficiency to achieve effective isotropic radiated power (EIRP), high spectrum resolution and

high sensitivity in the case of spectroscopy imaging. On-chip antenna serves as an advantage for these applications due to their wide frequency band, improved beam shaping combined with lower production costs and compactness. Designing on-chip antenna on a thick and high dielectric substrate like GaN-on-LR Si can result in surface mode excitation and conduction loss [8] [9]. Various solutions have been proposed in the literature such as High Impedance Surface (HIS), micromachining and Artificial Magnetic Conductor (AMC) [10]-[14] which requires high temperature fabrication combined with complex assembly and design limiting TMIC potential.

In this paper, we report on the design, fabrication and characterization of various stack configurations using the shielding technology. Heights of both dielectrics (single and stack antenna) are optimized to produce better antenna performance; stack dielectric is evaluated using air and BCB for better antenna performance. This study provides an extension of our previous work [15] and [16] where a single patch antenna and rectangular-circular stack antenna was demonstrated. From these studies, we showed that a rectangular-circular stack antenna gave an improved fabrication result at BCB and stack height of 5 µm with gain, directivity and radiation efficiency as high as 3.4 dB, 8.3 dB and 32% respectively. Whereas the simulation result represented better antenna performance at the BCB height of 30 µm using single antenna and air and BCB dielectric of 15 µm using stack configuration.

II. Antenna Design

The intended design was carried out first using the software HFSS 3-D full-wave electromagnetic field solver. Fig.1 (a), shows the schematic of a single rectangular antenna where dimensions of the single rectangular patch was designed to be 372 × 333 (W×L) µm. Fig.1 (b), (c) and (d) shows double-rectangular, double-circular and rectangular-circular microstrip stack antenna, where dimensions of first stack patch was designed to be 373 × 308 (W×L) µm, 182 µm (radius) and 310 × 320 µm (W×L) respectively to ensure fundamental TM^{x}_{010} mode excitation at 0.27 THz and second patch of dimension 500 × 308 µm, 220 µm and 225 µm respectively to improve the gain and directivity of the antenna. The driven or first patch is designed on a low permittivity dielectric material BCB (ε_r=2.7) where the antenna was shielded by silicon nitride and a gold ground plane. Fig. 2 (a) shows the simulated volume current inside the substrate when it is not shielded and fig.2 (b) shows the volume current when it is shielded. This image clearly shows that there is no current leakage into the substrate thus making this design more practical at terahertz frequencies. The second patch was simulated both on a BCB layer as well as air to find the best stack antenna performance. Rectangular gold posts of dimensions 18.6 µm × 18.6 µm is used to support the elevated patch suspended in air. Microstrip feed line of width 13.2 µm is used to excite the driven patch which in turn excites the parasitic patch via electromagnetic

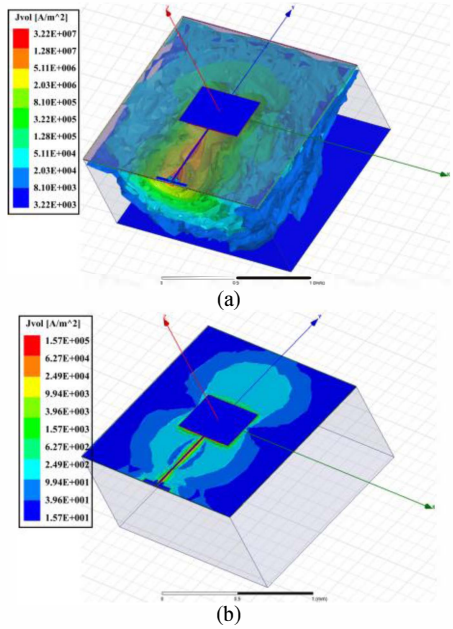

Fig. 2 Electromagnetic Simulation of volume current in the entire circuit design (a) when the substrate is not shielded (b) when the substrate is shielded

coupling. A via hole CPW to microstrip transition is added to the end of microstrip feed line to make the design compatible for the on-wafer probe measurement. Thus a complete microstrip technology is developed for TMIC realization.

III. Fabrication

The fabrication process of the proposed integrated antenna in this study is related to our previous work [16]. First, 200 nm Si_3Ni_4 was deposited onto GaN-on-LR Si using ICP-CVD deposition. Next a ground plane is formed by depositing Ti/Au (50/600nm) by electron beam evaporation which also acts as a shielding for the antenna. A BCB dielectric was then spun and

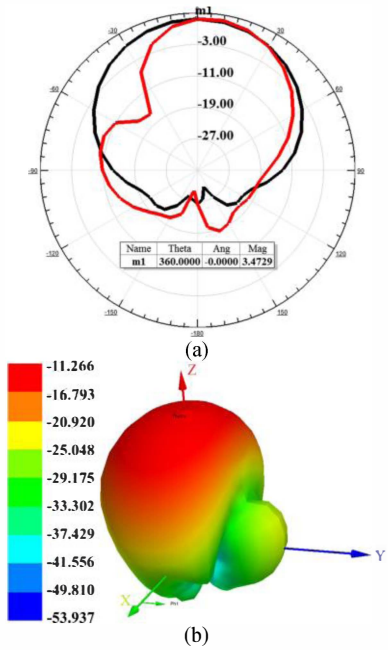

Fig. 3 BCB as stack substrate (a) Directivity (b) Gain

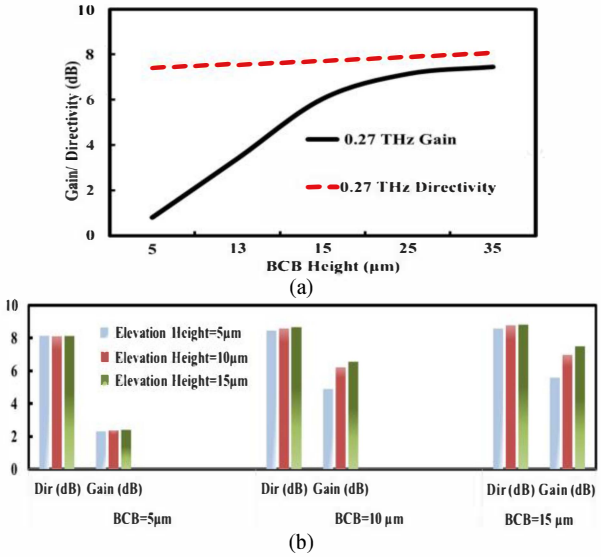

Fig. 4 (a) Plot of BCB height change vs gain/ directivity (b) Plot of Stack height with fixed BCB height

fully cured in an oven to achieve a uniform thickness of 5 µm. CPW to microstrip transition pads are defined by etching the BCB down to the ground plane using plasma RIE and then evaporating Ti/Au (50/600nm) to form the driven patch and feed line. A III-V MMIC air bridge process was used to create both the post and elevated parasitic patch. For this process AZ4562 resist was patterned by photolithography and developed to define the gold posts and elevation height. Electroplating was then used to deposit 2 µm Au on top of a Ti/Au as seed layer and S1818 photoresist as pattern for the top patch.

IV. Results And Discussion

Agilent PNA Vector Network Analyzer was used to characterize the fabricated stack antenna over 220-325 GHz frequency range using OML probes. Off-wafer LRRM (Line-Reflect-reflect-match) calibration technique was performed using an ISS standard substrate and 50 µm pitch Pico-probes.

Fig. 3 shows the performance of the BCB with air as the second dielectric material. The results show BCB offers very low antenna performance compared to air due to the surface charge degradation and relatively low mutual coupling between the first and second patch. Therefore, it can be concluded that air provides better directivity and gain performance than BCB. Fig. 4 (a) shows an optimization plot of BCB heights and (b) shows an optimization plot of stack height at various BCB heights. As the height of the BCB layer changes the directivity of the antenna is maintained within ± 0.5 dB, however gain of the antenna increases by 50% for the same thickness. A maximum gain of 6.7 dB was obtained at a BCB height of 30 µm. A final height of 5 µm was chosen for the BCB layer, representing a trade-off between the antenna performance and feed line size. To optimize the elevation height of the antenna the height was simulated at a value of 5, 10 and 15 µm. Each set of elevation values was repeated at a BCB height of 5, 10 and 15 µm, shown in Fig. 4. Maximum

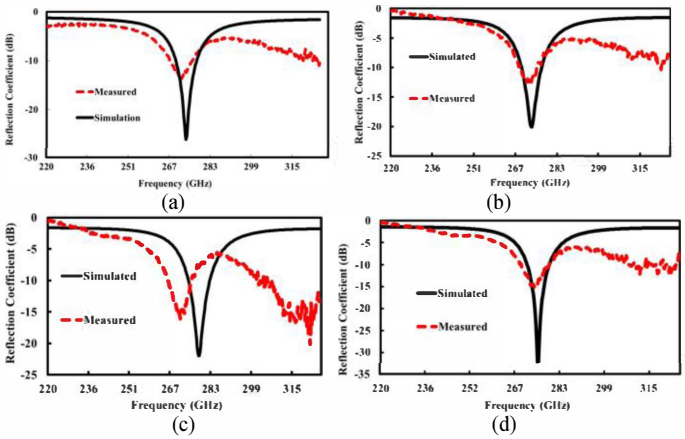

Fig. 5 Reflection Co-Efficient Plot (a) Single rectangular antenna (b) Double rectangular antenna (c) Double circular antenna (d) Rectangular-circular antenna

performance was obtained at 15 µm BCB with an elevation height of 15 µm. However, it was observed during fabrication that a post height greater than 10 µm resulted in collapse of the stack, therefore the final stack height chosen was 5 µm.

Fig. 5 shows the simulated and measured reflection coefficients of all the designs operating at the designed frequency with a 5 µm BCB and elevation height. The simulated reflection coefficient attained was as low as -26 dB, -20 dB, -21 dB, and -33 dB for single rectangular, double-rectangular, double-circular and rectangular-circular respectively at 272 GHz and the relative bandwidth of ($|S_{11}|$<-10dB) 10 GHz, 7 GHz, 8GHz, and 11 GHz was achieved. Table 1 shows measured reflection-coefficient, directivity, gain, radiation efficiency and front-to back ratio of the single and the three-stack antenna. As it can be seen the antenna performance is same for all the three-stack antenna and it shows good improvement of about 51.4% in the gain

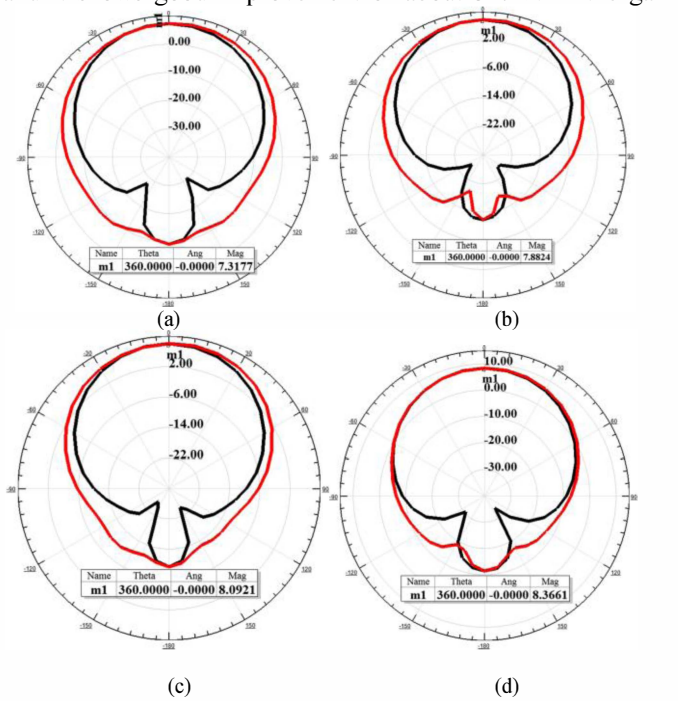

Fig. 6 Directivity Plot (a) Single rectangular antenna (b) Double rectangular antenna (c) Double circular antenna (d) Rectangular-circular antenna

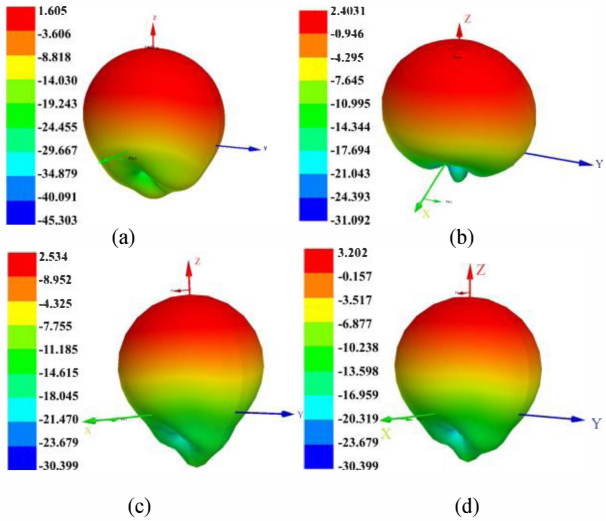

Fig. 7 Gain Plot (a) Single rectangular antenna (b) Double rectangular antenna (c) Double circular antenna (d) Rectangular-circular antenna

and 33.3% in the radiation efficiency over single microstrip patch which reached 1.6 dB and 24% respectively. Fig. 6 & fig. 7 shows the directivity and gain radiation pattern at $0^0 < \theta < 360^0$ and φ=-90^0 and 0^0 at 0.27 THz.

Antenna Type	Measured Reflection Co-efficient	Directivity	Gain	Radiation Coefficient	Front -to- back ratio
Single rectangular antenna	-14 dB	7.5 dB	1.6 dB	24 %	17.8 dB
Double rectangular stack antenna	-13 dB	7.8 dB	2.4 dB	29 %	20 dB
Double circular stack antenna	-16 dB	8.1 dB	2.5 dB	30 %	18 dB
Rectangular-Circular stack antenna	-18 dB	8.3 dB	3.4 dB	32 %	21 dB

Table 1

V. Conclusion

Various configurations of antennas have been presented on GaN-on-low resistivity silicon substrates, these configurations are designed for Terahertz Monolithic Integrated Circuits (TMICs). Simulation and experimental results are presented for the single and stack antennas where a rectangular-circular shaped stack antenna showed superior performance, exhibiting a reflection co-efficient as low as -33 dB (Simulated) and -18 dB (measured) at a BCB and elevation substrate height of 5 µm. Also, directivity, gain and radiation efficiency as high as 8.3 dB, 3.4 dB and 32 % respectively has been achieved. These results shows that low dielectric material with an air-filled stack configuration serves as a promising technique at terahertz frequency. To the authors' knowledge this is the first time a study of various stack antenna configurations has been demonstrated for TMIC compatible technology applications. In addition, this technology helps to utilize newly emerging high speed electronics on GaN-on-LR Si Substrate without any complex micromachining or use of high temperature fabrication. Thus making this technology cost effective, mass producible, compact and suitable for portable TMICs wireless communication and spectroscopy imaging.

Acknowledgment

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