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Terahertz Microstrip Elevated Stack Antenna Technology on GaN-on-Low Resistivity Silicon Substrates for TMIC

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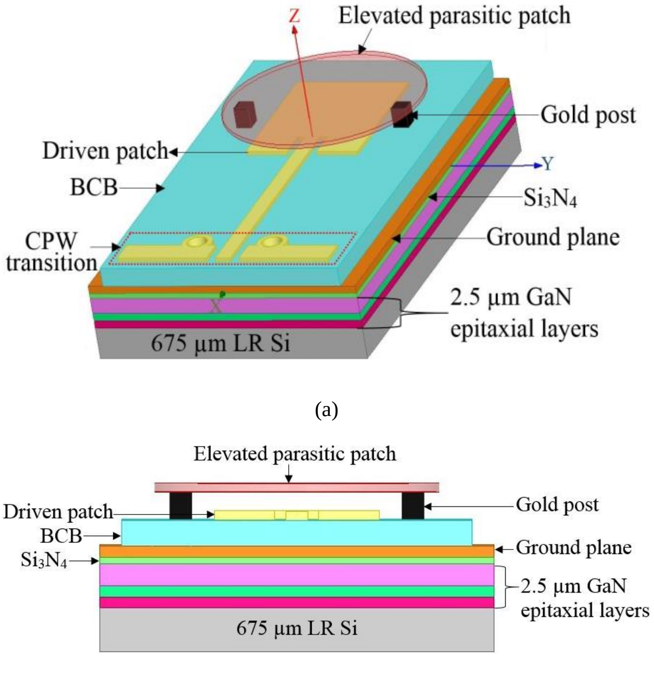
***Abstract*— In this paper we demonstrate a THz microstrip stack antenna on GaN-on-low resistivity silicon substrates ($\rho < 40$ Ω.cm). To reduce losses caused by the substrate and to enhance performance of the integrated antenna at THz frequencies, the driven patch is shielded by silicon nitride and gold in addition to a layer of benzocyclobutene (BCB). A second circular patch is elevated in air using gold posts, making this design a stack configuration. The demonstrated antenna shows a measured resonance frequency in agreement with the modeling at 0.27 THz and a measured S11 as low as -18 dB was obtained. A directivity, gain and radiation efficiency of 8.3 dB, 3.4 dB, and 32% respectively was exhibited from the 3D EM model. To the authors' knowledge, this is the first demonstrated THz integrated microstrip stack antenna for TMIC (THz Monolithic Integrated Circuits) technology; the developed technology is suitable for high performance III-V material on low resistivity/high dielectric substrates.**

Keywords— ***RF GaN on LR Si, Terahertz integrated antennas, TMICs, Stack Antenna, Submillimeter wave technology, Submillimeter wave passive devices, and Terahertz integrated components.***



(a)

(b)

Fig. 1. Schematic of microstrip stack rectangular patch antenna
(a) Top view (b) Cross-sectional view

I. INTRODUCTION

THz technology has many applications in imaging, sensing, spectroscopy, astronomy and communications [1] [2]. The short wavelength of THz frequencies allows for unique spectral interaction with matter and can achieve high resolution imaging [3]. Recent interest in new emerging applications is motivated by advances in high-speed semiconductor devices and nano-technology; which has enabled the advent of TMIC [4]. The advantage of using III-Nitride based material devices in TMIC such as higher power density and power added efficiency makes it more suitable than other material systems such as GaAs or InP [5]. The utilization of TMIC technology in THz frequency applications is a critical component to suppress unwanted moding effects and hence reduce signal loss. In addition, TMIC offers the advantage of higher functionality, lower system costs and smaller chip size. Currently, GaN high-electron-mobility-transistors (HEMTs) on semi-insulating (SI) SiC have achieved a cutoff frequency (f_T) of 450 GHz through the intensive progress in GaN HEMTs scaling technologies toward THz operation; applying such devices in TMIC technology will yield systems operating in multiple frequencies of their f_T [6]. However, SiC substrates are expensive and have limited availability in large diameters required for low cost manufacturing.

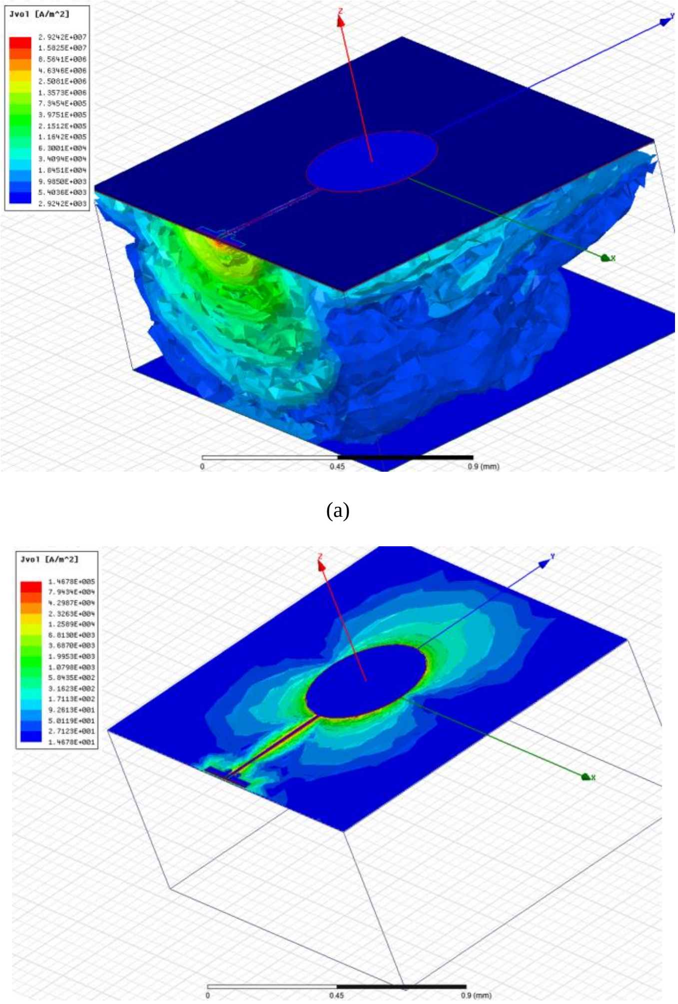
The potential use of GaN HEMTs grown on LR Si for MMIC circuits offers the advantage of cost-effective and large diameter wafers, resulting in manufacturing costs of GaN-on-LR Si becoming potentially competitive with existing high-resistivity (HR) Si and SiC technologies. However, RF substrate coupling effects are the main cause of performance degradation when considering LR Si as a substrate [7]. Therefore substrate loss suppression is a crucial step towards the industrialization of high-quality interconnects and passive elements in GaN-on-LR Si technology.

In communication applications for front-end systems, antenna gain and efficiency are critical parameters to achieve effective isotropic radiated power (EIRP), high spectrum resolution and high sensitivity in the case of spectroscopy imaging. For these applications, on-chip antennas are advantageous due to their wide frequency band and improved beam shaping, combined with lower production costs and compactness. Designing antenna on a thick and high dielectric substrate can result in surface mode excitation and conduction loss [8] [9]. Various solutions for this problem such as substrate thinning, use of High Impedance Surface (HIS), micromachining and Artificial Magnetic Conductor (AMC) have been proposed [10]-[14]. These techniques generally require high temperature fabrication coupled with more complex design and assembly which limits TMIC potential.

In this paper we report on the design, fabrication and characterization of TMIC integrated microstrip stack patch antenna using Benzocyclobutene (BCB) as an insert layer. Simulated and measured results show reflection co-efficient as low as -33 dB and -18 dB respectively. Also gain, directivity and radiation efficiency as high as 3.4 dB, 8.3 dB and 32% respectively are achieved. This design offers high gain compared to single element patch and since at terahertz very large arrays are required to overcome the high patch loss of the THz band channel, stack configuration provides more gain and minimizes feed losses. These results show great promise for the application of GaN on LR Si for TMIC devices.

II. ANTENNA DESIGN

The intended design was carried out first using the software HFSS 3-D full-wave electromagnetic field solver. Fig.1 shows a schematic of the proposed microstrip stack antenna. A driven rectangular patch (1st level patch) of dimension 310 µm (width) × 300 µm (length) is designed to ensure fundamental TM^{x}_{010} mode excitation at 0.27 THz. A low permittivity dielectric BCB (ε_r=2.7) is inserted below the patch to increase the distance between the radiator and the lossy silicon substrate. This insert layer offers low dissipation factor, low moisture absorption, excellent chemical, thermal and mechanical stabilities with high planarization and low curing temperature (<250^0C) [15]. In addition, shielding the lossy substrate with the silicon nitride and ground plane enhanced antenna performance allowing a higher gain and better radiation efficiency [16]. Another gold circular parasitic patch of radius 225 µm is placed 6 µm above the lower patch separated by an air gap and supported by two gold rectangular posts each of dimension 18.6 µm × 18.6 µm. Air is chosen as the second dielectric material between the rectangular driven patch and the circular elevated radiator in order to further improve the performance of the antenna. Thus two resonances are created using two patches, where the first resonance is related with the resonator formed by the lower patch with ground plane and the second resonator formed by the upper patch and the driven patch [17]. As a result the parasitic patch is excited via electromagnetic coupling from the driven patch and in turn the driven patch is excited using a microstrip feed line of width 13.2 µm. A Via hole CPW to microstrip transition is added into the design for on-wafer probe measurement and a full microstrip technology was developed in this work making it a viable option for TMIC realization. Fig.2 shows the electromagnetic simulation of the volume current in the entire circuit design. As can be seen in fig. 2 (a), excited current is induced in the Si substrate as the result of no shielding and in fig. 2 (b) no current in induced in the substrate as a result of shielding.



(a)

(b)

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

III. FABRICATION

The fabrication process of the proposed integrated antenna in this work was started by depositing a 200 nm Si_3Ni_4 on GaN–on-LR Si using ICP-CVD deposition tool. This was followed by the Ti/Au (50/600nm) deposition using electron beam evaporation that forms the ground plane as well as the shielding for the antenna. Next, BCB was spun and fully cured in an oven to achieve a thickness of 5 µm. To create CPW-pads via-holes, BCB was etched down to the ground plane using plasma RIE and then Ti/Au (50/600nm) was evaporated to form the driven patch and feed line. Finally, a standard III-V MMIC air bridge process was used to create together the post and elevated parasitic patch. AZ4562 photoresist was then used to define the elevated patch and gold posts. A Ti/Au seed layer was deposited

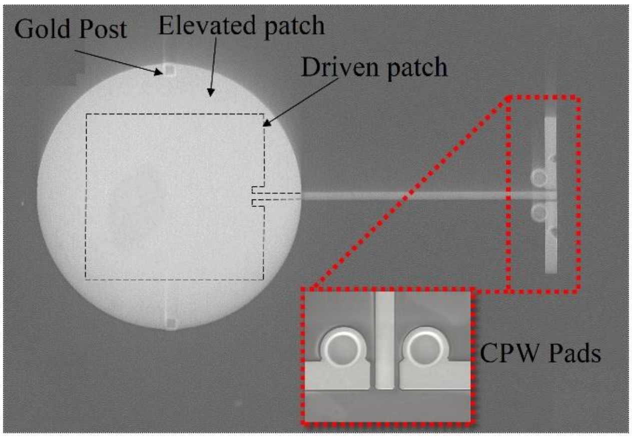


Fig. 3. Scanning Electron Microscopy (SEM) image of the fabricated antenna

prior to electroplating and the upper patch was formed in S1818 photoresist with subsequent electroplating of 2 µm Au onto the seed layer. Fig. 3 shows an SEM image of the complete stack antenna.

IV. RESULTS AND DISCUSSION

Measurements of the fabricated stack antenna were done using an Agilent PNA vector Network Analyzer with 220-325 GHZ OML probes. An ISS standard substrate was used to calibrate the PNA using the LRRM technique (Line-Reflect-reflect-match) and antennas were probed using 50 µm pitch Pico-probes.

Fig. 4 shows the simulated and measured reflection coefficient at the designed frequency. A good agreement between the measured and designed results was observed, this verifies our design will give good reliability at THz frequencies. The simulated and measured reflection coefficient achieved was as low as -33 dB and -18 dB respectively at 272 GHz and the relative bandwidth of 4.1% ($|S_{11}|$<-10dB) was attained. Fig. 5 shows the plot of gain and radiation efficiency of both an individual patch and the stack patch. A gain and radiation efficiency of 3.4 dB and 32% respectively was attained for the stack patch, which shows good improvement of about 51.4% in the gain and 33.3% in the radiation efficiency over single microstrip patch which reached 1.6 dB and 24% respectively.

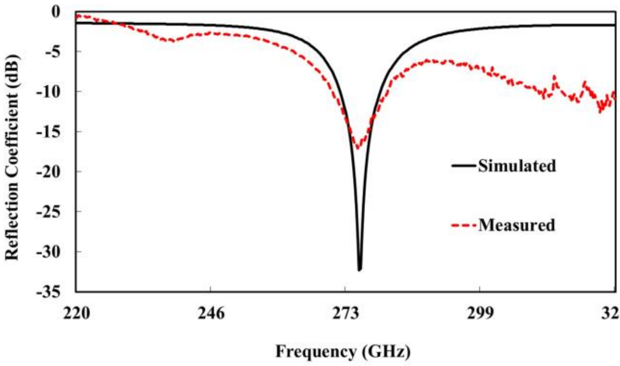


Fig.4. Measured and simulated reflection coefficient of stacked rectangular patch antenna

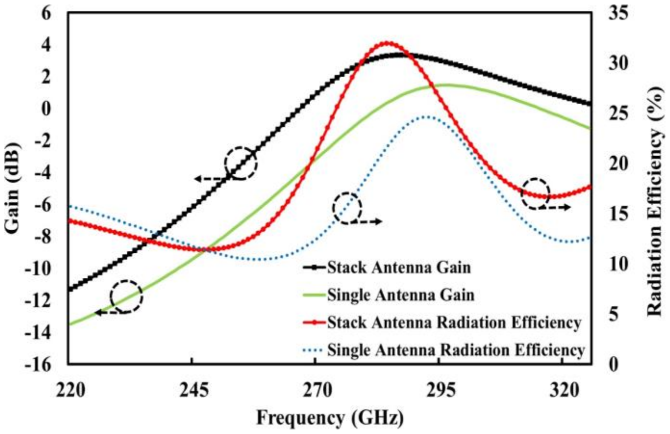
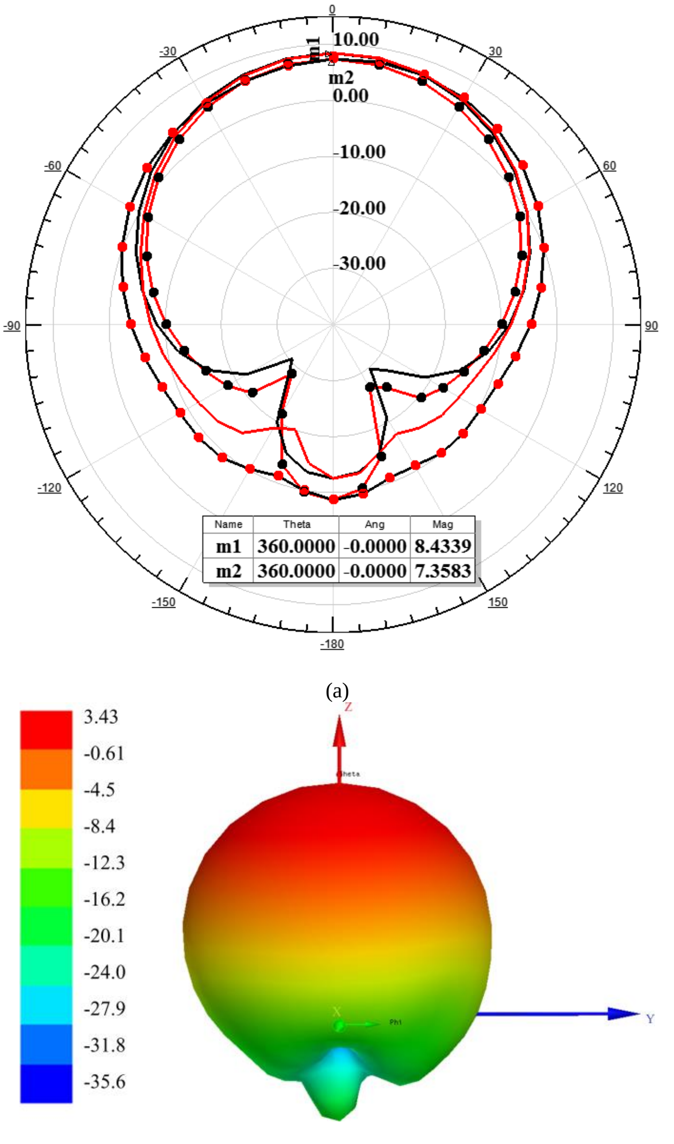


Fig. 5. Plot of gain and radiation efficiency for both single and elevated stack antenna



(a)

(b)

Fig. 6. Simulated radiation pattern of elevated stack antenna (a) Plot of directivity pattern for both single and stack antenna (b) 3-D plot of gain

Fig. 6 (a) & (b) shows the directivity and gain radiation pattern at $0^0 < \theta < 360^0$ and $\varphi=-90^0$ and 0^0 at 0.27 THz. Furthermore, directivity and front to back ratio of 8.3 dB and 21 dB for stack and 7.3 dB and 18 dB for single antenna respectively were reached.

V. CONCLUSION

An elevated stack patch antenna has been presented on GaN-on-low resistivity silicon substrates which is compatible with Terahertz Monolithic Integrated Circuits (TMICs). Experimental and simulated results are presented to demonstrate the efficiency of the antenna design. Our results show a return loss as low as -33 dB (simulated) and -18 dB (measured). Also gain, directivity and radiation efficiency as high as 3.4 dB, 8.3 dB, and 32% respectively have been obtained. These performance results illustrate that low dielectric constant materials and lossy substrates can be used in TMIC without degrading the antenna performance. To authors' knowledge, this is the first demonstration of a microstrip elevated stack terahertz frequency integrated antenna for TMIC compatible technology applications. This technology development paves the way to utilize newly emerging high-speed electronics III-V semiconductor on low resistivity substrate in terahertz frequencies such as GaN where high power is an advantage. The technology detailed in this paper does not require complex micromachining techniques or high temperature fabrication processes, making it suitable for cost effective, compact, mass production, with easy integration suitable for portable TMICs wireless communication and spectroscopy imaging.

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