Eblabla, A., Benakaprasad, B., Li, X., Wallis, D. J., Guiney, I., Humphreys, C. and Elgaid, K. (2017) Passive Components Technology for THz-Monolithic Integrated Circuits (THz-MIC). In: 18th International Radar Symposium (IRS), Prague, Czech Republic, 28-30 June 2017, pp. 1-7. ISBN 9783736993433 (doi:10.23919/IRS.2017.8008166)

Passive Components Technology for THz-Monolithic Integrated Circuits (THz-MIC)

Abdalla Eblabla[1], Bhavana Benakaprasad[1], Xu Li[1], David J. Wallis[2], Ivor Guiney[2], Colin Humphreys[2] and Khaled Elgaid[1]

[1]Electronic and Nanoscale Engineering, School of Engineering, University of Glasgow, Glasgow, United Kingdom
email: Khaled.Elgaid@glasgow.ac.uk

[2]Cambridge Centre for Gallium Nitride, University of Cambridge, Cambridge, Cambridge, United Kingdom

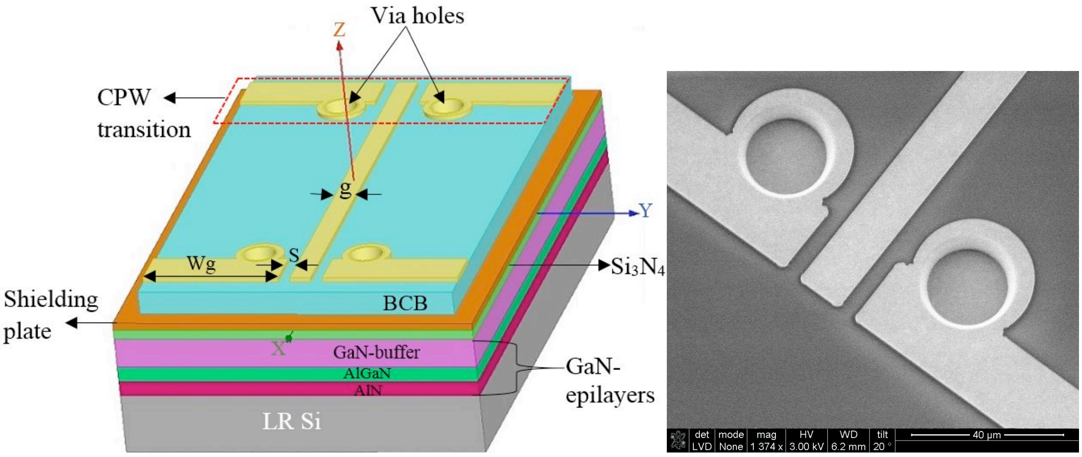
Abstract: *In this work, a viable passive components and transmission media technology is presented for THz-Monolithic Integrated Circuits (THz-MIC). The developed technology is based on shielded microstrip (S-MS) employing a standard monolithic microwave integrated circuit compatible process. The S-MS transmission media uses a 5-μm layer of benzocyclobutene (BCB) on shielded metalized ground plates avoiding any substrate coupling effects. An insertion loss of less than 3 dB/mm was achieved for frequencies up to 750 GHz. To prove the effectiveness of the technology, a variety of test structures, passive components and antennas have been design, fabricated and characterized. High Q performance was demonstrated making such technology a strong candidate for future THz-MIC technology for many applications such as radar, communications, imaging and sensing.*

1. Introduction

THz technology has many applications in imaging, sensing, spectroscopy, astronomy, and communications [1]. The short wavelengths of THz frequency radiation makes it a promising technology due to the unique interaction of this spectral regime with matter and the achievable high-resolution imaging [2]. This interest in new emerging applications is motivated by the recent advances in high-speed semiconductor devices and nanotechnology, which have enabled the realization of THz monolithic integrated circuits (THz-MIC) [3] [4]. The utilization of THz-MIC technology in THz frequency application is a critical component to suppress unwanted moding effects and, hence, reducing signal loss which will improve system signal to noise ratio. In addition, THz-MIC offers the advantage of higher functionality, low system costs, and smaller chip size. In this study, we have demonstrated a viable high performance THz passive components, interconnect and integrated antennas for THz-MIC technology by eliminating the high dielectric constant substrate coupling effects. This was achieved by using low dielectric constant, low tangential loss BCB with EM shielding using metal deposited on the semiconductor substrate.

2. Material and Device Technology

The study was performed on a GaN-based material structure that could be used to realize AlGaN/GaN HEMTs. The epitaxial layers were grown by Metal-Organic Chemical Vapour



(a) (b)

Fig. 1: (a) Oblique projection of the fabricated 1 mm-length 50Ω S-MS with S = 4.5 µm, W = 13.2 µm. and W_g = 100 µm. (b) Scanned Electron Microscopy (SEM) of the fabricated devices.

Deposition (MOCVD) on 675 µm thick LR (σ < 40 Ω.cm) P-type Si (111) substrates. The layer stack, from the substrate up, consists of a 250 nm AlN nucleation layer followed by a 850 nm Fe-doped graded AlGaN buffer to accommodate the lattice and thermal expansion mis-match, a 1.4 µm insulating GaN buffer and channel layer, a 25 nm $Al_{0.25}Ga_{0.75}N$ barrier and a 2 nm GaN cap. Epitaxial layers and growth procedure are detailed elsewhere[5].

The fabrication process of the proposed technology in this study is related to our previous work [6]. First, 200 nm Si_3Ni_4 was deposited onto GaN-on-LR Si substrate using ICP-CVD deposition on the mesa floor, where the transistor active region was etched away. Next a ground plane is formed by depositing Ti/Au (50/600nm) by electron beam evaporation which also acts as shielding for the antenna. A BCB dielectric was then spun and cured in an oven to achieve a uniform thickness of 5.5 µm. Co-Planar Waveguide (CPW) to microstrip transition pads are defined by etching the BCB down to the ground plane using plasma reactive ion etching (RIE) and then evaporating Ti/Au (50/600nm) to form the driven patch and feed line. Fig. 1 shows the vertical structure and an SEM image of the developed technology for an S-MS, indicating that all the processes used are THz-MIC compatible.

3. Results and Discussion

A. Transmission Media

Simulated and measured *S*-parameters results of the developed transmission media are shown in Fig. 2. The simulation results were performed using Ansoft HFSS at the University of Glasgow, and were verified by the good agreement between measured and simulated *S*-parameters. In addition, the measured results shown in Fig. 2 of the fabricated S-MS on GaN on low resistivity Si substrate show low insertion loss (S21) of less than 3dB/mm at frequencies up to 750GHz with a matching better than 15dB across the full measured band (500GHz - 750GHz). This proves the total shielding from the substrate where the electrical field is being confined in the BCB between the ground plane and the microstrip signal line, rather than penetrating through to the silicon substrate. Therefore, the choice of a dielectric layer with low dielectric constant, along with low loss tangent is essential, especially in the THz frequency range. However, the developed S-MS technology can not only be used for

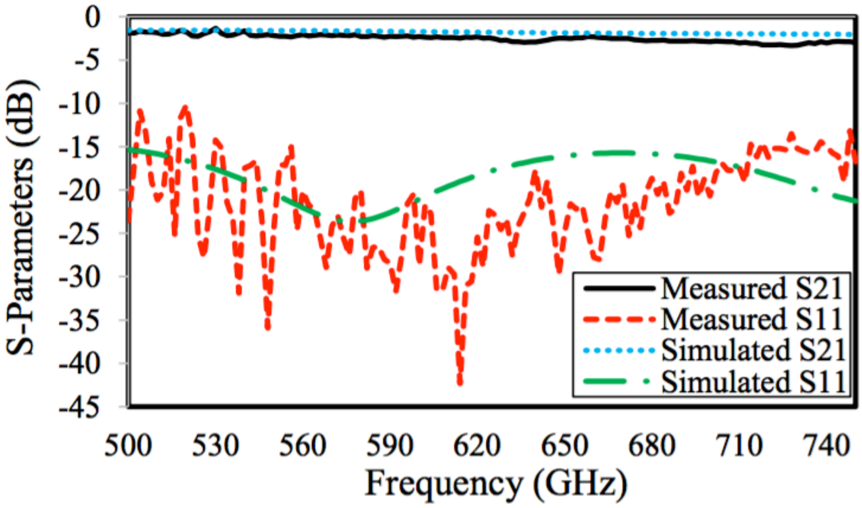


Fig. 2: Measured and simulated *S*-parameters results of the proposed transmission media technology.

conductive substrates, but also could be successfully utilised for semi-insulating substrates, e.g. GaAs and InP. This is because radiation losses is dominant for semi-insulating substrates at THz frequencies, basically owing to the very presence of a high dielectric constant material [7].

For better understanding of the loss mechanism when operating at very small wavelengths (less than 0.54 mm), the effect of CPW-via depth on the parasitic loss was extensively studied based on HFSS simulations. The CPW-via acts as a low pass filter to the RF signal, and can be modelled as an in-series resistance (*R*) and inductance (*L*). The extracted *R* and *L* values at 700 GHz are shown in Fig. 3. It is clear that the CPW-via depth has a great influence on both R and L. The parasitic resistance and inductance were noticeably increased from 0.44 Ω and 4.11 pH to 214.43 Ω and 82.77 pH when the depth was increased from 5.5 µm to 50.5 µm, respectively. This increase will lead to a dramatic degradation in transmission media performance. Therefore, the CPW-via structure design needs to be carefully considered during simulation.

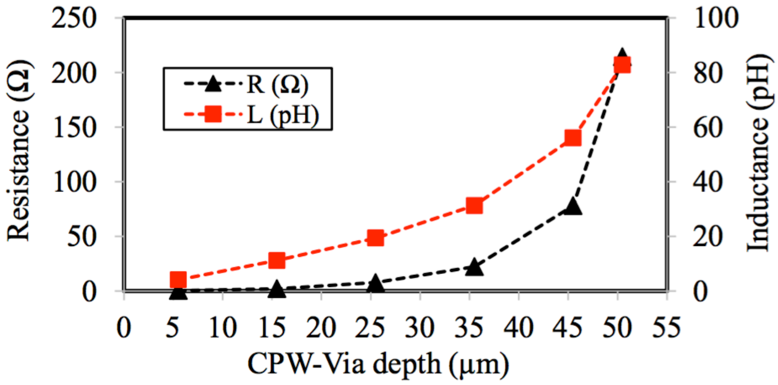
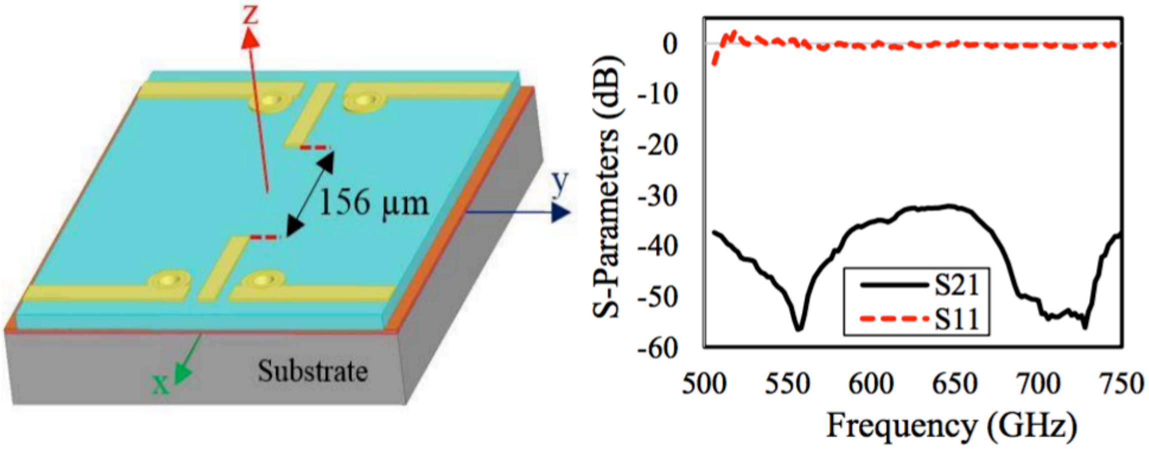


Fig. 3: Extracted parasitic Resistance and inductance of the CPW-via as a function of depth based HFSS simulation results.

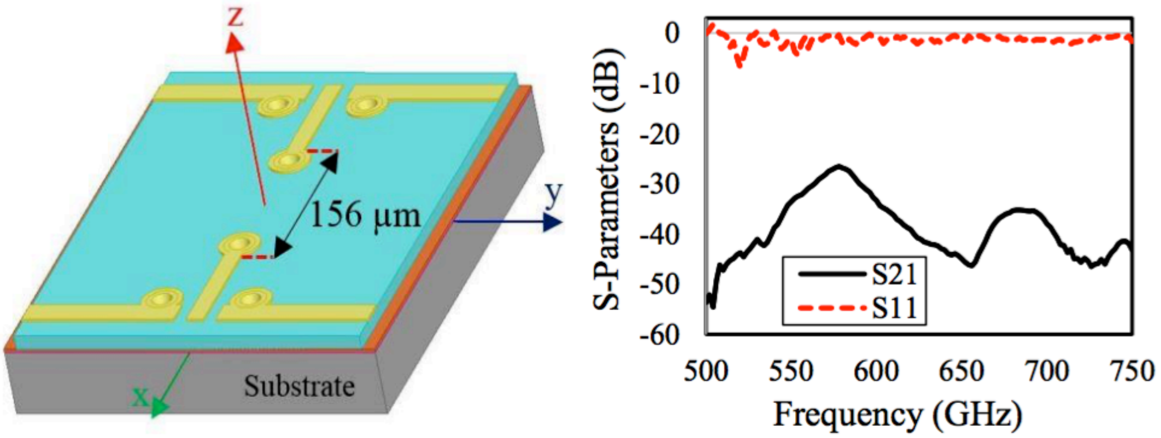
B. Open and short test pad structures

Open and short test structures were designed, fabricated and characterised to further investigate the developed transmission media performance at THz frequencies. The designed open and short structures using S-MS technology are shown in Fig. 4a and Fig. 5a, respectively. The RF signal leakage was found to be negligible for both structures, indicating the viability of the S-MS technology for THz operation, as shown in the measured *S*-parameters in Fig. 4b and Fig. 5b.



(a) (b)

Fig. 4: (a) 3-dimentional view. (b) Measured *S*-parameters of the fabricated open structure using S-MS technology.



(a) (b)

Fig. 5: (a) 3-dimentional view. (b) Measured *S*-parameters of the fabricated short structure using S-MS technology.

C. Power Divider

Fig. 6 shows S_{11} and S_{N1} (N=2-5) plots of a simple T-junction power divider designed using shielded microstrip technology. Characteristic impedance of 100Ω transmission line was used in parallel to achieve the power splitting, a quarter wave transformer of 70.7Ω impedance was used to make the end of the transmission line 50 Ω. This was repeated one more time to achieve four output ports. Insertion loss presented at the output ports was about -7.5 dB and the return loss of the input port was as low as -25 dB which compares favorably to other technology developed so far.

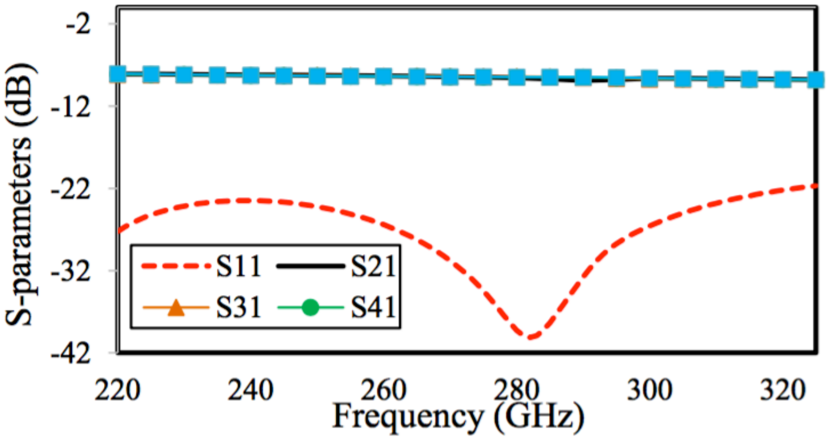
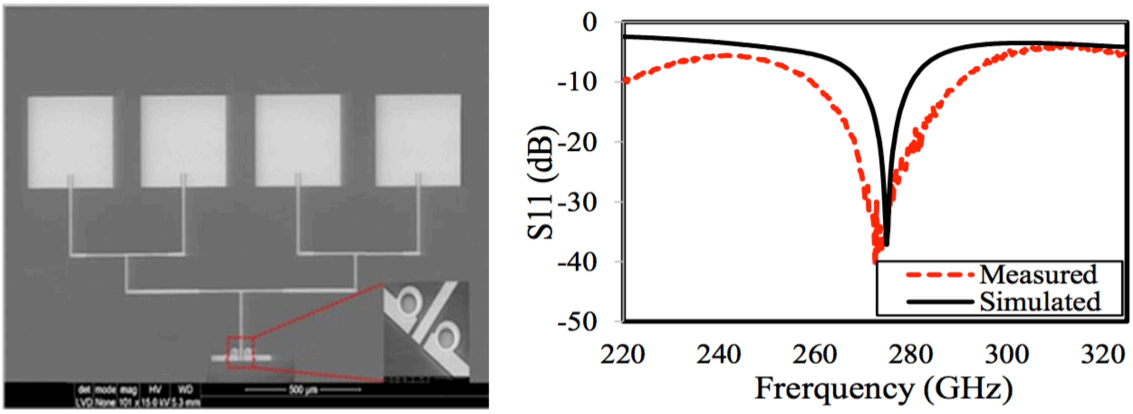


Fig. 6: Power divider in HFSS. (a) T-junction circuit. (b) Plot of S11, S21, S31, S41 and S51.

D. Array Antenna

Using the above divider, 4×1 array antennae were designed as shown in fig 7 (a). Dimensions of each antenna was 372×333 µm and these were combined with the power divider to form a microstrip array antenna [8]. Fig. 5(b) shows the reflection coefficient of both simulated and measured array antenna which was as low as -37 dB and -41 dB respectively. The measured reflection coefficient showed a -10 dB bandwidth of 32 GHz from 259 GHz to 291 GHz, presenting a relative bandwidth of 11.6 %. Simulated antenna revealed directivity and gain as high as 11.2 dB and 5.2 dB respectively. Further, radiation efficiency of 20% was observed. This proves S-MS technology is promising for high performance on GaN-on LR Si substrate.



(a) (b)

Fig. 7: 4×1 array antenna. (a) SEM image and (b) Measured and Simulated reflection coefficient.

Summary

The proposed Shielded Microstrip (S-MS) on BCB technology presented in this work offers a promising route for the integration of high performance RF active devices and low-loss passive elements for a THz-MIC technology. The insertion loss of 3dB/mm at 750GHz that was achieved is to our knowledge the lowest reported for such a THz-MIC compatible technology. The developed technology was also used to develop integrated THz antennas with a bandwidth of 32 GHz from 259 GHz to 291 GHz.

ACKNOWLEDGMENT

This work was supported by the EPSRC under grant EP/N014820/1. The research Team would like to acknowledge Mr. Hermann Massler, Microelectronics Group Manager, Fraunhofer Institute for Applied Solid State Physics IAF, Freiburg, Germany for conducting the THz on-wafer measurements.

References

[1] D. L. Woolard, *et al.*, "Terahertz frequency sensing and imaging: A time of reckoning future applications?," in *Proceedings of the IEEE*, vol. 93, no. 10, pp. 1722–1745, Oct. 2005.

[2] M. Mikulla, *et al.*, "High-speed technologies based on III-V compound semiconductors at Fraunhofer IAF," in *2013 European Microwave Integrated Circuits Conference,* Nuremberg, 2013, pp. 169–171.

[3] E. Feiginov, *et al.*, "Semiconductor Terahertz Technology: Devices and Systems at Room Temperature Operation,", John Wiley & Sons, Ltd, 2015.

[4] A. Eblabla, *et al.*, " GaN on Low-Resistivity Silicon THz High-Q Passive Devices Technology," *IEEE Transactions on Terahertz Science and Technology.*, vol. 7, no. 1, pp. 93–97, Jan. 2017.

[5] A. Eblabla, *et al.*, " High Performnce GaN High Electrone Mobility Transistors on Low Resistivity Silicon for X-Band Applications ," in *IEEE Electrone Device Letters*, vol. 36, no. 9, pp. 899–901, Sep. 2015

[6] B. Benakaprasad *et al.*, "Terahertz microstrip elevated stack antenna technology on GaN-on-low resistivity silicon substrates for TMIC," *2016 46th European Microwave Conference (EuMC),* London, 2016, pp. 413-416.

[7] F. Alghamoradi, *et al.*, " Low-Loss Grounded Elevated Coplanar Waveguide for Sub-Millimeter wave MMIC Applications." *Progress in Electromagnetic Research Journal, PIER B*, vol. 34, 2011.

[8] B.Benakaprasad, *et al.,* "Terahertz Monolithic Integrated Circuits (TMICs) Array Antenna technology on GaN-on-Low Resistivity Silicon Substrates" 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz), 2016.