GaN on Low Resistivity Silicon THz High-Q Passive Device Technology

Abdalla Eblabla, Xu Li, David J. Wallis, Ivor Guiney and Khaled Elgaid.

***Abstract*—In this paper, viable transmission media technology has been demonstrated for the first time on GaN-on-low resistivity silicon (LR-Si) substrates (ρ < 40 Ω.cm) at H-band frequencies (220-325 GHz). The shielded-elevated (SE) CPW lines employ a standard MMIC compatible air bridge process to elevate the CPW traces above a 5 µm layer of benzocyclobutene (BCB) on shielded metalized ground plates. An insertion loss of less than 2.3 dB/mm was achieved up to 325 GHz, compared with 27 dB/mm for CPW fabricated directly on the substrate. To prove the efficiency of the technology, a short-circuited stub filter with a resonant frequency of 244 GHz was realised. The filter achieved an unloaded Q-factor of 28, along with an insertion loss of 0.35 dB and a return loss of -34 dB. To our knowledge, these results are the best reported to date for GaN-based technology.**

***Index Terms*—GaN-HEMTs, low resistivity silicon substrates, coplanar waveguides (CPWs), H-band, High-Q THz filters, TMICs.**

I. INTRODUCTION

THz technology has many applications in imaging and sensing, spectroscopy, astronomy and communications [1] [2]. The short wavelength of THz frequencies makes it a promising technology due to the unique interaction of its spectral regime with matter and the achievable high resolution imaging [3]. 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 TMIC (THz Monolithic Integrated Circuits) [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, InP or Si [5]. The utilization of TMIC technology in THz frequencies application is a critical component to suppress unwanted moding effects and hence reducing signal loss. In addition, TMIC offers the advantage of higher functionality, low 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 frequencies higher than their f_T [6]. However, SiC substrates are expensive and have limited availability in large substrate diameters.

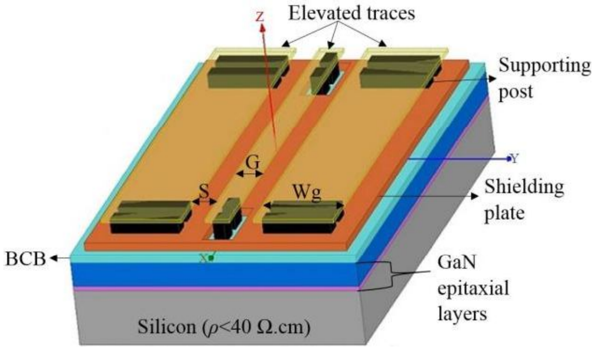

Fig. 1: Oblique projection of the fabricated 1 mm-length 50 Ω SE-CPW on BCB with $G = 21$ µm, $S = 18$ µm and $W_g = 100$ µm.

The potential use of GaN HEMTs grown on LR Si for MMIC circuits offers the advantage of cost-effective and large diameter wafers, which make manufacturing costs of GaN-on-LR Si 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 using GaN-on-LR Si technology.

However, At frequencies above 220 GHz, designing high-Q passive components is very challenging as the wavelength becomes comparable with the substrate thicknesses [8]. To capitalize on the advantages in utilizing GaN on LR Si for millimeter-wave and THz applications, a technology with minimal substrate coupling is required. Insertion of a low-loss, low dielectric constant, k, layer of BCB as an insulator has proven to be a successful technique for substrate coupling reduction [9]. This approach, compared to other complicated techniques [10] [11], has the advantage of accommodating active circuits underneath the passive components and interconnections with no degradation of active device performance [12].

In this work, substrate coupling effects were eliminated by the complete isolation of the substrate, where the CPW

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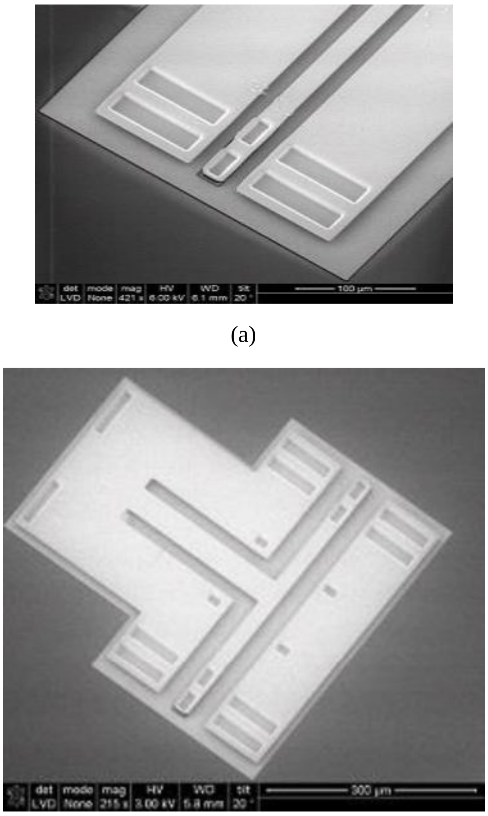
interconnect have no direct contact to the lossy Si in addition to EM shielding. The developed SE-CPW transmission media use a reliable fabrication process to elevate all the CPW traces above a 5 µm layer of BCB on shielded metalized ground plates. Hence, the insertion loss was dramatically reduced to less than 2.3 dB/mm, compared to 27 dB/mm for that of CPW fabricated directly on the substrate over the whole H-band frequency range. For further investigation of the viability of the proposed technology, a band bass filter was simulated, fabricated and characterized. A sharp resonance with Q-factor of 28 was obtained at a center frequency of 244 GHz. This indicates the suitability of III-V-on-LR Si technology for millimeter-wave and THz applications.

I. 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 Vapor 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 AlGaN graded buffer to accommodate the lattice and thermal expansion mismatch, 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, as shown in Fig. 1. Epitaxial layers and growth procedure are detailed in [13].


(a)

(b)

Fig. 2: Scanned electron microscopy (SEM) image of the fabricated devices on BCB. (a) SE-CPW, and (b) Band-pass filter.

All levels of device definition were realized using optical lithography and all steps required to realize the transmission media are compatible with standard MMICs technology. As in a standard MMIC process, passive devices were fabricated on the mesa floor, where the transistor active region (the upper two layers) were etched away.

Fabrication process of the SE-CPW technology started with spinning a 5 µm-thick BCB film, and then fully cured at 250 ^{0}C in N_2 atmosphere. Following this, Ti/Au (50/600 nm) was deposited to form the fabrication alignment markers and shielding plates. Next, air-bridge technology was utilized to elevate the CPW traces. Finally, the sample was metalized using 2 µm Au electroplating. Fig. 2 shows a micrograph of the fabricated devices.

II. MODELLING AND MEASUREMENTS

A 3-D full-wave electromagnetic simulation tool, Ansoft HFSS was employed to design the SE-CPW technology. Optimization of structure geometrics and highs was carried during the simulation for better performance and to ensure the suppression of RF energy dispersion introduced by the conductive Si substrate.

On-wafer measurements of small-signal S-parameter were performed using an Agilent PNA network analyzer over the range 220-325 GHz (H-band). The system was calibrated using short-open-load-thru (SOLT) calibration based on an off-chip ISS impedance standard. 50 µm-pitch WR-03 waveguide Picoprobes were used for probing; where a durable device input/output pads were realised by placing adjacent two air-bridges, as shown in Fig 2. The samples were placed on a thick quartz spacer to eliminate any possible parasitic substrate modes caused by the metal chuck.

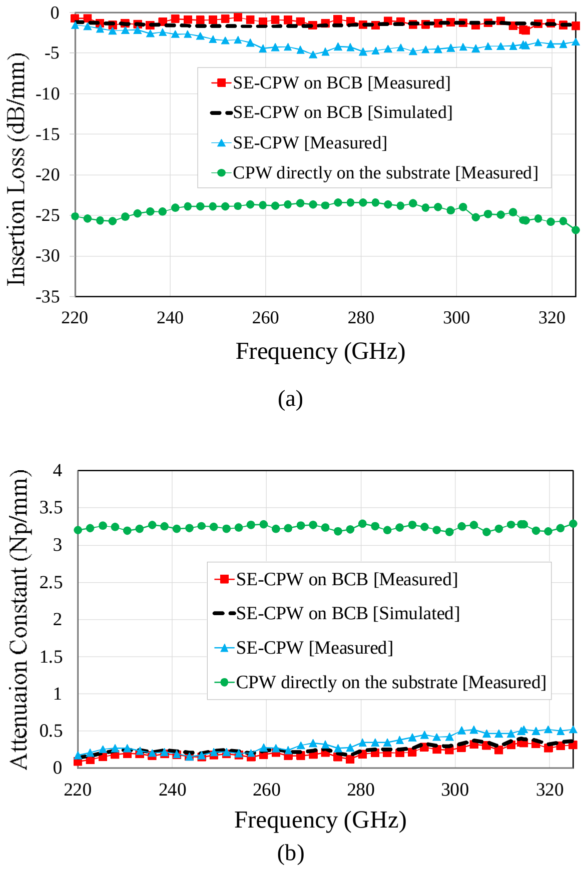
III. RESULTS AND DISCUSSION

A. *Transmission media*

RF signal coupling to the lossy substrate was investigated by the comparison of CPW layout fabricated directly on GaN-on-LR Si substrate with that using the SE-CPW with BCB technology (by shielding using metal layer, inserting low dielectric constant BCB and additional elevation using air-bridge support), as shown in Fig. 3. In addition, measured results of the elevated CPW using air-bridge technology and shielding metal (excluding the BCB insert) was included, as shown in Fig. 3.

From Fig. 3a, substrate losses were clearly dominant for the CPW structures realized directly on the substrate for the whole H-band frequency range, where an insertion loss of more than 23 dB/mm was observed. This means that most of the E-field was penetrating through to the lossy Si substrate. The insertion loss was reduced across the frequency band to less than 5.4 dB/mm by using an elevated CPW and shielding plates on the substrate (excluding the BCB insert). This reduction in substrate effects is mainly due to the electric field being mostly concentrated within the air-gap between the shielding plate and elevated CPW traces. However, as the SE-CPW structure requires the use of ground holes in the shielding plate, there are small areas in the shielding plate in which the CPW signal trace is in direct contact with the lossy substrate. Losses are very sensitive to these exposed areas (ground holes) especially at H-band frequency range, where the wavelength dimensions become comparable to the substrate exposed area at the base of the air-bridge support. To overcome this issue, the SE-CPW was fabricated on top of a 5 µm thick layer of BCB. This eliminated substrate coupling effects where the CPW traces are totally isolated from the lossy substrate. Hence, the return loss was improved to less than 2.3 dB/mm up to 325 GHz, the lowest reported to date for GaN based technology.

To further characterize the transmission media performance developed in this work, attenuation constant (α) was calculated [14]. As shown in Fig. 3b, using the proposed SE-CPW technology with BCB insert, α was noticeably minimized especially at the higher frequency range of the H-Band. An attenuation constant (α) of the developed technology as low as of 0.3 Np/mm was obtained up to 325 GHz, and is the best reported to date at THz frequencies. This proves the complete isolation of the conductive substrate and THz signal confinement in the transmission media of this work. The measured results obtained are verified by the very close agreement between measured and simulated S-parameters, as shown in Fig. 3.



(a)

(b)

Fig. 3. S-parameters results for the fabricated 1 mm-length 50 Ω transmission media. (a) Insertion loss, and (b) attenuation constant.

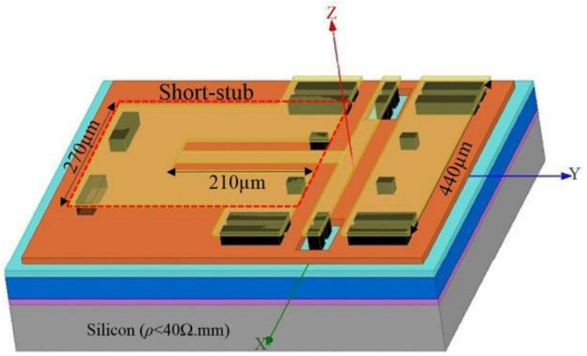


Fig. 4: Oblique projection of the fabricated SE-CPW short-circuited stub filter with the fabricated dimensions.

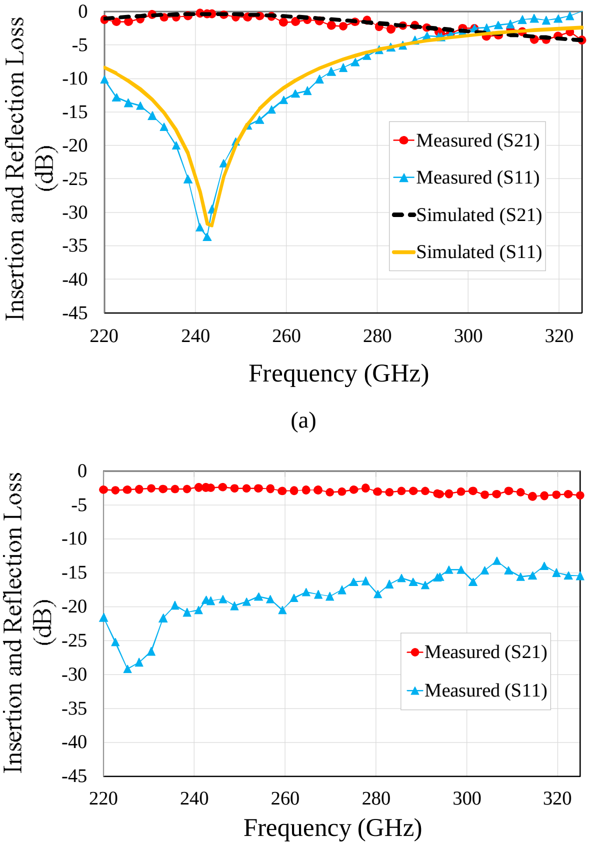
B. *Short-circuited stub filters*

The short-circuited shunt matching network is a key topology for a variety of circuits including band-pass filters, diode detectors and matching / DC return networks [4] [15]. However, in the H-band frequency range, short-circuited matching stubs exhibit low quality factor even for SI GaAs substrates which makes them a non-viable component for TMIC technology [16].

Fig. 4 shows a 3-D plot of the fabricated SE-CPW on BCB dielectric short-circuited stub filter structure. The short stub characteristic impedance, Z_0 is approximately 36 Ω, and dimensions are; W= 39 µm and S = 19 µm. While the feed line was designed to be $Z_0 = 50$ Ω, W = 24 µm and S = 30 µm.

Fig. 5a shows the simulated and measured *S*-parameters of the SE-CPW short stubs on BCB dielectric insert. It is clear that insertion of an insulating layer of BCB between the GaN-on-LR Si substrate and shielding plate resulted in superior performance and a relatively sharp resonance, with a Q-factor of 28 and return loss of -34 dB and at 244 GHz. In addition, an insertion loss and 3dB-bandwidth of as low as 0.35 dB and 101 GHz were obtained respectively at a resonance frequency of 244 GHz. This improvement in performance is an indication of the complete isolation of the lossy substrate.

Previous work done by other researchers obtained a Q-factor of 21 and insertion loss of -4.1 dB/mm on RF CMOS technology operating at 60 GHz [10] . These results obtained by the newly developed technology are superior to those of the same structure using shielded elevated CPW on air-bridge supports without the BCB dielectric insert layer as shown in Fig. 5b. Higher insertion loss was observed in additional to the low quality factor.



(a)

(b)

Fig. 5. S-parameters results of the fabricated SE-CPW short-circuited stub filter (a) with BCB insert, and (b) without BCB insert.

IV. CONCLUSIONS

In this paper, for the first time, high-Q transmission media on GaN-on-LR Si substrates ($\rho < 40$ Ω.cm) technology are simulated, fabricated and measured at H-band. The SE-CPW lines employ a standard MMIC compatible air bridge process to elevate the CPW traces above a 5 µm layer of BCB on shielded metalized ground plates. An insertion loss and attenuation constant of less than 2.3 dB/mm and 0.4 Np/mm were achieved, respectively up to 325 GHz. The viability of the proposed SE-CPW technology was investigated by the realization of a short-circuited stub filter. The filter achieved an unloaded Q-factor and insertion loss of 28 and 0.35 dB, respectively at 244 GHz. To our knowledge, these results are the best transmission media performance reported to date for mm-wave and THz GaN based technology. The proposed SE-CPW on BCB offers a promising technology for the integration of high RF performance active devices and low-losses passive elements for the realization of TMIC technology.

V. ACKNOWLEDGMENT

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VI. REFERENCES

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Ivor Guiney is a MOCVD expert and is the growth specialist for GaN power and RF applications in the University of Cambridge. Prior to this role, he had various project management roles in industry which were focused on the growth of graphene, GaN, GaAs, InP and GaSb device structures by MOCVD and various dielectrics by ALD. The main areas of device development in this work were in GaN blue LEDs on sapphire, GaN on Si and SiC power electronics, InGaAsP-based telecomms modulators and IR-laser diodes. He has authored or co-authored over 30 publications and has given two invited talks at international conferences on the topics of GaN optoelectronics and power electronics. He currently sits on the Semiconductor Group Committee of the Institute of Physics as the treasurer.

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