Novel Shielded Coplanar Waveguides on GaN-on-Low Resistivity Si Substrates for MMIC Applications

A. Eblabla, D. J. Wallis, I. Guiney, and K. Elgaid

***Abstract*—Shielded-Elevated Coplanar Waveguides (SE-CPWs) with low loss have been successfully developed for the first time for RF GaN on low-resistivity silicon (LR-Si) substrates ($\sigma < 40\ \Omega.\mathrm{cm}$). Transmission losses ($S_{21}$) of less than 0.4 dB/mm at X-band and better than 2 dB/mm at K-band with less than 20 dB return loss were exhibited by the developed SE-CPW, making them comparable in performance to those on traditional (semi-insulating) SI substrates. The developed waveguides use air-bridge technology to suspend CPW tracks above the HEMT GaN layer on LR-Si, directly above an additional thin layer of SiN and shielded ground planes. EM simulation was used to adjust structure parameters for performance optimization. In this work, we eliminated RF energy coupled into the substrate, paving the way for a cost-effective and higher integration GaN MMICs on LR-Si.**

***Index Terms*—AlGaN/GaN HEMTs, Attenuation constant and conformal mapping, coplanar waveguides (CPWs), low resistivity silicon substrates.**

I. Introduction

OVER a number of years, mm-wave systems using high power, high frequency transistors have found broad application in the telecommunication and radar fields. In order to become economy viable, such applications require low-cost transistors which can deliver significant power at mm-wave frequencies. The wide energy gap ($E_G = 3.4$ eV), high breakdown fields ($E \sim 3 \times 10^6$ V/cm), high saturation electron velocities ($v_S > 2 \times 10^7$ cm/s) and high channel electron densities ($\mathrm{n_S} \sim 10^{13}/\mathrm{cm}^2$) found in GaN HEMTs enable the fabrication of devices which can deliver high power densities at both microwave and mm-wave frequencies [1], [2]. Recent work has extended the frequency performance of GaN HEMTs grown on silicon, with cutoff frequencies as high as $_T = 153$ GHz attained for 75 nm gate AlGaN/GaN HEMTs with high saturation current density $I_{DS} > 1.3$ A/mm and a low $R_{ON} = 1\ \Omega.\mathrm{mm}$ [3].

Realization of low-loss waveguides and capacitors and inductors with high-quality factor at mm-wave frequencies are of great importance for circuit application where interconnects and passive components are needed. Therefore, low-loss transmission media is necessarily required for cost-effective GaN-based MMIC technology.

Previously, a number of researchers have attempted to develop high quality CPWs on LR Si substrates. Some reports have shown a reduction in losses using thick insulators such as polyamide [4], benzocyclobutene (BCB) [5], Ajinomoto Build-up Film (ABF) and SU-8 [6] but these still have relatively high attenuation at mm-wave frequencies. On the other hand, reports have shown that attaching silicon dioxide ($\mathrm{SiO_2}$) to the surface of the Si substrate, induces a low-resistivity layer at the interface between the $\mathrm{SiO_2}$ and the Si surface [7]. These phenomena cause degradation of the attenuation constant. Several approaches have been suggested to avoid such undesirable effects, such as introducing polysilicon at the Si-$\mathrm{SiO_2}$ interface [8], removing the Si substrate from the backside substrate by micromachining [9] and using the floating shield technique [10]. However, each of these methods requires complex and lengthy fabrication processes.

In this letter, a Shielded-Elevated CPW (SE-CPW) is proposed to suppress the effect of the conductive substrate. In this structure, a ground plane is placed on top of the substrate to provide near-complete isolation of the elevated CPW from the substrate. The structure provides transmission lines fabricated on GaN-on-LR Si with much reduced dielectric loss and with a very low attenuation per unit length up to 67 GHz.

II. Expermental Work

The study was carried out on AlGaN/GaN HEMTs supplied by the Cambridge Centre for GaN in the University of Cambridge. The epitaxial layers were grown by MOCVD on 675 μm LR P-type Si (111) substrates. The original layer stack, from the substrate up, consists of a 200 nm AlN nucleation layer followed by a 750 nm Fe-doped AlGaN graded buffer to accommodate the lattice and thermal expansion miss-match, a 1.4 μm insulating GaN buffer and channel layer, a 20 nm $\mathrm{A}l_{0.25}\mathrm{Ga}_{0.75}\mathrm{N}$ barrier and a 2 nm GaN cap, as shown in Fig. 1.

The fabrication process was carried out at the James Watt Nanofabrication Center (JWNC) at the University of Glasgow. The transistor active region (the upper two layers) were etched away prior to transmission media fabrication. As in a standard MMIC process, the CPWs were fabricated on the isolation mesa floor on top of a 200 nm $\mathrm{Si_3N_4}$ dielectric layer. The first step of SE-CPW fabrication is to define the lower ground plane by e-beam exposure and development of a 1520 nm thickness bi-layer PMMA, followed by electron beam evaporation of a

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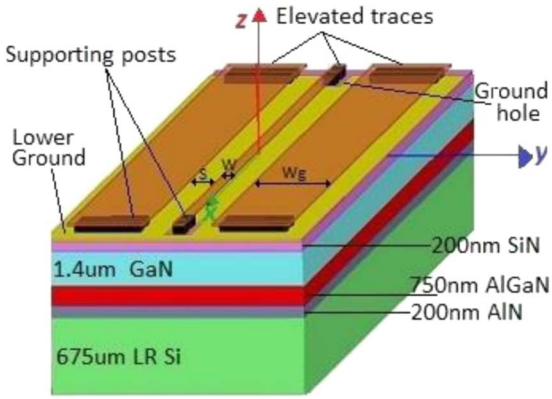

Fig. 1. Oblique projection of the fabricated 50 Ω SE-CPW line with $S = 35\ \mu$m, $W = 19\ \mu$m, $W_g = 100\ \mu$m and of length 1 mm.

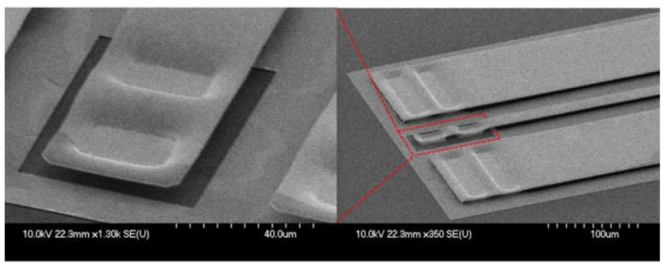

Fig. 2. Scanned Electron Microscopy (SEM) of the fabricated SE-CPW line.

50 nm NiCr/400 nm Au layer and lift-off. Following this, the elevated traces' structures, including a number of supporting posts, were realized. These posts were defined by spinning AZ4562 photoresist at 3000 rpm for 30 s (corresponding to 5.5 μm elevation height). A 50 nm Ti/50 nm Au seed layer was then deposited prior to electroplating. Next, the elevated traces were formed in 2 μm S1818 photoresist followed by exposure, development and ashing in a dry etch machine. The sample was then metallized using 2 μm cold electroplating. Finally, different levels of exposure and development were performed. Fig. 2 shows SEM photos of the fabricated SE-CPW line.

III. Measurements and Modelling

On-wafer S-parameter measurements were performed with an Agilent PNA network analyzer over the range 0.1–67 GHz. The system was calibrated using Line-Reflect-Reflect-Match (LRRM) calibration, and the lines were probed using Picoprobes with 100 μm pitch on the top of a double set of posts located at either end. Then the samples were placed on a thick quartz spacer to eliminate any possible microstrip-like mode caused by the metal chuck.

For modelling, the prefabricated SE-CPW lines were designed and simulated using a 3-D full-wave electromagnetic simulation tool, Anasoft HFSSTM, at the University of Glasgow. The structure was precisely optimized during the simulation for better performance and to minimize RF energy dispersion introduced by the lossy substrate.

IV. Results and Discussion

We initially investigated the performance of the SE-CPW by comparing its measured and simulated data with that of a conventional CPW line between 0.1 and 67 GHz. Measured and

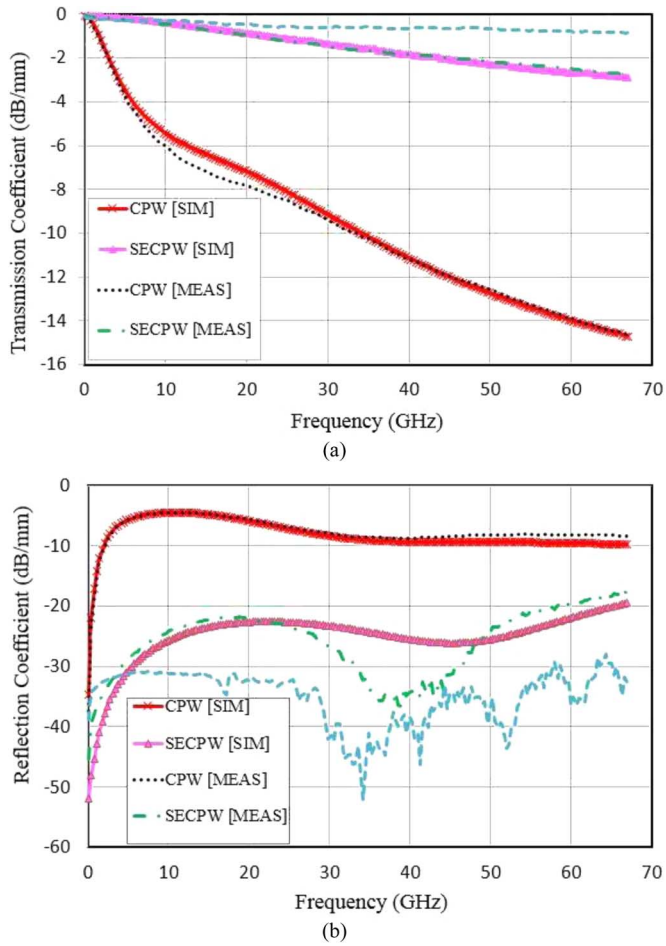

Fig. 3. Measured and simulated S-parameters for conventional CPW and SE-CPW lines. (a) Transmission coefficient (S_{21}). (b) Reflection coefficient (S_{11}).

simulated S-parameters are in very close agreement, as shown in Fig. 3. It is clearly shown that the effect of the conductive substrate is dominant, even at low frequencies, for conventional CPW lines. Since all the CPW traces are in direct physical contact with the substrate, most of the E-field is coupled onto the conductive substrate even whilst employing a thin Si_3N_4 insulating layer. The losses are mainly due to two phenomena: one is capacitive coupling which allows the flow of conduction current not only through the metal strips but also through the lossy substrate contact areas. The other reason is inductive coupling which induces current loops and associated losses by penetration of the magnetic field through the lossy substrate. Losses continuously increase over the whole frequency band, reaching a maximum of more than 14 dB at 67 GHz. On the other hand, by using an SE-CPW structure, improvements of the line performance in terms of dB/mm (up to 12 dB/mm) over a conventional CPW line can be achieved. Losses also increase gradually over the entire band for the SE-CPW line, showing a comparable performance to that of a CPW line fabricated on a semi-insulating GaAs substrate [11], [12] as illustrated in Fig. 3(a).

Not only does SE-CPW introduce improvements in terms of transmission losses (S_{21}), but it also provides acceptable matching, with as low as -22 dB/mm return loss, and more than 20 dB/mm reduction over a conventional CPW line. Moreover,

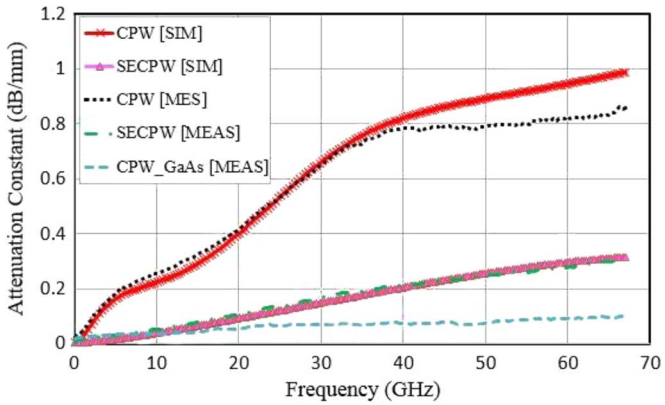

Fig. 4. Measured and simulated of the attenuation constant, α, of conventional CPW and SE-CPW lines.

the resonant frequency is shifted by nearly 5 GHz using the proposed transmission media. Consequently, SE-CPW lines mitigate the unwanted in-band resonances, providing even better efficiency than CPW-on-GaAs at K-band, as shown in Fig. 3(b).

Another figure of merit in evaluating the performance of passive components is the attenuation constant, α, detailed in [13]. Fig. 4 clearly shows that the attenuation constant rises steeply to very high values for conventional CPW lines; 1 dB/mm at 76 GHz. However, a reduction of the attenuation constant of more than 0.6 dB/mm can be obtained using the SE-CPW structure, owing to the electrical isolation of the signal trace from the bottom ground plane and the substrate. EM simulation was carefully optimized to insure complete-isolation of the elevated signal and ground CPW traces by employing ground holes. These holes need to be as small as possible to reduce the effect of the conductive substrate. There are small areas in the lower ground in which the line has physical contact with the substrate and the supporting posts are in physical contact with the substrate via exposed rectangular areas in the lower ground plane bond pad layer. For these reasons, SE-CPW line has slightly larger attenuation constant (less than 0.2 dB/mm) compared to that of CPW-on-GaAs line at K-band.

We believe that the SE-CPW could operate with similar performance without the CPW ground planes; although variations in gap width (S) in proportion to the elevation height (h) may make it behave as a conductor-backed CPW.

V. Conclusion

We have developed and characterized a high-performance novel SE-CPW transmission media on AlGaN/GaN HEMT buffer layers grown on LR-Si. The developed SE-CPW line has effectively suppressed the effects of the low resistivity substrate resulting in excellent power confinement. A transmission loss, S_{21}, and attenuation constant, α, of better than 2.4 dB/mm and 0.4 dB/mm at 67 GHz were achieved respectively. These results are comparable to those achieved for CPWs implemented on SI substrates such as GaAs and InP, demonstrating the feasibility and viability of mm-interconnects on GaN-on-LR Si epitaxial layer stacks. The proposed SE-CPW transmission media provides promising results of a mature GaN-on-LR Si process technology.

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