GaAs on Quartz Coplanar Waveguide Phase Shifter

M. S. Islam, A. J. Tsao, V. K. Reddy, and D. P. Neikirk

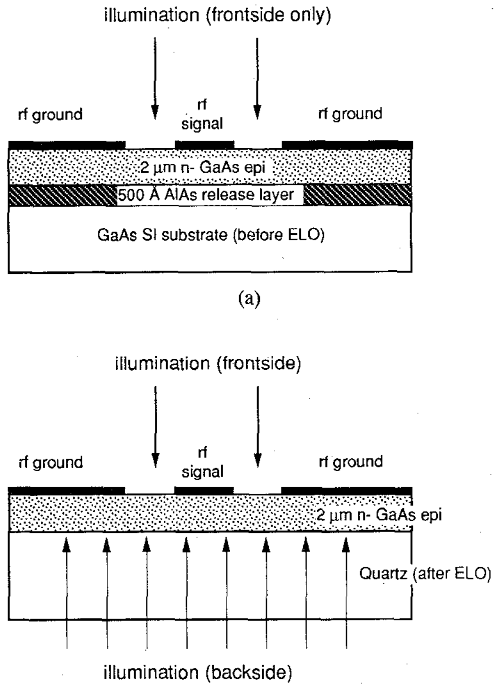
Abstract—**An optically controlled Schottky-contacted coplanar waveguide (CPW) phase shifter on a thin epitaxial GaAs film bonded to a quartz substrate has been fabricated using the epitaxial lift off (ELO) technique. This allows the original semi-insulating GaAs substrate to be replaced by an optically transparent, low dielectric constant quartz substrate. A significant reduction in insertion loss and increase in phase shift was observed after lift-off. The ELO device allows the use of backside illumination for optical control, avoiding any metal shadowing effects, thus producing higher sensitivity to the optical signal. From 5 to 40 GHz, the ELO device gave an insertion loss of approximately −0.1 dB per degree of phase shift. At a backside illumination intensity of 0.65 mW/cm^2, a one centimeter long device produced over 350° of phase shift at 30 GHz.**

I. Introduction

Microwave signals carried on a Schottky-contacted coplanar waveguide (CPW) on GaAs substrates can undergo large phase shifts when the substrate is optically illuminated, even at very low illumination intensities [1]. Previous devices allowed illumination of the GaAs only through the small gaps between the CPW electrodes. It is now possible to remove large areas of epitaxially grown GaAs from the original growth substrate using the epitaxial lift off (ELO) technique [2], [3]. The thin epitaxial layer of GaAs can then be bonded to an optically transparent substrate, such as quartz, using Van der Waals bonding [4]. GaAs on quartz has also been proposed for use in microstrip filter applications [5], and ELO GaAs on silicon has been used for the fabrication of GaAs MESFET's [6]. For the CPW, use of a quartz substrate allows illumination of the device from its back side that avoids electrode shadowing, providing larger area for light absorption.

II. Device Description and Fabrication

The CPW phase shifter substrate consists of an epitaxial layer of lightly-doped n-type ($\sim 7 \times 10^{15}$ cm^{-3}) GaAs grown on a semi-insulating (SI) (100)-oriented GaAs wafer. For the lift off sample, an additional 500 Å thick AlAs release layer is grown between the SI substrate and the 2-μm thick active epitaxial layer of GaAs (Fig. 1). CPW electrodes are then fabricated on the n^- GaAs–AlAs–SI GaAs substrate combination. The CPW electrodes consist of 300 Å of chrome and 1.2 μm of silver. To remove the epitaxial layer and CPW from the SI substrate, Apiezon W wax is applied over the top of the device. The sample is then placed overnight in a 10% hydrofluoric acid solution to selectively etch away the thin AlAs release layer [2]. After the epitaxial layer has been lifted off it is transferred onto a quartz substrate, and the combination is baked at 50°C overnight in a vacuum bag [3]. Following removal from the vacuum bag, the bake temperature is increased to 90°C to promote better adhesion to the quartz substrate. After cooling, the wax is removed with trichloroethane. A cross-section of the CPW phase shifter before and after ELO is shown in Fig. 1.



(b)

Fig. 1. Cross-sectional diagram of CPW phase shifter (a) before epitaxial lift off (ELO) and (b) after ELO. CPW central conductor is 10 μm wide, with a 7 μm gap to the ground planes. Epitaxial layer is lightly-doped n-type ($\sim 7 \times 10^{15}$ cm^{-3}) GaAs.

III. Results and Discussions

Maximum sensitivity to optical illumination is obtained when a dc reverse bias is applied to the CPW electrodes that just depletes the epitaxial layer under the metal at zero illumination intensity. At this dc bias very low levels of illumination induce large changes in the device capacitance [7]. For the doping concentration and layer thickness used

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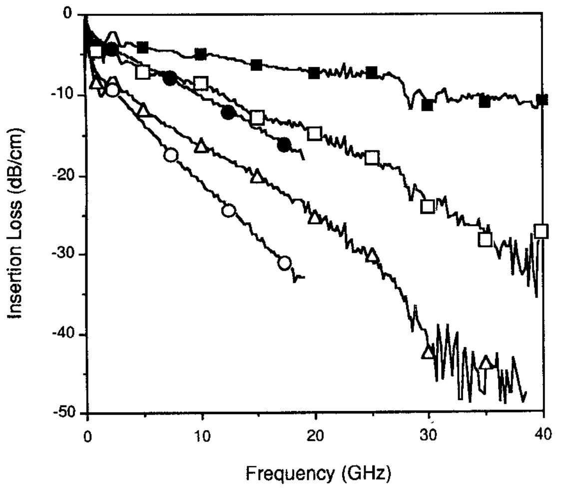

Fig. 2. Insertion loss of the CPW before and after ELO at 20 V dc reverse bias applied to the ground plane conductors. Filled dots ●: before ELO, no illumination; open dots ○: before ELO, illumination from the front; filled squares ■: after ELO, no illumination; open squares □: after ELO, illumination from the front; and open triangles △: after ELO, illumination from the back. Optical illumination intensity was 0.65 mW/cm^2.

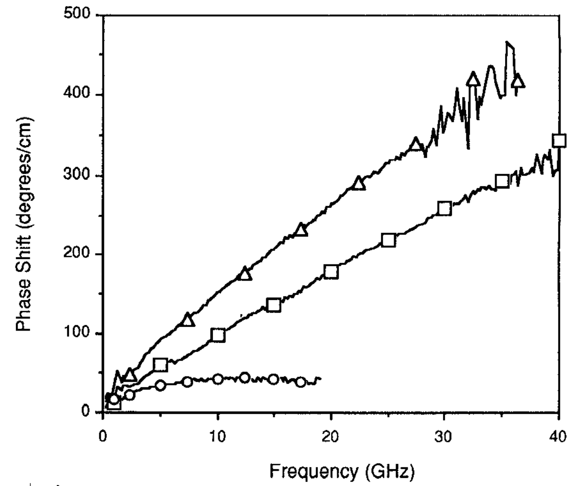

Fig. 3. Optically induced phase shift at 20 V reverse bias before and after ELO. Open dots ○: before ELO, illumination from the front; open squares □: after ELO, illumination from the front; and open triangles △: after ELO, illumination from the back. Optical illumination intensity was 0.65 mW/cm^2.

here, a dc reverse bias of 20 V applied to the ground plane conductors produced maximum sensitivity. The device was illuminated with a laser diode operating at 809 nm. Typical maximum intensity at the sample surface was 0.65 mW/cm^2. The phase and insertion loss were measured with an HP 8510B automatic network analyzer and wafer probes.

DC current-voltage measurements taken before and after ELO gave nearly identical results. However, under both unilluminated and illuminated conditions, the high-frequency characteristics after ELO showed a large decrease in insertion loss and increase in optically-induced phase shift, compared to that measured before ELO (Figs. 2 and 3). In general, the device performance before lift off was much worse than for a comparable n^- GaAs epitaxial layer grown directly on a SI substrate without the intervening AlAs layer. This is primarily due to a difference in band bending at the bottom surface of the GaAs epitaxial layer: before ELO band bending at the AlAs-GaAs interface accumulates this surface, while Fermi level pinning depletes it for either an epitaxial layer on SI GaAs or on quartz. After ELO, comparing frontside and backside illumination, backside illumination produced a larger insertion loss and phase shift for the same illumination intensity. These effects are mainly attributed to the lack of CPW electrode shadowing when the device is illuminated from the back, resulting in a larger absorbed optical power. In either illumination case, the performance of the device was dramatically improved after lift-off. For comparison, at 30 GHz and comparable illumination intensity, a CPW on an n^- epitaxial layer directly on a SI GaAs substrate gave a phase shift of 45° with an insertion loss of −15 dB when illuminated from the front [8]; the ELO CPW on quartz illuminated from the front gave a phase shift of about 250° with an insertion loss of −25 dB. Illuminated from the back, the phase shift increased to 350° with an associated insertion loss of −40 dB.

The most important figure of merit for this type of phase shifter is the loss per degree of phase shift. Fig. 4 shows this

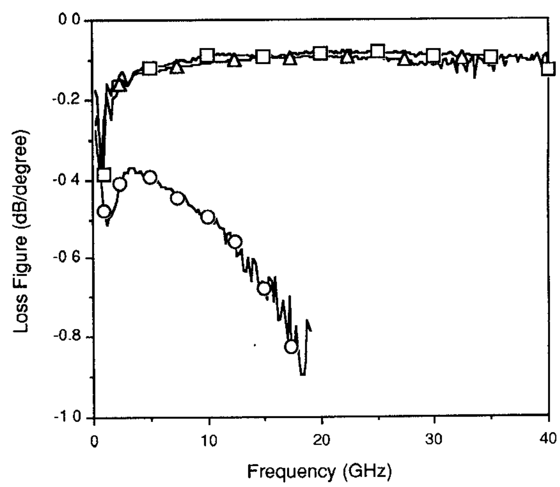

Fig. 4. Loss per degree phase shift (loss figure) at 20 V reverse bias before and after ELO. Open dots ○: before ELO, illumination from the front; open squares □: after ELO, illumination from the front; and open triangles △: after ELO, illumination from the back. Optical illumination intensity was 0.65 mW/cm^2.

loss figure for frontside illumination before ELO, and after ELO for both frontside and backside illumination. The larger phase shift from backside illumination (compared to frontside) is almost exactly compensated by the larger loss, producing nearly identical loss figures for both frontside and backside illumination. For frequencies between 5 and 40 GHz, the loss figure of −0.1 dB per degree of phase shift is, to our knowledge, the best performance reported to date for an optically controlled phase shifter. At 30 GHz, this is an improvement of about 50% over the best loss factor we have previously obtained from a CPW on a p^- epitaxial layer/SI GaAs substrate [1].

IV. Conclusion

A new optically controlled GaAs on quartz CPW phase shifter has been fabricated using the epitaxial lift-off technique. The device exhibits a significant improvement in performance after lift-off, and also performs better than structurally similar devices on n^- or p^- epitaxial layers directly on SI GaAs substrates. The use of a transparent quartz substrate allows frontside or backside illumination to be used. The device also exhibits extremely high optical sensitivity. At 30 GHz, a 1-cm long device illuminated from the back at an intensity of only 0.65 mW/cm^2 produced over 350° of phase shift. The use of optimized doping and epitaxial layer thickness for the ELO CPW should lead to an even greater improvement in phase shifter performance.

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