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Low-Loss Silicon Micromachined Waveguides Above 100 GHz Utilising Multiple H-plane Splits

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Abstract—For sub-millimeter and millimeter wave applications rectangular waveguides are an ideal transmission medium. Compared to conventional, metal-milled rectangular waveguides, silicon micromachined waveguides offer a number of advantages. In this paper we present a low-loss silicon micromachined waveguide technology based on a double H-plane split for the frequency bands of 110 – 170 GHz and 220 – 330 GHz. For the upper band a reduced height waveguide is presented, which achieves a loss per unit length of 0.02 – 0.10 dB/mm. This technology has been further adapted to implement a full height waveguide for the lower frequency band of 110 – 170 GHz. The full height waveguide takes advantage of the benefits of the double H-plane split technique to overcome the challenges of fabricating micromachined waveguides at lower frequencies. With measured insertion loss of 0.007 – 0.013 dB/mm, averaging 0.009 dB/mm over the whole band, this technology offers the lowest insertion loss of any D-band waveguide to date. The unloaded Q factor of the D-band waveguide technology is estimated to be in excess of 1600, while a value of 750 has been measured for the reduced height upper band waveguide.

Keywords—RF MEMS, micromachined waveguide, rectangular waveguide, submillimeter-wave

I. INTRODUCTION

Advances in semiconductor design and processing technology over the past decade have enabled the development of low-cost, commercial semiconductor technologies with operating frequencies above 100 GHz, such as silicon germanium BiCMOS [1]. Future commercialisation of these technologies is very attractive for applications such as wireless backhaul, automotive radar and medical/security imaging [2]. The high insertion loss of transmission lines realised in the back-end-of-line (BEOL) of advanced semiconductor processes places a major limitation on the design and implementation of such systems. A low-loss, high- Q transmission medium is required for the creation of passive components, which are a necessary part of any transceiver system. Microstrip lines integrated in an indium phosphide HBT BEOL, with BCB as the inter-layer medium, achieve an insertion loss of 0.88 dB/mm at 330 GHz [3]. Rectangular waveguides offer suitably low loss and are, as such, the transmission medium of choice in state-of-the-art millimeter wave transceiver systems. Insertion loss as low as 0.015 dB/mm has been reported for gold electroplated waveguides at 280 GHz [4]. However, these waveguides were based on metallic split-block technology, manufactured using precision CNC milling. Such components are prohibitively

expensive and bulky, while offering limited mechanical tolerances and feature sizes.

Micromachining (MEMS) offers the potential to create high-performance, low-cost waveguides for frequencies above 100 GHz. Due to the use of photolithography techniques, micromachined waveguides can incorporate complex geometries with small, accurate features. Existing MEMS fabrication infrastructure can be used to create such devices on a large-scale using batch processing, reducing the fabrication cost per unit. The integration of classical MEMS devices, such as comb drive actuators, with micromachined waveguides enables the creation of reconfigurable RF MEMS components which cannot be otherwise realised [5]. These features are crucial for the foreseen large-scale commercialisation of transceiver systems above 100 GHz. This development cannot be supported by existing waveguide fabrication methods. For the frequency band of 500 – 750 GHz H-plane split micromachined silicon waveguides have been implemented, with losses as low as 0.06 – 0.12 dB/mm [6] and 0.10 – 0.20 dB/mm [7]. Waveguides for the frequency band of 220 – 330 GHz with losses of 0.03 – 0.05 dB/mm [8] using SU-8 micromachining have been reported.

In [9], a silicon micromachined waveguide technology based on a double H-plane split was reported. The double H-plane split is realised using a metalized triple-wafer stack, wherein the waveguide is formed in the handle layer of a silicon-on-insulator (SOI) wafer. This technology achieved the lowest insertion loss reported to date for any silicon micromachined waveguide at 220 – 330 GHz. By making use of integrated waveguide loads [10], this same technology has previously been used to implement state-of-the-art low-loss passive waveguide devices between 220 – 330 GHz, including a 4-port coupler [11], a power splitter [12] and high- Q cavity resonators for material characterisation [13].

Here, this double H-plane split waveguide technology is further developed to create waveguides for the frequency bands of 110 – 170 GHz and 220 – 330 GHz. The reduced height waveguide [9] for the frequency band of 220 – 330 GHz was modified to fabricate a full height waveguide for the frequency band of 110 – 170 GHz (D-band) utilising two SOI wafers. This technique takes advantage of the reduced surface roughness of the double H-plane split to realise very low-loss micromachined waveguides at frequencies above 100 GHz. The waveguide technology outlined in this paper enables the creation of waveguides with state-of-the-art insertion

Fig. 1. Micromachined waveguide surface roughness: (a) E-plane split, waveguide halves DRIE along the waveguide width and subsequently joined together [6], [14]; (b) single H-plane split DRIE along the waveguide height [6], [7], [15]; and double H-plane split DRIE along the waveguide height for (c) a full height waveguide for 110 – 170 GHz, consisting of two waveguide halves bonded together, and (d) a reduced height waveguide for 220 – 330 GHz [9].

loss across both frequency bands. In particular, the D-band micromachined waveguide presented here has the lowest insertion loss between 110 – 170 GHz of any waveguide reported to date, regardless of technology.

II. WAVEGUIDE DESIGN AND FABRICATION

The primary method of fabricating silicon micromachined waveguides is to utilise deep reactive-ion-etching (DRIE) to create trenches in a silicon wafer which form the body of the waveguide. These trenches are subsequently metallised and the silicon wafer is then bonded to a separate metallised chip to complete the waveguide. As with split-block techniques, micromachining can be used to create waveguides split along

either their E- or H-plane. Whereas an E-plane split is preferred in split-block waveguides, sufficiently low surface roughness and high-quality metal-metal bonds can be achieved with micromachining techniques to enable the use of H-plane split designs. The reduced sensitivity of H-plane split waveguides to misalignment simplifies final assembly of the waveguide, while providing other benefits related to the use of DRIE in the fabrication process.

In an E-plane split micromachined waveguide, where the split is along the centre of the waveguide, all four waveguide walls have high surface roughness resulting from the DRIE process (Fig. 1a). This surface roughness directly increases the insertion loss of the waveguide [16]. A single H-plane split along the top of the waveguide results in high surface roughness on three of the four walls, as the cap wafer which acts as the roof of the waveguide need not be etched (Fig. 1b). By contrast, in a double H-plane split design, both the top and bottom surfaces of the waveguide are not etched and as such have surface roughnesses of the order of a few nanometers (Fig. 1c-d). Only two of the four waveguide walls then contribute to its insertion loss, drastically reducing the loss of the waveguide in comparison to either E- or single H-plane split techniques [9].

Numerous challenges arise when attempting to fabricate silicon micromachined waveguides at frequencies below 200 GHz. Due to the increased width of the waveguide at lower frequencies, a significantly wider trench must be etched. This increase in etch area leads to a series of issues, including sloped sidewalls and aspect ratio dependent etching effects [17]. The necessary increase in etch depth to form a full height waveguide at lower frequencies requires significantly thicker silicon wafers (for example, over 800 μm at D-band), which may become practically infeasible. Increasing the etch depth also causes a degradation of the sidewall roughness, worsening the waveguide's RF performance.

To overcome these issues, we propose to apply the SOI based triple wafer stack of [9] to create a full-height D-band waveguide that is split along its centre. This is achieved by utilising two separate SOI wafers, and etching one half of the waveguide into the handle layer of each wafer (Fig. 1c), before subsequent metallisation, assembly and bonding of the two halves. The waveguide is composed as follows (Fig. 2e):

- (1) the device layer of SOI 1 acting as the waveguide bottom;
- (2) the handle layers of SOI 1 and 2 forming the hollow waveguide; and
- (3) the device layer of SOI 2 as the waveguide top.

This approach ensures that both the top and bottom surface of the waveguide have surface roughness of a few nanometers, while the need to etch to only 50% of the waveguide height in each SOI handle layer reduces the roughness of each of the sidewalls.

The fabrication process for the waveguides in both frequency bands is outlined in Fig. 2. SOI wafers with different specifications are used for the alternate bands: for 110 – 170 GHz, a 30 μm device layer, 2 μm buried oxide layer

Fig. 2. Fabrication process: (a) bare SOI wafer with (1) device, (2) handle and (blue) buried oxide layer; (b) waveguide structure after DRIE silicon etch and subsequent removal of the buried oxide layer; and (c) metallization (red) using gold sputtering and (d) final waveguide after thermo-compression bonding with a flat metallized chip (4) for a reduced height waveguide for the frequency band of 220 – 330 GHz. Fig. (e) shows the cross section of a full height waveguide for the frequency band of 110 – 170 GHz, where two waveguide halves from (c) are joint together by thermocompression bonding (with (3) device layer of SOI wafer 2).

Fig. 3. SEM cross-sectional view of an etched waveguide for the frequency band of 220 – 330 GHz after metallization and before thermocompression bonding [9] (refer to Fig. 2c).

(BOX) and 400 μm handle layer, resulting in a waveguide height of 800 μm ; for 220 – 330 GHz, a 30 μm device layer, 2 μm BOX and a 275 μm handle layer. Both waveguides have the standard width for their given frequency band; 1651 μm and 864 μm , respectively. A three-step Bosch process is first used to etch the handle layer of each SOI, where the BOX layer acts as an etch stop. The BOX is then removed by plasma etching. Sputter deposition is used to apply 1 μm of gold to all waveguide walls, before the complete waveguide is assembled and thermocompression bonding at 200 $^{\circ}\text{C}$ joins the parts together. Fig. 3 shows scanning electron microscope (SEM) image of the cross section of a waveguide for the frequency band of 220 – 330 GHz after metallization and before thermocompression bonding.

III. RF-CHARACTERISATION

To characterise the performance of the waveguides, two sets of frequency extenders (Rohde & Schwarz ZVA-Z170, ZC330) were used, fed by a Rohde & Schwarz ZVA-24 VNA. In each case, micromachined on-chip TRL calibration kits were used to shift the reference plane inside the micromachined waveguide. Straight waveguide lines, of length 24 mm and

11.5 mm, respectively, were then measured to determine the attenuation constant (α) of the waveguide technology.

Between 110 – 170 GHz, the insertion loss per unit length of the double-SOI H-plane split waveguide technology is 0.007 – 0.013 dB/mm, averaging 0.009 dB/mm (Fig. 4). The theoretical insertion loss per unit length for the same waveguide with an ideal gold conductivity of $\sigma = 4.1 \times 10^7 \text{ S/m}$ is plotted as a reference. Given this measured insertion loss, the unloaded Q factor of the full-height waveguide is estimated to be greater than 1600. Despite its reduced height, the insertion loss per unit length of the single-SOI H-plane split technology, for the frequency band of 220 – 330 GHz, is between 0.02 – 0.10 dB/mm (Fig. 5). Previous measurement results indicate that the unloaded Q of this reduced-height waveguide is around 750 [13].

As outlined in [9], the low loss of this waveguide technology can be directly attributed to its design, which results in greatly reduced surface roughness on all four surfaces of the waveguide. The low-loss performance of this waveguide technology is also achieved without the use of any surface roughness reduction process steps during fabrication, as used elsewhere [14]. Such methods introduce additional complexity and require the use of costly thermal-oxidation tools.

IV. CONCLUSION

This paper reports on a new micromachined waveguide technology utilizing multiple H-plane splits. The technology has been used to fabricate rectangular waveguides for the frequency band of 110 – 170 GHz and 220 – 330 GHz. For both bands, the fabricated waveguides experience the lowest insertion loss of any state-of-the-art micromachined waveguide.

A triple wafer stack based on SOI technology has been used to implement a full height waveguide in the lower band, and a reduced height waveguide in the upper band. The reduction in surface roughness on all waveguide walls leads to a waveguide insertion loss per unit length of 0.007 – 0.013 dB/mm over the frequency band of 110 – 170 GHz, which sets the state-of-the-art for silicon micromachined waveguides at D-band. The insertion loss of a reduced height waveguide at 220 – 330 GHz is 0.02 – 0.10 dB/mm, confirming the excellent performance of the technology across a wide band of frequencies.

Fig. 4. Insertion loss per unit length of a waveguide line with length $l = 24$ mm for the frequency band of 110 – 170 GHz and the theoretical loss for an ideal gold conductivity of $\sigma = 4.1 \times 10^7$ S/m as reference.

Fig. 5. Insertion loss per unit length of a waveguide line with length $l = 11.5$ mm for the frequency band of 220 – 330 GHz and the theoretical loss for an ideal gold conductivity of $\sigma = 4.1 \times 10^7$ S/m as reference.

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