Bulk-Titanium Waveguide – a New Building Block for Microwave Planar Circuits

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ABSTRACT

We developed a new building block for constructing planar microwave circuitry: bulk titanium waveguide. The waveguide is formed by deep trench etching, dielectric gap filling, and planarization. The high aspect ratio of the resulting structure provides superior field confinement, low crosstalk, therefore a small footprint. To enable bulk titanium as a substrate compatible with microfabrication, we developed a suite of techniques that overcome unique manufacturing issues associated with titanium. The propagation loss of the waveguides was measured to be ~0.68dB/mm at 40GHz.

Keywords: titanium, MEMS, waveguide, RFMEMS

1 INTRODUCTION

The majority of microwave planar circuits are based on transmission lines of two basic topologies: Microstrip [1-2] and Coplanar Waveguide (CPW) [3-4]. Microstrip offers low loss, while suffering from large circuit size, high dispersion, poor design flexibility, and the necessity of large via holes. CPW improves upon microstrip by bringing the ground to the same level as the signal, therefore providing low dispersion, smaller circuit size, high design flexibility and no via holes. However, the fields in CPW concentrate on the thin edges and are therefore less confined. This translates into higher conductor loss, cross-talk and poor power handling capability.

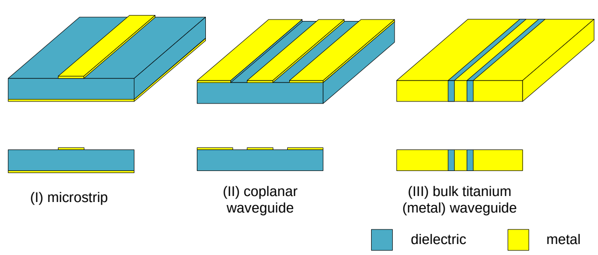

Figure 1. Bulk titanium waveguide compared to conventional planar circuits

We present a new topology for planar microwave transmission line: bulk titanium waveguide. As shown in Figure 1, the waveguide is formed by coplanar titanium regions separated by low-loss dielectric that is planarized to the same level as the titanium. Due to the high aspect ratio of the dielectric cross section, the electric field is confined primarily within the dielectric, therefore reducing losses due to radiation and parasitic coupling. This geometry distributes the surface current across the entire height of the structure, reducing conductor losses while enhancing power handling capabilities. The high aspect ratio in-plane electrical isolation also serves as through-wafer interconnects with a high packing density. When integrated with a bulk titanium package, this waveguide provides a robust, compact, packaging solution for microwave subsystems as well as other microcomponents such as MEMS. We have successfully designed, fabricated and characterized packaged waveguides which measured, at 40GHz, ~0.68dB/mm insertion loss and the impact due to package < 0.1dB. Additionally, we developed a quasi-static model based on conformal mapping that accurately describes the characteristics of the waveguide.

Titanium [5-7] has one of the highest strength to weight ratio among metals. It is also one of the few materials with an endurance limit, a desirable property as a robust packaging material. It is naturally resistant to corrosive environments and is widely used as implants due to its bio-compatibility. The discovery of anisotropic plasma etching of bulk titanium [8-9] has opened new doors to numerous MEMS applications [10-12]. However, the current manufacturing processes for titanium sheets are not tailored for microfabrication. We developed a suite of technologies that overcome issues such as residual stress, thickness variation, embedded defects and surface roughness. With a typical 1"x1" starting substrate with roughness ~100 nm, a thickness variation of ~10 μm, and a bow of >~50μm, our processes achieved a thickness variation of <2μm, a bow of ~7μm, an average roughness as low as 2.8 nm, and μm-scale features with >200μm etching depths.

2 ANALYTICAL MODEL

While numerical simulation typically gives more accurate answers, analytical models provide more physical intuition and conceptual understanding.

The field distribution in the bulk titanium waveguide is illustrated in Figure 2. The waveguide height is h; center conductor width w; gap width s. Device packaging is completed by attaching a metal cavity of height h_p. The electromagnetic signal is confined primarily within the high aspect ratio gaps filled with low loss dielectric material with dielectric constant ε_d.

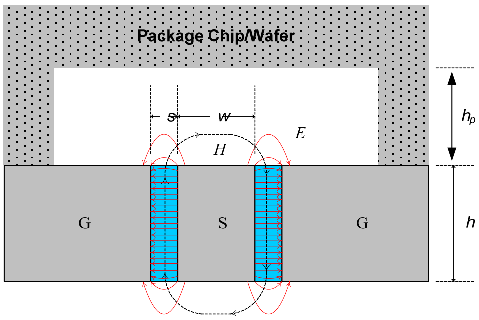

Figure 2. Cross section of packaged bulk titanium waveguide.

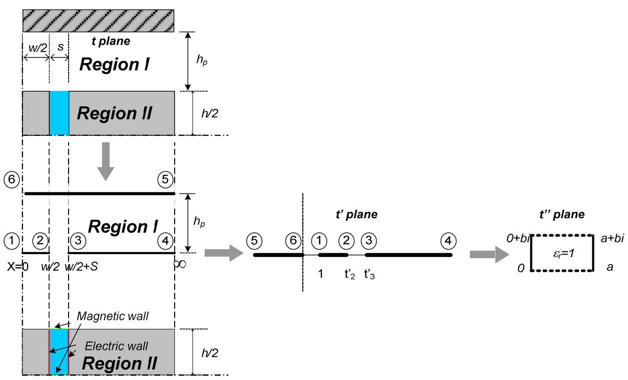

Figure 3. Conformal maps for quasi-static analysis

While parallel plate assumption offers a qualitative description, much more accurate modeling can be obtained by using conformal mapping.

Using a series of Schwartz-Christoffel transformations [13], the different regions of the device are transformed into mathematically solvable geometries. The reverse transformation gives the approximate solution.

At microwave frequencies and for the case in which the loss is primarily due to the conductors, the propagation loss can be simplified:

$$\alpha \approx \frac{\mu_0\mu_d \tan\delta_d \omega\varepsilon_d\varepsilon_0 + \frac{2}{h}\sqrt{\frac{\omega\mu_c\mu_0}{2\sigma_c}}\varepsilon_0\left[\frac{2K(k)}{K'(k)} + \frac{K(k_1)}{K'(k_1)} + \frac{\varepsilon_d h}{s}\right]}{2\sqrt{\frac{\mu_0\mu_d\varepsilon_0 s}{h}\left[\frac{2K(k)}{K'(k)} + \frac{K(k_1)}{K'(k_1)} + \frac{\varepsilon_d h}{s}\right]}} \quad (1)$$

where: $k_1 = \tanh(\pi w / 2h_p) / \tanh[\pi(w+2s)/2h_p]$, $k=w/(w+2s)$, and $K(k)$ is the complete elliptic integral of the first type, $K'(k) \equiv K(k' = \sqrt{1-k^2})$.

In case loss is primarily due to the finite conductivity of the conductors, the additional loss due to the presence of the metal package can be approximated by:

$$\Delta\alpha_{pac} \approx \sqrt{\frac{\omega\mu_c\varepsilon_0}{2\mu_d\sigma_c hs}}\left(\sqrt{\frac{2K(k)}{K'(k)} + \frac{K(k_1)}{K'(k_1)} + \frac{\varepsilon_d h}{s}} - \sqrt{\frac{2K(k)}{K'(k)} + \frac{\varepsilon_d h}{s}}\right) \quad (2)$$

The advantage of the high aspect ratio waveguide is demonstrated in the reduced coupling between waveguide and a metal package reflected in the small change in propagation loss: the change in loss, $\Delta\alpha$~0.04dB at 40 GHz using Equation (2).

3 EXPERIMENT

3.1 Titanium planarization

Although titanium has a long history of industrial, medical and military applications [5-7], it had not been used as a MEMS substrate until recently. Titanium sheets as obtained, especially thinner (<200 μm) and smaller (non-wafer scale) samples, may suffer from planarity issues, such as rolling hills, due to the manufacturing processes. The sample surface may contain defects which result in etching difficulties. Samples undergo plastic deformation around the edges during cutting and improper handling. We develop a suite of processes which correct these problems, thus enabling the use of bulk titanium as a MEMS material.

At elevated temperatures, titanium can be annealed to release the stress [7]. We used a stress-anneal straightening process to correct the global deformations in thinner samples.

Figure 4. Lapping and polishing development

We developed a lapping and polishing process for removing the defects embedded near the titanium surface. Shown in Figure 4 is the Engis Hyprez polisher we used and the associated tools for mounting samples.

3.2 Waveguide fabrication

The process starts with a 200μm titanium substrate. As shown in Figure 4, first, deep trenches are etched into the substrate using a CL_2/Ar chemistry in an ICP etcher [9,12]. High density PECVD SiO_2 etch mask is used to ensure uniformity. Once etching is finished and the remaining mask oxide removed, a ~ 1μm Au layer is sputtered. This layer covers the sidewall of the trenches and enhances the waveguide conductivity. The trenches are then filled with BenzoCycloButene (BCB) and cured. The polymer fills the trenches and forms the waveguide dielectric. The first lapping and polishing process is done to remove the excess BCB and expose the trenches. Next, Au bonding pads are deposited and patterned to ready to receive the packaging chip.

Similar to the device chip, the fabrication of the packaging chip is also done by deep etching and Au sputtering. Once both chips are ready, they are bonded together by using Au thermal compression bond at 300°C for 30 minutes. The bonding creates a sealed metal cavity that can be used for future device packaging as well as providing additional shielding against undesirable electromagnetic waves. Last, the chip/wafer assembly is polished to remove excess substrate titanium and the waveguide structure is completed.

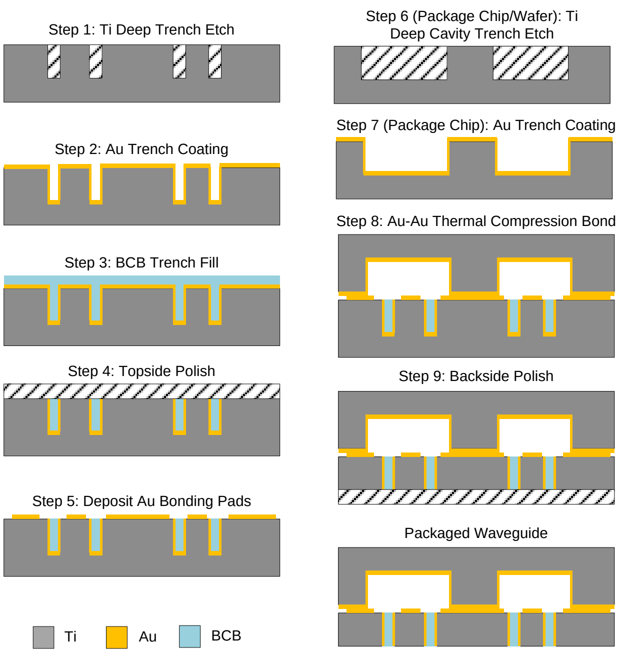

Figure 4. Process sequence for bulk titanium waveguide

Figure 5a shows the structure after trench etching and conformal Au sidewall coating; Figure 5b demonstrates the completed device. The regions isolated by the BCB-filled trenches produced charging in the SEM.

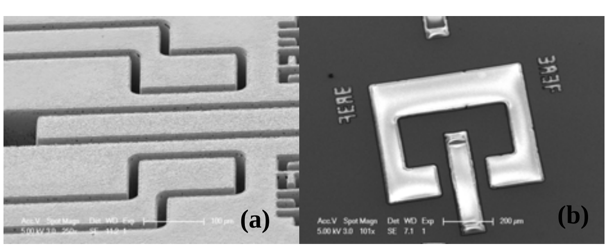

Figure 5. a) waveguide structure after sputtered Au sidewall enhancement; b) completed waveguide

A close-up view is shown in Figure 6. BCB demonstrates good structural integrity after the final planarization step.

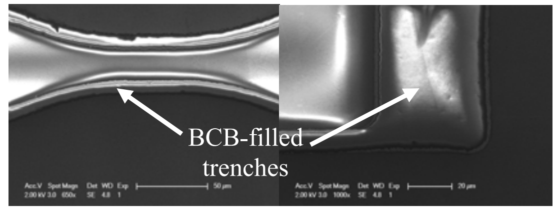

Figure 6. Close-up view of BCB-filled isolation trenches

3.3 Measurement setup

For improved accuracy, a set of TRL calibration devices are fabricated on the same chip. Line lengths ranging from 100µm to 2mm are used to calibrate the entire measurement range of 18GHz to 40GHz, as well as to characterize the propagation loss.

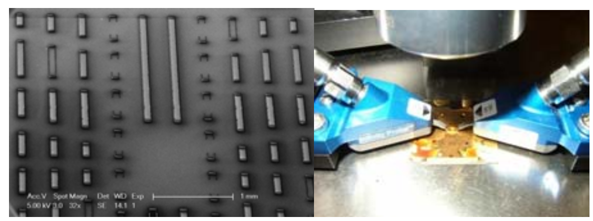

Figure 7. Microwave measurement setup. Left: on-chip TRL calibration devices; Right: packaged device under test

4 RESULTS AND DISCUSSION

4.1 Titanium planarization

Although with a Young's modulus of 108.5 GPa [7], the metallic nature of the titanium makes thinner (<200µm) samples subject to plastic deformation due to cutting and improper handling. Residual stress may also exist resulting from the manufacturing process. The stress-anneal straightening process proves effective in removing such deformations. The average gross deformation of 5 samples, measured by optical interferometry, is reduced from ~52.8µm to ~6.9µm.

Other issues with large impact to subsequent fabrication steps and RF performance include thickness variation and surface defects. The thickness variation of the 200µm thick samples is measured to be ~9.51µm and reduced to ~1.58µm after planarization. Roughness, an important indicator of the surface, is reduced from ~50-100nm to as low as ~2.8nm.

4.2 Loss characterization

The propagation loss of the bulk titanum waveguide is measured and compared to theory in Figure 8. Waveguide lengths range from 100µm to 600µm long with 100µm increments. At 40 GHz, the loss for the 600µm long waveguide is measured to be ~22.3% higher than theory. This can be attributed to the process imperfection, measurement error and the approximations used in the derivation.

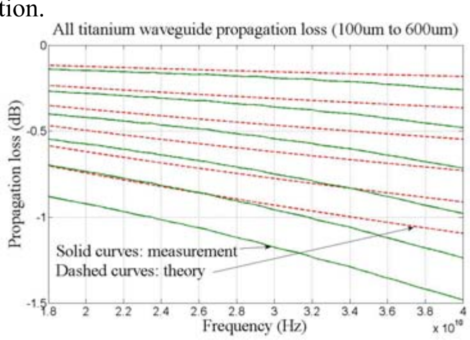

Figure 8. Propagation loss of bulk titanium waveguides. From top to bottom: 100µm to 600µm with 100µm increments. Solid: theory; Dashed: measurement

The loss is significantly reduced by Au coating on the sidewall. As shown in Figure 9, the loss at 40GHz is limited to ~0.68dB/mm. Ripples in the curves may be due to uneven Au thickness on the sidewall.

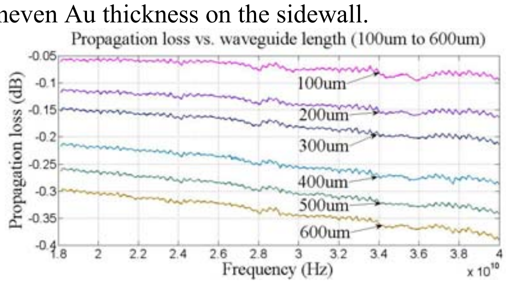

Figure 9. Propagation loss at 40GHz. From top to bottom: 100µm to 600µm with 100µm increments

The additional loss at 40GHz due to packaging is measured to be ~0.06dB, consistent with model prediction.

5 CONCLUSION AND FUTURE WORK

Bulk titanium waveguide has distinct advantages over traditional topologies of microwave planar circuits. The superior field confinement helps reducing undesirable coupling, as demonstrated in the low measured impact due to packaging. Overall circuit area can be condensed due to reduced parasitic coupling. The integrated, high-density, through-wafer interconnects further reduce circuit size while improving performance due to shorter signal paths. For packaging applications, this translates into a compact, titanium packaging well suited for corrosive environments such as sea water. In addition, the bio-compatibility of titanium lends itself to potential implantable biomedical applications.

We have successfully demonstrated the low-loss and low parasitic coupling of bulk titanium waveguide. In order to further explore the opportunities of potential applications based on the bulk titanium RF platform, it is necessary to investigate the fundamental properties of the waveguide in implementations beyond its original ideal waveguide form. The most notable implementation in this case involves discontinuities. Fully understanding these discontinuities is essential for device applications beyond waveguides.

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