SILICON MICROMACHINED WAVEGUIDES FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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Abstract -- The majority of radio receivers, transmitters, and components operating at millimeter and submillimeter wavelengths utilize rectangular waveguides in some form. However, conventional machining techniques for waveguides operating above a few hundred GHz are complicated and costly. This paper reports on the development of silicon micromachining techniques to create silicon-based waveguide circuits which can operate at millimeter and submillimeter wavelengths. As a first step, rectangular WR-10 waveguide structures have been fabricated from (110) silicon wafers using micromachining techniques. The waveguide is split along the broad wall. Each half is formed by first etching a channel completely through a wafer. Potassium hydroxide is used to etch smooth mirror-like vertical walls and LPCVD silicon nitride is used as a masking layer. This wafer is then bonded to another flat wafer using a polyimide bonding technique and diced into the U-shaped half waveguides. Finally a gold layer is applied to the waveguide walls. Insertion loss measurements show losses comparable to those of standard metal waveguides. It is suggested that active devices and planar circuits can be integrated with the waveguides, solving the traditional mounting problems. Potential applications in Terahertz instrumentation technology are further discussed.

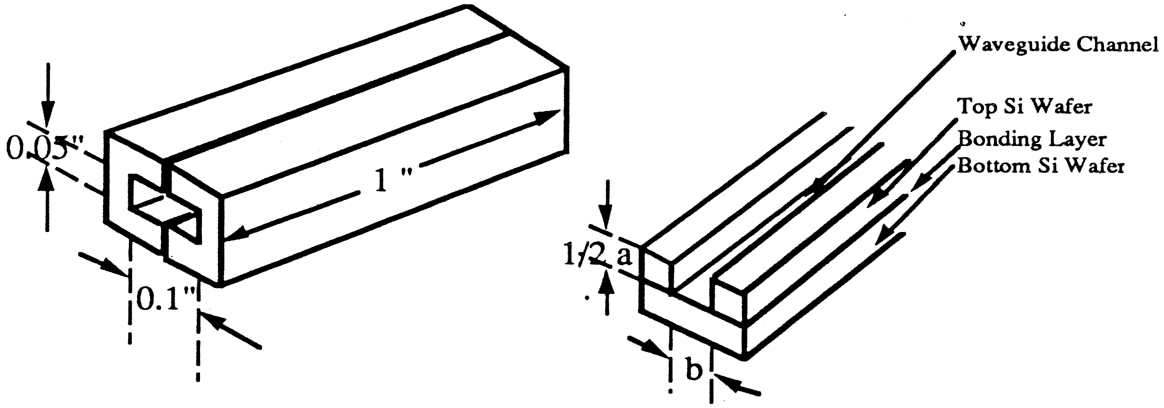
I. Introduction

Rectangular waveguide is a well characterized transmission medium which is used in a variety of complex rf components and circuits. Many sophisticated applications including radar, communications systems, test instruments, and heterodyne radiometers use waveguide components up to millimeter wave frequencies. The long history of development of waveguide components provides a broad base of knowledge to synthesize and evaluate new designs for higher frequencies.

Waveguide is typically fabricated from metals such as brass and copper using conventional machining techniques. However, at frequencies above a few hundred GHz, waveguide becomes so small (less than 0.3 mm x 0.15 mm for 500 GHz - 1000 GHz waveguide) that fabrication utilizing these conventional techniques is time consuming, costly and difficult. In addition, mounting active and passive devices such as mixer diodes, filters and planar probes on these waveguides is difficult.

A substantial research effort in recent years has been devoted to fabricating micromechanical structures in silicon using micromachining techniques. Moveable structures such as slider, gears, and spiral springs in the dimensional scale of 50-200 μm have been fabricated [1, 2]. We have taken a new approach in developing and adapting silicon micromachining techniques to create silicon-based waveguide circuits which can operate up to millimeter and submillimeter wavelengths.

As a first step we have started fabricating rectangular waveguides for frequencies between 100 GHz and 1000 GHz. Here we only emphasize WR-10 waveguides (operating at 75 GHz - 115 GHz) because it is compatible with our existing measurement equipment. Conventional WR-10 waveguide is a rectangular channel with inner wall dimensions of 0.1 x 0.05 inches. Our waveguide, however, is made of two half sections split along the broadwall as shown in Fig. 1. The reason for splitting the waveguide is to simplify the fabrication process and to facilitate integration of planar circuits and devices, which is further discussed in Section IV.



(a) (b)

Fig. 1. a) The waveguide is split into 2 half sections.
b) One half section of a waveguide.

II. Fabrication Process

The fabrication process for the half sections with emphasis on the cross section is shown in Fig. 2. A thick (0.05 inches) double-side polished silicon wafer with (110) surface orientation is used. The major flat has a normal in the [111] direction within 0.4°. After a standard piranha-bath cleaning, a 1000 Å Low Pressure Chemical Vapor Deposited (LPCVD) silicon nitride layer is deposited on both sides of the wafer. Photolithographic techniques are then utilized to pattern the waveguide etching windows. Photoresist is used as a masking layer for etching the silicon nitride windows with an SF_6 plasma. The silicon nitride is used as an etching mask to define b, the waveguide height, shown in Fig. 1b. After removal of the photoresist using acetone solvent as shown in Fig. 2a, the wafer is put in a reflux system and etched in a water based solution of 40 % KOH at 80 °C. Figure 2b shows the wafer after it has been etched completely through to form half of the waveguide. The etching rate of (110) silicon in this KOH solution is 2 μm/min and the etching ratio of (110):(111) planes is 170:1. At this rate 0.05 inches (1270 μm) of silicon is etched thru in ~11 hours. Following removal of the nitride mask using hot hydrophosporic acid at 150 °C, a polyimide bonding technique is used to glue these etched grooves to a smooth silicon wafer with an identical thickness (0.05 inches) as shown in Fig. 2c. The wafer is then diced into pieces of half waveguides. Such a half waveguide is shown in Fig. 2d. Metalization is done by first depositing a thin (200 Å) chrome layer followed by a thicker (5000 Å) gold layer on the waveguide walls using vacuum evaporation. Further metalization is done by electroplating gold to a thickness of ~3 μm to reduce rf conduction losses.

III. Experimental Results

In order to perform insertion loss measurement, we designed a pair of brass mounting blocks. The two waveguide half-sections are put on the brass mounting blocks and mated together. This allows the silicon waveguide to be connected to microwave test equipment using conventional waveguide flanges. The silicon waveguides are rugged and can be firmly clamped to metallic flanges. The insertion loss of the WR-10 waveguide is measured over a frequency range of 75 GHz to 110 GHz. The measurement system is shown in Fig. 3. The source is a BWO which produces several milliwatts. A reference sweep is first taken without the waveguide. This is compared to a sweep with the waveguide inserted between the source and detector. The insertion loss for a 2.5 cm long section of waveguide is shown in Fig. 4 (the small wiggles in these curves are noise and do not reflect any resonances in the waveguide components). The measured loss is about 0.05 dB per wavelength (at 100 GHz) across most of the band. This is very good performance and is comparable to the result for commercially available waveguide which shows a loss of about 0.024 dB per wavelength. The small difference of 0.026 dB per wavelength is most probably due to differences in the quality of the gold plated surfaces. Our evaporated gold showed small pits which were still present in the plated layer. Also there was no gold on the ends of the silicon waveguide where contact was made to the metallic flanges of the test equipment. We expect improvements in the gold surface to be directly reflected in improvements in the rf losses.

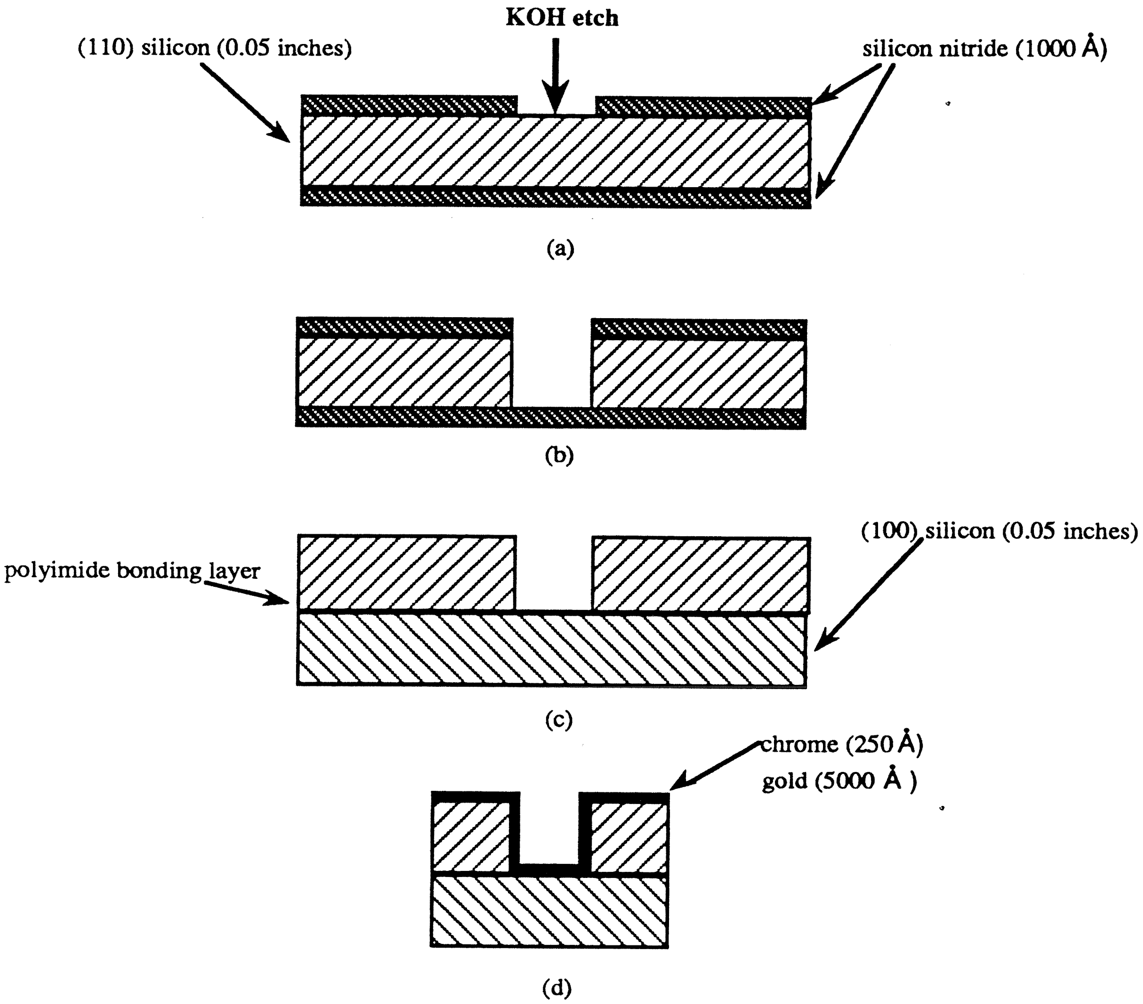


Fig. 2. A cross section view of the fabrication process.

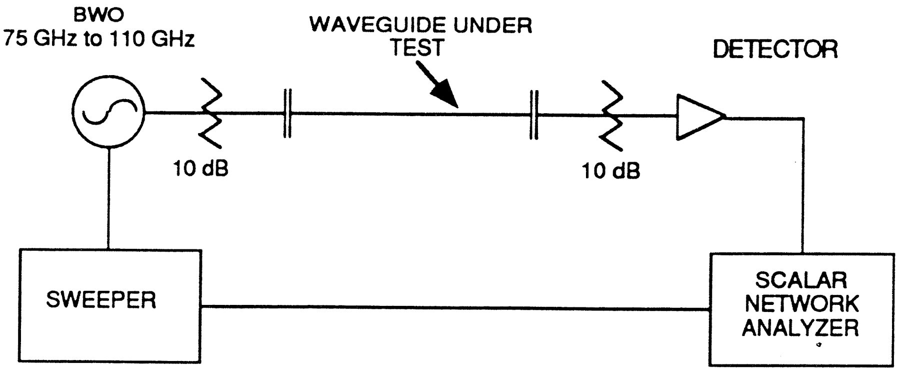


Fig. 3. Block diagram of millimeter wave insertion loss test system.

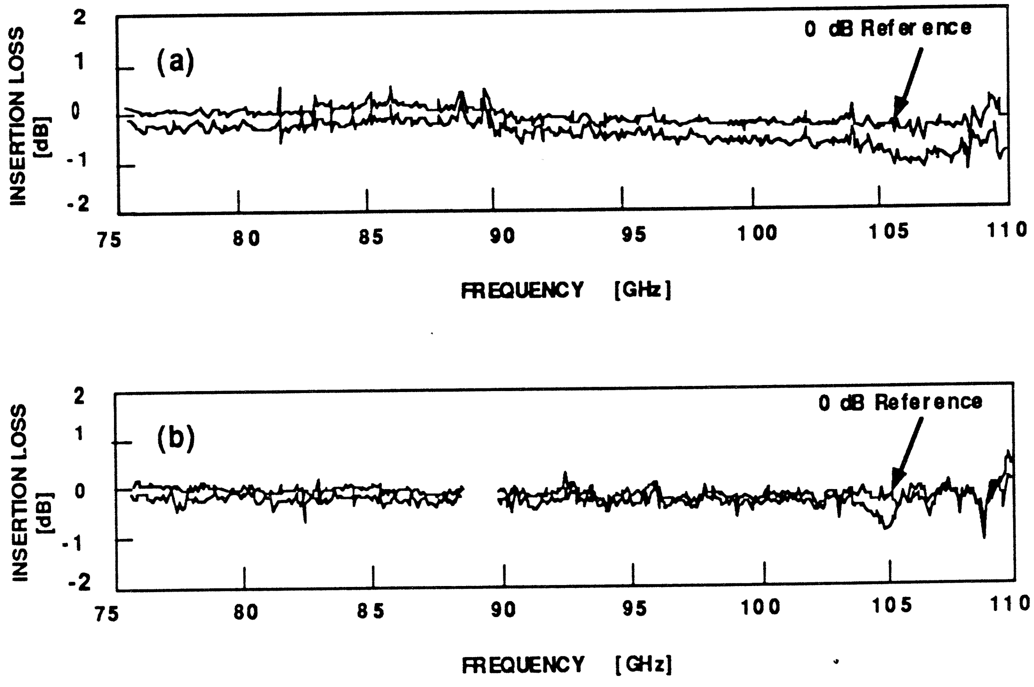


Fig. 4. (a) Measured loss of a 2.5 cm long section of Si-based WR-10 waveguide. The surface of the silicon was metallized with approximately 3 μm of gold to reduce rf losses. (b) Measured loss of a 2.5 cm long section of conventional metallic waveguide.

IV. Discussion

Waveguide circuits are preferable at frequencies above 100 GHz since waveguide has the advantage of adjustable rf tuning. This solves the difficulties of accurately designing fixed-tuned planar microwave integrated circuits. Unfortunately, millimeter and submillimeter waveguide components are hard to manufacture by conventional machining techniques. We have shown here the feasibility of making silicon waveguides. It is also possible to use silicon micromachining techniques to fabricate other components such as: directional couplers, waveguide transformers, waveguide-to-planar circuit transitions, low-loss filters, rectangular and conical feedhorns, and dichroic plates. This wide variety of waveguide components will become the building blocks for complicated circuits. For example, complex mixer and frequency multiplier embedding circuits can be built. These are important for ground-based and space-based radar, communications, and remote-sensing applications.

Silicon micromachined waveguide components have several important advantages: 1) These structures are produced by projecting the desired pattern onto silicon with photolithographic techniques. Therefore waveguides with dimensions suitable for use above 100 GHz can be easily fabricated. 2) Dimensional accuracy is in the order of a few microns, which is essential for the fabrication of high-Q components. 3) The waveguide walls would be atomically smooth, thereby minimizing rf losses [3]. 4) Several versions of a single component (with variations of a critical parameter) can be produced at the same time on a single wafer. This would allow for rapid optimization and reduced cost compared to conventional machining techniques where only one variation at a time is produced. 5) Most importantly, active and passive devices can be integrated with the waveguide. For example, a thin (~ 1μm) rf transparent silicon nitride membrane can be fabricated across the end of the waveguide or parallel to its length in the E-field direction. Active devices such as Schottky diodes and SIS tunnel junctions as well as micromechanical rf tuning elements[1, 4] can then be fabricated directly on the membrane as shown schematically in Fig. 5. This would eliminate the long-standing problem of mounting the devices and would represent a significant advance for waveguide technology.

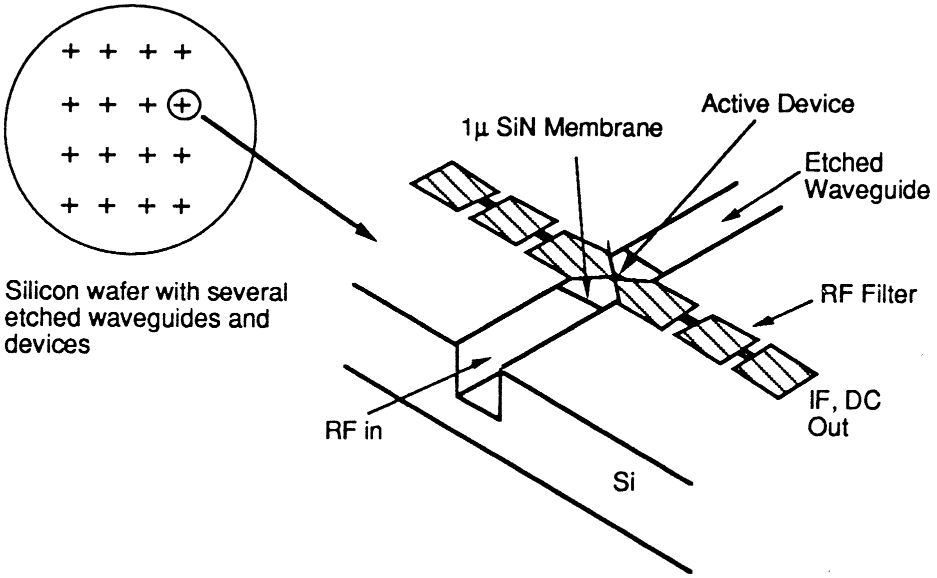


Fig.5 A schematic view of an integrated waveguide circuit. Several waveguide components can be produced on a single wafer. Active devices and planar circuits can be integrated directly on thin membranes spanning the waveguide. Micromechanical rf tuning elements can also be included in the waveguide.

Currently, we are fabricating WR-10 waveguides with SiN membranes in between the two half pieces of the waveguide. Metalization of the half sections of these waveguides will require selective plating of the silicon walls without plating the silicon nitride membranes. Tungsten substitution of silicon in an LPCVD environment [5] is proposed to meet this need. In this process, tungsten hexafluoride (WF_6) gas attacks silicon surface and a thin layer of tungsten atoms substitute for silicon atoms on the surface. Further metalization can be done by electroplating the tungsten surface with gold.

V . Summary

We have demonstrated a new approach in fabricating waveguide circuits using silicon micromachining technology. In particular, we have fabricated a 100 GHz silicon rectangular waveguide. The insertion loss of 0.05 dB/λ is comparable to a commercially available metal waveguide. As we improve our plated gold quality, we expect to improve the insertion loss. We have also proposed a new approach of integrating active/passive devices and micromechanical rf tuning elements with waveguide.

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