Silicon Micromachined Waveguides for Millimeter-Wave and Submillimeter-Wave Frequencies

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***Abstract*—Rectangular waveguide is commonly used up to high millimeter-wave frequencies. However, conventional machining techniques for waveguides operating above a few hundred GHz are complicated and costly. The development of silicon micromachining techniques to create silicon-based waveguide circuits, which can operate up to high submillimeter-wave frequencies, is reported. As a first step, WR-10 waveguide has been fabricated from (110) silicon wafers. Insertion loss measurements of gold plated silicon waveguide show performance comparable to standard metal waveguides. It is suggested that active devices and planar circuits can be integrated with the waveguides, solving the traditional mounting problems.**

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, communication systems, test instruments, and heterodyne radiometers use waveguide components up to millimeter wave 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 × 0.15 mm for 500–1000-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 in these waveguides is difficult.

A substantial research effort in recent years has been devoted to fabricating micromechanical structures in silicon using micromachining techniques. Movable structures such as sliders, gears, and spiral springs with dimensions 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-wave frequencies.

As a first step, we have begun fabricating rectangular waveguides for frequencies between 100 GHz and 1000 GHz. RF measurements are reported here for WR-10 waveguide (operating at 75–115 GHz) because it is compatible with our existing measurement equipment. Conventional WR-10 waveguide is a rectangular channel with dimensions of 0.10 × 0.05 inches. Our waveguide, however, is made of two half sections split along the broadwall. Fig. 1(d) shows an end view of one half-section of waveguide. This approach was chosen to simplify the fabrication process and to facilitate integration of planar circuits and devices, which is further discussed in Section IV.

II. FABRICATION PROCESS

The fabrication process [3] for the half sections with emphasis on the cross section is shown in Fig. 1. A thick (0.05 inches) double-side polished silicon wafer with (110) surface orientation is used. A 1000 Å thick layer of low pressure chemical vapor deposited (LPCVD) silicon nitride (Si_3N_4) is deposited on both sides of the wafer. Photoresist is used to pattern the Si_3N_4 windows with an SF_6 plasma. These windows define b, the waveguide height, shown in Fig. 1(d). The wafer is put in a reflux system and etched in a water based solution of 40% KOH at 80° C. Fig. 1(b) 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. 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. 1(c). The wafer is then diced into pieces of half waveguides as shown in Fig. 1(d). Metallization 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. These evaporations were done at three different angles, 0° and ±45°, to give approximately uniform coverage on the sidewalls, corners, and bottom of the waveguide channel. Further metallization is done to reduce RF conduction losses by electroplating gold to a thickness of ~ 3 μm, which is over 12 times the skin depth at 100 GHz.

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 to an accuracy of $\leq 4\%$ of the waveguide height. This

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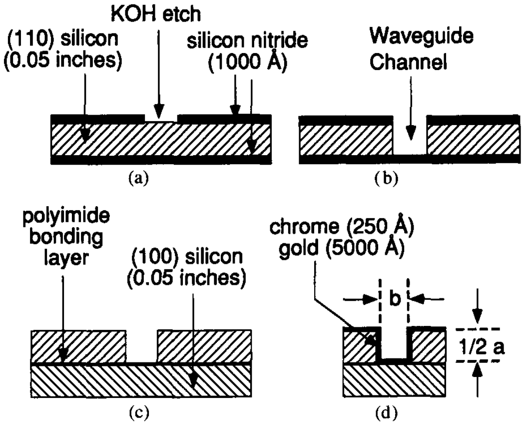

Fig. 1. Cross-section view of the fabrication process. (a) Si_3N_4 mask defines the waveguide height. (b) Wafer is etched completely through. (c) Wafer with waveguide channels is bonded to an unetched wafer which forms the waveguide side wall. (d) Completed half-section of waveguide with gold plating. Two of these sections are mated to form the waveguide. "a" is the waveguide width and "b" is the height.

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 75–110 GHz using a backward wave oscillator as a swept-frequency source, a direct detector, and a Wiltron 560A scalar network analyzer. A reference sweep is first taken without the waveguide section. The insertion loss for a 2.5-cm long section of waveguide is shown in Fig. 2(a) (the small wiggles in these curves are noise and do not reflect any resonances in the waveguide components). The measured loss is about 0.04 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 (see Fig. 2(b)) which shows a loss of about 0.024 dB per wavelength. The small difference is most probably due to differences in the quality of the gold plated surfaces. Fig. 2(c) shows the calculated loss [4] for a 2.5-cm long section of waveguide for 2 different values of conductivity, σ', normalized to bulk copper, which approximately fit our measurements. As can be seen, the conductivity of the gold plating of the commercial waveguide is about 1/10 that of copper, and for our sample it is about 1/30. Our gold layer showed a surface roughness ≤10 μm whereas the commercial gold film was significantly smoother. 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.

IV. DISCUSSION

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 will be atomically smooth, thereby minimizing RF losses [5]. 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 (~ 1 μm) 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], [6] can then be fabricated directly on the membrane as shown schematically in Fig. 3. This would eliminate the long-standing problem of mounting the devices and would represent a significant advance for waveguide technology. In addition, many RF components besides simple waveguide sections can be fabricated such as: directional couplers, waveguide transformers, waveguide-to-planar circuit transitions, low-loss filters, rectangular and conical feedhorns, and dichroic plates.

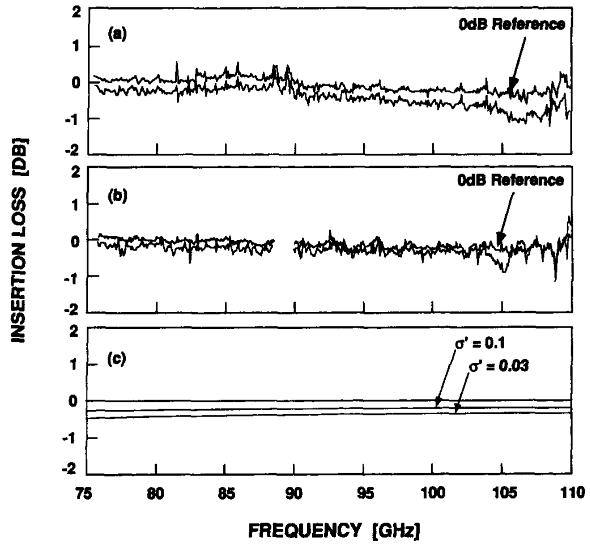

Fig. 2. (a) Measured loss of a 2.5-cm long section of Si-based WR-10 waveguide. The surface of the silicon was metallized with approximately 3 μm of gold to reduce RF losses. (b) Measured loss of a 2.5-cm long section of conventional metallic waveguide (the small gap in the data near 90 GHz is due to an instability in the BWO). (c) Calculated loss of a 2.5-cm long section of waveguide for two different values of conductivity σ' normalized to copper.

Currently, we are fabricating WR-10 waveguides with SiN membranes in between the two half pieces of the waveguide. Metallization 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 [7] is proposed to meet this need. Further metallization can be done by electroplating the tungsten surface with gold.

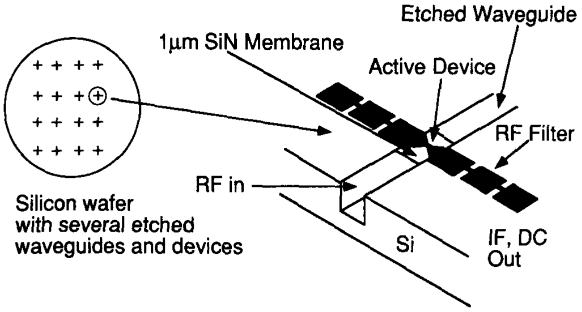

Fig. 3. Schematic view of an integrated waveguide circuit. Several waveguide components can be produced on a single wafer. Active devices and planar circuits can be integrated directly on thin membranes spanning the waveguide. Micromechanical RF-tuning elements can also be included in the waveguide.

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 0.04 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.

REFERENCES

[1] L.-S. Fan, Y.-C. Tai, and R. S. Muller, "Integrated movable micromechanical structures for sensors and actuators," *IEEE Trans. Electron. Dev.*, vol. 35, pp. 724–730, June 1988.

[2] M. Mehregany, K. J. Gabriel, and W. S. N. Trimmer, "Integrated fabrication of polysilicon mechanisms," *IEEE Trans. Electron. Dev.*, vol. 35, pp. 719–730, June 1988.

[3] M. Yap and Y.-C. Tai, "Fabrication of silicon micromachined waveguide," to be submitted to *IEEE/ASME J. Microelectromechan. Syst.*

[4] T. S. Saad, Ed., *Microwave Engineers Handbook, Volume I.* Dedham, MA: Artech House, 1971.

[5] F. J. Tischer, "Experimental attenuation of rectangular waveguides at millimeter wavelengths," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 31–37, Jan. 1979.

[6] V. M. Lubecke, W. R. McGrath, and D. B. Rutledge, " Sliding backshorts for planar circuits," *Int. J. Infrared Millimeter Waves*, vol. 12, pp. 1387–1397, Dec. 1991.

[7] N. Kobayashi, M. Suzuki, and M. Saitou, "Tungsten plug technology using substitution of *W* for Si," *IEEE Trans. Electron. Dev.*, vol. 37, pp. 577–582, Mar. 1990.