Integrated Silicon Micromachined Waveguide Circuits For Submillimeter Wave Applications

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Abstract --**Rectangular waveguides are commonly used as circuit elements in heterodyne sensor systems at millimeter wavelengths. However, conventional machining techniques for such components operating above a few hundred GHz, are complicated and costly. Previously we reported on the development of silicon micromachining techniques for fabricating silicon-based waveguide circuits which can operate up to high submillimeter wave frequencies. Continuing this work, we have used (110) silicon wafers as a substrate and fabricated WR-4 (170 - 260 GHz) waveguides. The new capability of placing a nitride membrane that runs the length of the waveguide's central axis has been developed and demonstrated. Submicron SIS tunnel junctions have also been successfully fabricated on nitride membranes which will allow them to be integrated into the waveguide design. This eliminates the traditional mounting problems of thin substrates for high frequencies. Low temperature, selective metallization techniques (electroless nickel) have been developed which coat the silicon waveguide walls but leave the nitride membranes untouched. By avoiding a high temperature metallization process, integration of the temperature sensitive Superconductor-Insulator-Superconductor (SIS) junctions with the waveguide channels is made possible. Insertion loss measurements of WR-4 waveguide sections show performance comparable to conventional metal waveguides.**

I. Introduction

Rectangular waveguides are used in a variety of rf components and circuits. In particular, heterodyne radiometers use waveguide circuits at millimeter wavelengths and even recently at submillimeter wavelengths [1]. Conventional machining techniques for metallic waveguides become time consuming, costly, and difficult for frequencies above a few hundred GHz. Waveguide dimensions are comparable to the wavelength, which is λ = 0.3 mm at 1000 GHz for example. In addition, mounting small dielectric substrates with devices such as mixer diodes, filters and planar probes in these waveguides is difficult.

We are developing and adapting silicon micromachining techniques [2, 3] to create waveguide circuits which can operate up to high submillimeter wave frequencies. Silicon micromachined waveguide components have several advantages, as previously discussed [4], including precise tolerance control, atomically smooth walls, rapid turnaround for

optimization, and the inclusion of membranes as integrated substrates for planar devices and circuits. Initial efforts have produced straight waveguide sections for WR-10 band (75-115 GHz) [4]. In this work, the focus has been on higher frequencies (170-260 GHz), improved metallization techniques (electroless nickel), and incorporation of thin (≈ 2 μm) silicon nitride membranes which can support planar devices and circuits.

II. Fabrication Process

Overview - The major steps of the fabrication process for the half sections with emphasis on the cross section is shown in Fig. 1.

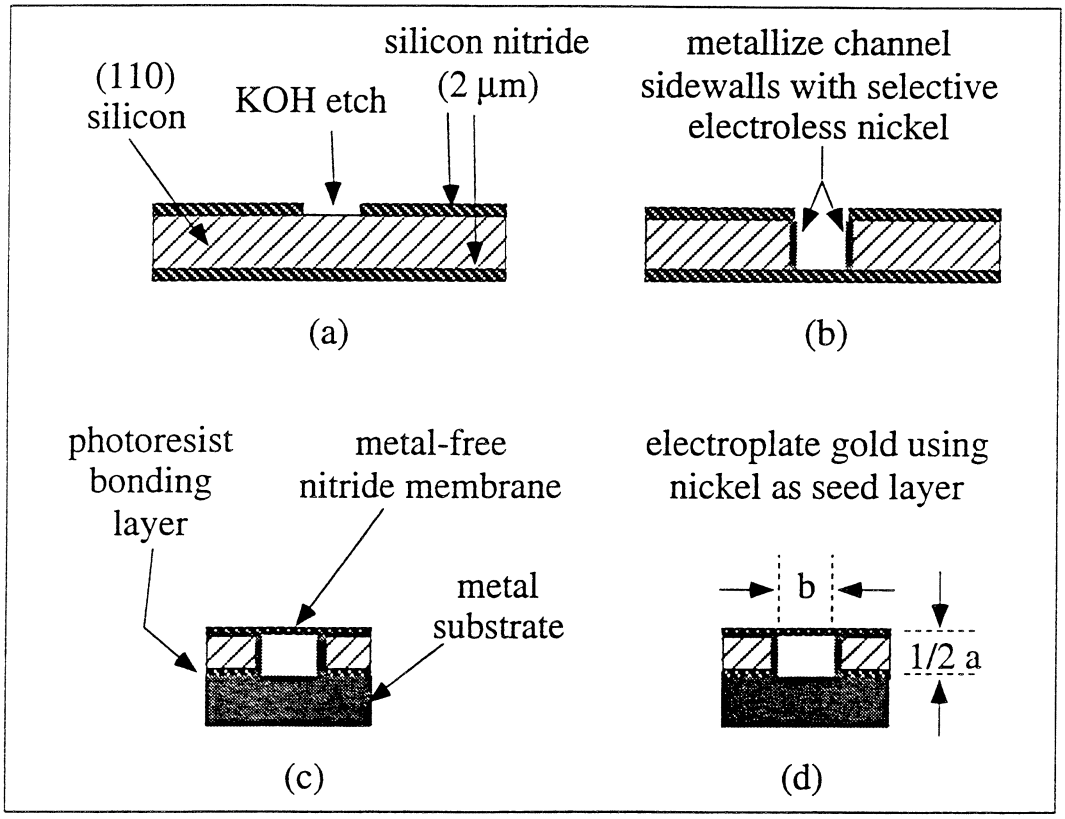

Fig. 1. A cross section view of the fabrication process. (a) Si_3N_4 mask defines the waveguide height. (b) Wafer is etched completely through and the channel sidewalls are metallized (c) Wafer with waveguide channels is bonded to an smooth metal substrate which forms the floor of the half-channel. (d) 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.

Double-side polished silicon wafers with (110) surface orientation and 0.0215 inches thick are used. A thick (≈ 2μm) 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 windows in the Si_3N_4 on the backside of the wafer 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 potassium hydroxide (KOH) to form the channel. Figure 1(b) shows the wafer after it has been etched completely through to form half of the waveguide. Not only does the etch create waveguide half-channels but it also forms the nitride on the front side of the wafer into a membrane as it

removes silicon from behind. Metallization is done using a selective nickel plating bath, and a photoresist bonding technique is used to glue the channels to a smooth metal substrate, as shown in Fig. 1(c), to form the third wall of the half-channel. After patterning of the nitride membranes, the wafer is diced into individual waveguide halves 25.4 mm in length as shown in Fig. 1(d). Further metallization is done to reduce rf conduction losses by electroplating gold to a thickness of ~3 μm.

Channel Formation - As noted above, a water based solution of KOH is used to etch the channels into the silicon wafer. We are using a continuously stirred 40% solution heated to 80°C. As we reported previously [4], the etching rate of (110) silicon by this solution is 2μm/min and the etching ratio of (110):(111) planes is 170:1. It is the large etching ratio that makes this etchant attractive. A (110) wafer has its (111) planes perpendicular to its surface. When etched by KOH, the (111) planes are effectively not etched when compared to the other planes. As a result, channels with vertical sidewalls can be obtained. If alignment to the (111) crystal plane is very accurate (≈ 0.1°), the walls of the channels will be atomically smooth. Figure 5 shows how smooth the (111) defined sidewalls can be when compared to the planes that are being etched down to form the channel. The figure shows a partially etched channel spanned by a patterned "air bridge." The sidewalls are extremely smooth as compared to the rough bottom which needs to be etched further. (Note the abrupt transition between the rough, wood-like texture of the bottom and the smooth sidewalls.)

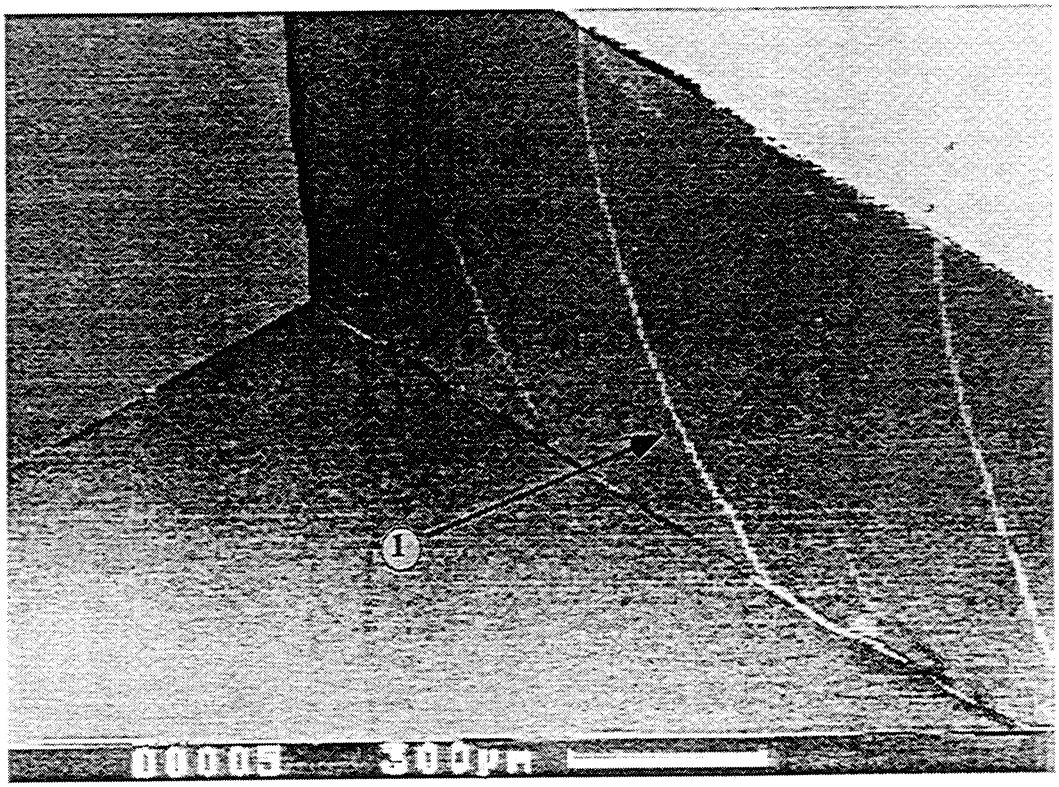

Fig. 2 SEM photo of a channel's sidewall. (1) indicates one of the curved steps that were formed during the KOH etching. They are caused by poor alignment to the (111) plane.

Since extremely smooth sidewalls are desired, especially to minimize rf losses at higher frequencies, accurate alignment of the channel masks to the (111) crystal plane is

required. The wafers used have their major flats cut along the (111) plane but alignment to this alone is insufficient to assure featureless sidewalls. Wafer specifications state that major flat alignment to the designated plane is only to within ± 1°. We have found that alignment to the (111) plane must be within a ±0.25° in order to avoid producing ridges in the sidewalls during etching (see fig. 2.)

Fine alignment to the (111) plane is achieved by KOH etching a fan pattern into the wafer before the channels are defined. The fan pattern consists of an array of lines with each line rotated 0.1° with respect to its neighbor. These fans consist of fifty one lines which allows for a correction of ±2.5°. The KOH etching of the fan pattern is short in comparison to the etch that creates the waveguide channels, being only about 30 minutes. This is sufficient to generate significant undercut in those lines that are poorly aligned to the (111) crystal while negligible undercut occurs in the well-aligned lines. The pair of lines deemed to have the least amount of undercut is then used as the alignment marks for the exposure with the channel mask.

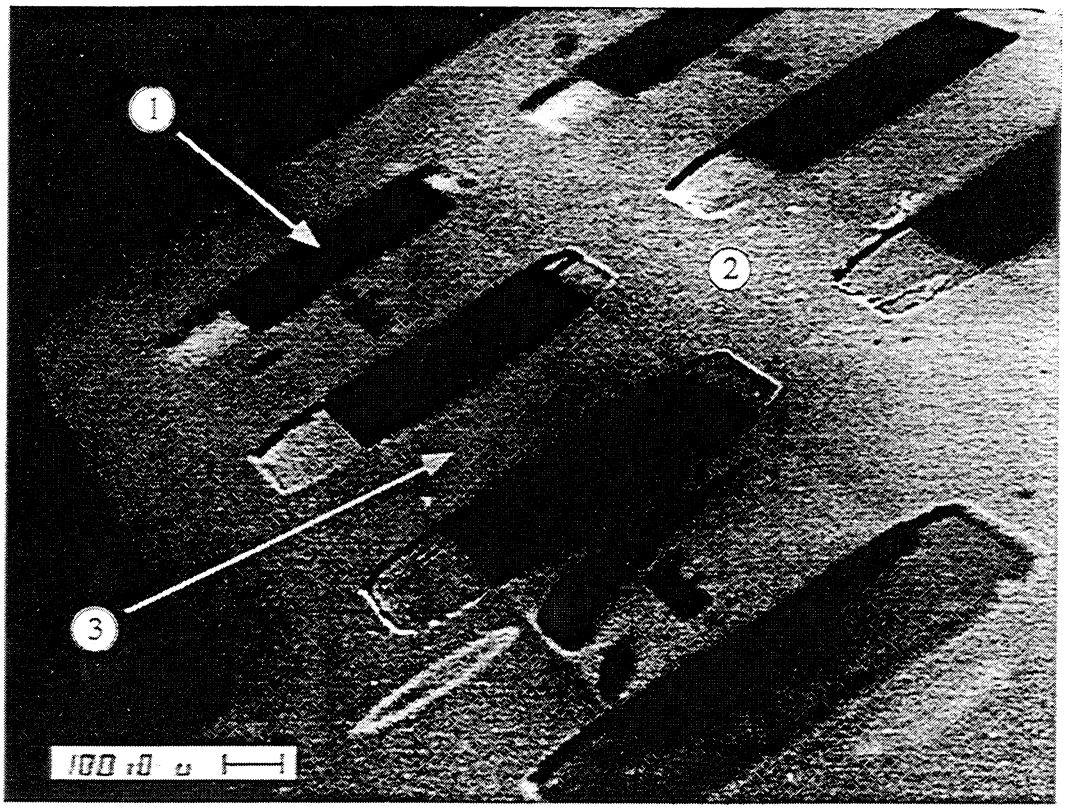

Fig. 3 SEM photo of a silicon waveguide channel spanned by three nitride air bridges, 2μm thick. (1) show the channel, (2) shows the silicon substrate that is the channel's sidewall and (3) shows the one of the nitride air bridges. The front nitride air bridge has fractured. Both the front and back nitride air brides are inscribed with a name. A portion of a second, neighboring channel can be seen in the upper right corner of the photo.

Membranes - Of particular interest is the development of a technique which permits thin membranes of dielectric material (such as silicon nitride) to be fabricated across the waveguide channels. As noted in the channel fabrication section, this is done by coating the wafer with a relatively thick layer (≈ 2 μm) of nitride and etching away the silicon from one side of the wafer. This permits the entire channel to be spanned by silicon

nitride and if desired, allows further processing to be performed on the wafer. This provides for the possibility (but not the requirement) of fabricating SIS junctions and planar tuning circuits on the membranes after the channels have been created. The membranes can be patterned into air bridges if desired to limit the amount of dielectric crossing the channel. Figure 3 shows waveguide spanned by three nitride air bridges. The front and back air bridges have a name inscribed in them. The front bridge is fractured due to handling but is still mainly intact. Figure 4 shows a close-up of a single air bridge spanning the channel.

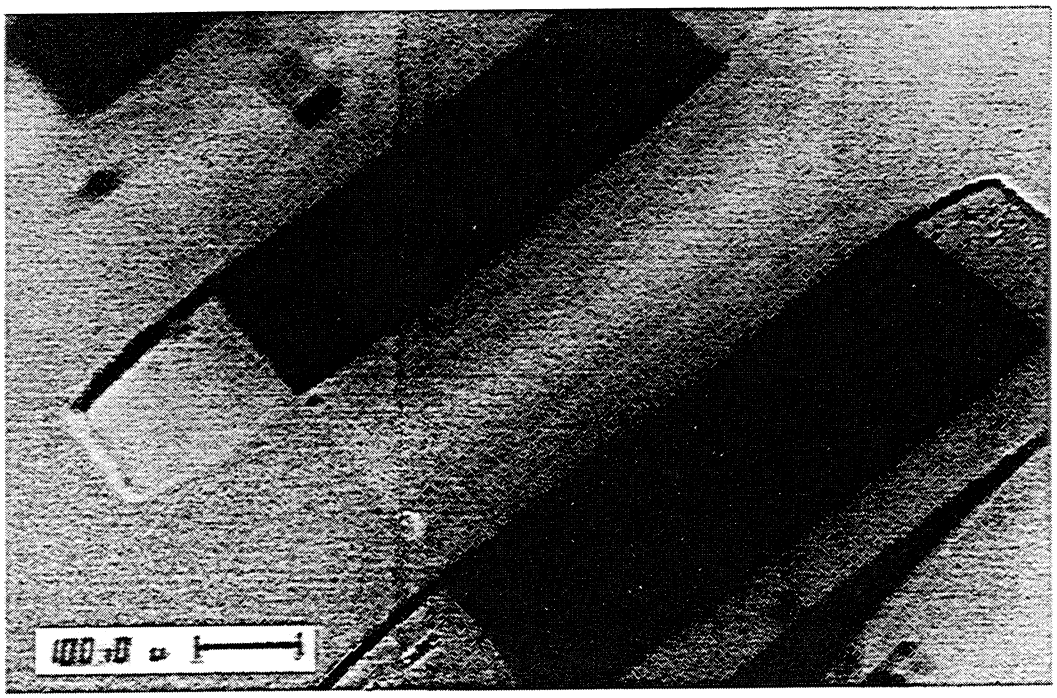

Fig. 4 Close-up of the blank air bridge identified in figure 3

A second method for fabricating air bridges has been demonstrated which allows the channels to be etched from the membrane side of the wafer as opposed to the backside as used to produce the 200GHz waveguides. Figure 5 shows an air bridge spanning a partially etched channel. The diamonds holes in the nitride are needed to ensure that the silicon beneath the air bridge is removed. An improvement on this process which involves adding a sacrificial oxide layer beneath the nitride should eliminate the need for such holes but it has yet to be demonstrated.

Metallization - Metallization of silicon waveguides is a crucial step in fabricating components that show comparable insertion losses to conventional waveguides. Because the bulk material from which the channels are produced is a semiconductor and not metal, RF losses are extremely high. In previous work, evaporated metal, deposited at varying angles, was used to coat the walls of the silicon waveguides [4]. Followed by an electroplated gold step, this technique was shown to produce waveguides with good performance. Evaporation, however, cannot be used when nitride air bridges span the channels. Evaporation is not conformal, i.e. it is a directional deposition, and thus areas beneath the air bridges are "shadowed" and will not be metallized. Furthermore, the nitride membranes will themselves be metallized rendering any junctions or tuning

circuitry on them useless. A final issue involved with evaporated metal is temperature. During the deposition the temperature of the wafer, and particularly the nitride air bridges, can easily exceed 150°C which will result in the destruction of sensitive devices such as SIS tunnel junctions.

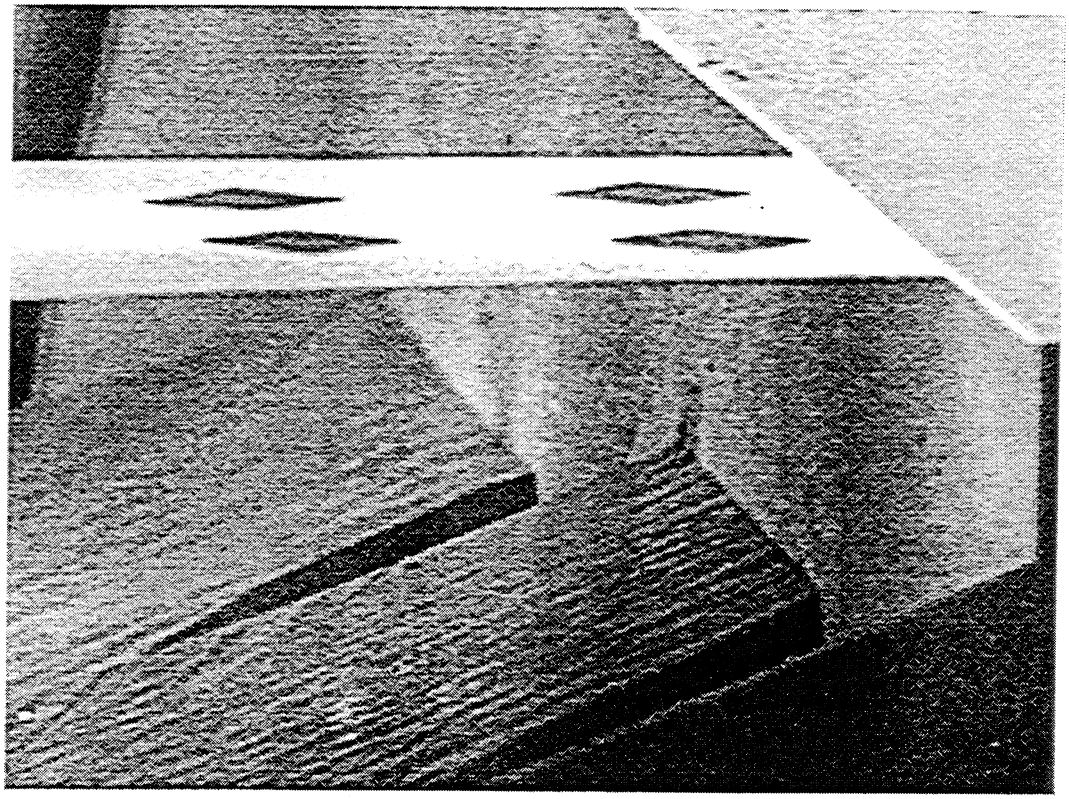

Fig. 5 SEM photo of a partially etched waveguide spanned by a silicon nitride air bridge. Note the smoothness of the sidewalls as compared to the rough etched floor. The change from rough floor to smooth sidewalls is very abrupt.

One process we investigated that would have addressed most of these issues is LPCVD tungsten. In this process, tungsten metal selectively deposits on any exposed silicon surface. It is expected that even silicon "hidden" beneath air bridges can be coated. After a thin layer of metal is deposited it can act as a seedlayer for a subsequent electroplated gold layer. Unfortunately, the deposited tungsten layer has an very high intrinsic stress, too high it turns out to permit coating a continuous surface area as great as the sidewalls of the waveguide channels. Extensive flaking of the tungsten film occurred after the deposition and the final metallization of the channels was spotty at best. If the stress in the film could be reduced, this may be a viable process for future waveguides. One additional constraint that must be observed if this process is used is that SIS junctions must be fabricated after the tungsten deposition since they will be destroyed by the high temperature used in the metallization technique.

The process finally developed that addresses all of the aforementioned issues is a selective, electroless nickel deposition. The plating solution used is an alkaline bath, pH 8 - 10, reported in [5]. This bath was chosen for its many attractive qualities which include selective plating of silicon, high quality, and excellent adherence (see fig. 6). Because plating occurs in a liquid bath, issues of shadowing due to air bridges are no

longer a concern. This process is also SIS junction compatible as the plating temperature is < 95°C.

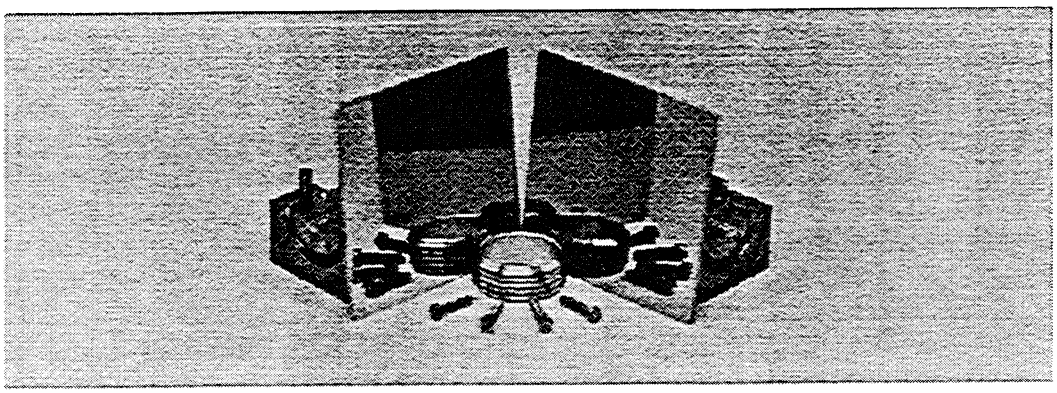

Fig. 6 The photo shows two square, mirror-like samples positioned to create a reflective corner. The sample on the right is bare, polished silicon and on the left is a similar silicon sample onto which electroless nickel has been plated. The two samples are nearly indistinguishable.

Selectivity in the nickel plating is the main attraction of this process. Nickel is deposited only on those surfaces that are non-insulating. Thus for the waveguide components, only the silicon sidewalls will be plated by the bath. Nitride, however, being an insulator will remain metal free. This permits the nitride air bridges to be left unprotected during the metallization. Simultaneously, the silicon beneath such structures will be plated guaranteeing that there will be continuous metallization down the length of the channel.

It should be noted that the plated nickel will not be the final metal lining the channels. The layer deposited, while not necessarily thin, is kept thin for this process. As an RF conduction material, this nickel is relatively poor. It can, however, perform more than adequately as a seed layer upon which high quality gold or copper can be electroplated. Measurements indicate that 25.4 mm long channels metallized by nickel alone have an insertion loss on the order of -10dB. Once covered by electroplated gold, the losses become comparable to commercial waveguides as described in the following section. For gold electroplating we used AU125 by Selrex [6] which is an acidic bath that is heated to 60°C and continuously stirred.

Wafer Bonding - Due to the relatively large dimensions of the 200 GHz channels and size limitations of the silicon processing equipment, it is not possible to fabricate the half channels in a single silicon wafer. The present process relies on the wafer into which the channels are etched to be as thick as the half-width, a/2, of the target waveguide. This means that once fabricated, the channels must be bonded to a substrate which forms the third wall, or bottom of the channel. The method of bonding is relatively unimportant as long as: 1) it is strong enough to withstand the processes which follow it, 2) the thickness of any adhesive layer used is negligible compared to the waveguide dimensions and 3) after bonding, gold can be plated onto the "third wall." Preferably the gold plate can electrically connect the bottom to the sidewalls.

We chose to use photoresist to bond the channels to the substrate. The main reason being ease of use. Since photoresist is a part of almost every major step in silicon processing, it is a well characterized, easily deposited material. Its bonding strength is adequate for our needs and it can withstand both dicing and gold electroplating steps. Of

particular importance is the fact that it can be deposited in a very thin layer (1 to 2 μm) and it can be selectively removed after exposure to UV light.

Bonding with the photoresist is a very straightforward process. We first choose the substrate. The main requirement is that it is conductive. A silicon wafer coated with a layer of evaporated gold is used. A thin layer of positive photoresist (AZ1350J @ 3500RPM) is then spun onto the wafer. Immediately following the spinning step, the wafer into which channels have been etched and metallized is placed onto the photoresist coated wafer, membrane side up. The two bonded wafers are then soft baked at 100°C for half an hour. Following the bake, the two wafers are globally exposed with UV light and developed. This removes the photoresist from the bottom of the channels while leaving the resist involved in the actual bonding intact. The end result is two wafers bonded together to form half channels. The distance between the sidewalls and the bottom is ≈ 2μm which should be easily covered by a 3μm thick gold plate, the final step in the waveguide fabrication process.

Photoresist is, of course, not the only option for the bonding step. Previously we have used polyimide as the bonding material which, in this process, is simply a more rugged form of photoresist [4]. Other bonding options include anodic bonding, metal-to-metal pressure bonding and common glue or epoxy bonding. There are benefits and drawbacks associated with each of these depending on the specific application for the waveguide component. Photoresist, however, is preferable for rapid turnaround development work. As a final note, for waveguides with target frequencies of 350 GHz and higher, wafer bonding will no longer be necessary. Instead, silicon-on-insulator (SOI) wafers can be used which are essentially two wafers bonded together with a layer of oxide between them.

IV. Experimental Results

In order to perform insertion loss measurements, a pair of brass mounting blocks was designed and fabricated as shown in figures 7 and 8. The two waveguide half-sections are put in the brass mounting blocks and mated together. This allows the silicon waveguide to be connected to microwave test equipment using conventional waveguide round mini-flanges for WR-4 band. The silicon waveguides are rugged and can be firmly clamped to metallic flanges. The insertion loss of the WR-4 waveguide was measured over a frequency range of 200 GHz to 255 GHz in ≈ 10 GHz steps using a backward wave oscillator as a swept-frequency source and a direct detector. For each frequency a reference measurement was first taken without a waveguide section present, and then measurements with the commercial and silicon waveguides were made. These steps were

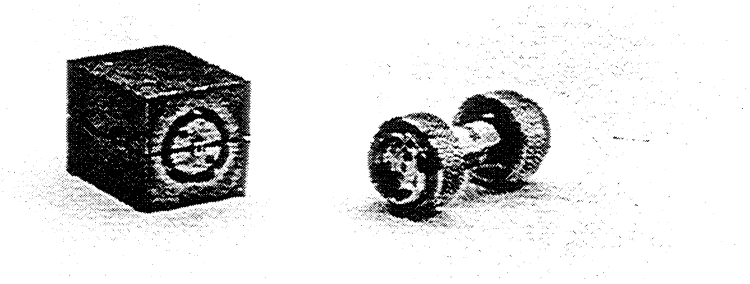

Fig. 7 On the right is a 25.4 mm, commercial WR-4 waveguide section. On the left is our silicon micromachined WR-4 waveguide section. Two fabricated silicon half-channels are assembled in the mounting block to form a functional waveguide.

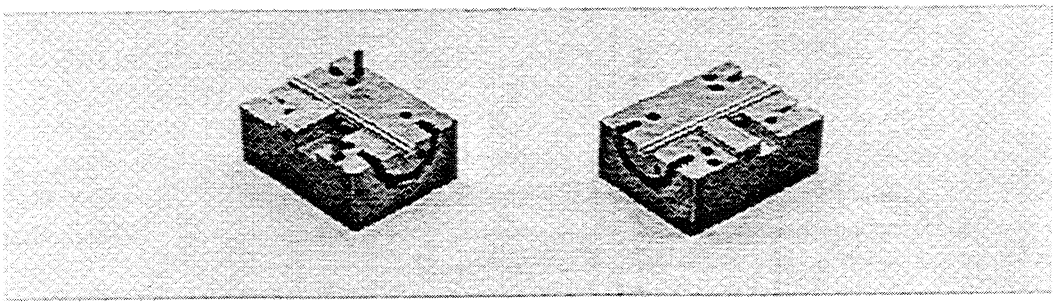

Fig. 8 The photo shows our waveguide mounting block split into its two halves. A waveguide half-channel is mounted in each of the two mounting block pieces.

repeated several times to reduce any variation from the frequency source itself. The insertion loss measurements for a one inch long section of waveguide is shown in Fig. 9. The measured loss is about -0.80 dB across the band for both the commercial and silicon waveguides.

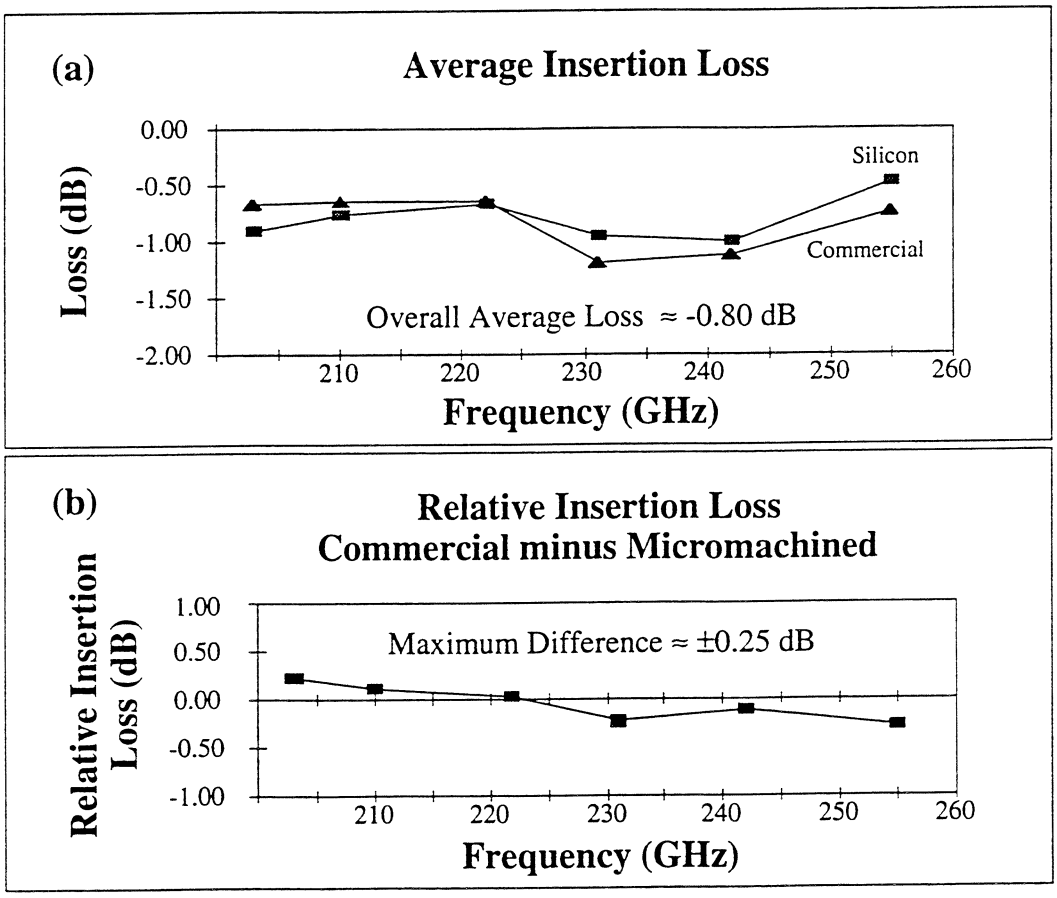

Fig. 9 (a) Measured loss of a 25.4 mm long section of a silicon and a commercial WR-4 waveguide. The surface of the silicon was electroplated with gold to reduce rf losses. (b) Relative loss comparison between silicon and commercial waveguides showing maximum deviation between the two as < ±-0.25 dB.

Assuming bulk copper as the wall material, calculations predicts a loss of ≈ -0.30 dB. The difference between theory and experiment is most probably due to differences in the quality of the gold plated surfaces and bulk copper. Calculations show that the metal coating the channels of both the commercial and silicon waveguides has ≈ 1/12 the conductivity of bulk copper which is reasonable for electroplated gold. A comparison between the two types of waveguides shows that the relative losses are < |0.25| dB. The data shows that the commercial channel performs better for the lower frequencies while the silicon guide performs better at the higher frequencies. We believe that this apparent trend is an artifact of the measurement since the differences are within the experimental error, rather than it reflecting actual changes in performance. Regardless, these results show that there is little discernible difference in the performance of the two types of waveguides.

VI . Summary

We have improved upon a new approach in fabricating waveguide circuits using silicon micromachining technology. In particular, we have fabricated a 200 GHz silicon rectangular waveguide spanned by ≈ 2μm thick silicon nitride air bridges. A new technique for metallizing the waveguide channels using an electroless nickel plating bath has been introduced to the fabrication process which produces a high quality, selectively deposited film. The plated nickel acts as a seed layer for a subsequent layer of electroplated gold. The measured insertion losses of the fabricated devices are found to be ≈ -0.80 dB which is comparable to losses incurred in commercially available, conventional waveguides. The present fabrication process is fully compatible with the integration of SIS junctions and planar RF tuning circuits with the devices.

Acknowledgments

The research described in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, and the Dept. of Electrical Engineering, California Institute of Technology. It is jointly sponsored by the National Aeronautics and Space Administration, Office of Space Access and Technology and the JPL Director's Discretionary Fund.

References

[1] Morvan Salez, Pascal Febvre, William R. McGrath, Bruce Bumble, Henry G. LeDuc, "An SIS Waveguide Heterodyne Receiver for 600 GHz - 635 GHz", International Journal of Infrared and Millimeter Waves, vol. 15, pp. 349-368, February 1994.

[2] L.-S. Fan, Y.-C. Tai, and R. S. Muller, "Integrated Movable Micromechanical Structures for Sensors and Actuators," *IEEE Trans. on Electron Devices,* vol. 35, pp. 724-730, June 1988.

[3] M. Mehregany, K. J. Gabriel, and W. S. N. Trimmer, "Integrated Fabrication of Polysilicon Mechanisms," *IEEE Trans. on Electron Devices,* vol. 35, pp. 719-730, June 1988.

[4] W.McGrath, C. Walker, M. Yap, and Y.C. Tai, "Silicon Micromachined Waveguides for Millimeter-Wave and Submillimeter-Wave Frequencies," *IEEE Microwave and Guided Wave Letters*, Vol 3, pp. 61-63, March 1993.

[5] M. V. Sullivan and J. H. Eigler. "Electroless Nickel Plating for Making Ohmic Contacts to Silicon," *Journal of the Electrochemical Society,* vol. 104, No. 4, pp. 226-229, April 1957.

[6] Enthone - OMI Inc., 2779 El Presidio, Long Beach, CA 90810. (310) 537-0288.