Silicon Micromachined Components at Terahertz Frequencies for Astrophysics and Planetary Applications

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***Abstract* — At the Jet Propulsion Laboratory (JPL) we are using deep reactive ion etching (DRIE) based silicon micromachining to develop the critical waveguide components at submillimeter wavelengths that will lead to highly integrated multi-pixel spectrometers, imagers, and radars. The advantage of DRIE over wet anisotropic etching is that DRIE exhibits little crystal plane dependence and therefore reduces geometric restrictions. As a result, DRIE enables fabrication of trenches that are independent of crystal planes, thus making it possible to develop micromachined waveguides with vertical sidewall profiles. In this paper we describe the design and fabrication of silicon micromachined critical waveguide components operating in the range 325-500 GHz frequency band for astrophysics and planetary applications from space. We also address the challenges of testing these devices when interfaced with metal waveguide test fixtures.**

I. Introduction

Future multi-pixel, multi-functional, high performance instruments operating at frequencies from hundreds of gigahertz to several terahertz will require waveguide circuits with very small feature sizes and high precisions. Indeed, state-of-the-art missions currently in development, such as the ground-breaking HIFI instrument on Herschel [1], are based on single-pixel, single-ended double-sideband receivers. It is well known that at frequencies beyond a few hundred gigahertz, the feature sizes of all but the simplest waveguide circuits are too small and the required tolerances are too demanding to be fabricated using even the best state-of-the-art conventional machining. On the other hand, silicon micromachining shatters the barriers of conventional machining, and brings the added benefits of rapid turn-around time and excellent process control. Furthermore, silicon micromachined circuits are light weight and capable of achieving a high degree of integration on a single chip. While there have been several demonstrations of waveguide circuits fabricated with silicon micromachining [2] and other techniques [3], few if any of these circuits have been subjected to any significant electrical testing.

Submillimeter-wave integrated silicon micromachined circuits for array receivers have never been demonstrated. Deep reactive ion etching (DRIE) based silicon micromachining is the most viable option for the fabrication of these high performance components in an array instrument which require deep vertical profiles in waveguides [4]. The silicon etching process in DRIE consists of an etching cycle flowing only Sulphur hexafluoride (SF_6) and a sidewall passivation cycle flowing only octofluorocyclobutane (C_4F_8). The advantage of DRIE over wet anisotropic etching is that DRIE exhibits little crystal plane dependence, therefore, reducing the geometric restrictions [5]. As a result, DRIE enables fabrication of trenches that are independent of crystal planes, thus making it possible to develop micromachined waveguides with vertical sidewall profiles. Compared to silicon laser micromachining [6], DRIE is more efficient in etching large volumes of substrate. Moreover, the DRIE process is much simpler for mask alignment issues as compared to other micromachining techniques where the mask alignment has been proven to be extremely challenging. Moreover, one of the key problems with the current generation of silicon micromachined components has been the difficulty to design an interface to mate the components to metal waveguide test equipment for the proper characterization of the individual components. In this paper we will describe the design and fabrication of silicon micromachined critical waveguide components operating in the 325-500 GHz frequency range (WR-2.2 waveguide band). We will also discuss the design of a novel test fixture that we have developed at JPL to address the issues of testing and characterization of radar array.

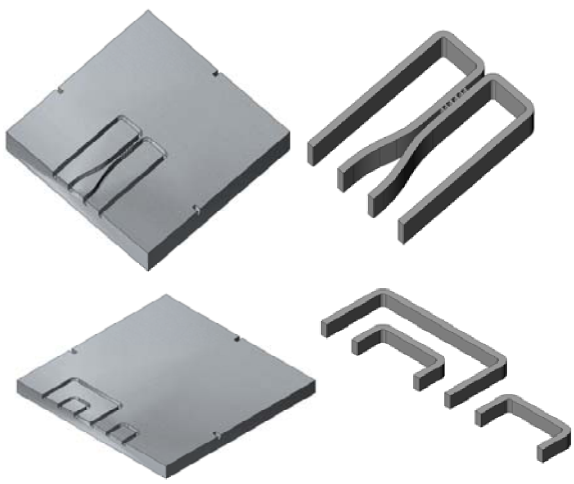

Fig. 1: Quadrature hybrids, different lengths of waveguides, and other components designed in the 325-500 GHz frequency band for silicon micromachining.

II. Design, Fabrication, and Testing

We designed broadband quadrature-hybrid couplers, directional couplers, in-phase power dividers, and other components, as shown in Fig. 1, for operation in the 325-500 GHz frequency range using three-dimensional electromagnetic simulators (Ansoft HFSS) and linear circuit simulators (Agilent ADS). We also designed waveguides of different lengths for on-wafer calibration capability. These components were fabricated on silicon substrates in JPL's Micro Devices Laboratory using DRIE technique. In our laboratory, we developed a preliminary DRIE fabrication recipe for developing silicon micromachined components; the process steps are shown in Fig. 2. We coat the high resistivity silicon wafer with a 5 µm thick layer of SJR-5740 positive photo resist and expose it for approximately 40 seconds using 25 W·cm^{-2} 320 nm ultraviolet (UV) light. We then develop it in a mixture of AZ400K and DI water in 1:3 ratios until the pattern clears. The wafer is then mounted on a backing wafer using crystal bond. The etching rate is approximately 2 µm/min and achieves ±10% uniformity across the wafer. For developing the components for this work, we further developed and optimized this step in order to achieve a good vertical etch for the walls. The final parts are released in acetone. We also fabricated silicon alignment pins to align the two spilt waveguide blocks. We evaporated gold on the silicon micromachined components by mounting the wafer at an angle for uniform metal deposition. Fig. 3 shows SEM photograph of the fabricated components, showing close up of the surface properties of the wall. Fig. 3 shows uniform gold deposition and no noticeable excessive deposition at the base of the post for the hybrids. Fig 4 shows

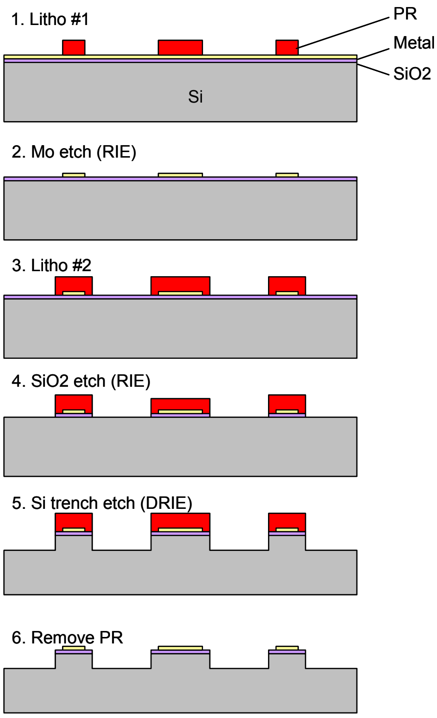

Fig. 2: Deep reactive ion etching fabrication process flow diagram.

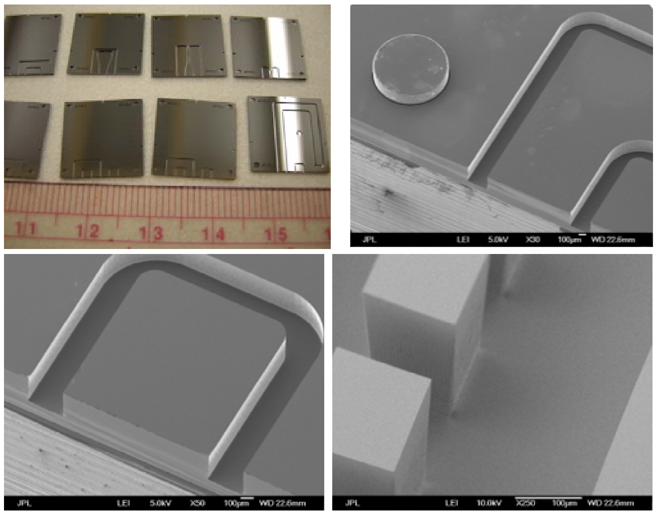

Fig. 3: SEM photographs of the fabricated silicon machined waveguides and the silicon alignment pin (top right) and close-up of the posts for the hybrid (bottom right).

the roughness of the gold plated surfaces measured with Wyko interferometer system, and surface roughness after gold evaporation was found to be in the 50-200 nm range.

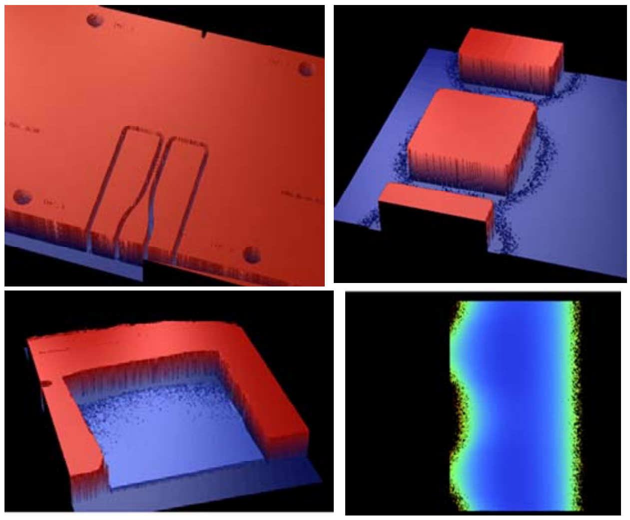

Fig. 4: Photograph of the roughness of the surfaces measured with Wyko interferometer system.

Previous efforts to demonstrate micromachined waveguides have been severely limited by the difficulty of testing the fabricated components, especially due to issues involving mating the silicon components to calibrated test equipment. We have invented a novel test system to eliminate these difficulties and allow rapid and accurate testing of the micromachined circuits. With our system, the prototype components were assembled in an innovative test fixture, as shown in Fig. 5. Preliminary testing with a 325-500 GHz vector network analyzer is under progress now. Our test fixture brings the dual benefits of being compatible

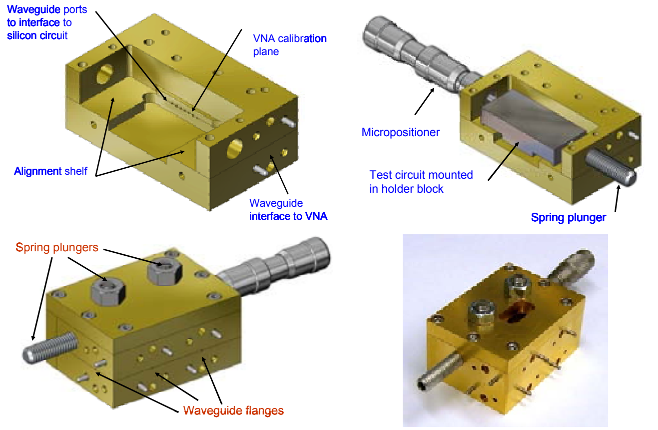

Fig. 5: Schematic of the test fixture used to measure the silicon micromachined components. A photograph of the machined test fixture is shown on the bottom right.

with the brittle nature of silicon (e.g., no screws or alignment pins mate to the silicon components, with spring plungers providing the necessary contact forces) as well as allowing the waveguides to be quickly aligned with the test equipment with a precision several times better than what is achievable with the best conventional microwave flanges. Furthermore, with our system, the vector network analyzer can be calibrated a single time, and then used to test a whole series of test components all in a single test fixture. Only one test fixture will be required to test all the prototype components. In future we will integrate multi-component waveguide circuits such as the waveguide portions of sideband-separating and balanced heterodyne receivers and will characterize them in the 325-500 GHz frequency band.

CONCLUSIONS

We have fabricated waveguide components in the 325-500 GHz band using DRIE-based silicon micromachining. We have also machined a metal test fixture to measure the fabricated components in a rapid and reliable fashion. On wafer calibration standards will be used to calibrate the network analyzer for testing these components. The gold plated micromachined components shows good vertical profile and smooth surface characteristics. Testing and characterization of the components are under progress currently in our laboratory.

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REFERENCES

[1] T. de Graauw, N. Whyborn, E. Caux, T. Phillips, J. Stutzki, X. Tielens, R. Güsten, F. Helmich,W. Luinge, J. Pearson, P. Roelfsema1, R. Schieder, K. Wildeman, and K. Wafelbakker, "The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)," Proceedings SPIE, vol. 6265, 2006.

[2] J. P. Becker, J. R. East, and L. P. B. Katehi, "Performance of Silicon Micromachined Waveguide at W-band," Electron. Lett., vol. 38, no. 13, pp. 638-639, June 2002.

[3] V. Desmaris, D. Meledin, A. Pavolotsky, and V. Belitsky, "Microfabrication Technology for All-Metal Sub-mm and THz Waveguide Receiver Components", To appear in the Proc. of the Nineteenth Intl. Symp. on Space Terahertz Technology, Groningen, Netherlands, April 2008.

[4] Y. Lee, J. P. Becker, J. R. East, and L. P. B. Katehi, "Fully Micromachined Finite-Ground Coplanar Line-to-Waveguide Transistors for W-Band Applications," IEEE Trans. Microwave Theory and Tech., vol. 52, no. 3, pp. 1001-1007, March 2004.

[5] J. P. Becker, "Silicon Micromachined Waveguide Transition and Three-Dimensional Lithography for High Frequency Packaging," Ph.D. dissertation, Dept. Electrical Eng. Comput. Sci., The University of Michigan, Ann Arbor, MI, 2001.

[6] C. K. Walker, G. Narayanan, H. Knoepfle, J. Capara, J. Glenn, and A. Hungerford, "Laser Micromachining of Silicon: A New Technique for Fabricating High Quality Terahertz Waveguide Components," Proc. of the 8th. Int. Space Terahertz Tech. Symp., Cambridge, MA, pp. 358-376, March 1997.