Design and Fabrication of Silicon Stacked Architecture for 2.06 THz Receiver Front End

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***Abstract*— By designing a Si three-dimensional stack, a reproducible process for iterative-use and accurate assembly at 2.06 THz is created. Low noise temperature is measured at 2.06 THz with a metal block at room temperature. The Si block system created via multi-step DRIE process is described. The mask layout and design considerations are discussed. Design for fine assembly, as well as process specifications of side wall smoothness and accurate etch depths of the µm-scale waveguides are essential to optimal sub-harmonic mixing performance. Variability tolerances are described, with future explorations covered.**

***Index Terms*—Aerospace components, Silicon, Space technology, Submillimeter wave propagation, System integration, Wafer scale integration**

I. INTRODUCTION

NASA's earth science directorate includes as a focus understanding the atmospheric dynamics in Earth's upper atmosphere [1]. Schottky diode mixers operating at several THz have historically been a stable method of passive sensing in space, with prior mission deployments [2]. The capability to leverage silicon (Si) fabrication [3] and integrate the local oscillator (LO) and intermediate frequency (IF) signal onto a compact Si micro-machined package has the potential to introduce new features and design paradigms, including multi-functional arrays for compact systems.

Fig. 1. Target science in Region 2 and Region 3, while prior missions have occurred in Region 1, like Terra. O_2 will be measured in Region 3, which is <100 km above Earth. Meanwhile, dynamics including those in Region 2 will be measured via Doppler shift and OI emission.

A heterodyne receiver front end is being developed to perform measurements at 2.06 THz, where a neutral oxygen [OI] line exists. By measuring this atmospheric feature, thermos-spheric models can be created for understanding space weather and its impact on earth climate. Recently, laboratory measurements have been performed with traditional metal machined blocks to validate design. The system currently consists of a LO chain with a frequency synthesizer, followed by a gallium nitride (GaN) power amplifier and a solid-state-based tripler chain up to 1.03 THz. At 63.9 K ambient temperature, the mixer was measured to have a double sideband (DSB) noise temperature of 8186 K at 2.0034 THz.

This paper introduces a Si stacked architecture designed to replace the metal blocks, specifically the interface housing the low-parasitic 2.06 THz Schottky diode mixer. Si micro-machining allows for desirable features such as accuracy and reproducibility. While the Si fabrication is utilized for the last stage of this LO chain, the scheme is such that it could be extendable to combine with lower frequency mixers due to the modularity of each of these parts. The Si block houses the waveguide structure, IF and bias boards, as well as the interconnection to the electrical output feeds. Considerations for this hybrid Si and metal interface include having a reusable interface assembly between the metal and Si block and having an interchangeable Si block for different interface design. Compared to Computer Numerical Controller (CNC) milling, lithographical features can result in better precision. Furthermore, by having the vertical waveguide coupling, the design envisions a compact coupling in of the RF signal. With high-resistivity Si, it is estimated that losses are comparable with metal-machining.

II. BACKGROUND

Silicon micromachining is used to create the fine waveguide features in the three-dimensional stack. The fabrication process consists of two main steps. In order to etch straight side walls, reducing ohmic losses, multiple SiO_2 masks are used. This type of process allows for thicker structures and multiple-levels for different feature heights [4]. The recipe used in this particular paper was first developed and described in [3] at Jet Propulsion Laboratory and adapted to be used for this work. The main steps

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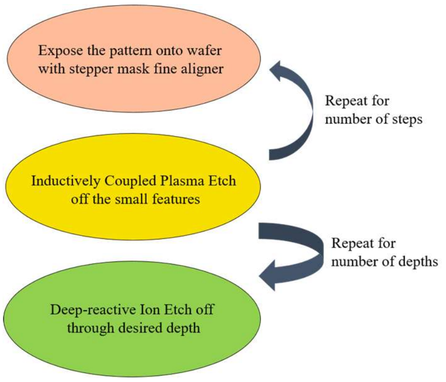
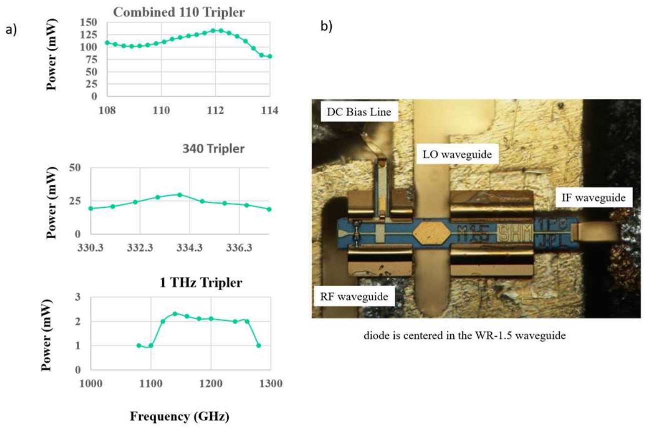


Fig. 2. In order to have high-aspect ratio feature size in silicon, deep-reactive ion etching is used. This consists of a three-step cycle of etching with SF_6 and passivation with C_4F_8.

are illustrated in Fig. 2, where a three-step process for deep-reactive ion etching is performed. Negative photoresist is lithographically patterned on the 4-inch Si wafer. With the pre-determined selectivity of the process, inductively coupled plasma (ICP) etch is initially performed on the SiO_2. This step allows for finer precision over final target thicknesses. Then, deep-reactive ion etching (DRIE) is done, creating the desired depths of the Si waveguide. Each etch creates the vertical waveguide features. Waveguide depths are measured using a profilometer, in order to ensure accuracy of process, which will be discussed further in Sec. IV.

III. METHODOLOGY AND MEASUREMENT RESULTS

The Si stack is designed to be embedded into a LO chain depicted in Fig. 4. The GaAs Schottky diode mixer is a technology optimized for lower parasitics and high-frequency mixing [5]. The chain is composed of a sequence of Schottky-diode based multiplier blocks, all the way up to 1 THz. Each component of this chain is characterized, as shown in Fig. 3a. The LO chain, with the experimental setup shown in Fig. 4, was measured to capture the power across frequency at each step of the multiplier chain. The key desired metric for this room temperature LO source is generating enough power, relative to existing sources, to enable the 2.06 THz subharmonic mixing, which has been developed in prior works [6-8]. Alignment tolerances become tighter as frequency is scaled. In the 2.06 THz subharmonic mixer, the interface between the 1 and 2 THz blocks are crucial. Fine assembly will dictate the performance of the mixer.



diode is centered in the WR-1.5 waveguide

Fig. 3. a) The diagrams on the left are frequency sweeps at each stage of the multiplier chain. b) The diagram on the right is the top down view of device layout.

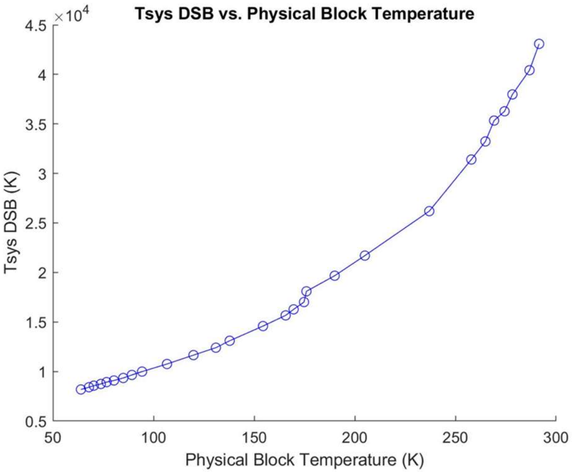


Fig. 5. Double side band (DSB) noise temperature measurement of the Schottky diode mixing in a metal-machined waveguide block structure at 2.003 THz.

The noise temperature measurement with the metal block is shown in Fig. 5, a world-record value of 8186 K measured at 63 K. With such a development of the chain, the Si micro-machined part will be introduced. This will minimize the cost and time to delivery. It will also miniaturize the assembly, integral for flight purposes. In the next section, Si micromachining is examined for the 2.06 THz Si architecture.

IV. SILICON INTEGRATION RESULTS AND DISCUSSION

As frequency scales, the size of the waveguide and device anode miniaturize, increasing complexity for assembly. The considerations become much tighter for 2.06 THz mixing.

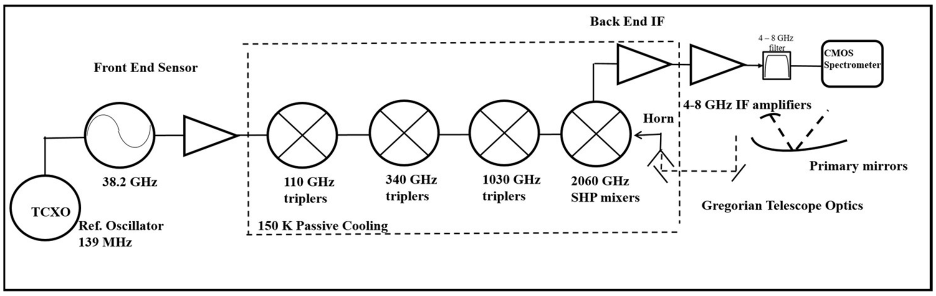


Fig. 4. Flight instrument configuration, with the experimental setup comprised of the frontend portion, illustrating how the 2.003 THz mixer is being measured

Diode alignment at the center of the waveguide is essential. Performance can deviate from simulated behavior when device is not coupling the quasi-TEM mode signal as expected in the center of the waveguide [9]. With a 40 µm pitch, a misalignment of 20 µm is already 13% of the wavelength.

Mechanically, the contact pads as seen in Fig. 3b are effectively sandwiched between the top and bottom blocks. Where these regions are relatively located will influence the overall soundness of assembly. Beyond assembly expertise, design considerations for optimized integration are integral for alignment of such tight tolerance. This makes integration design all the more essential to an optimized process and optimal performance.

The Si blocks were designed based on prior experience with high-frequency alignment. A key challenge for this type of integrated architecture is to perform reliable testing given sub-millimeter constraints. With the features being etched onto two pieces of 350-µm Si wafer, the Si block is designed to be assembled with fine tolerance by incorporating both prior metal block assembly strategies and a novel optical alignment scheme. Using a previous mechanism of fine alignment by placing Si pins within etched cavities between each of the interfaces [3], the chain can be assembled sequentially. Crucial also to optimal performance is fabrication accuracy. By measuring the waveguide features across wafer, accuracy and uniformity are verified during the fabrication process. The vertical waveguide, which bridges the two wafers, must have fine fabrication alignment in order to have any mismatch <1 µm order.

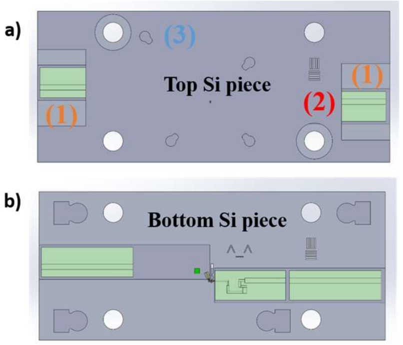


Fig. 6. The (a) top and (b) bottom Si pieces, with several places denoted. (1) quartz-based IF boards, (2) indirect monitor of coupling through relative power shifts, and (3) interfaces to block via pins. During assembly, the two pieces are stacked on top of each other.

From Fig. 6, the top and bottom of the Si stack is shown. These are aligned via the alignment marks indicated. Prior work in this area of alignment have yielded H-plane signal losses at 500-650 GHz to 0.08 dB/mm at 600 GHz, which overlaps with the idealized waveguide loss and is only 0.02 dB/mm greater than a metal machined waveguide [10]. In order to attain such high precision, on the fabrication side, losses due to sidewall roughness are minimized, and accuracy as compared to vertical waveguide lengths simulated are ensured, both possible per the steps described in Sec. II.

Considerations for methods of extracting the IF line out are explored, including with smaller, integrated I/O. More compact integration of IF line is possible at the expense of a slightly higher power loss over SMA output, with room for improvement.

Once these pieces of the Si stack are aligned, the signal is designed to be coupled out via a Si microlens antenna [11]. Novel alignment protocols allow for alignment monitoring prior to and during measurement.

V. CONCLUSION

Future THz instruments may be strengthened in the arena of multi-pixel arrays and integrated subsystems through exploring and refining new fabrication technologies [12]. The scheme presented in this paper will help to enable these larger-scale array architectures with reliability at a much smaller stack area of around 400 mm^2 area than previously demonstrated. Furthermore, the next steps in realizing a 2.06 THz mixer for THz limb sounding in the lower earth atmosphere are developed.

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