Microfabrication Technology for All-Metal Sub-mm and THz Waveguide Receiver Components

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***Abstract*— A novel technology for manufacturing of micromachined all-metal waveguide circuits and structures for the frequency band from 200 up to 7000 GHz (Sub-Millimeter and THz) is presented. The waveguide circuits are formed using metal electroplating with preceding sputtering of a thin metal film seed layer over a photo-lithographically patterned thick SU-8 photo-resist. The process provides possibility of making 3-dimensional structures via facilitating of multi-level (layered) designs. Surface roughness of the THz waveguide structure was demonstrated to be below 0.1 µm. This technology was used to build a state-of-the art waveguide balanced 1.3 THz Hot Electron Bolometer mixer and other application for radio astronomy instrumentation.**

I. Introduction

Pushing the instrumentation receiver technology above 1 THz should make waveguide technique the technology of choice since waveguide gives the lowest possible insertion loss among other types of transmission line and a corrugated horn interfaces naturally to the waveguide. Corrugated horns producing nearly perfect Gaussian beam are the most efficient way to couple the antenna signal to a receiver at frequencies where the dimensions of such feed could be made practical. Nevertheless, since Maxwell equations' solution scales with the frequency, the shortening of the wavelength decreases the waveguide dimensions and, due to the skin-effect and associated RF loss increases the demand on the quality of the waveguide inner surface. These drive the required manufacturing accuracy and surface quality beyond the possibilities of existing machining tools. As a first approach of solving the problem for the extremely small dimensions and high required surface quality, Silicon micromachining has been used to produce waveguide structures for THz receivers [1]-[2]. This technique is largely limited to fabrication of 2 layer structures, with inherent difficulty of making grooves of different width, and, generally, the process somewhat cumbersome. On our view, this approach is also especially impractical for a cryogenic receivers due to integration problems of silicon components to the surrounding metal blocks because of the large stress developed during cooling down to cryogenic temperatures caused by sufficient mismatch of thermal expansion coefficients. Similar problems are also likely to occur when waveguide structures are defined and processed exclusively out of thick SU-8 photoresist [3] or combining Si etching and thick photoresist [4].

A perfect solution for these problems would be a process delivering all-metal structures with dimension accuracy better than 1 µm and with surface roughness lower than the skin depth at the waveguide circuit operating frequencies. This kind of technology has been demonstrated by Pavolotsky et al. [5] to fabricate 3-dB waveguide hybrids for THz mixers [6]; however the fabricated circuit consisted of a single layer. Mata et. al. [7] demonstrated the feasibility of six-layer structures in bare SU-8 layer. With a similar concept based on the metal electroforming over a photoresist mould, we propose a new micro-fabrication technique by combining of the two approaches [5], [7] in order to fabricate all-metal 3-layer Sub-Millimeter and THz waveguide structures and circuits. The technique description and waveguide components and circuits, already fabricated with the proposed micromachining technology, are presented in this paper.

II. Waveguide Fabrication Technique

Clearly, a "layered fabrication" technique should be facilitated by preceding tedious designing process to achieve desired electromagnetic performance and keep compatibility with the processing of the waveguide "layered" structure [6]. In order to take full advantage of photolithography, a 4" silicon wafer is used as a carrier substrate for a photo-resist mould and provides the desired planarity. An optional release layer could be applied to ease the separation of the ready structure from its Si-carrier.

All three SU-8 layers are then sequentially spun, baked, exposed and post-baked. As recommended by the SU-8 manufacturer, an i-line mask aligner is employed to expose the resist while filtering out wavelengths shorter than 350 nm to ensure improved resist pattern wall verticality. Development of the photoresist is then carried out in Mr-Dev 600 for 10 to 30 minutes depending on the overall thickness of the structure in our case varying between 90 and 350 µm.

Consequently the conducting metal seed layer was deposited by magnetron sputtering, prior to the copper electro-plating. The copper electro-plating is performed in two steps using the same proprietary solution. At first, a low current is applied to ensure fine gap filling and thus an accurate definition of the structure. In a second step, a higher current is set for rapid growth of the bulk copper. The silicon carrier wafer is then either etched away in warm tetra – methyl ammonium hydroxide (TMAH), or released by dissolving the release layer. Finally the SU-8 mould is stripped away in a Piranha etching solution before gold-plating of the whole Cu waveguide structure.

III. TECHNOLOGY DEMONSTRATORS

A. Balanced Waveguide 1.25-1.39 THz HEB Mixer

In order to investigate the suitability of the developed micro-fabricating technique, we used it to produce a mixer block for a prototype of a 1.25-1.39 THz APEX T2 Hot Electron Bolometer (HEB) heterodyne receiver [6].

The receiver employs a balanced scheme allowing an effective use of available local oscillator (LO) power and rejecting the noise coming via LO port. The front section of the mixer block contains two corrugates horns, a 3 dB 90 degrees waveguide hybrid providing LO injection and RF signal distribution between the HEB mixers. The hybrid employs split-block technique and was fabricated using one layer SU-8 lithography as described in [5], [6].

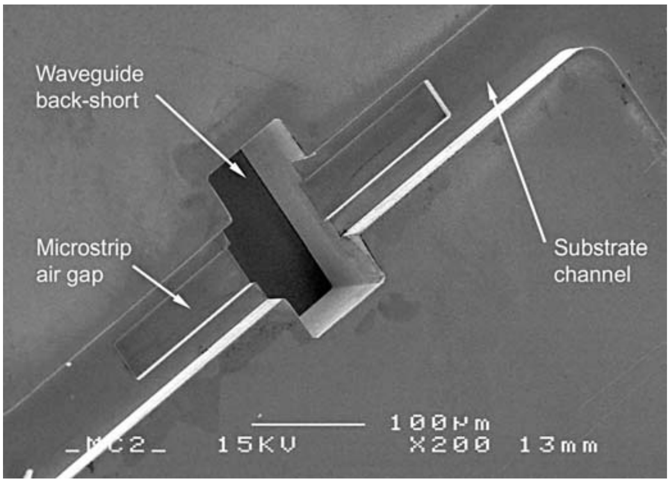

Fig.1. SEM image of the fabricated multi-level structure: a back-piece of the 1.3 THz HEB mixer block.

The second part of the mixer block is made in a back-piece layout and designed to take advantage of a multi-level micro-fabrication technology. The substrate channel uses suspended microstrip line configuration as depicted in Fig. 1 and accommodates a pair of HEB mixer substrates of 1000 μm×70 μm×17 μm in size. The back-short depth of 68 μm was chosen to provide an optimum input match of the mixer element over the entire signal frequency band 1.27–1.39 THz. The linear dimensions of the produced back-piece were within ±0.5 μm accuracy and the surface roughness was measured to be below 0.1 μm at all levels. The dimensions of the substrate channel are 31 μm deep and 80 μm wide; an air gap is 10 μm deep and 40 μm wide. Surface roughness measurement of the back-short bottom, seen as a darker area in the middle of Fig. 1, taken by Veeco Wyko NT1100 surface profiler, is presented in Fig.2.

Noise temperature measurements of the prototype 1.3 THz HEB balanced mixer were performed at an intermediate frequency of 2.5 GHz and are shown in Fig. 3. At these signal frequencies our balanced mixer demonstrates noise performance quite comparable to a single-end waveguide HEB mixer receiver [9], despite substantially longer waveguides are employed. Detailed description of the final receiver is presented in [10].

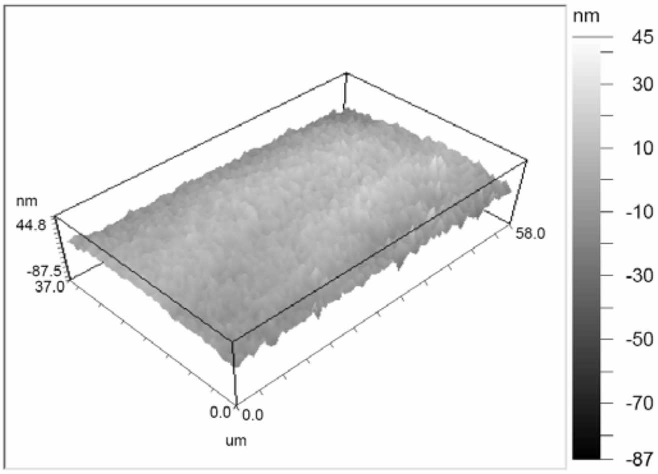

Fig. 2. Surface roughness measurement at the bottom of the back-short structure. The roughness scale is at the right.

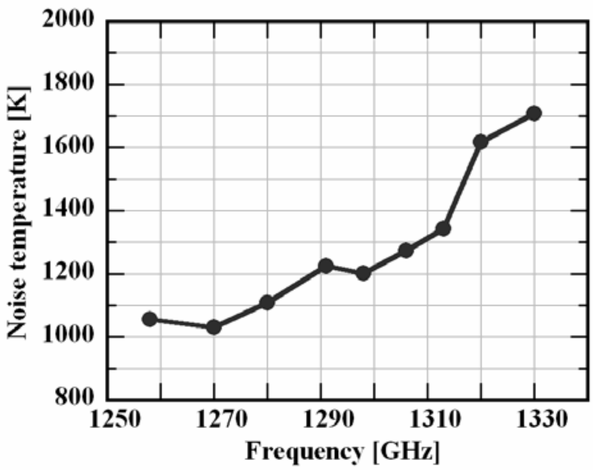

Fig. 3. Noise temperature of the prototype 1.3 THz HEB waveguide balanced receiver as a function of frequency taken at 2.5 GHz intermediate frequency.

G. 600-750 GHz Sideband Separation SIS Mixer

A 600 – 750 GHz Sideband Separation SIS mixer has been developed, produced by traditional mechanical technology and demonstrated [8]. As part of a collaborative project with SRON, Groningen, we have produced a micro-machined version of the mixer block this time employing the split-block layout. In this case, a complete waveguide circuit comprising the interface waveguides to RF and LO horns, 3-dB 90o hybrid, LO divider and LO injection directional couplers, the two substrate channels with air-gap for suspended microstrip line was manufactured in a three level waveguide integrated structure, Fig. 4. The linear dimensions of the produced back-piece were all within ±0.5 µm accuracy and the rms surface roughness was measured by the Veeco Wyko NT1100 surface profiler to be below 250 nm.

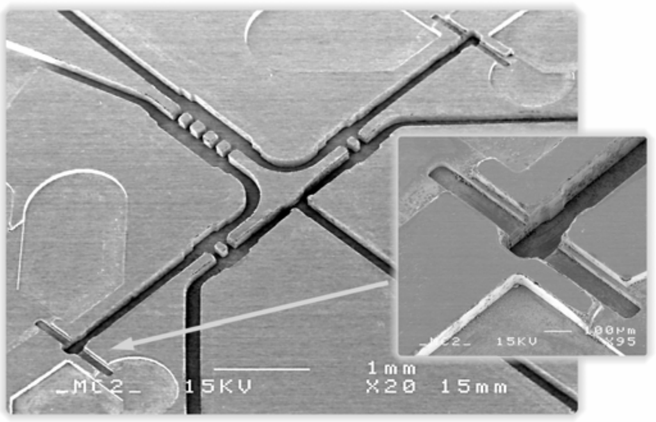

Fig. 4. SEM picture of the micro-fabricated 600-750 GHz 2SB SIS Mixer. The insert shows enlarged area of the substrate channel made in the 3-layer processing.

B. DISCUSSION

The application of the presented micromachining technique for the fabrication of Sub-Millimeter and THz components faces different limitations in reproduction of structures' geometry at the lower frequency end. For Sub-Millimeter wave components with bigger waveguide dimensions some peculiarities of the photolithography process should be taken into account. The verticality of the SU-8 pattern walls and internal photoresist stress issues could be challenging.

In order to explore possibilities of the presented micro-machining technology, we have fabricated a waveguide circuit for 2SB SIS mixer with even larger waveguide dimensions. The measured depth of the processed waveguides was 350 µm, which suggests that, used in a split-block layout the waveguide circuits down to 200 GHz could be fabricated using the proposed micromachining technique.

Towards higher THz frequencies, where the waveguide and substrate channel dimensions become of the order of a few microns, the accuracy of the photoresist layer thickness and the geometry patterning precision would play a major role in the fabrication yield. We envisage that use of DUV lithography would allow pushing this technology up to 6 7 THz while the major constrains would probably come from the availability of active elements, e.g., HEB, SIS, Schottky mixers and the ability of mounting such components into the waveguide mixer block.

Additional advantage of using the suggested technology is a possibility to ease the production of relatively complex waveguide circuits by employing a single photo-mask set. Along with achieving extremely high waveguide surface quality and thus low RF loss and possibility of using multi-level designs, the suggested technology opens solid prospects for building complex waveguide circuits, e.g., a balanced receiver scheme comprising the hybrid, bends and waveguide lines providing interfaces to the input horns and to the mixer back-piece or a sideband separation scheme with similar complexity. We plan a further step by employing the proposed technology for multi-pixel Sub-Millimeter and Terahertz receivers.

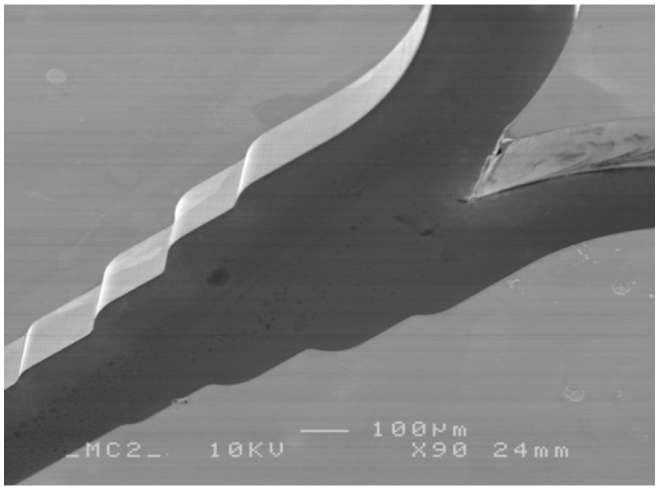

Fig. 5. Scanning electron microscope picture of the power divider in split-block technique with wall height of 350 microns

CONCLUSIONS

A new micromachining method combining multilayer photolithography and metal electroforming for the micro-fabrication of all-metal waveguide circuits and assembles comprising up to 3 levels is presented. Sub-micrometric linear dimension accuracy and excellent surface roughness of the components have been demonstrated. The processed components and circuits were implemented in various designs described above including a unique 1.3 THz balanced waveguide HEB mixer. The developed fabrication process allows fabrication of waveguide structures from about 200 GHz and up to approximately 7 THz and is extremely suitable for implementing waveguide-based designs including single end, balanced, sideband rejection and multi-element receivers.

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