Micromachined Coplanar Waveguides in CMOS Technology

Veljko Milanović, Michael Gaitan, Edwin D. Bowen, Mona E. Zaghloul

Abstract— **Coplanar waveguides were fabricated in standard complimentary metal–oxide semiconductor (CMOS) with post-processing micromachining. IC's were designed with commercial CAD tools, fabricated through the MOSIS[1] service, and subsequently suspended by maskless top-side etching. Absence of the lossy silicon substrate after etching results in significantly improved insertion loss characteristics, dispersion characteristics, and phase velocity. Measurements were performed at frequencies from 1 to 40 GHz, before and after micromachining. These show improvement in loss characteristics of orders of magnitude. For the micromachined line, loss does not exceed 4 dB/cm. Before etching, loss as high as 38 dB/cm is measured. Phase velocity $v_p \approx 0.8 \cdot c$ is achieved for the micromachined line.**

I. Introduction

With constantly increasing frequencies in communications and integrated circuits, there is a great demand for low-cost, miniature microwave components [1]–[3]. In most applications, there is also a need for easy integration with analog and digital circuits [4], [5]. It is for this reason that the recent advances in micromachining techniques have been finding numerous applications in the microwave field. Various passive microwave components fabricated by micromachining have been proposed by others [1]–[5]. In the previous work, however, many photolithographical masking steps both on the top and bottom side of the wafer are needed for micromachining and metal deposition [1]–[3]. The processes also include wafer bonding and are not compatible with commercially available CAD tools and CMOS foundries. Consequently, they do not provide easy integration with analog and digital circuits.

This letter presents a design of miniature microwave coplanar waveguides through a standard CMOS process with subsequent top-side etching. Generally, standard CMOS substrates are not suitable for fabrication of microwave components due to high losses in the silicon at microwave frequencies. The removal of the lossy silicon substrate material in the vicinity of the metal structures, however, significantly improves the insertion loss characteristics, transmission line dispersion characteristics, phase velocity, and impedance control capability. Thus, efficient microwave transmission lines can be obtained through CMOS. The design is fully compatible with commercial CAD tools, fabricated through the MOSIS service [6], and micromachined with no additional photolithographical steps [7].

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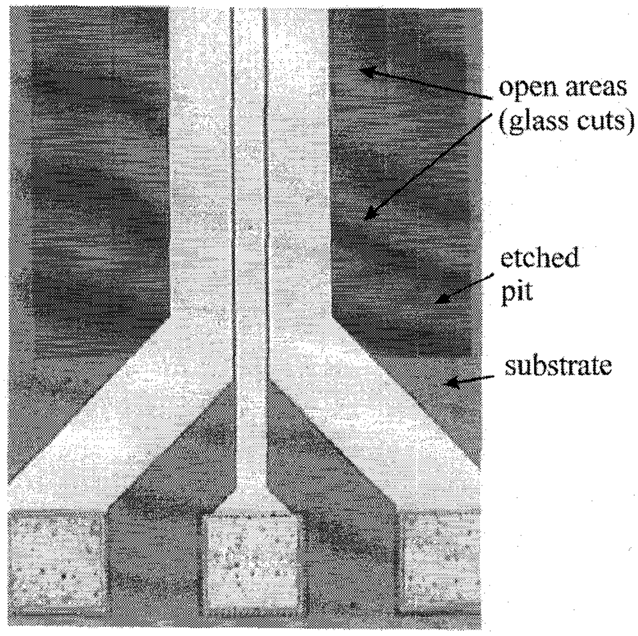

Fig. 1. Photograph of the fabricated coplanar waveguide near the electrical probing pads.

II. Design and Fabrication

The coplanar waveguides were designed to operate in TEM mode, with 50-Ω nominal characteristic impedance. Photograph of the fabricated waveguide in Fig. 1 shows the three coplanar waveguide strips in GSG-configuration (ground–signal–ground), the electrical probing pads, and the *open* areas that are necessary for micromachining of fabricated IC's. The cross-sectional diagram of the structures in Fig. 2 shows the important waveguide dimensions that determine the characteristic impedance and propagation modes. The layout for the transmission lines was created in Magic[1] [7], a public-domain CAD graphics layout editor. The conductor strips were laid out in the first-layer metal (aluminum). The waveguides connect with electrical probing pads in GSG configuration, with 160-μm pitch. The pads consist of both

[1]Certain commercial products are identified in this lettter to specify the procedure adequately. This does not imply recommendation or endorsement by NIST, nor does it imply that those commercial products are the best available for the purpose.

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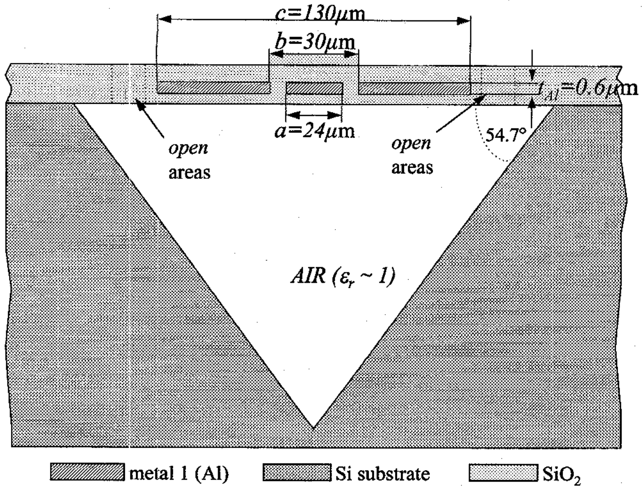

Fig. 2. Simplified diagram of the coplanar waveguide for CMOS implementation showing the cross section of the transmission line structure with the etched V-shaped pit.

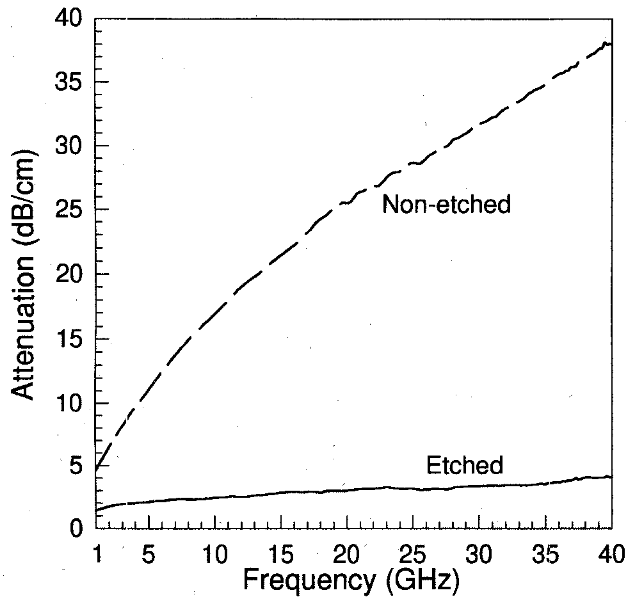

Fig. 3. Attenuation measurements of the coplanar waveguides before and after etching.

first- and second-layer metal connected by many vias. To fabricate the micromachined transmission line elements, one must design a structure that incorporates appropriate openings in the glass layers. Glass cuts must be patterned in such a way to allow the chemical etch to produce the desired cavity under the metal strips. The openings in the glass layers are designed using the *open* layer [7] in Magic, which incorporates all of the necessary glass cuts to expose the silicon substrate. This subsequently permits the etchant to penetrate from the top side of the chip and remove the substrate silicon from beneath the transmission lines, leaving only the desired metal and the encapsulating glass.

The IC's are fabricated in a commercial 2-μm CMOS n-well process, on a 460-μm-thick $\langle 100 \rangle$ wafer. After the IC fabrication process is complete, the chips are etched in two steps. In the first step, a gaseous isotropic etchant, xenon

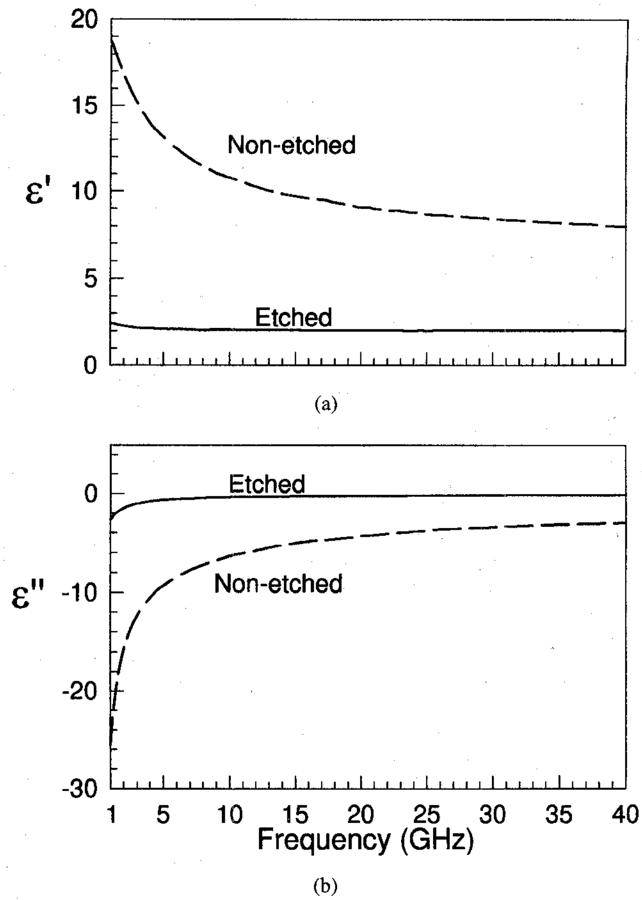

Fig. 4. Measured effective permittivity of the coplanar waveguides before and after etching: (a) real and (b) imaginary part.

difluoride (XeF_2) [9], is applied. Isotropic etch creates small cavities around each open area which propagate outwards radially. After approximately 10 min of etching (20 30-s pulses), the cavities from the two sides of the waveguides connect beneath the signal line. At that point, in the second step, the chips are etched by an anisotropic etchant, ethylene diamine-pyrocatechol water (EDP) [7]. The anisotropic etch follows the crystalline structure of the $\langle 100 \rangle$ wafer, forming a V-shaped pit as shown in Fig. 2. The completed walls of the etched pit slope at an angle of 54.7° from the surface plane and are aligned to the $\langle 111 \rangle$ crystallographic plane of the substrate material. The EDP etch takes approximately 80 min at 92°C.

III. Measurement Setup

For the experimental characterization of the transmission behavior of the waveguides, the test chip included lines of three different lengths along with short and open stubs. The longest line was 3.7 mm long, while the thru was 0.8 mm. Measurements were performed at frequencies in the 1 to 40 GHz range, using the HP8510C automatic network analyzer and a microwave probing station. A full set of measurements was performed on the transmission line elements both before and after micromachining. In both cases, one-tier thru-reflect-line (TRL) [10] calibration was performed on three lines of different lengths and short and open stubs. Because the sizes of the structures were small compared to the wavelengths of the test signals, probe placement had to be performed with high precision in order to ensure accurate phase measurements. From the de-embedded measurements [11], [12] of the s-parameters, the propagation constant and the effective permittivity was extracted at each frequency.

Insertion loss was calculated from transmission line measurements before and after etching. The attenuation results in Fig. 3 are given in dB/cm length. The measurements of the effective complex permittivity, $\varepsilon_{\text{eff}} = \varepsilon' + j \cdot \varepsilon''$, are shown in Fig. 4(a) and 4(b).

IV. Discussion of the Results

The measurements of transmission line insertion loss and effective permittivity show great improvement in performance after the structures were suspended. At 20 GHz, insertion loss is decreased 22 dB, while at 40 GHz, a 34-dB improvement is shown.

Absence of the lossy silicon substrate ($\varepsilon_{\text{Si}} = 11.7$) gives much better dispersion characteristics and higher phase velocity. Recently, methods for increasing phase velocity in coplanar waveguides have been proposed [13], outlining the need for extremely fast transmission lines. Our proposed methodology could possibly find similar applications. The micromachined transmission lines have phase velocity slightly below that in free space, $v_p \approx 0.7 \cdot c$. Before etching, at 20 GHz, $v_p \approx c/3$.

Unfortunately, the overall performance of the new transmission lines is limited by the relatively high series impedance in the metal strips due to the very small thickness of the metal layers in commercial CMOS (<1 μm). Because this is not an available MOSIS design parameter, the thickness cannot be varied, and losses can be further decreased only by increasing the line-widths.

V. Conclusion and Future Work

A new coplanar waveguide design suitable for application in a broad class of sensors and integrated circuits was described. The new design is based on the process of micromachining of the semiconductor substrate material in the vicinity of the transmission line. The advantages of the proposed design are the low cost of fabrication and monolithic integration with analog and digital CMOS circuits. The presented coplanar waveguide exhibits low loss and very high phase velocities in the 1 to 40 GHz range. The availability of efficient microwave structures on CMOS substrates might in the future allow for larger scale integration for microwave sensor and communication circuits at greatly lowered costs.

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