Minimization of Passive Circuits Losses realized on Low Resistivity Silicon Using Micro-Machining Techniques and Thick Polymer Layers

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Abstract — **In this paper, a novel technological solution using both silicon surface micromachining and thick polymer layer deposition on low resistivity silicon substrate (20 Ω.cm) has been investigated. The proposed structure achieves both a low attenuation level and a high quality factor. The silicon etching into the coplanar slots leads indeed to a noticeable decrease of the losses, whereas filling the gaps with the polymer BCB avoids a degradation of the effective permittivity.**

I. Introduction

In the last few years, the demand of broadband microwave and millimeter-wave communication systems has seriously increased. Consequently, the use of standard silicon as a basic substrate for monolithic integrated circuits (MICs) has emerged as an attractive option in the field of microwave and millimeterwave communications because of its low cost and high integration ability [1].

However, transmission lines and passive circuit components, realized directly on top of a standard low resistivity silicon substrate, show high loss dispersion and low Q-factors in the high frequency range [2,3]. To overcome these drawbacks, different approaches have been investigated.

The first approach consists in bulk micromachining [4,5] or in surface micromachining [6] in order to remove the lossy silicon. In the second approach, a polyimide layer is used on top of the low-resistivity silicon substrate [7,8]. In that way, the low loss polyimide is substituted for the lossy silicon in the region where the electric field lines are concentrated.

Based on these previous investigations, our study deals with a novel technological issue. It consists in micromachining the silicon substrate into the coplanar slots, which are subsequently filled with a thick polymer layer (cf. Figure 1).

In order to be able to well estimate the characteristics and the interests of this structure, we have also realized CPW lines on 10 μm thick polymer layer without and with organic etching in the slots, as illustrated in Figure 2.a and b respectively.

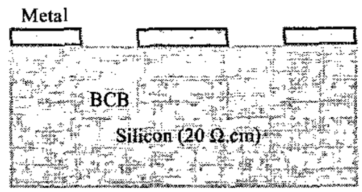

Figure 1 : Cross schematic of CPW lines on BCB with silicon micromachined in the slots

Regarding this organic layer, we have chosen to use the Benzocyclobutene (BCB) dielectric because of its attractive advantages, especially its low dielectric constant (2,65), low dissipation factor ($0.8.10^{-3}$-2.10^{-3} at 1kHz-10GHz), and low water absorption compared to polyimide [9].

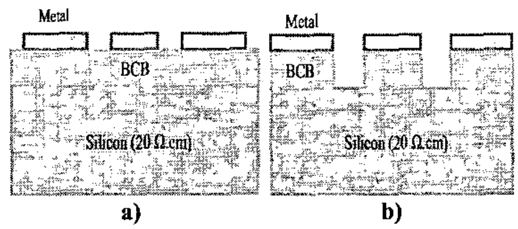

Figure 2 : Cross schematic of CPW lines (a) without and (b) with polymer micromachining in the slots

A comparative study between the durimide 7320 from the Arch chemicals company and the benzocyclobutene 4026-46 (BCB) from the Dow chemicals company has indeed shown that the BCB presents the lowest insertion loss, with 0.33 dB at 20 GHz rather than 3.2 dB for the durimide, as illustrated in Figure 3.

Therefore, the BCB looks as an ideal candidate for millimeter-wave applications.

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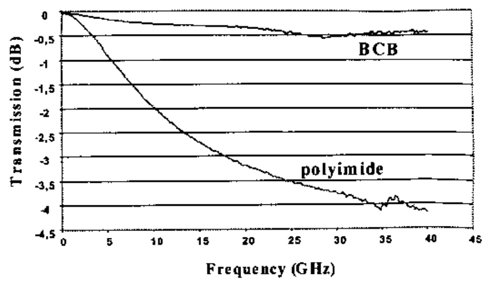

Figure 3 : Transmission of CPW lines on BCB and polyimide

This paper is organized as it follows. The first section is dedicated to the technological process developed for the realization of coplanar transmission lines (CPW) on low-resistivity substrate, including the silicon surface micromachining and the thick polymer interface layer. Next, we present the correspondent experimental results. Finally, we conclude.

II. TECHNOLOGICAL PROCESS

In the case of the basic structure described in Figure 2.a, the technological process is divided in seven main steps.

First, we proceed to an adequate cleaning of the low resistivity silicon wafers (20 Ω.cm) immediately before dispensing BCB films, in order to avoid any organic impurities and other contaminations, and thus to obtaining minimal losses in the substrate [10,11]. Then, we use the AP 3000 adhesion promoter on top of the silicon substrate. Just after this step, 10 µm of polymer layer is spun onto the silicon substrate. Follows a hardcure of the BCB layer for one hour at 250 °C under nitrogen flowing. After the polymerization of the organic layer, the next step consists in the evaporation of a titanium and gold (Ti/Au) seed layer on top of the wafer, with a thickness of 1000 A° and 5000 A° respectively. The 3 µm thick coplanar conductors, realized in gold, are then electroplated in a thick photoresist mould with a process similar to the LIGA one. Finally, gold and titanium etchings in the coplanar slots are performed in order to release the CPW conductors.

In order to obtain the structure of the Figure 2.b, an additional micromachining of the BCB layer is achieved into the coplanar slots, where the electromagnetical fields are tightly concentrated. This etching was performed through a plasma composed of both oxygen and fluorine during 40 minutes for a BCB layer of 10 µm thick. The coplanar conductors were used as a mask protection during this step. A picture of one of the two coplanar slots with the BCB etching is presented in Figure 4.

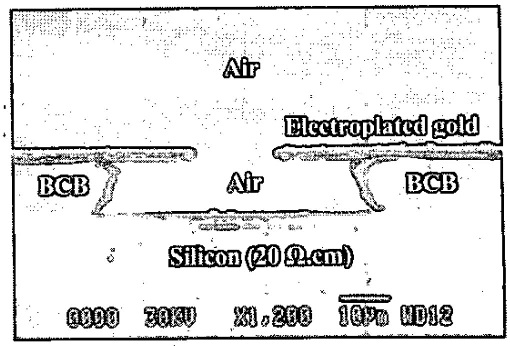

Figure 4 : Picture of a CPW lines with BCB etched in coplanar gaps

The proposed technique presents the advantage that the etching is self-aligned thanks to the metallization. Nevertheless, as it behaves isotropically, there is some BCB over-etching under the conductors.

Concerning the structure of Figure 1, an additional silicon surface micromachining before the BCB deposition is applied into the coplanar slots. This technique is enabled thanks to the high planarization level of the polymer (DOP: >90%). The silicon etching is made with a deep RIE tool. A picture of the correspondent structure with 10 µm depth of silicon etched is presented in Figure 5.

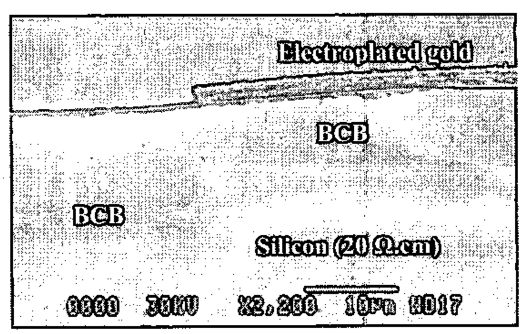

Figure 5 : Picture of a CPW lines using silicon micromachining in the coplanars gaps

All these processes present the interest to be CMOS and BiCMOS compatible with a low thermal budget absolutely needed for post-processing.

Next paragraph presents the characterization results of these structures.

III. RESULTS

The characterization has been performed from 0.4 to 67 GHz. Attenuation coefficient, effective permittivity and quality factor have been extracted from the measurements and are presented in Figure 6, Figure 7 and Figure 8 respectively.

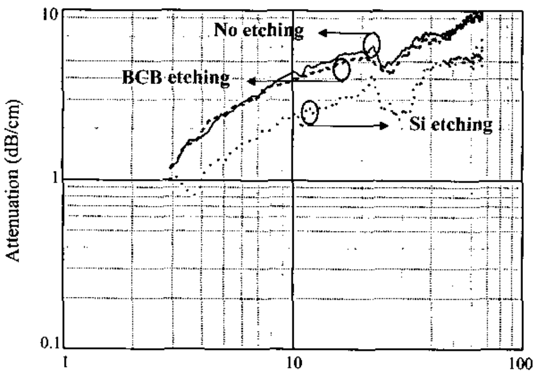

Figure 6 : Attenuation coefficient of the studied CPW lines on BCB

Attenuation and Q factor in figures 6 and 8 present a notch and a peak at 30 GHz respectively, which are only due to a non ideal calibration and do not result from the realized structures.

On Figure 6, only a small difference between the non-etched CPW line and the one including the BCB micromachining is noticeable. On the other side, an improvement of approximately 50 % of the attenuation parameter has been obtained with the silicon etched structure with respect to the basic one. This result is as expected since the silicon presents higher losses (tg δ = 0.018) than BCB (tg δ = 0.002). Coplanar transmission lines present thus a lower insertion loss close to 4.6 dB/cm at 40 GHz with silicon etching, instead of 6.3 dB/cm at the same frequency for the basic structure.

Concerning the effective permittivity results, we can notice a decrease of this parameter for both BCB and silicon etchings, with 2.5 and 2.2 values respectively, compared to the 2.8 one observed without any micromachining. The last one is, of course, much lower than for the BCB micromachining, as the silicon permittivity (11.9) is higher than the polymer one (2.65).

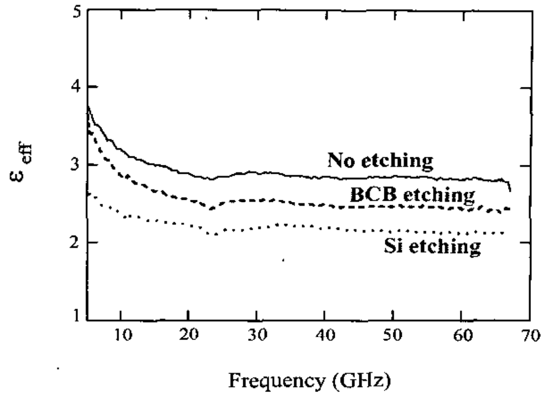

Figure 7 : Effective permittivity of the studied CPW lines on BCB

Nevertheless, the observed improvements on the attenuation and effective permittivity parameters are not sufficient to prove the superior performances of the new realized components. The quality factor Q needs also to be evaluated especially for filtering applications. This parameter is presented in Figure 8.

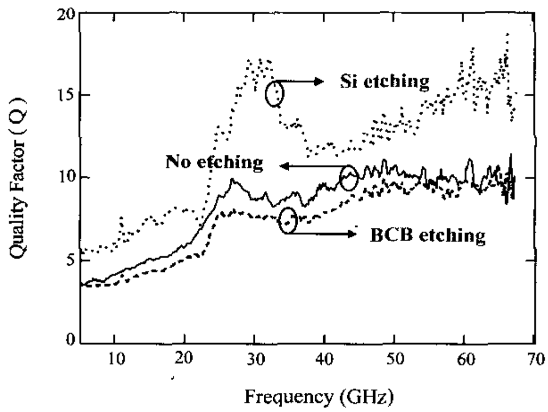

Figure 8 : Quality factor of the studied CPW lines on BCB

In fact, the quality factor, Q, of a coplanar transmission lines (CPW) is expressed as the ratio of propagation constant, β, and attenuation constant, α, as given by the following formula:

$$Q = \frac{\beta}{2.\alpha} = \frac{\omega.\sqrt{\varepsilon_{reff}}}{2.\alpha.c} \qquad (1)$$

where ω is the angular frequency, c is the velocity of light in vacuum, and ε_{reff} is the effective dielectric constant.

A high quality factor value, Q, can thus be obtained with an optimization of both the attenuation, α, and the propagation constant, β. This last one is proportional to the square root of the effective dielectric constant. A larger reduction of this last quantity compared to a small decrease of the attenuation constant versus frequency induces a deterioration of the quality factor. As described in Figure 8, the silicon micromachined structure exhibits the best quality factor values compared to the non-etched lines, whereas the BCB etched one presents a degradation of this parameter. The superior Q in the silicon etched structure is due to the fact that, in this case, the attenuation coefficient reduction is not compensated by the decrease of the effective permittivity.

This new class of silicon micromachined technology has thus demonstrated excellent performances, easiness in fabrication, and very low cost in development.

IV. CONCLUSION

In this paper, we have presented a technology based on the use of simultaneously a silicon surface micromachining and a thick polymer layer (BCB) inserted between the lossy silicon substrate and the coplanar transmission lines (CPW) strips. This technique presents the advantage of being compatible with IC post-processing. Thanks to the micromachining of the silicon substrate in the coplanar gaps, which are subsequently filled with polymer, a noticeable insertion loss reduction has been achieved. Both a 50% reduction of the attenuation coefficient and an important improvement (30 to 50%) of the quality factor value are demonstrated using this kind of structure.

ACKNOWLEDGEMENT

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