Micromachined Strip Line with SU-8 as the Dielectric

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Abstract **For the first time this paper presents strip lines fabricated using SU-8 as the dielectric material. It shows the complete fabrication process of micromachined strip lines with a total height of 35.5µm as well as their characterization by on-wafer S-parameter measurements with frequencies up to the mm-wave range. Strip lines with a a strip thickness of 2.5µm, a line length of 3mm and variations of strip width between 6 and 30µm were manufactured and measured. The characteristic impedance, the phase constant, the phase velocity and the attenuation constant of the lines were determined from the measured S-parameters. Characteristic impedance values between 86Ω and 38Ω were measured and on the 48Ω strip line an attenuation constant of 1.9dB and 0.58dB at 10GHz and 48GHz respectively were determined. Since the fabricated strip line is totally shielded and its dielectric consists solely of SU-8, determination of the relative dielectric constant and the loss tangent of SU-8 was performed from microwave measurements on the strip lines. A relative dielectric constant of 3.1 and a loss tangent of 0.043 for SU-8 was determined.**

I. Introduction

The epoxy based photoresist SU-8 is widely known to MEMS producers, who appreciate the possibility of this material to form thick layers with excellent aspect ratio [1]. The micromachining capabilities of SU-8 in conjunction with microwave applications represent an interesting research area. Recently, some contributors have reported on microwave applications of SU-8 [2], [3]. In [3] the fabrication of microstrip transmission line using SU-8 was presented showing some measurements but missing more details on the electrical loss properties of SU-8. From [4] and [5] more information on the loss properties of SU-8 can be obtained, but this data is based on time-domain spectroscopy rather than microwave measurements. In this paper we report on the design, fabrication and characterization of micromachined strip lines using SU-8 as the dielectric. Based on these measurements we are able to determine the relative dielectric constant ε_r and the loss tangent $\tan\delta$ of SU-8.

II. Design And Fabrication

The schematic cross section of a shielded strip line is shown in Fig. 1. It consists of a signal electrode surrounded by a dielectric which is likewise surrounded by a shielding ground electrode. In this shielded form the strip line is very similar to a rectangular coaxial line. The geometrical parameters of the strip line are the thickness t and width w of signal electrode as well as the height h and the width w_g of the dielectric. From the electrical parameters, the conductivity σ of the metal and the relative dielectric constant ε_r and loss tangent $\tan\delta$ of SU-8 have been taken into account.

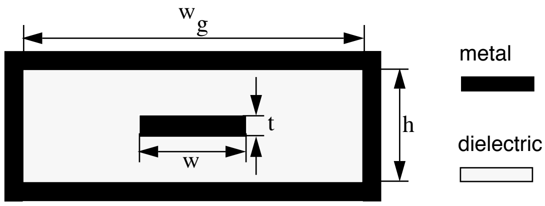

Fig. 1. Schematic of a shielded strip line with relevant geometrical parameters.

Variation of the strip width w when the other parameters are kept fixed implies a variation of the characteristic impedance Z_0. In order to determine Z_0 from design values two approaches were applied. One refers to the approximate equations from [6] which are:

$$Z_0 = \frac{1}{\sqrt{\varepsilon}} \frac{94.172}{x(w/h) + (1/\pi)\ln F(x)} \qquad (1)$$

$$F(x) = \frac{(x+1)^{x+1}}{(x-1)^{x-1}} \qquad (2)$$

$$x = \frac{1}{1 - t/h} \qquad (3)$$

In these equations the ground electrode is assumed to be very long which corresponds to the configuration of a strip line which is not shielded. Therefore the parameter w_g is not included. Some calculated curves for the characteristic impedances as function of the strip width w and relative dielectric constant ε_r are shown in Fig. 2.

The second approach to determine Z_0 was the Finite Element Method which was implemented in a program in order to calculate the static capacitance per unit length C which is associated to Z_0 by the following expression:

$$Z_0 = \frac{\sqrt{\varepsilon_r}}{c_0 C} \qquad (4)$$

In (4) c_0 is the phase velocity in air. As opposed to the approximate equations (1)-(3), in the FEM-program the parameter w_g is used.

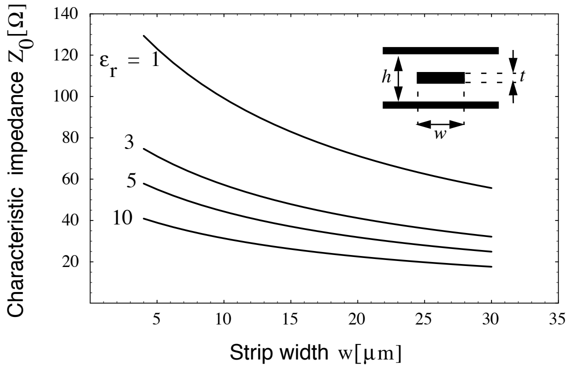

Fig. 2. Characteristic impedance Z_0 of the strip line calculated using analytical expressions (1)-(3) as a function of ε_r and w. Remaining parameters are $h = 30\mu m$ and $t = 3\mu m$.

Comparison of the results from both, the FEM-program and the approximate equation (1)-(3), demonstrates that the approximate equation is very accurate, as can be seen in Fig. 3, and that the shielded and not-shielded strip line produces the same characteristic impedances when w_g is kept as least three times h.

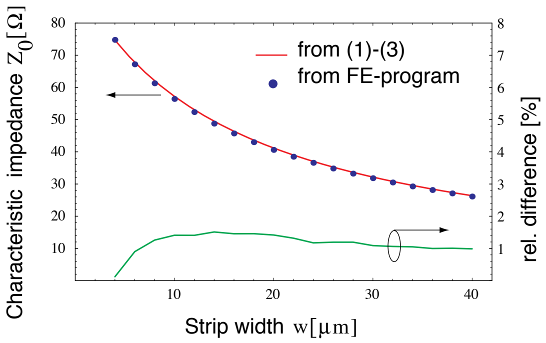

Fig. 3. Comparison of Z_0 calculated by analytical and numerical approaches, assuming $\varepsilon_r = 3$, $h = 30\mu m$ and $t = 3\mu m$.

In the design of the strip lines a relative dielectric constant ε_r of SU-8 between 3-4 was considered in accordance with the reported values in [3] and [4].

The fabrication process of the strip line consists mainly of 3 metallization, 2 SU-8 deposition and one planarization steps (Fig. 4). Metallization is made by sputtering of 50nm TiW and 100nm Ni followed by electrodeposition of a 2.5μm thick copper layer. Each dielectric layer is made by spin-on of 16.5μm of SU-8 and a subsequently photolithography step. After deposition and processing of the first SU-8 layer planarization of the whole wafer is performed by electroplating of the uncovered area of the first metal with a 16.5μm thick copper layer. In the next process step, the signal electrode and the contact pads are fabricated. In Fig. 5. a 3-dimensional representation of a strip line with the contact pads is shown. In one picture the visibility of the dielectric layer is suppressed in order to observe in a better way the transition from the contact pads to the strip line, which in essence represents a transition between coplanar and strip line.

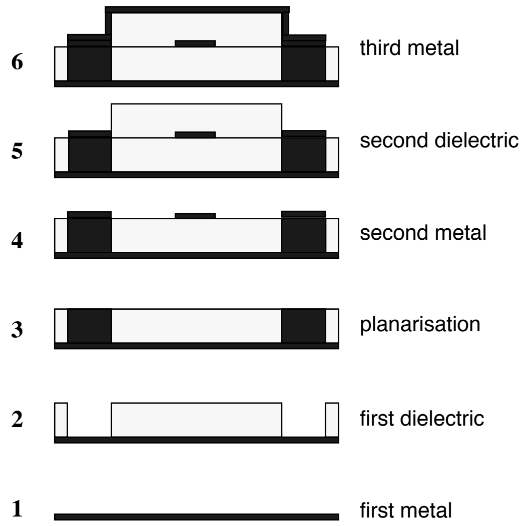

Fig. 4. Fabrication steps of the strip line. Dimensions are not to scale. See text for geometrical dimensions and materials used.

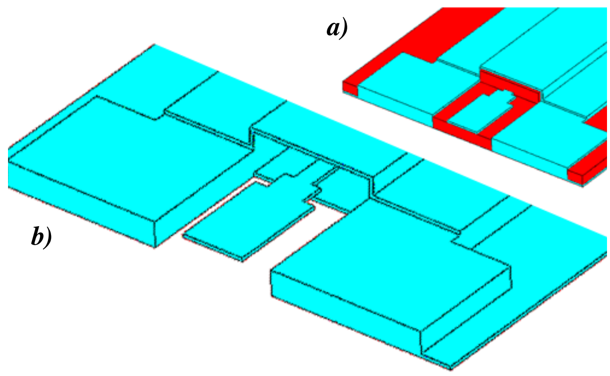

Fig. 5. Three dimensional representation of strip line with contact pads for microwave on-wafer measurements, (a) with dielectric being visible and (b)with the visibility of dielectric being suppressed.

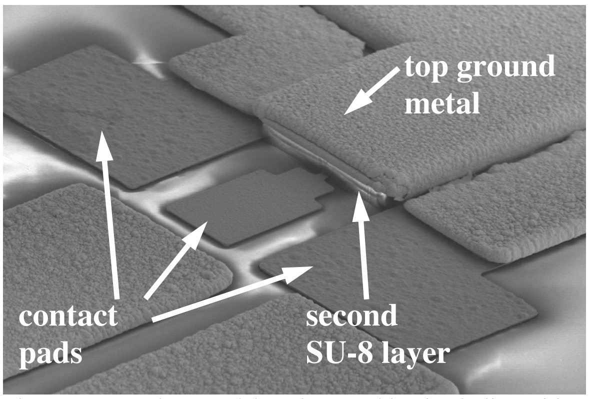

Fig. 6. SEM-image of the micromachined strip line with SU-8 as the dielectric. The strip line is connected to the contact pads for on-wafer measurements.

The contact pads were designed in order to be used with commercial microwave probes with 100μm pitch coplanar tips. Furthermore, the 50Ω port impedance of the measurement system was considered in its design. A variety of strip lines were designed for characterization purposes. Variation consisted in a combination of 6 values of strip width w[μm] = 6, 8, 10, 15, 20 and 30, and 4 values of strip length l[mm] = 0.5, 1, 2 and 3.

The strip lines were fabricated on a 4 inch Si-Wafer but we would like to point out that many other substrates can be used. In Fig. 6 an SEM-image of the fabricated strip line with contact pads is shown.

III. Results And Discussion

An HP8510C network analyzer and an on-wafer probe station were used for microwave measurements in the frequency range up to 48GHz. Line-Reflect-Match (LRM) calibration was applied to the system. S-parameter measurements were performed on all strip lines but in order to minimize the influence of the contact pads, the longest strip lines, which has $l = 3mm$, were chosen for extraction of the characteristic impedance Z_0 and propagation constant $\gamma = \alpha + j\beta$. Extraction of these line parameters was performed according to [7] and under consideration of the electrical length of contact pads. The phase constant β for all the strip lines are shown in Fig. 7.

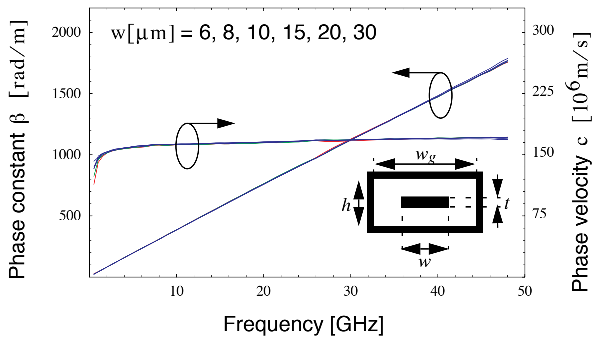

Fig. 7. Phase constant β and phase velocity c of the fabricated strip lines. $w_g = 98\mu m$, $h = 35.5\mu m$, $t = 2.5\mu m$.

The phase constant β is nearly linear with respect to frequency f as expected from the quasi-TEM model. The linearity factor between the phase constant β and the angular frequency $\omega = 2\pi f$ is the phase velocity $c = \omega/\beta$ which is also shown in Fig. 7. With the phase velocity $c = c_0/\sqrt{\varepsilon_r}$ and the velocity in vacuum $c_0 = 1/\sqrt{\varepsilon_0\mu_0}$, the relative dielectric constant ε_r of SU-8 can be determined. In Fig. 8 the determined ε_r for all strip lines are shown as function of frequency. We determine a value of 3.1 for ε_r of SU-8 at 48GHz.

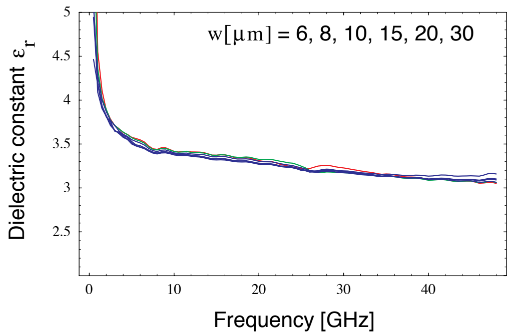

Fig. 8. Relative dielectric constant ε_r of SU-8 determined from S-parameters measurements on strip lines with different strip width w. $w_g = 98\mu m$, $h = 35.5\mu m$, $t = 2.5\mu m$.

The real and imaginary part of the characteristic impedance Z_0 of the strip lines are shown in Fig. 9. The frequency is limited to 20GHz because near 26GHz a nontypical run of the curves was observed. The reason is that the length of the measured strip lines which is $l = 3mm$ represents half of the wavelength λ at this frequency. Beginning from 10GHz the imaginary part of Z_0 nearly vanishes. At this frequency Z_0 consists only of the real part, these values as function of the strip width w are depicted in Fig. 10 where also the Z_0 calculated with equations (1)-(3) is shown. For the latter an ε_r of 3, $t = 2.5\mu m$ and $h = 35.5\mu m$ were assumed.

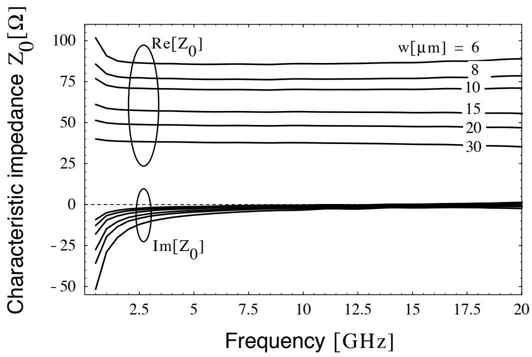

Fig. 9. Real and imaginary part of the characteristic impedance as function of the frequency for strip lines with different strip width w.

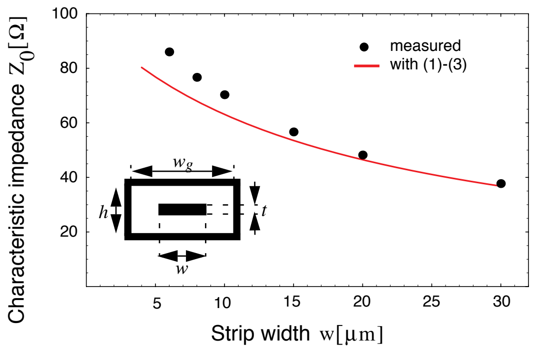

Fig. 10. Measured characteristic impedance at 10GHz as function of the nominal values of strip width w compared with calculated values. $w_g = 98\mu m$, $h = 35.5\mu m$, and $t = 2.5\mu m$.

One can observe that the deviation between measured and calculated Z_0 is small for wider strip widths whereas for narrow strip widths it becomes more significant. The manufacturing tolerance of the strip width has obviously more impact on narrow strips than wider ones. The attenuation constant α vs. frequency is shown in Fig. 11. The attenuation of the strip lines consists of both the conductor loss and the dielectric loss. The former is related to the skin-effect in non-ideal conductors and the latter is related to the conductance of the dielectric which is itself related to the loss tangent $\tan\delta$ of the SU-8. The skin-effect dominates in almost the whole frequency range because the strip thickness $t = 2.5\mu m$ is more than 3 times the skin depth $\delta = 1/\sqrt{\pi f\mu\sigma}$ beginning with $f = 7GHz$ ($\delta = 0.79\mu m$). The 48Ω strip line ($w = 20\mu m$) has an attenuation constant of $0.19dB/mm$ and $0.58dB/mm$ at 10GHz and 48GHz respectively.

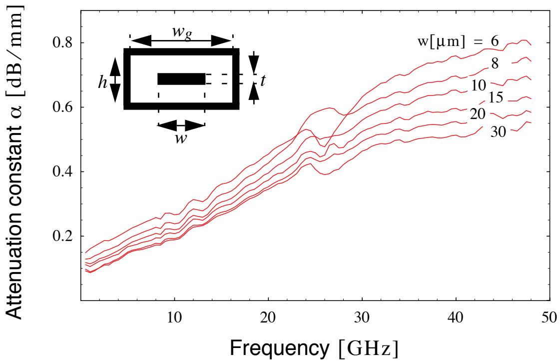

Fig. 11. Measured attenuation constant α for strip lines with different strip width w.

In a next step the lumped elements per unit length (p.u.l) of the equivalent circuit model for the strip line were extracted. The following expressions, valid for quasi-TEM transmission lines, were used

$$R = \mathrm{Re}[\gamma \cdot Z_0] \qquad L = \mathrm{Im}[\gamma \cdot Z_0]/\omega$$
$$G = \mathrm{Re}\left[\frac{\gamma}{Z_0}\right] \qquad C = \mathrm{Im}\left[\frac{\gamma}{Z_0}\right]/\omega \tag{5}$$

The capacitance and inductance per unit length for all strip lines are listed in Table 1.

Element p.u.l.	**Strip width** w [μm]					
	6	8	10	15	20	30
C, $\left[\frac{pF}{m}\right]$	72	80	87	108	127	163
L, $\left[\frac{nH}{m}\right]$	528	471	431	347	295	231

Table 1 Capacitance and inductance per unit length for the fabricated strip lines with different strip width w.

The loss tangent $\tan\delta$ of SU-8 is related to the capacitances p.u.l. C and the conductances p.u.l. G by the following expression

$$\tan\delta = \frac{G}{\omega C} \tag{6}$$

Using (5) the $\tan\delta$ of SU-8 was determined from the measurements performed on all strip lines. The result is depicted in Fig. 12.

All strip lines with different strip widths w show a nearly constant curve of loss tangent $\tan\delta$ as function of frequency. At 10GHz the mean value is $\tan\delta = 0.043$. To the author's best knowledge the loss tangent of SU-8 was determined for the first time directly from microwave measurements. However a loss tangent of 0.043 is too high when compared with the values of other microwave dielectrics.

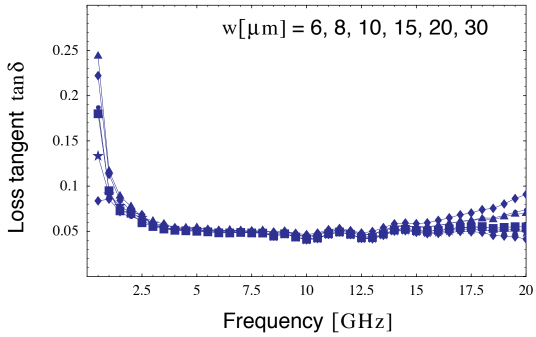

Fig. 12. Loss tangent $\tan\delta$ of SU-8 determined with (6) and using the p.u.l. capacitances and conductances measured on the strip lines with different strip width w.

IV. Conclusion

An ε_r of 3.1 at 48GHz and a loss tangent $\tan\delta$ of 0.043 for SU-8 were determined from microwave measurements. Due to the high value of its $\tan\delta$, SU-8 is not optimal for high frequency and, at the same time, low loss applications. However SU-8 offers a diversity of high-frequency applications when its excellent micromachinable property is exploited rather than its use as the dielectric. The developed technology consisting of SU-8 and electrodeposition of copper is useful for this aim.

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