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Wide Band-stop Microwave Microstrip Filter on High-resistivity Silicon

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Abstract: Low-resistivity silicon (standard CMOS-grade silicon) is a troublesome issue for the microwave passive components. One solution is using high-resistivity silicon (HRS). Wide band-stop filter on high-resistivity silicon (HRS), 5 kΩ-cm, is introduced. The filter is simulated and successfully fabricated in microstrip technology. Relative stop band width is over 70 % for 20 dB suppression. Reflection, S11, in the pass band is -17 dB or lower. Metallization was sputterd aluminum (Al) and silver epoxy was used for bonding.

Key words: Microwave, High-resistivity silicon (HRS), Band-stop filter, Sputtered aluminum (Al)

Širokopasovni zaporni mikrovalovni Mikrotrakasti filter na visoko uporovnem siliciju

Povzetek: Nizko uporovni silicij (standardni CMOS silicij) ni primeren za mikravalovne pasivne elemente. Ena izmed rešitev je visoko uporovni silicij (HRS). Predstavljen je širokopasoven zapeerni filter na visoko uporovnem 5 kΩ-cm siliciju. Filter je simuliran in uspešno izveden v mikrotrakasti tehnologiji. Relativna bločna širina je preko 70 % pri dušenju 20 dB. Refleksija S11 v prepustnem pasu je -17 dB ali manj. Metalizacija je izvedena z napRševanjem aluminija, bondiranje pa s srebrno pasto.

Ključne besede: mikro valovi, visoko uporovni silicij (HRS), pasovni zaporni filter, napršeni aluminij

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1. introduction

Microwave passive components on silicon (Si) substrate in microstrip technique are important for microwave integration. Wide band-stop filters are, also, important function of passive components. Si is a vital material for present microelectronics but has some functional problems.

Low-resistivity silicon (standard CMOS-grade silicon, resistivity 1 - 30 Ω-cm) is a troublesome issue for the microwave passive components [1], [2]. Due to high substrate loss it is a problem to fabricate useful traditional passive microwave components on such substrate. One of the solutions is to apply benzocyclobutene (BCB) to serve as the interface layer [2], [3]. BCB has a low dielectric loss and low dielectric constant. The problem is a new material in technology and a weak compactness of the structure due to two substrates. Thin BCB layer, also, need very narrow microstrip lines (<< 100 μm).

Another solution is using high-resistivity silicon (HRS) with resistivity higher than 2 kΩ-cm [1], [4]-[7]. Simulated and successfully fabricated microstrip attenuator on high-resistivity silicon (HRS) was presented in [4]. In [4] microstrip lines were fabricated as a metallization of 2 μm thick sputtered aluminum (Al) layer. Examples of the sputtered Al applied to HRS was, also, reported in [5,6]. Aluminum was chosen as the conductor because this is the standard foundry metal [6], even for the band around 30 GHz [5].

The aim of this paper is to simulate and fabricate wide band-stop filter on the HRS substrate. The idea is to simulate circuit with ideal waveguides and to apply it for fabrication of microstrip filter structures [8]. The solution is adjusted to the conditions of HRS and common etching technological ability. The narrowist microstrip line is fixed to 50 μm for the classical etching technology. Metalization is sputtered Al and silver epoxy is used for bonding SMA connectors to the microstrip lines [9, 10].

2. Design and simulation

Calculation of the circuit with the ideal waveguide is done according to design curve presented in [8]. The

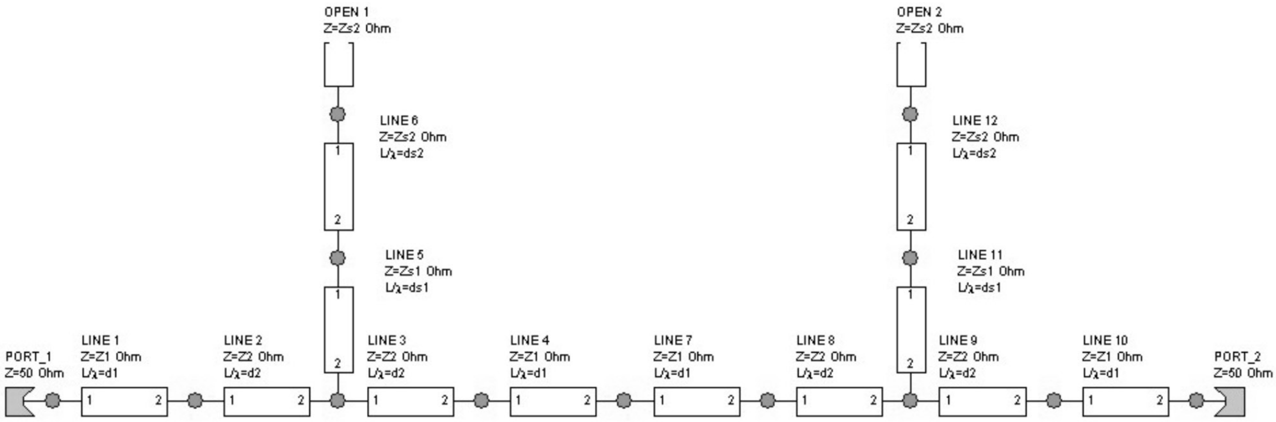

Figure 1: Ideal circuit of the introduced low-pass filter, $Z_2 = Z_{s1} = 84.2\ \Omega$; $Z_1 = Z_{s2} = 31.9\ \Omega$

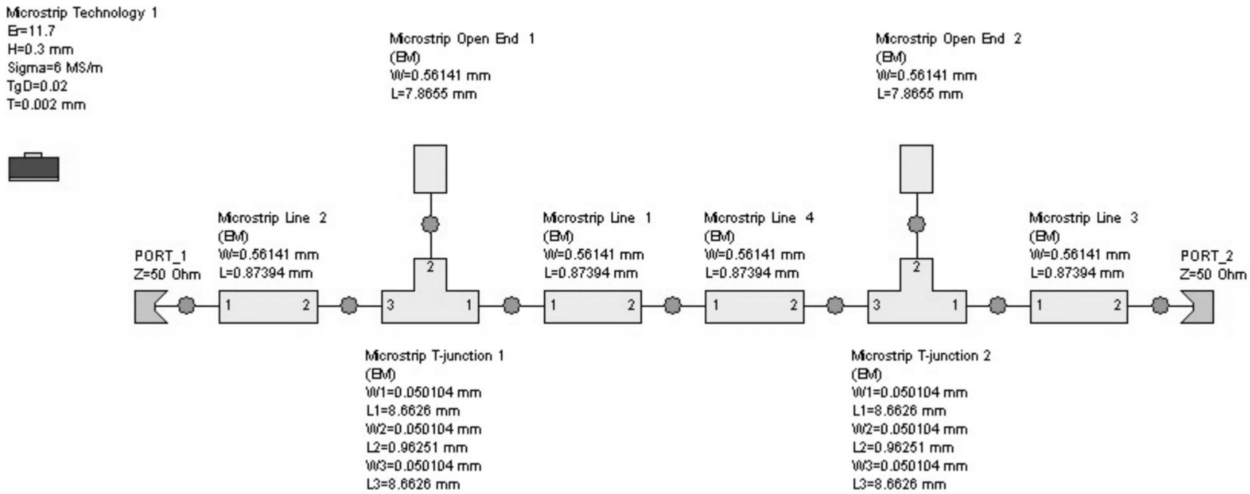

Figure 2: Ideal microstrip presentation of the filter (narrow line, 84.2 Ω, is 50 µm).

curves present optimal values of the pair of maximum and minimum characteristic impedances.

Characteristics of the used HRS substrate are: substrate height h = 300 µm, relative dielectric constant ε_r = 11.7 and resistivity is ρ = 5 kΩ-cm. Dielectric losses were chosen to be tgδ = 0.02. Metallization is Al thickness t = 3 µm with chosen conductivity to be low, 6 MS/m. The highest characteristic impedance is to adjust common etching technological ability. It is related to the minimum microstrip line width which is chosen to be 50 µm and corresponds to 84.2 Ω. The lower characteristic impedance is 31.9 Ω. Ideal filter circuit and the ideal filter in microstrip technology are presented in fig. 1 and fig. 2, respectively.

Fig. 3 presents pattern of the introduced filter. Wide microstrip lines are something shortened according to influence of edge effect. Open stubs are folded to reduce the size of the structure. 50 Ω lines (240 µm wide) for connectors are included at both ends, as shown in fig. 3.

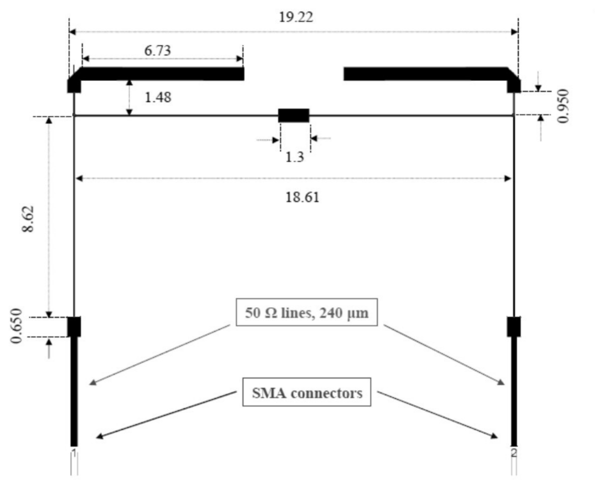

Figure 3: Compact version of the filter (19.22 mm x 11.36 mm). Narrow lines are 50 µm wide ; wide lines are 560 µm wide.

Simulation results for the ideal model, fig. 1, and 3D electromagnetic simulation (IE3D Zeland Software ver. 10) of the real pattern, fig.3, are presented in fig. 4. They are in agreement for frequency position of the stop-band minimum and the filter shape. Logical difference is for losses, especially in the pass-band region. Relative band-width of the stop band is around 70% for 20 dB suppression.

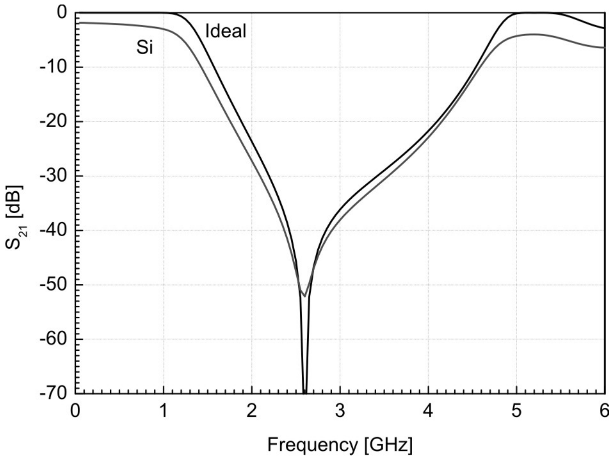

Figure 4: S_{21} of ideal circuit and 3D EM simulation

3. Fabrication and measurement

Photo of the fabricated filter with SMA connectors is presented in fig. 5. Aluminum (Al) with 1% of Si was sputtered on Si substrate (wafer) to form metallization 3 μm thick. Content of 1% of Si obtains no penetration of Al into the Si substrate. Pattern of the filter, presented in fig. 3, was etched in Al metallization. SMA connectors were bonded on the ends of the 50 Ω microstrip lines (240 μm wide, fig. 3) using silver epoxy. Ground plane is a brass metal plate bonded to the lower side of the silicon substrate using silver epoxy.

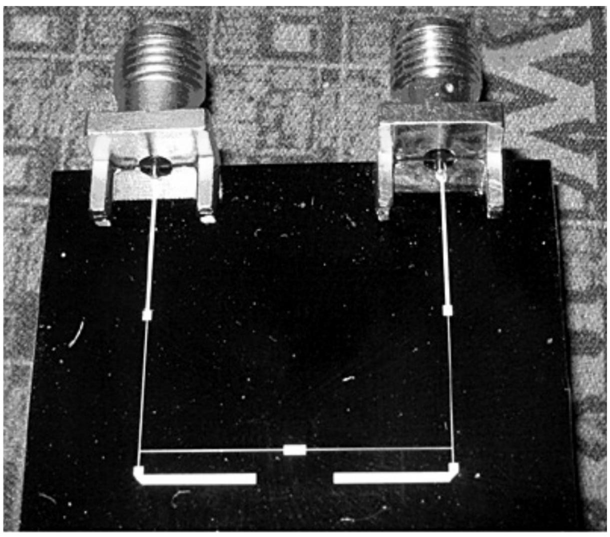

Figure 5: Photo of the fabricated filter with SMA connector

It was mesured in dark. S_{21}–parameters for the structure in fig. 5 are presented in fig. 6. Losses in the pass-band are high (-10 dB). Beside that, they are in an agreement with graphics in fig. 4 for frequency position of the stop-band minimum and the filter shape. The problem were only losses. The reason for the high losses was discovered to be out of date (old) silver epoxy.

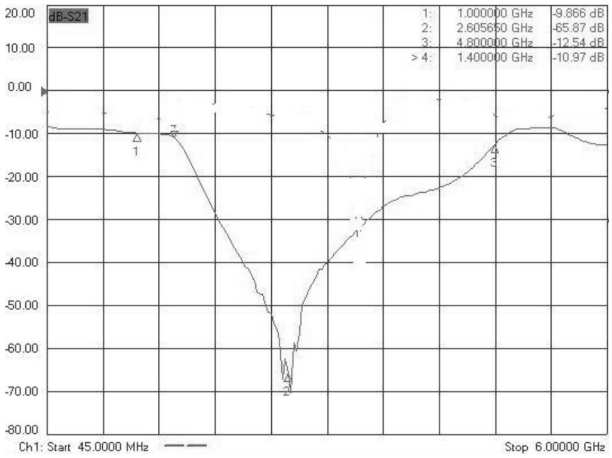

Figure 6: Measured S_{21} of the filter using out of date (old) silver epoxy

Then, SMA connectors were removed and both the connectors and the contact aresa on the microstrip were cleaned from the old silver epoxy. The SMA connectors were again bonded using the fresh silver epoxy. It was also mesured in dark. *S*–parameters for the filter with the fresh silver epoxy are presented in fig. 7.

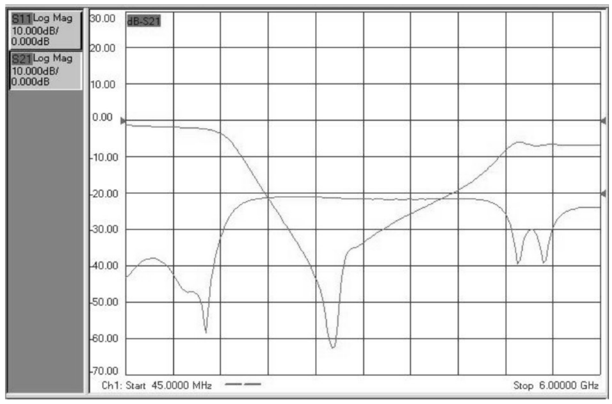

Figure 7: Measured (in dark) *S*–parameters of the filter using fresh silver epoxy

Measurement under light source illumination can degrade filter characteristics in pass-band. The illumination causes higher losses in the pass-band [11] which is not acceptable for the filter. According to that, operation of the filter is only in dark (protected from light). One example of extreme illumination is presened in fig. 8: filter positioned 1m from 1000 W photo lamp gets totally degraded pass-band. Even small power laser (650 nm, around 1 mW), applied at the end of one microstrip stub, increases losses in the pass-band is near 0.3 dB.

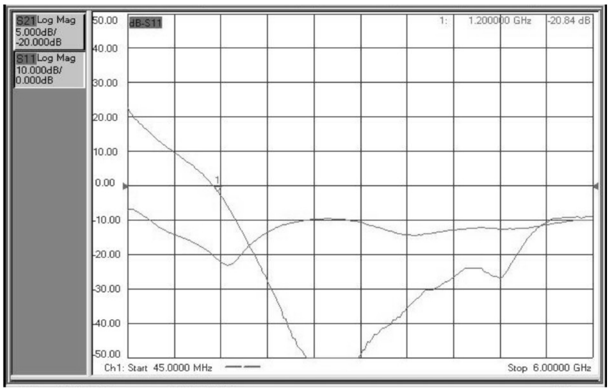

Figure 8: Measured *S*–parameters of the filter positioned 1m from 1000 W photo lamp. (S_{21} at 1.2 GHz is near -21 dB comparing with around -3 dB in dark)

Compared S_{21} parameters for ideal circuit, EM simulation and measured filter are presented in fig.9. All results are in a good agreement. Relative stop band width is over 70 % for 20 dB suppression. Reflection, S_{11}, in the pass band is -17 dB or lower.

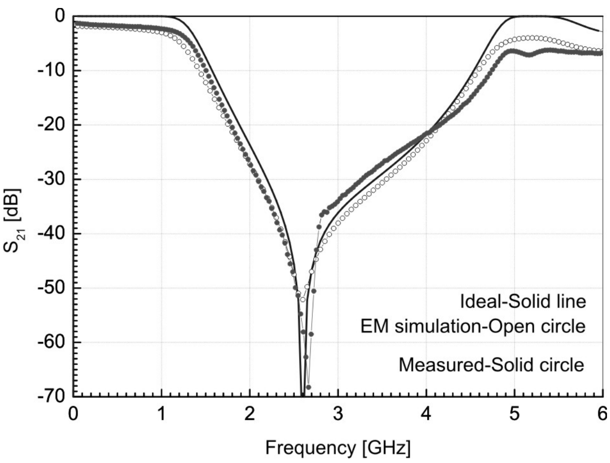

Figure 9: Compared results of S_{21} for ideal circuit, EM simulated and measured filter

Losses in the pass-band can be caused by: 1) connectors, 2) bonding between connectors and Al metallization using silver epoxy, 3) sputtered Al metallization t = 3 µm thick, 4) Si dielectric losses 5) mismatching and 6) radiation. Parameter S_{11} in fig. 7 is less than -17 in the pass-band and mismatching is not a problem. Simulation of the same filter structure (and the same Si dielectric losses) with copper (Cu) metallization as an excellent conductor are presented in fig. 10. (Cu metalization is rarely used and is electroplated which is different technology). In fig. 10 pass-band losses are small, below 1 dB, for frequencies below 1 GHz. Radiation is not significant. Differences in the case of our fabricated filter are: 1) losses in the silver epoxy bonding between SMA connectors and Al metallization and 2) losses in the sputtered Al metallization and its roughness.

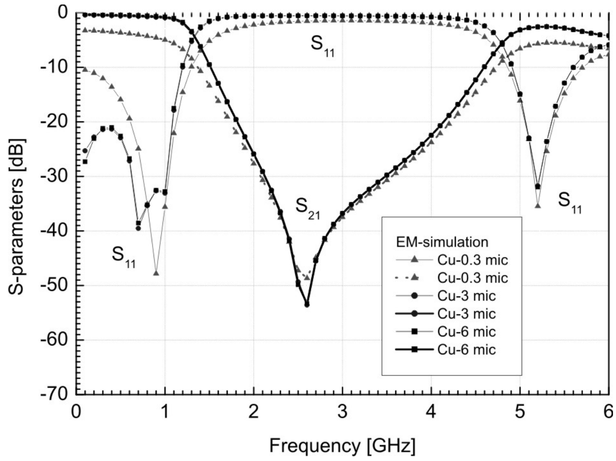

Figure 10: S_{21} of 3D EM simulation with copper (Cu) metallization of various thickness *t*

Passive intermodulation was measured using signals on 1 GHz and 1.05 GHz with 2 x 4 dBm on input port of the filter. Each signal generator has one circulator for isolation and input into the filter is trough a power divider (from two ports to one). Spectrum analyser is connected to the output of the filter. Intermodulation was not noticed.

4. conclusion

Low-resistivity silicon (standard CMOS-grade silicon) is a troublesome issue for the microwave passive components. One solution is using high-resistivity silicon (HRS). Circuit with ideal waveguides was simulated and successfully applied to band-stop microstrip filter on HRS (ρ = 5 kΩ-cm). The filter was fabricated using aluminum (Al) sputtered metalization and etching of the filter pattern in Al. SMA connectors are bonded using silver epoxy. The fabrication stressed importance of the quality (fresh) silver epoxy for low losses.

There is a high agreement between ideal circuit simulation, 3D electromagnetic simulation in microstrip technology and measured results. Relative stop band width is over 70 % for 20 dB suppression. Reflection, S_{11}, in the pass band is -17 dB or lower. It means that the sputtered Al and the silver epoxy can be successfully applied for microwave structures on HRS.

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