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A simple method to estimate the loading effects of Al/Si on the characteristic impedance of multilayer microstrip line

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The present study aims to experimentally determine the microwave transmission and reflection properties of aluminum thin film grown on silicon using sputtering. A simple microstrip line based structure has been used for the microwave characterization in the frequency range 10 MHz to 26.5 GHz. Complex S-parameter measurements reveal only small differences on silicon loading and aluminum/silicon loading in comparison to the microstrip line. The characteristic impedance (Z) of the microstrip line loaded with silicon and with aluminum/silicon have been obtained corresponding to the length of the loadings using two port microwave analysis. Comparison of loaded microstrip line with no loading shows large changes in the real part well as imaginary part of the characteristic impedance in the frequency range less than 10 GHz. Percentage changes in the real (Z) and imaginary (Z) have been found as ± 40% and ± 10% in average, respectively, for silicon loading in comparison to the no loading case, whereas these changes have been found to be below ±5% for aluminium/silicon loading, thus these smaller changes suggest the similar responses for aluminium/silicon loading and no loading. The results reveal that the propagation can be restored with the application of aluminum with any semiconductor or dielectric as loading on the microstrip line, which shows its potential to be explored for making an individual microwave component.

Keywords: Thin film, Microwave reflection properties, Microwave transmission, Impedance

1 Introduction

To optimally design and analyse the performance of microwave electronic systems at high frequencies, knowledge of the conducting materials is essential for a wide range of commercial applications and for the fundamental research as well. Although the use of copper for printed circuit board (PCB) and aluminum (Al) on silicon (Si) wafer are widely preferred, gold and silver are also used as the conducting materials at high frequencies[1]. These metals are bulky and thus increase the cost of overall circuits except Al. Recent interest in the use of Al for the microwave electronic systems has been developed not only due to its non-ferrous property but also due to its superconducting properties[2]. One of the studies[3] showed the critical temperature of 1.2 K for a 100 nm thin Al film was obtained with a surface resistance near 0.2 Ω/sq whereas the average conductivity of the thin-film Al layer was measured to be 2×10^7 S/m using a four-point probe[4]. Also, thermally evaporated Al thin films of thickesses varying from 30 to 50 nm were studied by performing high-precision microwave experiments at low temperatures to map the frequency and temperature dependence of the conductivity coherence peak with intentionally reduced mean free path[5]. Recently[6] the growth mechanism and microstructure studies of the ultra thin Al films on Si oil surfaces showed the Al films exhibit self allign morphology. In addition, Al has other advantages like providing heat dissipation, light weight and better durability[7]. Owing to these advantages, Al based PCBs are now commercially available[8,9]. The role of Al is required to determine the propagation of microwaves when it is used with any semiconductor like Si. The losses have also been measured for Al thin fims fabricated on Si for different frequency range[4,10]. These studies support the fact that the Al metallization on Si can be used for microelectronics technology. The knowledge of interaction effects between Al and Si can help to develop the

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understanding required for microwave active devices which may have superconducting properties as well as applications at THz frequency. Such study would be the first step towards making Al based microwave systems.

Here, we report the microwave effects of Al thin film deposited on Si wafer with a simple microstrip line. The Si and Al/Si was placed on top of the microstrip line as a non-destructive sample holder[11] and the S-parameters were measured in 10 MHz to 26.5 GHz range. By employing the microwave network theory, the reflection coefficient and input impedance of the loaded microstrip line were obtained to analyse the properties of Al at the room temperature in the desired frequency range.

2 Proposed Theory

To characterize the Al thin film on Si at microwave frequency, we have used the microstrip line based measurement fixture[11] as shown in Fig. 1(a). The front view of the loaded fixture is shown in Fig. 1(b) where the quasi- Transverse electromagnetic (TEM) mode propagates in the microstrip line[12]. The fields get perturbed on placing Si and Al with Si over the microstrip line. The corresponding change in the measured S-parameter can be used to obtain the variation in conductor loss eventually in terms of reflection coefficient and impedance.

From the two-port network analysis as shown in Fig. 2(a), we know that the impedance of the through connection after the vector network analyzer (VNA) calibration may be considered as impedance of two-port network (Z_0') and can be obtained from the measured S-parameters of calibration stage[13] and standard characteristic impedance (Z_0 = 50 Ω) using Eq. (1):

$$Z_o' = \pm Z_o \sqrt{\frac{1+s_{11}+s_{22}+s_{11}s_{22}-s_{12}s_{21}}{1-s_{11}-s_{22}+s_{11}s_{22}-s_{12}s_{21}}} \quad \ldots (1)$$

This impedance of through connection may be served as a load as well as source impedance for any device connected between calibrated ports of VNA.

Then the load reflection coefficient (Γ_L) in terms of network impedance and standard load impedance (Z_0 = 50 Ω) can be obtained using $\Gamma_L = \frac{Z_o' - Z_o}{Z_o + Z_o}$.

On connecting the microstrip line with test fixture as shown in Fig. 2(b), the input reflection coefficient Γ_{in} is related to the S-parameter of two port component (microstrip line) and Γ_L by the following[12] Eq. (2):

$$\Gamma_{in(n)} = S_{11} + \frac{s_{12}s_{21}\Gamma_L}{1-s_{22}\Gamma_L} = \frac{z_{in(n)} - z_o'}{z_{in(n)} + z_o} \quad \ldots (2)$$

where $Z_{in(n)}$ is the input impedance looking towards the terminated loaded microstrip line (n = 1, 2, 3), 1 for microstrip line only, 2 for Si loaded microstrip line and 3 for Al/Si loaded microstrip line. $\Gamma_{in(n)}$ can be computed for loaded microstrip line from corresponding measured S-parameters using Eq. (2). In addition, as Z_0' represents the network impedance on load side as well as on the source side, $Z_{in(n)}$ can be obtained for without loading, Si loading and Al/Si loading on the microstrip line using equation (2). However, the characteristic impedance of microstrip line (Z_n) cannot be directly obtained using Eq. (1) in this non-destructive method, as the properties of microstrip line with test fixture and discontinuities at both coaxial to microstrip transitions are embedded in measured S-parameters between Port 1 and Port 2, and de-embedding would be a complex procedure to obtain the effects of Al thin film. As loading of microstrip line divides it in three parts, where first and last parts are associated to microstrip line length with no loading and mid part with loading, respectively. If

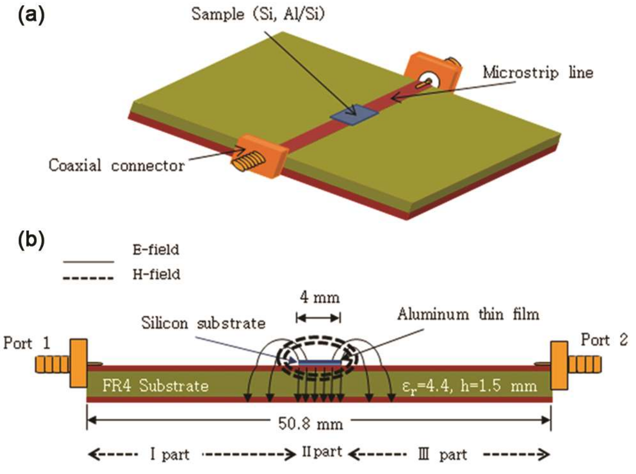

Fig. 1 – (a) Measurement arrangement for sample and (b) side view with EM distributions.

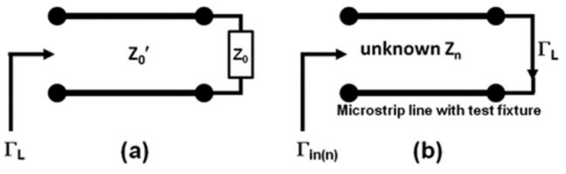

Fig. 2 – Schematic representation of reflection coefficient and impedance for (a) through connection at calibration stage, and (b) microstrip line with test fixture, *n*: different loadings

the quasi-TEM propagation mode holds over the microstrip line on loading, the complex propagation constant (γ_n) is considered uniformly and obtained from the measured S-parameters[13,14]. Then, the following relation is used to obtain Z_n from $Z_{in(n)}$ and γ_n on taking lengths (l_n) corresponding to the length of microstrip line with no loading and loading[12]:

$$Z_n = Z_{in(n)} \frac{1-\Gamma L^{e^{2\gamma l_n}}}{1+\Gamma L^{e^{2\gamma l_n}}} \qquad \text{...(3)}$$

In this way, the changes in impedance values with different loading will be helpful to obtain the microwave properties of deposited Al thin film by comparing the changes only due to Si.

3 Experimental Methods

3.1 Material preparation

An assembled DC sputtering system from M/S Excel Instruments, India was used to grow Al thin film, which has a cylindrical chamber size of 12″. Al thin films were grown on Si (100) substrate by magnetron sputtering at a dc power of 30 W. Before deposition, the base vacuum of the chamber was maintained at 9×10^{-7} mbar. Al target of size 2″ was commercially procured from M/S American Elements, USA. The films were deposited from Al target under 5N pure argon gas pressure of 6.7×10^{-3} mbar at room temperature. The target to substrate distance was fixed at 5 cm and the deposition time was 5 mins. The thickness of Si wafer used is 0.5 mm and 100 nm thin Al film is obtained by deposition. The length of Al with Si wafer is maintained as 4.5 mm for the present study. The Al/Si sample used for the measurement in this work is shown in Fig. 3.

3.2 Microwave characterization

For S-parameter measurements, a microstrip line of 3.024 mm width and 50.8 mm length was made on FR-4 substrate (relative permittivity ε_r = 4.4 and height h = 1.5 mm). To measure the S-parameter measurements of microstrip line without samples, Vector Network Analyzer (VNA) model N5227A of Keysight Technologies Inc. was first calibrated using using short-open-load-thru (SOLT) technique by an SMA calibration kit in 10 MHz to 26.5 GHz. After S-parameters were stored, microstrip line was loaded by Si and Al/Si, individually and the S-parameters were measured for respective loadings.

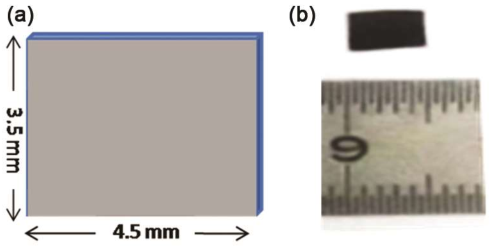

Fig. 3 – Sample used for the microwave measurement; (a) Schematic of the sample and (b) actual sample used.

4. Results and Discussion

4.1 S-parameters of microstrip line with different loadings

The measured reflection (S_{11}) and transmission (S_{21}) parameters of microstrip line with no loading i.e. air, Si loading and Al/Si loading, are shown in Fig. 4(a-d).

In Fig. 4 (a,b), the input reflection coefficient (S_{11}) values for air and Al/Si loadings are found to be same whereas some deviations in S_{11}(dB) have been observed for Si loading on the microstrip line from air loading case. This means that due to Si loading, the mismatch has been increased by perturbation in electromagnetic fields in quasi-TEM mode at lower frequency from 1 GHz to 10 GHz, which is clearly evident in S_{11} phase (Fig. 4(b)). For higher frequency above 10 GHz, the absorption of signals is significantly high (> 3 dB) which suggests that the reflections are same for all loadings, which has been also observed in terms of the reduction in S_{21}(dB) (Fig. 4(c)). In addition, difference in S_{21}(dB) shows that small amount of microwave signal has been absorbed in Si thin film, whereas signal transmission is almost same for Al/Si loading as for no loading case. Comparing Fig. 4(a) and 4(c), we estimated that through absorption in Si is same as on Si only and Al/Si loading, higher S_{21}(dB) of Si loading is due to large S_{11}(dB). Loading of Al/Si forces EM fields to confine within Si avoiding radiation and thus the transmission is better than the case of Si loading. Although infinitesimal changes have been noticed in S_{21} phase as illustrated in Fig. 4(d), the phase has been varied with frequency along the length of the microstrip line which is usual behaviour of phase with frequency and found to remain unaffected irrespective due to the loading of Si and Al with Si. The microstrip line structure became more reflecting near 15 GHz, where S_{11}(dB) > -15 dB and S_{21}(dB) has been reduced by 6 dB.

4.2 Reflection coefficient variations with different loadings

Since reflections are noticed in lower frequency range due to loading, we can estimate amount of

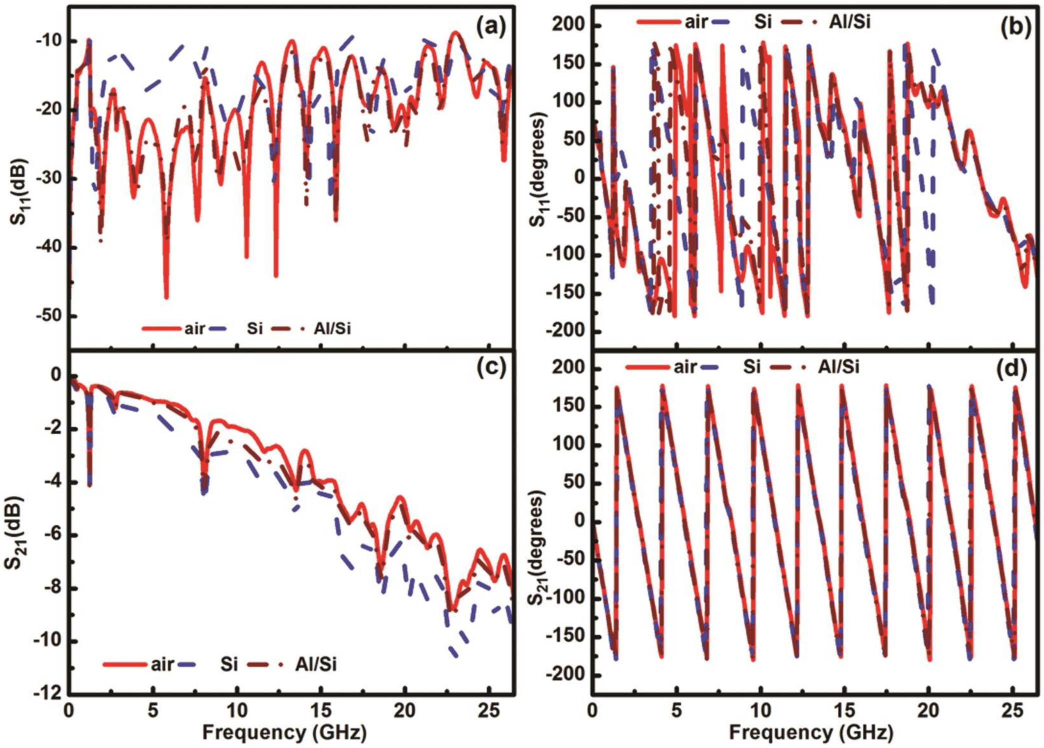

Fig. 4 – S-parameters for microstrip line with no loading (air), Si loading, Al/Si loading, (a) S_{11}(dB), (b) S_{11}(degrees), (c) S_{21}(dB) and (d) S_{21}(degrees).

reflection power in terms of reflection coefficient for various loadings. From the S-parameters of loaded microstrip line, the input reflection coefficients are obtained using Eq. (2) for air, Si and Al/Si loadings and shown in Fig. 5.

For these loadings, the Re(Γ_{in}) has been found to vary within ± 0.4 whereas Im($\Gamma_{in)}$ has variations in ± 0.35 range in the studied frequency range. It has been clearly noticed at few frequencies below 8 GHz in Fig. 5(a), the Re(Γ_{in}) for Si loading is greater than Al/Si loading in lower range. Al/Si loading has similar Γ_{in} values as unloaded microstrip line, which confirms Al/Si loading has not increased the reflection loss. In case of Si loading, higher negative Re(Γ_{in}) represents shifting of reflected wave by 180º. However in most of frequencies, this phase shift is less than 180º. Similarly Im(Γ_{in}) for Si loading was found higher than Al/Si loading which indicates more portion of reflected wave amplitude has 90º out of phase with input microwave signal at the point of reflection.

4.3 Input impedance of loaded microstrip line with different loadings

We obtained the input impedance (Z_{in}) of loaded microstrip line parameter using Eq. (2) for any behaviour change due to loadings and shown in Fig. 6.

The Re(Z_{in}) represents the dissipative nature of loaded microstrip line along with terminated load whereas Im(Z_{in}) temporarily confines the microwave energy in loaded microstrip line. We noticed in Fig. 6(a) that the most of Re(Z_{in}) values are near 50 Ω till 17 GHz for the microstrip line with Al/Si loading, which is similar to case for no loading i.e. air and so this loading also absorbs microwaves without offering additional reflections as the loading is very thin. It also shows that quasi-TEM mode propagation stillcontinues on the loaded microstrip line. Contradictory, silicon loading causes more change in Re(Z_{in}) values due to reflections as large variations have been noticed in between 10 MHz to 8 GHz, and between 13 to 17 GHz. Beyond this frequency, almost same value of Re(Z_{in}) is obtained, which shows the microstrip line behaviour is now independent of loadings. In Im(Z_{in}) response, larger variation are noticed for silicon loading than Al/Si loading, which again reaffirms that confinement of microwave energy is higher on Si loading whereas Al/Si loading does no harm to the microwave propagation.

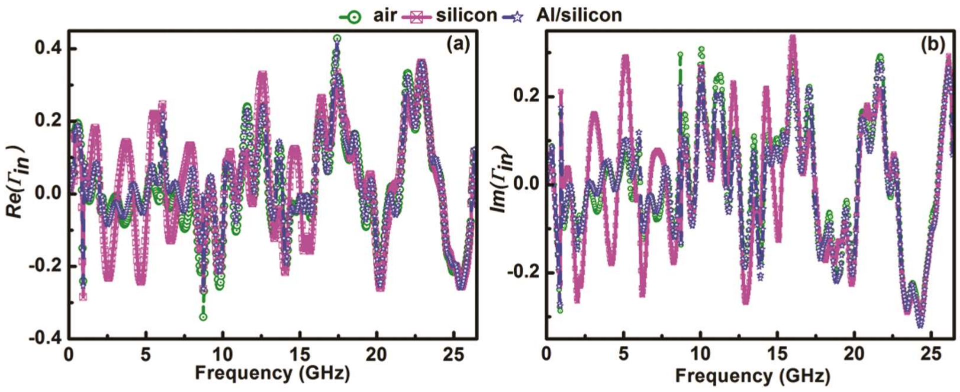

Fig. 5 – Variations due to air, Si and Al/Si loadings in (a) real (Γ_{in}) and (b) imaginary (Γ_{in}).

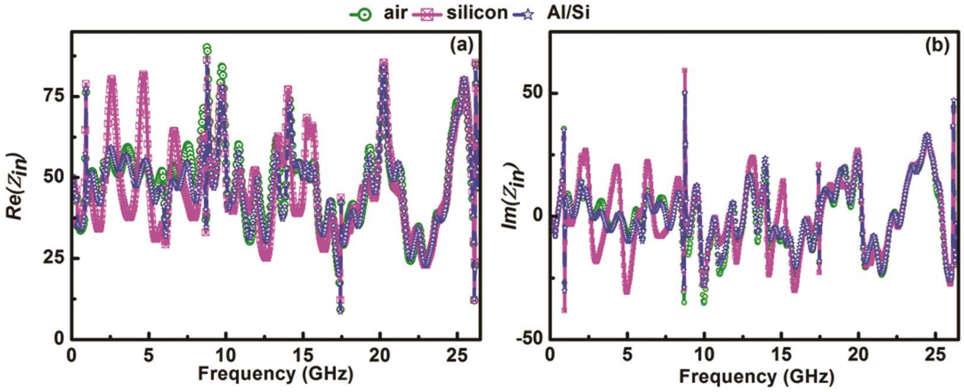

Fig. 6 – Variations due to air, Si and Al/Si loadings in (a) real Z_{in} and (b) imaginary Z_{in}.

4.4 Characteristic impedance of loaded microstrip line with different loadings

The impedance (*Z*) of loaded microstrip line is useful to analyze the electrical behaviour of loaded film at the microwave frequency. Figure 7 illustrates the Re(*Z*) and Im(*Z*) for each loading on the microstrip line. For a microstrip line, Re(*Z*) represents the dissipative loss whereas Im(*Z*) indicates the presence of reactive losses on the line like inductive or capacitive, since $Z = \sqrt{{(R + j\omega L)}/{(G + j\omega C)}}$. Here, ω is the angular frequency (2π*f*), *R*, *L*, *G* and *C* are the resistance, inductance, conductance and capacitance per unit length of line[13]. As shown in Fig. 7(a), Re(*Z*) is found to ~ 50 Ω except for Si loading in lower frequency range say below 10 GHz where the losses due to resistance and conductance are prominent. So with Si loading, these losses have become higher. This is also confirmed by low values of Im(*Z*) less than 10 Ω in the same frequency range and for Si loading, it is greater than 20 Ω in Fig. 7(b). For higher frequency, since $\omega L \gg R$ and $\omega C \gg G$, Re(*Z*) as well as Im(*Z*) had large variations with frequency. Change of Im(*Z*) from positive to negative values shows that observed dominant loss is shifted from dielectric to conductor kind, which is again found to be same for no loading and Al/Si loading.

To analyze the effects of Al/Si on the impedance or microwave propagation, we have evaluated the percentage changes in Re(*Z*) as well as in Im(*Z*) due to loading in comparison to no loading case shown in Fig. 7. With Si loading, significant changes have been found in lower frequency range maximum upto 50% @5 GHz, which become similar to Al/Si loading near 10 GHz frequency (Fig. 7(c)). Again with frequency, Si loading has offered large change in Re(*Z*) as well as in Im(*Z*) at 11 GHz and these changes then reduce to the values offered by Al/Si loading on further increasing the frequency upto 26 GHz. In Fig. 7(d), except few frequencies, the changes in Im(*Z*) is zero on Al/Si loading in compared to no loading, whereas minor changes have been observed on Si loading. Thus the responses of *Z* for loaded microstrip line confirmed that even though the microwave transmission and reflection properties of microstrip line change on semiconductor or dielectric loading, the response can be found again if metallic layer is placed over it.

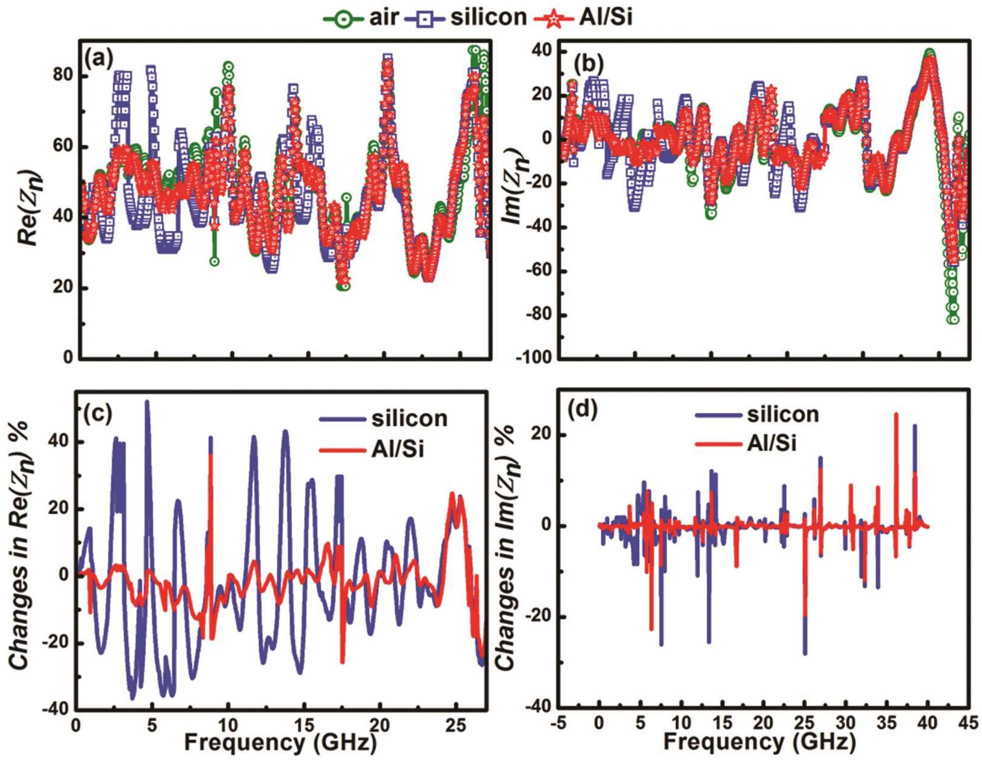

Fig. 7 – Variations due to air, Si and Al/Si loadings on the microstrip line (a) real Z, (b) imaginary Z, (c) % change in real (Z) and (d) % change in imaginary (Z).

5 Conclusions

In the present work, we have evaluated characteristic impedance of microstrip line with no loading and loading by Si and Al/Si, which have been obtained from the measured S-parameters and the theory discussed. Though, the length of the different loadings are very small as compared to the microstrip line, significant variations have been found the extracted input impedance and characteristic impedance of the loaded microstrip line. The obtained results show higher variation due to changes in resistance and conductance per length in the lower frequency range, and their effects on impedance have been ignored at the higher frequency. Any change in these impedances due to Si loading is observed to be restored with Al/Si loading. Thus, the initial propogation conditions can be obtained when Al/Si is being used as transmission line or as a part of it. As Al has high conductivity, the analysis presented in this paper can help to develop the Al based microwave components.

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References

1 Humpston G, *Gold Bull*, 32 (1999) 75.
2 Liang C T, Yeh M R & Lin S D, *Chin J Phys*, 50 (2012) 638.
3 Smolyaninova V N, Jensen C & Zimmerman W, *Sci Rep*, 6 (2016) 34140.
4 Ramazani M, Miladi H, Shahabadi M & Mohajerzadeh S, *IEEE Trans Electron Dev*, 57 (2010) 2037.
5 Steinberg K, Scheffler M & Dressel M, *Phys Rev B*, 77 (2008) 214517.
6 Fang Z N, Yang B & Chen M G, *Thin Solid Films*, 517 (2009) 3408.
7 Yanniello B, *Aluminum-The other conductor*, (Eaton), 2006.
8 Meulenbroeks D, *Aluminum versus copper conductors*, A white paper issued by Siemens, (Siemens AG) 2014.
9 Pryor L, *A comparison of aluminum versus copper as used in electrical equipment*, A white paper issued by GE.
10 Schöllhorn C, Zhao W, Morschbach M & Kasper E, *IEEE Trans Electron Dev*, 50 (2003) 740.
11 Queffelec P, Gelin P, Gieraltowski J & Loaec J, *IEEE Trans Magn*, 30 (1994) 224.
12 Pozar D M, *Microwave engineering*, 4th Edn, (John Wiley & Sons, Inc: USA), 2012.
13 Zhang J & Hsiang Y T, *PIERS Online*, 3 (2007) 1102.
14 Obrzut J, *Measurement*, 46 (2013) 2963.