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ANNEALED COPPER IN RF MEMS PROCESS FLOW WITH SI_XN_Y AND SIO_2

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Abstract
Using Cu as a main structural material along with SixNy and SiO2 as a dielectric and a buffer layer respectively in RF MEMS fabrication process flow is described. Thin copper films are sputtered and then electroplated. This is followed by thermal processing in N2 atmosphere in order to improve conductivity of the copper films to be used in the developed RF MEMS fabrication process flow.

Keywords: RF MEMS technology, Cu thermal processing, Cu electroplating, Cu films.

Introduction
RF MEMS present an alternative to semiconductor elements in a number of reconfigurable devices such as filters, matched antenna systems and phase sifters [1]. This is due to low loss, high linearity and low power consumption of RF MEMS elements [2].
Literature has many examples of capacitive RF MEMS devices made of gold [3], nickel [4], aluminium [5, 6] and copper [7]. However, despite the wide use of copper as a conductive material, its use in RF MEMS technology is not so popular. This paper provides an example of using copper as a main structural material and its thermal treatment in the context of RF MEMS device manufacturing. The aspects of combining materials used in the process flow are also discussed.

Three-step RF MEMS process flow
A three-step process flow is proposed for manufacturing RF MEMS structures such as varactors, switches, and various devices based on them (filters, phase shifters, etc). Copper is used as a main structural material due to its potentially high conductivity and stiffness [8]; silicon nitride (SixNy) is used as a dielectric layer, and silicon oxide (SiO2) is used as a buffer layer.
In the first step, a lower metallization layer is patterned by magnetron sputtering of 100 nm thick Cu layer. At this step, actuation electrodes are formed which will activate movable elements (membranes) of an RF MEMS device.
The second step involves patterning of the dielectric and buffer layers as they are both deposited during the same technological process of vapor deposition.
At the third step, the formation of membrane contours takes place as a result of copper electroplating process.
The last stage of the proposed process flow is the release of membranes by etching of the buffer SiO2 layer in the solution of hydrofluoric acid.
A 100 nm thick copper film is deposited on a 0.5 mm thick sapphire substrate using magnetron sputtering in argon atmosphere. This is followed by the electroplating process such that the copper thickness is 1 um. The electroplating system comprises copper electrolytic solution (copper (II) sulfate pentahydrate), a soluble anode, a substrate (acting as a cathode) and a current power supply. Under the applied voltage, copper from the electrolyte is plated onto the metallized substrate surface, in the electrochemical cell. Current density is 2 A/dm2 with the corresponding deposition rate of 0.5 um/m. As a test structure, we chose 3 mm long coplanar waveguides. Studying their S-parameters allows to assess the quality of the electroplated copper, as well as the influence of thermal processing on its electrical conductivity. The simplicity of the chosen topology excludes the possible influence of constructive effects.
S-parameters of the copper coplanar waveguides (CPW) on sapphire have been measured with the probe station SUMMiT (Cascade) connected to the vector analyzer PNA-X N5242A (Agilent). As a reference, CPW S-parameters measured on a cascade impedance standard sapphire substrate have been taken. Figure 1.1 shows the comparison of CPW reference parameters with the results obtained by copper electroplating on sapphire.

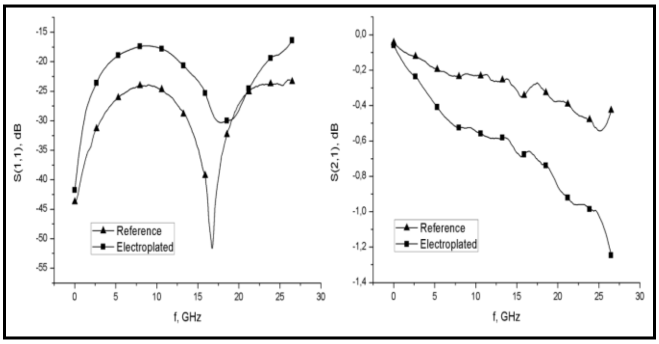

Figure 1.1: S-parameters of the reference (triangle) and the copper CPW on sapphire (square).

As can be seen from the Figure 1.1, insertion loss of electroplated CPW is higher than reference. In order to improve the quality of the electroplated copper, the wafer has been placed into the thermal processing camera with N2 atmosphere under the pressure of 150 mT. First, the substrate with CPW has been annealed for 15 seconds at 400°C. A small decrease in insertion loss has been recorded. This was followed by a reprocessing for 5 minutes at 400 °C, which resulted in a significant improvement in insertion loss. Finally, an additional processing has been done for 9 minutes

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at 550°C, which resulted in a small improvement over the previous iteration. As a result, the obtained CPW after the thermal processing demonstrated insertion loss comparable to the reference and equals to 0.24 dB at 10 GHz (Figure 1.2).

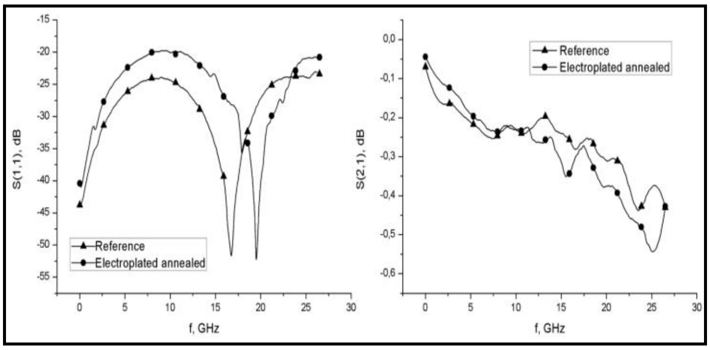

Figure 1.2: S-parameters of the reference (triangle) and the copper CPW on sapphire (square) after annealing.

Figure 1.3 shows SEM images of the electroplated copper films before and after the thermal processing.

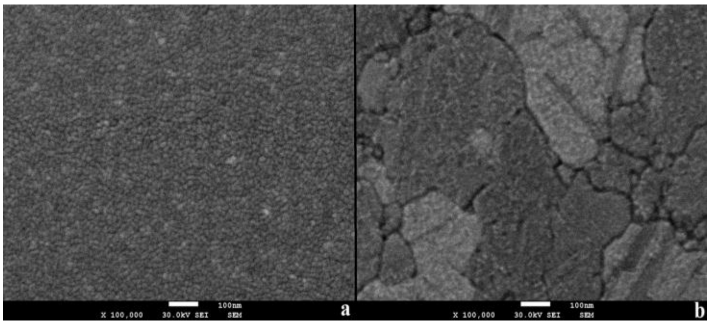

Figure 1.3: Electroplated copper a) before thermal processing b) after thermal processing.

It should be noted that as a result of thermal processing the size of grains increases significantly and, as a consequence, according to the measured S-parameters, the resistivity of the deposited copper films decreases.

Another problem of using copper as a main structural material in the proposed RF MEMS process flow is its response to the buffer solution of hydrofluoric acid (BHF) which is used as an etcher of the silicon oxide buffer layer. The SEM image shows the effect of BHF on the copper film during different time intervals (Figure 1.4).

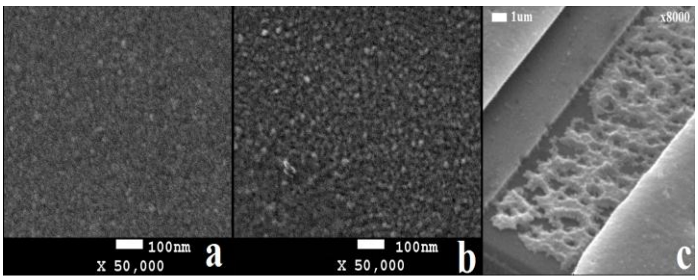

Figure 1.4: Effect of BHF on a copper film a) as deposited b) 10-minute BHF c) 10-minute BHF during SiO2 etching.

A significant degradation of the sputtered copper layer is observed during the etching of SiO2 buffer layer in the technological process of membrane release. It should be noted that copper is affected not only by BHF, but also by RIE reaction products (Figure 1.4c).

Figure 1.5 shows SEM images representing the effects of interaction of annealed cooper film with BHF.

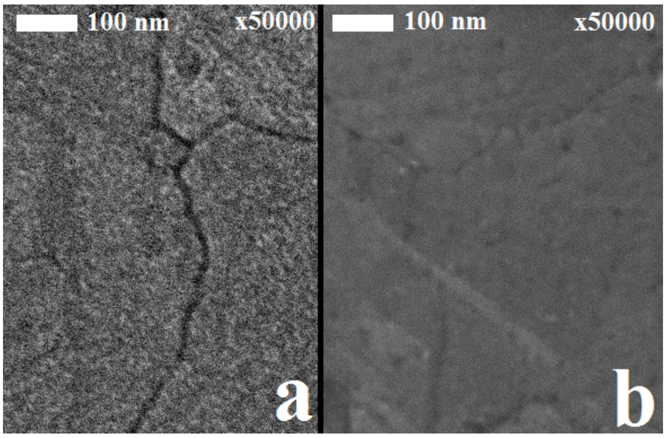

Figure 1.5: Effect of BHF and sputtered copper after annealing. **a)** sputtered copper**, b)** 10-minute BHF.

As a result of 10-minute interaction of BHF with the annealed sputtered copper, only planarization of surface and grain boundaries is observed.

Discussion

CPWs on sapphire fabricated using copper electroplating technique have shown insufficiently low loss. Copper thermal processing has been used for insertion loss minimization. After annealing, CPW's insertion loss halved and became comparable to the reference insertion loss, and as far as CPW's return loss still showed 50 Ohm matching it can be stated that copper resistivity has lowered too (Figure 1.2), which is consistent with the results in [9]. The obtained results can also be compared with [7] where the insertion loss on 1.4 mm long CPW on surface-passivated HR silicon turned out to be 6 times higher.

The decrease in copper resistivity is connected with the rearrangement of the copper structure caused by thermal processing. It is assumed that the growth of copper film resistivity is connected with lower electron scattering on grain boundaries [10] which is caused by an increase in average grain size in copper films illustrated in Figure 1.3.

As can be seen from Figure 1.4b, copper film exposure to BHF for 10 minutes results in the surface roughening which affects its conductivity. SiO2 etching in BHF may result in degradation of the copper film (Figure 1.4c) which in the context of RF MEMS fabrication leads to a low Q-factor. However, thermal processing of copper allows to protect copper films from BHF exposure. A general planarization of surface and grain boundaries is observed with no evident degradation as before annealing. Therefore, thermal processing of copper films also provides an improved resistance to BHF exposure.

It should also be noted that SiO2 buffer layer changes its properties during the thermal processing and the etching rate in BHF falls down significantly, which dictates the need to anneal RF MEMS elements at the final fabrication stage after the membrane release.

Conclusion

This paper has described the aspects of the use of copper as a main structural material in the proposed three-step RF MEMS process flow along with SixNy as a dielectric and SiO2 as a buffer layer.

Thermal processing of copper at 400°C in N2 atmosphere significantly lowers copper film resistivity and results in a double decrease in CPW insertion loss as well as an improved resistance of copper to BHF exposure. Therefore, it is recommended to perform copper annealing to obtain RF MEMS elements with maximum Q-factor.

Acknowledgments

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