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Non-toxic Liquid Metal Microstrip Resonators

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***Abstract*— In this paper, we report for the first time the design and fabrication of non-toxic liquid metal (Galinstan) half-wavelength ($\lambda_g/2$) microstrip resonator. Patterning techniques of Galinstan microstrip resonators are presented. Resonators of different lengths are measured to cover a frequency range of 3-20 GHz. We have characterized the conductivity of Galinstan by matching the measured quality factor with finite element model of the resonators. The conductivity of Galinstan is found to be $3.83 \pm 0.16 \times 10^6$ S/m. The liquid metal holds great promises as a low contact resistance, highly reliable, high temperature tolerant material. This work will benefit future implementations of Galinstan based RF/Microwave reconfigurable devices and systems with high reliability.**

***Index Terms*— liquid metal, Galinstan, microstrip resonator.**

I. Introduction

With the rapid development in MEMS and micromachining technologies, the past decade has seen tremendous growth of RF MEMS devices and systems. A typical RF MEMS device involves one or more moving parts, in most cases made of thin film metal or dielectric, to physically alter its high frequency response. The use of solid metal, however, has several limitations in terms of contact resistance, power handing, temperature tolerance, yield and reliability. In order to overcome these problems, researchers from several groups [1], [2] have looked into the possibility of using room temperature liquid metals as functional component in RF MEMS devices.

While some of the early work involving liquid metal as part of a RF MEMS device is done with mercury [1], [2], the toxicity of this material has made it undesirable for more general use. Non-toxic replacement of mercury have been sought after and Galinstan is one promising candidate [3]. Galinstan is an eutectic alloy of Gallium, Indium and Tin. The exact composition of each of the ingredients is kept proprietary but its overall physical and chemical properties resemble those of other Gallium-Indium alloys. A remarkable property of Galinstan is that it is in liquid phase at room temperature and does not solidify until $-19\,^{\circ}$C. The fluidic nature of Galinstan at room temperature makes it possible to implement reconfigurable liquid metal components and circuits with a micropump [4]. An additional merit of Galinstan is its very high boiling point ($> 1300\,^{\circ}$C), making it ideal for high temperature applications. It has been shown that solid metal thin film traces can degrade over extreme temperature cycling due to stress and strain caused by thermal expansion coefficient (CTE) mismatch between the metal traces and the substrate [5]. Due to its liquid form, traces made from Galinstan can freely expand and contract as environment temperature changes, therefore avoids stress-induced degradation.

Early applications of Galinstan are mainly in biological and medical areas [7]. A few researchers have also investigated Galinstan for electronics applications, such as flexible electrode [8], reliable interconnects [9] and RF MEMS devices. Recently, Chen et al. [10] and Liu et al. [11] reported RF MEMS switches and switchable interconnects using Galinstan as the movable structure. The conformal contact at the liquid-solid interface and high temperature tolerance make them ideal solution for reliable reconfigurable RF applications.

In this paper, we report the design and fabrication of microstrip resonators made of Galinstan. Although these resonators have slightly lower quality factor than with static resonators made from high conductivity metal, they exhibit the potential of high tunability due to the fluidic nature of the liquid metal. When coupled with on wafer micro-pumps [4], tunable liquid metal microstrip filters can be implemented. In this paper, we present the techniques to pattern Galinstan on silicon wafers. We also employ finite element modeling (FEM) to extract the conductivity of Galinstan at several frequency points by matching the quality factor. These development and characterization efforts will benefit future implementation of Galinstan based RF MEMS devices.

II. Design

In this work, 50 Ω half-wavelength ($\lambda_g/2$) microstrip resonators are designed on 525 μm thick high-resistivity silicon substrate. All the resonators are 396 μm wide with their lengths varying from 2.5 mm to 14 mm to cover a 3-20 GHz frequency range as shown in Table I.

Fig 1 gives the top and side view of the resonator design. A CPW to microstrip transition is designed as the feeding network to facilitate the use of ground-signal-ground (G/S/G) RF probes in measurements. The center conductor of the line is tapered at the end to give enough capacitive coupling to the resonator. The gap between the center feed line of the transition and the resonator varies from resonator to resonator to give only weak coupling. Weak coupling allows for more accurate extraction of the unloaded quality factor of the resonators.

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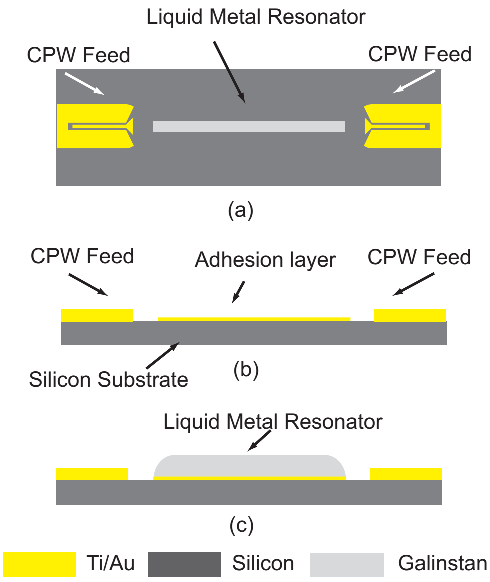

Fig. 1. Design of the liquid metal microstrip resonator:(a)Top view;(b)Side view with only the Ti/Au layer;(c)Side view with liquid metal resonator.

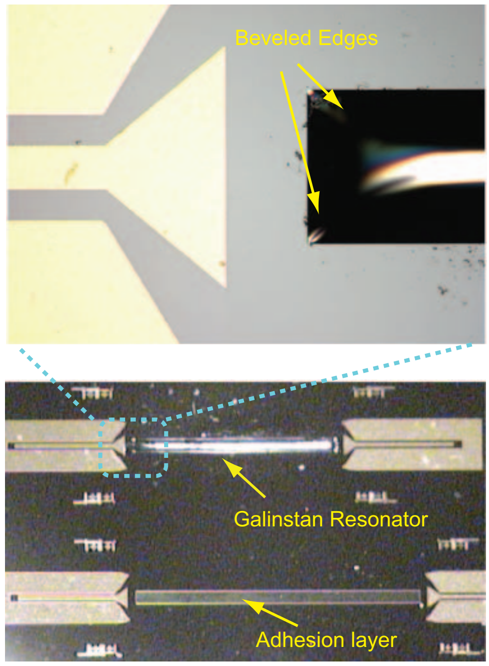

Fig. 2. Picture of the fabricated Galinstan resonator.

III. Fabrication

The resonators are fabricated on double-side polished high resistivity silicon wafers. 500/10000 Å Ti/Au layers are first evaporated on the front and back side of the silicon wafer to form the feeding networks and the ground plane.

Because Galinstan is liquid at room temperature, there needs to be a way to confine the liquid to form the rectangle resonator shape. In order to do this, a thin layer of 100/300 Å Ti/Au is used as an adhesion layer. The Ti/Au layer is then patterned to define the dimensions of the microstrip resonators. Galinstan is dispensed through a hypodermic syringe and needle onto the adhesion layer. Good adhesion is achieved because Galinstan readily alloys with Au. Adhesion between Galinstan and silicon dioxide layer is poor except when Galinstan is oxidized severely. In such cases, the oxide can be cleaned off by a quick dip in 1% HCl solution followed by DI water rinse. Fig. 2 shows pictures of fabricated Galinstan resonators.

IV. Measurement and Discussion

A. Quality Factor Measurement

Measurement of the resonators is carried out on an Agilent 8722 Network Analyzer with 150 μm pitch G/S/G RF probes mounted on a Cascade probe station. 2 port SOLT calibration is carried out over the frequency range of interest. The measured results (S_{21}) are shown in Fig. 3.

The measured quality factor (Q_m) is calculated as the ratio of the resonant frequency to the 3 dB bandwidth. The measured quality factors fall in the range of 39.2-57.5 and are listed in Table I. The measured quality factor Q_m and the unloaded quality factor Q_u are related by (1) [12]

$$Q_m = \frac{Q_u}{1 - 10^{-IL/10}}, \qquad (1)$$

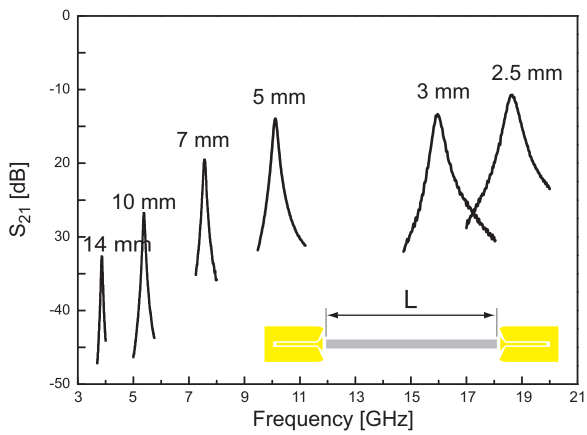

Fig. 3. Measured S_{21} of weakly coupled Galinstan resonators.

where IL is the mid-band insertion loss of the measured power transmission. In weak coupling mode, the insertion loss is large enough that the denominator term in (1) is negligible and the measured quality factor approximate the unloaded quality factor. The extracted unloaded quality factors are listed in Table. I.

The unloaded quality factor Q_u consists of several terms, each representing a different form of energy dissipation, as shown in (2)

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r}, \qquad (2)$$

where Q_c is the quality factor due to conductor loss, Q_d is the quality factor due to dielectric loss and Q_r is related with radiation loss.

The quality factor due to dielectric loss is in the order of the inverse of the loss tangent of the substrate. In this work, high-resistivity silicon wafer is used as the substrate with a loss tangent in the order of 0.001. Q_d is then in the order of 1000. The radiation loss of the microstrip resonator is negligible at this frequency range. Therefore, the conductor loss is the dominant loss factor in the designed microstrip resonator. Metal resistivity, film thickness and substreate surface roughness all contribute to the conductor loss. Each of these terms is addressed in the modeling.

B. Conductivity Extraction

A commercial FEM based high frequency solver, Ansoft HFSS [13], is used to model the Galinstan microstrip resonators. As mentioned in Section II, $100/300$ Å thick Ti/Au is deposited to as an adhesion layer to define the shape of Galinstan resonators. In order to take into account the effect of this adhesion layer correctly, measurement with only the Ti/Au layer is first done before Galinstan is applied onto it. The thin metal layer is modeled as a finite conductivity boundary condition in the HFSS model. The thickness of the boundary is set to 400 Å and its conductivity is swept to match the measured quality factor. An effective conductivity of 2.3×10^7 S/m is found to match the measurement consistently. No dielectric loss or surface roughness is assumed in simulation. Therefore this effective conductivity value also takes into account additional losses from the substrate dielectric loss and surface roughness.

A 3-D model is constructed in Ansoft HFSS to model the exact shape of the Galinstan resonators, as shown in Fig. 4. The thickness of applied liquid metal layer is in the range of $100 \sim 150$ μm. Exact thickness value is extracted from microscope measurement. Due to this large thickness and surface tension, Galinstan microstrip resonators exhibit beveled edges, especially around corners (Fig. 2). The FEM modeling takes account these effects as well.

The bottom of the resonator model is assigned to a layered-impedance boundary condition in HFSS with the thickness and conductivity of the adhesion layer from the above extraction. Then the conductivity of Galinstan in the model is swept to match the simulated quality factor with the measured ones. Conductivity of Galinstan at each frequency point is listed in Table. I. The conductivity of Galinstan is found to be $3.83 \pm 0.16 \times 10^6$ S/m. One sample simulation results for the 10mm long resonator is shown in Fig. 5.

TABLE I
MEASUREMENT RESULTS

Resonator Length [mm]	Resonant Frequency [GHz]	Quality Factor	Extracted Conductivity [S/m]
2.5	18.2	39.2	3.5×10^6
3	16.1	43.5	3.8×10^6
5	10.0	48.4	4.0×10^6
7	7.49	52.3	3.8×10^6
10	5.35	54.8	3.9×10^6
14	3.87	57.5	4.0×10^6

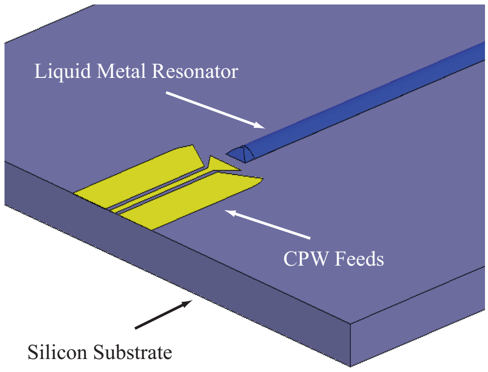

Fig. 4. HFSS model for the liquid metal microstrip resonator simulation.

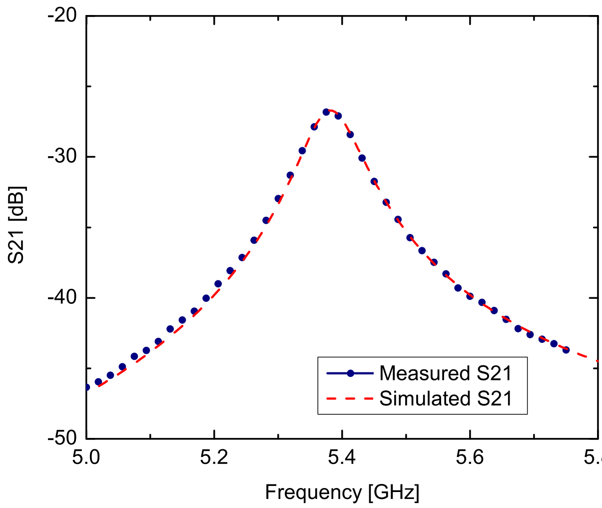

Fig. 5. Measured and simulated power transmission for the 10mm liquid metal resonator.

V. CONCLUSION

In this paper, we have designed and fabricated microstrip resonators made of a liquid metal, Galinstan. A patterning technique for Galinstan on silicon wafers is presented. FEM based modeling of the resonators has enabled us to characterize the conductivity of Galinstan over the frequency range of 3-20 GHz. The extracted conductivity of galinstan is $3.83 \pm 0.16 \times 10^6$ S/m. The outcome of this work can greatly assist future modeling and design of Galinstan enabled liquid metal RF/Microwave reconfigurable devices with high reliability.

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REFERENCES

[1] S. Kiyawat, "Micro-Electro-Mechanical Radio Frequency (MEMS RF) Switches: Design and Test of Concept", *Master Thesis*, University of California, Losangelis, 2003.

[2] C.H. Chen and D. Peroulis, “Electrostatic Liquid-Metal Capacitive Shunt MEMS Switch”, *2006 IEEE MTT-S International Microwave Symposium*, San Francisco, CA, USA, Jun. 2006.
[3] Geratherm AG, “Galinstan Material Safety Datasheet”, Geratherm AG, Fahrenheitstraff, D-98716 Geschwenda.
[4] J Lee, H Moon, J Fowler, T Schoellhammer, CJ Kim, “Electrowetting and electrowetting-on-dielectric for microscale liquid handling” *Sens. Actuators A*, 2000.
[5] G.E. Ponchak, J.L. Jordan, M.C. Scardelletti, “High Temperature Characteristics of Coplanar Waveguide on R-Plane Sapphire and Alumina,” *IEEE Transactions on Advanced Packaging*, vol.32, no.1, pp.146-151, Feb. 2009
[6] M Knoblauch, JM Hibberd, JC Gray and AJE van Bel,“A galinstan expansion femtosyringe for microinjection of eukaryotic organelles and prokaryotes”, *Nature Biotechnology*, 17, 906 - 909, 1999.
[7] RG Medical Diagnostics, 21130 Bridge Street, Southfield, MI 48034.
[8] H.J Kim, C. Son, and B. Ziaie, “A multiaxial stretchable interconnect using liquid-alloy-filled elastomeric microchannels,” *Applied Physics Letters*, vol. 92, Jan. 2008.
[9] J. Wood, K. Vummidi, P. Ralston, L. Chen, N.S. Barker and S. Raman, “Liquid Metal Vertical Interconnects for RF Flip-Chip Assembly,”, *2009 IEEE MTT-S International Microwave Symposium*, Boston, MA, USA, Jun. 2009.
[10] C.H. Chen and D. Peroulis, “Non-Toxic Liquid-Metal 2-100 GHz MEMS Switch”, *IEEE MTT-S International Microwave Symposium, 2007*, Holonunu, Hawii, June 2007.
[11] X. Liu, L. P. B. Katehi, D. Peroulis, “MEMS liquid metal through-wafer microstrip to microstrip transition,” *2008 IEEE MTT-S International Microwave Symposium Digest,* pp.41-44, Jun. 2008.
[12] D. M. Pozar, *Microwave Engineering*, 3nd ed. New York: Wiley,2005
[13] Ansoft, *High Frequency Structure Simulator*, Version 10, Ansoft Corporate, Pittsburgh, PA 15219, USA