Integration Aspects of RF-MEMS Technologies

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Abstract - This paper presents an overview about existing fabrication and packaging solutions for RF MEMS switches with regard to an integration with other passive or active devices. Achievements and problems are discussed from a technological point of view.

I. INTRODUCTION

It is well known that especially new RF architectures integrating switches with other passive and active devices will benefit from all the advantages of RF MEMS. The feasibility of integration has been still proven by many research groups for various substrates. At Philips Research capacitive switches and varactors with a tuning range of 17 have been integrated with inductors and MIM capacitors in their PASSI^{TM} process [1]. In Ref. [2] an ohmic switch developed and fabricated by CEA-LETI and ST Microelectronics on top of a driver circuit in 0.25 µm BiCMOS technology is descibed. Promising RF performance has been shown. Many other developments could be mentioned. However, MEMS switches and RF systems based on them are still not in industrial mass production. Apart from reliability issues the lack of an hermetic low temperature wafer-level packaging to protect the movable structures prior to the separation into individual dies is now the key problem.

An integration of MEMS with on-chip electronics is not in any case the best solution. For example, surface-micromachined inertial sensors are fabricated mostly as discrete sensor chips. A hybrid mounting of sensor chip and ASIC in one package has been identified as the most flexible solution. In contrast to sensor applications RF systems often contain several to tenth of MEMS. Any single package requires additional space and influence the RF performance of the device inside. Besides, even if for RF switches a cheap packaging solution would be available, the costs of single MEMS switches probably will not undercut the prices of single semiconductor PIN diodes. An integration of switches with other devices in circuits together with a smart packaging technique would be a promising solution from a technical point of view too.

In the following achievements and problems of RF switch fabrication and packaging processes will be discussed with special regard to integration aspects.

II. FABRICATION ASPECTS

Fig. 1 schematically shows the two different types of RF MEMS switches. In a capacitive switch the RF signal can pass if the membrane is up (off-capacitance) and is reflected if the membrane is down (on-capacitance). Due to the limited ratio between on- and off-capacitance such switches are more suitable for applications above 10 GHz. Ohmic switches are interrupt or close the signal path directly. They can be used from DC to 30-40 GHz depending on the contact resistance which should be as low as possible. In both cases mainly electrostatic forces are utilised for the actuation of the membrane. In a capacitive switch the actuation voltage can be applied between membrane and underpath. In ohmic switches an additional electrode is needed.

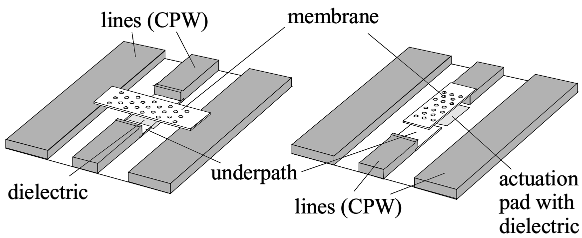

Fig. 1. Schematic view of a capactitive switch (left) and an ohmic switch (right) with electrostatic actuation.

In tunable capacitors (varactors) the capacitance can be changed continuously by varying the air gap or the electrode area. The ratio between maximum and minimum values is called the tuning range.

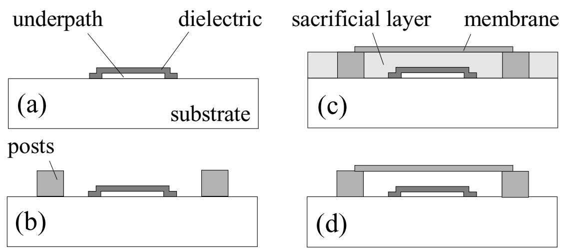

Fig. 2 - Schematic description of a basic fabrication process for a capacitive switch like shown in Fig. 1.

Fig. 2 describes a common fabrication process for a capacitive switch. First, the part of the metallic signal line below the switch membrane in Fig. 1 (underpath) is fabricated. On top of the underpath an dielectric is deposited and structured (a). Then, metallic lines are fabricated which are contact the underpath and act as posts for the membrane (b). The next step is the deposition and structuring of the sacrificial layer. Above the sacrificial layer the metallic membrane is formed (c). Depending on the membrane deposition process an alternative approach is to fabricate the membrane first and then posts and lines. In any case as final step the sacrificial layer is removed by dry or wet etching with subsequent supercritical dying (d). To meet the loss requirements of RF systems all used metals should be highly conductive.

A. Underpath layer

In capacitive switches the underpath is not a critical part. Table 1 compares some common materials. The surface roughness should be low to achieve a high on-capacitance. Therefore, despite a lower conductivity often refractory metals are used. In contrast to Au or Al their surface roughness does not increase during the subsequent deposition of a dielectric layer at typically 200-400°C. At Fraunhofer ISiT a Pt/ Au/ Pt stack has been used as underpath instead of pure Au to suppress the roughness growth [3]. At ITC-irst the Al underpath has been stabilized by an TiN top layer [4].

underpath metal	Au	Al/ TiN	Pt/ Au/ Pt	W, Ta, Ti
IC standard	no	yes	no	yes
structuring easy	yes	yes	yes	yes
thermal stability	low	med	high	high
roughness	med	low/med	low	low/med

TABLE 1

Metals used for the underpath in capacitive RF MEMS switches.

In ohmic switches the underpath is part of the contact together with the membrane. The contact degradation is the main reason limiting the reliability of ohmic switches. The standard is an Au-Au contact since a low resistance (1-2 Ω) can be reached with the weak forces characteristic for electrostatically actuated surface-micromachined structures. But Au-Au contacts degrade quickly even under a load of 1 mW [5]. However, if the switches are operated under cold switching conditions a significant lifetime is possible. A commercial device packaged on chip level is offered by Terravicta [6].

B. Dielectric layer

The dielectrics in the active area is currently the most problematical part of capacitive switches. Charging of the dielectric is the main reason restricting the switch reliability. Some dielectric materials are shown in Table 2.

By far the most used is PECVD Si_3N_4 (PE nitride) It has a has a nice ε_r and is a standard passivation in IC technology. But it exhibits strong charging. As one consequence the actuation voltage must be alternated in sign before each switching cycle. Most of the reported devices fail after a certain number of cycles. A lot of work has been spent on the improvement of switches with PE nitride. At particular conditions some devices have been operated for millions of cycles without failure.

Much lower charging was observed for switches with LTO fabricated at ITC-irst which could been operated with unipolar voltages [4]. However, the low ε_r and the noticeable roughness of this dielectric are limiting the on-off ratio to about 10. With Ta_2O_5 which is usually applied for capacitors in DRAM cells on-off ratios above 100 can be obtained easily. But for sputterd Ta_2O_5 similar to PE nitride significant charging has been observed at Fraunhofer ISiT [3].

dielectric	LTO	Si_3N_4	AlN	Ta_2O_5	PZT
IC standard	yes	yes	yes	yes	no
diel. constant ε_r	≈ 2	≈ 7	≈ 10	≈ 30	≈ 160
switch reliability	high	low	high	low	?
thermal stability	high	high	high	high	high

TABLE 2

Dielectric materials used in capacitive RF MEMS switches.

An interesting material is PZT although it exhibits charging as well. Switches with an on-off ratio of several 100 could be realised. But apart from the material properties the dielectric layer must be available with high quality at reasonable costs. PZT is not IC compatible. Deposition processes are still on a laboratory stage, AT IRCOM also Al_2O_3 and BST are investigated as alternative dielectric materials [7].

Advanced sputtering processes on state-of-the-art equipment are available for AlN which is used for BAW resonators. In cotrast to PE nitride and Ta_2O_5 capacitive switches with sputtered AlN fabricated at Fraunhofer ISiT could be operated repeatedly with unipolar voltage for any required duration in a wide range of conditions without charge induced failures [4]. From the authors point of view AlN is the most promising material to overcome the reliability problems of capacitive RF MEMS switches.

C. Sacrificial layer

As a temporary material the sacrificial layer has no direct impact on the switch properties. Although, it is of great importance for the whole technological process. The simplest and most popular technology with sacrificial photoresist, usually polyimide, is described in Fig. 2. A big advantage is, that a resist can be removed easily and with high selectivity by dry etching in O_2 plasma as well as by wet etching in organic solvents. However, the high sensitivity of photoresists to heat treatments restricts the membrane deposition. For switches integrated in an IC process the membrane material of choice would be the standard metallisation. But sputtering of Al or Al alloys at 200-400°C cause mechanical and chemical degradation of the photoresist resulting in warped membranes and residuals after release etching. After membrane structuring additional processes required for example for packaging purposes are critical since they could damage the unprotected sacrificial layer. However, this problems can be solved as demonstrated by Raytheon in [8].

An alternative to photoresist is PE silicon oxide. It is the common sacrificial material in the fabrication of surface-micromachined polysilicon inertial sensors. At Philips it has been used to build up the capacitive switches integrated in the PASSI™ process [1]. To avoid residuals between the surfaces in contact wet etching in buffered HF was applied to release the MEMS structures instead of the common HF gas phase etching. Additional effort was required to protect the PE nitride dielectric and the Al alloy membrane during the release procedure. Besides, after wet sacrificial layer etching usually supercritical drying is required.

At EPFL sputtered amorphous Si was applied as sacrificial layer in combination with Al as structural material and LTO as the dielectric for capacitive switches and varactors [9]. The sacrificial Si was removed in SF_6 plasma with good selectivity. As in the case of PE oxide postprocessing at up to 400°C is not critical.

In the process of Fraunhofer ISiT electroplated Cu is used as sacrificial layer [3]. It can be wet etched with high selectivity to most other materials including photoresist is possible. However, Cu is rather difficult to handle since it can not be structured by dry etching. Although it is used as metallisation in ULSI circuits it is not IC compatible. Probably, with respect to the specifics of IC technology the other named materials are more suitable.

sacrificial layer	photoresist	PE oxide	Si	Cu
IC standard	yes	yes	yes	no
structuring easy	yes	yes	yes	no
thermal stability	very low	high	high	med
dry release etching	yes	yes	yes	no
etch selectivity	high	med	high	high

TABLE 3

Materials used as sacrificial layer for RF MEM switches.

D. Free standing structural layer

Most common are Au and Al due to the easy deposition and structuring. The big problem is the sensitivity of the released elements made from Au or Al to heat treatments. Thermally induced relaxation effects in the metal result in increased surface roughness and irreversible stress changes causing warped membranes even at 200-300°C. Besides, due to their softness pure Al and Au structures can degrade mechanically as a result of the deformation during switching. Depending on the composition the primary creep in Al alloys can be lower by an order of magnitude compared to pure Al [10]. In particular AlCuMgMn is identified as promising material for RF MEMS showing high yield strength and low creep.

Higher thermal stability and good mechanical properties are known for Ni based structures. Ni membranes with stress compensating anchoring survive temperature treatments at up to 450°C for 1 hour without degradation [3]. Composite Au/Ni/Au membranes can be annealed at up to 350°C. The mechanical behaviour of Ni is pretty good. Although, Ni is not IC compatible. Also, for pure Ni membranes the skin effect is more relevant due to its permeability.

structural metal	Au	Al	Al alloys	Ni	Cu
IC standard	no	yes	yes	no	no
bulk conduct. $\mu\Omega\times cm^{-1}$	2.1	2.6	2-3	6.8	1.7
mechanical reliability	med	med	med/high	high	?
thermal stability	low	low	low/med	med	?

TABLE 4

Metals used as structural material for RF MEM switches.

Copper can also be considered as an alternative material for the structural layer. With PE oxide as sacrificial layer common damascene technique could be used for deposition and structuring. RF switches made from Cu still have been demonstrated. However, much more investigations are required in terms of mechanical and thermal properties.

III. PACKAGING ASPECTS

RF switches must be packaged on wafer level to protect the fragile movable structures against humidity and contaminants prior to the separation into individual dies. It is called the 0-level packaging. Possible types with lateral and vertical feedthroughs are illustrated in Fig. 3. Probably, vertical feedthroughs in the device wafer as shown in Fig. 3a would be the simplest task allowing any type of bonding. If the vertical feedthroughs are in the cap in addition to the sealing electrical contacts must be created during the bonding procedure (Fig. 3b) For the case of lateral feedthroughs on the device wafer and a metallic seal an additional isolation between them is required (Fig. 3c). The width of the metallic seal is another critical issue. As it has been mentioned above the packaging temperature should not exceed 250-300°C to avoid a degradation of the movable metallic elements.

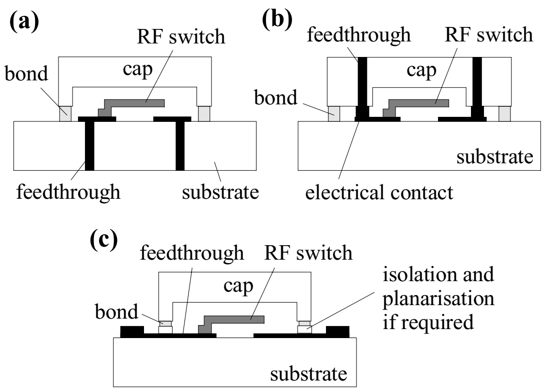

Fig. 3. Possible types of 0-level packaging with vertical and lateral feedthroughs.

Anodic bonding require 350°C and more. It could be used only with vertical feedthroughs since the bond frame must be pure silicon or glass.

Thermo compression bonding is performed typically at 300-350°C. In the case of lateral feedthroughs the bond frame must be planarized and electrically isolated like shown in Fig. 3c. Wafer-t-wafer packaging with vertical feedthoughs has been demonstrated at the University of Michigan applying Au thermo compression bonding at 350°C [11]. The feedthroughs were realised by anisotropic etcing of the Si substrate with subsequent passivation and selective metallisation prior to the switch fabrication.

With glass frit bonding a surface topography resulting from lateral feedthroughs could be sealed without additional planarisation, see Fig. 3c. But the bonding temperature is likewise above 350°C. Outgassing of the glass frit during reflow probably could contaminate the MEMS switches inside the cavity. Anyhow, at BOSCH wafer-to-wafer packaging of capacitive switches using glass frit bonding at about 450°C has been successfully performed [12]. It is noted that the packaged switches remain fully functional. No detailed information about degradation effects is given.

Bonding at temparatures below 300°C is possible with solders. However, it is not easy to control the width of the bond frame. The liquid solder can be pressed out of the frame area due to inhomogeneous pressure distribution resulting from wafer warp and thickness variations. Nevertheless, the mounting of single caps on wafer level has been demonstrated.
A capping technique developed at IMEC together with Philips Research utilizes a SnPb solder [13]. The lateral feedthroughs of the switches are isolated by a PECVD Si_3N_4 against the bond frame. The caps containing the solder consist of high resistivity silicon. Chip-to-wafer bonding (0-level packaging) was performed on a standard flip-chip bonder at 240°C under athmospheric pressure. After wafer dicing in a second step individual chips were flip-chip mounted at 240°C to an laminate RF board using common solder ball technique (1-level packaging). The insertion losses increase by about 0.3 dB at 2 GHz after 0- and 1-level packaging. The package is hermetic. No significant degradation of the switch performance was found.
Another capping process developed at IMEC is based on a BCB seal [14]. BCB is a photosensitive polymer developed as low-k dielectric for CMOS applications. Like in the previous case a standard flip-chip bonder was used for cap placing and the application of temperature and pressure. In contrast to [13] no additional isolation or planarisation on the device wafer is needed since the polymer starts to reflow at 170°C during bonding. The final curing at 250°C results in a quasi hermetic sealing around the switch. Obviously, the outgassing of BCB is low since no impact on the lifetime of the switches could be observed. After common stud-bump bonding of the single chips on a laminate substrate at 275°C (1-level packaging) an underfill was applied to avoid a delamination under thermally induced stress. The measured insertion loss of the whole package was below 0.6 dB at up to 15 GHz [15].
Both described cap-to-wafer packaging techniques are well approved. Although the are probably not cheap enough for real mass production they could be an excellent solution for small volume applications or prototyping.

Lateral feedthroughs can be used probably only up to several tenth of GHz. At least in the high GHz range vertical feedthroughs seems to be better suited. Up to now, only anisotropically etched vias in Si with subsequent passivation and selective metallisation have been presented [11]. But the process is complex and the feedthroughs are relatively large. Vertical vias etched in high resistivity Si using DRIE and metallised by Au electroplating are presented by BOSCH in [16]. Excellent performance in the K-band has been measured. Another solution based on the reflow of glass has been demonstrated at ISiT. Fig. 4 shows a photo of a 6" glass substrate with embedded Si plugs. Since the resistivity of Si is to high for microwave applications a metallisation technique for the feedthroughs is currently under development.

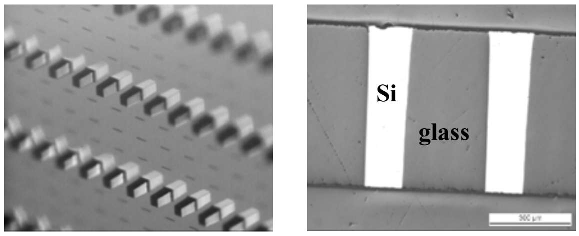

Fig. 4. Photo of a 6" glass substrate with vertical feedthroughs made from highly conductive Silicon (left). Photo of the cross-section through such a substrate (right). The footprint of the feedthroughs is approximatly $150\times150\ \mu m^2$.

VI. CONCLUSIONS

The lack of commercial RF circuits based on RF MEMS is rather a problem of the IC technology then a question of packaging. The development of a cheap, low temperature wafer-to-wafer packaging technique is now the most important task. It could been expected, that the reliability problems of capacitive RF MEM switches will be solved in the next future.

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