SMALL, LOW-OHMIC RF MEMS SWITCHES WITH THIN-FILM PACKAGE
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ABSTRACT
We report on small, low-ohmic RF MEMS switches with a circular membrane actuator design. A low temperature process is used to manufacture both the MEMS switch as well as its hermetic, thin-film package resulting in a very small footprint device. The hermetic seal of the package significantly increases the switch lifetime and reliability. The switches demonstrate good RF performance and high switching speeds. A comparison with other MEMS switches reveals that these MEMS switches possess a low on-resistance while occupying only a very small area on the wafer.

INTRODUCTION
Although there has been a tremendous progress in the RF performance and reliability of ohmic RF MEMS switches, most of these switches are still relatively large and costly compared to transistors. Moreover, MEMS switches are commonly encapsulated using a large and thick cap wafer, which increases footprint and cost even more. As a consequence, the length of the interconnects increases, which results in reduced RF performance compared to transistor based RF switch solutions. For cost and performance reasons it is therefore desirable to miniaturize ohmic MEMS switches, a paradigm shift that has also been proposed for capacitive MEMS switches [1].

Moreover, it would greatly facilitate high-volume production of ohmic MEMS switches, if they can be manufactured and packaged using processes very similar to CMOS wafers or can even be processed on top of CMOS wafers. In order to enable this, both the MEMS switch and its package need to be fabricated using CMOS back-end compatible lithographic processing at low temperatures (≤400 °C), without reduction in RF performance and reliability. Since a deposited thin film package protects the MEMS switch, the wafer can follow the standard grinding, dicing and moulding steps used for CMOS.

In this paper we present a metal-contact RF MEMS switch technology that meets the following requirements:
- Small-size
- High RF-performance
- Hermetic thin-film package
- High reliability and lifetime
- Processing temperature ≤400 °C

After discussing the fabrication process, the hermeticity of the thin-film encapsulation and its effect on the switch reliability will be demonstrated. To our knowledge this is the second report [2] of a thin-film packaged ohmic MEMS switch and the first time the hermeticity of the thin-film package and its effect on switch lifetime is demonstrated. It is shown that the small size of the switch enables high switching speed, while at the same time retaining good RF performance. Finally, a benchmark of contact resistance and size reveals that the switch demonstrates a comparatively low contact resistance at a small size.

FABRICATION
The process flow of the MEMS switch is shown schematically in Fig. 1. After structuring of the Au bottom electrode (yellow), the sacrificial layer is deposited (blue). Then the movable membrane is processed consisting of a Au top electrode embedded in SiN layers. On top of the membrane a second sacrificial layer and a thin-film package layer is deposited. Finally, the sacrificial layers are etched. To minimize contact contamination [3] the cavity is sealed immediately by a plug deposition.

![Figure 1: Schematic process flow of the MEMS switch from top to bottom. Blue: Si substrate and sacrificial layer; green: SiN; yellow: Au electrodes; purple: sealing plug.](image)

All process steps needed to manufacture and package the switch occur at low CMOS back-end compatible temperatures (≤400°C).

In Fig. 2 a microscope top-view image of the completely processed switch is shown. The thin-film package membrane has been removed for clarity. The outer dark circle is the edge of the thin-film package with a radius of 60 µm. The movable membrane has a radius of 50 µm.
RESULTS

Package Hermeticity

In order to determine the hermeticity of the thin-film package, the mechanical Q-factor of the fundamental membrane resonance is measured as a function of external pressure. The membrane is excited by a small AC voltage superposed on a larger DC voltage between the actuation electrodes. The amplitude of the packaged switch at atmospheric pressure $P=1000$ mbar is determined with an impedance analyzer that measures the electrical conductance $G$ and with a laser vibrometer that measures the deflection $x$ of the center of the membrane as shown in Fig. 4A. Both methods yield an identical resonance frequency and Q-factor. Then the pressure inside the measurement chamber is reduced to 50 mbar for several hours. The same switch as in Fig. 4A is measured (Fig. 4B, black curve).

The Q-factor is found to be independent of the external pressure providing evidence for the hermeticity of the thin-film package. After removing the package cap of the MEMS (Fig. 4B, blue curve) the Q-factor increases to 80 at 50 mbar due to reduced air damping. This clearly demonstrates the sensitivity of the Q-factor to pressure variations. It is concluded that the package is hermetically sealed at a pressure higher than 50 mbar.
Switching Lifetime and Reliability

In order to evaluate the effect of the hermetic package on the reliability, the contact resistance is measured as a function of the number of cold switching cycles on many switches. It is observed that switches without package or with a carefully removed package consistently fail within 10 million switching cycles in air (a typical measurement is shown in Fig. 5A).

In contrast, thin-film packaged switches on the same wafer show a drastically improved lifetime and reliability of typically more than 500 million cycles (Fig. 5B). The reliability measurement is performed at a switching rate of 2 kHz. After every third switching cycle the on-and off-resistance between the contacts is measured using a 4-point measurement to ensure that the switch opens and closes properly.

By comparing Fig. 5A and B it is observed that the absolute value and the variation in the contact resistance is much lower for a packaged than for an unpackaged switch. The significant increase in the number of switching cycles by more than a factor 50 is attributed to the clean atmosphere inside the hermetic package, which improves the contact cleanliness. It has been shown [3] that contamination of the Au contacts has a detrimental effect on the switching reliability.

Switching times

Besides the aforementioned advantages of small switches, they also have the advantage of short switching times [1,4,5]. The electrical resistance and the mechanical displacement are simultaneously determined as a function of time using a 4-point resistance measurement and the laser vibrometer.

The on-switching times depend strongly on the actuation voltage. The time to close the contact electrically and mechanically is less than 3 µs at 50 V actuation voltage. In contrast, the opening time depends only on the mechanical properties of the switch. The MEMS switch breaks the electric contact within 5 µs. It takes around 40 µs until the membrane is completely open and at rest as determined using the laser vibrometer.

RF Performance

RF measurements of the thin-film packaged RF MEMS switch are shown in Fig. 6. Insertion loss measurements in the closed state (Fig. 6A) and isolation measurement in the open state (Fig. 6B) are performed up to 8 GHz.

Figure 6: RF insertion loss (A) and isolation (B) of the packaged switch in the closed and open state. The insertion loss data is deembedded up to the contacts to reveal the intrinsic RF characteristics of the contact.

The insertion loss data are deembedded up to the contacts. In the closed state the contacts behave as a resistor of 0.8 Ohm. In the open state the RF performance can be
described by a series capacitor of 2 fF. The isolation data are not deembedded and include effects from the interconnect and the Si substrate. The measured isolation of more than 40 dB at 8 GHz is better than most other packaged MEMS switches [6]. The thin-film package barely reduces the RF performance.

**Ohmic MEMS Switch Benchmark**

To reduce costs, interconnect length and package dimensions, it is important to reduce the size of the MEMS switches. Moreover, switch miniaturization facilitates circuits containing a large number of MEMS switches. However, it should not lead to a degradation of the switch performance.

In Fig. 7 the area \( A \) and the contact resistance in the on-state \( R_{on} \) of the switch presented in this work (labeled NXP) are compared to other ohmic MEMS switches from literature [2,6,7-11] (labeled by their affiliation). For fair comparison, the area on the y-axis of Fig. 7 does not include the package. Since the thin-film package of the NXP and RFMD [2] switches is much smaller than wafer-bonding packages of other ohmic MEMS switches, the benchmark would turn out even more favorable for the thin-film packaged switches if the area of the package was included.

![Figure 7: Benchmark of the estimated lateral area and contact resistance of different MEMS switches. The lateral area does not include the package. The lines indicate constant products of the area times the contact resistance.](image)

There is a trade-off between area and resistance, since the total on-resistance can be reduced by connecting several switches in parallel on a bigger surface area, as is done by Radant [5]. However, this increases the lateral area. This trade-off is illustrated by the lines in Fig. 7 indicating constant products of area and contact resistance \((A\times R_{on})\). The figure shows that the NXP switch has a comparatively low contact resistance on a small footprint, enabling high density MEMS switch arrays.

**CONCLUSIONS**

We present a small-size, low-ohmic, thin-film packaged MEMS switch. The switch operates using a movable circular membrane, which differentiates it from more common cantilever-based MEMS switches. Experiments demonstrate the hermeticity of the package and the beneficial effect of the package on the switch lifetime. The combination of small size, high RF performance and thin film package can help pave the way to low-cost, high volume production of RF MEMS switches.

**REFERENCES**