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RF-MEMS technology as an enabler of 5G: Low-loss ohmic switch tested up to 110 GHz

JacopoIannacci

Center for Materials and Microsystems – CMM, Fondazione Bruno Kessler – FBK, Via Sommarive, 18 – 38123, Povo, Trento, Italy

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ABSTRACT

Microsystems for Radio Frequency (RF) passive elements, known as RF-MEMS, have been attracting the attention of academic and industrial research since their first discussion, thanks to the remarkable performance they can trigger. Despite the flattering premises, RF-MEMS technology did not score consistent spread into mass-market applications, yet, as technical issues still needed to be managed, but also because consumer products did not use to really need such pronounced characteristics. Nowadays, the application scenarios of 5G (i.e. 5th generation of mobile communications and networks) and of the Internet of Things (IoT), highlight a growing need for cutting edge performance that RF-MEMS are capable of addressing. Given such a context, this short communication discusses an RF-MEMS series ohmic micro-switch, electrostatically driven and fabricated in a surface micromachining process, exhibiting good characteristics up to 110 GHz. In brief details, the micro-relay shows isolation (when OPEN) better than −15 dB and loss (when CLOSE) better than −1 dB up to 40 GHz. The actuation voltage is around 50 V, although it can be lowered acting on the release step temperature. Despite the design concept admits margins for improvement, the characteristics of the micro-switch reported in the following are already quite interesting in the discussion of next generation of RF passive components for 5G and IoT.

1. Introduction

The field of MicroElectroMechanical-Systems (MEMS) for Radio Frequency (RF) applications, known as RF-MEMS, has been gathering interest since the early discussions in the scientific literature, about two decades ago [1,2]. The unprecedented performance of Microsystem-based RF passive components, conjugated to relative ease of manufacturing in planar microfabrication technologies (e.g. surface micromachining), triggered intense research activities (mainly within academic sector) around their demonstration, as well as concerning possible market exploitations [3,4], i.e. mainly pursuing a *technology push* approach. As a matter of fact, the variety and diversity of functionalities enabled by RF-MEMS is remarkable, as it ranges from very-simple components, like switches and varactors (variable capacitors), to complex networks, like reconfigurable filters, phase shifters, impedance matching tuners, programmable step attenuators, and so on [5–9].

In spite of such favourable premises, RF-MEMS did not spread into the consumer market segment as it was forecasted, for more than one decade, starting from the first years of the 2000s. The reasons for such a limited success are multiple. From the point of view of technology, RF-MEMS suffer from a wide range of mechanical-related reliability issues, exposing them to failure mechanisms (both reversible and irreversible), which need to be properly accounted for at design, fabrication and operation level [10–12]. Also important, fabrication of Microsystems is typically incompatible with standard active technologies (i.e. CMOS). Therefore, packaging and integration solutions must be developed in order to enable integration of RF-MEMS with the rest of the system or sub-system [13–16], thus increasing technical complexity and cost of manufacturing. If, on one side, all these issues have been solved at research and engineering level, on the other hand, potential killer applications paving the way for a robust spread of RF-MEMS technology into the market have started to peek out just in very recent years.

In this respect, the emerging field of 5G (i.e. 5th generation of mobile communications and networks), along with the comprehensive reference scenario of the Internet of Things (IoT), seems to be a very suitable context for benchmarking and testing the potentialities of RF-MEMS solutions [17–19]. Also interestingly, IIIV technologies are being discussed against 5 G applications, and they exhibit, at the same time, significant potential for integration with RF-MEMS with respect to standard technologies, thus opening up interesting opportunities of hybridisation with Microsystems [20–24].

Despite the discussion against system-level characteristics and functionalities is still hectic and, above all, open, it is possible identifying target performance to be complied by RF passive components, in order to enable and sustain 5G and IoT high-level requirements [17]. Among them certainly stand frequency wideband operability (e.g. from a few GHz up to 60–70 GHz), low-losses, very-limited cross-talk, good isolation, etc.

Email address: iannacci@fbk.eu (I. Jacopo)

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The focus of this short communication is spent around the crucial building block of high-performance RF-MEMS passive devices and networks, i.e. micro-switches. A novel relay design is introduced, along with the discussion of its measured performance up to 110 GHz.

2. Micro-switch design and working principles

The discussed RF-MEMS micro-relay is implemented by a clamped-clamped suspended Gold membrane, electrostatically driven in order to open/close ohmic contact between the input/output RF terminations. The movable membrane is framed within a Coplanar Waveguide (CPW) structure, suitable both for on-wafer probe measurements, as well as for wire-bonding and Surface Mount Technologies (SMTs). The measured 3D topology of the series ohmic switch was acquired with an optical profilometer and is shown in Fig. 1.

The suspended Gold membrane is 2 µm thick and underneath it a fixed counter-electrode is placed in order to drive it, along with Gold contacts to connect the input/output terminations when the MEMS is pulled-in. Straight flexible suspensions are 15 µm wide and 150 µm long. The central square plate size is 150 µm and has 10 µm wide strip openings, in order to ease the release of the suspended structure, when the sacrificial layer is removed. The micro-fabrication process is based on surface micromachining technique performed on 6 inch Silicon wafer [25,26]. The whole technology platform is available at the Center for Materials and Microsystems (CMM) of Fondazione Bruno Kessler (FBK), in Italy. A schematic cross-section of the process is depicted in Fig. 2.

The process flow features two buried layers, namely Polycrystalline Silicon (PolySilicon) and Aluminium Multimetal layer, for DC biasing lines/electrodes and RF underpass, respectively. MEMS membranes are realised in electroplated Gold and airgaps are defined by photoresist sacrificial layer patterning [27,28].

The switch is equipped with an active mechanism in order to improve its reliability in case of stiction (i.e. missed release of the membrane when the bias is zeroed) induced by charge accumulation and/or micro-welding. It is based on a micro-heater, embedded underneath the anchoring MEMS areas, and is not further discussed here, as it was previously reported in literature [31,32]. In the following, the experimental characterisation of the RF-MEMS micro-switch is discussed.

3. Experiments and discussion

The experimental testing of the RF-MEMS physical samples was performed according both to the electromechanical and electromagnetic (RF) characteristics. Concerning the former, the experimental pull-in curve was observed by means of input/output DC current versus applied bias (I-V) measurements, compared against simulated results obtained in Ansys Workbench [16]. Differently, in the latter case, S-parameters onwafer measurements were performed up to 110 GHz, and observed against simulated traces [19].

As known, residual stress builds within thin-films, as a consequence of presence of other materials as well as of thermal treatments. Such stress, depending on its characteristics (i.e. compressive and tensile, leading to a gradient distribution) as well as on the

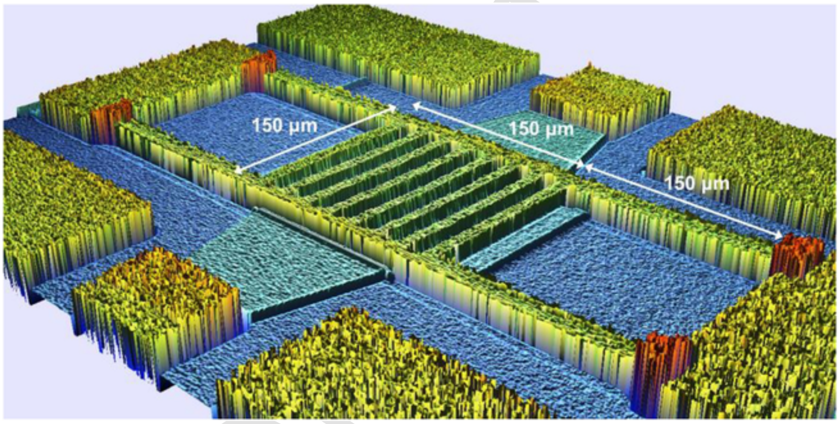

Fig. 1. 3D measured topology of the RF-MEMS clamped-clamped ohmic switch, acquired by means of a profiling system based on optical interferometry.

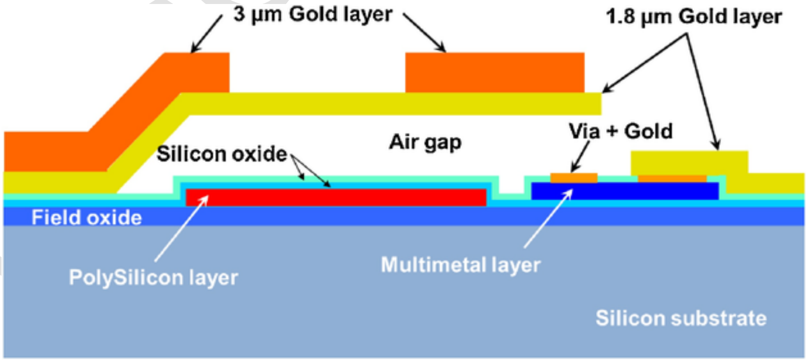

Fig. 2. Schematic cross-section of the RF-MEMS technology available at the Center for Materials and Microsystems (CMM) of Fondazione Bruno Kessler (FBK), in Italy.

MEMS topology, can lead to issues like non-planarity, buckling, and stiffening [33–35]. In the case of the RF-MEMS here discussed, its clamped-clamped anchoring characteristic (see Fig. 1) in conjunction with the predominantly tensile stress characteristics of electrodeposited Gold layers [25,26] in the CMMFBK technology, lead to stiffening of the MEMS membrane. This, in turn, it causes significant increase of the pull-in voltage, with respect to its nominal value. The presence of stress can be modelled and accounted for in simulations by imposing suitable initial state conditions [36,37]. The comparison of measured and simulated pull-in of the RF-MEMS switch here discussed, is reported in Fig. 3.

The IV measured trace highlights a transition of current from the pA to the mA range at 56 V, corresponding to the activation (pull-in) of the MEMS. Concerning simulations, when an initial condition accounting for a tensile stress of about 100 MPa is set, the pull-in is predicted at around 54 V (solid line in Fig. 3). The stress value was not set for best fit, but was extracted from test structures purposely included in the same fabrication batch (not discussed here for the sake of brevity). Differently, when residual stress in neglected in the simulated model (nominal case), the pull-in voltage is predicted at 21 V (dashed line in Fig. 3). While it the former case the disagreement is around 3%, in the latter the nominal pull-in voltage is underestimated 2.7 times with respect to the physical sample. This proves that residual stress can exert significant impact on the characteristics of RF-MEMS switches. Nonetheless, it also has to be stated that it can be significantly mitigated by lowering the temperature of the sacrificial layer removal step, at the cost of more time consuming etching step [25,26]. Dipping into more details, the temperature needed for proper plasma Oxygen release of MEMS suspended structures, lets the Chromium-Gold seed layer diffuse into the MEMS structural Gold. This leads to the generation of a stress gradient distribution through the Gold thickness. Such gradient turns from more to less tensile, when passing from the bottom to the top of the metallisation. Its presence is evident when dealing with cantilever-type structures, i.e. hinged only on one end, as they typically bend upward towards the free end [38]. Differently, clamped-clamped structures, like that in Fig. 1, do not exhibit visible out-of-plane deformations for predominantly tensile stress distributions. However, the resulting effect it stiffening of the mechanical structure, leading to pull-in voltage significantly higher than nominal (see Fig. 3). As mentioned above, stress gradient building is a thermally dominated phenomenon. Therefore, reducing the temperature during plasma Oxygen release mitigates significantly the stiffening of clamped-clamped suspended MEMS membranes, at the expense of lower sacrificial layer removal rate (i.e. longer release time).

Concerning reliability of the RF-MEMS switch in terms of cycling and lifetime, comprehensive studies and experimental analyses were carried out before, on similar design topologies realised in the same technology platform. Such characterisation campaigns proved that micro-switches can reach the million cycles range without significant S-parameters degradation, also when thermally stressed [39,40].

The RF characteristics of the MEMS ohmic micro-relay are now discussed. As it will be shortly reported, the RF-MEMS switch was tested on a very-wide frequency range, i.e. from 100 MHz up to 110 GHz. The micro-relay behaviour is rather satisfactory up to around 50 GHz, while above such a frequency S-parameters tend to degrade. Despite this, it was decided to report anyway the whole RF-MEMS behaviour up to 110 GHz, in order to perform more consistent validation of the simulation methodology. On the other hand, it was done also to acquire comprehensive insight of intrinsic limitations in the proposed design concept when operating in the millimetre waves range.

The plot in Fig. 4 shows the comparison of the measured and simulated characteristic of reflection (S11) and isolation (S21) when the RF-MEMS micro-switch is OPEN (i.e. MEMS in its rest position – OFF).

At first, accurate match between simulations and measurements is visible. To this regard, it should be kept in mind that the analysed frequency range is as wide as 110 GHz. In this respect, it is typically quite complex having accurate simulations on such a broad span by relying on a unique model. Focusing on reflection (S11), the qualitative agreement gets worse above around 50 GHz. Nonetheless, the measured characteristic is quite noisy above such a frequency threshold. Furthermore, the disagreement between the measured and simulated traces is never larger than about 2 dB. For what concerns the RF-MEMS switch performance, isolation (S21) is better than -24 dB up to 20 GHz, and better than -15 dB up to 40 GHz. Then, above 40 GHz, the S21 ripples in between -10 dB and-20 dB.

The measured versus simulated characteristic of reflection (S11) and loss (S21) when the switch is CLOSE (i.e. MEMS pulledin – ON), is reported in Fig. 5.

The DC bias imposed when performing S-parameters measurements in the ON state is 60 V, i.e. slightly larger than the pull-in level in Fig. 3. Current absorption of the DC probes was also monitored during experiments. It increases from leakages in the order of 10-30 pA when the MEMS is biased below pull-in, i.e. below 56 V, to about 1 nA at 60 V (i.e. after pull-in occurs). This means that the power

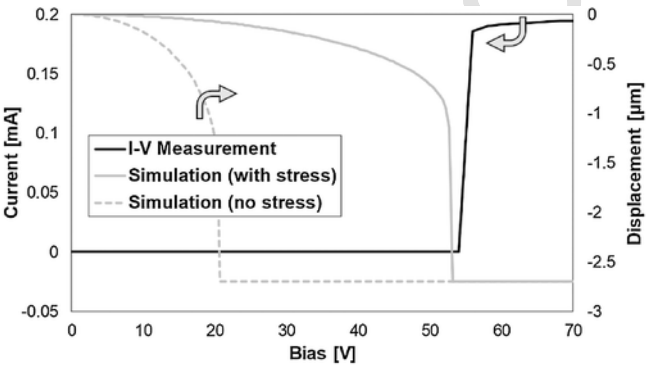

Fig. 3. Comparison of the measured and simulated pull-in characteristic (vertical right and left axis, respectively). The measured trace refers to I-V measurement. Simulated characteristics report vertical displacement versus bias, in case intrinsic Gold stress is neglected (dashed line) or counted in (solid line).

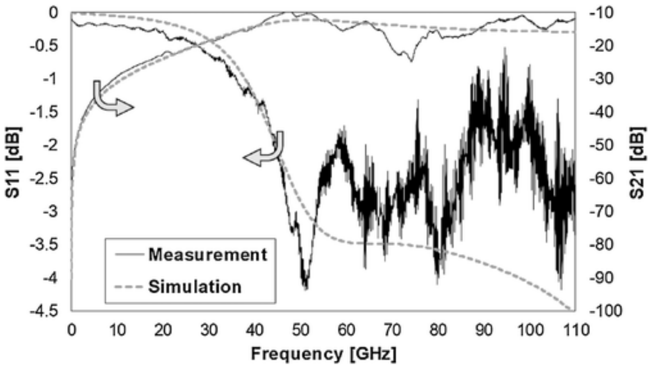

Fig. 4. Measured versus simulated S-parameters characteristics of the RF-MEMS micros-witch in OPEN state (i.e. MEMS OFF), between 100 MHz and 110 GHz. Reflection (S11) and isolation (S21) are displayed on the vertical left and right axis, respectively.

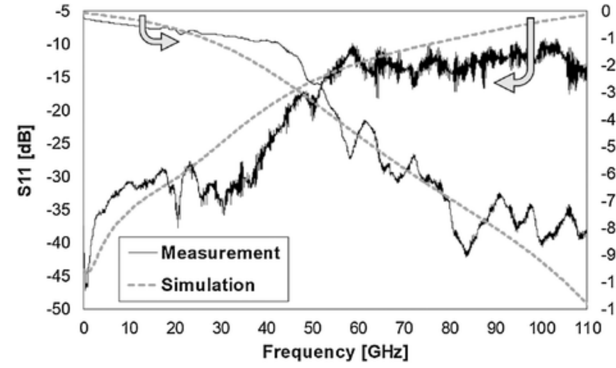

Fig. 5. Measured versus simulated S-parameters characteristics of the RF-MEMS micro-switch in CLOSE state (i.e. MEMS ON with 60 V DC bias imposed), between 100 MHz and 110 GHz. Reflection (S11) and loss (S21) are displayed on the vertical left and right axis, respectively.

consumption when keeping the RF-MEMS switch ON is below 0.1 μW.

Concerning the RF behaviour in Fig. 5, the agreement between simulations and measurements is rather satisfactory. In spite of some frequency portions where separation of traces is more pronounced, the qualitative behaviour is well-predicted by the 3D model. In terms of performance, it must be noted that loss (S21) is below -1 dB up to 40 GHz, while reflection (S11) is better than -25 dB up to the same frequency. Such characteristics are quite satisfactory, in line with other research items discussed in literature [41–44], and in any case unknown to switches realised in standard semiconductor technologies [45,46]. Above 40 GHz, reflection (S11) increases, despite remaining always better than about -12 dB. Loss (S21) follows a worsening trend bringing it to the worst value of about -8 dB at 110 GHz.

Comprehensive insight of the RF-MEMS micro-switch S-parameters behaviour can be inferred by device modelling based upon extracted lumped element network. Detailed network architectures for the discussed device are not reported here for the sake of brevity, despite a suitable technique for extracting lumped networks of RF-MEMS devices was reported in the past by the author [28–30]. However, keeping in mind the qualitative topology of RF-MEMS lumped element network architectures with respect to their geometry, considerations can be developed after looking at the comparison between the switch discussed in this work and other RF-MEMS devices reported in recent literature (see Table 1).

From a general point of view, looking at Table 1, the RF-MEMS micro-switch discussed in this work is well-placed when compared against typical performance of other recent solutions in literature, concerning both research and commercial items. Differently, when focusing on loss (S21) of conducting (ON state) switches, the works reported in [48] and [53] outperform the device here discussed, at 40 GHz and 20 GHz, respectively. To this regard, beside the fact that the RF-MEMS switch in [53] works in superconducting condition, both mentioned MEMS switching membranes are tiny in comparison to this work, them being a narrow bar [48] and an inline cantilever [53]. On the other hand, the RF-MEMS device in Fig. 1 features a bulky transversal membrane placed across the central RF line. When actuated, the two lateral Gold patches of the MEMS load the RF line with a small shunt inductive contribution that can cause additional losses when the frequency approaches the millimetre wave range. To this regard, it must also be stressed that critical trade-offs between RF performance and mechanical robustness of MEMS exist and arise. From this point of view, the switching membrane of this work is mechanically more robust than cantilevers and tiny suspended bars.

Table 1
Comparison of the performance achieved by the RF-MEMS switch discussed in this work against relevant recent results available in literature.

Isolation (S21) OPEN[1]	Loss (S21) CLOSE[1]	Reflection (S11) CLOSE[1]	Type of RF-MEMS switch	Reference
−16 dB (20 GHz)	−0.8 dB (20 GHz)	n/a	Series ohmic cantilever switch [Research]	[47]
−24 dB (40 GHz)	−0.3 dB (40 GHz)	n/a	Series ohmic clamped-clamped narrow bar-based switch with thin-film package [Research]	[48]
−15 dB (40 GHz)	−0.7 dB (40 GHz)	−20 dB (40 GHz)	Series ohmic cantilever switch [Research]	[49]
−25 dB (12 GHz)	−0.5 dB (12 GHz)	n/a	Series ohmic cantilever switch [Commercial]	[50]
−23 dB (25 GHz)	−1 dB (25 GHz)	n/a	Centrally-hinged metal membrane with externally placed contact in package [Research]	[51]
−20 dB (40 GHz)	−5 dB (40 GHz)	n/a	Single Pole Double Throw (SPDT) based on series ohmic clamped-clamped cascaded switches [Research]	[52]
−23 dB (20 GHz)	−0.2 dB (20 GHz)	−23 dB (20 GHz)	Series ohmic cantilever switch with Niobium superconducting contact at cryogenic temperature [Research]	[53]
−23 dB (26 GHz)	−0.7 dB (26 GHz)	−23 dB (26 GHz)	Ohmic switches-based SPDTs with thermally driven latching actuation mechanism [Research]	[54]
−7 dB (14 GHz)	−1.5 dB (14 GHz)	n/a	Series ohmic cantilever switch in-package [Commercial]	[55]
−47 dB (10 GHz)	−1.5 dB (10 GHz)	−7 dB (10 GHz)	Laterally actuated switch [Research]	[56]
−15 dB (40 GHz)	−1 dB (40 GHz)	−25 dB (40 GHz)	Series ohmic clamped-clamped switch [Research]	This work

1) Better than the S11/S21 number up to the shown frequency. E.g., -1 dB (40 GHz) = better than -1 dB up to 40 GHz.

Concerning reflection (S11) in the ON state, the RF-MEMS switch of this work scores better performance when compared to the other solutions reported in Table 1.

4. Conclusion

Microsystem (MEMS) technology for Radio Frequency applications, i.e. RF-MEMS, after about two decades of fluctuating expectations, is currently starting to meet the high-potential application scenarios of 5G (i.e. 5th generation of mobile communications and networks) and of the Internet of Things (IoT). The RF-MEMS series micro-switch discussed in this work represents a valuable starting point relying onto which a new generation of high-performance, highly reconfigurable and very-wideband operable RF passive components could be developed.

The micro-relay was tested and simulated against its electromechanical and electromagnetic (RF) characteristics. The measured pullin voltage is above 50 V, despite its nominal value was expected to be around 20 V. Such an increase is due to the building of residual stress within the Gold membrane, and can be significantly mitigated by acting on the temperature of the sacrificial layer removal step (i.e. dry etching).

Concerning RF performance, the RF-MEMS micro-switch was tested in the frequency range from 100 MHz up to 110 GHz (S-parameters). Isolation (S21 parameter) when the micro-relay is OPEN (i.e. MEMS in its rest position – OFF) is better than -15 dB up to 40 GHz, while above it ripples between -10 dB and20 dB. When the switch is CLOSE (i.e. MEMS pulledin – ON), loss (S21 parameter) and reflection (S11 parameter) are better than -1 dB and-25 dB, respectively, up to 40 GHz. Differently, reflection increases above 40 GHz, despite remaining better than about 12 dB. Loss, instead, follows an increasing trend bringing it to the worst value of about -8 dB at 110 GHz.

Despite the discussed design concept admits margins of improvements concerning its overall characteristics, i.e. both electromechanical and RF, its performance is already quite satisfactory, especially if one aims at applications below 40 GHz. For higher frequencies, reaching 110 GHz, isolation and loss worsen, despite scoring better numbers than a certain part of switches in other technologies.

The quite accurate and reliable modelling and simulation techniques adopted in the discussion above can enable further improvement of the mentioned characteristics, especially when specifications driven by 5G and IoT applications will be more precisely defined, deriving them from system-level requirements, according to a top-down approach.

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Jacopo Iannacci received the MSc Degree in Electronic Engineering in 2003 from the University of Bologna, Italy, and the PhD in Information Technology in 2007 from the ARCES Center of Excellence at the University of Bologna, Italy. Since 2007, he is Researcher in MEMS technology with the Center for Materials and Microsystems (CMM) at Fondazione Bruno Kessler (FBK) in Trento, Italy. His scientific focuses are on (compact) modelling, design, optimisation, integration, packaging and testing for reliability of RF-MEMS (Radio Frequency MicroElectroMechanical-Systems) passive devices and networks, EHMEMS (Energy Harvesting MEMS), as well as SA-MEMS (MEMS Sensors and Actuators). In 2005 and 2006, he worked as Visiting Researcher at the DIMES Technology Center of the Technical University of Delft, the Netherlands, where he focused on development of packaging and integration solutions for RF-MEMS devices. In 2016, he visited the Fraunhofer Institute for Reliability and Microintegration IZM in Berlin, Germany, as Second ed Researcher, studying the integration of RF-MEMS devices and their optimisation against market requirements. He authored/co-authored numerous scientific contributions for international journals and conference proceedings, as well as books and several book chapters in the field of MEMS and RF-MEMS technology.