RF-MEMS switches based on a low-complexity technology and related aspects of MMIC integration

V. Ziegler[1], C. Siegel[1] , B. Schönlinner[1] , U. Prechtel[1] , H. Schumacher[2]

[1]EADS Corporate Research Center Germany, Dept.: LG-ME, Willy-Messerschmitt-Str., 85521 Ottobrunn, Germany,
email: volker.ziegler@eads.net , Tel: +49 (0)89 607 20294
[2] University of Ulm, Dept.: Electron devices and circuits, Albert Einstein Allee 45, 89081 Ulm, Germany

Abstract — **This paper presents RF-MEMS devices, which are based on low-complexity fabrication technologies. Tuneable filters and phase shifting elements for Ka-band have already been realized by using a fabrication process which requires only two photo-lithographic steps. Adding just one more lithographic process step results in the realization of high performance switching devices with insertion losses of -0.2dB at 30GHz. Due to their low fabrication complexity, all these RF-MEMS devices minimize technological challenges and have the potential for being highly reliable due to their design principle. In addition, these technologies may pave the way for the monolithic integration of RF-MEMS based circuits with compound semiconductor MMICs for highly integrated and high performance multi-functional circuits.**

I. INTRODUCTION

Looking at the near future of communication and radar equipment, one will find two obvious trends for next generation systems, namely electronically scanned antennas and multi-function operation. Due to the key functionalities of these systems, which are electronic phase shifting and multi-band capability, there is a growing need arising for high performance phase shifters, tuneable filters and switches. Common to the most of these systems is the need to optimize the transmit-receive circuitry in terms of the RF performance and the DC-power consumption. RF-MEMS based devices are well known for their extremely low insertion loss and negligible power consumption compared to other solutions [1]. Therefore, circuits based on RF-MEMS technologies would be ideal candidates to be used in large antenna arrays in general or especially directly in front of the low-noise amplifier in the receive path of a system. However, several reliability issues due to various technological challenges, which have already been intensively discussed in literature, are still hindering these devices from being used in products [2]. In addition, good reliability data is even harder to achieve, if high RF-powers are incident on the RF-MEMS device [3].

Therefore, this paper discusses two RF-MEMS technologies, which are rather simple from the technological point of view. Together with the design of the devices it is believed that they have the potential for realizing highly reliable and cost-effective RF-MEMS circuits. Furthermore, a combination of these proposed RF-MEMS devices and circuits with compound semiconductor technologies (GaAs, SiGe) might lead to high performance and multi-functional MMICs. Possible ways to integrate the RF-MEMS with a GaAs foundry process will be discussed in the last chapter.

II. LOW-COMPLEXITY RF-MEMS TECHNOLOGIES FOR PHASE SHIFTERS, TUNEABLE FILTERS AND SWITCHES

In the frame of developing very low-complexity RF-MEMS technologies, a process for realizing phase shifting elements with only two lithographic steps was already demonstrated [4]. The basic principle of these RF-MEMS devices and circuits is the switchable suspension of parts of a coplanar or a microstrip transmission line from the substrate into the air. Consequently, the effective dielectric constant of the line is changed, which results in a variation of the phase shift of the travelling wave. This rather simple technology was also used to demonstrate a wideband tuneable filter in Ka-band, which exhibited an insertion loss of -1.5dB at 30GHz and a switchable shift of 20% in operational frequency [5].

Now, the focus of this paper is on the realization of RF-MEMS switches by adding just one single photo-lithographic step to the above mentioned technology. The necessary fabrication steps to realize the switches are depicted in Fig. 1 in detail and are also discussed in the frame of the later on presented integration aspects with other semiconductor technologies.

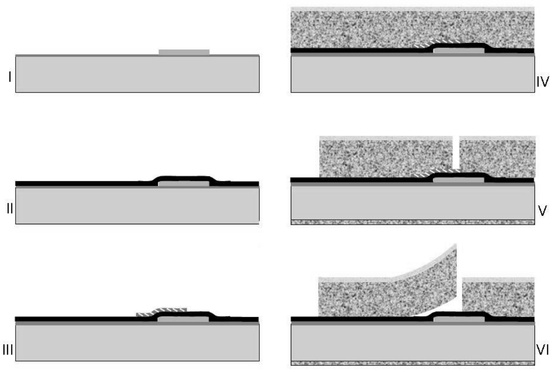

Fig. 1: Process flow of the low-complexity RF-MEMS switches

The processing begins with the thermal oxidation (approx. 250nm thick) of a highly resistive silicon wafer, the removal of the thermal oxide on the backside and the evaporation of a CrAu layer with an overall thickness of 100nm (I). Then, the wafer is covered with a 300nm thick plasma oxide, acting as a passivation layer between the electrodes (II). The requirements for this layer with respect to the integration aspect are threefold: a) the thickness should be between 200nm and 400nm to minimize capacitive coupling losses in the switch, b) it has to withstand the actuation voltage of the switches (20V-80V) and c) it has to be of high quality to minimize the effect of dielectric charging during switching operation. The next steps are the deposition of the sacrificial layer, its patterning (III) and the subsequent evaporation of an intrinsically strained metal sandwich consisting of 4µm aluminium and 0.2µm silicon (IV). Further on, the metal sandwich is patterned by wet chemical etching (V) and the cantilevers are released by removing the sacrificial layer again by wet chemical etching. Finally, the devices are dried with nitrogen gas or by critical point drying (VI). Due to the residual stress gradient in the metal sandwich, the released cantilever bends upwards.

The thickness of the metallic layers and the amount of the residual stress determine the resulting actuation path for the switching device and its actuation voltage. For a typically 300µm long cantilever, actuation paths, which varied between 10µm and 30µm have been realized by controlling the stress gradients. These parameters result in actuation voltages between 25V and 80V. In principle, the voltages needed to actuate the switch become larger with increasing stress gradients and metal layer thickness.

To actuate the switching element, a voltage is applied between the front-side cantilever metal and the backside metallization. Consequently, the cantilever is pulled down electrostatically without additional actuation pads. In this ON-state of the switch, the RF-signal is capacitively coupled from the cantilever to the CrAu metallization layer and back again to the top metal on the other side of the switch. Under OFF-state conditions, the cantilever is bended upwards and represents a small series capacitance to the circuit.

The advantages seen by using these switching elements are besides their simple and robust fabrication processes that the restoring forces are rather high. This fact makes them less sensitive to in-process and operational sticking effects (e.g. released devices can easily be dried by using propanol and nitrogen gas). Additionally, the large actuation path, the small hysteresis between the pull-down and the release voltage and the fact that all parts of the switch consist of 4.2µm thick metal, should increase the power-handling capability of these switches by reducing self-actuation and electro-migration effects.

In comparison to the low-complexity technology demonstrated in [4] and [5], the proposed process provides additional degrees of freedom during MMIC design due to the possibility of implementing MIM capacitors for DC-blocking between different devices.

III. TEMPERATURE INFLUENCE ON THE CANTILEVER

Because temperature is a major factor on the residual stress gradients in a bi-morph layer structure, the principal behaviour of the bended cantilever was analysed with respect to different thermal loads occurring during the operational lifetime of the device. A first indication of the temperature range, in which the device can be used, is derived from the monitoring of the tip height and corresponding actuation voltage after thermal cycling of the cantilever. Fig. 2 depicts the remaining variation of the tip height as a function of thermal load applied to the device by heating to a certain temperature and subsequently returning to room-temperature.

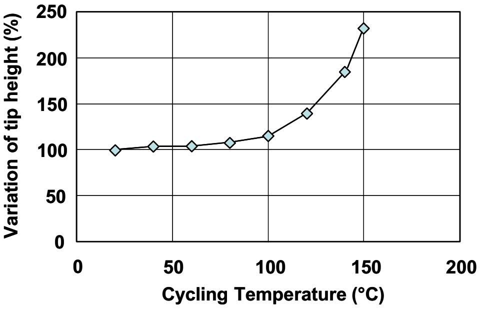

Fig. 2: Variations in the cantilever tip height with different temperature loads and after returning to room-temperature

It can clearly be seen that there is no significant change in the tip height up to a cycling temperature of 80°C. In excess of this temperature, the bi-morph layer changes its residual stress significantly and starts to bend up more and more after returning to room-temperature. The related actuation voltages exhibit the same behaviour with an increase of the needed voltage after cycling to temperatures higher than 80°C.

IV. RF-MEMS SWITCH PERFORMANCE

By using the technology described in chapter II, several switching devices for operation in Ka-band were fabricated. For example, a series switch consisting of two parallel cantilevers is shown in Fig. 3. The device is embedded in a 50Ω microstrip line including radial stubs for measurement purposes (grounding of the RF-probes). The bended parts of the cantilevers appear in black colour because of the deflection of the microscope light.

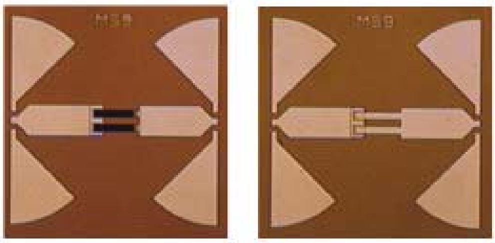

Fig. 3: RF-MEMS series switch. Black parts are bended upwards. Left picture (OFF-state), right picture (ON-state)

In this particular layout, the switchable cantilevers have a length of 300µm, which led to an actuation path of approx. 17µm. The resulting actuation voltage is around 30V with a corresponding release voltage of 24V.

This switch has been measured on-wafer up to 40GHz and its ON-state and OFF-state performance is presented in the following picture (Fig. 4).

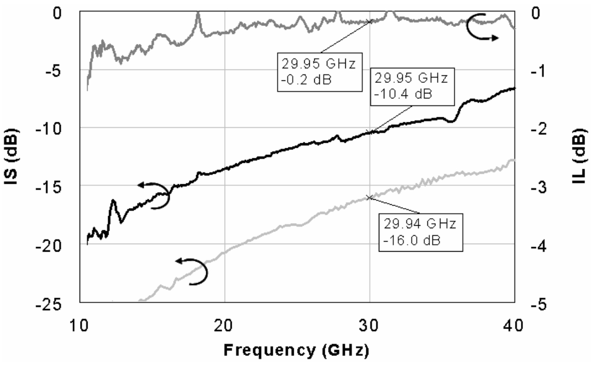

Fig. 4: Measured S-parameter of the Ka-band series switch. Dark grey: ON-state insertion loss, black: OFF-state isolation, grey trace: OFF-state isolation with higher residual stress gradient.

The series switch exhibits a very low insertion loss (dark grey trace) of less than -0.3dB from 22GHz to 40GHz. At the design frequency of 30GHz, an insertion loss of -0.2dB and a corresponding isolation (black trace) of -10.4dB is observed.

Some applications do require a higher isolation value than -10dB for each individual switching device. Therefore, to improve the isolation behaviour of the switch, several approaches can be foreseen without severely affecting the insertion loss performance.

The first and most obvious one from the layout point of view is to use a parallel device instead of a series switch, especially at higher frequencies.

For another option, if one can accept an increased actuation voltage, the way to go is to increase the residual stress in the layers, which will result in a higher actuation path and thus in an improved OFF-state performance by reducing the parasitic coupling capacitances. This idea is illustrated by the third trace in Fig. 4 (light grey). This one corresponds to the measured isolation performance of the same switch (Fig. 3), fabricated with a higher residual stress in the cantilever. The isolation performance improves from -10.4dB to -16dB at 30GHz, while the actuation voltage increases from 30V to 80V.

If the actuation voltage is to be held at a constant level, the choice of a cantilever with a larger length will also increase the actuation path and thus the isolation performance while keeping the insertion loss in the ON-state approximately constant. This assumption is validated by the measured data shown in Fig. 5, which is taken from a slightly different series switch layout compared to the one in Fig. 3.

The graph shows the insertion losses and isolation parameters of the series switch as a function of the cantilever length. It can be seen that by varying the length from 200µm to 500µm, the isolation values are improved from -4dB to -12dB without sacrificing significant insertion loss (in the order of -0.1dB). The actuation voltage of all switches was almost constant around 30V.

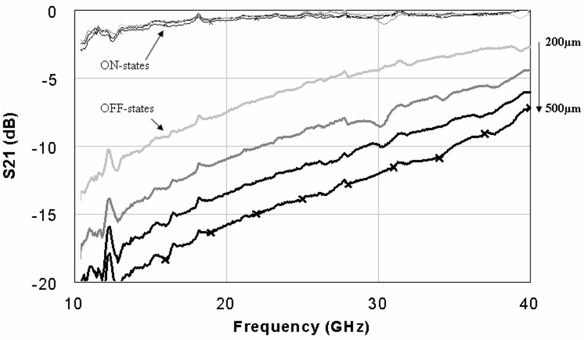

Fig. 5: Insertion losses (ON-state) and isolation values (OFF-state) for series switches with different lengths of the cantilevers. Light grey: 200µm, dark grey: 300µm, black: 400µm, and black with crosses: 500µm

In conclusion, by using the switch layout of Fig. 3 and by changing the length of the cantilever to 500µm, an insertion loss of -0.3dB with an isolation of -15dB can be expected.

V. ASPECTS OF INTEGRATION WITH OTHER SEMICONDUCTOR TECHNOLOGIES

The principle questions to this integration approach are, which overall benefits can be expected from integrating high-performance RF-MEMS switches, phase shifters and tuneable filters with other semiconductor technologies. The first one is to save space in tightly occupied T/R-modules, especially at very high frequencies where the module area is strictly limited by the lateral geometries of the single phased array element. In this case, the integration of the RF-MEMS circuits with their DC-bias circuitry and therefore with CMOS processes seems to be advantageous.

Another interesting aspect is the integration of RF-MEMS circuits with GaAs- or SiGe-based MMICs to realize multi-functional circuits with optimum performance of each functionality as demonstrated previously by the monolithic integration of different III/V devices [6,7]. If such an integrated circuit is used for example in a multi-band system or in a passive phased array antenna, the realization of RF-MEMS based tuneable filters, switches or phase shifters with low insertion losses in front of the low-noise GaAs amplifier, can lead to significant performance improvements with respect to the overall system noise figure in the receive chain. Further on, by using this multi-functional approach, one gets rid of the bond-wired interconnections between the separate MMICs and one reduces the testing efforts.

A possible arrangement of the proposed integrated circuitry for multi-band operation is depicted in the upper part of Fig. 6. Coming from the receive antenna (right end of the picture), a RF-MEMS-based antenna switch together with a tuneable RF-MEMS based filter (or a RF-MEMS based filter bank surrounded by two SP3Ts) is integrated with the subsequent GaAs PHEMT LNA. The same principal idea could be used to realize RF-MEMS based phase shifters in front of the LNA for passive phased array antennas.

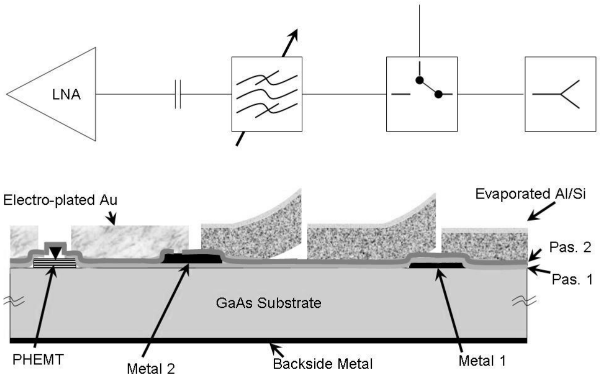

Fig. 6: Possible arrangement and technological integration of the RF-MEMS based circuits and a GaAs PHEMT LNA

A possible implementation of the proposed low-complexity RF-MEMS technologies with the standard GaAs PHEMT technology provided by the company United Monolithic Semiconductors (UMS) is presented in the lower part of Fig. 6. The basic idea is to use a fully processed GaAs PHEMT wafer and use the RF-MEMS processes described in chapter II as add-on (or back-end) technologies.

If one uses the standard foundry process (which is for cost reasons the only choice) the GaAs wafer comes, from bottom to top, with a backside metallization and a first metal layer which is deposited directly on the GaAs substrate. This “Metal 1” can be used as the lower conductive layer for the switching devices. Then, two passivation layers with a total thickness of approx. 400nm are available, which can act as the passivation for the switch (between “Metal 1” and the cantilever) or the filter (between the substrate and the cantilever). In between the two passivation layers, there is one additional metal layer. This “Metal 2” can be used for the realization of MIM capacitors either within the RF-MEMS MMIC or for the DC-blocking between the RF-MEMS and GaAs circuits. The electroplated gold is available for the transmission line connection to the LNA.

Starting from these standard foundry layers, the additional process steps that have to be performed to integrate the RF-MEMS circuits, are: the deposition of the sacrificial layer, the evaporation of the metal sandwich, the subsequent etching of the metal sandwich and finally the release of the cantilevers (see steps III-VI in chapter II). Therefore, the monolithic integration of the proposed RF-MEMS technology and a standard GaAs foundry process seems to be feasible.

VI. CONCLUSION

In this paper, two low-complexity RF-MEMS technologies were presented, which lead to phase shifting elements, tuneable filters and switching devices. The first two can be realized by using a two-step photo-lithographic process and by adding one more lithography step, switching devices with very promising microwave characteristics (insertion loss of -0.2dB and isolation of -10.4dB at 30GHz) were realized. It is expected that these RF-MEMS technologies have the potential to realize high performance and highly reliable devices and circuits. Furthermore, due to their simple fabrication processes, these RF-MEMS technologies might be integrated with other compound semiconductor MMICs for the realization of multi-functional MMICs. To underline this potential, a possible integration with a standard GaAs PHEMT foundry process was discussed and positively evaluated.

ACKNOWLEDGEMENT

The authors would like to thank Franck Bourgeois and Peter Abele from UMS for technological discussions.

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