Re-configurable MMIC: on-wafer fine tuning capabilities

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Abstract

While today's MMIC chips suffer from lack of tuning ability, millimeter and microwave communication applications face a demand for very high MMIC performance. At the chip level this calls for wide band, high overall gain, return loss, output power, and low noise. The proposed concept of re-configurable MMIC (RMMIC) will reduce cost/performance of highly integrated circuits by providing tuning ability to the chip components.

RMMIC is a traditional MMIC upgraded with special elements that allow adjusting the essential circuit parameters after the wafer manufacturing is finished. The circuit adjustment is realized at the wafer level and "survives" through the rest of the circuit lifetime with no additional power consumption.

INTRODUCTION

Microwave circuits consist of capacitors, inductors, transmission lines, switches and transistors. Each of these elements has a unique influence on the final circuit performance. In this work, we introduce a novel approach to on-wafer adjustment of the MMIC components. Adjustment is completed during the testing stage and can considerably shorten design loops and time-to-market. RMMIC is based on changing the initial value of basic passive elements by connecting and disconnecting them from the circuit.

RMMIC transfers a fine tuning solution from MIC technology to the MMIC level. This method is applied to stand-alone passive elements as well as to fully integrated circuits. Connection or disconnection of the element is performed by special techniques. Local heating or ultrasonic performs fixation of the final state. DC current passes through the element and irreversibly changes its state. In this way, the value of the element can be either decreased or increased. We have designed a library of tunable passive elements that includes capacitors, resistors and stubs. Integrated into the MMIC, those passive elements can overcome process variation problems and provide fine-tuning at the post-fabrication stage. RMMIC should solve several problems:

- Tunable frequency band, wide band design with option of electrical tuning to narrow band.
- Yield improvement, based on electrical tuning of the passive elements in order to bring the design to specifications.
- Reduction of statistical scattering-"self organized MMIC". Electrical trimming is performed in order to bring the product to target.

TECHNOLOGY

Recently reported tunable capacitors and switches are usually implemented using MEMS technology. This technology suffers from reliability issues, such as reduced lifetime of the elements [1,2]. This prevents MEMS from integration into MMICs.

In contrast to MEMS, RMMIC does not include any moving mechanical parts. RMMIC technology is fully compatible with Gal-El power PHEMT 0.25 μm baseline process. In the proposed technology we change the electrical parameter value by two irreversible mechanisms: "sticking" and "fusing". Sticking connects elements to the circuit, while fusing disconnects them.

Two sticking methods for connecting the air-bridge and the underlying first inter connect (FIC) were developed and tested. The interconnect element before the sticking is presented in Figure 1.

Sticking can be performed by micro soldering which produces an AuGe eutectic between the air-bridge, FIC and the Ge interlayer. To perform micro-soldering, we apply a current pulse to the interconnect area. This pulse locally heats the area, producing the energy required for eutectic formation and soldering. In addition, sticking can be performed by micro welding. This process is based on inter-diffusion of the bridge and FIC layers. Local heating and/or ultrasonic energy is applied to the interconnect area. No fluxes or filler metals are used in this technique.

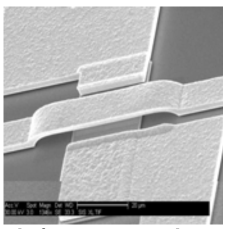

Figure1. Sticking element before actuation. The air bridge is above the FIC. There is no electrical connection between layers.

Figure 2 presents the sticking element after actuation. The air bridge is stuck to the FIC.

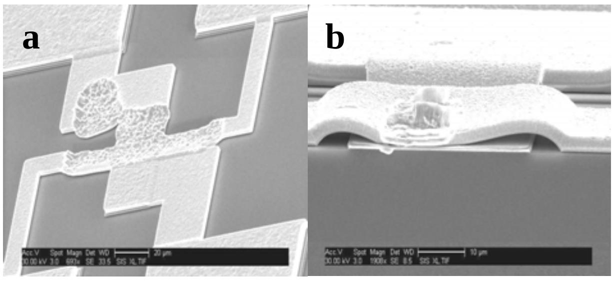

Figure 2. Sticking element after actuation: a- ultrasonic welding of the two layers b – eutectic soldering.

Electrical disconnection is realized by fusing. Figure 3 shows a fuse SEM image. The fuse is built as an air bridge, and consists of two metals – Au and Ge. A thick gold air bridge formed by electroplating is followed by Ge deposition on top of the air bridge. When a DC current pulse is applied to the air bridge, the temperature increases resulting in eutectic Au-Ge alloy formation. Due to the relatively low melting temperature of Au-Ge eutectic (365ºC), part of the Au-Ge sandwich fuses completely and provide an open-circuit state. A special fusing matrix was designed and fabricated with several air bridge and fuse geometries.

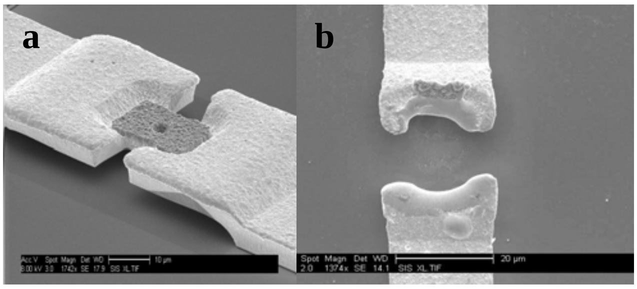

Figure 3. SEM image of fuse before (a) and after burning (b).

DESIGN

Capacitors are widely used in MMIC applications and provide a key element for biasing and matching networks. Therefore, a tunable capacitor can be an effective tool for design optimization at the testing stage.

The design goal was to create a set of standard MMIC components capable of changing their electrical parameters. Depending on the actuation mechanism, the initial value can be either increased or decreased. Once provided with such a library, a designer may regulate circuit performance in real time. Two basic topologies were selected for design and fabrication: a shunt MIM capacitor and a series MIM capacitor. Various structures, including single tunable elements - the building blocks, and arrays – tunable capacitors were developed. Design and simulation were carried out with "Agilent ADS 2003C" simulation software.

A layout of single 3.15 pF (105x100 μm^2) shunt capacitor is presented on Figure 4. The device is equipped with a sticking mechanism and is initially disconnected from signal line.

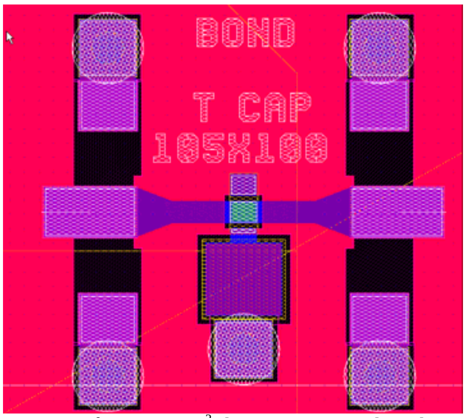

Figure 4. Layout of 105x100μm^2 shunt capacitor with sticking element

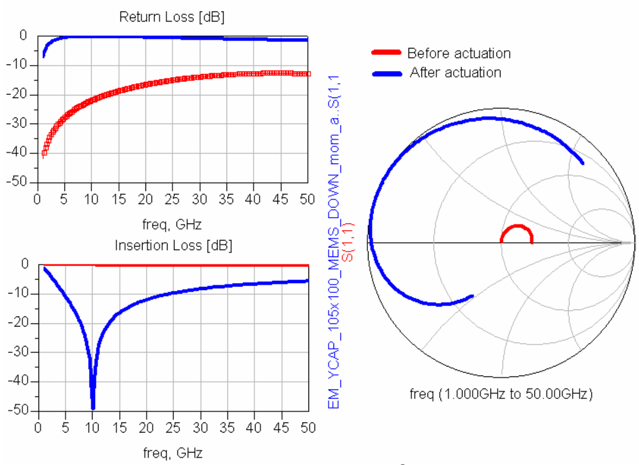

Figure 5. Simulation results of a 105x100 μm^2 shunt capacitor equipped with sticking mechanism, before and after actuation

Simulation results are presented in Figure 5. Before the actuation device performance is characterized by low insertion losses and high return losses, which indicates formation of a transmission line. After actuation of the sticking, the device performs as a shunt capacitor that is characterized by a notch at 10 GHz.

We have obtained results for a single tunable capacitor as well as for capacitor arrays. Electro magnetic simulations were carried out to provide reliable data for the design. All devices were simulated in the initial and final positions to observe all possible parasitic effects.

TESTING

A test matrix of tunable capacitors with various geometry and actuation mechanisms has been fabricated and tested. The capacitance varies from 0.3 pF to 3 pF. We have fabricated all the devices in two basic configurations: connected and disconnected to the signal line.

Device performance was obtained by measuring small signal parameters at 1 GHz to 50 GHz. All measurements were done "On-wafer", using a HP 4155C semiconductor analyzer and an 8510C network analyzer.

Results obtained from measuring the shunt capacitor equipped with sticking mechanism before and after actuation are presented in Figure 6.

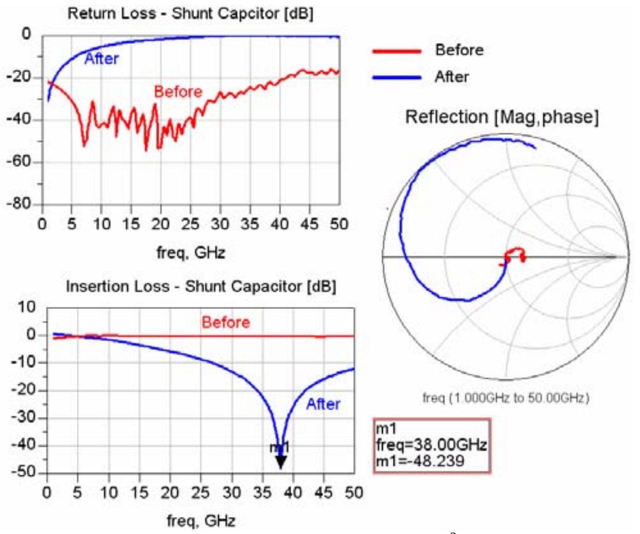

Figure 6. Small signal performance of 50x50 μm^2 shunt capacitor

The Smith chart shows that the 50 Ohm impedance transfers to a capacitive impedance after sticking actuation. In the insertion loss graph there is a notch at 37 GHz, formed by the shunt capacitor and via hole. We have extracted the capacitance from the measurement and the value is 0.76 pF while the design simulation was 0.75 pF. No parasitic effects associated with the sticking were observed. Device is shown in Figure 7.

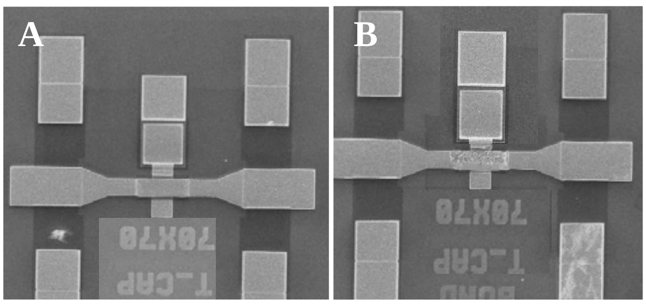

Figure 7. Sticking shunt capacitor before (A) and after actuation (B).

After measuring the sticking capacitor, we measured a device equipped with a fusing element. Figure 8 presents a measurements of a single shunt capacitor based on fusing mechanism. In its initial position the device is a 1.6 pF (70x70μm^2) shunt capacitor. After the fusing burning it turns into a transmission line.

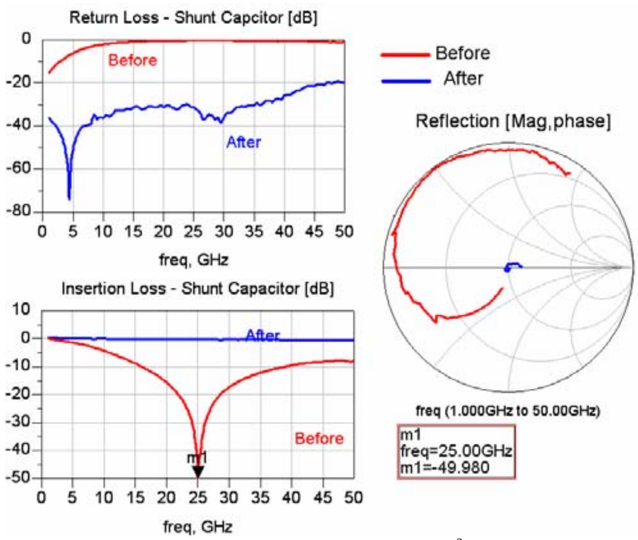

Figure 8. Small signal performance of 70x70 μm^2 shunt capacitor

A fused capacitor before and after actuation is shown in Figure 9.

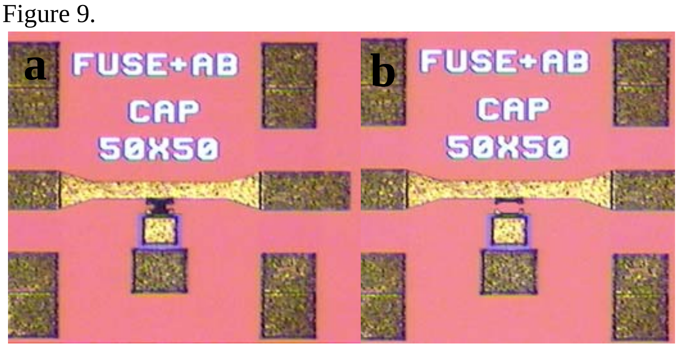

Figure 9. Fusing Shunt capacitor before (A) and after actuation (B).

Following a single capacitor evaluation, a tunable capacitor array was measured. The layout of a specific device is presented in Figure 10. It is based on three 0.74 pF (35x70 μm^2) parallel capacitors. A fixed series capacitor is originally connected to the signal line. To change the total capacitance, two other capacitors are connected by sticking. Device measurements were performed after actuation of each capacitor. In Figure 9 we observe a change in the small signal performance and gradual increase in capacitance. Total tuning was obtained in two steps after both capacitors were connected. The capacitance changed from 0.75 pF to 2.26 pF which represents a 200% tuning range.

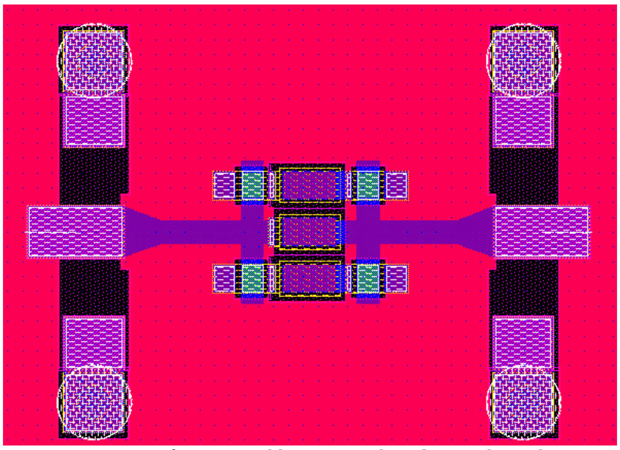

Figure 10. Layout of series tunable capacitor based on sticking element, 3 capacitors in size of 70x35 μm^2 shunt provide tuning range 0.74-2.2pF

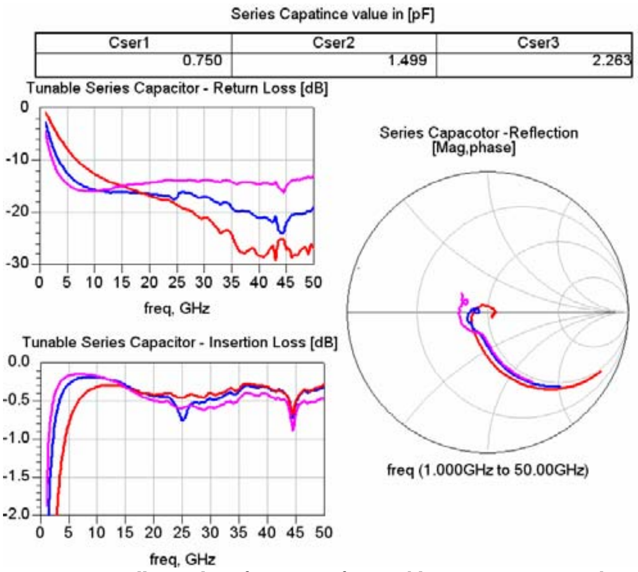

Figure 11. Small signal performance of a tunable series capacitor. The 3 curves represent initial and tuned capacitance. Table summarizes extracted capacitance.

In Figure 12 we present a SEM image of 2x3 tunable capacitor array .

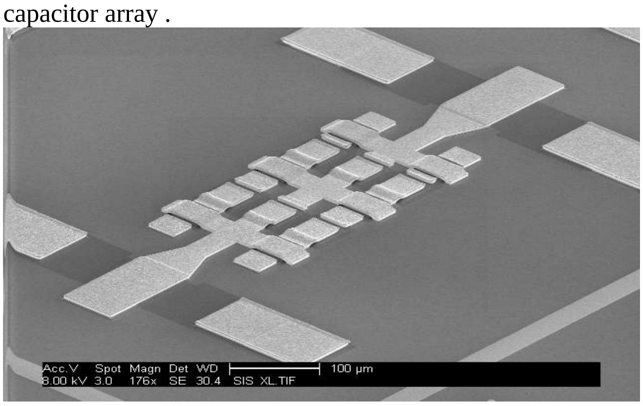

Figure 12. Layout of series tunable capacitor array based on 6 capacitors.

CONCLUSIONS

In this work we present feasibility of RMMIC technology. RRMIC proves to be fully compatible with PHEMT 0.25 μm technology and crucial for post-fabrication fine tuning purposes. Sticking and fusing mechanism can be integrated into standard passive elements and provide reliable actuation.

ACKNOWLEDGEMENTS

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ACRONYMS

RMMIC: Re-configurable MMIC
MIM: Metal Insulator Metal
MEMS: Micro Electro Mechanical Systems
PHEMT: Pseudomorphic High Electron Mobility Transistors