MEM Relay for Reconfigurable RF Circuits

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***Abstract*—We describe a microelectromechanical (MEM) relay technology for high-performance reconfigurable RF circuits. This microrelay, fabricated using surface micromachining, is a metal contact relay with electrical isolation between signal and drive lines. This relay provides excellent switching performance over a broad frequency band (insertion loss of 0.1 dB and isolation of 30 dB at 40 GHz), versatility in switch circuit configurations (microstrip and coplanar, shunt and series), and the capability for monolithic integration with high-frequency electronics. In addition, this MEM relay technology has demonstrated yields and lifetimes that are promising for RF circuit implementation.**

***Index Terms*—Broadband, MEM, reconfigurable, relay, reliability.**

I. Introduction

MICROELECTROMECHANICAL (MEM) switches present a promising technology for high-performance reconfigurable microwave and millimeter-wave circuits. The low insertion loss, high isolation, and excellent linearity provided by MEM switches offer significant improvements over the electrical performance provided by conventional PIN diode and MESFET switching technologies. These superior electrical characteristics permit the design of MEM-switched high-frequency circuits not feasible with semiconductor switches, such as high-efficiency broadband amplifiers and quasioptic beam steering arrays.

As a result, a growing number of corporate and university research groups are developing MEM switch technologies. Early research in this field focused on the demonstration of different voltage-actuated MEM switch geometries, such as metal contact [1]–[3] and capacitive contact [4], [5] devices. Several recent efforts [6], [7] have addressed one device characteristic relevant to circuit implementation: development of low actuation voltage devices. There is little published work, however, addressing other (perhaps more challenging) device issues critical for successful integration of MEM switches into RF circuits.

We present a metal contact MEM relay technology under development at the Rockwell Science Center (RSC). RSC microrelay design and fabrication have been driven by considerations critical for RF circuit use. Features of the developed technology include versatility in RF configurations, good yields and lifetimes, and the capability for monolithic integration with high-frequency circuits. In this paper, we present the structure, fabrication, and performance characteristics of the RSC MEM relay. An accompanying paper demonstrates this technology in a broadband 4-bit True Time Delay Circuit [8].

II. Structure and Operation

The structure and operation of the RSC microrelay are shown in Fig. 1. This microrelay is a surface-micromachined structure fabricated from thin films deposited atop the substrate. The relay consists of a metal bridge bar that is suspended over a broken RF signal line on the substrate. This bridge bar is suspended via insulating beams that attach to a mechanical structure consisting of two plates and two pairs of folded-beam springs, both also made of insulators. This entire suspended structure is anchored to the substrate via four legs at the ends of the springs. The device covers an area of size $\sim$250 μm $\times$ 250 μm, with the suspended structure sitting a few microns above the substrate plane. The microrelay allows RF signal line widths of 20–40 μm and has a length of 200 μm parallel to this signal line.

Relay functionality is controlled by the application of a bias voltage, which actuates the bridge-supporting mechanical structure. In its unbiased state, the structure is suspended so the bridge bar is separated from signal line via an airgap and the relay is nonconducting (OFF). The effective capacitance for this switch state, set by coupling across a micron-sized airgap, is $\sim$2 fF. When a threshold bias is applied, the structure is pulled down so the bridge bar contacts the signal line and the relay is conducting (ON). The effective resistance for this state, formed by contacting metal surfaces, is $\sim$1 Ω. The relay is switched ON to OFF by reducing the control voltage to allow the deflected springs of the mechanical structure to pull the structure and bridge bar upward.

III. Fabrication

The RSC relay is fabricated by surface micromachining techniques, using low-temperature ($<250\,^\circ$C) thin films deposited atop the substrate. Details of the fabrication process have been previously published [1], so the process will only be summarized here. First, signal lines found on the substrate are defined by liftoff patterning of evaporated Au films. A sacrificial layer is then formed from a spun and planarized polyimide layer. This polyimide layer serves as a platform for building the relay mechanical structure. Windows etched in the polyimide define the anchor regions for the mechanical structure. The electrical bridging bar is then defined atop the polyimide by liftoff patterning of evaporated gold. Next, the mechanical structure is constructed from plasma enhanced chemical vapor deposition (PECVD) of the dielectric structural layer, liftoff of the drive metal patterns, and etching of the PECVD film. The entire relay

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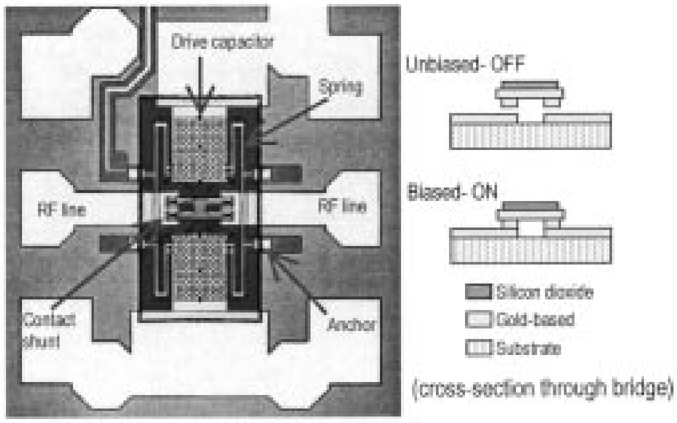

Fig. 1. Structure and operation of MEM relay. The relay consists of a metal bridge bar that is moved to make and break contact with an underlying signal line. Bridge motion is achieved by voltage biasing a mechanical actuator supporting the bridge.

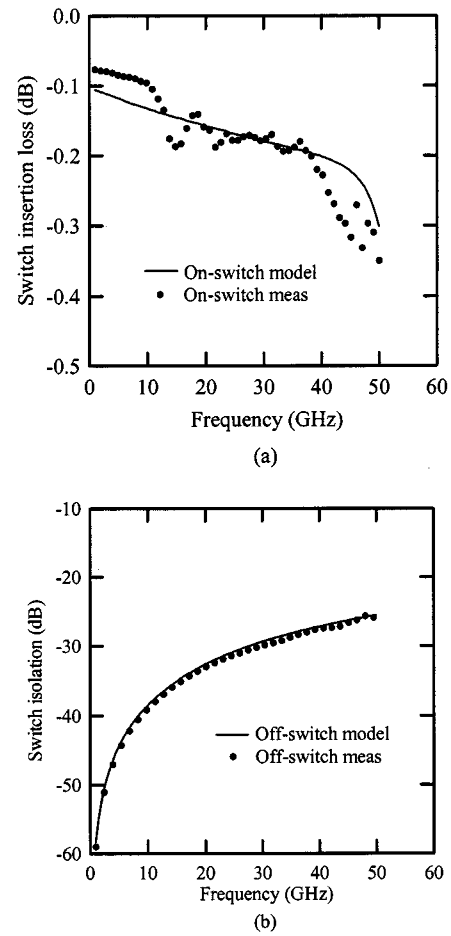

Fig. 2. Measured versus modeled (a) on-switch insertion loss and (b) off-switch isolation. Insertion loss includes switch contact resistance and microstrip conductor losses. The measured switch insertion loss ripples are due to coupling to the dc-bias probes through the switch dc control lines. The model assumes an open-circuit for the dc probes and, thus, does not show the ripples.

microstructure is made freestanding in the final fabrication step by isotropic O_2 dry etching of the sacrificial polyimide.

This fabrication technology offers versatility in substrate selection. Switch devices can be fabricated on any substrate material that is sufficiently smooth for thin-film fabrication and that can withstand temperatures to 250 °C. To date, the RSC microrelay has been fabricated on GaAs, epitaxial GaAs, silicon, and quartz substrates. Devices, furthermore, have been fabricated on both standard thickness and thinned substrates. We expect the microrelay can be realized as well on other high performance substrates (alumina, gallium nitride, etc.) of any chosen thickness.

IV. Switch Performance

Switch performance for the RSC microrelay has been characterized over a broad frequency range, from dc to W band. Typical S-parameter data are shown in Fig. 2 for a microstrip-configuration relay on a semi-insulating GaAs substrate. Microrelay S-parameters are determined from network analyzer measurements of short-length ($\sim$500 μm) devices. Relay isolation in its OFF state is very good (particularly at lower frequencies), with >60 dB isolation at low frequencies and $\sim$30 dB isolation at 40 GHz. This isolation is mostly limited by electrical coupling through substrate. Insertion loss for the relay ON state is excellent over the entire band, due to the metal contacts. Total device insertion loss is $\sim$0.2 dB from dc to 40 GHz, with $\sim$0.1 dB provided by relay contact and $\sim$0.1 dB provided by the signal line. Return loss (not shown) is also very good, ranging from -40 dB at 1 GHz to -25 dB at 40 GHz.

In addition the RSC microrelay offers excellent RF linearity and electrical isolation between RF signal and lc control lines. Two-tone measurements have been used to characterize relay RF linearity for its conducting state. These two-tone measurements show intermodulation products with amplitudes of 80 dB below tone levels. The electrical isolation between signal and control lines has been evaluated by modeling. These simulations show isolation of $\sim$50 dB between the two conductors.

The electrostatic actuation scheme and mechanical design determine microrelay actuation characteristics. Mechanical actuation occurs at $\sim$70 V with low electrical resistance provided by voltages $\sim$20% higher ($\sim$85 V). This actuation voltage agrees well with mechanical models. Power consumption for actuation is very low, due to the electrostatic technique. Switching times are $\sim$10 μs, facilitated by mechanical design for the OFF–ON transition and by stiff mechanical springs for the ON–OFF transition.

Good reproducibility and yields have been demonstrated for the RSC microrelay technology. A typical spread in actuation voltage values is ±15% for devices across multiple fields of wafer. The variation in device electrical performance over such a sample is shown Fig. 3, which shows the distribution of ON-state insertion loss values for 128 microrelays on a wafer. An electrical yield of 90% is reflected by this data, defined here as $|S21| < 0.3$ dB at 2 GHz (for 85 V actuation). Such performance is the result of extensive use of process control methodology developed and applied to three device generations.

An important and challenging requirement for microrelays is switch lifetime. The RSC microrelay has been subject to significant switch lifetime characterization. These lifetime measure-

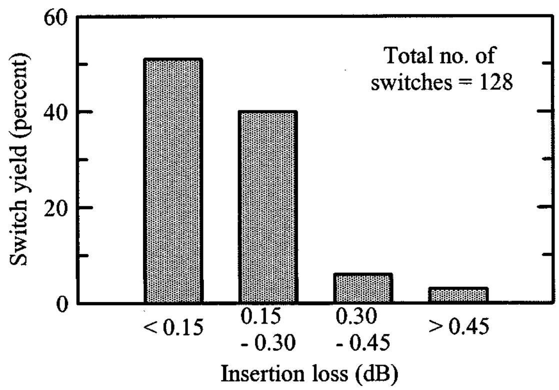

Fig. 3. Measured RF yield at 2 GHz for an array of MEM relays. Data summarizes the ON-state insertion loss of 128 devices located in four fields across a wafer.

ments have been conducted at both hot and cold switching conditions and various signal levels. Generally, microrelay lifetime is a function of switching conditions. Best device results for relays probed in standard ambient include cold-switched lifetimes of ∼100 million and hot-switched small signal (1 mA) lifetimes of tens of millions. Typical good-lot device lifetimes are ∼1 million for hot-switched, small signal conditions. To address device applications requiring longer relay lifetimes, the Rockwell Science Center has an extensive research program to identify important physical phenomena for metal microcontacts.

V. RF Implementation

Complete RF models for the MEM switch have been developed and validated using S-parameter measurements. These RF models have been generated (using Momentum and HFSS tools) from device layouts and one adjustable parameter for switch contact resistance. The value of this input contact resistance is obtained by comparison of single-switch simulated and measured RF response. Input resistance values of 0.4–1 Ω provide good agreement between simulated and measured microrelay performance over a wide frequency range (see Fig. 2). This agreement has been validated further in data for integrated RF circuits, including filter bank and true time delay circuits.

The RSC microrelay has been developed and demonstrated in a variety of RF configurations. The microrelay has been designed, fabricated, and characterized in both coplanar and microstrip RF geometries. Both series and shunt electrical configurations have been developed. Microrelay electrical performance for all these RF configurations is nearly identical, since they utilize the same mechanical and contact device designs. In addition, airbridge structures useful for some RF circuit layouts have been demonstrated using the switch fabrication technology.

One aspect of the RSC microrelay technology that exploits its excellent RF characteristics is the ability to monolithically integrate these relays with high-frequency circuits. Such monolithic integration has been demonstrated in integrated devices fabricated with MEM switches and PHEMT amplifiers [9]. This monolithic integration of the two technologies has been accomplished without affecting the yield or performance of either device. Devices that have been demonstrated include selectable amplifier circuits for broadband operation. We anticipate the microrelays can be integrated with other high-frequency circuit technologies, such as MESFETs and HBTs.

VI. Conclusions

We have developed a metal contact MEM relay technology displaying excellent performance over a broad frequency band, good yields and lifetimes, versatility in switch circuit configurations and the capability for monolithic integration with high-frequency electronics. This relay technology has been demonstrated in various high performance reconfigurable RF circuits, including broadband true time delay [8] and amplifier [9] devices.

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