A Novel Bidirectional Z-Shaped Thermally Actuated RF MEMS Switch for Multiple-Beam Antenna Array

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Keywords: Bidirectional motion, Z-shaped thermal actuator, dielectric embedded antenna array, electronically switched multiple beams, smart antenna

Abstract. In this paper RF MEMS switch is designed for dielectric-embedded electronically switched multiple-beam (DE-ESMB) antenna array. To achieve small stiffness without buckling, a novel bidirectional Z-shaped thermal actuator is used instead of V-shaped thermal actuator, which can generate large displacement and high contact force at low actuation voltage. With the actuation current from -0.6 A to 0.6 A, the electrothermal actuator can achieve a bidirectional motion in a dynamic range of -10.08 μm to 10.17 μm . RF performances are improved by suspending the structure 25 μm from the substrate using MetalMumps process. An ON state insertion loss of -0.14 dB at 10 GHz and an OFF state isolation of -67 dB at 10 GHz are achieved on low resistivity silicon substrate.

Introduction

With the tremendous advancement in communication technology, new technologies are being investigated to improve performances and usage of the available spectrum in the most efficient way. Smart antennas with controllable directionality are promising candidate as they allow higher reuse of channels and increased system performances. However, one of the most challenging aspects of smart antenna design is inclusion of the necessary switching circuitry.

Fig. 1: Geometry of the dielectric embedded antenna array. (a) Configuration of DE-ESMB antenna array. (b) Switching circuits for beam control.

In previous work, PIN Diodes were used for the RF switching for dielectric-embedded electronically switched multiple-beam (DE-ESMB) as illustrated in Fig.1 [1]. However, PIN diodes have lower Q at high frequencies and therefore high insertion loss. Compared with the PIN Diodes, MEMS switches offer higher Q at high frequencies, low insertion loss, higher isolation and smaller packaging size. Also, the idea of System on Chip (SoC) becomes more realistic on the communication system due to compatibility of MEMS switch with the IC process. Hence, the integration of MEMS switches into RF subsystems is expected to provide benefits.

In the past, various actuation approaches have been demonstrated utilizing various operation principles such as the electrothermal actuation, the electrostatic actuation, the piezoelectric actuation, and the electromagnetic actuation. Among them, the electrostatic actuators are most commonly used due to low power dissipation, high driving frequency and bidirectional capability.

However, to simultaneously achieve a large displacement and a high force, a rather large actuator footprint is required, which may not be practical in applications in which space is limited. Also, stiction and/or failure between two electrostatic plates can degrade the yield of large overlapping areas and complaint suspension structures [2].

In contrast, electrothermal actuators offer large displacement and force. The actuation is based on thermal expansion of the actuators beam caused by Joule heating. This is achieved by passing current through beams thus generate large displacement at low voltage. Electrothermal actuators such as V-shaped thermal actuators have been employed in many applications including microengines as they offer high force and reasonable large displacement [3]. However, it possesses an extremely high mechanical stiffness when forced against their direction of operation, rendering them unsuitable for bidirectional motion. Hence, V-shaped actuator cannot be used in some the applications such as actuation of a nanopositioning stage [4].

In this paper, we introduce Z-shaped thermal actuators having bidirectional capability, that are used to replace PIN Diodes for switching purpose as illustrated in Fig 1 (b). The proposed RF MEMS switch is optimized by using MetalMumps process [5], a commercially available Multi Project Wafer (MPW) service. Through MetalMumps process the substrate loss (25- μm deep trench is carved under the device, resulting in a suspended switch) can be reduced substantially. Also, it can provide a good solution for the integration of MEMS with IC. Hence, bring the concept of System on Chip (SOC) into reality.

Mechanical Design of Bidirectional MEMS Switch

Working Principle

Figure 2 shows the working principle of bidirectional Z-shaped thermal actuator. A Z-shaped actuator, which is made of nickel beam, is employed to provide lateral motion in the wafer plane. This switch adopted a piece of silicon nitride as an isolation layer between the driving structure and contact structure. When current flows through the bottom nickel layer, temperature of nickel beam increases and allow contact heads to move forward and connect to RF signal lines to turn on the switch. Similarly, the central shuttle will move downward when applying current through upper actuator and connect antenna signal to ground. On removing the current, the switch returns back to its original position due to internal restoring force of the beam as illustrated in Fig 2 (a).

Fig. 2: Working principle of bidirectional Z-shaped thermal actuator

Thermal Driven Structure

Fig. 3: Schematic diagram of the Z-shape parallel beams thermal driven structure

As illustrated in Fig 3, a Z-shaped actuation beam is used to overcome the problems of V shaped thermal actuator that control on and off state for RF MEMS switch. The actuators consists of three pairs of symmetrical beams are powered by clamped-clamped Z shape beams, which are fixed between anchors. As electrical current flows through a beam, joule heating causes it to expand and allow mechanical motion in specific direction. Hence generate large displacement force and high force comparable with V- shaped actuators. Z-shaped actuator as shown in Fig 3 consists of length ($L = 500 \mu\text{m}$, $L' = 250 \mu\text{m}$), thickness ($20 \mu\text{m}$), and width ($10 \mu\text{m}$) respectively.

Fabrication

The device is optimized on a low resistivity substrate ($1\text{-}2 \Omega\text{-cm}$) using MetalMumps technology, a recent commercially available multi project wafer process and simulated in virtual clean room simulation module (Visualize in Fabviewer) in Intellisuite software. The design process includes a $2 \mu\text{m}$ thick isolation layer on starting silicon wafer [see Fig 4 (a)]. This is followed by the deposition of a $0.5 \mu\text{m}$ thick sacrificial layer (oxide 1) defining the area where the trench under the device will be patterned at the end of the process [see Fig 4 (b)]. Afterwards, two sequential silicon-nitride layers (nitride 1 + nitride 2) are deposited and patterned [see Fig 4 (c)] forming structural connection as well as electrical and thermal isolations between actuator and RF signal lines. Then, access pads are defined in a ground sacrificial layer [see Fig 4 (d)]. The wafer is patterned with $20 \mu\text{m}$ thick structural nickel layer into the patterned resist stencil [see Fig 4 (e)]. After electroplating, gold layer is elec-

(g)

Fig. 4: Process flow for the fabrication of RF MEMS switch using MetalMumps

-troplated [see Fig 4(f)]. Finally, KOH solution is used to form a 25 μm deep trench in the silicon substrate [see Fig 4 (g)].

Simulation Results

The structure was simulated using Intellisuite software. The ends of the beams were fixed and the boundary was set at the temperature of 25°C at the ends of the beams. When voltage is applied at the end of the beams, current flows through the beams and generates heat. Hence, actuators generate movement due to expansion of its material. Fig 5 (a) and Fig 5 (b) shows the measured static displacement and maximum temperature as a function of actuation current for an electroplated Ni Z-shaped bidirectional thermal actuator. It indicates that the displacement and temperature increased with the actuation current as expected. With the actuation current changed from -0.6 A to 0.6 A , the electrothermal actuator can achieve bidirectional motion in a dynamic range of $-10.08\text{ }\mu\text{m}$ to $10.17\text{ }\mu\text{m}$ and maximum temperature in the range of 53.42°C to 54.49°C .

(a)

(b) Current (Amp)

Fig. 5: Simulated (a) displacement and (b) temperature as a function of input current

Fig 6-9 illustrates S parameter results for the off and on state for RF MEMS switch in the frequency range of 1GHz to 10 GHz using COMSOL Multiphysics. The plot shows that micro switch on the low resistivity substrate has an isolation of about -87 dB at 1 GHz and about -67 dB at 10 GHz. Higher contact force provides low RF insertion loss thus insertion loss of about -0.14 dB at 10 GHz is obtained for the same switch. Also, switch shows good return loss at the frequency range of 1GHz to 5 GHz. The measured RF results confirm the approach to suspending the structures on a low resistivity substrate to obtain high performances of switch at low gigahertz frequencies.

Fig. 6: OFF state return loss

Fig. 7: OFF state isolation

Fig. 8: ON state return loss

Fig. 9: ON state insertion loss

Conclusion

This paper reported a novel RF MEMS switch, which can move bidirectionally in a plane. RF performance is improved by suspending the structures 25 μm from the substrate, which is good for future integration with active devices in the SOC concept. Measured insertion loss and isolation are -0.14 dB and -67 dB at 10GHz respectively. The return loss of the switch is also better than -20 dB at frequency range of 1GHz to 5GHz. It is expected that the proposed MEMS switch will provide good performances compared with PIN diode.

Acknowledgment

This work is supported by Griffith University, Australia under “Griffith University New Researcher Grant” research fund.

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