MICROMACHINED MICROWAVE ACTUATOR (MIMAC) TECHNOLOGY - A NEW TUNING APPROACH FOR MICROWAVE INTEGRATED CIRCUITS

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ABSTRACT

This paper describes a new approach for the realization of tunable/variable III-V planar microwave integrated circuits, which employs micromachined electrostatically controlled actuator technology. This technology is potentially compatible with conventional MMIC fabrication techniques, and allows precise positioning and re-positioning of metal conductors (tuning stubs, switches, capacitor plates, etc.) on an insulating substrate after fabrication is complete.

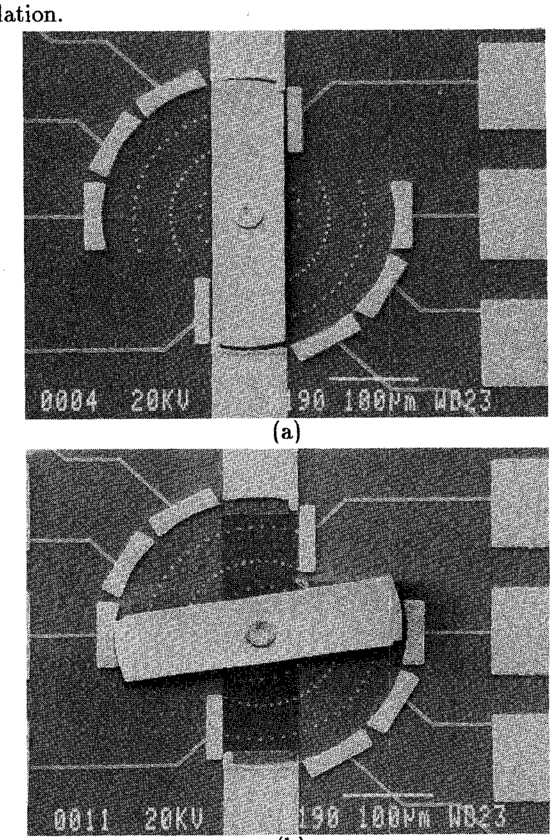
A variety of structures have been fabricated, including electrostatic micro-motors, rotating microwave switches, and variable interdigitated capacitors. A rotating microwave transmission line switch exhibited less than 0.5 dB insertion loss and greater than 35 dB isolation from dc to 45 GHz. A variable interdigitated capacitor exhibited a variation from 35 fF to 100 fF. A number of aspects of the technology require further research, including improvement in starting voltages, repeatability of contacts, and microwave design.

INTRODUCTION

Electrostatically controlled micromachined actuators have been extensively investigated in silicon integrated circuit technology for the purpose of fabricating "micro-machines" [1], [2]. These devices include rotating and linear micro-motors, sliding electrostatic logic, and electro-mechanical resonators. Maximum rotation speeds are typically in the tens of kHz, and starting voltages are on the order of 100 V. Despite the impressive recent progress in the field, the practical uses of this technology have remained limited.

However, the application of micromachined microwave actuator (MIMAC) technology to GaAs MMICs has a number of unique applications, some of which were previously difficult to achieve. When applied to GaAs IC's, this technology can allow the limited positioning, and repositioning, of tuning stubs, capacitors, and transmission lines on the planar substrate, significantly enhancing the tunability of MMICs.

For example, Figs. 1(a) and (b) shows an SEM microphotograph of an electrostatically controlled rotating microwave switch in the "open" and "closed" positions. The operation of this switch is similar in principle to that of a silicon micro-motor, except that the substrate is GaAs (instead of Si), and the conductors are gold (instead of heavily doped polysilicon). In the "closed" position, the switch acts like a 50Ω transmission line, with a low insertion loss and high return loss. In the "open" position, the switch exhibits high isolation.



(b)

Fig. 1. SEM microphotograph of rotating transmission line MIMAC switch in (a) closed position and (b) open position.

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Our initial designs have been based on a number of assumptions, since the fundamental mechanical properties of structures fabricated in GaAs on this scale are presently unknown. These aspects of the technology require further investigation. This paper will discuss our initial results with this technology, including fabrication issues, optimized microwave structures, experimental results, and areas requiring further research.

MICROWAVE ACTUATOR PROCESSING

The fabrication of these circuits is straightforward, and potentially compatible with conventional GaAs processing technology. Fabrication typically begins (Fig. 2(a)) with a layer of gold patterned on the GaAs substrate. This layer forms "bearings" that the rotating/sliding layer rests on - reducing the contact area between the rotor and the substrate - as well and as an interconnect layer. In our MMIC process, this layer is identical to overlay metallization.

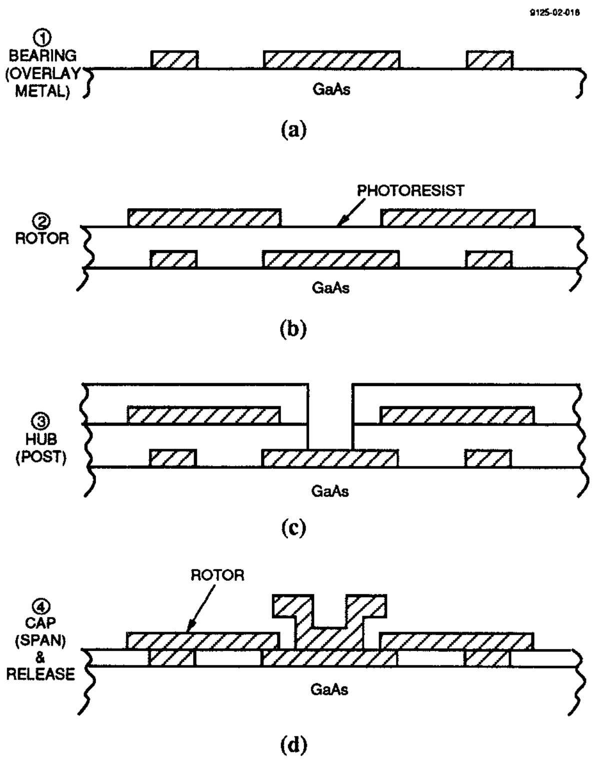

Fig. 2. Fabrication of MIMAC circuits (a). Bearing metal fabrication, minimizes contact area of rotor and substrate. (b). Rotor fabrication by electroplating. Photoresist remains in place as "sacrificaial" layer. (c). Hub fabrication, (d) Cap fabrication by electroplating and solvent removal of photoresist.

Next, a layer of photoresist is spun on the wafer, and the gold "rotor" is patterned and plated. The membrane metal is removed by ion-milling, but the underlying photoresist remains in place (Fig. 2(b)) as a "sacrificial" layer. The sacrificial layer holds the rotor in place until processing is complete. Next, a second layer of photoresist is patterned on the surface, and opened where the "Hub" is to be placed (Fig. 2(c)). Finally, a second layer (cap) is plated, the membrane removed by ion-milling, and the photoresist removed by a suitable solvent (Fig. 2(d)). The resulting structure is a "pin-joint" and allows unconstrained movement of the rotor in two-dimensions across the planar surface of the substrate. Note that the final two steps in the process (Figs. 2(c) and 2(d)) are identical to those required for a typical "air-bridge" fabrication. As a result, the complete processing of the MIMAC is very compatible with typical GaAs MMIC processing.

A key requirement of the rotor material is low residual stress, in order to minimize unwanted deflection of the rotating beam after release. This is accomplished in silicon technology by a high temperature anneal of the depoited polysilicon. Assuming a uniform residual stress, the deflection of an unconstrained beam is [3]

$$Deflection \approx \frac{3}{2}\frac{SL^4}{t^3E} \qquad (1)$$

where L is the length of the beam, t is its thickness, E is Young's Modulus, and S is the stress per unit area. The Young's Modulus for gold is approximately $8x10^{11} dynes/cm^2$, so a defelection of less than one micron in a 100 micron long, one micron thick, beam will require a residual stress of less than $10^5 dynes/cm^2$ in the plated metal. Stresses of this low magnitude can be achieved through careful optimization of the plating process [4]. The plated gold beams and rotors fabricated in our process exhibit deflections due to residual stress of less than 0.5 microns in most cases.

DESIGN OF OPTIMIZED MICROWAVE ACTUATOR STRUCTURES

The design of electrostatically controlled micromotors is discussed in detail in [5]. The physical principles of a rotating micromotor are illustrated in Fig. 3. The motor rotates as a result of electrostatic attraction between the "stators" - which have an applied voltage of $\pm V$ - and the "rotors", due to the induced image charge. The induced torque on the rotor is given by:

$$Torque(\theta) = \frac{1}{2}V^2\frac{\partial C(\theta)}{\partial \theta} \qquad (2)$$

where V is the applied voltage and $C(\theta)$ is the fringing capacitive coupling between the rotor and stator as a function of angular position.

So the torque is increased by an increase in the fringing capacitance between the stator and the rotating switch, or by an increase in the applied voltage. Typical torques are on the order of pico-Newton-meters for these structures, at applied voltages of approximately 100 V.

The potentially deleterious effects of parasitic coupling capacitance between the stators and rotors - which should be maximized in order to minimize starting voltages - on the microwave performance of the structure can be minimized by employing a high valued resistor in series with the stator, since the only current supplied to the stator during operation is a small ac current.

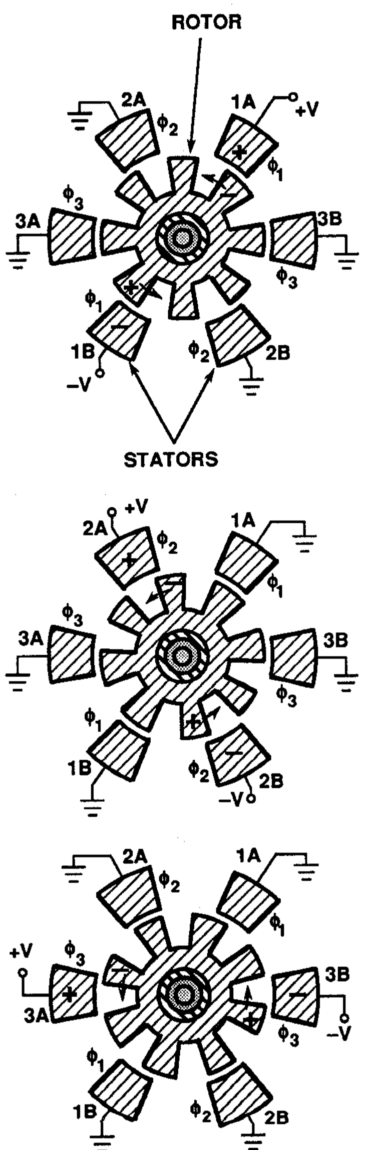

Fig. 3. Physical principles of rotating micromachined micro-motor. Torque is exerted on the rotor by an image charge induced by the applied voltage to the stator. The rotor rotates in order to maximize the stored electrostatic energy.

EXPERIMENTAL RESULTS

Fig. 4 shows the results of high-frequency measurements on the rotating transmission line microwave switch of Fig. 1. The insertion loss is less than 0.4 dB from 2 to 45 GHz, and the isolation is greater than 35 dB across the same frequency range. These results are similar to what can be attained with mechanical microwave switches, but in a much smaller volume [6]. The isolation can be further improved by lengthening the rotor, and minimizing capacitive coupling between input and output.

There are a number of other possible applications of this technology for GaAs microwave integrated circuits. Fig. 5 shows an interdigitated capacitor, where the value of its capacitance is controllable by altering the overlap between the opposing fingers. This is an example of a sliding micromotor, where the position of the capacitor is controllable by the phasing and amplitude of the voltages applied to the side electrodes. Fig. 6 is a plot of the measured capacitance of this structure as a function of position. With further optimization, a structure like this could be employed for tuning microwave circuits.

There are a number of areas of this technology that require further study. The voltages required to initiate movement of the structures are in the 80 V to 200 V range. These voltages are similar to those obtained in silicon technology [1], and are a result of the very small fringing capacitance between the stator and rotor ($\approx 5fF$), and the high electrostatic charge at the semiconductor surface, which tends to increase the static coefficient of friction. We are trying to improve the starting voltages by designing structures with increased coupling capacitance and torque. Because of the high starting voltages, these initial microwave results have been attained using mechanical motion of the movable elements.

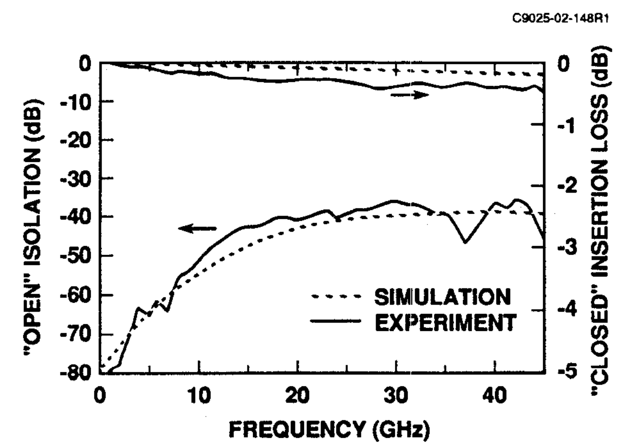

Fig. 4. RF measurements on rotating MIMAC switch in open and closed postions, with comparison to two-dimensional electromagnetic simulation of the structure.

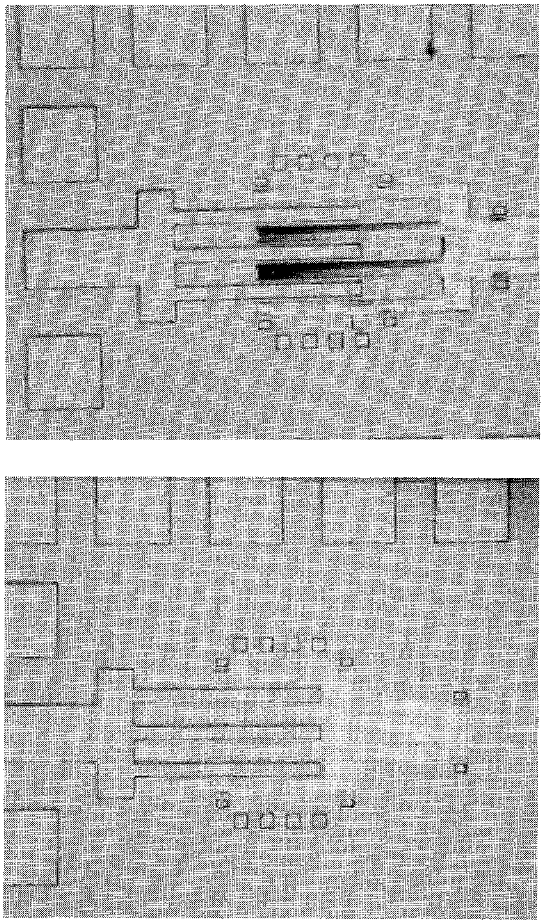

Fig. 5. Interdigitated MIMAC capacitor in open and closed positions.

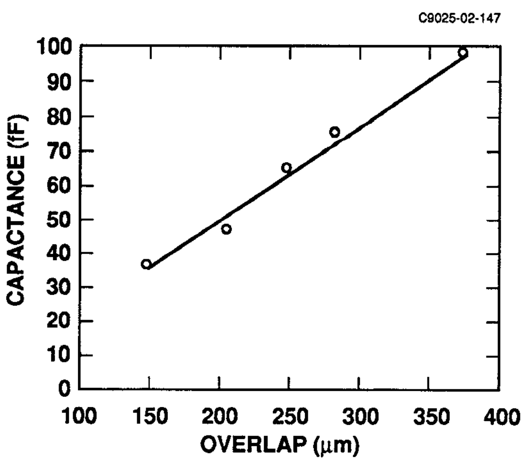

Fig. 6. Measured capacitance variation of the circuit of Fig. 5.

Another area for research is improvement of the repeatability of contact resistance with these structures. This is especially important for switches and tuners, where insertion loss and Q can be degraded by high series resistances. The contact resistance can be improved by conductor "pull-down" schemes and improved metallizations. Finally, the switching, or tuning, speed of these circits needs to be investigated. Viscous drag and friction are key limitations on the speed performance of silicon-based micromotors [7]. In this sense, the limitations on these circuits are similar to those of mechanically-based electromagnetic rf switches, which typically operate on the milli-second time frame.

CONCLUSIONS

Micromachined microwave actuator technology holds the promise for a number of unique applications. For example, sliding transmission-line tuners, controlled by electrostatics, could provide for dynamic tuning of MMIC circuits after fabrication, significantly enhancing the yield and lowering the cost of these circuits. Tuning could also be accomplished with variable electrostatic capacitors. Other novel applications of the technology to passive planar microwave circuitry can also be imagined. However, extensive research remains to be done on the mechanical properties of MMIC materials at these dimensions, before this technology can be applied more widely.

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