Electro/Thermal Measurements of RF MEMS Capacitive Switches

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***Abstract* — An aspect-ratio-limited fabrication procedure for the secondary handling of miniaturized micromachined and fiber-fed gallium arsenide electrothermal probes is presented, and a completed probe is used to measure the electric field and temperature above an RF MEMS capacitive switch. The probe dimensions are 125 μm x 125 μm x 100 μm. Measurements of switches with dimensions of 250 μm x 640 μm are performed for RF powers between 252 mW and 6.7 W in the UP and DOWN states. Non-contact temperature measurements 25 μm above the switch in the UP state show a thermal rise time of 0.63 ± 0.05 seconds for an RF input power of 6.7 W. The accompanying temperature rise is 16.8 ± 0.7 °C. In the DOWN state, the increase in temperature is 3.0 ± 0.8 °C. Spatial line scans of temperature show the localization of heat energy in the UP state and its delocalization in the DOWN state due to conductive heat transfer into the substrate. Electric field measurements yield traveling waves in the UP state and standing waves in the down state. Standing waves in the DOWN state are consistent with preferential substrate heating on the input side to the switch.**

I. INTRODUCTION

Optical excitation and bandgap modulation near the conduction band edge of gallium arsenide, along with electro-optic modulation via the Pockels effect, have resulted in the invention of electrothermal probes capable of simultaneously measuring electric and thermal fields [1]. While the electric-field spatial resolution is determined by the diffraction of the optical beam in the crystal, the temperature resolution is dominated by thermal propagation in the crystal lattice and is therefore dependent on the overall volume of the probe itself. Bulk micromachining of GaAs allows for the possibility of etching probes with spatial dimensions approaching tens of microns and therefore provides the capability of performing electrothermal measurements on the variety of microstructures developed to date. In this paper, an aspect-ratio limited fabrication procedure for the miniaturization and secondary handling of such probes is presented and a completed probe is employed to measure the electric field and the RF induced temperature distributions associated with capacitive RF MEMS switches. Data has been collected for RF powers between 252 mW and 6.7 W for the switch in both the UP and DOWN state configurations. Several authors have investigated thermal effects in capacitive RF MEMS switches via modeling or numerical techniques, however, no thermal measurements have been reported to our knowledge [2]-[3].

II. PROBE MINIATURIZATION - FABRICATION

Probes with edge dimensions below 500 μm become extremely difficult to mount and handle directly. In previous work, free-space, 100-μm diameter probes have been fabricated by first bonding a sample of the probe crystal on a fused-silica support and then polishing the surfaces [4]. Since GaAs can be bulk micromachined by wet chemical etching, a fabrication procedure has been developed for fiber-mounted sensors that allows for the micromachining of miniaturized (tens of microns) probes and that is limited only by the aspect ratio allowed from wet chemical etching. Miniaturization is possible because the probes do not need to be handled directly.

Fig. 1 shows the fabrication procedure. A liftoff process is first performed to pattern the Bragg reflector on one side of a double-side-polished GaAs crystal. On the opposite side, an infrared alignment is performed to pattern the probe mask that consists of SC1827 photoresist. The crystal is then mounted on a silicon carrier using AZ9260 photoresist. The GaAs is then etched using a wet chemical process and the photoresist mask is removed with a short exposure and subsequent development. Due to the thickness difference and developer selectivity between SC1827 and AZ9260 photoresist, the probe mask is removed while the micromachined probes remain on the silicon carrier. The optical fiber is then mounted on the

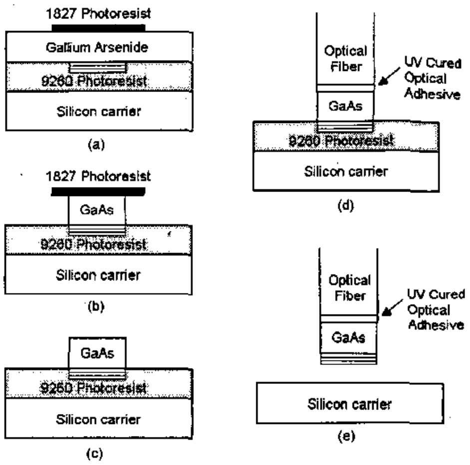

Fig. 1. Aspect-ratio-limited probe fabrication procedure for probe miniaturization: (a) Bragg reflector, (b) Probe mask, (c) Wet etch, (d) Fiber mounting, (e) Acetone release.

GaAs probes via UV-cured optical adhesive. After curing, the adhesive is insensitive to solvents. Therefore, the probe can be released with a few drops of acetone.

III. Experimental Setup

Probes with 125 µm x 125 µm x 100 µm dimensions have been fabricated for the initial measurements of RF MEMS switches. An edge length of 125 µm was selected to match the diameter of the optical fiber. A smaller probe with 40 µm x 40 µm x 100 µm dimensions is currently being characterized.

The RF MEMS measurement setup is shown in Fig. 2. The output of a 20 mW RF synthesizer operating at 10.003 GHz is fed into an X-Band traveling-wave tube (TWT) amplifier capable of amplifying the RF signal to 8 W. The coaxial cable from the TWT is terminated with on-wafer probes which serve as the input port for the switch-shunted co-planar waveguide. A second on-wafer probe serves as the output port whose output passes through an isolator (measured S_{21} –30.4 dB at 10.003 GHz via network analyzer) and is terminated with an RF power meter with ±1 dB precision. A 40 V DC source provides electrostatic switch actuation via DC contact probes placed on on-wafer DC pads. The electrothermal probe is mounted on an electromechanical x-y translation stage with 1 µm step resolution. A manual translation support provides movement of the probe in the vertical direction. A horizontally mounted low–power-objective microscope allows for the vertical positioning of the probe above the switch with ±10 µm accuracy.

The switch under investigation is shown in Fig. 3 [5]. The switch dimensions are 250 µm x 640 µm. The switch membrane (Au) was fabricated with internal stresses conducive to conformal contact in the DOWN state. The measured insertion loss in the DOWN state, from network analyzer measurements at 10 GHz, is –11.1 dB, and the return loss is –4.4 dB. The loss associated with the CPW line (1.5 cm) is included in these numbers.

A mode-locked Ti:Sapphire laser tuned to 905 nm is used to generate a linearly polarized sampling beam (80 MHz repetition rate, 100 fs pulse duration). Appropriate phase retarders are configured to yield a 50% transmission intensity modulator for electric field measurements. An RF synthesizer configured for harmonic mixing is used to down-convert the sampled electric fields to an IF frequency of approximately 3 MHz.

A photodiode functions as an envelope detector that transforms the 3 MHz modulation and the 80 MHz pulse repetition component to electrical signals for detection. For optimum signal-to-noise ratio, a lock-in amplifier is employed whose reference-in signal is switched between 3 MHz (for electric-field measurements) and 80 MHz (for temperature measurements). The time constant of the lock-in was placed at 100 ms, which sets the upper limit on the temporal resolution of the measurement system.

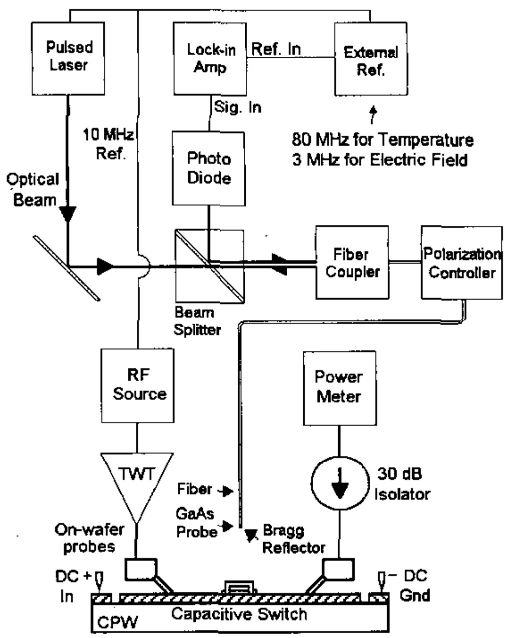

Fig. 2. Experimental setup for RF MEMS switch measurements.

IV. MEASUREMENTS

A. Point Measurements 25μm Above Switch - Temperature

Non-contact point measurements with the probe 25 μm above the switch were performed first. The air between the switch and the probe forms a moving conductive medium for convective heat transfer. The temperatures measured are not that of the switch itself but of the air as measured by the probe at the height above the switch. Numerical modeling is in progress to deduce the actual switch temperature from non-contact measurements. The rise and fall times of the switch in the UP and DOWN states are shown in Fig. 4. The probe was placed 25 μm directly over the center of the switch and the input RF power was varied between 252 mW and 6.7 W. These are the input powers at the switch determined by considering the CPW line loss (1.67 dB/cm) and the nominal on-wafer probe insertion loss (0.5 dB). No self-actuation due to high RF power was observed at any point. This is consistent with previously reported findings [6]. Data acquisition commenced with the RF off for 10 seconds, the RF on for 20 seconds, and the RF off for 10 seconds. The temperature of the probe shows a rise time, computed between the 10 % and 90 % points, at 6.7 W input RF, of 0.63 ± 0.05 seconds. The measured temperature change between on and off RF powers is 16.8 ± 0.7 °C at 6.7 W input RF. The fall time, computed between the 10 % and 90 % points at 6.7 W input RF is observed to be 0.52 ± 0.05 seconds. At 252 mW input RF power, the temperature difference between on and off RF powers is 1.5 ± 0.7 °C. In the down state, the measured temperature difference between RF off and RF on times is 3.0 ± 0.8 °C with 6.7 W input RF power. At 252 mW input RF power, the temperature does not change significantly. The lower temperatures in the down state suggests sufficient contact between the switch membrane and the silicon nitride dielectric thereby allowing for conductive heat transfer into the substrate.

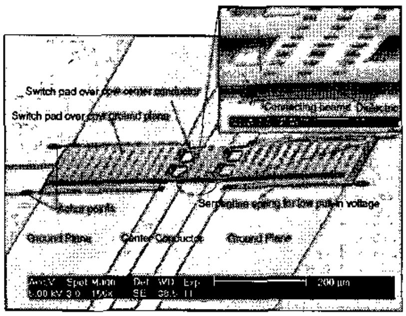

Fig. 3. Measured RF MEMS capacitive switch.

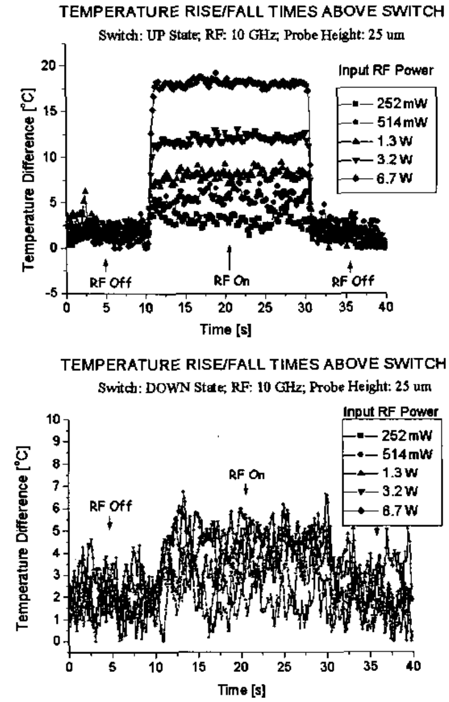

Fig. 4. Point measurements of temperature 25 μm above switch. Top plot: UP state, Bottom plot: DOWN state.

B. Line Scans 100μm above switch - Temperature

To perform line scans of the temperature and electric fields, the probe was raised to 100 μm above the surface in order to avoid accidentally driving the probe into the circuit surface. Line scans using 6.7 W input RF power for the switch in the UP/DOWN states are shown in Fig. 5. A peak is present in the UP state but is absent in the down state. This is consistent with the hypothesis of efficient conductive heat transfer between the membrane and the substrate in the DOWN position. In the DOWN state with the RF on, the temperature is slightly higher along the CPW when compared against the DOWN state with the RF off. In addition, the temperature is slightly higher on the side of the input RF power. This is consistent with the presence of a large standing wave on the input side of the switch in the DOWN state and substrate heating from the switch. There is a slight slope in the RF-off measurements due to residual heating from repeated line-scan measurements with the RF on and the RF off.

C. Line Scans 100μm above switch – Electric Field

Line scans of the electric field phasor are shown in Fig. 6. in the UP and the DOWN state. In the UP state, the

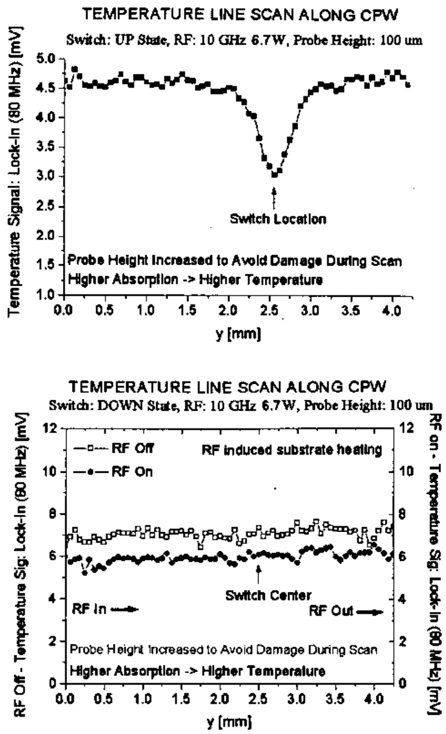

Fig. 5. Line scans of temperature 100 μm above switch. Top plot: UP state, Bottom plot: DOWN state

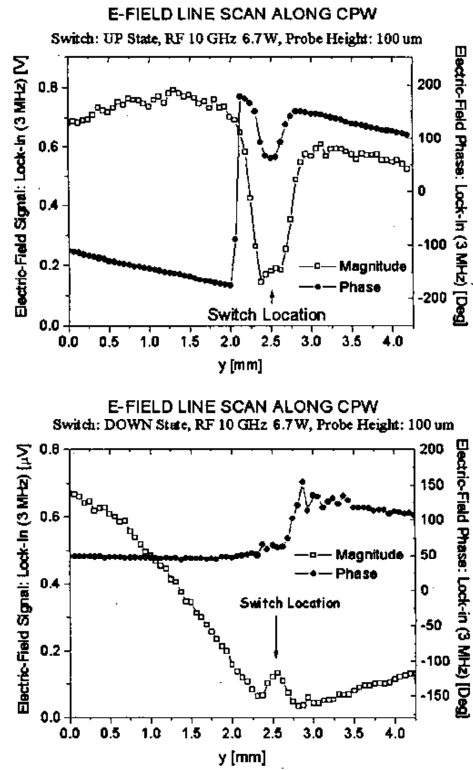

Fig. 6. Line scans of electric-field 100 μm above switch. Top plot: UP state, Bottom plot: DOWN state

electric field is seen to drop by approximately 25% across the switch indicating that the switch is performing the function of passing power through. This is supported by the slope in the phase measurements which is indicative of traveling waves. In the DOWN state, the electric field drop is greater than 80% which shows that the switch is performing a blocking function for the RF power. This is supported by the flat slope of the phase measurements, which is indicative of standing waves on the input side of the switch.

V. CONCLUSION

A novel fabrication method for electrothermal probe miniaturization has been developed. Measurements with the probe have been taken on RF MEMS switches, yielding insight into their electro/thermal behavior.

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REFERENCES

[1] R. Reano, K. Yang, L. P. B. Katehi, J. F. Whitaker, "Simultaneous Measurements of Electric and Thermal Fields Utilizing an electro-optic semiconductor probe," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-49, no. 12, pp. 2523-2531, Dec 2001.

[2] J. Rizk, E. Chaiban, G. M. Rebeiz, "Steady State Thermal Analysis and High-Power Reliability Considerations of RF MEMS Capacitive Switches," *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, June 2002, pp. 239-242.

[3] W. Thiel, K. Tornquist, R. Reano, L. P. B. Katehi, "A Study of Thermal Effects in RF-MEM-Switches using a Time Domain Approach," *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, June 2002, pp. 235-238.

[4] M. Shinagawa, T. Nagatsuma, "Electro-optic sampling using an external GaAs probe tip," *Electron. Lett.*, vol. 26, pp. 1341-1343, Aug. 1990.

[5] D. Peroulis, S. P. Pacheco, K. Sarabandi, L. P. B. Katehi, "Electromechanical Considerations in Developing Low-Voltage RF MEMS Switches" to appear in *IEEE Trans. on Microwave Theory Tech.*, Jan. 2003.

[6] S. P. Pacheco, C. T. Nguyen, L. P. B. Katehi, "Design of Low Actuation Voltage RF MEMS Switch," *IEEE MTT-S Int. Microwave Symp. Dig., vol. 1, Jun. 2000, pp. 165-168.*