PIEZOMEMS DEVICES FOR ADVANCED COMMUNICATIONS AND PHASED ARRAY RADAR

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ABSTRACT

In this article, we report on the successful demonstration of lead zirconate titanate (PZT) thin film based MEMS devices for use in radio frequency (RF) systems. Individual series switches and single pole multi-throw switching elements operating at or below 10 V have been developed capable of operating over a wide temperature range. The switch technology also provides an enabling technology for low voltage, mechanical logic. Along with switches and phase shifters, PZT based MEMS resonators show promise in the sub-GHz regime with demonstrated insertion loss values near 3.5 dB.

1. INTRODUCTION

RF MEMS devices have long held the potential to vastly improve communications and phased array radar systems with extremely low loss, high linearity, and near zero power consumption [Rebeiz]. . The substantially lower loss switches and phase shifters can have dramatic improvements in the power and thermal draw in electronically scanned antenna systems. Until recently, most RF MEMS devices in development concentrated on using electrostatic transduction for their principle of operation. The advances in piezoelectric AlN thin film bulk acoustic resonators, FBARs, [Ruby] have opened the possibility of using piezoelectric transduction as an alternative to electrostatic transduction in RF MEMS resonators and filters. Even more promising is the use of lead zirconate titanate (PZT) thin films for improved device performance and actuation voltages compatible with most CMOS electronics. For actuation, the most significant material property parameter of interest is the piezoelectric stress constant for which PZT has an effective, transverse piezoelectric stress constant, $e_{31,f}$, nearly an order of magnitude larger than AlN [Dubois].

Within the RF MEMS research community, there continues to be great interest in RF MEMS switches for creating low loss phase shifters for phased array antennas for communication and radar systems. The first reported demonstration of PZT thin film actuated RF MEMS switch utilized thin film actuators and bulk micromachining techniques along with co-planar waveguide (CPW) transmission lines [Lee]. These switches performed well up to 20 GHz with demonstrated performance as low as 3.5 volts. However, the bulk micromachining approach limits the integration potential of this technology. The first surface micromachined approach for creating a PZT actuated RF MEMS switch was developed by Polcawich et. al. and uses PZT thin film actuators. These devices achieved less than 10 volt operation and have demonstrated temperature stable performance from -25°C to 100°C for normally open series switches [Polcawich, Polcawich]. A key benefit highlighted by these efforts is the low voltage operation (less than 10 V) of PZT based switches compared to their electrostatic counterparts with voltages ranging from 30 to 90 volts [Rebeiz]. An additional benefit exhibited by these approaches is the decoupling of the actuator bias from the RF transmission line, which allows for independent actuation without the need for incorporating bias isolation techniques.

Another area of interest is in piezoelectrically transduced resonators and filters for UHF and VHF systems. PZT thin film based resonators using flexural resonance modes were first examined by Piekarski et al. for possible use at notch filters in VHF communication systems [Piekarski] However, large insertion loss dominated by large motional impedances and large parasitic capacitances prevented suitable device demonstrations using flexural mode devices. Recent efforts on dielectrically transduced [Bhave] and piezoelectrically actuated, ZnO contour-mode resonators [Piazza, Antkowiak] have renewed interest in using PZT thin film resonators for RF MEMS filters.

This article highlights the use of PZT thin films and an integrated PiezoMEMS fabrication process for creating RF MEMS devices. Starting with PZT actuators, the performance of series switches will be discussed followed by demonstration of MEMS mechanical logic operating at one volt. Finally, PZT based MEMS contour mode resonators and filters are demonstrated with frequency and impedance tuning using the dielectric tunability of PZT.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Piezomems Devices For Advanced Communications And Phased Array Radar**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **L-3 Communications Cincinnati Electronics Mason, OH 45040**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

2. PIEZOMEMS DEVICE FABRICATION

The U.S. Army Research Laboratory's (ARL) PiezoMEMS fabrication process has been previously described by Polcawich et. al. and Chandrahalim et. al. and will only be summarized in this section. The ARL PiezoMEMS process hinges on the deposition and patterning of chemical solution deposited PZT thin film. Using residual stress gradient engineering, an elastic layer comprised of silicon dioxide and silicon nitride is deposited atop a silicon substrate. The next fabrication steps involve the serial deposition of a Ti/Pt base electrode layer, PZT layer, and a Pt top electrode layer. Device patterning is accomplished through a series of Argon ion-milling, reactive ion etching, and wet chemical etching. Conductive metal layers are deposited via electron beam evaporation and patterned with a lift-off technique. In the final processing steps, a sacrificial photo-resist is used to create air bridge structures comprised of gold followed by a XeF_2 etch to release the piezoelectric devices from the silicon substrate.

3. PIEZOMEMS DEVICES

Using the fabrication process outlined above, a wide variety of devices can be created with examples highlighted in Fig. 1. The PiezoMEMS RF switch and its fabrication process has been used as the building block for more complicated device structures such as phase shifters [Polcawich], switching elements [Chung] for switch matrices, mechanical logic elements [Judy], and MEMS resonators and filters [Chandrahalim].

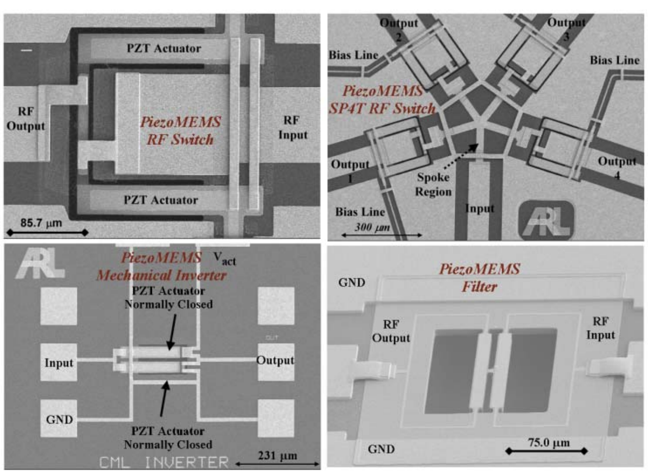

Fig. 1 SEM images highlighting the use of PZT transducers for RF MEMS switches, SP4T switching elements, mechanical logic elements, and MEMS resonators and filters.

The RF switches have exhibited excellent performance across a wide temperature range with insertion loss values less than 0.35 dB and isolation better than -20 dB from DC through 40 GHz (see Fig. 2). Operating at or below 10 volts, these switches are ideal for use in large scale RF circuits where loss and power consumption are of critical importance.

The switch has been installed into a single pole, multi-throw (SPmT) architecture with SP2T, SP3T, and SP4T devices for switch matrices. Using high frequency modeling to impedance match within the spoke region of the SPmT switch, a broad band switching element has been developed offering all of the benefits exhibited by the individual PiezoMEMS RF switch (see Fig. 3). The current devices exhibit reasonable insertion loss and isolation at all ports from DC through 25 GHz with higher frequency performance limited by non-optimal performance of the spoke region, which is currently under investigation.

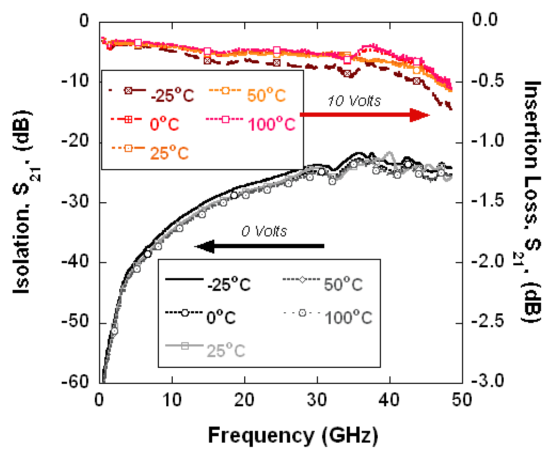

Fig. 2 S_{21} parameters of a PZT RF MEMS series switch as a function of temperature in both the unactuated (0) and actuated state (10 V).

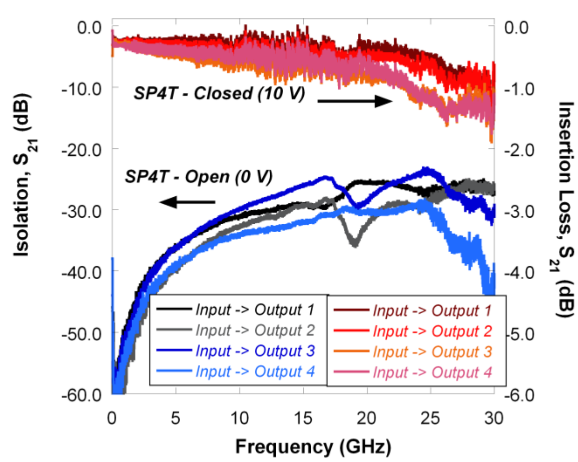

Fig. 3 S_{21} parameters of a PiezoMEMS SP4T switch in the open (0V) and closed (10V) state.

The basic actuator used for the RF switch can be used to build electro-mechanical logic components in the same manner as the transistor. Micro and nano-scale mechanical logic technologies are expected to provide significant advantages over CMOS with respect to dynamic and static power consumption, maximum operating temperature, and radiation tolerance. Low voltage mechanical logic circuits also offer the possibility of integrating control elements directly with a MEMS phase shifter (see Fig. 4). With this approach a serial input bit stream can be decoded to select the appropriate phase state required of the phase shifter. Basic functional units such as a NAND are illustrated and can be used to build ever increasing complex mechanical logic circuits similar to those created with state-of-the-art transistor logic. An example of a mechanical inverter is highlighted in Fig. 1. The complementary MEMS logic (CML) inverter has been shown to exhibited 1 V operation (see Fig. 5). The demonstration of a one volt inverter can be extended to build more complex circuits including NAND gates and ring oscillators [Judy]. These logic elements and decoder circuits can be designed to fit within the ground plane real estate of a MEMS phase shifter (see Fig. 4), and thus provide integrated microprocessor-like control of the phase states.

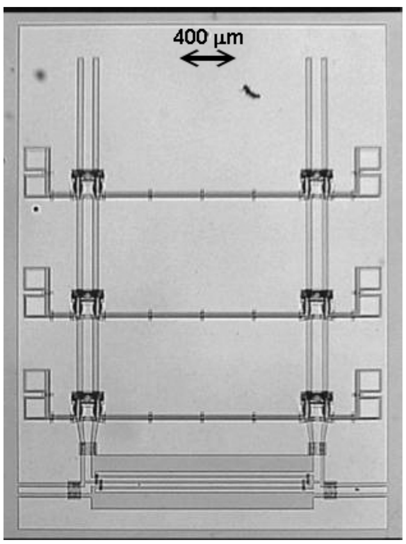

Fig. 4 Image of a PiezoMEMS phase shifter [Polcawich].

In addition to pure actuation applications, PZT thin films can be used to transduce a frequency modulated signal into or out of a single crystal silicon resonator. PZT-on-SOI devices trade the lowered effective coupling factor of the resonators for the increased intrinsic quality factor of the silicon resonator for a net improvement in device performance. A DC bias dependant coupling factor of the PZT allows tuning of the motional impedance of the resonators such that an as-fabricated, un-matched resonator shows an insertion loss improvement of nearly 10 dB (from 12 dB to 3.5 dB) with DC bias (see Fig. 6). As the resonant frequency is dominated by the silicon device layer, very little resonant frequency tuning is observed, although substantial improvements in the impedance and insertion loss occur. The PiezoMEMS resonator technology promises to provide a high performance filter technology for operation in the UHF and VHF bands. Furthermore, combining PiezoMEMS switches and resonators/filters will result in high performance low voltage, switchable filters capable of both frequency and impedance tuning for next generation secure communication systems.

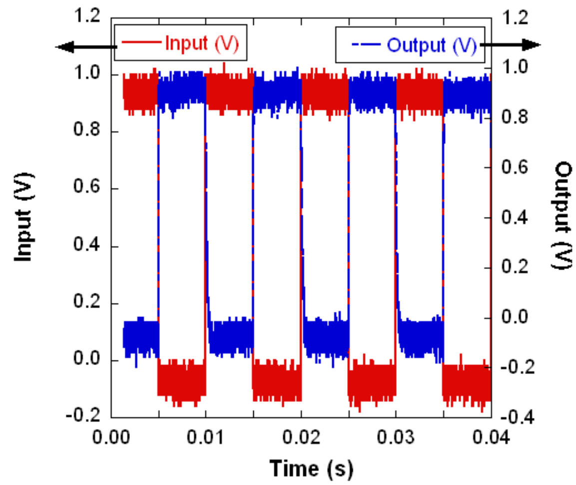

Fig. 5 Measured input and output voltages for a PZT MEMS inverter operating at 1 volt.

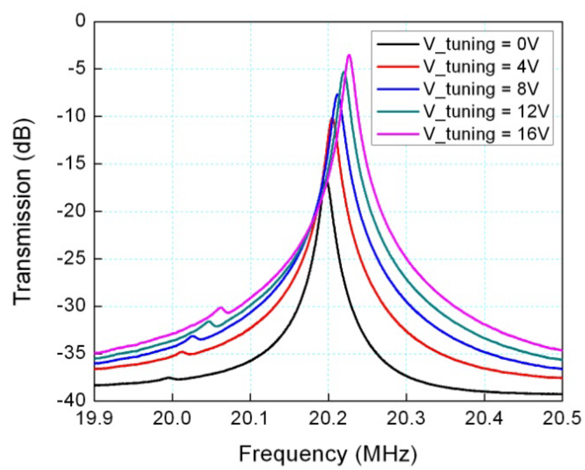

Fig. 6 Measured transmission of a 190 µm x 40 µm PZT transduced resonator on 10 µm silicon with different bias voltages in air at room temperature and pressure.

5. CONCLUSION

This review summarizes the capabilities of PiezoMEMS devices in the area of communication and phased arrays. The ARL PiezoMEMS fabrication process has been developed to enable a wide variety of device structures capable of meeting the demands of next generation systems. Switches and filters capable of 10 to 15 volt operation combined with minimal temperature sensitivities are the highlight achievements and targets of the aforementioned PZT thin film based devices.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and support of Richard Piekarz and Joel Martin of the Army Research Laboratory, Brian Power of General Technical Services, Sunil Bhave and Hengky Chandrahalim of Cornell University, and David Chung and John Papapolymerou of the Georgia Institute of Technology.

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