Flip-Chip Assembly and Liquid Crystal Polymer Encapsulation for Variable MEMS Capacitors

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***Abstract*—Packaging is a well-known barrier to the advancement of microelectromechanical systems (MEMS) for RF applications. To pave the way for the removal of this barrier, we have developed a flip-chip assembly technology to transfer foundry-fabricated MEMS devices from the host silicon substrate to a ceramic substrate. Specifically, posts have been designed and fabricated to assure excellent RF performance by achieving a precise gap between the device and ceramic substrate. In addition, a novel liquid crystal polymer (LCP) encapsulation technology has been developed to protect the RF MEMS device. LCP is a good encapsulation material for nonhermetic packaging because it significantly reduces the packaging cost. We have demonstrated excellent RF performance of variable MEMS capacitors that have been flip-chip assembled and LCP encapsulated. The quality (Q) factors of such capacitors were measured to be higher than 300 at 1.0 GHz.**

***Index Terms*—Liquid crystal polymer (LCP), microelectromechanical systems (MEMS) devices, RF packaging, variable capacitor.**

I. Introduction

COST AND reliability are two main challenges to the advancements of RF microelectromechanical systems (MEMS) application where can be brought out of the laboratory and introduced into commercial products. Based on the evolution of microelectronics, we understand that foundry-based manufacturing and nonhermetic packaging are essential to reducing costs while assuring reliability. Unfortunately, most RF MEMS devices demonstrated to date have been fabricated using custom-developed processes and have been protected by hermetic packages [1]. It is important to explore new packaging technologies that will enable future RF MEMS devices to be manufactured using foundry processes and protected in nonhermetic packages. Most of MEMS foundry processes are not directly compatible with RF MEMS. For example, the multiuser microelectromechanical systems processes (MUMPs) are based on low-resistively silicon wafers, which are not good substrates for RF applications due to their high losses at RF frequencies [2], [3]. To remedy this, a flip-assembly process with silicon removal technology was previously developed to transfer MEMS from the silicon to a ceramic substrate containing RF circuits [4]. However, the transferred devices did not perform well due to large gap variations corresponding to varied solder bump heights. As a result, a post-enabled precision flip-chip assembly technology has now been developed to assure high-quality transfer of the foundry-fabricated RF MEMS onto an RF substrate [5].

For nonhermetic packaging, moisture-induced adhesion is always a key mechanism for "*stiction*" failures [6], [7]. The energy of the moisture-induced adhesion was increases by 80 times after a 7-h 90% relative humidity (RH) test. However, the initial adhesion energy under 90% RH was very close to that under 5.0% RH. The undesirable increase was the result of the degradation of the self-assembled monolayer (SAM) coating. With advancements in atomic layer deposition (ALD), we have a great opportunity to create a super-strong hydrophobic inorganic surface coating to maintain the low adhesion energy even under a high humidity environment. ALD is described in [9], and its hydrophobic coating will be presented in the future. The next packaging challenge is the control of the humidity level inside a nonhermetic package so it is not affected significantly by the large variations in the environment outside the package. Liquid crystal polymer (LCP) has been identified as the best candidate to control the humidity in the nonhermetic packaging of RF MEMS. LCP has the following advantages:

1) its near-hermetic permeability of moisture can keep the MEMS local surroundings dry for months even in a humid environment;
2) its low RF loss properties assure excellent RF performance after packaging;
3) its moldability assures a high-speed glob-top encapsulation process [10]–[12].

An LCP encapsulation process has been developed for flip-chip assembled RF MEMS. In this paper, we will present the post-enabled precision flip-chip assembly and the LCP encapsulation of an RF MEMS variable capacitor. More importantly, we will present excellent RF performance by these new technologies.

II. Post-Enabled Flip-Chip Assembly

A. Flip-Chip Assembly With Silicon Removal

A two-dimensional MEMS variable capacitor array was assembled using flip-chip bonding with tethers on the donor substrate (see Fig. 1) [13]. In this study, the bottom alumina ceramic substrate was patterned with a 50-Ω microstrip gold transmission line, which acting as one large electrode. The gold layer thickness was 2.4 μm. A 2.0-μm indium was then

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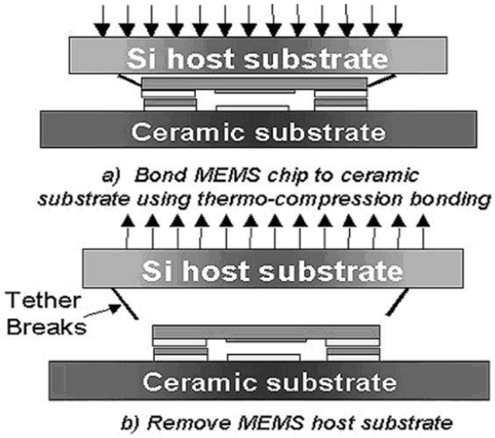

Fig. 1. Flip-chip assembly illustrations. Notice the tether breaks on the sides of the remaining device.

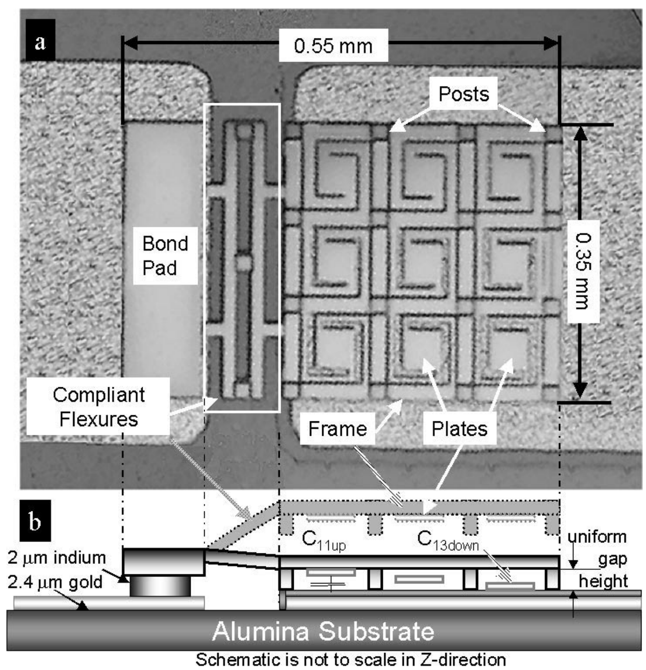

Fig. 2. 3 × 3 variable capacitor shows: (a) top view of the device feature an array, a compliant flexure and bond pad, (b) side-view of three capacitor plates in the up position before flip-chip and one plate in the down position after flip-chip assembly. The schematic demonstrates the uniform gab based on the post height.

deposited for bonding. In addition, a 160-nm-thick alumina dielectric layer was selectively deposited by ALD coating techniques [9]. Following foundry fabrication, but before bonding, the MEMS chip was released in 49% hydrofluoric acid (HF), followed by a CO_2 critical-point drying process. After the release, the MEMS-based variable capacitor array (M-VCA) was still connected to the silicon substrate by tethers. As shown in Fig. 1(b), during the bonding process, these tethers were broken, leaving behind the top plate of the M-VCA. As shown in Fig. 2(a), a 3 × 3 M-VCA was assembled and transferred to an alumina substrate. The side-view illustrates how the capacitor plates maintained a uniform air gap between the MEMS top plates and the electrodes on the substrate. Such a gap was achieved through the use of posts, which were

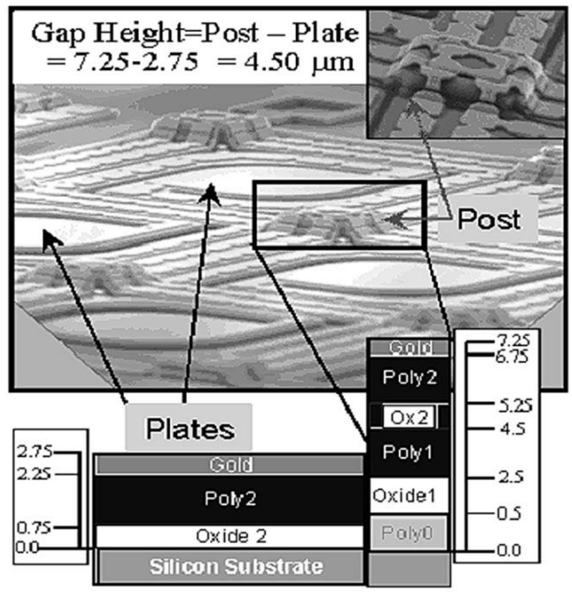

Fig. 3. Posts and plates before the flip-chip assembly.

critical to the precision flip-chip assembly. After bonding, the gap between the MEMS device and the substrate varied from one plate to the other. Such a variation was the result of processing variations, thermal mismatches, and residual stresses. As advantages of the new design, during electrostatic actuation, the entire array, which is supported by compliant flexures, was pulled down onto the posts, as shown in Fig. 2(b), leaving a uniform gap between the top plates and the substrate. The compliant flexure will absorb the thermal mismatch. These posts were the critical new feature specifically designed to provide uniform gap heights for foundry-fabricated flip-chip assembled MEMS [9].

B. Post and Layer Structure

Posts can be created in most of the MEMS foundry processes with features such as dimples. However, these dimples are not compatible with the flip-chip assembly because all the features are upside down. As a results, new post features had to be developed. Through a novel design, we were able to use existing foundry process to create new posts for the flip-chip assembly. Fig. 3 illustrates an example for the posts designed and fabricated using the MUMPs. The difference between the height of the post—which is made of poly0 (0.5 μm), poly1 (2 μm), oxide 2 (0.75 μm), poly2 (1.5 μm), and gold (0.5 μm)—and the height of the plate—which is made of poly2 (1.5 μm), gold (0.5 μm), and anchor1 (to remove oxide 1 layer)—is 4.5 μm. This is the uniform gap height for the M-VCA. If needed, other layer combinations for the posts and plates could provide different gaps. Table I lists three example gaps, although we have designed and tested 18 different gaps ranging from 0.25 to 4.50 μm in 0.25-μm increments.

C. C–V Relationship and Tuning Ratio

Fig. 4 shows the variable capacitance as a function of voltages applied. The maximum capacitance, measured at 74 V with three plates snapped down, was $C_{\rm down} = 1.5$ pF. In addition,

TABLE I
POST AND PLATE LAYER STRUCTURE

Gap (μm)	Plate layers	Post layers
1.00	P0, P2, gold	P0, P1, P2, via
2.50	P0, P2, anchor1,gold	P1, P2, via
4.50	P2, via, gold	P0, P1, P2, via, gold

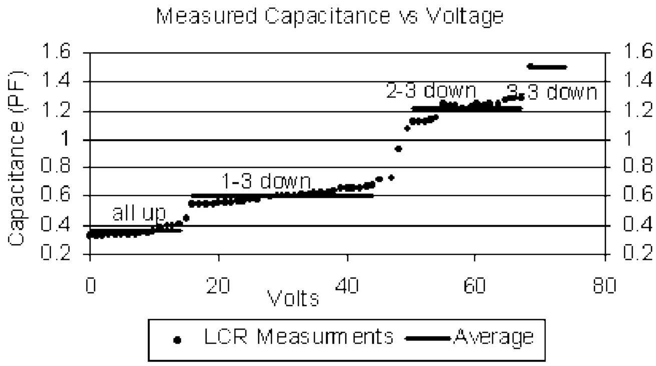

Fig. 4. Capacitance measurements of a 3 × 3 array resulted in a tuning range of 4.7 : 1 achieved between 0.32–1.5 pF.

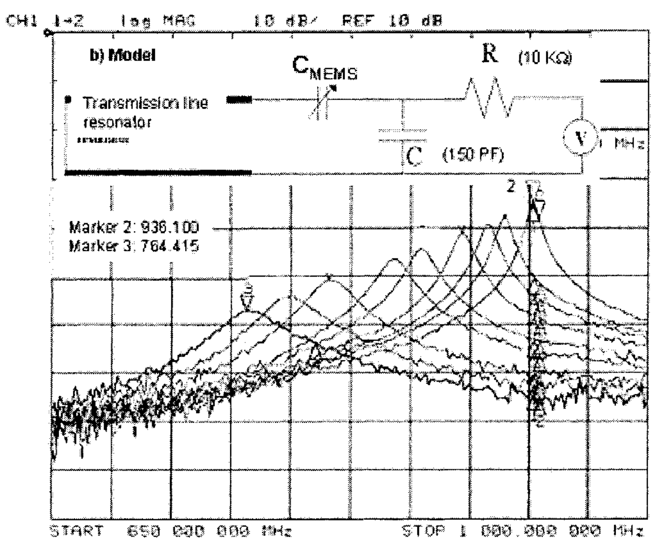

Fig. 5. Illustration of 171-MHz tuning range under applied voltage and equivalent circuit model. Markers 2 and 3 indicate the resonance peaks with 0 and 74 V applied, respectively.

this figure clearly demonstrates the digital increments of the capacitance. Such digital performance can tolerate large manufacturing variations such as the thickness or width variation of the plates. Further improvements are to optimize the spring stiffness of each plate for pull-in voltages well defined by the precision. Fig. 5 presents the tuning of 171 MHz and Q factor above 240 using the variable capacitors. More details were reported in [5].

III. ENCAPSULATION PROCESS

As previously mentioned, another major packaging issue is encapsulation for nonhermetic packaging. Fig. 6 illustrates a novel concept for the encapsulation. A micro-cap is placed over the MEMS after flip-chip assembly to protect it. This micro-cap can be made of glass or other materials, but in this case, we used a pressed glass frit. LCP can then be deposited with a high-speed dispensing machine for encapsulation. This concept is similar to glob-top epoxy sealing for microelectronics; it is expected to reduce packaging costs substantially. Fig. 7 shows the encapsulation process steps for a MEMS variable capacitor. Fig. 7(a) is a capacitor flip-chip assembled onto an alumina substrate. This device was different from the one shown in Fig. 2 in that it was only a 2 × 2 array and had small bonding pads to reduce RF losses. In addition, flexure widths were changed to meet a new voltage requirement. Fig. 7(b) shows a glass micro-cap placed over the device. The alignment between the cap and transmission line was critical to RF performance. With our in-house flip-chip bonder, we were able to place the cap within 1–2 μm. The cap also had to be bonded to the substrate. Using a thin layer of low vapor epoxy, we fixed the cap in place. If epoxy outgassing turned out to be a problem, the glass could be bonded directly to gold or aluminum pads. Such SiO_2 to metal bonding is commonly used for wire bonding to polysilicon MEMS [14]. Finally, Fig. 7(c) shows the LCP encapsulation completely covering the glass micro-cap. The LCP was placed on the cap, followed by heating above its melting temperature of 260 °C. Two remaining issues need to be addressed for this new technology: First, the sealing and mechanical characteristics of the package must be determined. Second, the effects on the RF performance of the M-VCA must also be measured. While the adhesion between molten LCP, the gold pads and alumina substrate seems to be very strong (a full analysis of the sealing and mechanics of the package has been reserved for a future paper). The RF performance of the packaged M-VCA is described in Section IV, though we will focus on the outstanding RF performance for the variable capacitor flip-chip assembled and LCP encapsulated.

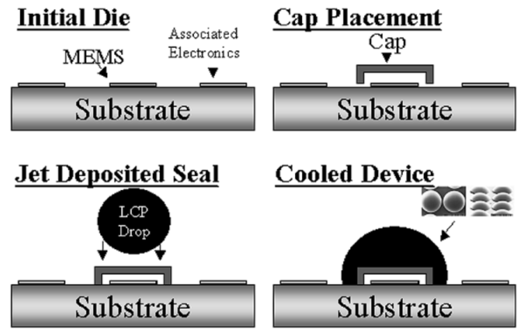

Fig. 6. Concept of the three major steps for applying LCP to flip-chip MEMS devices.

IV. RF CHARACTERIZATION

Two different experiments have been carried out for the RF characterization of LCP encapsulation. In the first experiment, Q factors of a fixed interdigital capacitor with and without LCP glob top encapsulation have been measured. As a second experiment, Q factors of a flip-chip-assembled and LCP-encapsulated M-VCA have been measured to quantify the overall packaging effects. All the measurements were conducted using an RF resonator. An HP 8510B network analyzer was connected to a resonator to measure the Q factor. We used an Aglient 85052D 3.5-mm calibration kit for the resonator calibration before the

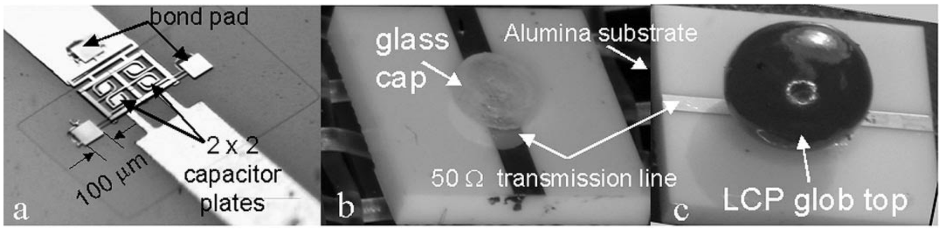

Fig. 7. 2 × 2 variable capacitor array sealed by the new LCP encapsulation processes. (a) Device transferred to an alumina substrate. (b) Glass micro-cap placed to protect the device. (c) LCP encapsulation.

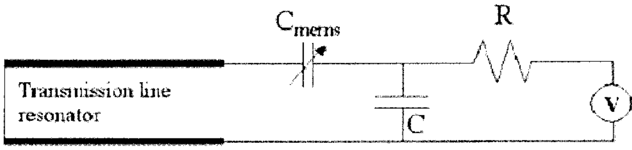

Fig. 8. MEMS device is wire bonded between the resonator and ground where a chip-capacitor(C $= 150$ pF) acts as a dc block, while a resistor $(R = 1\ k)$, together with a ribbon wire, acts as an RF choke [4].

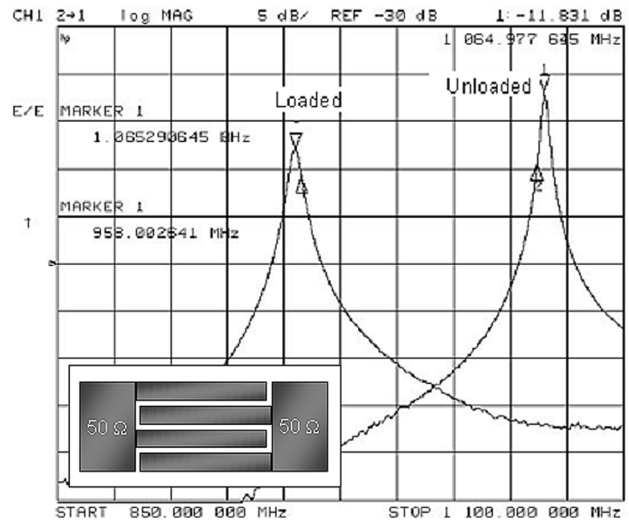

Fig. 9. Resonance frequencies of the unloaded and loaded (with the interdigital capacitor) resonator. y-axis represents reflection coefficient measurements with 5-dB increments.

measurement. Fig. 8 shows the circuit diagram for the resonator consisting of a coaxial line with an rectangular outer conductor and circular inner conductor. The Q factor of the resonator must be very high in order to estimate the high Q of the M-VCA. The resonance frequency of the resonator (without the MEMS capacitor) was designed to be 1.0 GHz. The 150-pF chip capacitor provides a ground path for the RF signal, and the 10-kW resistor prevents leakage of the RF signal into the bias circuit. The Q factor for this unloaded circuit was measured to be in the range of 310–375 at 1.05 GHz. The Q of the MEMS capacitor is calculated using the equation $Q_{\text{MEMS}} = (1/Q_{\text{Load}} - 1/Q_{\text{Unload}}) - 1$, where Q_{Load} and Q_{Unload} are the measured Q values of the resonator with and without the MEMS device, respectively. The Q factor is measured using the 3-dB point method. A resolution of 10–20 MHz is used for accurate Q-factor measurements.

A. Interdigital Capacitor

As shown in Fig. 9, a fixed inter-digital capacitor was patterned with a 50-Ω microstrip gold transmission line. The gold layer thickness was 2.4 μm on an alumina substrate. Its capacitance was 0.179 pF. The device was encapsulated by an LCP glob with a diameter of 1.5 mm. The encapsulated device was wire bonded to the rest of the resonator circuit.

Fig. 9 shows the resonance frequencies of the unloaded and loaded (with the interdigital capacitor) resonator. The decrease of the reflection from the unloaded to loaded cases was the result of impedance mismatch due to the capacitive loading. The measured Q-factor values for the unloaded and loaded (LCP glob and interdigital capacitor) resonator are 365 and 361, respectively. Since the measurements for such a high-Q system are very sensitive, the experiments were repeated three times with new wire bonds each experiment. In the second measurement, the Q factor for the unloaded resonator and the encapsulated interdigital capacitor by LCP was around 335. In the third measurement, both were 375. However, the new wire bonds resulted in different inductance values for the circuit. Thus, the measurements were repeatable, and the LCP encapsulation did not affect the RF losses.

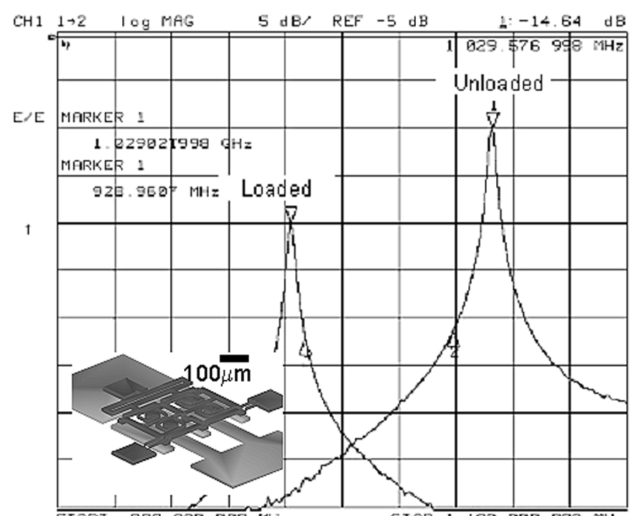

Fig. 10. Resonance frequencies of the unloaded and loaded (with MEMS with glass cap and LCP encapsulation material) resonator. y-axis represents reflection coefficient measurements with 5-dB increments.

B. MEMS Assembled and Encapsulated

Fig. 10 presents RF characterizations of the flip-chip assembled and LCP encapsulated MEMS variable capacitor. A scan-

TABLE II
RESONANCE FREQUENCY SHIFT CAUSED BY THE VARIABLE CAPACITOR

Center Frequency (MHz)	929	923	924	911	910	908
Bias Voltage (Volts)	0	30	40	45	60	70

ning electron microscopy (SEM) picture of this packaged device is shown in Fig. 7. The variable capacitor consist of a 2×2 capacitor plate, each moving plate is 50 μm^2, three 100-μm^2 bonding pads, and compliant flexure. The Q factor for the unloaded resonator was around 307 and, with the MEMS loaded, was around 277. As a result, the Q factor for the assembled and encapsulated MEMS device was above 2846! Of course, this value is not quantitative because it is higher than the Q factor of the unloaded resonator. Nevertheless, the results clearly indicate that the effects of LCP encapsulation on the RF losses are negligible. These results demonstrate that we have developed excellent MEMS devices, flip-chip assembly, and LCP encapsulation processes (with no effects on the RF performance at 1 GHz).

Table II summarizes the resonator frequency shift caused by application of the dc voltage to the variable capacitor. This tuning range is not large when compared with the results shown in Fig. 5. This capacitor was designed with a smaller array and, thus, provides a small capacitance ratio. The Q factor is a proportional capacitance value, which explains the higher Q factor for this design. MEMS variable capacitors can be designed and fabricated easily using the existing MEMS foundry processes. With the packaging technology developed, we are able to custom design a specific variable MEMS capacitor to meet different RF requirements.

V. CONCLUSION

An approach for low-cost and rapid encapsulation of RF-MEMS devices using LCP has been discussed. Furthermore, novel post designs for precise control of gap height and, hence, the capacitance values, have been presented. The Q-factor values for an unloaded and loaded (flip-chip assembled variable capacitor with LCP encapsulation) resonator were measured to be 307 and 277, respectively. Thus, the Q-factor value of the MEMS variable capacitor with LCP encapsulation is equal to or higher than the 307, which is the Q value of the unloaded resonator. Further studies are needed for RF characterization at higher frequencies.

REFERENCES

[1] G. Rebeiz, *RF MEMS: Theory, Design and Technology*, 1st ed: Wiley Interscience, 2003.
[2] [Online]. Available: http://www.memsrus.com
[3] J. J. Yao, "RF MEMS from a device perspective," *J. Micromech. Microeng.*, vol. 10, no. 4, pp. R9–R38, 2000.
[4] N. Hoivik, M. A. Michalicek, Y. C. Lee, K. C. Gupta, and V. M. Bright, "Digitally controllable variable high-Q MEMS capacitor for RF applications," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, Phoenix, AZ, May 20–25, 2001, pp. 2115–2118.
[5] F. F. Faheem, N. D. Hoivik, Y. C. Lee, and K. C. Gupta, "Post-enabled precision flip-chip assembly for variable MEMS capacitor," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, Philadelphia, PA, June 2003, pp. 1927–1930.
[6] A. Kolpekwar, R. D. Blanton, and D. Woodilla, "Failure modes for stiction in surface-micromachined MEMS," in *Proc. Int. Test Conf.*, Washington, DC, Oct. 18–23, 1998, pp. 551–556.
[7] S. J. Jacobs, S. A. Miller, J. J. Malone, W. C. McDonald, V. C. Lopes, and L. K. Magel, "Hermeticity and stiction in MEMS packaging," in *IEEE Proc. 40th Annu. Int. Reliability Physics Symp.*, Dallas, Texas, Apr. 2002, pp. 136–139.
[8] M. P. de Boer, J. A. Knapp, T. A. Michalske, U. Srinivasan, and R. Maboudian, "Adhesion hysteresis of silane coated microcantilevers," *Actamater*, vol. 48, no. 18–19, pp. 4531–4541, Dec. 2000.
[9] N. Hoivik, J. W. Elam, S. M. George, K. C. Gupta, V. M. Bright, and Y. C. Lee, "Atomic layer deposition (ALD) technology for reliable RF MEMS," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, Seattle, WA, June 2–7, 2002, pp. 1229–1232.
[10] K. Brownlee, P. M. Raj, S. K. Bhattacharya, K. Shinotani, C. P. Wong, and R. R. Tummala, "Evaluation of liquid crystal polymers for high performance SOP application," in *Proc. 52nd IEEE Electrical Compatibility and Technology Conf.*, 2002, pp. 676–680.
[11] G. Zou, H. Gronqvist, J. P. Starski, and J. Liu, "Characterization of liquid crystal polymer for high frequency system-in-a-package applications," *IEEE Trans. Adv. Packag.*, vol. 25, pp. 503–508, Nov. 2002.
[12] K. Jayaraj, T. E. Noll, and D. Singh, "RF characterization of a low cost multichip packaging technology for monolithic microwave and millimeter wave integrated circuits," in *Proc. URSI Int. Signals, Systems, and Electronics Symp.*, Oct. 25–27, 1995, pp. 443–446.
[13] A. Laws, F. F. Faheem, H. Zhang, and Y. C. Lee, "Tether system designed for flip-chip bonded system," presented at the *ASME Int. Mechanical Engineering Congr. and Expo.*, Washington, DC, Nov. 16–21, 2003.
[14] J. Smith, S. Montague, and J. Sniegowski, "Material and processing issues for the monolithic integration of microelectronics with surface-micromachined polysilicon sensors and actuators," in *SPIE Micromachining and Microfabrication*, vol. 2639, Oct. 1995, pp. 64–73.

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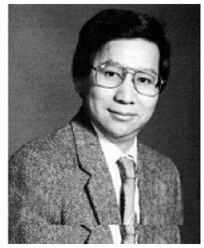

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