RF MEMS CAPACITOR INTEGRATION

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ABSTRACT

MEMS capacitor switches have been integrated with 50V-LDMOS/5V-CMOS 0.18 μ m generation ICs. The MEMS were formed with the final three Ti-cladded AlCu wiring levels in SiO₂ using a novel planar sacrificial silicon cavity process [1-3]. The MEMS cavities were hermetically sealed at less than atmospheric pressure at wafer level with a CVD dielectric lid. After Pb-free solder bumping, the MEMS chips are packaged in organic laminate packages. The capacitor portion of the MEMS beam has a capacitance density of $\sim 0.12\text{fF}/\mu\text{m}^2$ and the pull-in, restoring, self-actuation, and break down voltages are on the order of 30V, 10V, >45V, and >150V for 0.2pF devices, respectively. MEMS cycling lifetime of 500 million cycles has been demonstrated. This paper summarizes the critical integration, yield, and reliability issues associated with the L1 qualification of this HV CMOS [4], RF MEMS technology.

INTRODUCTION

This is the first report of the L1 manufacturing qualification and early production ramp of a monolithically integrated RF CMOS-MEMS capacitor technology. The technology is in manufacturing production to provide chips for antenna tuning in cell phones. The MEMS capacitors are integrated in large preprogrammed tunable arrays with CMOS controllers and on-chip 40V operation. Figure 1 shows an image of a 64 MEMS tunable capacitor chip. This paper summarizes the critical RF MEMS technology integration, yield, and reliability issues.

MEMS TECHNOLOGY OVERVIEW

MEMS Capacitor Design and Fabrication

The metal/oxide/metal MEMS beam is formed in a planar silicon cavity and the beam is released by removing the sacrificial silicon through holes in the oxide lid using XeF₂ gas. The cavity is hermetically sealed by depositing CVD oxide and nitride to form a dielectric lid. The $\sim 70\mu\text{m}$ by $400\mu\text{m}$ asymmetric bridge MEMS beams are formed with two beams per cavity with nominal capacitances of 0.1, 0.2 or 0.4 pF per beam. The MEMS capacitor electrodes are formed between the lower AlCu wire in the beam and the AlCu wire under the beam, both of which are coated with a thin MEMS capacitor dielectric to prevent aluminum-silicon reaction during fabrication and capacitor electrode shorting during actuation (Figures 2-3). 50nm tall oxide bumpers are formed inside patterned openings in the lower MEMS beam electrode (Figures 2-4) to prevent actuator-actuator contact, resulting in cycling lifetimes of >500 million cycles. The patterned openings in the lower beam electrode also act to reduce AlCu hillock density and height. The asymmetric actuators (Act) and RF capacitor (Cap) combined with the use of a longitudinal spring (Figure 5) act to minimize capacitance variability.

MEMS Capacitor Electrode Topography

We optimized the Ti-cladded AlCu metallurgy to reduce hillock density and height such that the average AFM-measured, random RMS roughness under the lower MEMS beam electrode and over the fixed electrode under the MEMS cavity are 2.3nm and 4.3nm, respectively (Figure 6). We sporadically observe metal

hillocks under the lower MEMS beam electrode, due to random process variability (Figures 7-8), and these hillocks can reduce capacitance density and act as cycling stiction nucleation points.

Figure 1: Optical image of $\sim 2.2 \times 2.8\text{mm}^2$ 64 MEMS capacitor Wispy tunable impedance matching chip post solder bumping.

Figure 2: Simplified cross-sectional drawing of 4 electrode MEMS capacitor beam showing actuator and capacitor electrodes.

Figure 3: SEM cross-section of released MEMS beam test structure showing cavity, beam, and $\sim 10\mu\text{m}$ thick lid.

Figure 4: AFM map of underside of MEMS actuator electrode showing 50nm deep oxide bumper array (70nm min-max height).

Figure 5: Optical profiler image of non-actuated (top) and actuated (bottom) MEMS capacitor beam including labels for the RF capacitor head (Cap) and actuators (Act).

Figure 6: Typical AFM images for $400\mu\text{m}^2$ areas (a) above the fixed electrode surface under the MEMS beam (63nm min-max) and (b) under the lower MEMS electrode (27nm min-max).

Figure 7: AFM roughness map of lower fixed MEMS capacitor electrode showing severe hillocks (64nm min-max height).

Figure 8: AFM line scan showing severe aluminum hillock profiles.

MEMS CAPACITOR ELECTRICAL TEST

The MEMS capacitor is operated by applying 40V between the moving actuator electrodes and the fixed actuator electrodes under the MEMS beam (Figures 2 and 5). The operating voltage of 40V is higher than the pull-in voltage. The MEMS beam consists of a metal/oxide/metal sandwich with oxide composing $\sim 2/3$ of the volume. The low CTE of oxide combined with both the longitudinal spring at the end of the large actuators in the MEMS beam and the volume matching of the high CTE upper and lower MEMS beam metal act to minimize process- and temperature-induced variability in beam shape. We measure $<2\%$ capacitance and $<2\text{V}$ pull-in voltage -25°C to 100°C variability.

MEMS capacitance is defined as the 0-40V delta capacitance difference (Figure 9). MEMS capacitor functional yields are determined by the delta capacitance and pull-in voltage (VPI). Figure 10 shows measured MEMS delta-capacitance and VPI data for $\sim 1/2$ year of early manufacturing production. The MEMS delta-capacitance has significantly increased in the past $1/2$ year, due to reduction of MEMS cavity residuals and metal hillocks on the MEMS capacitor electrodes. The primary functional yield loss mechanisms are delta-capacitance and VPI variability. VPI is proportional to (beam thickness)^{1.5} and (actuation gap)^{1.5} [5]. In addition, stress gradient changes in the MEMS beam induce positive or negative beam curvature which changes the actuation gap and resultant VPI. For example, a tensile beam stress gradient, i.e. having a more tensile film on the top of the beam, causes the beam center to bend downwards in a concave up fashion, resulting in reduced VPI due to a smaller actuation gap. Table 1 summarizes measured MEMS beam thickness and stress gradient variability and their effect on VPI variability for a MEMS capacitor centered with $\text{VPI}=30\text{V}$. We actively modulate the expected released MEMS beam shape to center it at target by changing the thickness of the nominally 80nm oxide thickness over the beam, which changes the MEMS beam stress gradient and resultant beam curvature. Figure 11 shows a 5V VPI shift per 10nm of oxide thickness over the beam, primarily because of increased beam curvature and resultant air gap change.

Figure 9: MEMS bipolar C-V data for seven individual 0.2pF wafer center, middle, and edge radius capacitors.

In addition to the obvious problem of no MEMS capacitor actuation when VPI is greater than the 40V operation voltage, a low VPI causes yield loss for self-actuation. Self-actuation occurs because the actuation force is proportional to (voltage)² and the RF voltage across an unactuated MEMS capacitor causes it to actuate. For the MEMS design and test data shown in this paper, self-actuation falls below specification (40V) when VPI is below ~26V.

Figure 10: 200fF MEMS capacitor delta capacitance and pull-in voltage data for ~70 production lots with 6-25 wafers/lot and 10 chips/wafer (lots/month shown in parenthesis).

Table 1: MEMS beam process effect on pull-in voltage variability.

Parameter	Measured Variability	Predicted VPI variability
Beam oxide stress gradient	28 +/- 6MPa/ μ m	+/- 2.7
Beam oxide thickness	2 +/- 0.1 μ m	+/- 2.3
Beam metal thickness	+/- 20nm	+/- 3.0
Under/over beam ox thick	80 +/- 5nm	+/- 2.5
Under/over beam ox stress	280+/-14MPa	+/- 1.0
Lower cavity height	1.9+/-0.2 μ m	+/- 4.4
Total VPI variability	+/-7V	+/- 6.9

Figure 11: VPI vs. oxide thickness over the MEMS beam.

MEMS Cavity Integrity

Upon exiting the fab, wafers are processed through standard Pb-free bump flip-chip assembly processes that include passivation, bumping, test, back-side grind, back-side coating, and dicing. The chips are then flip-chip mounted to an organic laminate carrier substrate with under fill and finally the substrate is mounted

to a printed circuit board. Figure 12 shows MEMS cavity cracks that occurred on ~6mm² packaged chips with 32 MEMS cavities per chip. We determined that these lid cracks became visible during back side grind and chip dicing and were exacerbated by the acute angle in the corner of the upper MEMS cavity (Figure 12). Lid cracks in packaged chips destroy the hermetic seal, which results in immediate stiction of the MEMS beam during electrical test. Lid cracking, which was modeled using finite element analysis, was eliminated by increasing the lid thickness from 6 μ m to 10 μ m, which reduced the modeled maximum principle stress by a factor of ~2.8 and also reduced the 130°C, 91% R.H. pressure cooker stress fail rate of packaged chips from ~20% to 0%.

Figure 12: (a) SEM cross-section and (b) optical top view micrograph showing depackaged MEMS chip cavity cracks originating in cavity corner with 6 μ m thick lid.

MEMS CAPACITOR RELIABILITY

Cycling

MEMS capacitor cycling is a challenging reliability stress. End user specifications are variable but typically are 0.1 to 1 billion cycles over the operating temperature. Historically, we observed two primary cycling fail modes: 0V stiction-induced capacitance increase and 40V defect- or wear-in-induced capacitance change [1]. Figure 13 shows representative cycling data for a single MEMS capacitor driver which connects 7 MEMS capacitors in parallel on a chip with 64 MEMS capacitors. Most drivers do not fail during our cycling tests (Chip 1) and, when they do, they fail for actuator stiction on one or more of the seven MEMS capacitors (Chip 2), which increases the 0V capacitance. 2 of the 7 MEMS capacitors in Chip 2 exhibited actuator stiction fails, the first at 290 and a second at 350 million cycles. We sometimes observe a simultaneous 0V and 40V increase in capacitance (Chip 3), which may mean that an actuator stiction fail caused the actuated beam shape to change, resulting in a 40V capacitance change. Cycling fails are rarely accompanied by dielectric breakdown, which means that the MEMS capacitor drivers continue to operate after the initial cycling fail. By cycling large numbers of chips and drivers, we calculated a fail rate of 1000ppm at 500 million cycles.

Figure 13: Cycling data for a 7 MEMS capacitor driver showing 0V (open symbol) and 40V (closed symbol) capacitance.

Failure analysis of cycling fails (Figure 14) consistently shows actuator stiction in areas between the oxide bumpers. We believe that this stiction is due to the random presence of metal hillocks under the MEMS beam, which leads to electric field enhancement and accelerated stiction fails. These metal hillocks provide a high electric field actuator stiction point during cycling and the likelihood of their causing a stiction fail increases over time as the oxide bumpers are eroded. Figure 15 shows a severe case of hillocks under the MEMS beam.

Figure 14: Typical MEMS cycling stiction fail showing (a) top side of fixed electrode and (b) underside of movable electrode.

MEMS Capacitor breakdown voltage

The MEMS capacitor dielectric needs to be reliable up to 40V DC actuation voltage and 80V peak-to-peak RF voltage. Figure 16 shows measured actuated MEMS capacitor voltage breakdown (VBD) for the MEMS bridge beam used in the tunable capacitor chip (Figure 5). VBD is centered at about 150V with little wafer-to-wafer and lot-to-lot variability and exceeds the 80V specification. We measure both capacitor to capacitor and ganged actuator-capacitor to actuator-capacitor electrode VBD and observe slightly lower values for the ganged actuator-capacitor measurement, as expected from the larger area.

Figure 15: SEM top view image showing severe metal hillocks under the MEMS beam electrode on the actuator (A) and capacitor (C) electrodes.

Figure 16: MEMS capacitor breakdown voltage.

SUMMARY

We have successfully L1 production qualified RF-MEMS capacitor switches into a 0.18 μ m high voltage CMOS process flow and begun the early manufacturing ramp. The MEMS capacitors were formed using a sacrificial silicon cavity process are hermetically sealed at wafer level, and flip chip packaged in organic laminate packages. No fails occurred during 130°C, 91% R.H. pressure cooker stressing of packaged chips. MEMS cycling lifetime of 500 million cycles has been demonstrated. The primary functional yield limiters are due to pull-in voltage and MEMS capacitance variability. This RF-MEMS technology has demonstrated preliminary yield and reliability sufficient for the initial application of cell phone antenna tuning.

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