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Materials and Processes for MEMS

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Commercial MEMS Case Studies: The Impact of Materials, Processes and Designs

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ABSTRACT

Minimizing risk is an important factor in new product planning because high volume breakthrough products require tens of millions of dollars to develop and bring to market. Sometimes risk can be minimized by following the IC model: build new devices on an existing process – just change the mask set. This approach obviously has limits. Adoption of new materials and processes greatly expands the horizon for "disruptive" products. This paper uses a case study approach to examine how changes in masks, materials and unit processes were used, and will continue to be used, to produce MEMS products for high volume applications.

INTRODUCTION

New devices typically start with an idea followed by a lab scale investigation. The next step – development focused towards a commercial product – is considerably larger. What lessons can we learn from a review of past successes and failures in commercial MEMS products? How can we build on those lessons for future products?

The MEMS industry is almost as old as the IC industry. MEMS pressure sensors have been commercially available since the early '70s. Through the '70s and '80s, MEMS was described as being on the verge of explosive growth. For example, it was the cover story [1] of the April 1983 issue of Scientific American. Yes, that growth is occurring. However, it has taken much longer than expected. This paper starts by examining three promising MEMS product opportunities that did not succeed. It then moves onto a series of successful examples, and how they were affected by material properties, product architecture and market forces.

DISCUSSION

Technical excellence is not sufficient

The 1983 Scientific American article described a variety of MEMS devices that had been demonstrated at an R&D level such as accelerometers, inkjet print nozzles and pressure sensors that had active circuitry integrated on the chip. However, the focus was a Stanford University gas chromatograph which had injection and carrier gas ports, a capillary column, valves, detector, exhaust port and connecting capillaries all integrated on a 2-inch silicon wafer. By minimizing system volume, this lab-on-a-chip optimized one important chromatograph design goal. Unfortunately, other performance metrics such as column separation efficiency did not match conventional chromatographs. Standard chromatographs with discrete components performed better and cost less. The wafer-level chromatograph was an impressive technology, but the resulting product could not compete in a marketplace.

There is a Lesson here: MEMS integration is difficult. The example involved integration of mechanical and chemical components, but electronic integration poses similar challenges. This does not mean that integration is impossible. Indeed, Texas Instruments' DMD image projection products with two million independently-controlled MEMS mirrors requires on-chip electronic integration. What it does mean is that level of integration is a key design factor in MEMS products. This issue is discussed later in this report.

Optical cross-connects were a highly visible MEMS product class that failed when the internet bubble collapsed in 2001. Most long distance voice and data communications is carried by optical fibers. These messages are switched electrically, so signal routing requires that they pass through optical-electrical and electrical-optical converters. Telecommunication system traffic projections in the late 1990s showed that the converters would soon become a serious bottleneck. The proposed solution was to deploy an all-optical network based on arrays of addressable MEMS mirrors (Figure 1). New optical cross-connects would send signals from each fiber in a bundle directly to the appropriate fiber of another bundle, thus avoiding optical-electronic conversion. When the market collapsed in 2001, major corporations like AT&T, WorldCom, Lucent, JDS and Nortel lost 2.5 trillion dollars in valuation and shed over 500,000 jobs. The first MEMS cross-connects were just coming onto the market – a market that had disappeared. It has recovered slowly in the last seven years but the "competition" (electrical-optical converters) has also improved.

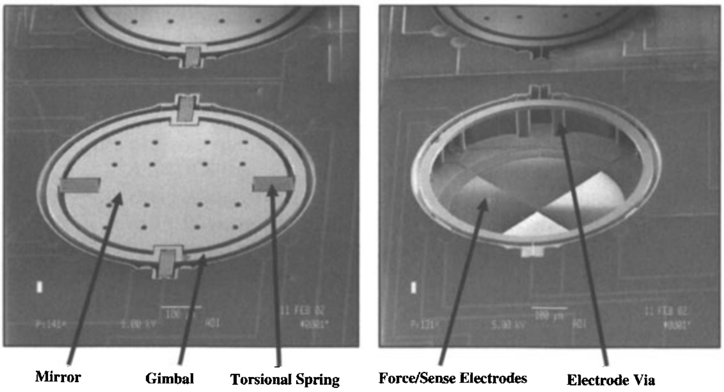

Figure 1: MEMS mirrors in an optical cross-connect. (Courtesy of Analog Devices, Inc.)

High performance RF MEMS switches were a less visible casualty of the 2001 economic turbulence. In the late 1990s, a Northeastern University consortium developed an electrostatically-actuated MEMS switch that extended early Foxboro Company R&D. These devices exhibited remarkable switch life. Analog Devices planned to produce them for automated test equipment (ATE) applications. Those plans were cancelled when collapse of the internet bubble devastated sales of semiconductor test equipment. Sample quantities had been incorporated in developmental defense systems so a license to Radant MEMS allowed them to supply the switches for limited defense applications [2]. Like optical cross-connects, there is renewed interest in MEMS switches. The challenge is to identify stable, high volume markets that place a value on switch capabilities that is consistent with manufacturing costs. ATE, handset, automotive and telecom applications have been proposed. This is not surprising, because MEMS switches offer unique capabilities with respect to architecture of small electronic systems. For example, different fab technologies can be integrated to re-partition products (example: high voltage bipolar with low voltage CMOS).

The optical cross-connect and MEMS switch experience offers a Lesson: There must be a Customer willing to buy the product at an acceptable price in sufficient quantity. Technology alone is insufficient.

AT&T Bell Laboratories developed integrated MEMS microphones in the 1980s [3-5]. However, they couldn't compete with electret microphones. Electret microphones are not particularly good; acoustic performance is mediocre and solder temperatures destroy them. However, they had one outstanding advantage over MEMS microphones: lower price. Knowles Acoustics broke the price barrier and made their first shipment of MEMS microphones in 2003. By the end of 2006, they had shipped 300 million foundry-manufactured microphones [6]. It took over 20 years but MEMS microphones are now a reality. We are now seeing competition from other MEMS suppliers, driven by acoustic performance as well as price.

The Lesson: In high volume products, price is paramount.

Even subtle material properties are critical in MEMS

In the mid-80s, The Foxboro Company introduced pressure and differential pressure transmitters based on piezoresistive pressure sensors. These instruments were used from -40 to +125°C in process control loops (refineries, paper mills, power plants, etc). The differential transmitter typically had a full scale of 20 kPa, but that measurement might be superimposed on a hydrostatic pressure of 20,000 kPa (3000 psi). Silicon pressure sensors are extremely sensitive to package stresses so they were anodically bonded to borosilicate glass (Figure 2). The glass provided a mechanically predictable, low stress mount to isolate the sensor from the metal transmitter housing. Unfortunately, performance tests showed that the measured differential pressure shifted as a function of hydrostatic pressure. The cause of the shift was traced to the glass. It was thermally matched to silicon. However, the bulk modulus of silicon and glass is different. As hydrostatic pressure increased, the difference in volumetric compression applied a torque to the silicon frame, causing it to rotate slightly. This rotation affected the output of piezoresistors implanted in the sensing diaphragm.

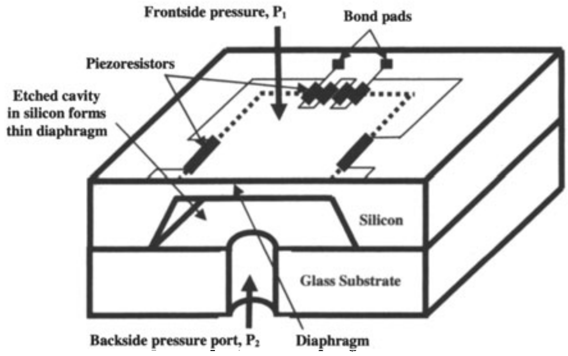

Figure 2: Piezoresistive pressure sensor anodically bonded to borosilicate glass.

To eliminate hydrostatic pressure sensitivity, the glass hard-mount was replaced by silicone rubber. Chemical interaction between this elastomeric mount and the hydraulic oil (a dimethyl silicone) was avoided by making the mounts from a fluorosilicone elastomer.

The Lesson: It is seldom possible to anticipate every effect of material properties on MEMS performance, yield and reliability. Thin film effects are particularly common.

The "Killer" Application

The MEMS literature has many references to "Killer" applications – high volume markets that place high value on a MEMS product. Reality is not that simple. As shown in Table 1, even companies that identify such applications typically wait about 15 years before achieving profitability.

Table 1
Historic MEMS Gestation Times
R&D to Break-Even

Company	Product	Time (years)
Texas Instruments	DLP	18 (27)
Analog Devices	Air Bag Sensor	13
Knowles	Microphone	14

In the late '80s, Analog Devices (ADI) recognized that automotive air bag sensors had the potential to be a killer application. The non-MEMS air bag sensors in use at the time were relatively unreliable so each installation had several sensors. The result was a high cost system that limited air bag use to high-end cars. In principle, a highly reliable MEMS crash sensor could be developed that would allow system cost to be reduced to the point where it would become standard in every car.

Auto manufacturers were understandably nervous – if an air bag sensor fires at the wrong time, it ***causes*** an accident! To address that concern, the ADXL50 incorporated a self-test feature that simulated an acceleration event by applying an electrostatic potential. Proper sensor response showed that both the MEMS and the supporting electronics were functioning properly.

The fears went beyond self-test. Would polysilicon fail due to fatigue caused by automobile vibration after a few years? In the early '90s, there was insufficient fatigue life data on polysilicon. On-chip integration allowed ADI to use closed loop electronics that generated an electrostatic force to oppose motion caused by an acceleration force. With this design, there was no motion, thus eliminating the issue of fatigue.

There's a Lesson here: Listen to your Customer and respond to his or her concerns.

This example illustrates how Material Properties can drive MEMS product design. Polysilicon actually has excellent fatigue properties. ADI switched to open loop designs after the fatigue data was generated.

Even with these conservative design features, the ADXL50 failed the initial qualification tests. Something was causing the output to very slowly drift. The effect could only be observed in high temperature accelerated tests. The cause was linked to the unpassivated MEMS surface. However, the solution was not obvious because standard IC passivation cannot be applied to suspended microstructures.

The solution took advantage of the fact that the MEMS die was mounted in the package with a thermoplastic polyimide-siloxane block copolymer. A short furnace bake (Figure 3) was inserted into the assembly flow in order to use the die attach as a source of organic vapors. The high temperature vapors generated in this process reacted with the polysilicon MEMS surface to create a monolayer passivation. The now-passivated ADXL50 readily passed qualification tests. As a historical point, the ADXL50 was the first integrated surface micromachined product of any type to be produced in high volume.

What's the Lesson here? MEMS products are extremely surface sensitive. This example described an electrical effect. As discussed below, mechanical stiction is more common.

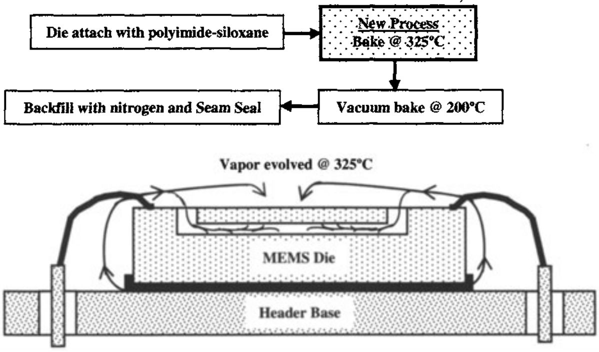

Figure 3: Organic vapors from die attach passivate MEMS.

Reusable engineering

Things are easier after the first product. ADI built design and manufacturing capabilities to produce air bag sensors. They then used these capabilities to build MEMS gyros and low-g multi-axis accelerometers. In essence, they followed the IC industry model: simply change the mask set to build new products in an existing fab.

It was not that simple. Beyond the difference in sensitivity, there were substantial packaging issues [7]. This is not a surprise because MEMS products often face packaging challenges. By building multi-axis sensors in an existing capability, it was financially possible for ADI to wait until the market learned how to use these products. This is a critical point because MEMS devices are not stand-alone products. Rather, they are ***disruptive technology components*** that enable ***higher-level products*** to do things that previously couldn't be done. If those higher level products don't yet exist, it takes several years to develop them. That was the case with these multi-axis sensors.

Sales grew slowly in first 5~6 years, before taking off like a rocket (Figure 4). The range of applications for multi-axis sensors is truly astonishing because virtually every new hand-held device has one. Yole estimates that the multi-axis sensor market is growing at 30% per year [8], so there are now about a dozen suppliers fighting for market share.

The Lesson: Competition follows the money. Once a large market is established, other suppliers will enter and compete for market share.

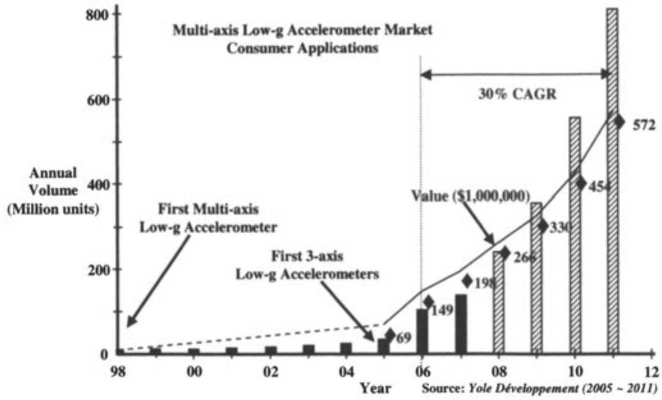

Figure 4: Breakthrough MEMS devices grow slowly until products they enable are developed.

Product Architecture and Level of Integration

ADI established the air bag sensor market with products that integrate support electronics and MEMS on one chip. The ADXL50 was assembled in metal headers but subsequent products were in ceramic cavity packages. Several years later, Bosch and Motorola (now Freescale) introduced competitive products. Their product architecture and packaging was quite different. Both suppliers produced the MEMS sensor and the support electronics on different wafers. MEMS die were capped with silicon, sealed with screen printed glass frit, assembled with a circuit die and molded in plastic. The Motorola designs sensed acceleration in the vertical axis while ADI and Bosch offered in-plane sensing products. Why these differences?

ADI utilized its strengths in fab process development and leading-edge signal processing when it integrated support electronics and MEMS on one chip. The output from MEMS inertial sensors is affected by mechanical stress. By using cavity packages, they avoided these stresses. Bosch and Motorola also capitalized on their respective strengths. Bosch had the world's largest hybrid manufacturing plant, so they were well-equipped to develop products sealed with screen printed glass frit. Motorola was in production of glass-mounted pressure sensors that were packaged in plastic. Thus, all three companies built on the expertise they already had in order to minimize risk, cost and time-to-market.

The Lesson: Do what you do best.

The Price-Cost Spiral

As noted above, many companies now offer multi-axis motion sensors for games, cell phones and a wide range of consumer devices. Most of them make MEMS wafers in one plant, purchase CMOS wafers from a foundry and mold them in one package. This product architecture raises some interesting possibilities. Competitive pricing is absolutely critical in high volume products, so fab costs must be low. Many MEMS suppliers are shifting from 150 mm to 200 mm wafers in order to reduce unit cost. However, there is another path: feature size. A quick analysis shows that the glass seal controls the die size of multi-axis motion sensors.

Figure 5 schematically shows a MEMS element hermetically sealed with glass under a silicon cap. Depending on the supplier, seal width can vary from 150 microns to over 300 microns. Reducing seal width to 30 microns or less doubles the number of die per wafer. This reduction in unit die cost can be a huge competitive advantage. Thirty microns is too narrow for glass frit and the seal must be hermetic. This suggests that metal seals might be the best answer.

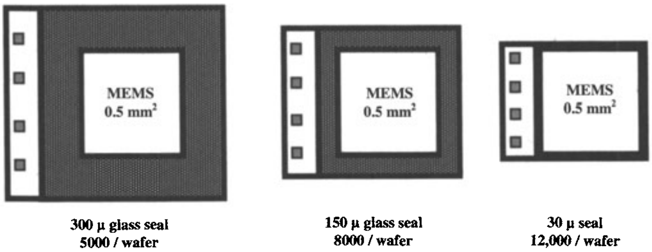

Figure 5: Die shrink from reduction in width of cap seal. Die count assumes 150 mm wafer.

But what metal? Gold is one possibility. Many groups are pursuing 3-D wafer-wafer interconnects based on copper so that is also a possibility.

Screen printed solder paste can't produce seal rings that are only a few 10's of microns wide so eutectic and thermocompression wafer bonding based on plating or sputter deposition are the obvious options. These bond processes require that metal be deposited on both wafers. This is a critical issue because it means that a patterned metal process has to be integrated with the MEMS process.

Gold and copper are deep trap contaminants so they are rigorously excluded from Front End wafer fabs. Back End wafer bonding with copper is feasible for standard IC wafers. However, MEMS release is a Front End process, so it would have to be integrated with deposition and etching of copper seal rings. This is not impossible, but it does require an unusual facility commitment.

Aluminum is not an obvious alternative because the oxide forms instantly. However, aluminum deposition and patterning are standard in IC fabs, so aluminum thermocompression bonding eliminates the process integration barrier. Aluminum wafer-bonded seal rings as narrow as 3 microns are hermetic [9,10].

Thermocompression bonding eliminates high energy interfaces by using high force to bring surfaces into intimate contact. Success requires high-quality alignment, temperature and uniformly-distributed high force. Aluminum is a reactive metal, so once the surface films are dispersed, the underlying metals fuse together with no trace of the interface (Figure 6). Aluminum thermocompression bonds illustrate some interesting Materials Science. For example, stress-induced crystallites nucleate and grow along the edges of the bond interface.

What's the Lesson? Cost reduction efforts will cause glass-sealed MEMS die to be replaced by smaller metal-sealed die. The example used aluminum thermocompression bonding. However, as high die counts are implemented in 200 mm wafers, the high, uniform forces required by thermocompression bonding will challenge the capabilities of commercial wafer bonders. This practical fact gives eutectic bonding a long term advantage.

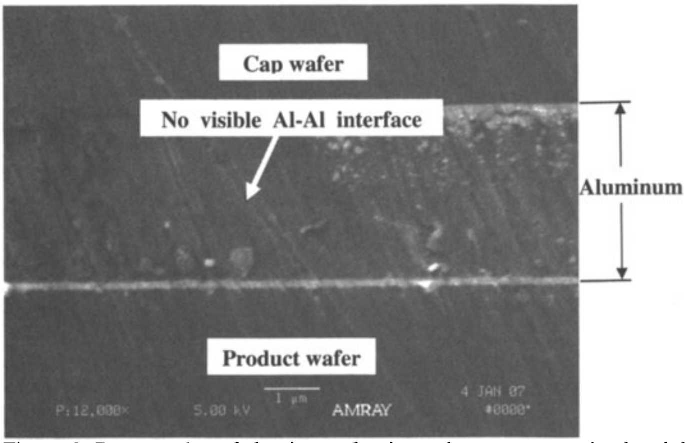

Figure 6: Cross-section of aluminum-aluminum thermocompression bond that had been PAN etched in an attempt to highlight the interface. (Courtesy of Analog Devices, Inc.)

The Tyranny of MEMS Surfaces

The high surface/volume ratio of MEMS devices causes both performance and reliability to be dominated by surface characteristics. A previous example described how an organic passivation suppressed high temperature electrical drift in the ADXL50. However, mechanical stiction is a more widely recognized surface effect. There is no one solution to stiction. Each company has its own design rules that specify pull-off force, surface roughness and a variety of other factors. Package technology also has a major effect.

Some suppliers use anti-stiction treatments. Most of these treatments cover high energy inorganic surfaces with a low energy organic film. ADI encountered stiction when it moved from the ADXL50 metal headers to ceramic cavity packages [11]. The solution was an organic treatment applied during the package seal process. A batch wafer process [12,13] replaced the package-level processes. It forms a one-nanometer thick, organic-rich surface (thicker dielectric films may support surface charges). Repeatability and uniformity are outstanding because the treatment is self-limiting and standard IC equipment is used. ADI's MEMS surface treatments were the first nanoscale processes used in high volume production.

The Lesson: Never rely on development of new equipment. The IC industry has invested countless billions of dollars to develop robust and reliable equipment. Use it. ADI's antistiction processes would have been more difficult to introduce, and more difficult to maintain, if they had required custom equipment.

CONCLUSIONS

The MEMS industry is a major supplier of disruptive technology components that enable higher-level products to deliver new functions at affordable prices. Success requires innovation, manufacturing expertise, market awareness and financial patience. With credibility now established, MEMS product growth will accelerate as new opportunities are recognized.