APPLICATION-SPECIFIC PACKAGING FOR CUSTOM MICROMECHANICAL STRUCTURES

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Introduction

The majority of the pioneering work in the development of silicon sensors and microstructures has taken place in universities and research laboratories, where device response is of prime importance. With the growth of the sensor field, more attention has been paid to packaging considerations because of the realization that the package is a key part of the interface between the sensor and the world. Although micromechanical elements share common fabrication technologies with integrated circuit devices, commercial sensors can rarely be housed in standard IC packages.

Most commercial devices developed to date have begun with the design of the sensor or transducer chip itself, and a package for the chip was then selected to accommodate the broadest range of applications. Users of sensors in these "generic" packages could easily and reliably design them into specific products and systems.

As the diversity of micromechanical structures has increased, the emergence of a systems approach to sensor and instrument design has fostered more interest in application-specific devices. In addition, the limitations of generic packages are providing the impetus towards the simultaneous design of the micromechanical device and the system in which it is to be used. The design of the chip is beginning to be tailored to its package and to its intended application. In such cases, the boundaries between the device, its package, and the system become less clear.

Generic vs. Application-Specific Design

The design of both a silicon microstructure and its package has widely different sets of performance, use, and cost objectives depending on whether the device is intended for generic use in a wide variety of markets or it is intended for a specific application. In the generic case, the package is designed for multiple uses and is planned to appeal to the widest possible market.

The generic device must typically have a package with a form factor that is compatible with standard fittings used in the instrumentation and machine manufacturing industries. It has to be convenient to handle and easy for the customer to design into a system. The cost typically has to be kept low in order to make the use of the device attractive in many markets and applications. Considerable economy is achieved if the same micromechanical chip can be incorporated in many different packages. The specification of the device and package is often a compromise between the performance needs of many markets.

Much of the advantage in using silicon micromachining techniques is lost due to packaging that does not fully exploit the increased performance and decreased cost and size of the silicon devices. Only by addressing the packaging issues as a part of system design can the optimum performance be obtained.

With an application-specific device, the cost-performance tradeoffs can be evaluated with the exact knowledge of their impact on the use of the device and on the system in which it is incorporated. When the system and component package are designed together, the interface between them can be optimized for performance, convenience, reliability, and cost.

When designing from the systems point of view, the incorporation of a silicon sensor or micromechanical structure can follow one of three paths:

- 1) The device can be incorporated in a generic package with a standard interface,
- 2) A custom package can be designed for a standard or a custom chip or,
- 3) The packaging issues can be incorporated into the design of the device itself.

It is the third approach which takes full advantage of the mechanical and electrical properties of silicon and can lead to the complete elimination of the package.

The Device as its own Package

The trend in high performance sensor systems is to address packaging issues and sensor design simultaneously, and, in many cases, to incorporate aspects of packaging in the sensor structure itself. The incorporation of packaging features into sensor design is driven by four major factors.

- 1) Individual sensor performance can be improved when limitations caused by conventional packaging, such as size, internal volume, thermal mass, or inertia, are removed.
- 2) The requirements of a planned system force unique approaches to sensor design and packaging, as is the case in indwelling medical systems.
- 3) Wafer level packaging reduces piecewise assembly and test time, thus reducing costs.
- 4) The desire to integrate sensors with electronics or other mechanical components requires the use of an application specific package, as in chemfets, capacitive accelerometers, or multiplexed tactile elements.

In some instances, improved sensor action or coupling to the environment can be achieved when the device is unencumbered by a package. A classic example of this is a strain gauge that was developed at Stanford University in the 1970's [1]. The device, as sketched in Fig. 1, was designed for a biomedical application in which the minute contractions of a rabbit's oviduct were to be monitored. The 1-mm diameter of the oviduct and the minuscule forces involved prohibited the use of a conventional package and standard silicon strain gauge. The silicon device was designed to include etched silicon suture loops with which the surgeon could attach the device to the oviduct, and a thin beam with a diffused piezoresistor to measure bending. With thin platinum wires attached to the gold bonding pads, the complete unit was covered with a 1-micron thick layer of Parylene for electrical insulation and biocompatibility. The mechanical, electrical, and chemical issues involved in the design of the sensor and the package were considered simultaneously, insuring adequate performance for the specific application.

Fig. 1 - Etched Silicon Force Transducer

A more recent example of such a self-packaged device is the multielectrode micro-probe for biopotential recording, developed by a group under Ken Wise at the University of Michigan [2]. This device consists of a narrow probe shank with twelve electrodes and a larger silicon area with multiplexing and buffering circuitry. Again, the interference of external packaging cannot be tolerated, and the self-packaged device adequately addresses the multitude of packaging requirements.

In systems where several of the micromachined components are used together, the cost of piecewise assembly and testing can be reduced by integrating the sensors together. This approach is exemplified by a mass flow sensor designed and fabricated by Transensory Devices for Innovus Corporation. For redundancy, this silicon device contains four flow channels, each with flow sensors. The sensors are tested together and mounted as a unit into the final system, a mass flow controller. The silicon device, shown schematically in Fig. 2, consists of two micromachined pieces of silicon bonded together to form the gas flow channels. The mating groove in the cap provides controlled, symmetrical flow past the sensor bridge, and the cap seal provides isolation between the redundant flow channels. The device is its own

Fig. 2 - Schematic Layout of Innovus Mass Flow Sensor

package. The sensing elements are fabricated on one of the wafers and are, in a sense, packaged by the silicon cap. The completed device can be routinely handled with little or no concern for damaging the delicate sensor elements.

The increased performance of this sensor is due to the combination of efficient thermal design, tight processing control, and advanced packaging techniques. By virtue of this increased performance, a more advanced mass flow controller can be realized.

Elimination of the separate package for a device can also be forced by unique requirements posed by system integration. As separate components are integrated together on a single silicon structure, their individual packaging and interface requirements have to be jointly satisfied. The "external" part of the system may dictate more of the device design than the miniaturized, micromachined silicon structures. As the size of the device is increased, the need for a package for the silicon device also decreases.

An example of a highly integrated mechanical system is the miniature gas chromatograph which was commercialized by Microsensor Technology [3]. This device incorporates a gas chromatography system comprised of miniature valves, a thermal conductivity detector, flow restrictors, and interconnecting gas channels on a three-inch diameter silicon wafer, as shown in Fig. 3. The motivation behind integrating the system lay in both the more efficient chromatography which could be achieved with closely-coupled, low-volume components and the small size of the resulting system. The overall size of the device was not dictated by the silicon structures but was determined by the external components such as solenoids, gas connections, and pressure sensors. These components are bolted to the glass and silicon device. As is evident in the photograph of the device in Fig. 4, the bolt holes themselves take up a significant amount of the available silicon area. The system was optimized with the components literally built around the silicon device. No package was necessary or desirable.

Although the instrument itself is a chemical sensor, the major packaging considerations are mechanical, in insuring that gas paths are leak-free and dead

Fig. 3 - Layout of Miniature Gas Chromatograph on a 3-inch Diameter Silicon Wafer

Fig. 4 - Photograph of Completed Silicon/Glass Gas Chromatograph

volumes are minimized. The packaging is truly application specific, in the sense that the GC wafer cannot be used in anything other than its intended application. In addition, the system design is tightly coupled to the sensor design, so that any changes in one typically require changes in the other. This tight coupling allows the maximum performance to be achieved from the sensor and from the system.

Consequences of Application Specific Packaging

Although the use of these advanced packaging techniques results in increased system performance, more care must be taken during the system design phase. Typically the device itself is called upon to provide more environmental protection than in a traditional packaging approach. The combination of deposited passivation layers, glass-to-silicon bonding, and silicon-to-silicon sealing offers a variety of ways to address these protection issues. These additional sealing steps, along with providing appropriate interfaces to the physical and electrical worlds, typically increase process complexity over a generic packaging design. Because these additional process

steps are performed at the wafer level, however, the added cost per chip/system can usually be less than that of the more complicated individual packaging at final assembly. In some cases, this also means that an application-specific silicon device increases in size over a generic counterpart, due to the silicon area dedicated to packaging. This possible area loss influences die cost, and this tradeoff must be addressed during system design to achieve the lowest total-system-cost-to-performance ratio.

Conclusion

Modern design practices support the method of top-down system design. If a system includes a sensor element, the performance and cost targets for the sensor must be set during system design. When these targets preclude the use of a generic device, then an application specific device and package become necessary. The sensor design can then be studied and the degree of application-specific packaging can be varied to best satisfy the system specifications. Recent examples show that inclusion of packaging aspects into the sensor itself result in higher performance systems than would be possible using generic packages. In the extreme case, the sensor becomes its own package. In all cases, the evaluation of the system cost/performance tradeoffs must include the total cost of the integrated packaging versus the discrete package.

References

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