STANDARD MANUFACTURING PROCESSES FOR ADVANCED SILICON SENSOR FAMILIES

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INTRODUCTION

Just as in other developing technologies most of the principles involved in the fabrication of silicon micromechanical structures have been known for many years. Fundamental processing techniques unique to these structures include,

- anisotropic etching on (100) and (110) substrates (using KOH, EDP, and other etchants)
- isotropic etching (using various HF/HNO3 acid mixtures)
- thin films for masking silicon etchants (primarily SiO_2, Si_3N_4, and Cr/Au)
- design of mask geometries to tailor the under-etched patterns in micromechanical structures
- doped layers in the silicon to stop and control etching (i.e. the p+ etch-stop for EDP and KOH, the preferential attack of heavily-doped silicon in some isotropic etchants, and the electrochemical behaviors of both these systems)
- epitaxial layers to control critical mechanical thicknesses
- dielectric isolation techniques for special high temperature applications
- anodic bonding of Pyrex to silicon for structurally supporting and hermetically sealing micromechanical structures
- glass frit and eutectic sealing (alternate methods for the same purposes)
- thermo-migration of aluminum in silicon to provide electrical feedthrus from one side of a wafer to the other and to fuse two wafers together
- etching of Pyrex glass to form complementary patterns in anodically-bonded structures

Although all of these techniques have already been incorporated in commercially available products, the full exploitation of micromechanical fabrication technology is far from being realized. Substantial evidence of this is apparent in the rapidly expanding number of papers in the field as well as in the overwhelming response to the announcement of this meeting.

THE ROLE OF INTEGRATED CIRCUITS

While micromechanical devices do require many unique thin film techniques such as those listed above, nevertheless, it is the principles of integrated circuit processing technology which have always been at the core of silicon micromechanics. From thermal oxidation, diffused resistors, epitaxial layers, aluminum metallization, and even packaging methods to the fundamental concepts of photolithography, silicon-based mechanical sensor technology and silicon IC technology were originally established from the same background during the same time frame. Since the early 1960's, however, the IC industry has advanced through at least 5 product generations while silicon micromechanics is barely into its second generation.

Certainly the primary reasons for such a relatively slow development are economic as shown in Figure1. The current DEMAND for large numbers of inexpensive, digital, smart-sensors could not have been initiated without the current PROLIFERATION of large numbers of inexpensive microprocessor chips.

Key to the continuing development of advanced silicon smart-sensors is the persistent exploitation of silicon IC technologies and methodologies... not only on the basis of higher integration levels, new thin film processes, and smaller line-widths but, just as importantly, on the basis of generalized, but versatile technology FAMILIES. In the same way that a single bipolar (or CMOS or NMOS) circuit process can support a large family of CIRCUIT products, it is possible to support a large family of smart-SENSOR products with a series of well-developed, standard micromechanical processes. Using these principles, new products are designed by applying well-understood design rules for a series of well-characterized process steps. As illustrated in Figure 2, a new mask set is generated, but the new product can be manufactured on an existing product line, along with other products in its family.

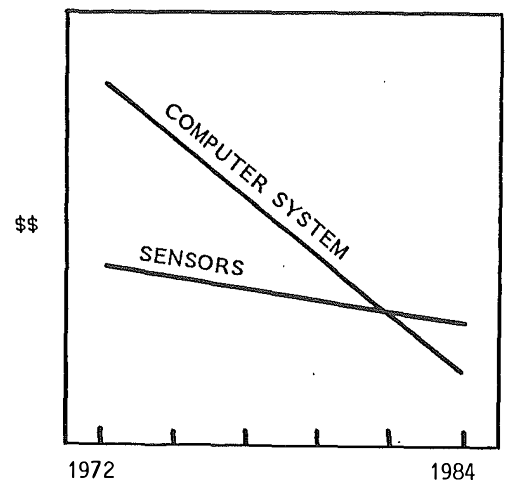

Figure 1

The intensive development of integrated electronics has resulted in plummetting costs of digital computers. Only recently have the costs of electronics dropped below those of sensors in computer-controlled systems. This turn of events has prompted an increased level of sensor development.

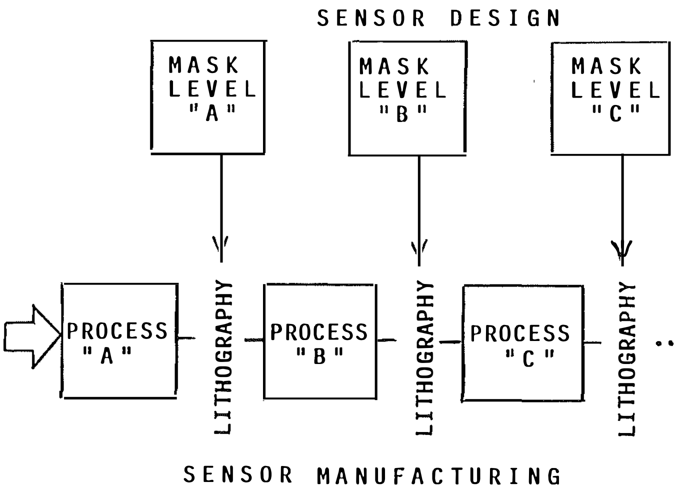

Figure 2

Just as in integrated circuit device families, advanced silicon sensor families can be based on standard manufacturing processes. Standard design rules are generated from these common processes which are then used to design a new mask set for each new sensor in the family.

Of course, such sensor families do currently exist to a limited extent, but the extension of these ideas to smart sensor families with on-board circuitry is a more demanding challenge. First of all, it is crucial to have an intimate knowledge of the details of the IC processes used in the circuit fab-line, as well as a basic understanding of the limitations of current circuit manufacturing technologies. As a general rule, for example, only limited pre-processing of a sensor wafer is acceptable prior to fabricating the circuits. Because of lithography and handling constraints, the very large topographies or unusual materials encountered in many types of sensors are steps which must wait until the circuitry is completed. In particular, pulling wafers out of a circuit fab-line, doing a special process, and re-introducing them midway through the sequence is even more frowned upon as illustrated in Figure 3.

Once a circuit processing sequence is established its optimum performance, yield, and reliability will only be maintained by following these considerations.

IC-COMPATIBLE SENSOR STRUCTURES

Integrated circuitry immediately adjacent to sensing devices and structures has the potential for enormously increased detection sensitivity and noise immunity in all types of sensor trandusction techniques. In addition, design and processing costs for low-volume integrated circuit chips continue to drop with the proliferation of CAD tools and custom silicon foundry services. It is inevitable that on-board integrated circuits will be increasingly employed in silicon-based sensor families. One basic approach to the smart-sensor family relies on the concept of hermetically sealing the circuitry - on a wafer scale - underneath Pyrex glass or another silicon wafer, similar to the strutures first demonstrated by Sanders and Knutti (1), Lee and Wise (2), and Ko, Bao, and Hong (3). Advantages to be expected from this approach are:

- circuitry is well-protected from the environment;
- the assembly is thermally matched;
- circuitry is also well-protected from subsequent etching steps for a wide range of sensor-related microstructures;
- packaging is simplified because a significant part of the packaging function is accomplished on the wafer level.

Such advantages are certainly not without development problems:

- hermetic sealing of circuitry within a small volume;
- hermetic, low resistance, well-insulated electrical feedthrus;
- bonding and sealing must be performed on a wafer scale;
- and all of these requirements must be completely compatible with established circuit technologies.

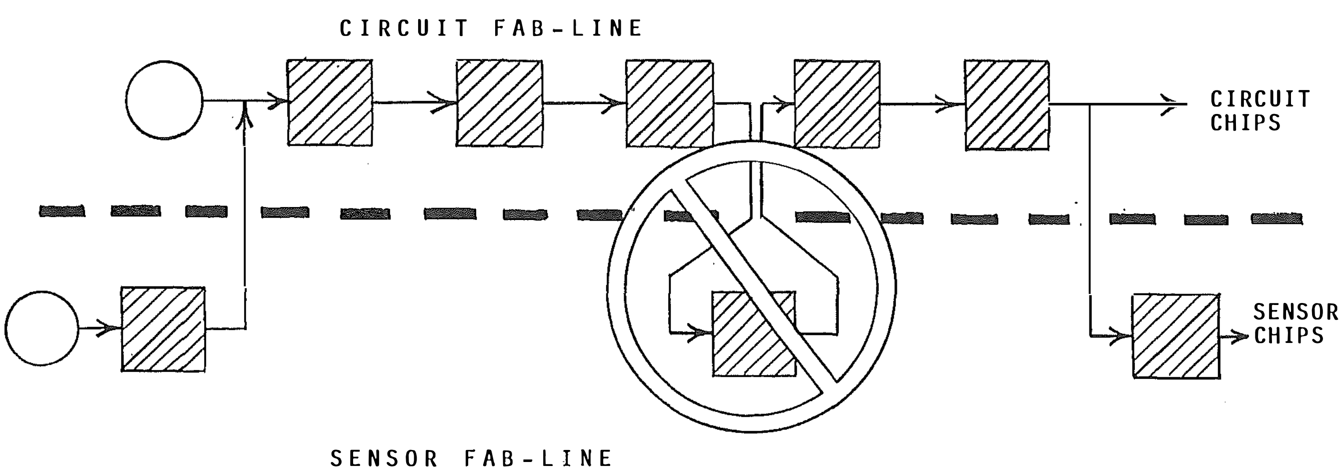

Figure 3

The processing sequence of a circuit fab-line should not be interrupted to perform special processing functions for sensors. This may compromise the circuit performance, yield, and/or reliability. Instead, special processing steps must be implemented prior to the start of circuit fabrication (these steps are very limited) or after complete circuit fabrication.

Each of these issues, complex problems by themselves, are made all the more difficult by being closely coupled. For example, high reliability, hermetic, wafer-scale bonding is very sensitive to surface topography, while IC topographies and various proposed electrical feedthru techniques are notorious for generating unacceptably large surface features.

Since this approach can resolve the common, long-standing pursuit of optimal circuit passivation and protection, the potential benefits are impressive. As shown in Figure 4, the concept is applicable to many types of silicon-based sensors, including pressure, temperature, force and chemical. It also provides a convenient separation between the sensing and circuit functions.

It seems that the many diverse aspects necessary to effectively commercialize silicon micromechanics, silicon micromachining, and silicon-based smart sensors are now in line. As described earlier, the proliferation of computers has supplied both the technical foundation and the economic impetus. In addition, there is now a critical mass of people working in these areas as well as a critical mass of technical literature. Finally, a number of highly successful commercial products have been identified which can serve as catalysts to increasing development efforts. The practical implementation of these concepts will greatly influence the next generations of miniature mechanical structures, physical sensing devices, and the important sensor/computer interface.

REFERENCES

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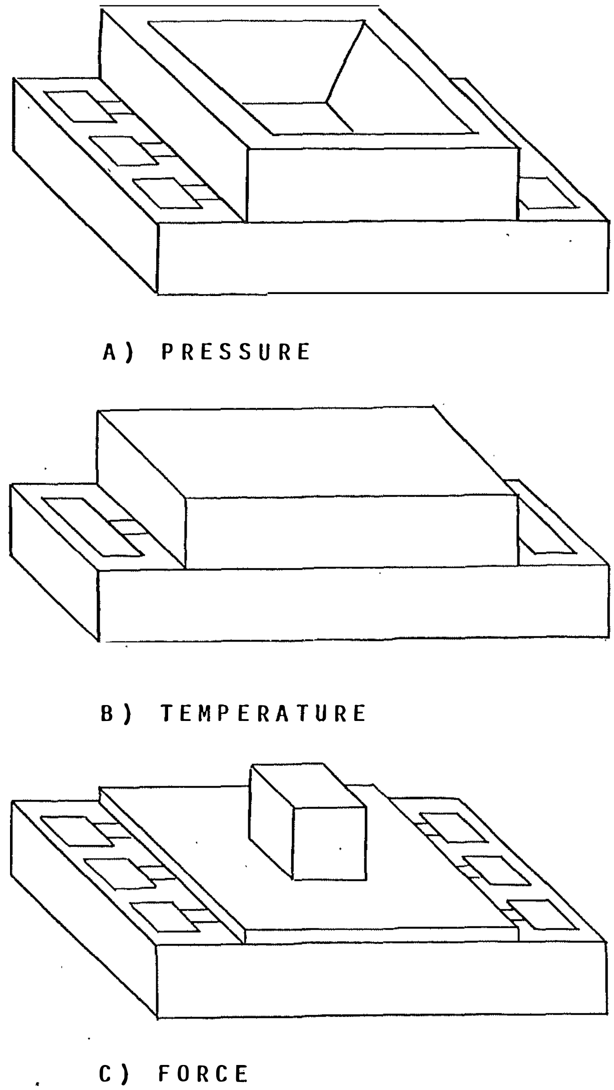

Figure 4

Examples of transducer structures from a proposed "smart-sensor" family with circuitry hermetically sealed between two chips.