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Extended Abstract

Technology Trends in High Temperature Pressure Transducers: The Impact of Micromachining

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Abstract

This paper discusses the implications of micromachining technology on the development of high temperature pressure tranducers. The introduction puts forth the thesis that micromachining will be the technology of choice for the next generation of extended temperature range pressure transducers.

The term micromachining is defined, the technology is discussed and examples are presented. Several technologies for high temperature pressure tranducers are discussed, including silicon on insulator, capacitive, optical, and vibrating element. Specific conclusions are presented along with recommendations for development of the technology.

Introduction

Silicon high temperature pressure transducers have been available since the late 1960's[1]. Small rugged high temperature pressure probes had a major impact on flight tests and engine development for the current generation of high performance military aircraft. The development of this technology was made possible by the confluence of a number of factors including

1. The existence of a new, under-exploited technology due to the discovery and elaboration of the Piezoresistive effect in silicon at Bell Labs in the 1950's.

2. Selective funding of semiconductor and silicon sensor research in the 1950's and 1960's.

3. The existence of several entrepreneurial companies that were instrumental in the field.

4. A pressing need for the development of new measurement tools for the development of high performance military aircraft.

The author contends that the 1990's may see the significant development of silicon high temperature pressure transducers as the result of the existence of a similar set of factors. I believe that silicon micromachining will be the fabrication technology of choice for the new generation of such high temperature sensors.

Micromachined Sensors

Micromachining is the three dimensional sculpting of silicon using the techniques of semiconductor manufacturing. Originally developed as a set of tools for the manufacturing of sensors, micromachining has become a technology in its own right.

Micromachining is expected to become increasingly important as the manufacturing of mechanical systems concentrates on smaller and smaller structures. Proponents of this technology see the dawning of a new age of micro-manufacturing and micro-robotics.

The technology has been very successful in the manufacturing of sensors. Today, over 90% of all pressure sensors representing over half of the industry revenues employ this technology.

Why micromachining for high temperature pressure sensing? It exploits readily accessible university and industrial semiconductor device and process technology research. In last decade, it has become the sensor technology of choice. The technology allows for the production of very small, highly accurate sensors It employs high temperature fabrication processes and high temperature materials. It is applicable to a variety of sensor modalities. Finally, it is cost effective for complex fabrication sequences.

Many micromachining technologies are relevant to high temperature pressure transducers, but particularly noteworthy is Silicon Fusion Bonding[2], a new "welding" tool for microstructures. It allows the bonding of silicon wafers with a bond strength which approaches that of silicon. The resulting structure is electrically stable. In fact, active devices such as transistors may be formed across a silicon fusion bonded interface.

Silicon fusion bonding is a high temperature, clean process which is compatible with semiconductor processing. High temperature processing at temperatures of 1200°C after wafer bonding is possible. This is unique to this wafer lamination technique. Finally, silicon fusion bonding allows the design and fabrication of novel three dimensional structures unobtainable with conventional micromachining techniques.

Silicon Pressure Sensor Technologies for High Temperature Applications

Fortunately, semiconductor fabrication techniques, which have been exploited by a number of researchers, have resulted in the development of several viable, high temperature sensor technologies exploiting several sensing modalities. These modalities include piezoresistive, capacitive, vibrating element, and thin film strain gage.

Although the initial developers of silicon high temperature pressure sensors investigated and sucessfully developed several viable piezoresistive technologies, including solder glass bonding of conventional strain gages, by far the most successful technique has been variants of what has come to be called silicon on insulator or SOI technology.
The first such technique was originally proposed by Kurtz and Gravel in the mid-1960's and realized by Mallon and Kurtz[3] in the late 1960's. This technique employed a polycrystalline silicon diaphragm and very small bulk silicon strain sensing elements separated by a thin film of quartz. These sensors made possible, for the first time, multiple transducer flight tests of inlet pressure distributions.

Newer SOI technologies have allowed the development of several generations of SOI sensors. Today's sensors exploit the superior properties of single crystal silicon. Kurtz, Weber et al. have developed a sensor based on electrostatically bonding two wafers separated by an intermediate pryex layer. Wilner employs a high temperature boron oxide-quartz glass to form the bond layer. Petersen, Mallon[4] et al. employ silicon fusion bonding to laminate two wafers.

All three techniques are commercially successful and viable. These sensors operate to about 600°F. The upper limits of SOI technology have not been reached due to a lack of suitable packaging and lead out, but it is anticipated that this technology should be viable to about 1000°F.

SOI technologies draw on the many excellent materials available with semiconductor technology, including the following:

Transducer element:
Silicon, quartz, silicon nitride, silicon oxide, deposited metal films, polysilicon, diamond

Sensor element:
Silicon, silicon carbide, silicon nitride, thin films of metal

Contacts:
Aluminum, platinum, tungsten, platinum silicide, titanium, chrome-gold

Silicon piezoresistive high temperature pressure sensors are ripe for further development. A suitable development path would include:

Package and interconnect development to extend range to 1000°F

Microprocessor compensation

Silicon on sapphire for higher temperatures

Silicon carbide for very high temperatures

Capacitive pressure sensors have been demonstrated in silicon. They have the advantage of being readily micromachined, small and suitable for dynamic measurement. Such sensors sense in a displacement mode and theoretically can produce smaller temperature errors. They have the disadvantages of low capacitance, lead out problems and high signal to noise ratio. Such sensors have the potential for high temperature applications.

A recent demonstration of light emission in silicon has given new impetus toward silicon integrated electro-optics. Micromachining technology is recognized as an adjunct to fiber optic sensors. Such sensors have an outstanding potential for applications in excess of 1000°F.

Another potential technology for very high temperatures is vibrating silicon element pressure sensor technology. These sensors employ a digital sensing mode and are free of analog temperature errors. They are very accurate - 1 to 2 orders of magnitude better than piezoresistive sensors and can be excited with fiber optics. Some issues limiting relevance for aerospace test applications are: packaging stress and issues concerning dynamic pressure measurement and concentration on known lucrative applications for processing technology.

Conclusions and Recommendations

Silicon micromachining should be pursued as the base technology for the next generation of pressure sensors. It is of concern that although the U. S. is the leader in micromachining, Germany and Japan are spending several times as much as the U. S. for government funded research in this area.

It is anticipated that silicon micromachining will be the technology employed for the next generation of high temperature pressure sensors. I suggest pursuing a dual strategy:

Extend current SOI technology to 1000°F.

Pursue an alternate technology for operation to 2000°F-Optical, vibrating and/or capacitive.

I further suggest that government funding in this area be increased and that agencies should promote university-industrial joint development.

Acknowledgment

The author was employed between 1965 and 1992 at Kulite Semiconductor Products where he was responsible, along with Dr. Anthony Kurtz, for that company's silicon technology. During this time Dr. Kurtz was the author's teacher, mentor and collaborator. High temperature sensing was a frequent area of investigation and the author's initial exposure to the field was a result of that collaboration. In 1985 the author founded NovaSensor along with Dr. Janusz Bryzek and Dr. Kurt Petersen. Many of the author's views on silicon micromachining and silicon fusion bonding resulted from this collaboration. Dr. Petersen is the preeminent pioneer in the field of micromachining and introduced silicon fusion bonding to sensors. Joseph Brown and Rose Siemeca were instrumental in the development of silicon fusion bonded high temperature sensors.

References

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