SiC MEMS Pressure Sensors:
Technology, Applications and Markets

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Silicon Carbide: Material Platform for Harsh Environment Solutions

Silicon carbide (SiC) has been used for many conventional applications that require mechanical and chemical stability at high temperatures. Mechanical stability is defined as the ability of a particular material to preserve its mechanical properties – elasticity, fracture toughness, hardness – at temperatures below and above room temperature. Chemical stability is similarly defined as the ability of a particular material to preserve its composition at temperatures below and above room temperature. For high temperature applications, mechanical properties tend to deteriorate and chemical stability is compromised as corrosion processes occur.

Any material that can overcome these mechanical and chemical limitations becomes a candidate for what are called “harsh environment” applications. Harsh environment means a combination of media properties that can interact with the exposed material and alter its originally intended behavior. Harsh environments can be classified in three broad categories: 1) *mechanically aggressive*: high loads, vibration, shock; 2) *thermally aggressive*: high temperature; and 3) *chemically aggressive*: corrosive media.

There are a variety of harsh environment materials that address different applications, but until the early 90’s, these materials were conventionally fabricated. They are typically expensive, used very selectively, and many times only for protection of an underlying material that performs a different function.

With advances in microfabrication technologies in the early 70’s and 80’s, the value proposition of using silicon (Si) as an electronic material became evident with the IC revolution. For the purpose of this article, the terms Si and SiC are used very loosely to encompass bulk, thin film, single crystal, polycrystalline, or amorphous material unless otherwise specified.

As the IC industry moved rapidly towards smaller critical dimensions, obsolete processes started to be employed by a nascent industry whose value proposition was to produce micron-scale sensors and actuators at extremely low unit cost, following the same miniaturization path as the IC industry. There was only one fundamental difference: sensors and actuators typically require moving elements, which necessitated understanding Si as a mechanical material.

The rest is history: the MEMS industry was born and there are now numerous examples of applications where MEMS solutions have been able to replace conventional solutions due to superior performance, low cost and efficient integration with signal conditioning electronics. The simplest way to look at MEMS is to reduce all these different applications into either sensors or actuators – either the microdevice collects information from the environment or it acts upon it. The best way to summarize the advantages of MEMS technology is simply to think about any physical, chemical or biological phenomena as being space and time dependent: 1) the smaller the point in space where the phenomenon needs to be measured and controlled, the more effective a micron-scale device will be; 2) the faster the phenomenon needs to be measured and controlled, the more effective a micron-scale device will be due to its extremely low mass.

Furthermore, if micro-scale devices are also more cost-effective, then it is definitely a win-win proposition both technically and commercially speaking. However, in the case of harsh environments, Si as a foundation material for MEMS is not necessarily ideal. Because of its inherent multi-physics nature, MEMS require stability of material properties not only in the mechanical domain but also, and most importantly, in the electronic domain; MEMS components have to leverage their integration compatibility with inexpensive electronics to preserve their competitiveness as a solution.

The question then becomes: is there a material that can duplicate the mechanical and electronic advantages of Si in harsh environments? The answer is yes, and SiC is the most effective candidate scientifically speaking.

Take away the long list of material properties and just think about the material itself and what fundamental properties indicate stability in harsh conditions: melting point and electronic band gap. Higher melting points imply superior mechanical and chemical properties. Similarly, larger electronic band gaps imply superior electronic properties.

The combination of SiC as a low cost, microfabricated material platform with its mechanical, thermal, chemical and electronic stability will position SiC MEMS as a potential solution for a wide range of harsh environment sensor and actuator applications. SiC MEMS can then follow the same steps as Si MEMS -- a low-cost replacement for existing solutions that currently rely on expensive material platforms and less than optimal packaging schemes.

SiC Microfabrication: Technology Background

Once MEMS researchers realized that SiC was a solution to harsh environment applications, the question then became: can Si MEMS be mapped onto SiC MEMS – are there similar deposition and etching processing steps, similar bulk and surface micromachining process flows, similar large area substrates, similar dielectrics and metals? At that point there was a serious obstacle – the same chemical stability that qualified SiC for harsh environments, also made it difficult to etch and integrate any process step with already established Si based processes.

A major research effort was undertaken at Case Western Reserve University, and later at UC Berkeley, and multiple techniques were evaluated. During this period of microfabrication technology development, the ultimate goals were to: (1) guarantee that SiC processes could reproduce the same quality as well established Si processes; (2) guarantee that SiC processes could reproduce the same cost-effectiveness as well established Si processes.

Entire process flows started to emerge, and success was achieved on a research level. Today one can think about SiC-based process flows that are equivalent to most standard Si bulk and surface microfabrication flows. Steps that were developed years ago for precise doping control and residual stress control in Si have also been implemented in SiC processes.

All in all SiC has come a very long way as a foundation material for MEMS. Considering that SiC research efforts were roughly 10 years behind Si MEMS, it is a reasonable claim that SiC microfabrication technology is ready to impact applications and markets in the same way as Si MEMS did 10 years ago.

SiC MEMS Applications

Once microfabrication processes became capable of producing devices with comparable or superior performance compared to conventionally fabricated devices, MEMS took their first step towards replacing existing solutions.

However, to become cost-effective, one of the major obstacles faced by MEMS was packaging. Whenever Si MEMS were developed and environmental effects needed to be addressed, the only available solution was to invest in packaging. If the environmental conditions were slightly aggressive, then the packaging diminished the cost-effectiveness of the solution. Multiple packaging schemes were developed, improved, and eventually driven down cost-wise until applications became commercially viable at price points attractive enough to replace existing solutions.

However, harsh environment challenges still remained, and even though some of them have been addressed technically, none of them has become attractive enough, from a commercial perspective, to address high-volume applications due to the complex packaging requirements.

Harsh environment applications are probably the only remaining domain where conventional fabrication technologies and materials remain the viable solution technically, and for lack of other options, commercially as well.

SiC MEMS can potentially change this paradigm by providing solutions that meet the stringent requirements of these applications and provide the missing cost-effectiveness associated with conventional solutions.

Mechanically Aggressive Applications

Mechanically aggressive applications typically involve very high static and dynamic loads. In the case of the oil and gas industry, downhole pressure sensors require pressure ranges up to 35,000 psi at temperatures that can be as high as 200°C. For diesel engine in-cylinder pressure measurement applications, pressure ranges of 1000-2500 psi, temperatures around 400°C and fast response rates of 7000 psi/msec are required. This market, even though not as price-driven as the conventional automotive market, still requires relatively low cost solutions that can be estimated to be between $10-20 per unit. Existing solutions can only be used for testing purposes and cost between $3000-5000 per unit.

For such mechanically demanding applications, conventional sensors are typically based on assembly principles that have been perfected to address reliability issues primarily. Besides the packaging challenges, Si MEMS have not been successful in this application domain due to their fundamental limitations regarding sensing principles and mechanical properties.

Quartz based devices seem to be the dominant technology due to their flexibility as sensors, which allows these devices to selectively isolate wanted loads from unwanted ones. As a piezoelectric material, quartz can produce electrical and mechanical signals in various modes that are either shear or compressive. Electronic circuitry for quartz sensors is well established, and as mentioned above, reliability is of such paramount concern that most applications are comfortable living with relatively high price points. There is also a myth that micromachined devices cannot withstand operation under high loads, which is not true.

Mechanically speaking SiC has superior elasticity and fracture properties compared to quartz. Whether MEMS capacitive and piezoresistive sensing and actuation principles are commercially viable remains a question mark since, after all, MEMS would certainly require operation under high tensile stresses that could compromise reliability. However, mass deployment of existing technology is still not possible cost-wise, and economic factors will eventually lead OEMs and device manufacturers to consider microfabrication technologies as a viable option.

Forward-thinking OEMs are already looking into the technical and economical viability of MEMS – more precisely of SiC MEMS.

Thermally Aggressive Applications

Thermally aggressive applications typically involve temperatures higher than 150-200°C. Si MEMS have managed to provide cost-effective solutions above 150°C with very modest success. At these temperature ranges, Si is still a viable material mechanically speaking but its electronic properties start to be compromised.

Above 200°C, piezoresistive SiC MEMS have been recognized as a potential cost-effective solution. However, as temperatures increase, piezoresistive coefficients degrade and the resulting non-repeatable hysteresis present a substantial technical challenge since the cost associated with the required signal conditioning electronics increases substantially. As the temperature approaches 400-500°C, quartz solutions are no longer possible - except for some new, extremely expensive quartz derivatives and unproven exotic piezoelectric materials.

Another application example is active combustion control in gas turbine engines, where the operating temperatures are around 600°C. No low-cost pressure sensor solutions are available. Even though commercialization of gas turbine combustion control systems is still 5-10 years away, major gas turbine manufacturers have started to consider technologies that are cost-effective, and the utilization of SiC MEMS is being investigated very seriously.

In addition, at temperatures around 200°C, many industrial applications abound in pressure ranges up to 100 psi at price points in the $20-30 range.

There are still significant engineering challenges in the development of cost-effective packaging solutions for SiC MEMS capable of sustained operation at temperatures above 400°C. However, these challenges are not expected to be insurmountable, or to require development of a new class of packaging materials.

Capacitive MEMS have not been explored broadly but could offer substantial technical advantages in thermally aggressive applications. The main technical challenge is to determine if dielectric properties present any non-repeatable hysteresis behavior as a function of temperature. So far, experimental evidence points to the contrary, and capacitive SiC MEMS devices have been characterized with repeatable hysteresis less than 2.5% at 300°C.

Chemically Aggressive Applications

Chemically aggressive applications typically involve highly corrosive environments. Of course, considering the kinetics of corrosion/oxidation reactions, the effects can be exacerbated at higher temperatures. There are many applications where the environment is both chemically and thermally aggressive, but in this section the focus will be on chemically aggressive media.

Conventional solutions still dominate this application. Solutions are based on corrosion-resistant materials – ceramics and metals – both on a transducer and on a package level. Mechanical reliability is not as important as device chemical stability.

“Isolated” Si MEMS are definitely gaining traction for these applications, but since Si cannot be exposed to corrosive media, the packaging costs are likely to remain high. SiC MEMS transducers, on the other hand, could be directly exposed to the media without any foreseeable problems, and therefore greatly reduce packaging costs.

The best application that exemplifies the need for corrosion resistant sensors is in semiconductor manufacturing. Highly corrosive gases, combined with tremendous pressure accuracy requirements, present formidable technical challenges since any downtime in semiconductor manufacturing is very costly. Any chemical deterioration of corrosion resistant sensors will automatically introduce inaccuracies capable of compromising the quality of a particular process step.

Beyond the chemical resistance and high accuracy requirements, multiple pressure sensors are needed to address a wide range of negative (i.e., vacuum) and positive pressures. Cost is not an obstacle in this market and sensors that cost more than $3000 are widely used.

FLX Micro: SiC MEMS pressure sensors

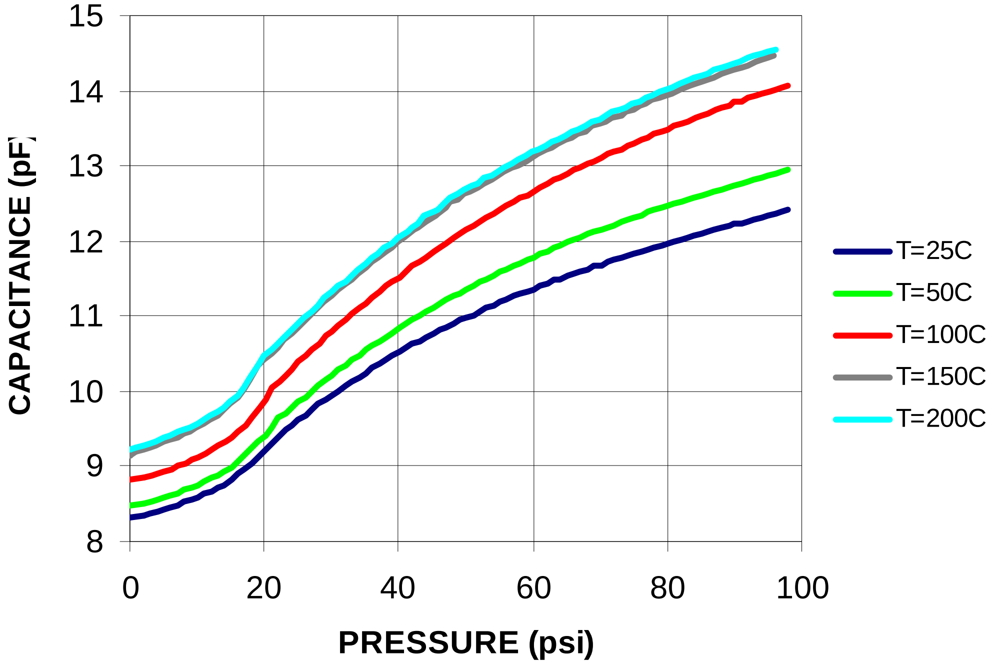
FLX Micro commercializes SiC MEMS capacitive pressure sensors to address the demanding pricepoints and technical requirements of harsh environment applications. Leveraging existing university research through technology licenses and internally developed proprietary processing techniques, FLX Micro has designed, fabricated and characterized the first generation of harsh environment pressure sensors capable of operating from 0-100 psi up to 200°C.

Figure 1 contains a plot of capacitance versus applied pressure for various temperatures. The increase in initial capacitance and sensitivity at higher temperatures are due to the thermal expansion mismatch between the poly-SiC membrane and Si substrate. Notice the characteristic operation of a touch-mode capacitive sensor. At a certain pressure the membrane deflects enough to contact the (fixed) sensing electrode. After membrane touch-down, the change in capacitance with pressure is quasi-linear because the area of contact is being modulated rather than the separation gap. Sensors can be operated in only the non-linear region below touch-down pressure, only in the quasi-linear region after membrane touch-down, or both. Beyond a certain pressure, the change in capacitance with pressure saturates, and sensor sensitivity decreases.

By adjusting design parameters such as membrane diameter, membrane thickness, membrane residual stress, and capacitive gap, various pressure ranges can be generated allowing the sensor to address from very narrow to very wide pressure ranges.

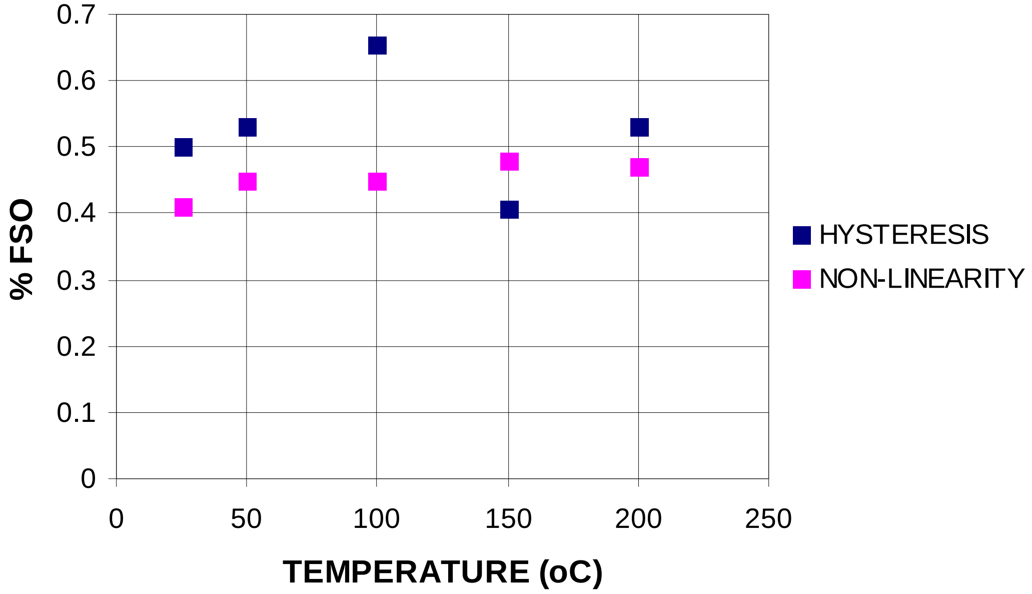
The same design parameters can also be used to adjust sensitivity and non-linearity. For example, sensitivity can be increased by configuring multiple membranes in parallel. The touch-mode capacitive approach leverages the chemical inertness of poly-SiC to prevent stiction problems that are common in any MEMS application that requires contact between dissimilar materials. It is one more example of the value of the material platform to the end application.

FIGURE 1



In Figure 2, non-linearity and hysteresis are presented as a function of temperature. Note that the combined effect on non-linearity and hysteresis is never much higher than 1% FSO over the operating temperature range. Furthermore, no significant changes in hysteresis can be observed as the temperature increases except at 100°C. This data point needs to be investigated further, but there is no clear evidence that temperature has a major effect on sensor hysteresis. These results are repeatable over multiple prototypes characterized to date.

FIGURE 2



Transducers have been integrated with proprietary, frequency-based signal conditioning electronics that can operate up to 200°C and packaged with off-the shelf components. Sensor prototypes are currently being deployed at selected customer sites for evaluation.

FLX Micro uses poly-SiC – a low-cost version of SiC – as its material platform. The microfabrication process is based on either a Si or SiC substrate, and incorporates common dielectrics for electrical insulation and sacrificial material. Movable membranes, sensing electrodes, and electrical traces utilize heavily doped poly-SiC. Metal interconnects utilize a stack of high temperature metals.

Current devices were fabricated on a Si substrate, but the product roadmap will target an all poly-SiC design that will produce sensors capable of operating in chemically aggressive environments without any protection from the media. An all poly-SiC sensor will also minimize differential thermal expansion effects and is expected to simplify packaging for high temperature applications.

FLX Micro's SiC MEMS pressure sensor technology is at a turning point where validation prototypes have been manufactured, technical differentiation solidified, and applications and markets identified. As the technology is validated and becomes mainstream, new applications are bound to benefit from it.

FLXmicro

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