The Effect of Silicon Fatigue on Kulite Silicon Pressure Sensor's Reliability

Application Note: AN 101

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Introduction

This white paper addresses the issue of fatigue on the reliability of all models of Kulite's silicon pressure sensors. For many years the scientific consensus has been that for single crystal silicon as a structural material, fatigue was not an issue of any concern. In general there are essentially four categories of material fatigue, cyclic plasticity (work hardening or dislocation motion fatigue), sliding or physical contact (fretting and rolling contact fatigue), environmental damage (corrosion fatigue), and elevated temperature (creep fatigue) [1]. Single crystal silicon is generally classified as a brittle material, meaning that when subjected to a stress larger than the material's fracture strength it will crack or break, generally along the {111} crystal plane, instead of plastically deforming. Single crystal silicon is also classified as an extremely elastic material, meaning that after a stress is applied that deforms that material's shape, it will return to its original shape after the stress is removed [2]. Transition from a brittle to a ductile solid does not start in single crystal silicon until temperatures above 500°C , and plastic deformation does not occur until extreme temperatures and strains (> 800°C at 3000 µstrain) [3]. Creep fatigue only occurs in ductile materials by definition, so single crystal bulk silicon is immune until extremely high temperatures (>500°C) [4]. Physical contact fatigue does not enter into consideration due to the structures found in MEMS devices as they generally, and in Kulite's case specifically, do not exhibit the criteria needed for this fatigue type to occur. One mechanism of cyclic plasticity fatigue, dislocation activity, is not evidenced in silicon at temperature below 500°C [5]. One physical mechanism for work hardening, grain bridging, does not exist in monocrystalline silicon, as it is a single crystal structure. There is little evidence for the other work hardening mechanism, microcracking, in single crystal silicon [6]. It has also been established experimentally and theoretically that single crystal bulk silicon does not undergo corrosion fatigue in moist air, water, or other airborne environmental species [7]. In 1992, fatigue in thin film single crystal silicon was reported [8], and in the following years more published reports documenting this phenomenon have been published [9] [10] [11], but it only occurs under an array of specific criteria. This cyclic fatigue has only been reported in thin film single and polycrystal silicon (2µm-20µm thick) at extremely high stress levels (higher than 50%

of fracture strength), with test structures specifically created with flaws to amplify the normal stress levels, tested most often in a high humidity environment and exhibiting the onset of fatigue at approximately 10^{11} cycles [12]. Even after it was discovered that thin film silicon displayed fatigue in very specific circumstances, the scientific consensus is still that bulk single crystal silicon is not affected by fatigue. "Indeed, there has been no evidence to date that bulk silicon is susceptible to fatigue failure [13]." For the issue of fatigue in commercial MEMS devices the consensus is as follows: "Fatigue has not turned out to be a lifetime limiting factor in any commercial MEMS device. [14]"

Silicon Material Properties

Single crystal silicon, also known as monocrystalline silicon, is an anisotropic material, properties of which depend on various factors such as: crystallographic orientations, geometry, load conditions, etc. Some properties of single crystal silicon are tabulated below from different sources [15] [16] [17] [18] .

Property	Value	Unit	Notes
Dielectric Constant	11.9		
Specific Heat	0.7	J/g-K	
Intrinsic Resistance	230	kΩ-cm	
Melting Point	1415	°C	
Thermal Conductivity	1.6	W/cm-K	
Hardness	850	kg/mm^2	
Fracture Toughness	0.7-1.3	$MPa\sqrt{m}$	
Yield Strength (Ultimate Fracture Strength):	7	GPa	
Young Modulus:	130-190	GPa	
Mass Density:	2.3	g/cm^3	
TCE (Temperature Coefficient of Expansion):	2.33E-6	K^{-1}	
Plastic Deformation:	> 800	°C	(>3000 µstrain level)
Poisson's Ratio:	0.28		(<100> orientation)

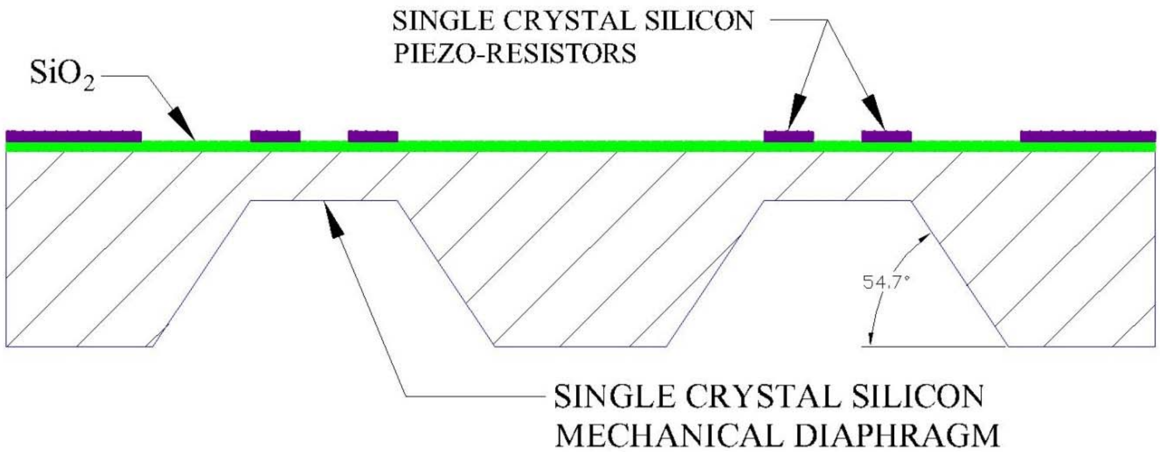

FIG. 1: KULITE SILICON SENSOR CHIP

Description of Kulite Silicon Sensor Chips

The general structure of the Kulite silicon pressure sensing chip is shown in Figure 1. The dimensions of the sensor chip are designed for each application. The sensor chip is composed of essentially three layers. The first layer is single crystal silicon used to fabricate the diaphragm of the sensor. The second is the single crystal layer used to fabricate the semiconductor gauges, and the last is an oxide layer that is used to electrically isolate the gauges from one another and the first layer. Thus, there are only two silicon layers in the structure of the sensor, and the oxide layer exists only for isolation, it plays no part structurally that can lead to a fatigue induced failure. The diaphragm layer is bulk single crystal silicon and is designed so that the layer never experiences strain levels that exceed 20% of the fracture strength level under any and all imposed requirements, including operational, proof and overpressure pressure requirements over the entire specified operation temperature range. The gauge layer is a thin film single crystal silicon layer designed so that it never experiences strain levels that exceed 20% of the fracture strength over the total pressure and temperature envelope. For both the silicon layers this result is achieved by Kulite's design philosophy and fabrication process, the combination of which eliminates points of stress concentration within the sensor. All sensor designs are evaluated theoretically, through finite element analysis, and experimentally by physically testing fabricated commercial sensors to verify that all the design criteria are met.

In all cases Kulite's silicon sensors have the thin film silicon gauge layer hermetically sealed from the environment and the pressure media. One example of a method used for achieving a hermetic environment for the sensor's gauges is the use of an oil filled cavity. The final assembly process of the oil filled transducer, in which the header with the silicon chip is oil filled, is performed in a heated chamber under vacuum. Any moisture present is drawn out by the vacuum, while being driven by the heat in the chamber. After vacuum is released, the oil is pulled into the chip area. At this point, the chip is completely encapsulated in the oil, and the header assembly is hermetically sealed in an ultra-dry environment by the sealing of the oil fill tube. Kulite's oil filled pressure transducers contain Silicon on Insulator (SOI) sensing chips sealed in a hermetic chamber filled with silicone oil. A metal isolation diaphragm allows the external pressure to be transmitted to the sensing die, while protecting it from the potentially harsh and/or conductive external environment and the pressure media. The metal isolation diaphragm is exposed to the pressure medium, while the silicon chip is exposed only to the ultra-dry oil under pressure.

Kulite's leadless technologies also incorporate all the fatigue resisting features that are incorporated into all of Kulite's MEMS sensors. All leadless sensor designs are evaluated theoretically, through finite element analysis, and experimentally by physically testing fabricated commercial sensors to verify that all the design criteria are met. This includes verification that stress risers are absent from the final sensor design, and that the ultimate stress levels experienced by the device at the worst case operational conditions remain below 20% of the fracture strength value for single crystal silicon. The integrated strain gauges themselves are encapsulated in a hermetic environment protecting them from any atmospheric contaminate. The structure that is exposed to the pressure media is bulk single crystal silicon, and as we have detailed previously, is immune from any fatigue effects.

Conclusion

Kulite silicon sensing chips, utilizing single crystal silicon diaphragms, are designed and manufactured to operate at stress levels significantly below the stress levels under which silicon fatigue was detected and reported by researchers. The gauge layer is maintained in a hermetic ultra-dry environment. The sensors are also designed to eliminate any stress concentrations, which would be the points of maximum potential fatigue. The test structures, used in fatigue research, on the other hand, are all built with flaws to purposely increase stress concentrations. "For silicon, the material most commonly used in MEMS, fatigue occurs only for applied stresses greater than half the single-cycle fracture strength, i.e. at stress levels close to fracture, and thus any reasonable design will not have stress levels sufficiently high for fatigue to be relevant [19]". In fact, in all of the reported literature the researchers took the necessary steps not only to expose the silicon samples to high stresses, but actually created stress risers, (some through design, some through induced flaws) to reach stress levels necessary to induce the cracks required for fatigue propagation. The Kulite design philosophy caps the stress levels occurring in the sensors at the worst possible environmental and use conditions at less than 20% of the silicon's fracture strength well below the maximum design levels reported to avoid fatigue in single crystal thin films. Additionally, the semiconductor gauges are only exposed to hermetically sealed environments thus avoiding any potential humidity induced problems.

The general industry consensus on commercial MEMS devices design with regard to high cyclic fatigue is as follows. "As a general rule, if either (a) the maximum cyclic stress is less than 20% of single-cycle fracture and if the humidity is not controlled, or (b) maximum cyclic stress is less than 40% of single-cycle fracture and the device is hermetically packaged in an ultra-dry ambient, high-cycle fatigue of silicon parts will not occur" [20]. These industry design standards derived to eliminate high cycle fatigue are exceeded by Kulites internal design standards. A high life cycle for Kulites sensors is to be expected, and has been experienced with Kulite silicon pressure transducers, some being in continuous operation for over 30 years.

References

[1] R. O. Ritchie, International Journal of Fracture, 100: p55-83, 1999

[2] K. E. Petersen, Proceedings of the IEEE, Vol.70, No. 5, May 1982

[3] R. O. Ritchie, 13th Workshop on Crystalline Solar Cell Materials, 2003

[4] G.L Pearson, et. al., Acta Metall., vol. 5, p181-191, 1957

[5] K. Sumino, Metall. Mater. Trans. A, 30A, p1465, 1999

[6] H. Kahn, et. al., Sens. Actuators A, A82 p274-280, 2000

[7] S. Bhowmick, et. al, Appled Physics Letters. 91, p201902-1, 2007

[8] J.A. Connally and S. B. Brown, Science, Vol. 256, p1537-1539, 1992

[9] H. Kahn, et. al., Solid State & Mater. Sci., 8, p71-76, 2004

[10] T. Ando, et. al., Sens. Actuators A Phys, 93, p70-75, 2001

[11]D. H. Alsem, et. al., Adv. Eng. Matrerials, 9, p15-30, 2007

[12]C. L. Muhlstien, et. al., Acta Materialia, 50 p3579-3595, 2002

[13]C. L. Muhlstien, et. a.l, Acta Materialia 50, p3579-3595, 2002

[14]A. L. Hartzell, et. al. , "MEMS Reliability", p118, Springer, 2010

[15]K. Petersen, Proc. of the IEEE, Vol 70, No. 5, p 420-457, 1982

[16]M.A. Hopcroft, Jour. of Microelectromech.Sys., Vol. 19, No. 2, 2010.

[17]C. Wilson, P. Beck, Jour.of Microelectromech. Sys., Vol . 5, No. 3, p142-150, 1996

[18] S. M. Sze, "Semiconductor Sensors", p535, Wiley Inter-Science , 1994

[19] A. L. Hartzell, et. al. , "MEMS Reliability", p118, Springer, 2010

[20] A. L. Hartzell, et. al. , "MEMS Reliability", p121, Springer, 2010