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NOTE

An argument for proof testing brittle microsystems in high-reliability applications

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Abstract
The vast majority of microelectromechanical systems (MEMS) for sensor and actuator applications are fabricated from brittle materials, such as Si, SiC and diamond. Numerous prior studies have shown that the structural reliability of these flaw-intolerant materials is governed by processing-induced critical defects, and that their failure strengths have a wide dispersion associated with a low Weibull modulus. This broad distribution of critical failure conditions creates an uncertainty that cannot be tolerated in high-risk or high-consequence applications. This note presents arguments for the adoption of proof testing methodologies which will provide a statistically-sound basis for certifying MEMS component reliability.

1. Introduction

The era of microelectromechanical systems (MEMS) was ushered in by Kurt Peterson's 1982 paper 'Silicon as a mechanical material' [1]. In that paper, which has now been cited over 1100 times, Petersen claimed that microfabricated Si is a 'high-precision, high-strength, high-reliability mechanical material'. This statement and the general sentiment that Si has 'excellent mechanical properties' have been echoed numerous times. It is now time, some 25 years later, to reconcile these rather simplistic notions of the excellent structural performance of Si with the complex realities borne out by two and a half decades of MEMS research and development. Such a 'taking-of-stock' reveals that while microfabricated Si has very significant shortcomings as a high-reliability mechanical material, proof testing [2, 3] offers promise for the use of Si and other flaw-intolerant MEMS materials in even the most high-risk, high-consequence future applications. The arguments presented herein are based largely on data for microfabricated polycrystalline Si (polysilicon) and single-crystal Si; however, these principles and observations generally extend to all brittle MEMS materials whose structural performance is governed by etch-induced surface defects, i.e. SiC, Si_3N_4, SiO_2, ultrananocrystalline diamond and diamond-like carbon.

2. Strength, toughness and process-induced flaws

The most pervasive modern misconception regarding the structural performance of Si is that it is 'stronger than steel'. While some researchers note that Si has a hardness (~11 GPa [4]) that is higher than most structural materials, the largely compressive hardness test is a poor measure of resistance to tensile failure in brittle materials. The fracture strength of these materials at or near room temperature is governed by processing-induced defects along the surface, and less commonly, within the volume. Variability in these defects leads to a wide variation in the material's tensile strength: while silicon and other brittle microfabrication materials may

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have an *average* strength that is comparable to or better than steel, there is often an unacceptable probability that some of the structures will fail at much lower strengths. While even Petersen recognized that 'the Si material should have the lowest possible bulk, surface and edge crystallographic defect density to minimize potential regions of stress concentration', eliminating processing-induced defects is not a trivial task.

The fracture toughness, and hence flaw tolerance of brittle MEMS materials is relatively low. Microfabricated polysilicon's toughness, reported to be in the range of 0.85–1.25 MPa$\sqrt{\text{m}}$ [5, 6], is comparable to that of window-pane glass. With the lack of intrinsic toughening mechanisms, failure in Si and other brittle MEMS materials is controlled by flaws that are only tens of nanometers in size. To further complicate matters, process-induced defects are often highly variable in size, orientation and shape, resulting in a broad distribution of corresponding fracture strengths.

There are numerous studies to draw upon for evidence of the variation in strength of microfabricated Si. In a subset of these works (e.g. [7–18]), enough repetitions have been performed to quantify strength distributions, which are typically assumed to obey the two-parameter Weibull model [17]. According to this extreme value distribution, the probability of failure P_f under an applied uniform stress, σ, can be expressed as

$$P_f = 1 - \exp\left[-\frac{\sigma^m}{\alpha}V_E\right] = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_\theta}\right)^m\right], \qquad (1)$$

where m is the Weibull modulus, V_E is the effective volume of the tested part, α is a constant and σ_θ is the characteristic strength, i.e. the stress level at which $P_\mathrm{f} = 63\%$. The statistical expected value for the tensile strength μ and its variance *Var* are given by

$$\mu = \left(\frac{\alpha}{V_E}\right)^{1/m}\Gamma\left(\frac{1+m}{m}\right) = \sigma_\theta\Gamma\left(\frac{1+m}{m}\right) \qquad (2)$$

$$\begin{aligned} Var &= \left(\frac{\alpha}{V_E}\right)^{2/m}\left[\Gamma\left(\frac{2+m}{m}\right) - \Gamma^2\left(\frac{1+m}{m}\right)\right] \\ &= \sigma_\theta^2\left[\Gamma\left(\frac{2+m}{m}\right) - \Gamma^2\left(\frac{1+m}{m}\right)\right], \end{aligned} \qquad (3)$$

where $\Gamma(x)$ is the Gamma function.

It is true that the expected value of the tensile strength of microfabricated Si is in some cases higher than even the strongest tool steels (~2 GPa). However, the Weibull modulus of microfabricated Si is in the range of 5–12 [7–11, 13], which is indicative of a wide variability in strength from sample to sample. In comparison, the Weibull modulus for structural alloys is typically so large ($m \gg 50$) that the very small dispersion in ultimate strength values is inconsequential and unreported. Assuming for the sake of argument that the extreme values (which may not have been captured in the experiments) could in fact be predicted by the two-parameter Weibull distribution, then combining equations (1) and (2) provides the ratio of allowable stress σ^{allow} to expected strength for a prescribed reliability,

$$\frac{\sigma^{\mathrm{allow}}}{\mu} = \frac{[-\ln(1-P_f)]^{1/m}}{\Gamma\left(\frac{1+m}{m}\right)}. \qquad (4)$$

Herein lies the challenge for high-reliability applications. If reliability considerations demand that only 1-in-1000 000 fails ($P_f = 10^{-6}$), then the allowable stress values for the reported low and high values of the modulus, $m = 5$ and 12, are only 6.8% and 33% of the expected strength, respectively. Thus, a high level of reliability requires a conservative design approach. In the case of the first freestanding layer of SUMMiT V$^{\mathrm{TM}}$ polysilicon ('poly1' or 'p1'), with a characteristic strength $\sigma_\theta = 1.35$ GPa and Weibull modulus $m = 9.71$ ($\mu = 1.28$ GPa, $Var = 0.553$ GPa^2) [11], there is a 1-in-1000 probability of failure at an applied stress of 0.66 GPa. While the risk of 1-in-1000 failure is acceptable for low-consequence applications, it is unlikely to be acceptable for applications where failure results in loss of life. For this particular polysilicon material, a failure risk of 1-in-1000 000 requires that the design stresses are below 0.325 GPa, well below the yield strength of most steels, titanium alloys, and even some aluminum and stainless steel alloys.

High-reliability applications require precise knowledge of the tail ends of the strength distribution [18]. At best, the use of Weibull statistics requires very large datasets, which have not yet been collected for MEMS materials. At worst, the extreme values may not be accurately represented by the two-parameter Weibull distribution. Certainly, the applicability of Weibull statistics is questionable in scenarios where stress-gradients, flaw-sizes, microstructure dimensions or characteristic specimen dimensions are of comparable magnitude. This similitude limitation to the continuum assumption in Weibull theory implies that the extrapolation from laboratory tests to predict failure in real components or components with same geometry but different dimensions from the tested samples [19] may not be reasonable.

Furthermore, subtle perturbations to the Si microfabrication process, especially in the etching stages, can induce a shift in the Weibull distribution. The effect of processing perturbations on the strength distribution has not been carefully investigated. In a recent study on the tensile strength of single-crystal Si produced by MEMSCAP's Si-on-insulator multi-user MEMS process (SOIMUMPs), one lot of material (run SOI14) was found to have a bimodal Weibull distribution thought to be caused by degradation of the photoresist mask (figure 1). This unpredictable change in the processing reduced the characteristic strength from 2 GPa to 1.5 GPa [13]. In the extreme case, undetected changes in the processing conditions can nearly destroy the structural integrity of Si. An example of this is taken from a SUMMiT V$^{\mathrm{TM}}$ polysilicon run. In this run, a particular die was found to have severe sharp crevice-like top surface defects that ran through nearly half of the thickness of one particular poly3 layer (figure 2). In this case, this unusual defect morphology was only found in the poly3 layer: the neighboring similar structure constructed from the poly2 layer had 'normal' surface topography. Moreover, the unusual defect found in the poly3 layer was local to one region of the die. Serendipitously, the rare defect morphology had formed on a tensile bar so that the catastrophic effect on the resulting strength could be quantified. While the characteristic strength of 'normal' poly3 is 2.35 GPa [11], this anomalous tensile

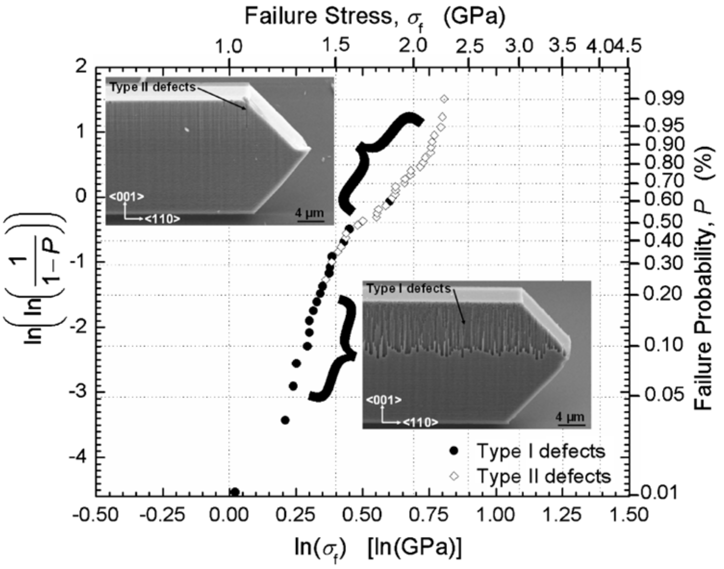

Figure 1. Bimodal Weibull distribution of tensile failure strengths in SOIMUMPs run 14 (25 μm thick single-crystal Si MEMS), based on data from [13]. In all tests, the top surface of the tensile bar was aligned with the (0 0 1) crystallographic axis, the tensile axis was aligned along the $\langle 1\,1\,0\rangle$ direction. Both defect types cause failure to occur on the $\{1\,1\,1\}$ family of planes. Failure strengths were calculated normal to the tensile axis (i.e. tensile force at fracture divided by the cross-sectional area); the resolved normal stress on the cleavage plane was lower by a factor of 0.816.

bar had a strength <0.05 GPa, below the resolution of the tensile test machine. Such a result suggests that there is not much hope for a sound statistical guarantee of some minimum strength in microfabricated Si. However, the implementation of a proof testing regimen can provide just such a guarantee for brittle MEMS.

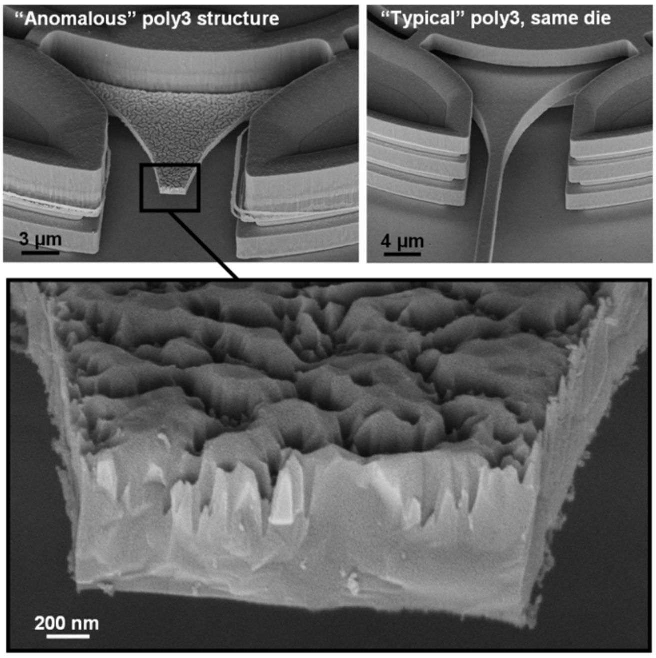

Figure 2. Discovery of an anomalous defect morphology found in the SUMMiT V polysilicon MEMS poly3 layer. This unusual defect was found in only one region of a single die. This particular specimen exhibited a fracture strength <0.05 GPa, whereas the characteristic strength from a large collection of tensile tests was 2.35 GPa.

3. The advantages of proof testing in high-reliability applications

Proof testing [2, 3] has been used to qualify structural components in many high-reliability applications from turbine disks to hand guns to medieval body armor. The premise is straightforward; prior to fielding a component, the component is tested under service-like conditions at or above the design stress. If the component survives, then it will be expected to survive in service, barring any thermal, environmental or mechanical degradation produced by corrosion or fatigue. It is a thresholding or truncationtechnique that permits the elimination of defected components whose failure strengths belong to the lower tail of the Weibull distribution [20].

Brittle MEMS materials are nearly an ideal candidate for proof testing. At room temperature, they do not experience significant plastic deformation. Therefore, unlike structural alloys, Si or other brittle MEMS materials will be unharmed by proof testing (with appropriate consideration for potential fatigue or stress corrosion damage, as discussed in the following paragraph). With a proof testing regimen in place, the impressively high average or characteristic strength of Si becomes an asset. To illustrate, one can return to the example of the poly1 layer in SUMMiT polysilicon. With the characteristic strength of 1.35 GPa and a Weibull modulus of 9.71, a proof testing regimen at 1.0 GPa would permit 95% of the devices to pass while eliminating the remaining 5% that belong to the lower tail of the distribution. Each of these devices that passed would have an allowable service stress of 1.0 GPa. The mass-production aspect of MEMS provides yet further benefit; most MEMS processes replicate an individual structure 100s of times in a single production run. Therefore, for very strenuous structural applications, poly1 could be proof tested to 1.5 GPa. While only 6 of every 100 components would survive the proof testing, the remaining intact components could be used at service stresses well above the expected or characteristic strengths. Because the MEMS structures are inherently mass-produced, applications with low volume requirements can trade yield for reliability.

The implementation of proof testing can also limit the possibility of fatigue failure in brittle MEMS components. Research over the past decade has shown micro-scale Si can fail at cyclic stresses well below their monotonic strength (e.g. [21–23]). While the precise mechanism of fatigue damage in microfabricated Si remains controversial, it is clear that there is both a mechanical and an environmental component to the process. However, the observed stress-life (S–N) behavior for various brittle MEMS materials can be used to establish proof testing limits. The required proof stress should be based on the observed ratio of the fatigue limit (at an appropriate cycle count) to the monotonic strength. For example, in polycrystalline Si, fatigue failures do not occur at applied cyclic stresses below ∼60% of the monotonic strength, even after 10^9 cycles or more. Therefore, if polycrystalline Si devices are proof tested to 2× their service stress, then the possibility of fatigue failure is essentially eliminated. On the other hand, single-crystal silicon material has exhibited fatigue failure at cyclic stresses as low as ∼20% of the monotonic strength in 10^9–10^{10} cycles, and therefore would require proof testing to 5× of the peak service stress.

There is some due caution that should be exercised if proof testing is to be applied to MEMS materials. First, the proof test loading conditions should match the in-service conditions. Otherwise the proof test will not sample the same flaw population as in service. Second, the environment for proof testing should be at least as aggressive as the worst-case service environments: humidity and temperature can both play a role on the strength of these materials. Finally, representative proof testing may not be feasible in all component designs. However, when the component is explicitly designed with proof testing in mind, it stands the greatest chance of engineered reliability.

4. Summary

The original enthusiasm regarding the mechanical performance of Si and other brittle MEMS materials must be tempered by the realities associated with their statistical unpredictability. While the expected value or characteristic strength of these materials can be quite impressive, high-risk applications require that design is based on ‘worst-case’ scenarios, which can create an insurmountable divide between component designers and safety engineers. Proof testing provides a means to overcome such a divide, and permits a statistically-sound, standardized methodology for the qualification of brittle MEMS materials.

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