Failure Mechanisms in MEMS

Micro-470: Scaling Laws in Micro & Nanosystems

H Shea

Goals of this lecture

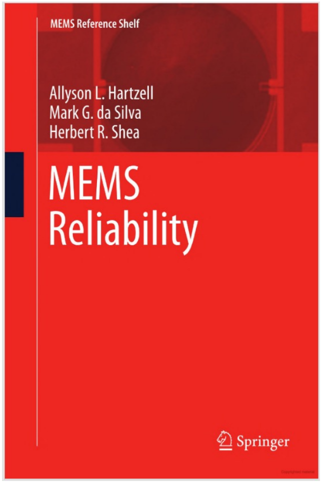
1) Understand main Failure Mechanisms in MEMS (especially mechanical)
2) Know how to mitigate those failure mechanisms

Reference:

"MEMS Reliability" by A. Hartzell, M da Silva, H. Shea.

free download from EPFL IP address
https://www.springer.com/gp/book/9781441960177

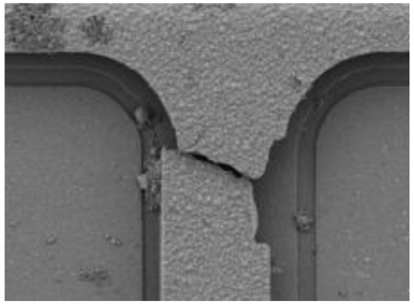
(and pdf on class moodle)



What are failure mechanisms?

Failure mechanisms are the physical, chemical, thermodynamic or other processes that result in failure.


Tacoma Narrows Bridge, 1940



reliability entails trade-offs…

reliability must be considered from design stage

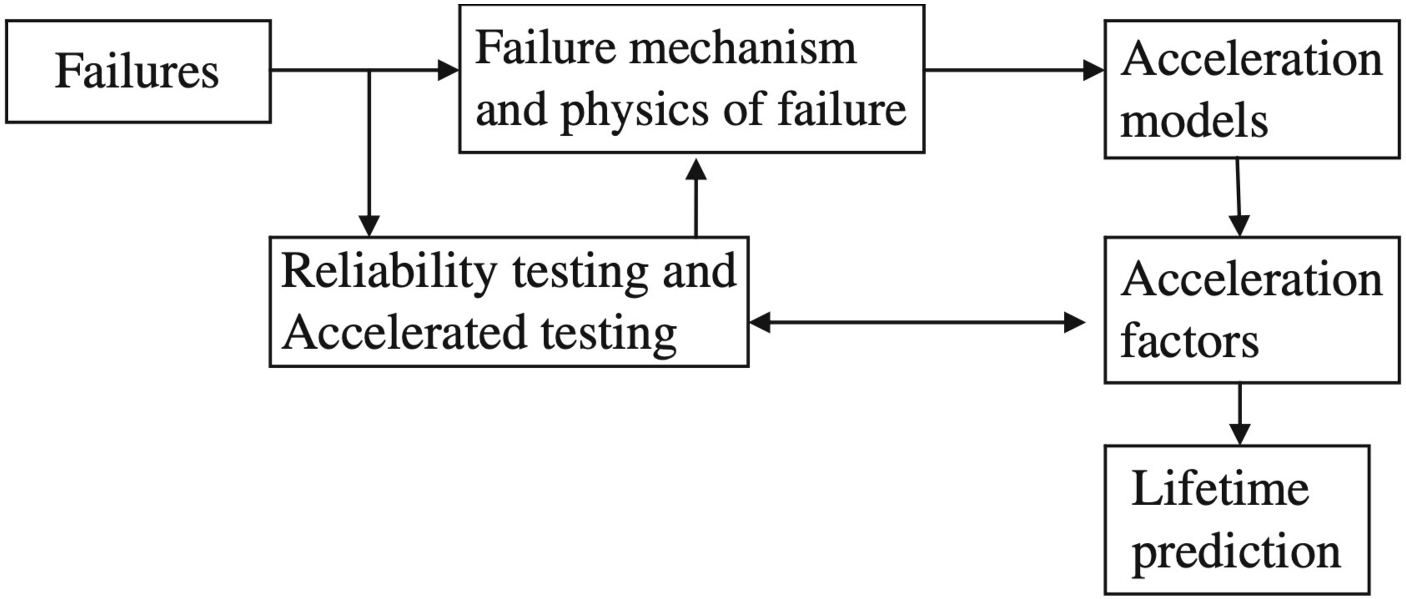
Reliability Statistics

"We spend too much time in our reliability courses on probability and statistical inference … that show us how to quantify our ignorance. We do not spend enough time removing that ignorance … the engineering, physics and chemistry of why things fail and why things don't fail"

R.A. Evans, editorial writer for the *IEEE Transactions on Reliability*, from Vol. 39, p.257, Aug 1990

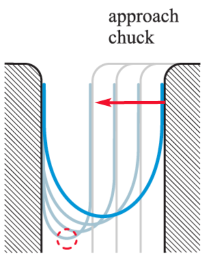
See chapter 2 of "MEMS reliability" book

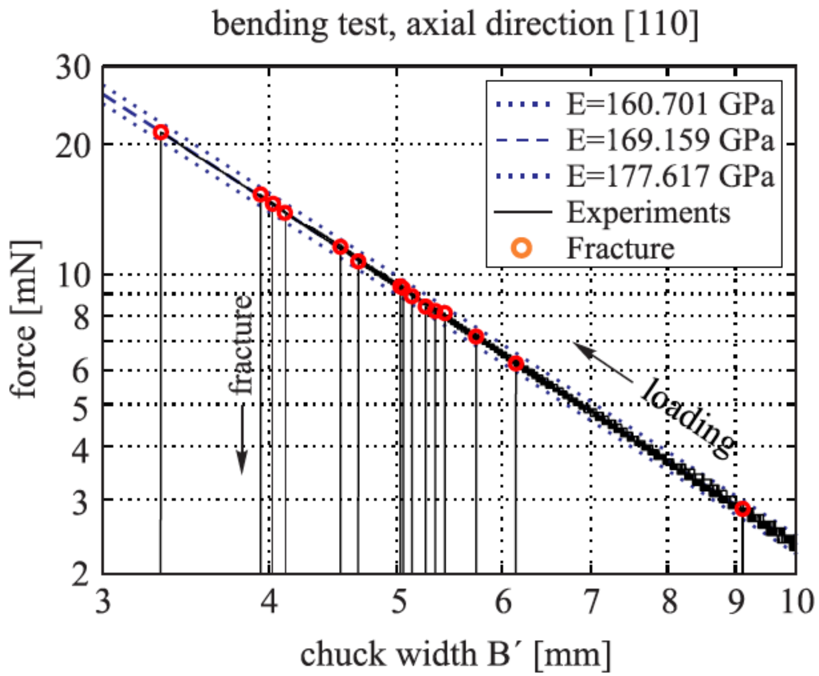
Statistics Goal 1: Predict Lifetime



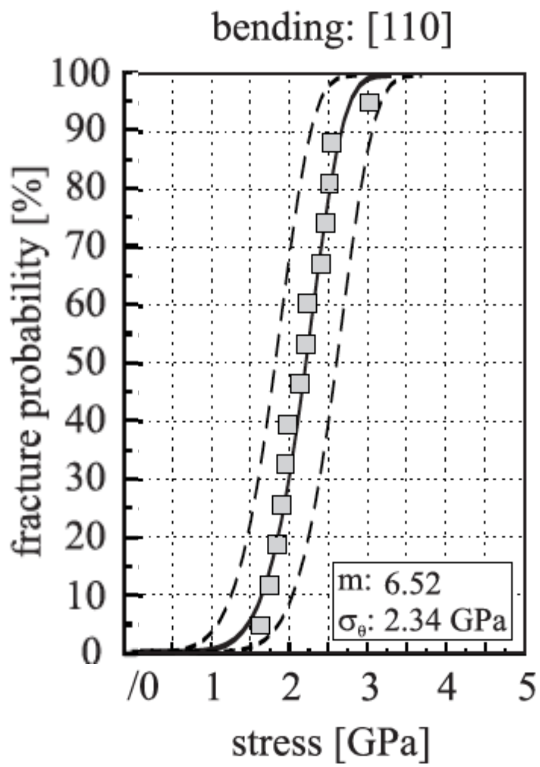
Statistics Goal 2: understand distributions

PhD thesis A. Schifferle, 2011, ETHZ



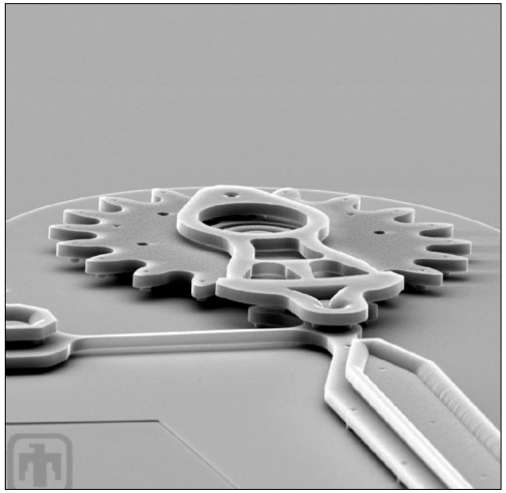


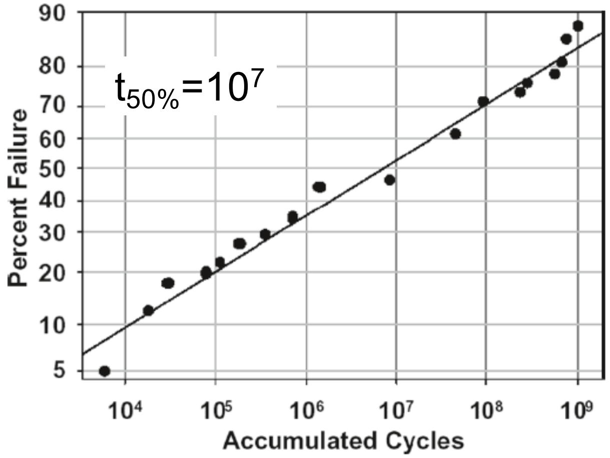
strain

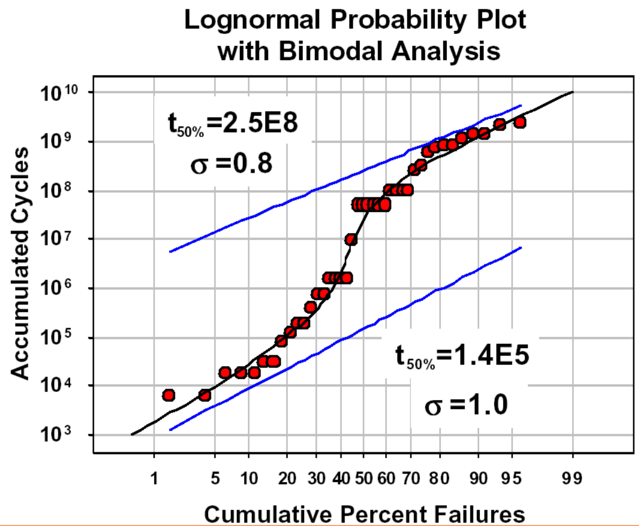


Weibull plot

Reliability Statistics: Motivation







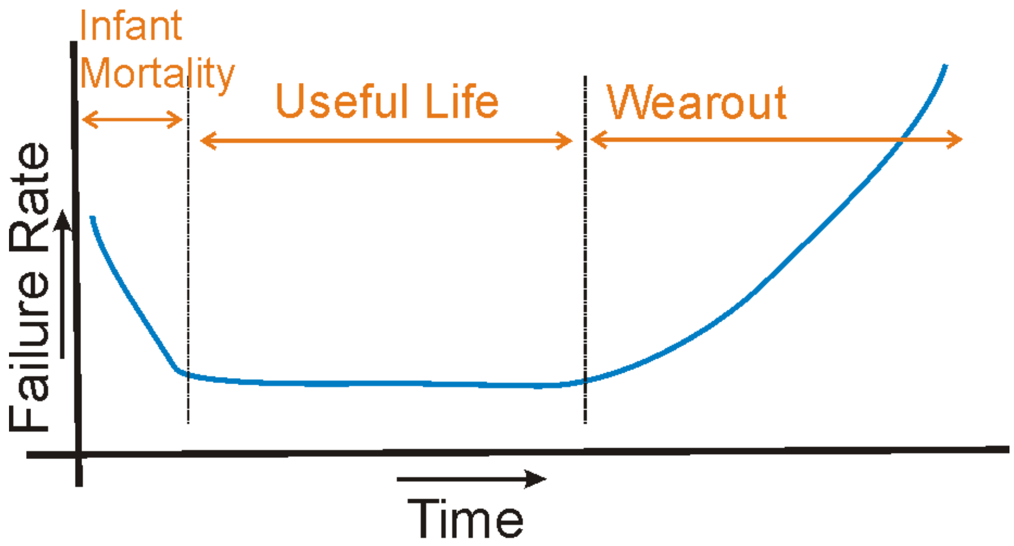
Data from: "*MEMS Reliability: Infrastructure, Test Structures, Experiments, and Failure Modes*", D. M. Tanner *et al.*, Sandia Report SAND2000-0091, 2000
Courtesy Sandia National Laboratories, Radiation and Reliability Physics Dept., www.mems.sandia.gov

- Why reliability Statistics?
  - Understand the distribution of failures: several failure modes, several populations?
  - Identify the correct model to determine the mean time to failure, and the width of the distributions
  - Extrapolate from accelerated testing to standard operating conditions
  - Determine the optimum burn-in conditions

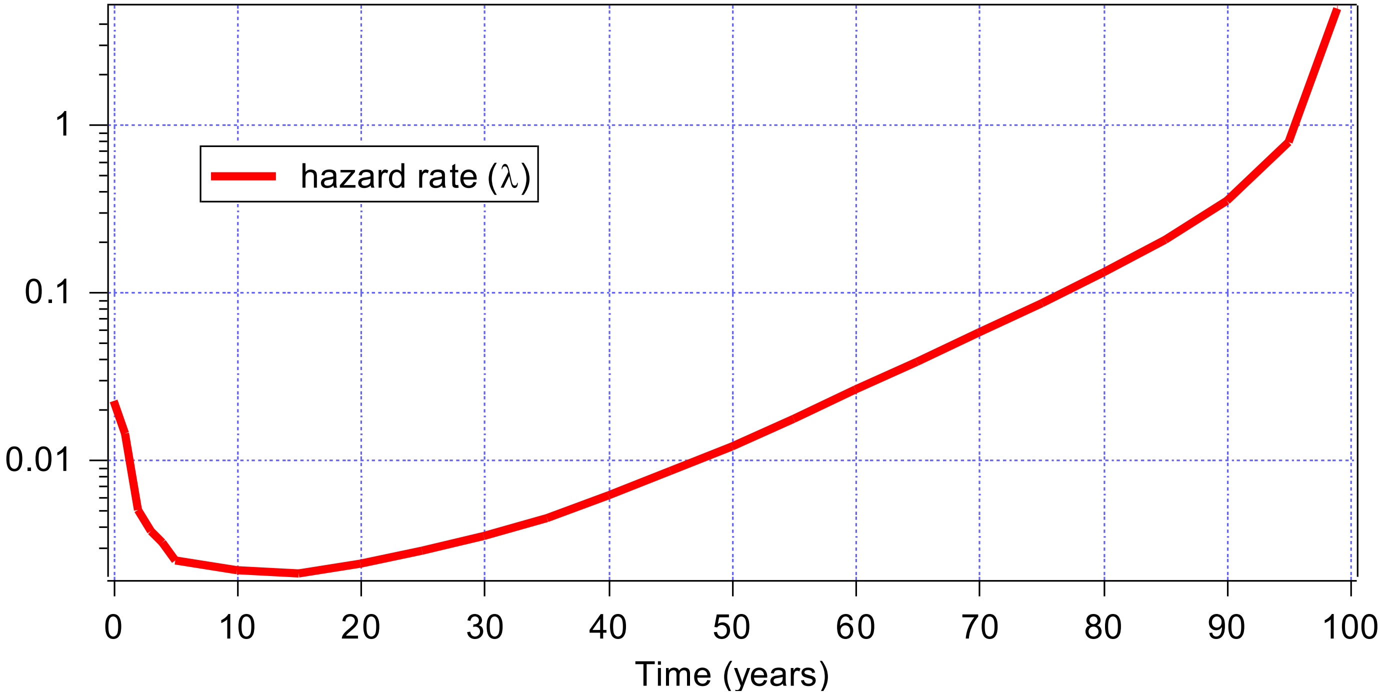
Bathtub curve

- <u>The Bathtub Curve</u>: describes failure rate of assorted products over their lifetime. 3 main regions

Plotting Hazard rate λ

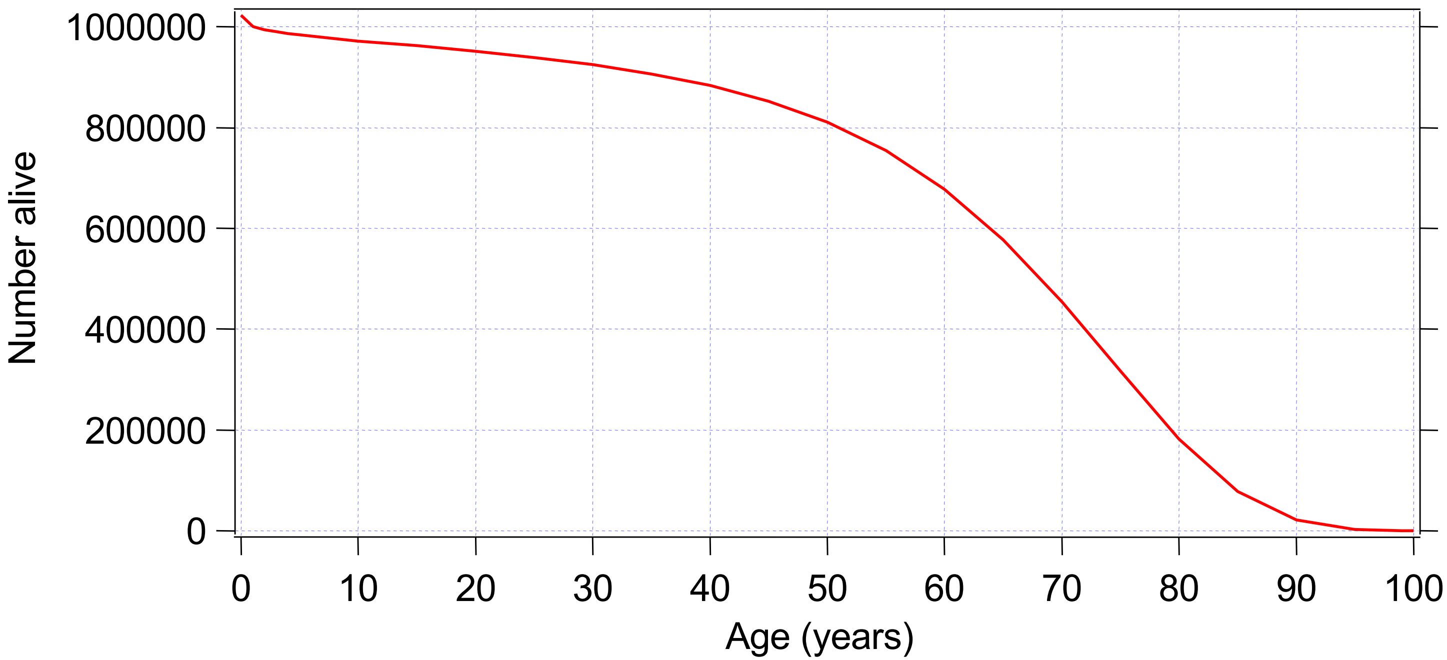


Human Mortality



Based on data from J.H Bompass-Smith "Mechanical Survival: the use of reliability data", McGraw-Hill, NY 1971

Mortality data circa 1970 (USA)



S= fraction surviving= $\frac{n(t)}{n(t=0)}$

Based on data from J.H Bompass-Smith “Mechanical Survival: the use of reliability data”, McGraw-Hill, NY 1971

Basic Definitions

F(t) = probability of failing before time *t*

= fraction of population expected to fail by time *t*

= CDF Cumulative Distribution function

$$F(t) = 1 - \frac{n(t)}{n(0)} = 1 - S(t)$$

f(t) = probability of failure per unit time at time *t* for any member of the initial population

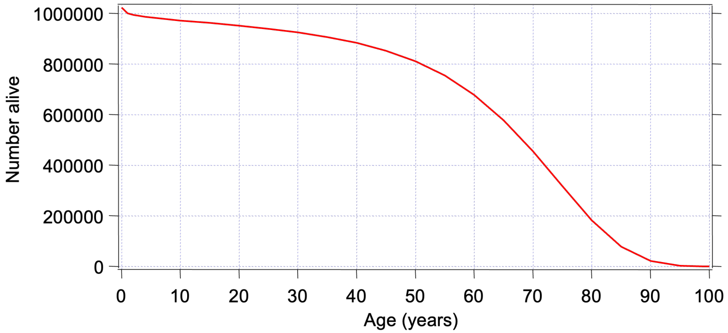
= PDF Probability Distribution Function

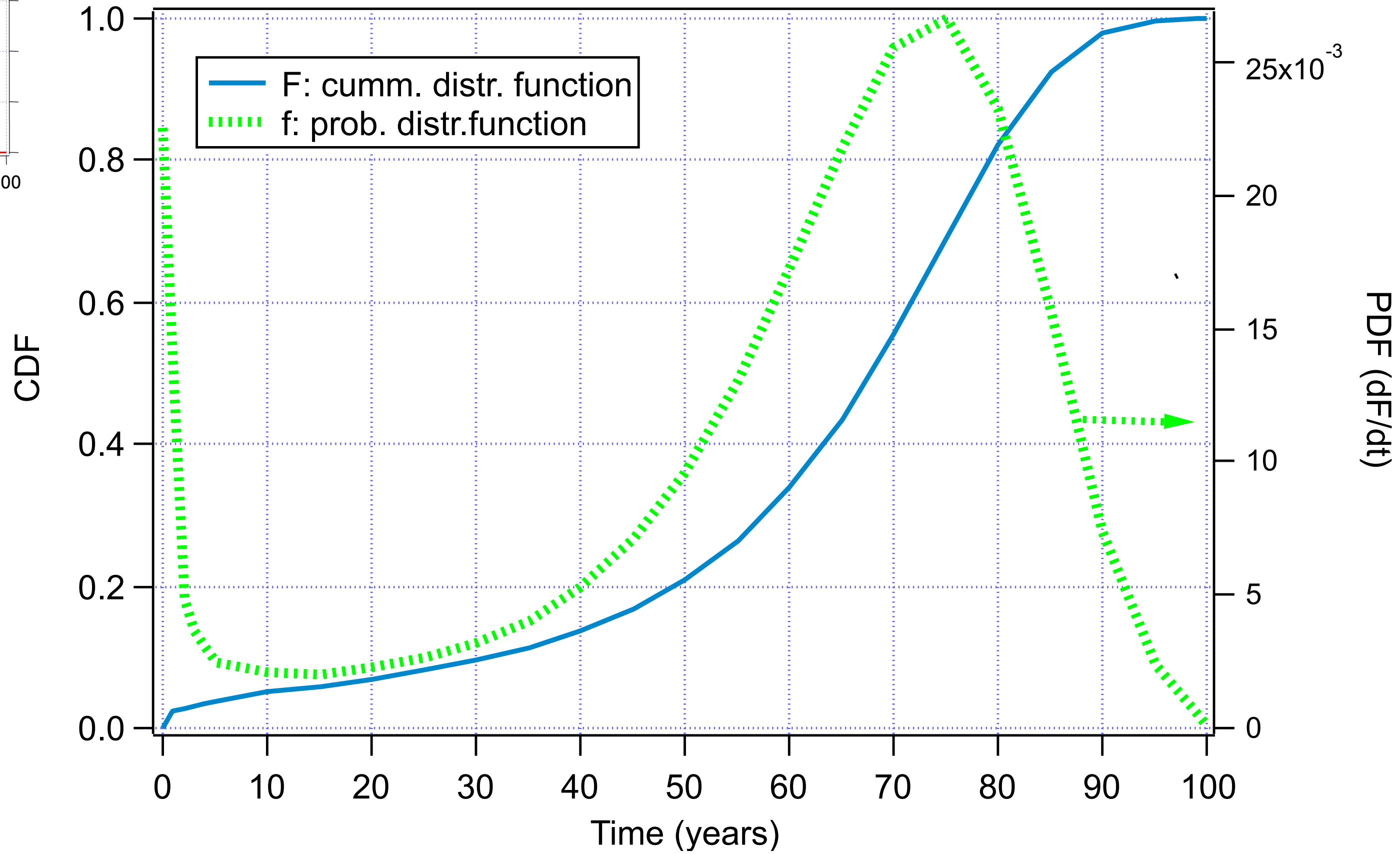
$$\mathrm{f}(t) \approx \frac{n(t) - n(t + \Delta t)}{n(0)\Delta t}$$

$$= \frac{\mathrm{d}F(t)}{\mathrm{d}t}$$

n(t)= healthy/operational population at time t

Mortality data





$$F(t) = 1 - \frac{n(t)}{n(0)}$$

$$f(t) = \frac{dF}{dt}$$

Basic Definitions, continued

$\lambda(t)$ = failure rate or hazard rate

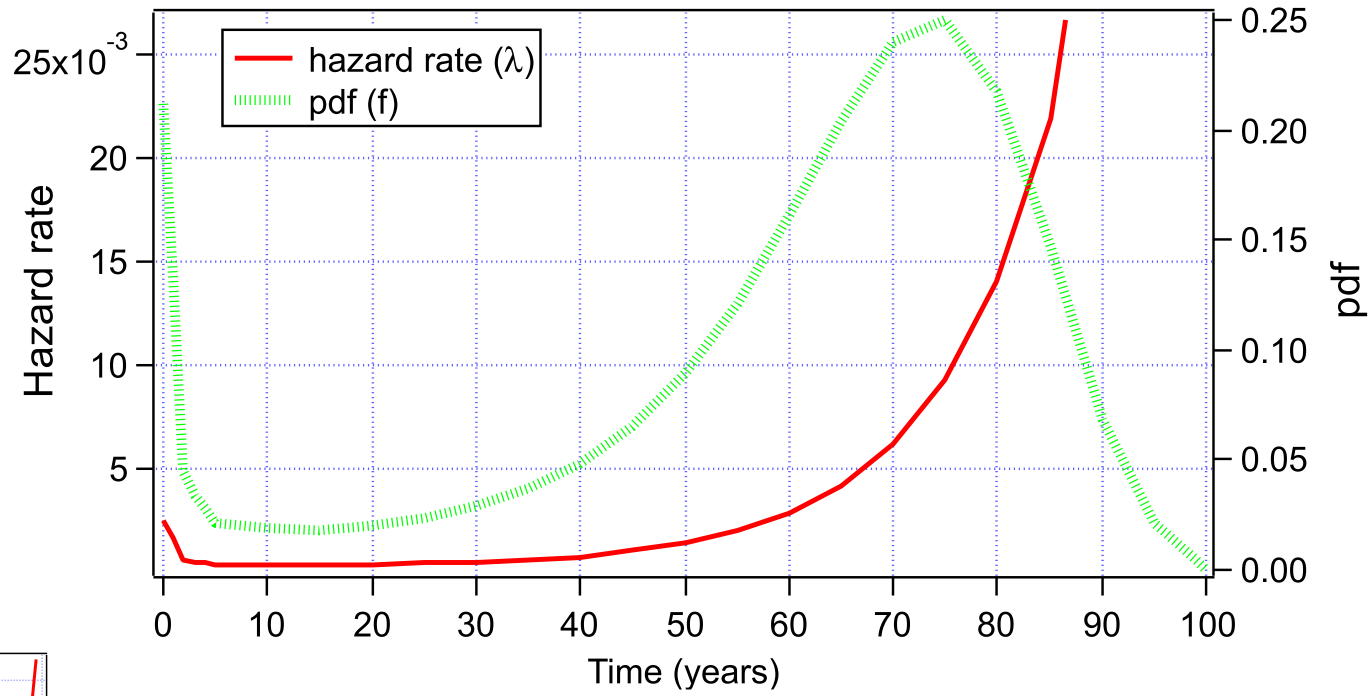
= probability of failure per unit time at time *t*, given that a member of the initial population survived until time *t*

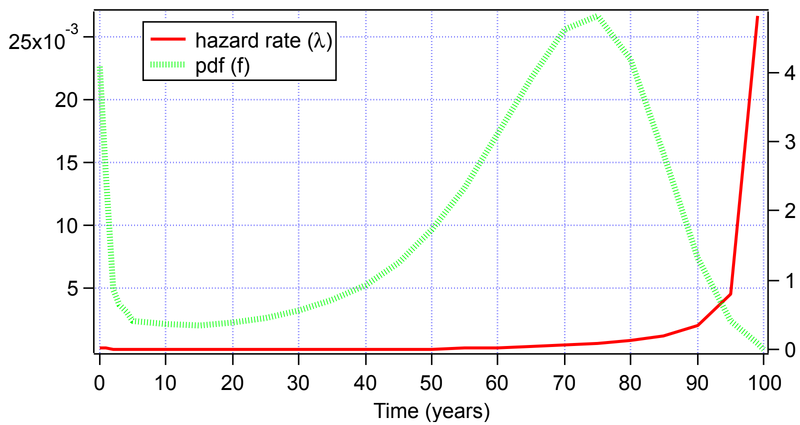
= failure rate of the survivors

$$\lambda(t) \approx \frac{n(t) - n(t+\Delta t)}{n(t)\Delta t} = \frac{f(t)}{1 - F(t)}$$

$$\mathrm{f}(t) \approx \frac{n(t) - n(t+\Delta t)}{n(0)\Delta t} = \frac{\mathrm{d}F(t)}{\mathrm{d}t}$$

Mortality data, hazard rate



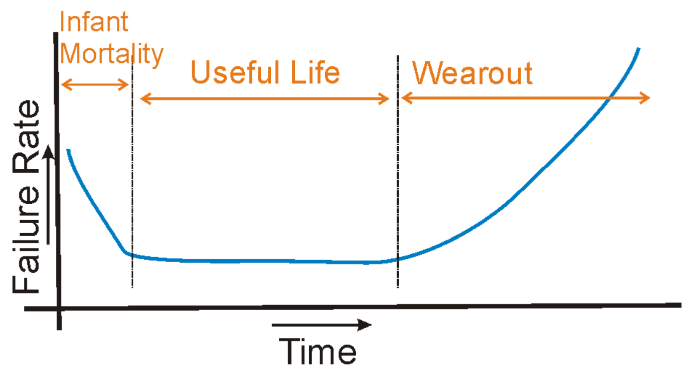


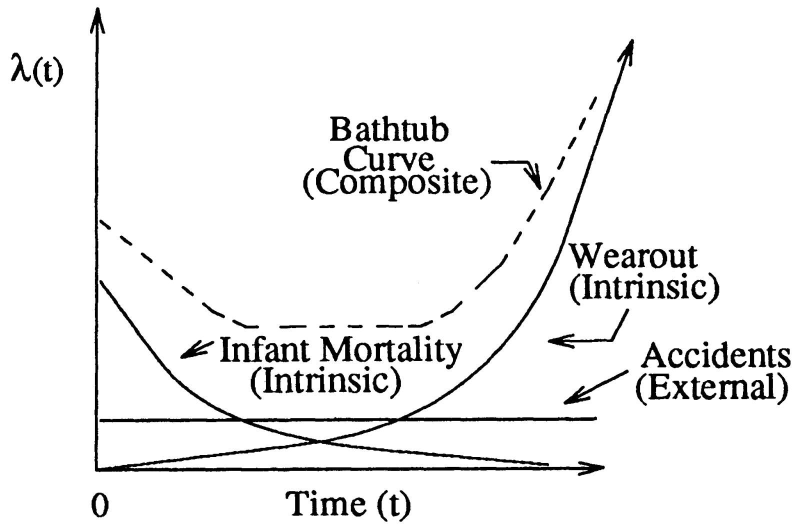
Three regions of the bathtub curve

1. Infant mortality: failures due to weak or defective products; justifies initial testing and burn-in (elevated temperature, overvoltage, etc.). Built-in weaknesses cause failures even in the specified operating limits

2. Useful Life: roughly constant failure rate. Failures are mostly due to external events, e.g. voltage surge or ESD

3. Wearout: failure rate starts to increase as device ages, parts wear from friction, wires fail due to electromigration…





Lower plot from: "*Estimating Device Reliability: Assessment of Credibility*", F.R. Nash, Kluwer Academic Publishers, 1993, p.64

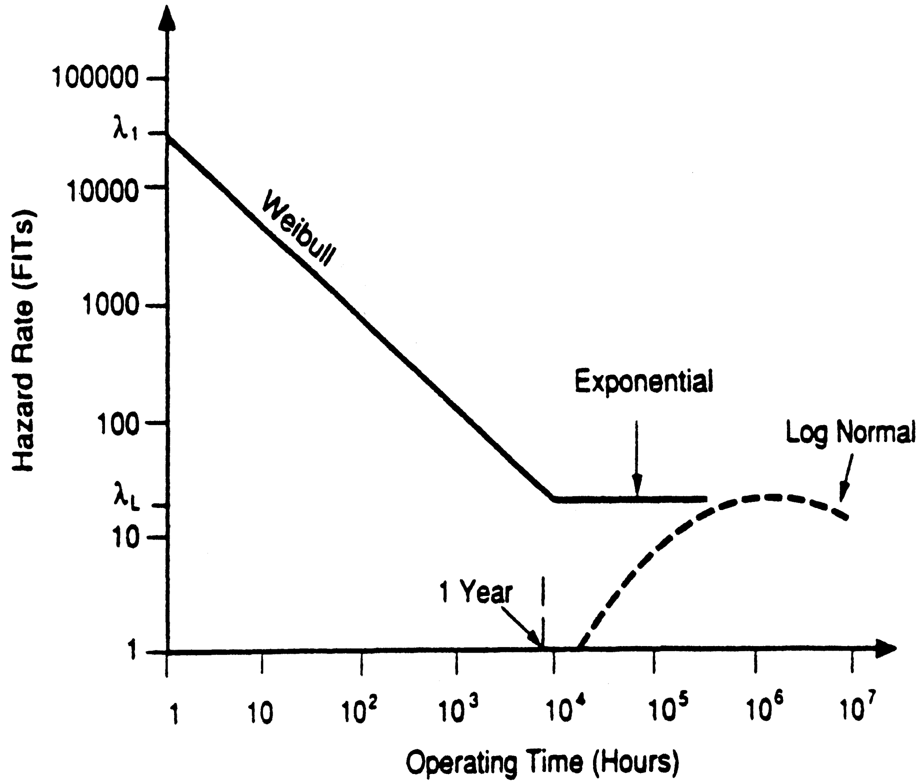
Reliability Statistics: 4 Standard Models

- 4 main Probability Models are used:
  - Exponential
  - Weibull
  - (Normal)
  - Lognormal

- Different models apply in different cases (or not at all) and it takes a lot of data to be able to determine which gives the best fit.
- Nash (1993) gives an excellent discussion of how to decide which model to use

- MTTF: Mean time to Failure

Models of λ (t)



Graph from: "*AT&T Reliability Manual*", D.J. Klinger *et al.*, Van Nostrand Reinhold, NY 1990, p27

Weibull Model

Weibull Model

- 2 parameter model, can apply to both:
  - Decreasing failure rates (typical of early failure) and
  - Increasing failure rates that describe wearout

$$\lambda(t) = \alpha^{\beta} \beta t^{\beta-1}$$

$$f(t) = \alpha^{\beta} \beta t^{\beta-1} \mathrm{e}^{-(\alpha t)^{\beta}}$$

$$F(t) = 1 - \exp\left[-(\alpha t)^{\beta}\right]$$

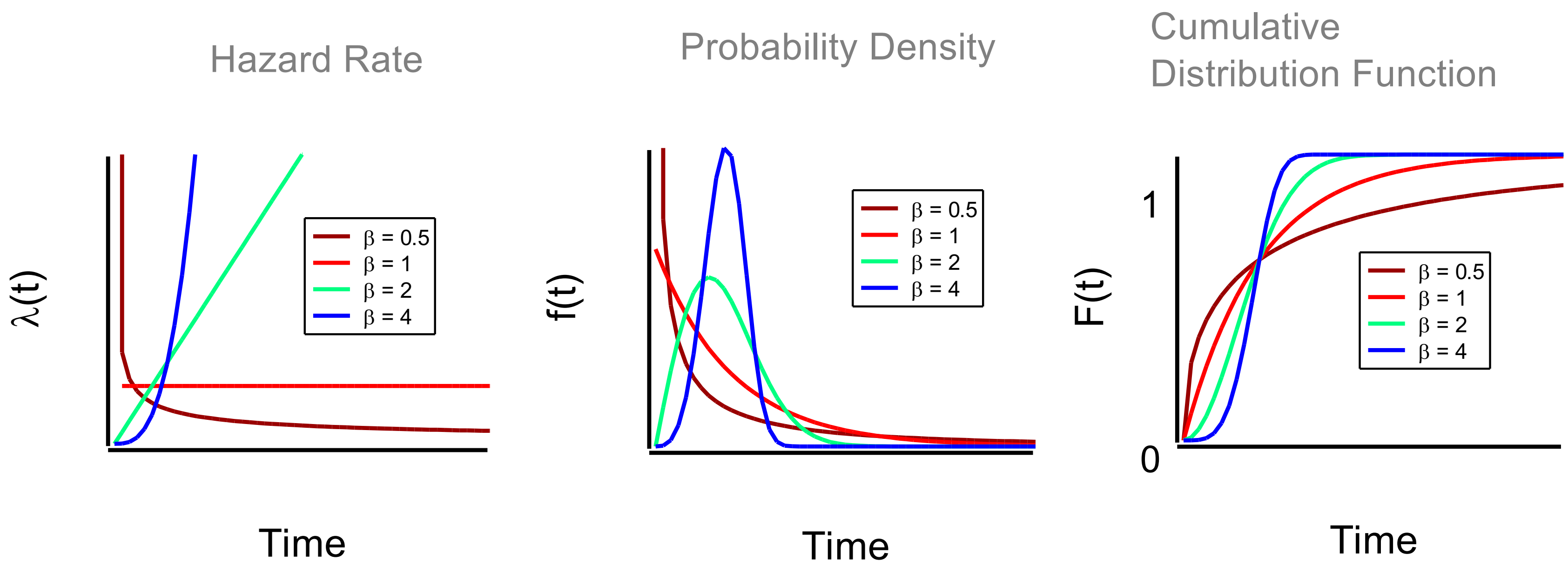
$$\mathrm{MTTF} = \frac{1}{\alpha}\Gamma\left(1 + \frac{1}{\beta}\right)$$

$$\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t}\, dt$$

- **α is the scale factor; 63.2% of failure occurs before t=1/α**
- **β is the shape factor, a measure of dispersion (big is good)**
- **The Weibull model describes infant mortality very well, but does not account for wearout as accurately**

Weibull Model for fixed MTTF

- $0 < \beta < 1$: failure rate $\lambda(t)$ decreases with time
- $\beta = 1$: exponential model: λ is a constant
- $\beta > 1$: failure rate $\lambda(t)$ increases with time



Plots for fixed α: same MTTF for all cases

Accelerated Testing

- It is essential to set up a careful accelerated test plan because "the options of waiting until every last issue that might affect reliability is unambiguously resolved does *not* exist" (Nash, 1993)
- In reality: never have all the data before the product is shipped: need a plausible and reasonable way to extrapolate from shorter testing times to true device lifetime
- The crucial assumption in accelerated testing is:

  The mechanism of damage is the same under normal and accelerated test conditions

  hatching an egg ≠ boiling an egg

- The Acceleration Factor (AF) is defined as:

$$\boxed{\mathrm{AF} = \frac{\mathrm{MTTF}(condition_1)}{\mathrm{MTTF}(condition_2)} = \frac{\mathrm{rate}(condition_2)}{\mathrm{rate}(condition_1)}}$$

Accelerated Testing

- Accelerating factors include
  - temperature,
  - voltage,
  - current,
  - vibrations,
  - thermal shock,
  - mechanical shock,
  - UV/sunlight exposure
  - pressure

Accelerated Testing

- If Temperature is used, a simple **Arrhenius law** is almost always assumed

$$AF = Exp\left[\frac{E_a}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

- Once the AF has been determined for one or more parameters, and one is confident the accelerated testing is reasonable (same failure mode and same mechanism), one can determine the device MTTF (Mean Time To Failure) under normal operating conditions:

  MTTF(a) = MTTF(b) / AF(a➔b)

  λ(a) = λ(b) . AF(a➔b)

- Use with great care if AF>>10 (as it is unlikely that the same failure mechanism is still dominant)

"*Acceleration factors of 10 are not unreasonable. Factors much larger than that tend to be figments of the imagination and lots of correct, but irrelevant, arithmetic*"
R.A. Evans, *IEEE Transactions on Reliability*, Vol. 40, p.497, 1991

Accelerated Testing

Powerful concept!!!

- How to scale to go from accelerated conditions to normal conditions?

- Weibull:

$$\alpha_{\mathrm{nominal}} = \alpha_{accel} . AF$$
$$\beta_{\mathrm{nominal}} = \beta_{accel}$$

(for other models, different scaling)

Accelerated Testing

- Example:
  - Laser modules tested at elevated temperature for 2 months, with AF estimated at 1000
  - Weibull distribution from accelerated testing is: α = 2.10^3 hours, and β =1.5
  - What is the probability the laser will last 5 years?

$$\alpha_{\text{nominal}} = \alpha_{accel}.AF$$

$$\beta_{\text{nominal}} = \beta_{accel}$$

$$F(t) = 1 - \exp[-(\frac{t}{\alpha})^{\beta}] = 1 - \exp[-(\frac{t}{\alpha_{accel}.AF})^{\beta}]$$

$$F(5.365.24) = 1 - \exp[-(\frac{5.365.24}{2.10^3.1000})^{1.5}] = 3.3.10^{-3}$$

S=1-F, so probability of lasting 5 years is 1-0.0033=99.7%

Failure Mechanisms in MEMS

1. Design Phase
2. Manufacturing
3. In-Use Failures

1. Design Phase Failure Modes

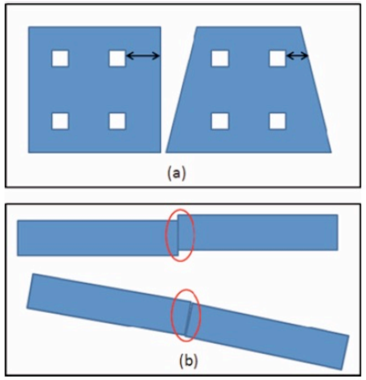
1. Design Phase Failure Modes

1.1. Functional

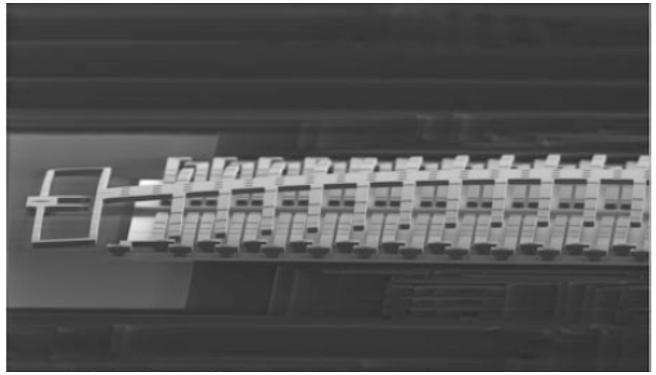
- 1.1.1 Element Design
- 1.1.2 System Level Design
- 1.1.3. Package Design

1.2. Material

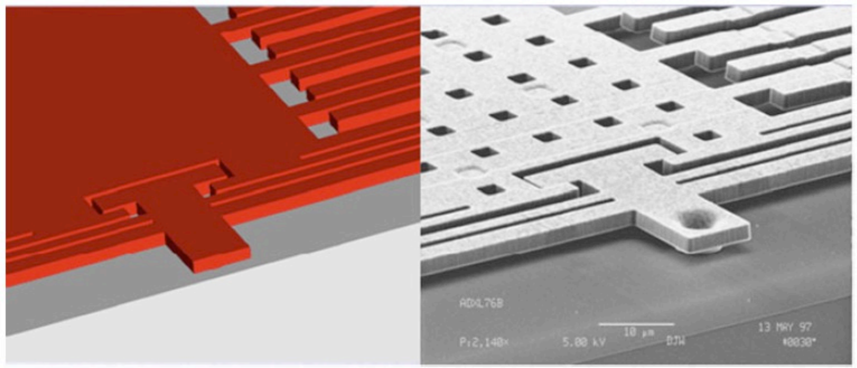
1.3. Non-analyzed Conditions



Mask Data Faults



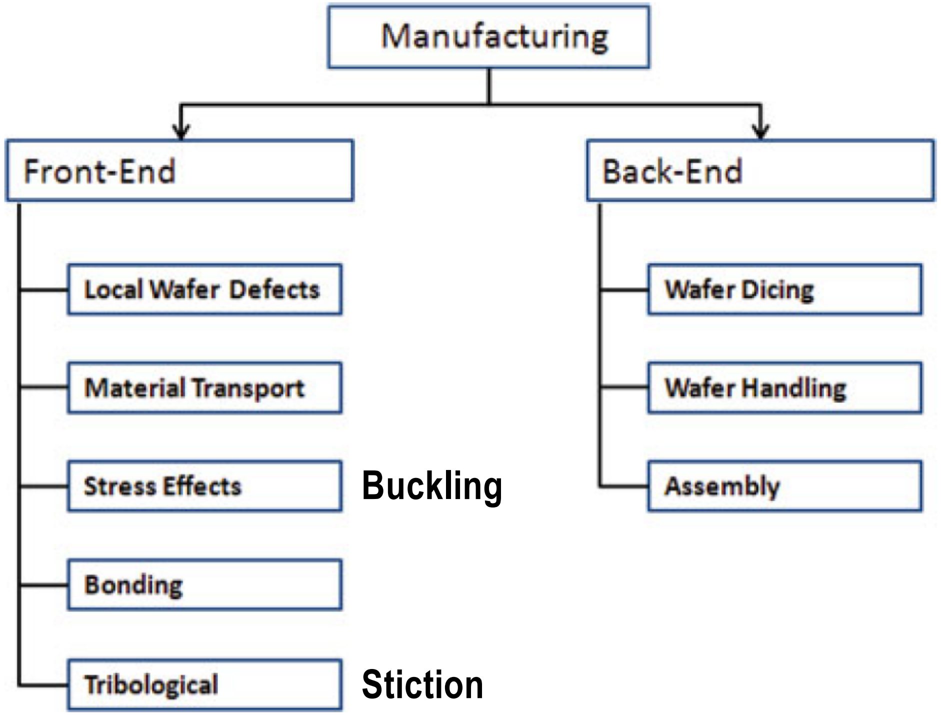
Material Properties

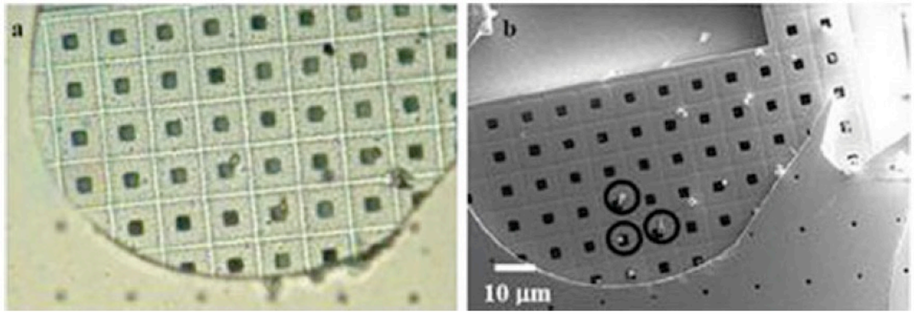


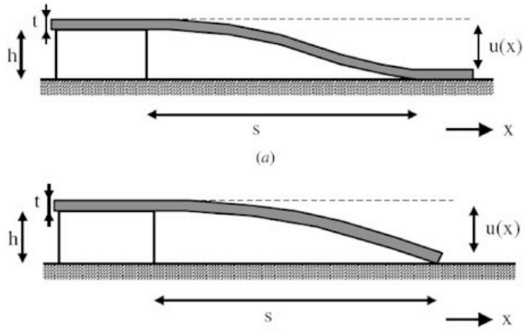
Analysis and Simulation

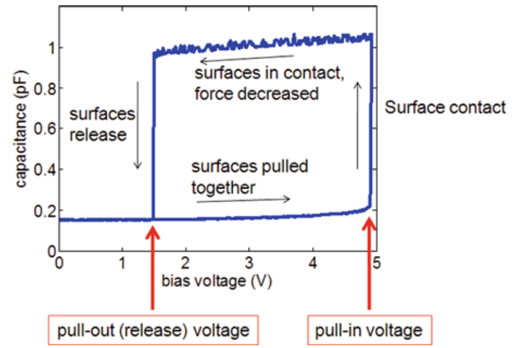
MEMS Reliability book
By A L. Hartzell, M G. da Silva, H R. Shea

2. Manufacturing Phase Failure Modes









From
MEMS Reliability book
By A L. Hartzell, et al.

3. In-use failures

In-Use Failures

3.1. Mechanical Failure Modes

3.2. Electrical Failure Modes

3.3. Environmental

What is the physics of the failure modes?

3.1. Mechanical Failure Modes

3.1.1. Fracture

3.1.2. Mechanical Shock Resistance

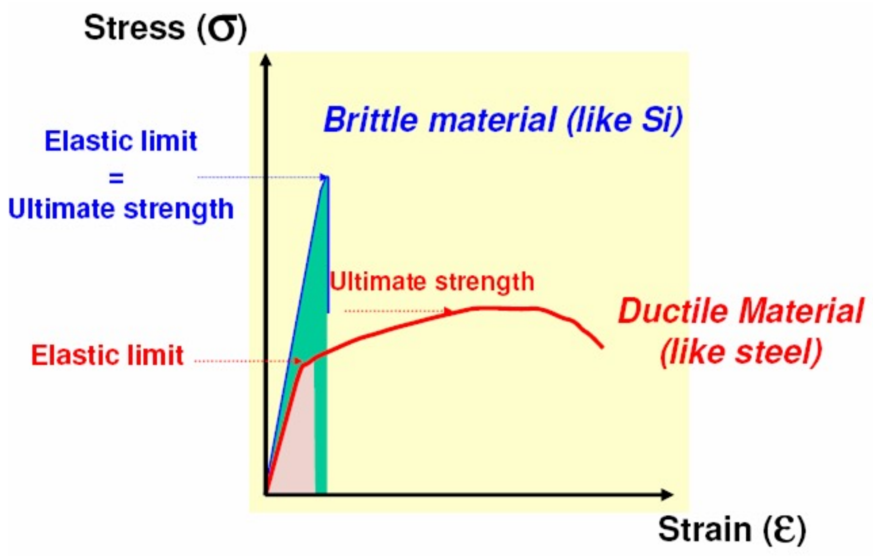
3.1.3. Vibration

3.1.4. Creep

3.1.5. Fatigue

Tensile Strength – Material Characterisation

- Material Characterisation
  - Uniaxial pull-test:
  - Young's Modulus
  - Limit of elasticity
    - Plastic deformation
    - Hyperelasticity
  - Ultimate stress
  - Fracture



Tensile Strength – Ductile Materials

- Materials that deform plastically
- Yield stress: limit of elasticity
- Yield stress (with safety factor) is the limit for mechanical structures

Brittle Fracture

Ductile Fracture

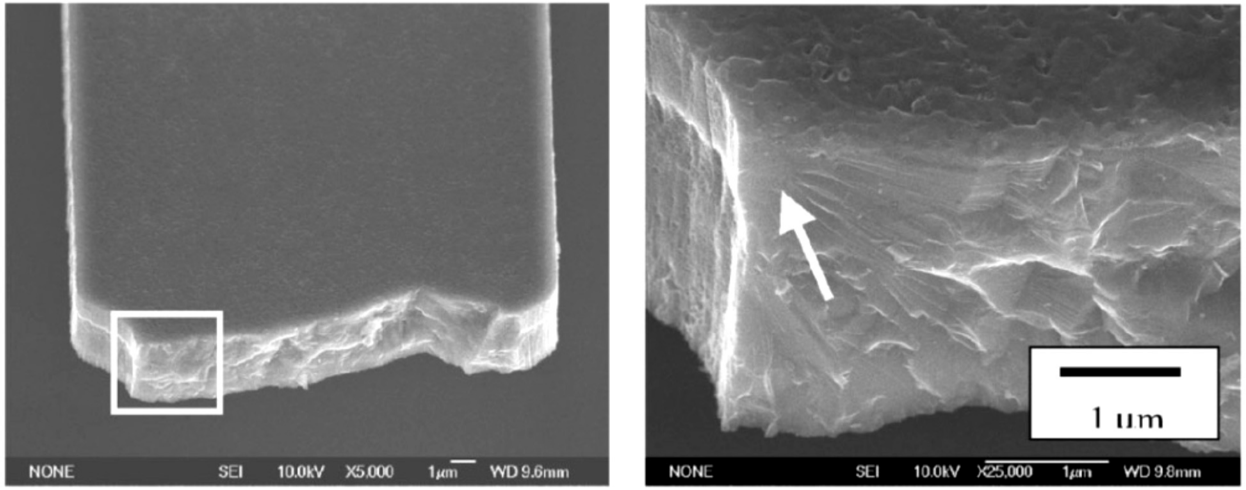
Failure Mechanisms of brittle materials

EPFL

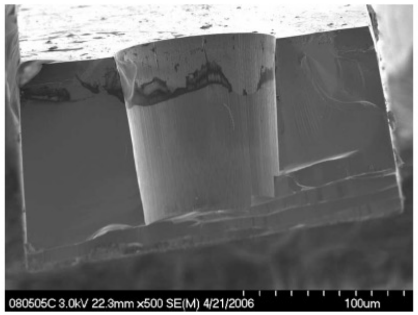
- Little-to-no plastic deformation before failure.
- Ceramics, glass, silicon, cold steel…

Important Parameters:

- Density of surface defects
- Grain size
- Surface area
- Temperature
- Processing
- Geometry

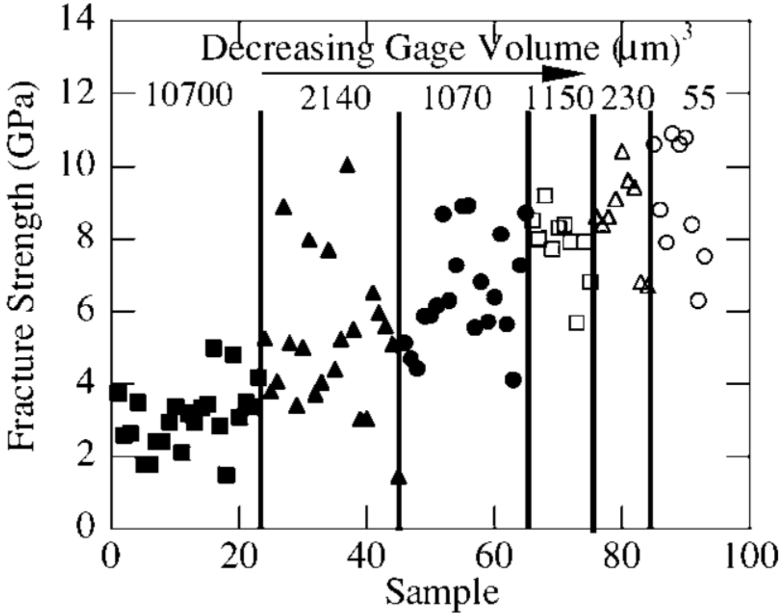


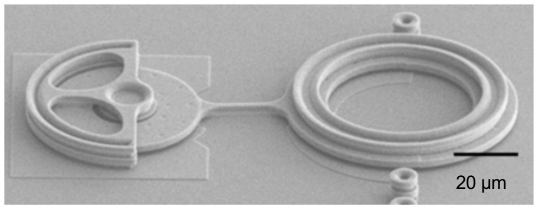
Bagdahn et al.: “Fracture Strength Of Polysilicon At Stress Concentrations”, Journal of Microelectromechanical Systems, Vol. 12, No. 3, June 2003

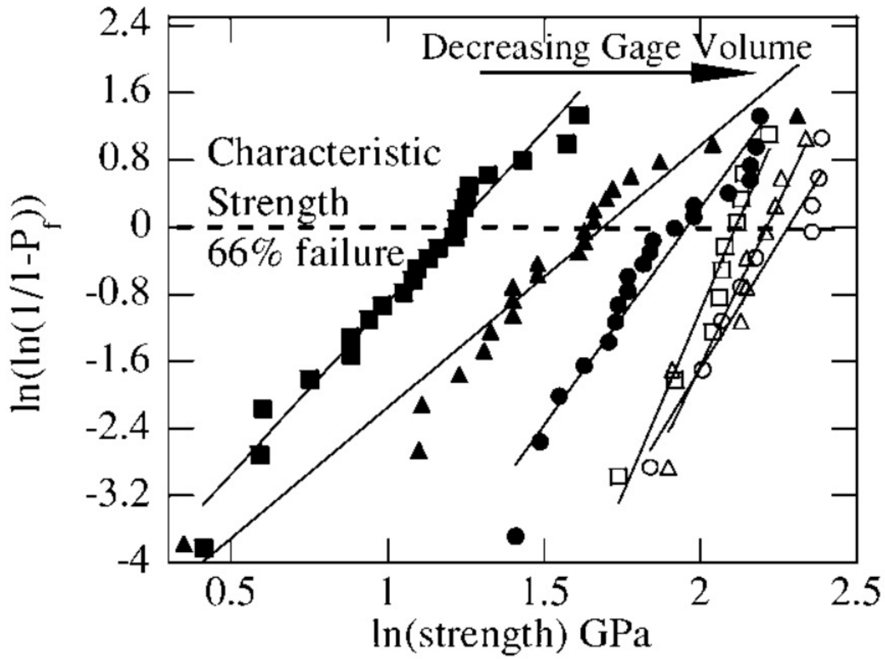


Sharpe, William et al . “Fracture Strength of Single-Crystal Silicon Carbide Microspecimens at 24° C and 1000° C.” Journal of Microelectromechanical Systems 17, no. 1 (2008): 244–254

Polysilicon fracture strength vs. area







Weibull plot

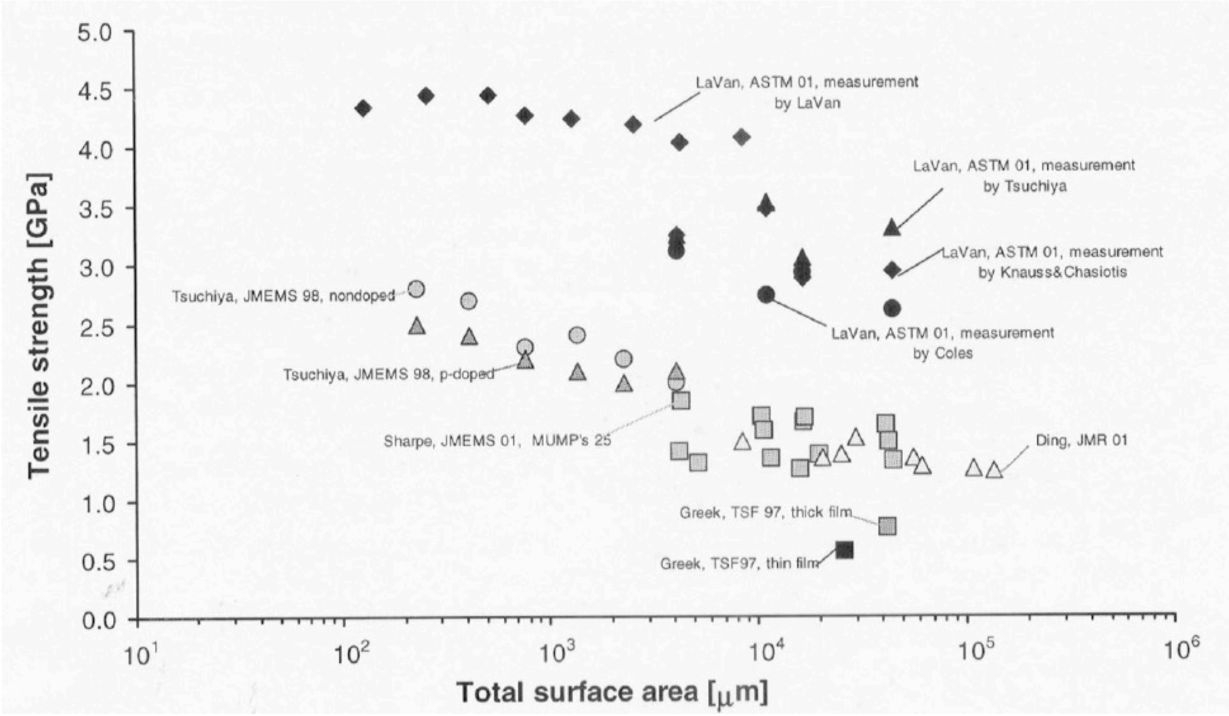
T. E. BUCHHEIT et al., “Micromechanical testing of MEMS materials”, Journal Of Materials Science 38 (2003) 4081 – 4086

Smaller = stronger

Polysilicon fracture data, Scaling

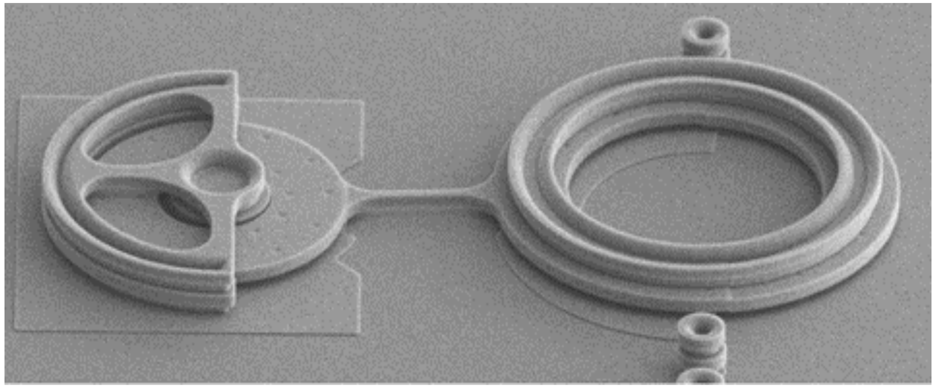
- Strength determined by size of the flaw
- If randomly distributed, larger volume or area: greater chance of bigger flaw
- Smaller sample : fewer defects, so larger failure strength
- Weibull: weakest link model, should be applicable

for brittle materials, failure is linked to defects

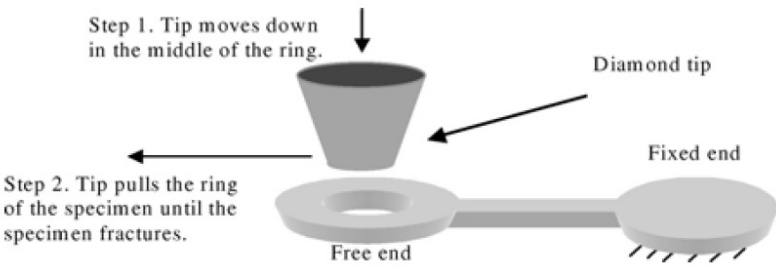


Jadaan et al, *Journal of Materials Science* 38 (2003) 4087

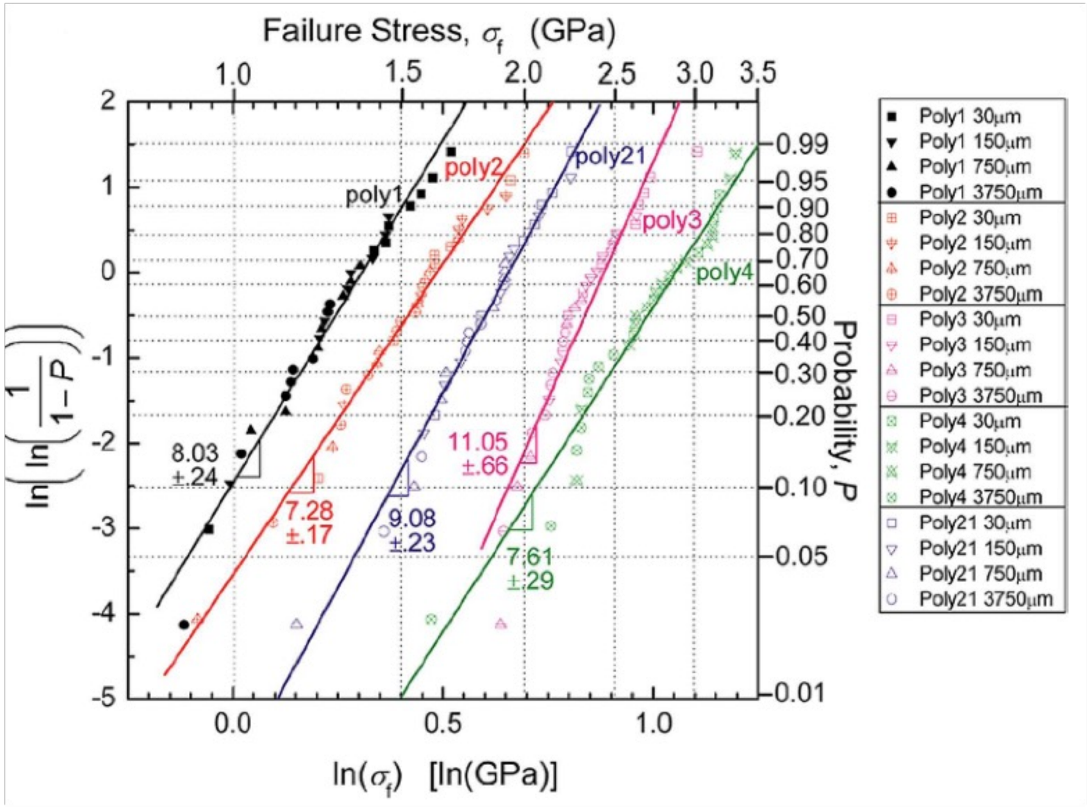
Fracture strength of different poly-Si layers



20 µm long beam



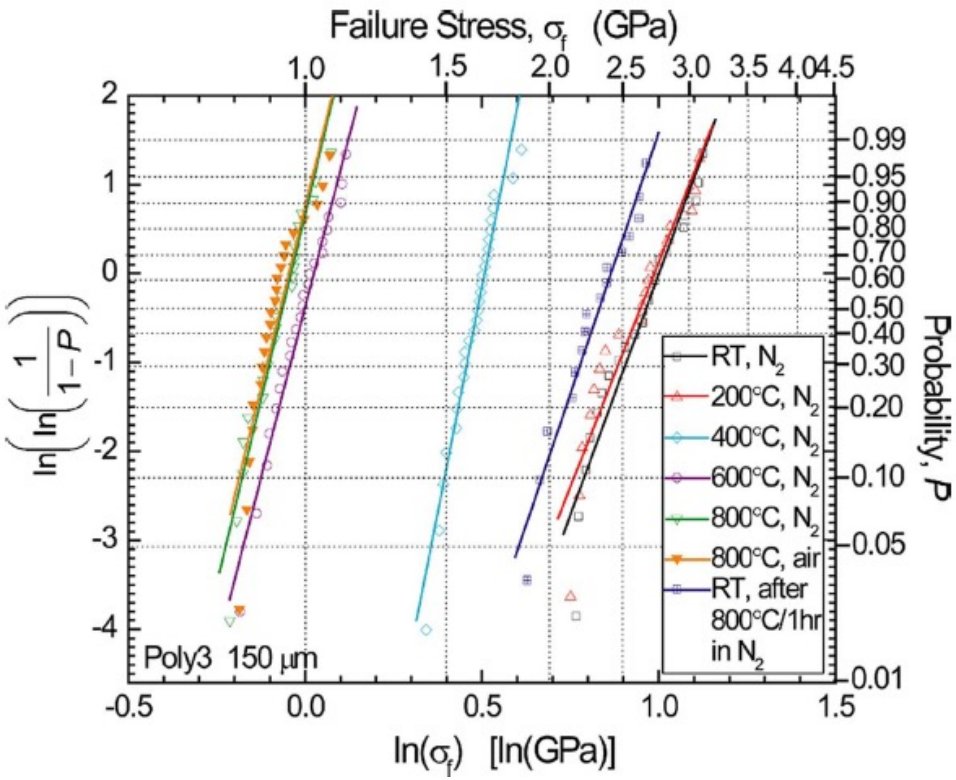
T. E. BUCHHEIT et al., "Micromechanical testing of MEMS materials", Journal Of Materials Science 38 (2003) 4081 – 4086



Weibull failure probability plot for each of five SUMMiT V™ poly-silicon layers

B. L. Boyce, J. M. Grazier, T. E. Buchheit, and M. J. Shaw, "Strength Distributions in Polycrystalline Silicon MEMS", JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 16, NO. 2, p. 179, 2007

Effect of temperature on fracture, poly Si

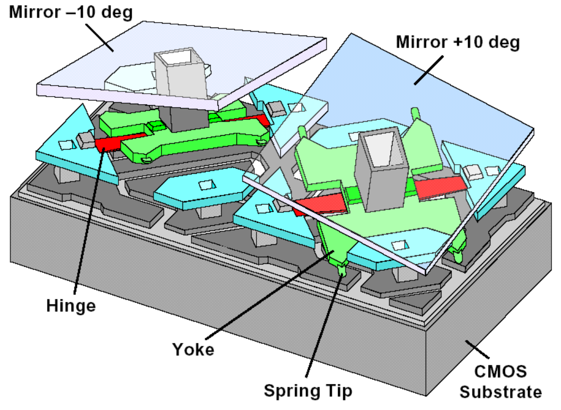


Weibull failure probability plot for one SUMMiT V™ polysilicon layer for several temperatures up to 800° C

B. L. Boyce, J. M. Grazier, T. E. Buchheit, and M. J. Shaw, "Strength Distributions in Polycrystalline Silicon MEMS", JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 16, NO. 2, p. 179, 2007

More complex structures and loading cases

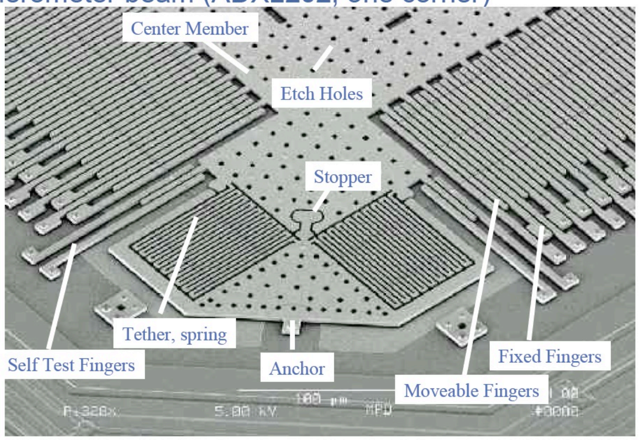
- Knowing the maximal stress of a material, how can we determine whether a complex structure and/or non-trivial loading exceeds the maximal stress?



for example

- loading on multiple directions, twisting
- stress concentration
- micro-structure blocking dislocations

Accelerometer beam (ADXL202, one corner)



Fracture Failure Models

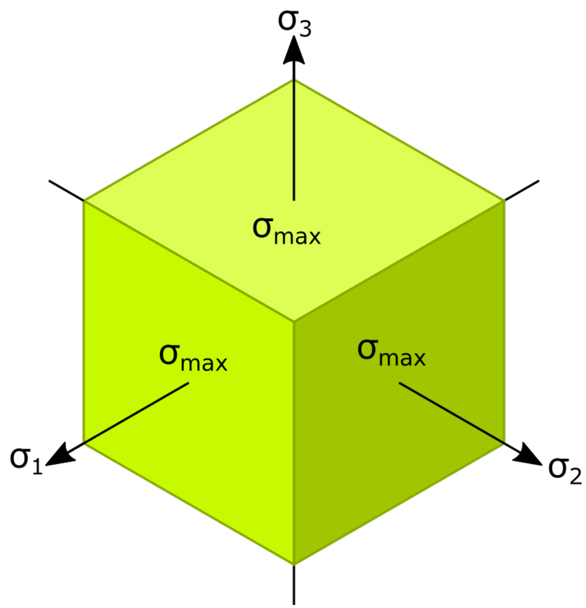
- Models for stress that is not uniaxial ($\sigma_1 \neq 0$, and $\sigma_2 \neq 0$, and $\sigma_3 \neq 0$)

- determine a Yield function $f(\sigma, \sigma_{\max})$:
  - $f < 0$ → elastic behaviour
  - $f = 0$ → limit of yield/failure
  - $f > 0$ →fail

- f can be defined in several ways
  - Principal Stress theory
  - Strain energy theory
  - Distorsional energy

Fracture Failure Models – 1. Principal Stress Theory

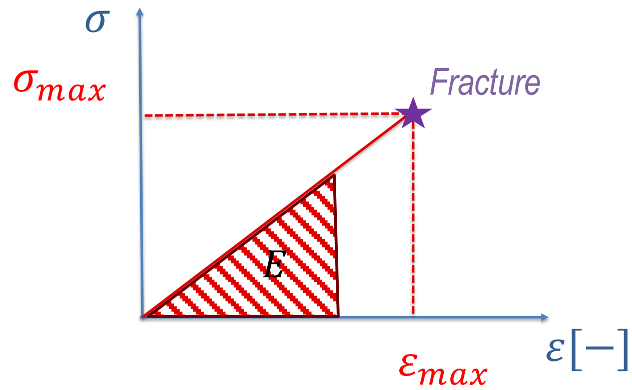
- **Failure occurs: when any one of the principal stresses ($\sigma_{1,}$ $\sigma_{2,}$ σ_3) exceeds the ultimate stress**
- Mainly used with brittle materials (e.g. Silicon)
- Yield function: $f = max(|\sigma_1|, |\sigma_2|, |\sigma_3|) - \sigma_{max}$



- Stress IN the cube: elastic deformation
- Stress Outside of the cube: failure

Failure Models – 2. Strain Energy Theory

- **Material fails if the strain energy is larger than strain energy at rupture in the uniaxial case**
- Uniaxial case: $\boxed{E_{lim} = \frac{1}{2}\sigma_{max}\varepsilon_{max} = \frac{{\sigma_{max}}^2}{2Y}}$
- General case: $$E = \frac{1}{2}(\sigma_1\varepsilon_1 + \sigma_2\varepsilon_2 + \sigma_3\varepsilon_3)$$



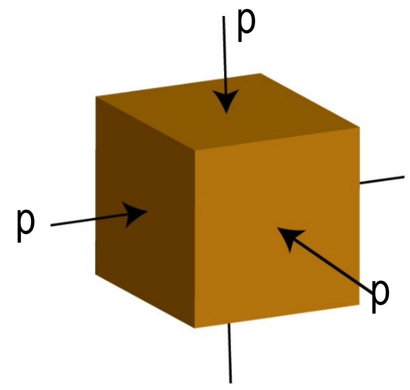
$$\varepsilon_1 = \frac{\sigma_1}{Y} - \frac{\nu}{Y}(\sigma_2 + \sigma_3) \qquad \varepsilon_2 = \frac{\sigma_2}{Y} - \frac{\nu}{Y}(\sigma_3 + \sigma_1) \qquad \varepsilon_3 = \frac{\sigma_3}{Y} - \frac{\nu}{Y}(\sigma_1 + \sigma_2)$$

$$E = \frac{1}{2Y}[{\sigma_1}^2 + {\sigma_2}^2 + {\sigma_3}^2 - 2\nu(\sigma_1\sigma_2 + \sigma_3\sigma_1 + \sigma_2\sigma_3)]$$

- Yield function: $\boxed{\boldsymbol{f = {\sigma_1}^2 + {\sigma_2}^2 + {\sigma_3}^2 - 2\nu(\sigma_1\sigma_2 + \sigma_3\sigma_1 + \sigma_2\sigma_3) - {\sigma_{max}}^2}}$

Failure Models – 3. Distortional Energy Theory

- Stress tensor can be separated in two:
  - Mean hydrostatic tensor (or volumetric stress tensor) = change in the *volume* of the body
  - Deviatoric tensor: *deforms* the body



$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix} = \underbrace{\begin{bmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{bmatrix}}_{\text{Hydrostatic part}} + \underbrace{\begin{bmatrix} \sigma_1 - p & 0 & 0 \\ 0 & \sigma_2 - p & 0 \\ 0 & 0 & \sigma_3 - p \end{bmatrix}}_{\text{Deviatoric part}}$$

$p=(\sigma_1+\sigma_2+\sigma_3)/3$

- Distortion energy is what causes failure (so we want the energy of deviatoric component)

Failure Models – 3. Distortional Energy Theory

- Distortional Energy = Uniaxial strain energy at maximal stress: $E_d = \frac{\sigma_{max}^2}{6G}$ with $G = \frac{Y}{2(\nu + 1)}$
- the Yield function f is:

$$\boxed{f = \frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] - \sigma_{max}^2}$$

- Failure criterion: f=0

$$\boxed{\sqrt{\frac{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}{2}} = \sigma_{max}}$$

Von Mises Stress!

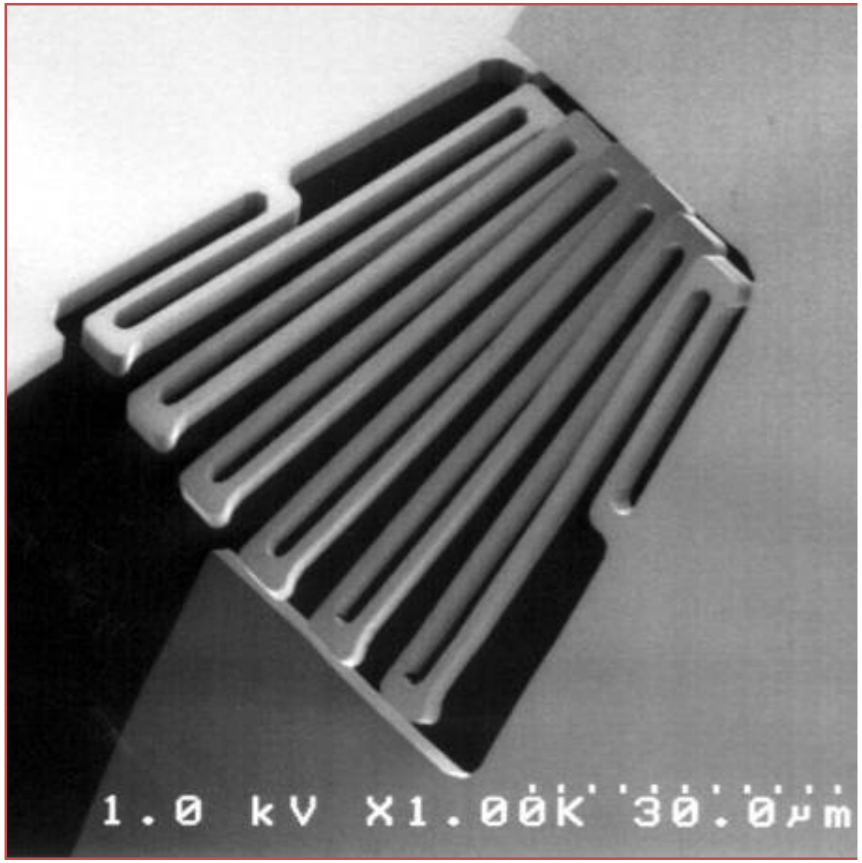
- One single value to calculate and compare stress to maximal acceptable stress !
- Used widely in industrial application and design
- best suited to **ductile** materials
- often integrated in FEM software, e.g. COMSOL

3.1.1. Fracture mitigation

Mitigation:

- Optimized geometry (no sharp corners!) to minimize stress concentration
- Well-controlled processing to minimize surface defects , e.g. can use an oxidation step followed by HF etch to get smoother surfaces after DRIE
- Proper material choice

- need a very large safety margin for brittle materials

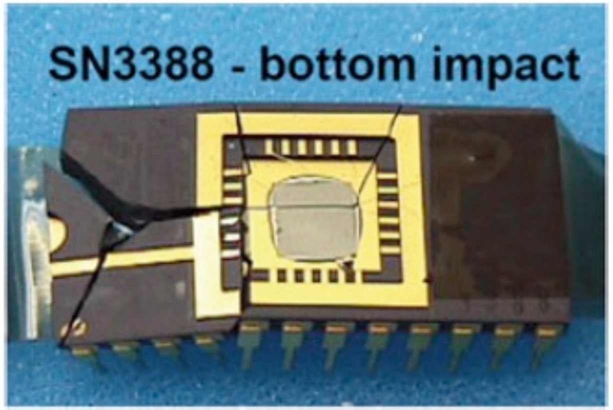


3.1.2. Mechanical Shock Resistance

Failures:

- Fracture due to exceeding the yield stress
- Stiction due to parts are coming in contact
- Delamination
- Particulates
- Short-circuits

- **Package and die-attach can fail too** (often more likely to fail than MEMS because of larger mass)

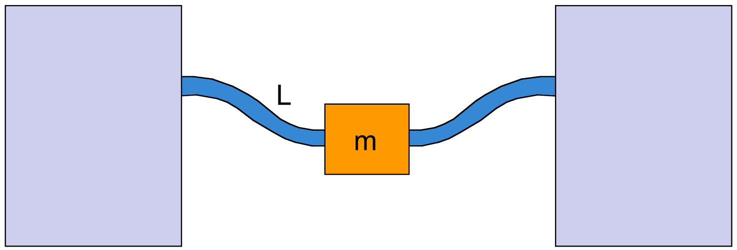


"MEMS reliability in shock environments", D. M. Tanner, Presented at IEEE International Reliability Physics Symposium in San Jose, CA, April 2000, pp. 129-138

From a scaling perspective, MEMS are more shock tolerant than larger devices.

Modeling shock response

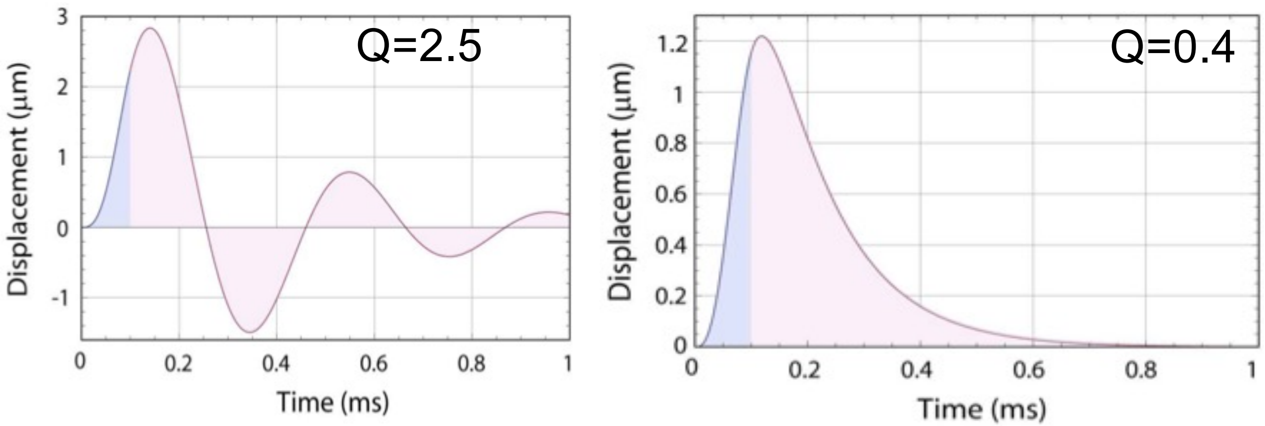
- Mass-Spring model can be used to estimate the displacement and max strain in the beam



$$a_{critical} = -\frac{2}{3}\frac{wt^2}{mL}\sigma_{\max}$$

$$a_{critical} \propto L^{-1}$$

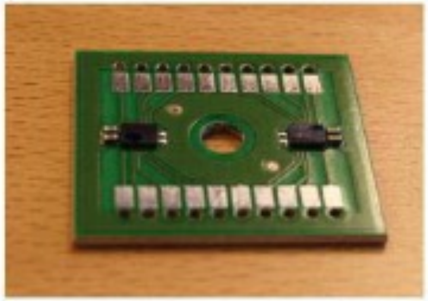
- Damping can be engineered to control motion due to shock

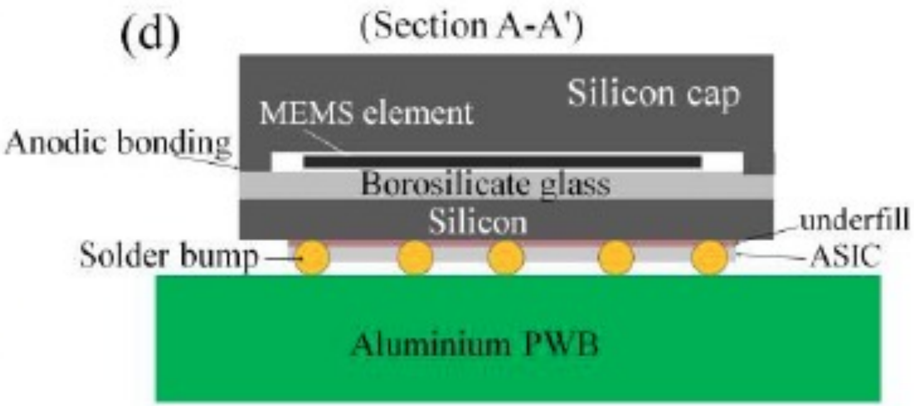


Calculated response to 100 µs long, 100 g peak amplitude single pulse for device with resonant frequency of 2.5 kHz (T_{res}=400 µs > 100 µs so have almost impulse response)

MEMS Reliability, chapter 4
By A L. Hartzell, M G. da Silva, H R. Shea

Package, chip, die bonding…





- Package failures
- MEMS device failures

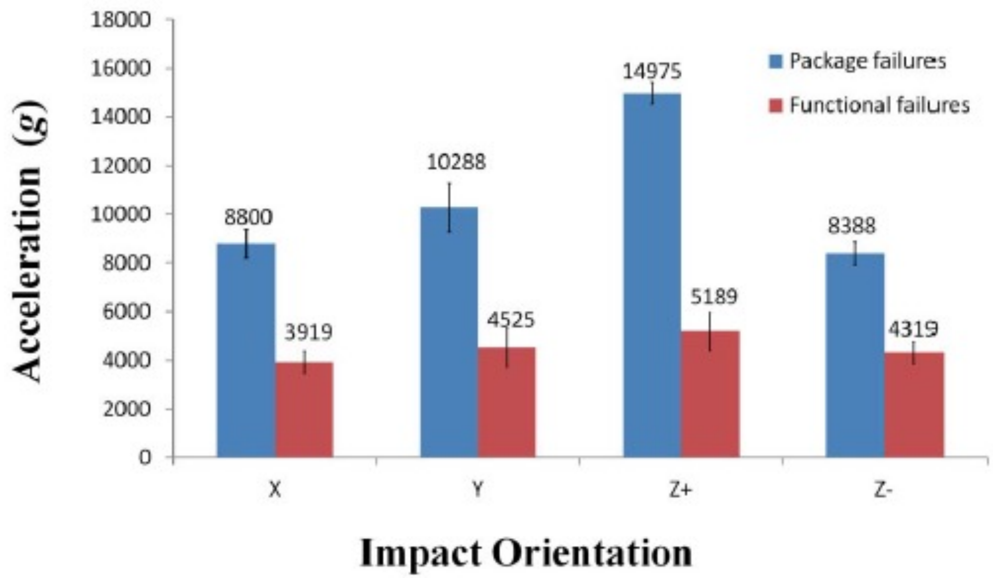


Fig. 5. The acceleration tolerance of the MEMS gyroscope with respect to package level failure and functional failures.

Package failure: borosilicate fracture (crack)

Jue Li et al, "Shock Impact Reliability and Failure Analysis of a Three-Axis MEMS Gyroscope", JMEMS 2014
[Doi: 10.1109/JMEMS.2013.2273802](https://doi.org/10.1109/JMEMS.2013.2273802)

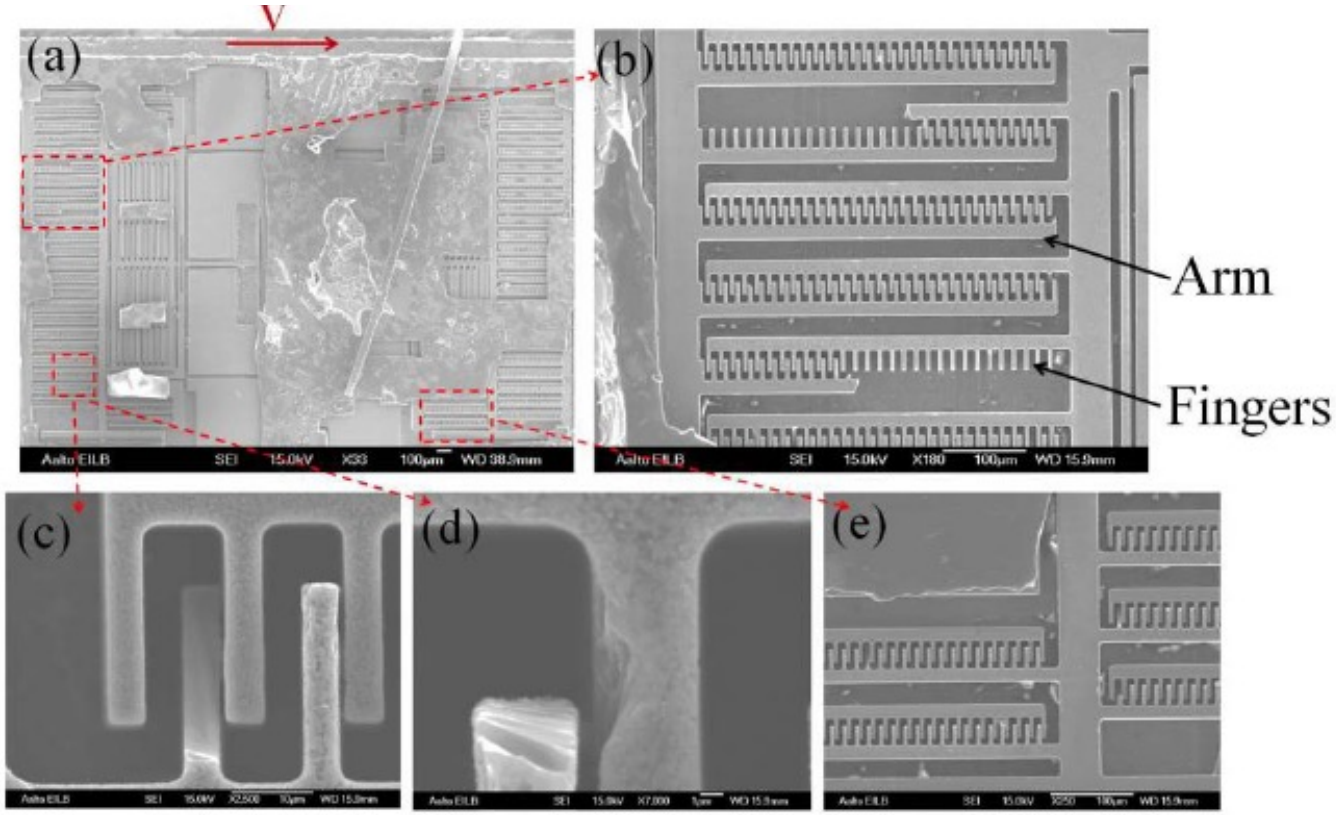
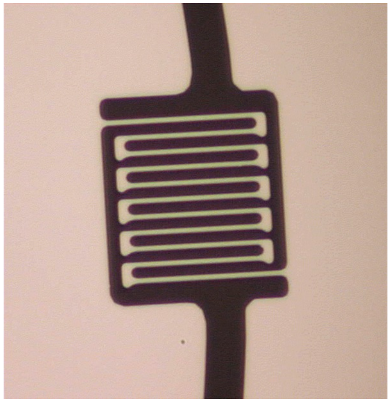
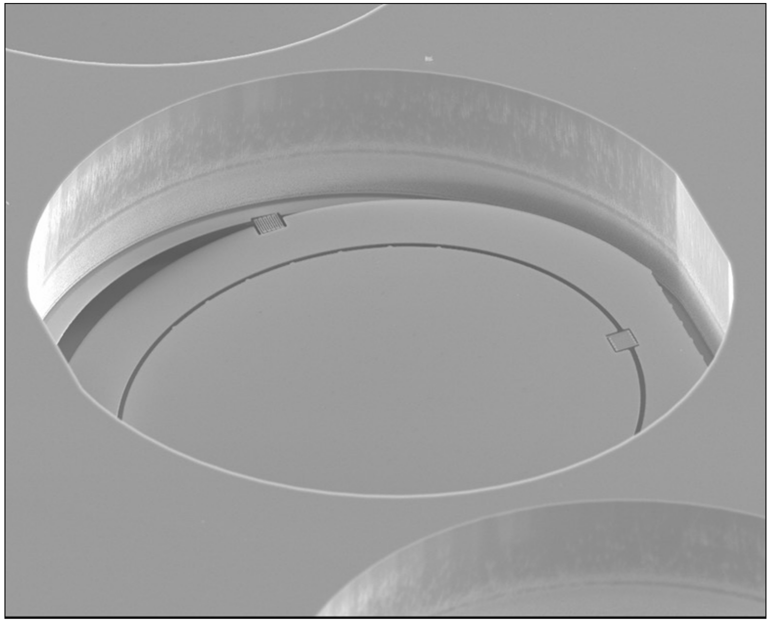


Fig. 9. Failure modes of the MEMS comb structure. (a) Top view of the cap-etched MEMS gyroscope; Shock impact orientation is indicated by the arrow; locations of the enlarged images (b)-(e) are indicated. (b) Fractured comb arms. (c) Fractured comb finger. (d) Chipped edges in the comb fingers. (e) Stuck MEMS elements due to particulate-induced blocking.

Jue Li et al, “Shock Impact Reliability and Failure Analysis of a Three-Axis MEMS Gyroscope”, JMEMS 2014

SOI mirrors





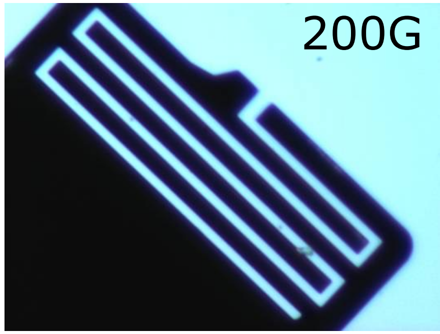
Stress tolerant SOI design: 60 μm long beams (serpentine,11 turns per spring), 1.1 μm wide, 5 μm thick.

Mirror mass = 7 μg

max computed safe acceleration = 2.6×10^5 ms^{-2} = 26’000G

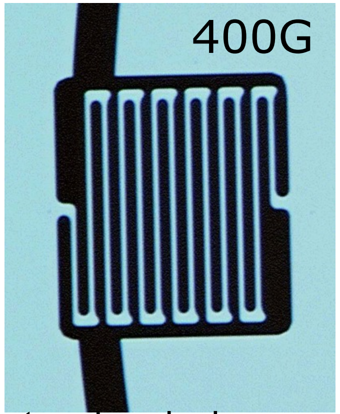
(but ignoring stress concentration, other modes, dynamics, etc)

Engineering Si springs for 1000 G (0.5 ms) shock tolerance: need resistance in 3 directions...

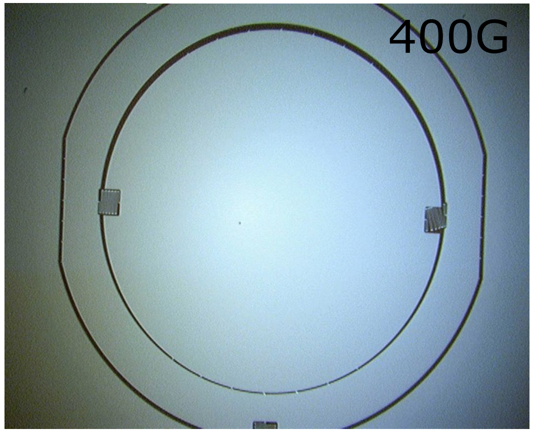


•First generation of mirrors failed at 200G

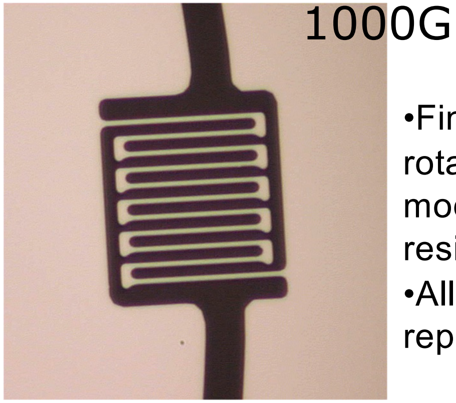
Failure mode: cracking of the spring at the 90^0 corner



•Next spring design incorporated widening at the 90^0 corners to suppress observed failure mode.



•Failure mode at 400G: due to soft lateral modes, mirror and/or gimbal slides under the gimbal and/or handle and gets stuck



•Final design of 5um thick mirrors had 90^0 rotated serpentine springs for stiffer lateral modes. Shows excellent mechanical shock resistance.

•All tested mirrors remained functional after repeated 1000G mechanical shocks

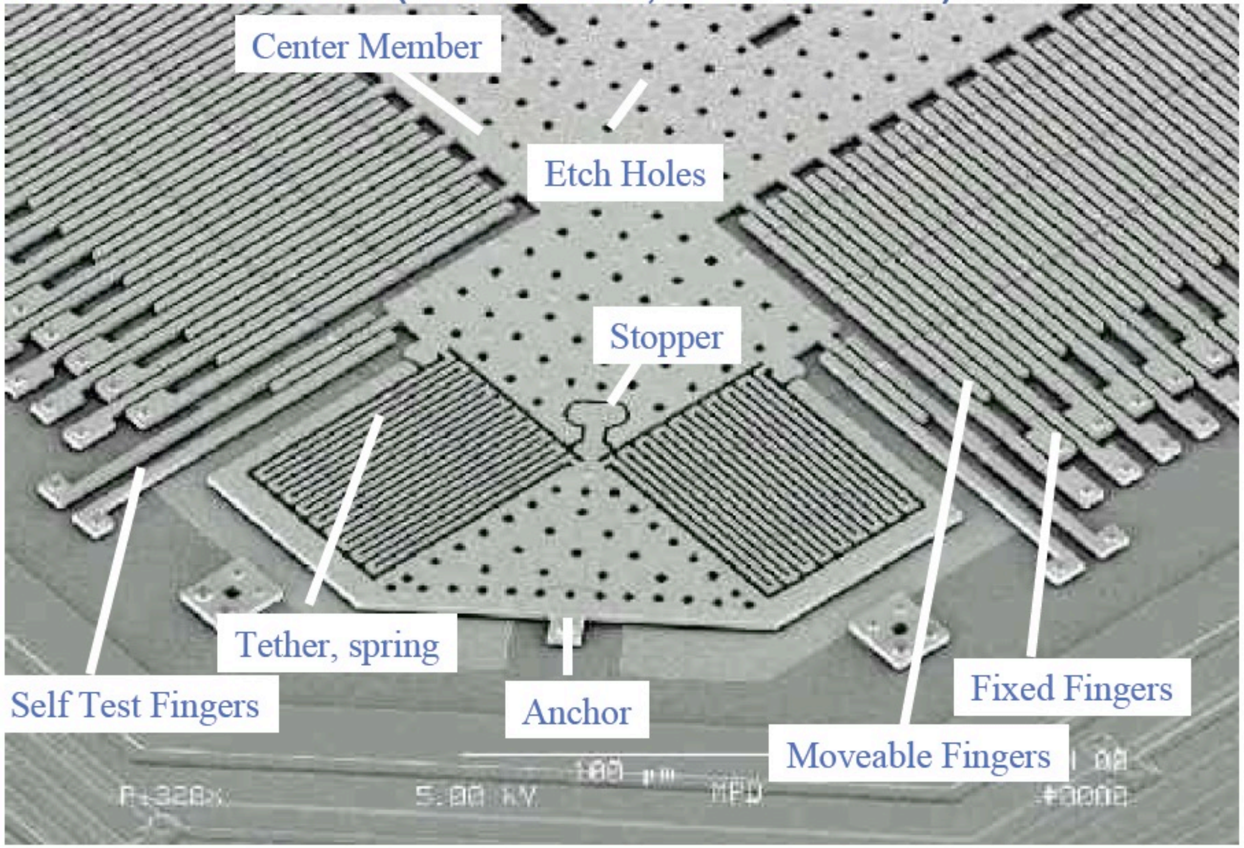
Best beam design for one mode may be poor choice for other modes…

3.1.2. Mechanical Shock Resistance - Mitigation

Mitigation:

- **Using stoppers to limit displacement**
- Stiffer springs (but then require higher actuation voltage)
- Elastic decoupling
- Intentional damping

Accelerometer beam (ADXL202, one corner)



Shock Conclusions

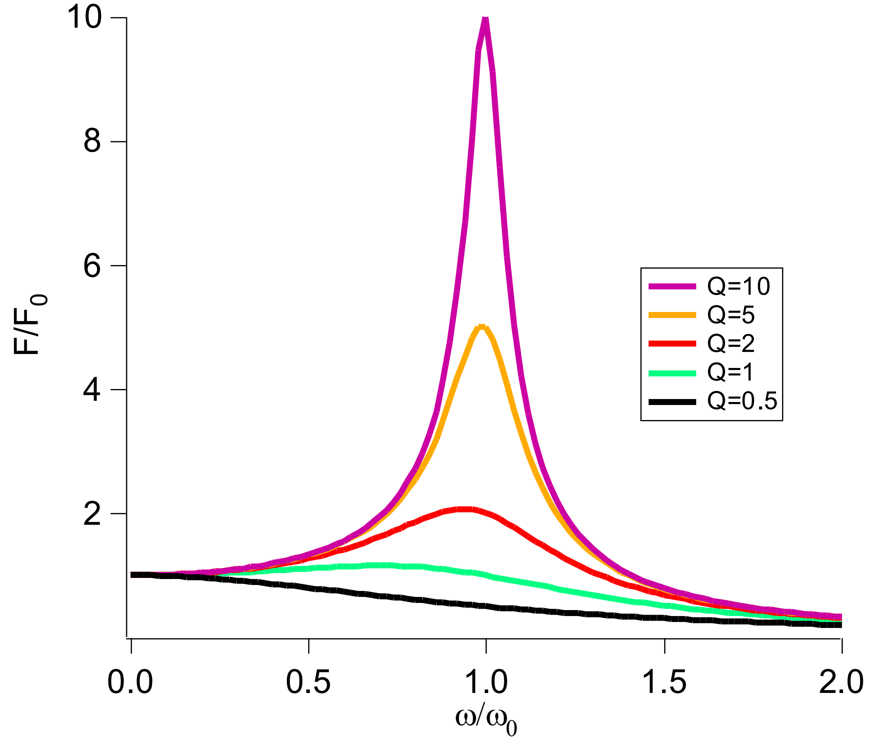
- Static loads of a few G are easy (trivial) to accommodate (due to small mass of MEMS devices)
- Shocks of up to 1000G can readily be dealt with by spring design (avoid stress concentration, symmetrical designs, beware of contacting parts…)
- Shock of 10’000G require more careful design (of MEMS but also of attachment and package)
- Can incorporate “stoppers”: mechanically limit motion of beams: OK (good to minimize displacement and kinetic energy), but stiction can be an issue

  - Need to design to uniformly spread loads, for all 3 axis
  - Need to make sure surfaces that might come into contact are at the same potential (e.g. accelerometer)
  - No dust that can move around
  - Careful choice of die attach material
  - Use package to dissipate the load
  - Stiction is most often observed failure mode

3.1.3 Robustness to Vibrations

The important factor is coupling of frequency ω of applied vibration with natural frequency ω_o of the MEMS structure.

The applied mechanical force F_0 is amplified, with Q is the quality factor of a given mechanical mode.



$$F = \frac{F_0}{\sqrt{\left((1-\frac{\omega^2}{\omega_0^2}\right)^2 + \frac{1}{Q^2}\frac{\omega^2}{\omega_0^2}}}$$

To define maximum safe vibration levels :

- Resonance frequencies
- damping
- Does motion lead to stiction? (ie if parts touch, are they stuck?)

3.1.4. Creep

- Creep: time-dependent increase in strain in a solid at constant temperature and stress (motion of dislocations)

- Fatigue: cycle dependent decrease in yield strength

So no creep for silicon?

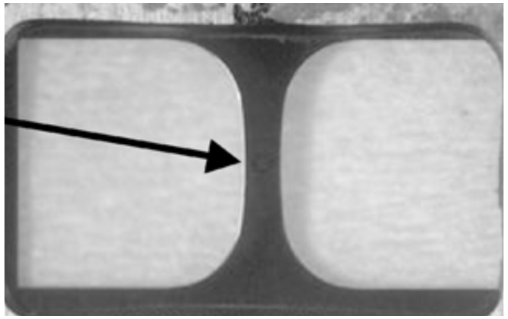
Table 4.3 Temperature at which $T_{homologous}$=0.5 for several materials

Material	T_c=0.5 T_M (in Kelvin)
60% Sn – 40% Pb (solder)	–45°C
Pb	27°C
Al and Al alloys	190°C
Ti	700°C
Si (brittle)	570°C
W	1600°C

MEMS Reliability
Hartzell, et al

Poly-silicon at high T can creep

- Silicon can be ductile when heated to >700° C (is brittle below 500° C)



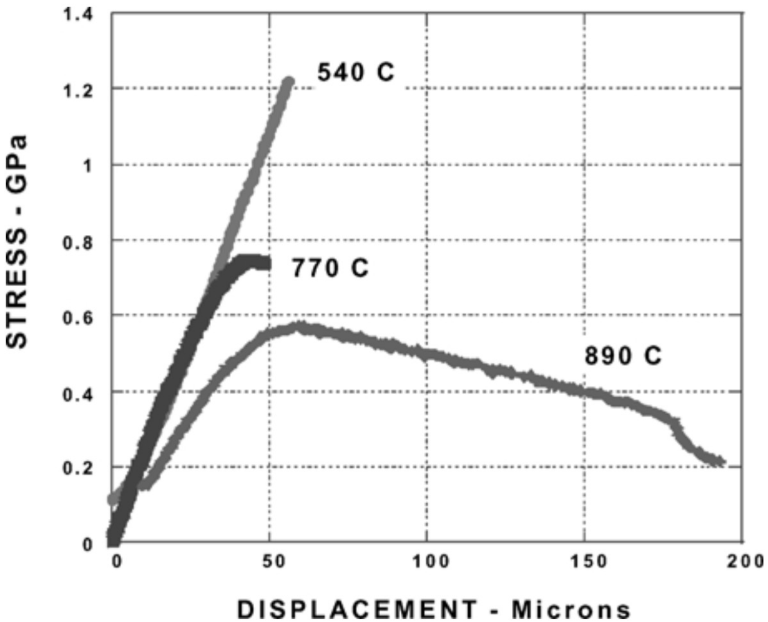


Figure 6 Polysilicon at high temperatures.

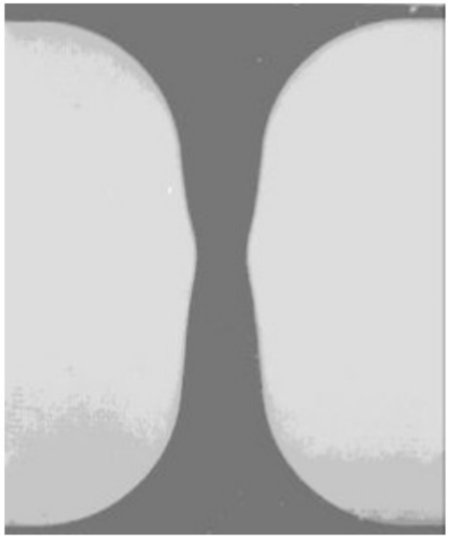
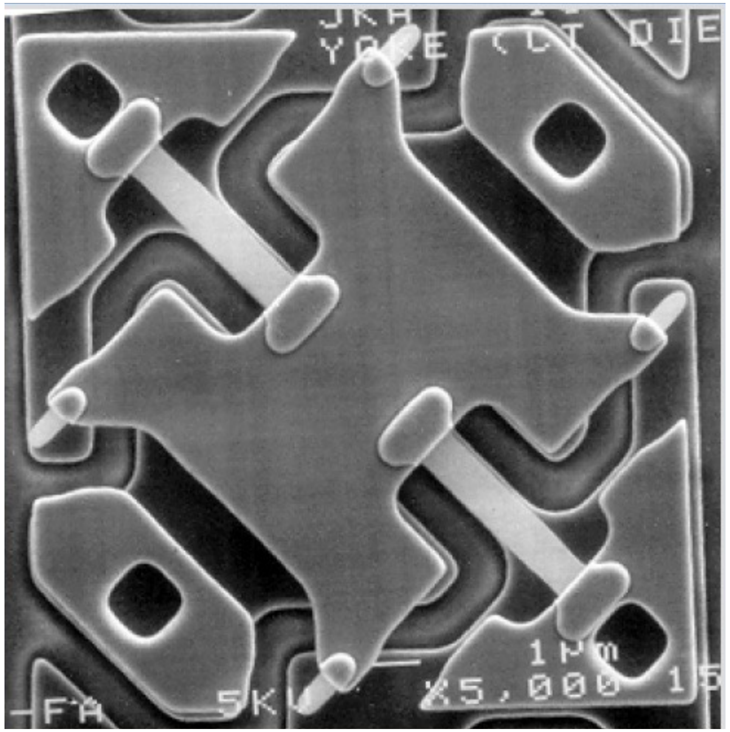


Figure 7 A polysilicon tensile specimen after tensile testing at 890°C.

"Tensile testing of MEMS materials—recent progress", by W. N. SHARPE et al, Journal Of Materials Science 38 (2003) 4075 – 4079

TI DMD mirrors (Al hinge)



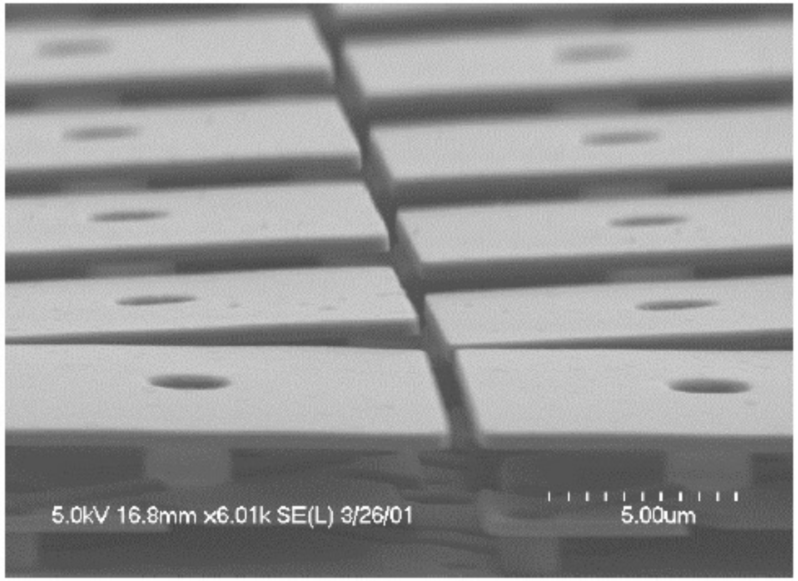
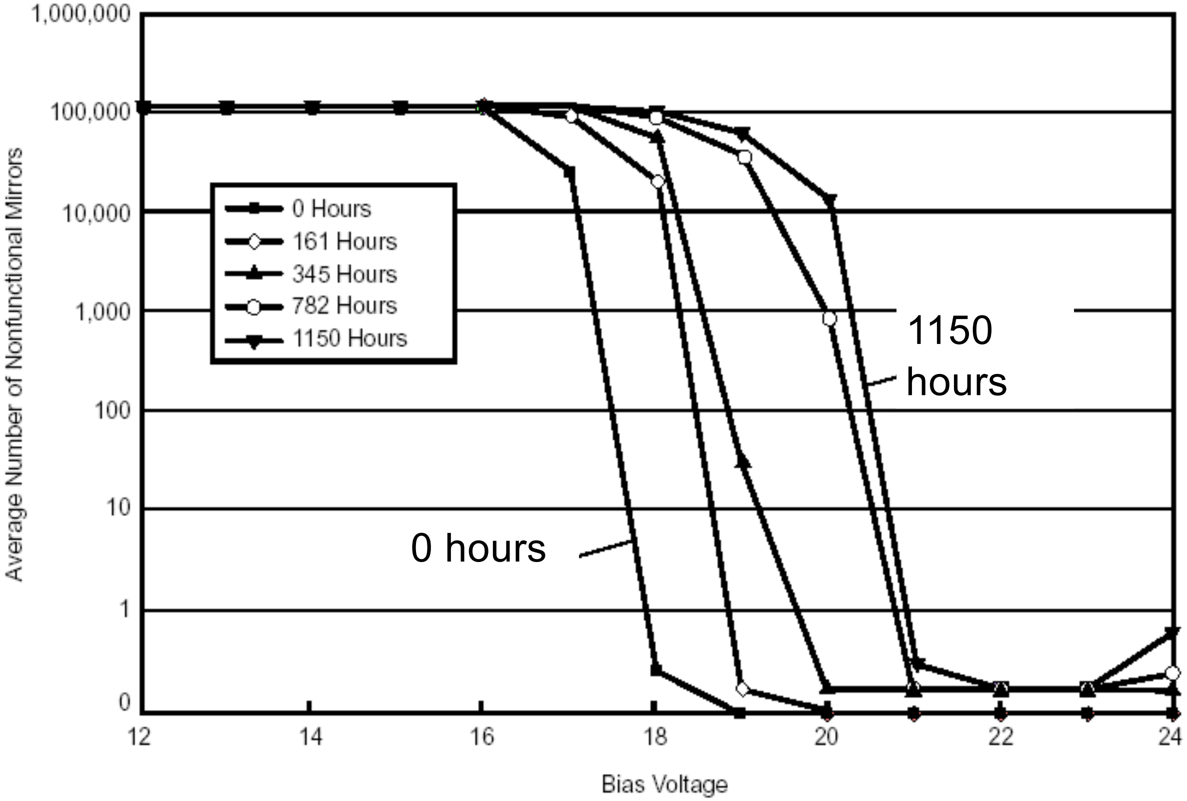


Figure 2. SEM image of mirrors exhibiting hinge memory. The first row at the bottom of the image is in the normal flat unbiased state. The second and subsequent rows are tilted to the minus side following extended operation at accelerated conditions.

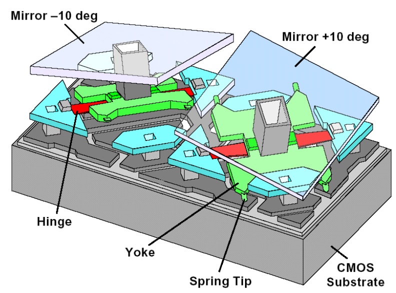
- Hinge, approx. 100 nm thick Al alloy

A.B Sontheimer, "DIGITAL MICROMIRROR DEVICE (DMD) HINGE MEMORY LIFETIME RELIABILITY MODELING." *40th IRPC 2002*, 118-121, 2002.

Creep in Aluminum MEMS Hinges



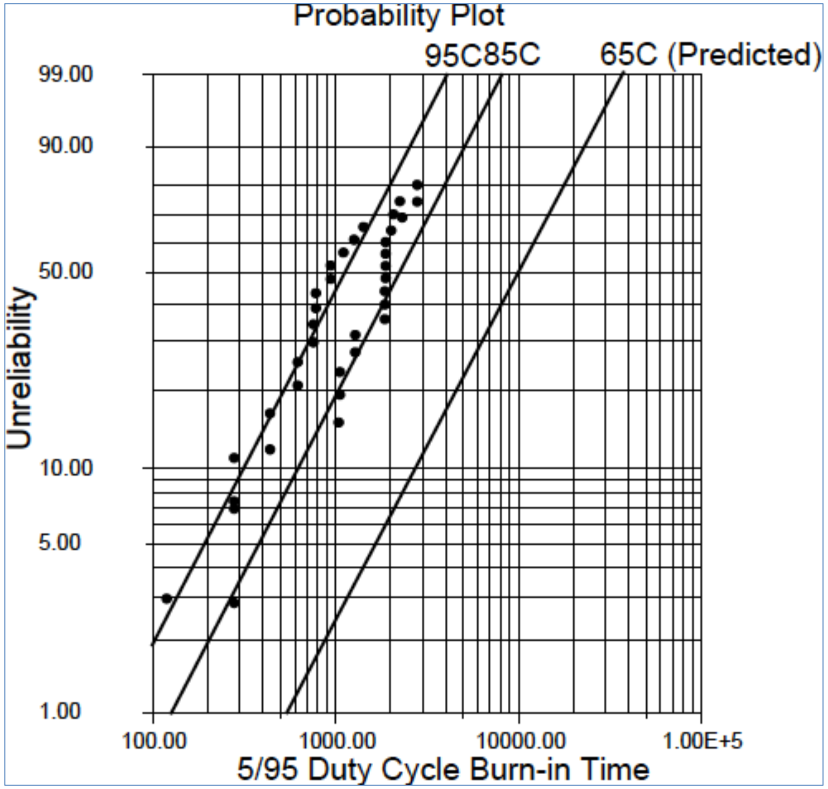
- Tilt-and-hold type actuation results in residual tilt angle when voltages are removed
- Residual tilt increases initial gap spacing between mirror and electrodes, which leads to higher actuation voltages
- The root cause of the "hinge memory" is metal creep of the hinge material



Operating temperature is the dominant factor in accelerating the failure due to the "hinge memory"

Data from: M.R.Douglass, *Lifetime estimates and unique failure mechanisms of the digital micromirror device (DMD)*, IEEE IRPS Proceeding, p.9, 1998

Weibull for Accel. Test TI Mirrors



E = 0.78 eV

Sontheimer, Andrew B. “DIGITAL MICROMIRROR DEVICE (DMD) HINGE MEMORY LIFETIME RELIABILITY MODELING.” In *40th IRPC 2002*, 118-121, 2002.

3.1.4 creep mitigation

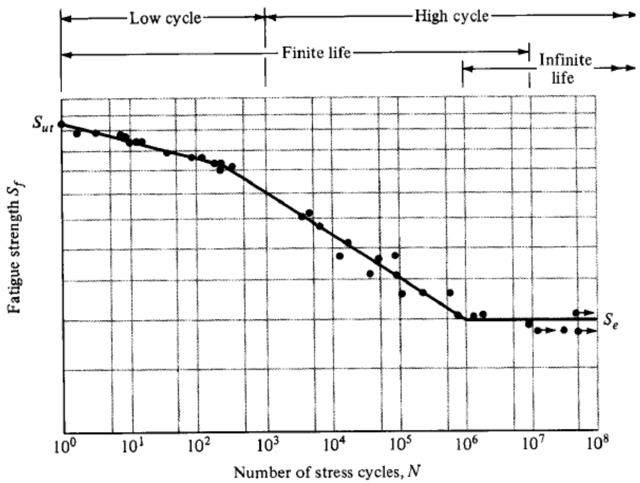
Mitigation:

- Silicon MEMS are not affected by creep under 600 C° (careful when you oxidize…)
- Must have no metal on Si flexures

- For metal MEMS,
  - reduce the applied stress : by geometry or by material change
  - Reduce the operating temperature (DMD has strict thermal design limits)
  - Use a better material: eg Al-Co alloy for TI DMD…

Fatigue

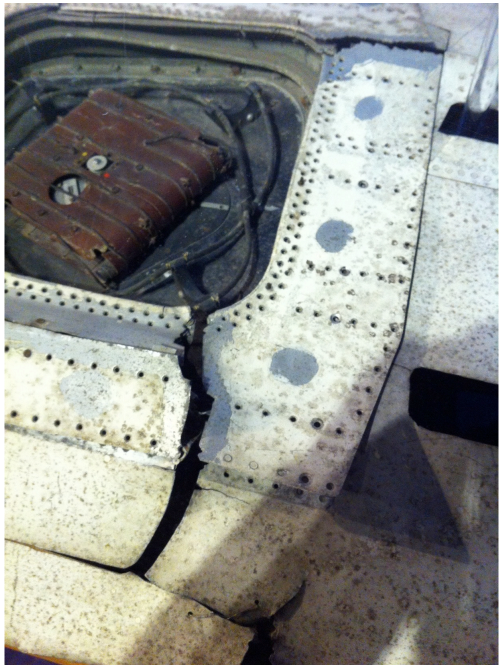
- Key idea: *Fluctuating loads are more dangerous than monotonic loads*
- Some materials, like steel, display an endurance limit: critical stress level below which failure does not occur regardless of number of cycles
  - Al and polymers do not show such a limit



Completely reversed cyclic stress, UNS G41200 steel

Example: de Havilland Comet 1 (1953)

- Cabin pressure differential at cruise was 0.6 bar
- Design pressure was 1.4 bar (more than x2 safety factor)
- But after thousands of pressurization cycles, crack initiated at stress concentrator (sharp corner on a square window opening), resulting in several crashes

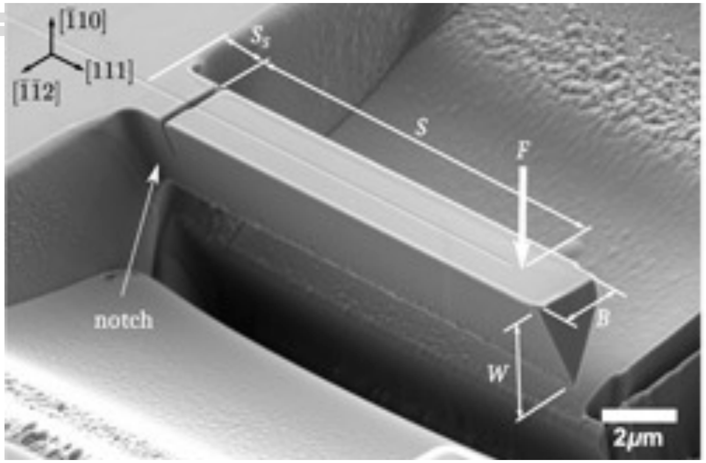


3.1.5. Fatigue

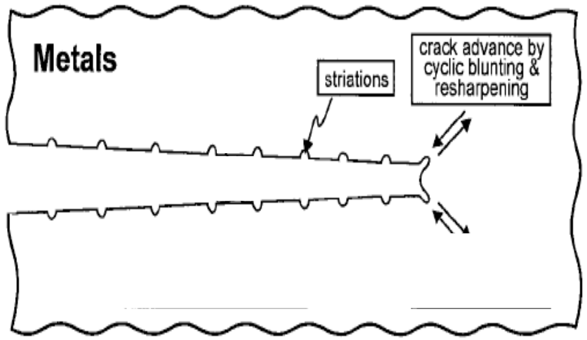
Fatigue is the cycle-dependent decrease in yield strength, i.e., a slow crack growth leading to failure due to a periodically applied stress.

The crack grows, reducing the strength of the material, eventually leading to failure.

- fluctuating loads can lead to failure when a monotonic load does not.
- In Ductile materials (e.g., most metals), fatigue is linked to plastic deformation at every cycle. Fatigue occurs over a large range of stresses
- In brittle materials (e.g., silicon, ceramics): Lack of dislocation mobility: Fatigue only occurs very near the yield stress level.



Mueller, G Žagar, and A Mortensen. *Journal of Materials Research* 32.19 (2017): 3617-3626.



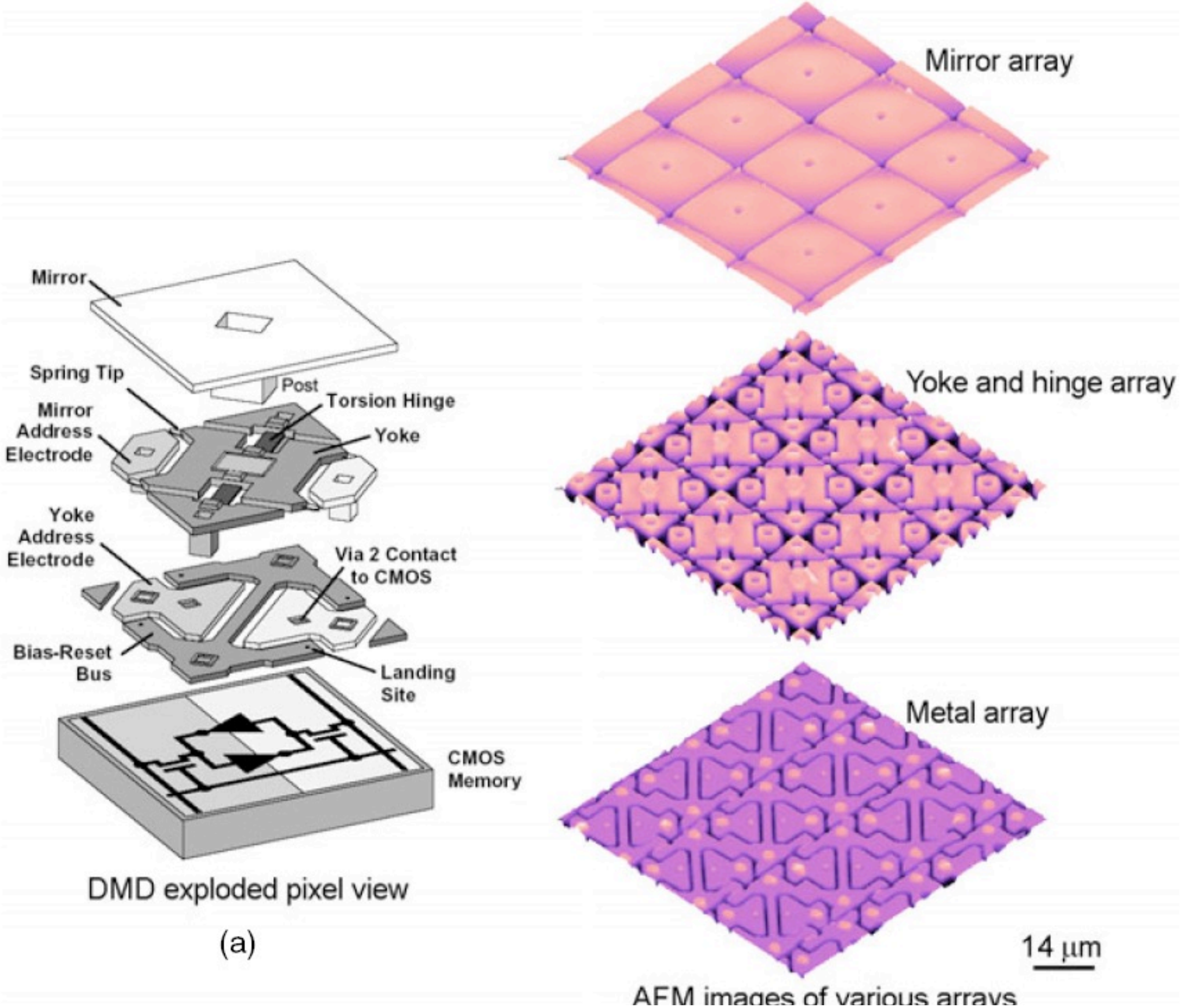
TI DMD
(Al, sputter deposited, plasma etched)

EPFL

Purpose	Test Conditions	Result	Equivalent Lifetime
Hinge Fatigue	1:1 Duty Cycle Accelerated 4-8X @ 65°C	> 3.67 Trillion Cycles > 69,000 hours	> 250,000 hours*
* Business projector application (1-chip, 8-bit) Assuming 1000 hours per year -- 250 years of useful life			

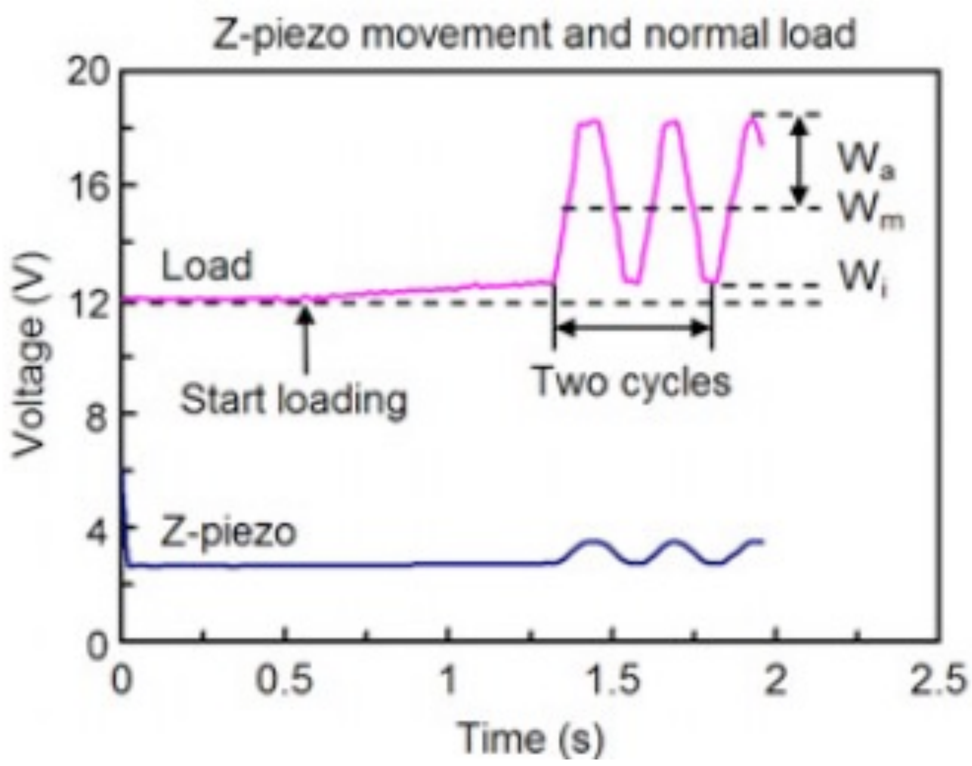
- No fatigue seen!
- Yet macro-scale models predicted rapid failure in Al hinge due to fatigue
- Basic COMSOL won't predict correct lifetime

Fatigue in TI DMD chips

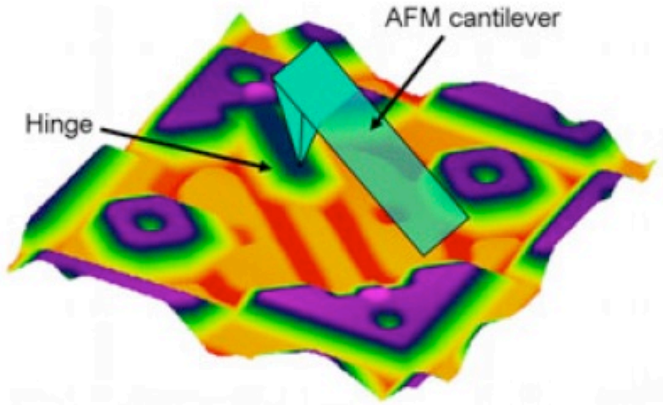


Nanotechnology 15 (2004) 1246–1251 “Bending and fatigue study on a nanoscale hinge by an atomic force microscope” H.Liu et al.

Fatigue in TI DMD chips

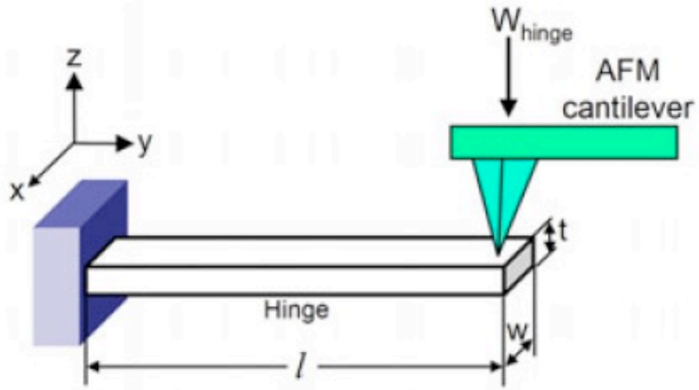


Nanotechnology **15** (2004) 1246–1251 “Bending and fatigue study on a nanoscale hinge by an atomic force microscope”, H.Liu and B. Bhushan



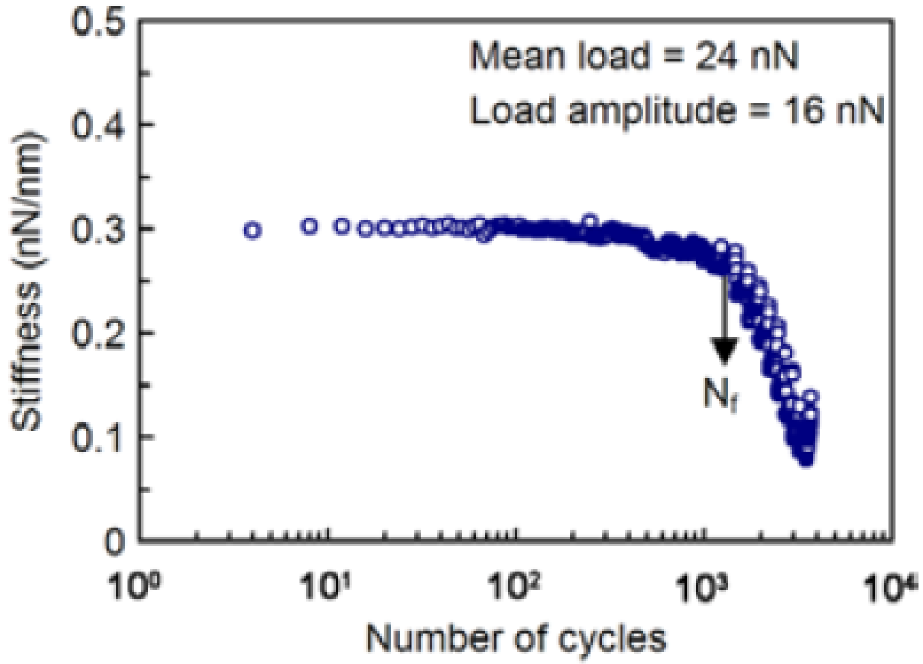
Hinge length = 3900 nm, width = 780 nm, and thickness = 100 nm

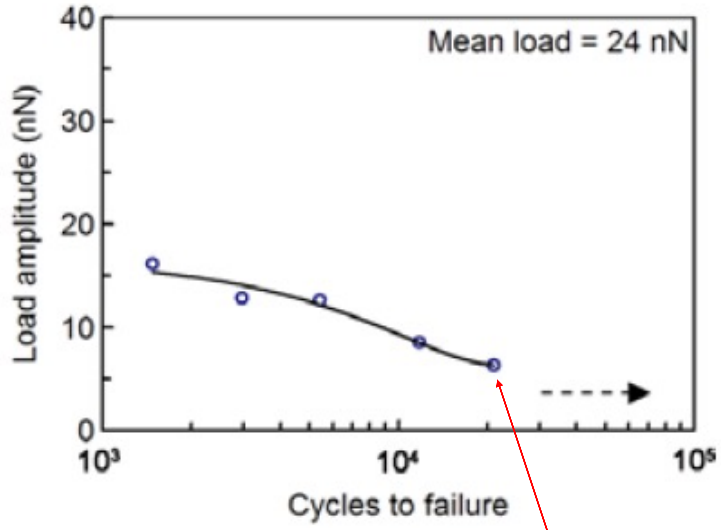
Residual hinge (yoke is removed)



$D_{hinge} = D_{piezo} - D_{tip}$
$W_{hinge} = W_{tip} = kD_{tip}$

Fatigue in TI DMD chips





3x lower stress (0.05 vs. 0.15 GPa) than in real device

Find a lifetime (10^4) smaller than in real operation (>>2.10^9): why such a big difference?

Some possibilities:

1) Frequency lower in test than in operation
2) Damage when removing mirror
3) Different motion (bending rather than torsion)

Nanotechnology 15 (2004) 1246–1251 “Bending and fatigue study on a nanoscale hinge by an atomic force microscope”, H.Liu and B. Bhushan

3.1.5. Fatigue

Mitigation:

- Re-engineer the suspensions to minimize the stress level
- Choosing more creep-resistant materials such as an alloy or ceramic rather than a pure metal
- Reduce the operating temperature or change the material

Electrical Failure Mechanisms

3. In-Use Failures

3.1. Mechanical Failure Modes

3.2. Electrical Failure Modes

3.2.1. Dielectric Charging

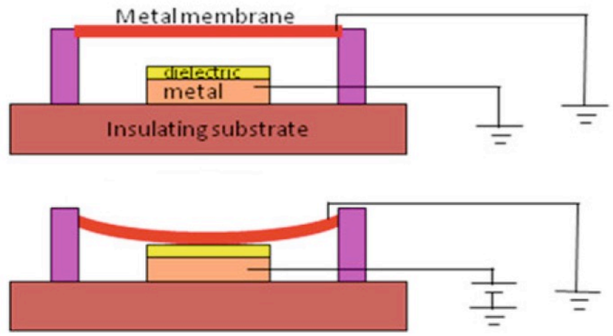
3.2.2 Electrical Breakdown and ESD

3.2.3. Electromigration

3.3. Environmental

MEMS: Dielectric Charging

- Electrostatically operated MEMS have high applied electric fields,
  - e.g., 200 V across a 1 μm dielectric: 2.10^8 V/m
- What happens?
  - Charges accumulate in the dielectric (charge injection)
  - Charge/discharge time constant long (seconds to days)
- What MEMS devices are affected?
  - electrostatically driven MEMS, especially RF capacitive switches
  - also micromirrors, accelerometers, gyros
- What are the effects?
  - shift in actuation voltage (e.g., calibration change)
  - change in rest or actuated position
  - shift in release voltage
  - Failed device

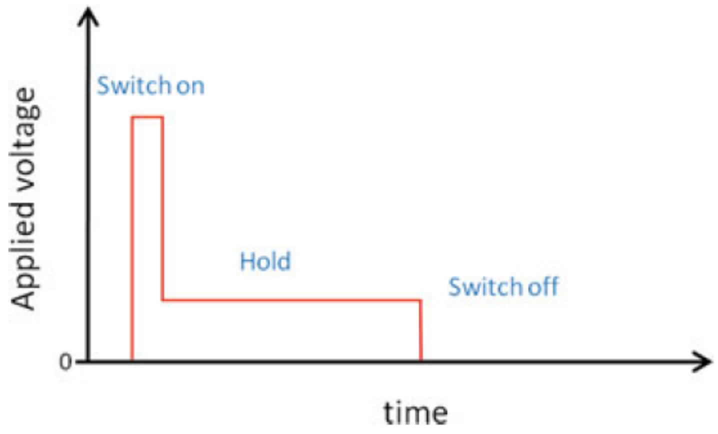


RF MEMS

Mitigation for dielectric charging

Mitigation strategies

- Bipolar AC drive voltage drive, but higher power consumption
- Geometry changes to
  - minimize area of exposed dielectric, or pattern the dielectric
  - shield movable parts (sense mass, actuators) from electric fields due to trapped charge.
  - Selectively remove dielectric to avoid charging
- Change dielectric (e.g, SiO_x better than SiN_x)
- Reduce electric fields (e.g., redesigned springs to operate at lower voltages)
- Optimized drive voltage (multi-level: one to actuate, one to hold)
- Control of packaging ambient to minimize humidity and contaminants



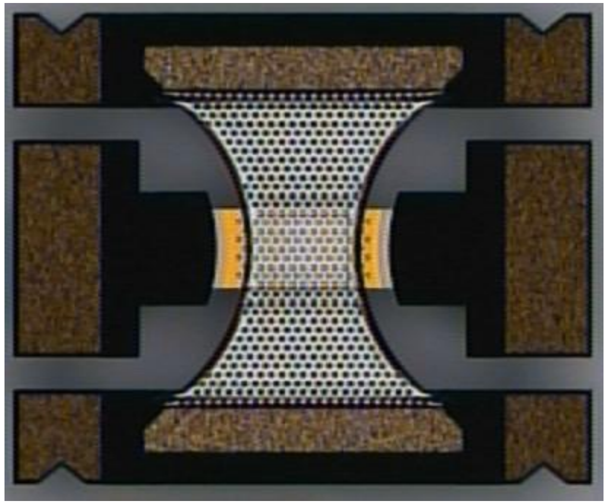
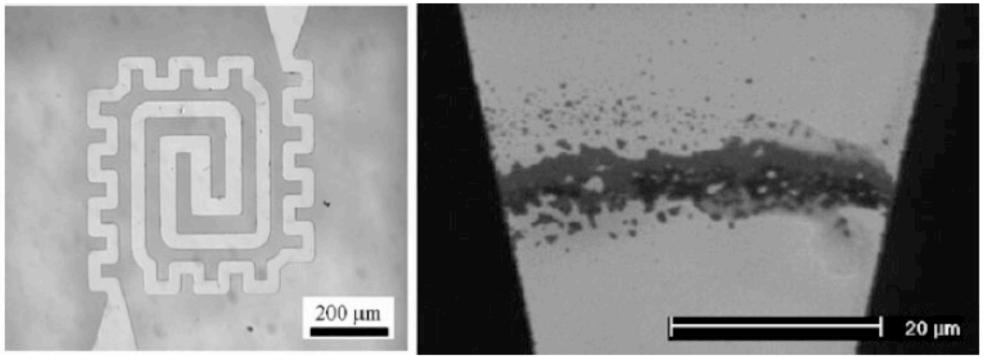


figure from C.L. Goldsmith, et al, "Understanding and improving longevity in RF MEMS capacitive switches," Proc SPIE, vol. 6884, 2008

3.2.3. Electromigration

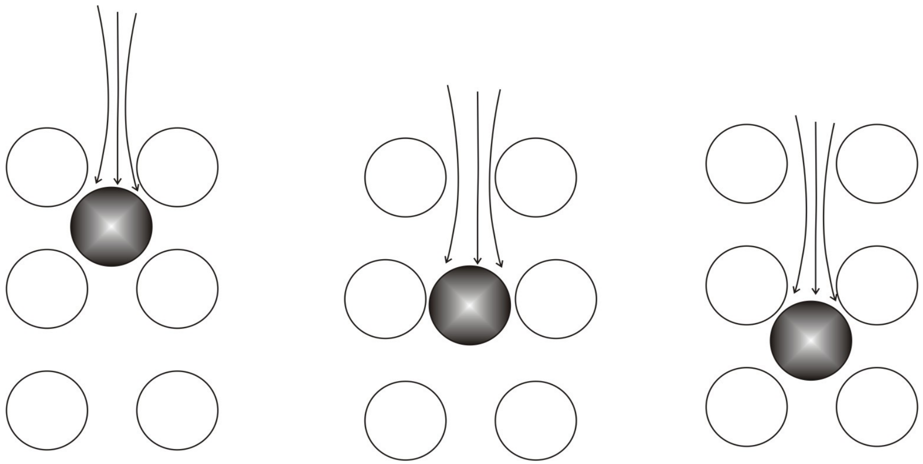
Electromigration is the migration of metal atoms under an applied electric field.(due to electron momentum transfer)

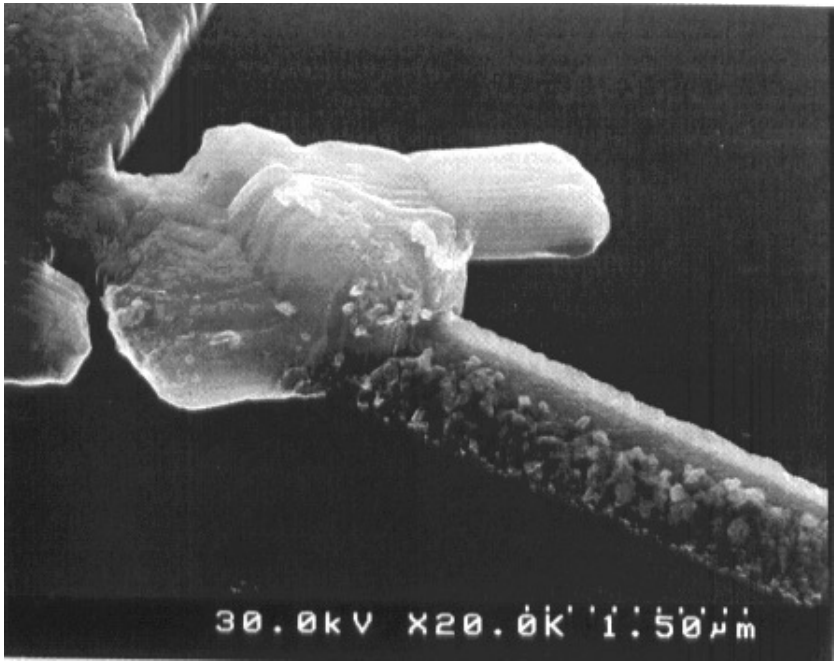
only occurs at extremely high current density (10^{10} A/m^2)

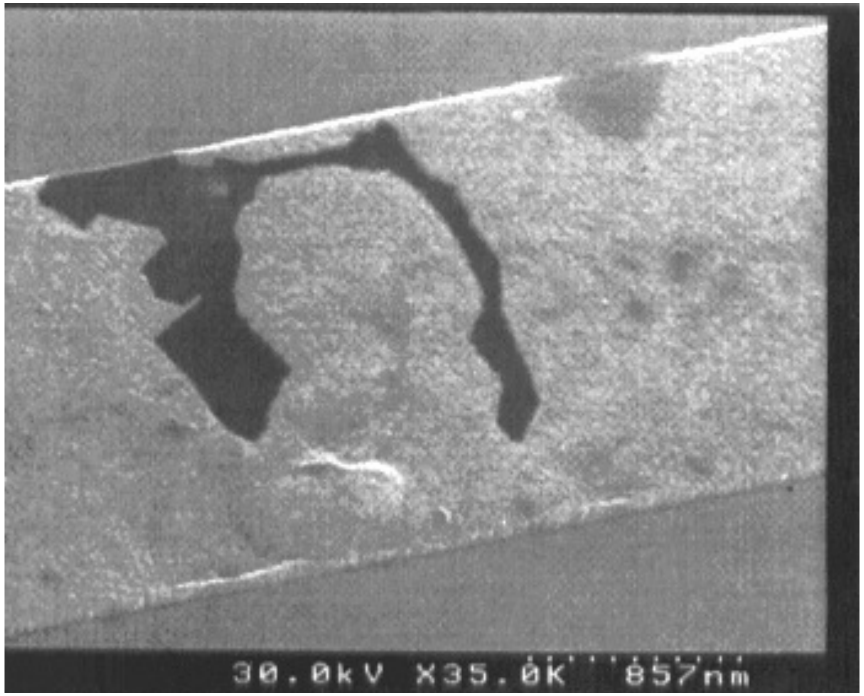


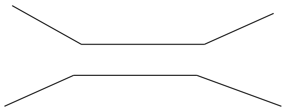
Notes:

- Atomic displacement under high current density
- Leads to voids and dendrites
- Not an issue in low-power MEMS.
- Seen however in hotplates (eg gas sensors) and infrared emitters









SEM Photos from www.nd.edu/~micro/fig20.html

What is 10^{10} A /m^2 ?

10 kA / mm^2

10 mA / µm^2

Al wire, 1 µm diameter

Resistance per mm = 30 ohm

Dissipated Power per mm = $I^2 R$ = 3 mW …

Surface = L 2Pi r = 1e-3 3e-6 = 3 10^{-9} m^2

Power / surface = 1 MW /m^2

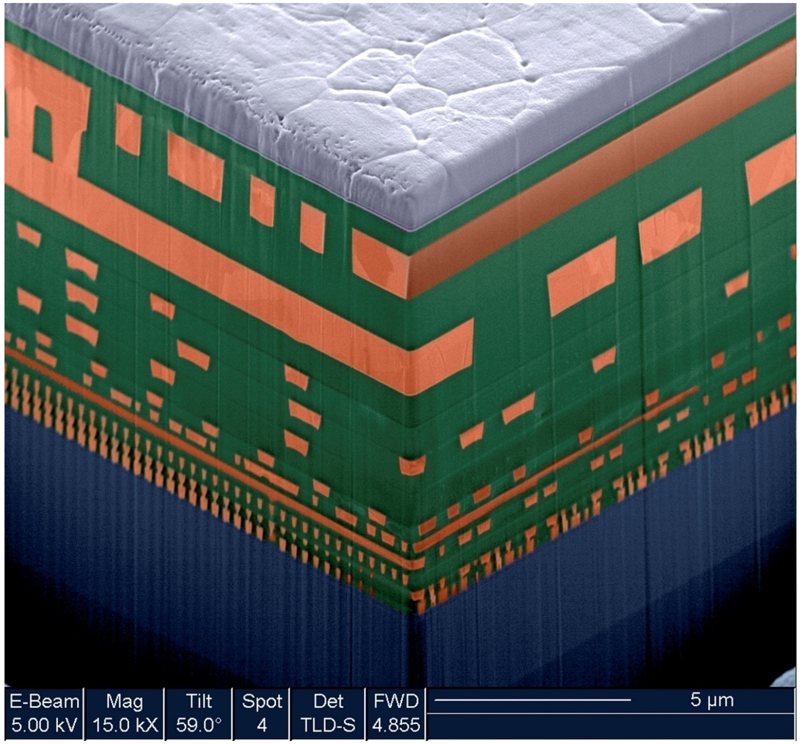
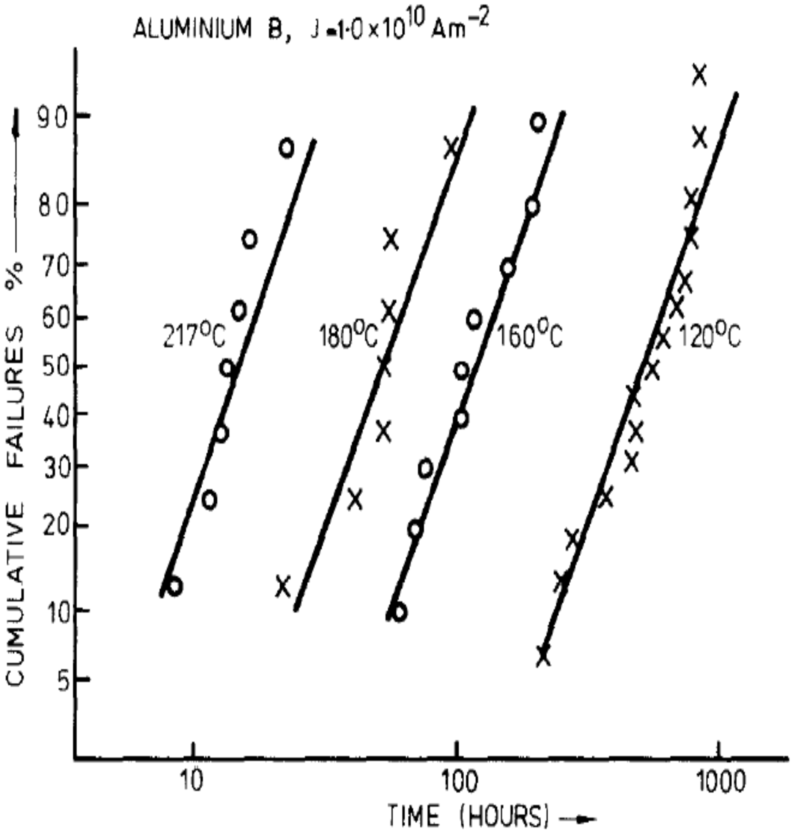
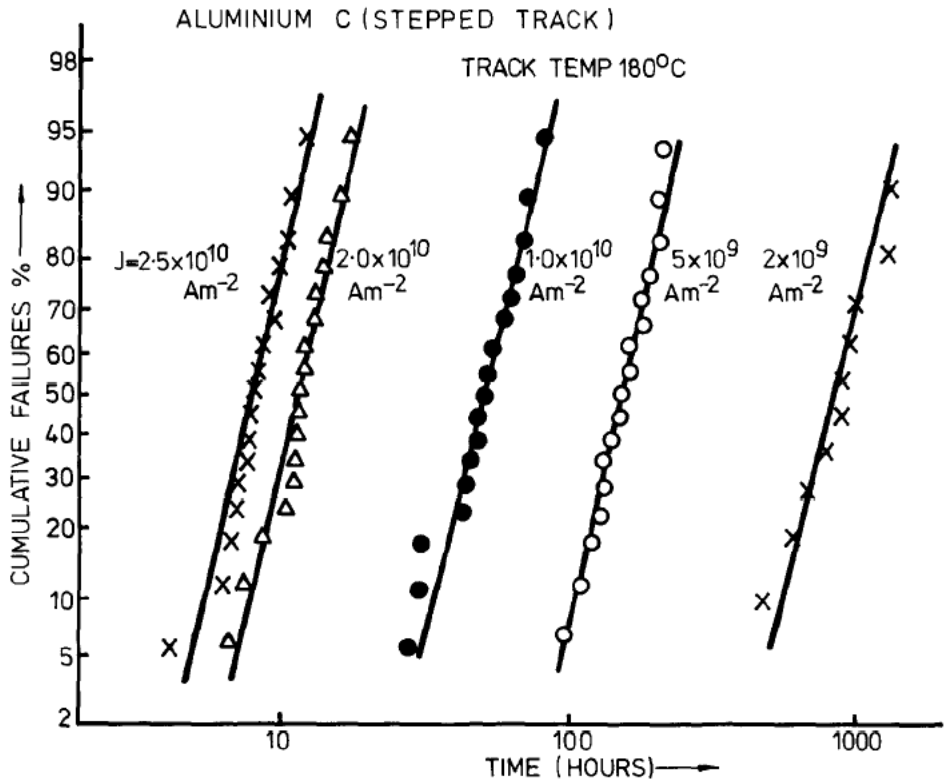


Image from IBM microelectronics Circa 2005

Such a high current density is only possible thanks to Si chip acting as a heatsink.

Scaling: only happens in sub 50 µm features, ususally for µm thick wires





$$\frac{1}{MTTF} = Bj_e^n \exp\left[-\frac{E_{act}}{k_B T}\right]$$

Sim, S.P. *Microelectronics Reliability* 19 (3), pp. 207-218

Temperature, Stress, and Current density are the three main accelerating factors. Grain structure also plays a key role.

Mitigation for electromigration

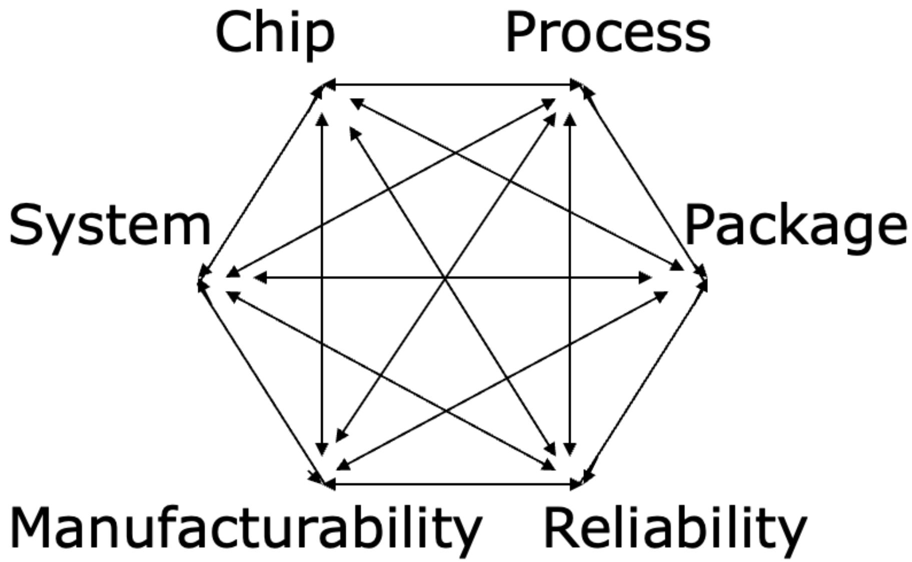
- Better metal choice:
  - Al with 0.5% to 5% Cu (pure Al never used in ME industry; 1% Si often added to prevent Al-Si diffusion at semiconductor contacts)
  - Cu (now standard for performance and power consumption) intrinsically less prone to EM, but still an issue
- Bamboo structure to block atom flow using transverse grain boundaries
- Diffusion barriers like TiN as liners that can carry the current when the Al has 'walked' off

- Lower current density
- Better cooling
- Lower stress

EPFL

- Reliability,
- Performance,
- Cost,
- Development speed,
- Packaging,
- Process flow,
- Control strategy

are all tighly linked



- ➢**Very tight feedback loop**
- ➢**Really a question of trade-offs**