Lilliputian Systems, Inc. has developed the world’s first Personal Power™ solution for Consumer Electronics (CE) devices, a revolutionary family of products targeted at the $50 billion portable power market. The Company’s breakthrough solution delivers the only viable small form factor battery replacement that provides the enormous run-time improvements demanded by today’s CE devices. Lilliputian’s patented Silicon Power Cell™ technology is based on highly efficient and proven solid oxide fuel cells (SOFCs) and MEMS wafer fabrication methods.
OUTLINE—Design for Reliability in MEMS Based Systems

- Systems Reliability Statistics (many component systems)
- Single Component Reliability Statistics
- Example of Lifetime Distribution Evaluation and Bathtub curve.
- Use and Storage Conditions for Market Segments
- Stresses for Failure in MEMS—what can be controlled with system?
- Shock Protection
- RF MEMS—what can be controlled with system?
- Hermeticity
- ESD for Electrostatically Actuated MEMS
- Case Study—TI Mirrors and System Design Changes to Improve Reliability
- Fin
- References
Series System of ‘n’ components

\[ R_S = R_1 \times R_2 \times ... \times R_n \] (if the component reliabilities differ, or)

\[ R_S = [R_i]^n \] (if all \( i = 1, ..., n \) components are identical)

Here, reliability of system components are independent of one another and

If exponential distribution the system reliability is:

\[ R(t) = \exp{-\lambda_1 t} \times \exp{-\lambda_2 t} \times ... \times \exp{-\lambda_n t} \]

As failure rate is constant with exponential distribution, system failure rate:

\[ \lambda_s = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + ... + \lambda_n \]
System Reliability Approaches

Parallel system of ‘n’ components.

\[ R_S = 1 - (1 - R_i) = 1 - (1 - R_1) \times (1 - R_2) \times ... \times (1 - R_n); \]

if the component reliabilities differ.

If not,

\[ R_S = 1 - (1 - R_i) = 1 - [1 - R]^n; \]

if all "n" components are identical: \([R_i = R; i = 1, ..., n]\)
System Reliability Approaches—2 Parallel Systems in Series

\[ R_S = R_A \times R_B \]

Where \( R_A \) and \( R_B \) are both parallel systems and their reliability is treated as such.
To calculate this properly, must know lifetime distribution statistics!

The reliability function is defined as the probability of operating without failure to time $t$.

\[ R(t) = 1 - F(t) \]

$R(t)$ = Reliability function, a.k.a. Survivor function

$F(t)$ = Cumulative failure distribution function (CDF), the probability that a random part will fail by time $t$. 
Distribution functions

The probability density function (PDF) is $f(t)$—the probability that the failure will occur at the time interval ‘$t$’.

$$F(t) = \int_{0}^{t} f(t') \, dt'$$

$$f(t) = \frac{d}{dt} F(t)$$
Hazard Rate is the instantaneous failure rate

\[ h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \]

Defined as the probability that failure will occur in the next time interval, divided by the probability of operating \textit{without failure} up until that time interval.
Mean time to failure

\[ \text{MTTF} = \bar{t} \equiv \int_{0}^{\infty} tf(t)dt \]

The prediction of how long a population will survive until a failure occurs.
Exponential Distribution:

$h(t)$ hazard rate is a constant, $\lambda$

Survivor function

\[ R(t) = e^{-\lambda t} \]

\[ F(t) = 1 - e^{-\lambda t} \]

\[ f(t) = \lambda e^{-\lambda t} \]

MTTF $= 1/\lambda$
Weibull Distribution
Survival Function
(2 parameter model is when failures start at time zero)

\[ R(t) = e^{-\left(\frac{t}{\alpha}\right)^\beta} = \frac{f(t)}{h(t)} \]

Beta \( \beta \) is the shape parameter.

Alpha \( \alpha \) is the characteristic life, or scale parameter.
Weibull CDF distribution

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta}$$

CDF
Weibull PDF distribution

\[ f(t) = \frac{\beta}{\alpha} \left( \frac{t}{\alpha} \right)^{\beta} e^{-\left( \frac{t}{\alpha} \right)^{\beta}} \]

PDF
Weibull Hazard Rate

\[ h(t) = \frac{\beta}{\alpha} \left( \frac{t}{\alpha} \right)^{\beta-1} \]

Instantaneous failure rate as a function of time
Lognormal Distribution

\[ f(t) = \frac{1}{\sigma t \sqrt{2\pi}} e^{-\frac{(\ln(t) - \ln(T_{50}))^2}{2\sigma^2}} \]

Probability Distribution Function (PDF)
Lognormal Cumulative Distribution Function

\[ F(t) = \int_0^T \frac{1}{\sigma t \sqrt{2\pi}} e^{-\left( \frac{(\ln(t) - \ln(T_{50}))^2}{2\sigma^2} \right)} \, dt \]

CDF

\[ F(t) = \Phi \left[ \frac{\ln(t/\tau)}{\sigma} \right] \]

where \( \Phi(z) = \frac{1}{2} \left[ 1 + \text{Erf} \left( \frac{z}{\sqrt{2}} \right) \right] \)

solution

\( \sigma = \) shape parameter, standard deviation
Lognormal Hazard Rate Curve

\[ h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \]

Instantaneous failure rate as a function of time
EXAMPLE OF MEMS COMPONENT LIFETIME FIT
SANDIA MICRO ENGINE

All Sandia data and images are courtesy of Sandia Labs, SUMMiT™ Technologies, www.mems.sandia.gov
Here, cumulative failure rate \([H(t)]\) is plotted as function of cycles.

Weibull fit applied. \(T_{50}\) is \(10^7\) cycles. \(\beta=0.22\) while production ready population has \(\beta\) range of 0.5 to 5.
Here, cumulative failure rate \([H(t)]\) is plotted as function of cycles.

Lognormal fit applied. \(T_{50}\) is 7.8 million cycles. \(\sigma = 5\) while typical semiconductor production ready population has \(\sigma\) range of 0.1 to 1.

\[
H(t) = \int_{0}^{t} h(t')dt = -\ln R(t)
\]
Sandia Micro-engine failure

Fit with lognormal, but study for bimodal distributions.

Actually is early life failure population with a wearout population (like bathtub curve). Fits are acceptable, best treatment of data.
Bathtub curve – Product Lifetime

- Infant Mortality
- Useful Life
- Wearout

Failure Rate vs Time

USEFUL LIFE
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– Fin
<table>
<thead>
<tr>
<th>Major market segment</th>
<th>Indoor</th>
<th>Consumer portable</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating life</td>
<td>5–10 years</td>
<td>5–10 years</td>
<td>7–25 years</td>
</tr>
<tr>
<td>Power on (hrs/week)</td>
<td>60–168</td>
<td>60–168</td>
<td>20–168</td>
</tr>
<tr>
<td>Cycles/day</td>
<td>Env. cycle: 1–2</td>
<td>Env. cycle: 2–4</td>
<td>Env. cycle: 2–4</td>
</tr>
<tr>
<td></td>
<td>Power cycle: 2–4</td>
<td>Power cycle: 4–6</td>
<td>Power cycle: 2–10</td>
</tr>
<tr>
<td>Moisture at low power</td>
<td>30–36°C @ 85–92% RH</td>
<td>30–36°C @ 85–92% RH</td>
<td>30–36°C @ 85–92% RH</td>
</tr>
<tr>
<td>Operating temperature (ambient in enclosure)</td>
<td>0–40°C</td>
<td>−18 to 55°C</td>
<td>−55 to 125°C</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>−40 to 50°C</td>
<td>−40 to 55°C</td>
<td>−40 to 55°C</td>
</tr>
</tbody>
</table>

Copyright 2000 International Sematech Technology [9].
### Stresses for acceleration of MEMS failure

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>Accelerating factors</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclic fatigue</td>
<td>No. of cycles, maximum applied strain, humidity</td>
<td>Models exist for this failure mechanism in mechanical engineering texts and literature, as well as some MEMS structures.</td>
</tr>
<tr>
<td>Creep (plastic deformation)</td>
<td>Temperature, applied strain</td>
<td>Well understood materials science field.</td>
</tr>
<tr>
<td>Stiction</td>
<td>Humidity, shock, vibration</td>
<td>Difficult to model. Surface conditions are critical.</td>
</tr>
<tr>
<td>Shorting and open circuits</td>
<td>Electric field, temperature, humidity</td>
<td>Well understood field, yet the geometries in MEMS and materials used could make this difficult to model for some structures. Again, processing effects can be critical.</td>
</tr>
</tbody>
</table>
### Stresses for acceleration of MEMS failure

<table>
<thead>
<tr>
<th>Failure mechanism</th>
<th>Accelerating factors</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arcing</td>
<td>Electric field, gas pressure, gas composition</td>
<td>Small gaps are prone to this in specific environments. Breakdown voltage relationships should be investigated.</td>
</tr>
<tr>
<td>Dielectric charging</td>
<td>Electric field, temperature, radiation, humidity</td>
<td>Some MEMS structures such as RF MEMS are particularly susceptible to this.</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Humidity, voltage, temperature</td>
<td>Polarity is important if accelerating anodic corrosion.</td>
</tr>
<tr>
<td>Fracture due to shock and vibration</td>
<td>Acceleration, frequency (resonance), vacuum</td>
<td>Models exist for this failure mechanism in mechanical engineering texts and literature, as well as some MEMS structures. Micro-scale materials properties are needed.</td>
</tr>
</tbody>
</table>

Circled items can be controlled external to MEMS.
Packaging Design for System Shock

Cushion MEMS from Shock, Vibration with Gel

Fig. 3.11 Cross-section of a typical plastic overmolded MEMS sensor – (reprinted with permission Copyright 2009 Chipworks [24])
Stoppers
For MEMS Protection During Shock Events

Fig. 4.19  Colibrys HS 8000 series accelerometer. (Left) packaged, (right) MS 8000 without package lid, showing the sensor chip and analog and digital signal conditioning circuits. Courtesy Colibrys SA

Fig. 4.20  Schematic isometric diagram of the Colibrys HS8000 accelerometer. The proof mass moves vertically in response to acceleration. Stoppers are implemented to limit motion of the chip. Courtesy Colibrys SA (patent pending)
Shock Limitation by clever MEMS packaging system design.

Fig. 4.21 Principle of a shock limitation by a combination of the elastic decoupling and stoppers, to limit the shock at the chip level to 2500 g while the package is accelerated to over 17,000 g.Courtesy Colibrys SA.
### Capacitive RF MEMS—Circled are fixes in packaging design and circuit design (along with MEMS design)

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Accelerating conditions</th>
<th>Possible design change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep of metal membrane</td>
<td>Temperature, RF power (leading to heating), stress in metal layer</td>
<td>More creep‐resistant alloy, better conductor for less ohmic heating</td>
</tr>
<tr>
<td>Stiction</td>
<td>Humidity, surface cleanliness, surface roughness</td>
<td>Hermetic packaging, roughness control of membrane and dielectric</td>
</tr>
<tr>
<td>Fatigue in membrane</td>
<td>Number of cycles, temperature</td>
<td>Reduce maximum stress by geometry change, change alloy</td>
</tr>
<tr>
<td>Dielectric charging</td>
<td>Humidity, electric field, temperature</td>
<td>Lower operating voltage, change dielectric, patterned dielectric, separate signal and drive electrodes</td>
</tr>
</tbody>
</table>
Humidity control of RF-MEMS
Wafer level hermetic cap—allows non-hermetic system

Fig. 2.35  Schematic cross-section of wafer-level packaging developed by MEMtronics to hermetically seal RF MEMS switches with minimal footprint. Reprinted with permission. Copyright 2005 ASME [33]
Electrostatic MEMS will have ESD;
Must design protect structures into component;
Must design system to withstand ESD stresses;
Handle and label components as ESD Sensitive.
Fig. 3.21  Catastrophic failure due to ESD in RF MEMS switches (reprinted with permission Copyright – 2008 IACM, ECCOMAS [45])
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ACCELERATION MODEL CASE STUDY—HOW TI IMPROVED LIFETIME WITH SYSTEM CHANGE

Texas Instruments

Fig. 2.19 Illustration of two landed DMD Mirrors. Reprinted with permission. Copyright 2003 SPIE [19]
CHANGE IN BIAS VOLTAGE OVER TIME AND TEMP WAS A CREEP-RELATED MECHANISM TERMED ‘HINGE MEMORY’, CREEP WITH SOME SURFACE EFFECTS

HOW WAS THIS HAZARD PLOT 65°C PREDICTION MADE?
Thermal Acceleration Factor
Arrhenius Relationship

\[ A_F = e^{\frac{E_a}{k}(\frac{1}{T_{use}}) - (\frac{1}{T_{accel}})} \]

HINGE MEMORY ACTIVATION ENERGY ~ 0.78 eV

\[ A_F = e^{\frac{0.78 \text{ eV}}{8.617 \times 10^{-5} \text{ eV/K}} \left(\frac{1}{(273+65) \text{K}} - \frac{1}{(273+85) \text{K}}\right)} = 4.46 \]

Acceleration factor using 85°C data to predict 65°C lifetime is 4.46.
Importance of using proper activation energy—small changes greatly affect acceleration factors!

<table>
<thead>
<tr>
<th>Activation energy (eV)</th>
<th>Acceleration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>3.16</td>
</tr>
<tr>
<td>0.65</td>
<td>3.48</td>
</tr>
<tr>
<td>0.7</td>
<td>3.83</td>
</tr>
<tr>
<td>0.75</td>
<td>4.21</td>
</tr>
<tr>
<td>0.78</td>
<td>4.46</td>
</tr>
<tr>
<td>0.8</td>
<td>4.64</td>
</tr>
<tr>
<td>0.85</td>
<td>5.11</td>
</tr>
</tbody>
</table>
TI Improvements to Increase Lifetime—
System Fixes Underlined

– Improvements TI made that improved their lifetime:

• Replacement of original aluminum torsion bars with aluminum alloy that had higher creep resistance.

• Changed electrical waveform that allowed reliable operation with larger residual tilt (allowed for creep effects).

• Thermal management in system and packaging to keep mirror below 45°C under normal conditions. (Creep is accelerated with temperature—activation energy driven mechanism.)

• Allowed lifetime prediction > 100,000 hours for failure due to hinge memory.
Fig. 4.36  DMD lifetime estimate for failures from hinge memory (creep), for two hinge generations (1992, 1997) as a function of temperature, and duty cycle, with 95% being an accelerated test condition. From [32] reprinted with permission Copyright 1998 IEEE
Learnings--Fin

Series System of ‘n’ components

If the MEMS component is any of the ‘n’ components above, a failure would fail the entire system!

TO DO:

1) Design the MEMS component for reliability.
2) Design the System for MEMS component reliability, for example:
   a) Hermeticity
   b) Shock absorbing
   c) ESD protection and handling
   d) Thermal management
   e) Electrical signals
3) Know your system and component reliability statistics
References

– Page 29, 30. Courtesy Colibrys SA.
– Page 34. Ruan, J. et al. (2008) ESD effects in capacitive RF MEMS switches. 8th World Congress Computational Mechanics (WCCM8), Venice, Italy.
– Page 38, 39, 40. MEMS Reliability Hartzell/da Silva/Shea, 2010 Springer Publishing