National Aeronautics and Space Administration

Low-Cycle Fatigue and Dynamic Fracture in Gold Thin Films on SiN Supported Membranes

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Symposium Q: Degradation Processes in Nanostructured Materials

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Outline

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- Experimental
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  - experimental methods
- Description of Device
- Mechanical response to vibration: substrate motion
  - closed form solutions
  - finite element modeling (FEM)
- Experimental Results
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- Conclusion
- Acknowledgements

Introduction

- NASA/JPL uses latest cryogenic detectors to search for present-day signatures of the big-bang, and the following inflationary period ($t \approx 10^{38}$ sec)
- The Cosmic Microwave Background (CMB) has been measured by experiments such as COBE, BOOMERANG, DASI, and WMAP
- The next generation of missions will search for gravity-wave signatures on the CMB; I.e., polarization of the CMB
- Advanced cryogenic detectors that operate at 100 mK are required
- Rigorous tests are conducted prior to launch; e.g., a short list includes
  - Optical tests at low-T
  - Thermal Cycling
  - Vibration
- This talk focuses on the dynamic mechanical response and fatigue behavior in sub-micron thick Au-films deposited onto amorphous Si_xN_y substrates, with spider-web geometry, that were subjected to forced vibration (3-axis random vibration with 2 kHz roll-off frequency)

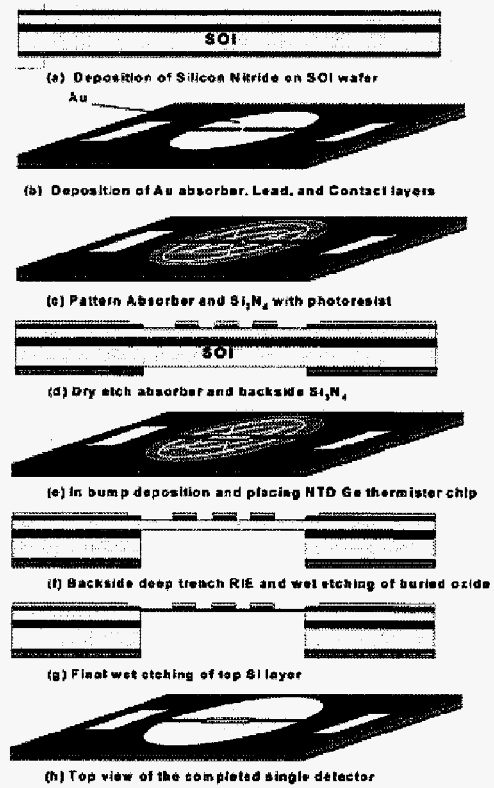
Experimental Methods

- Fabrication - thin film deposition on low stress, 1 μm thick silicon nitride substrates
- Vibration Test Spectrum
  - 3-axis random vibration with 2 kHz roll-off frequency
- Microscopy
  - Optical microscopy
  - Scanning electron microscopy

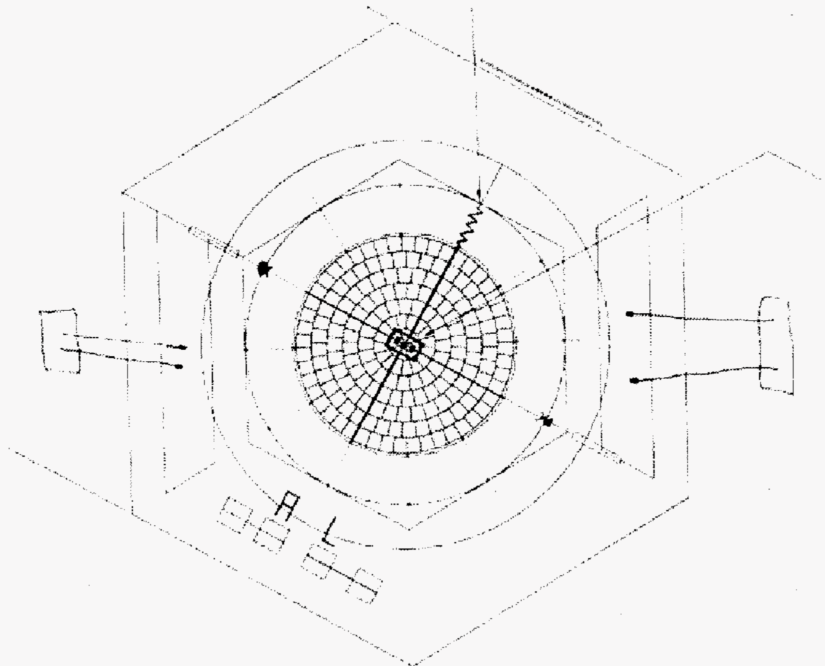
Fabrication Process

- Fabrication conducted in JPL's Micro Devices Laboratory (MDL).
- Au-metallized detectors are fabricated on thermally bonded SOI wafers with a (100) orientation
  - SOI wafers are prepared with a standard RCA cleaning
  - 1 µm layer of Si_3N_4 deposited on each side of the wafer using low-pressure chemical vapor deposition (LPCVD)
  - Si_3N_4 layer will ultimate form a large (~ 5 mm) free-standing structure, care must be taken in the deposition of the Si_3N_4 to ensure that the material is free of stress and pinholes
  - Ti-Au metal films are deposited using lift-off technique to form an IR-absorber layer
  - Au layer deposited on absorber chosen to give optimal infrared absorption, and is typically ~ 12 nm thick
  - Au layer forming the electrical lead layer is typically ~300 nm thick
  - reactive ion etching used to define the silicon nitride frame

Fabrication Process Flow Diagram



Description of Device



Web OD = 3.16 mm

Lead length = 4.66 mm

Au lead thickness = 0.3 μm

Lead width = 5.3 μm

Web width = 3.4 μm

Web thickness = 1 μm

Center chip size: 300 μm x 100 μm x 25 μm

Vibration Test Spectrum

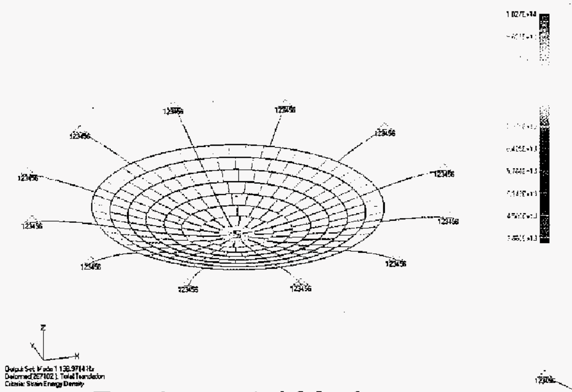
Frequency Range (Hz)	Spectral Density or Slope
20	.0323 g^2/Hz
20-75	+6 dB/octave
75-400	0.225 g^2/Hz
400-2000	-6. dB/octave
2000	.0182 g^2/Hz
Test duration: One minute per axis 12.3 G_{rms} overall	

- Detectors mounted inside sealed carrier plates; hence the units under test are not visible during the test.
- 3-axis random vibration with 2 kHz roll-off frequency

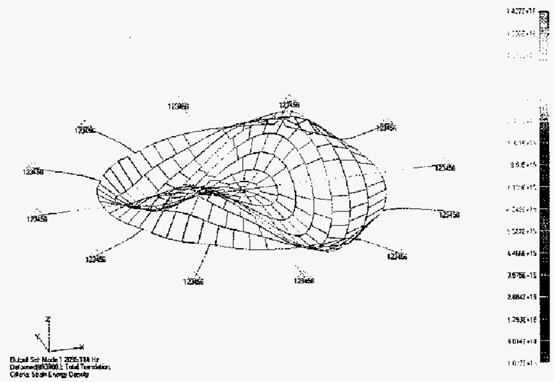
Mechanical response to vibration

Images show results of FEM calculations for stress-free substrate and substrates with residual stress

FEM results agree (≈) with closed form solution for tympani mode: $f_{resonance} \approx 1400$ Hz



Fundamental Mode
No preload; 139.0 Hz



With preload; 2095.1 Hz

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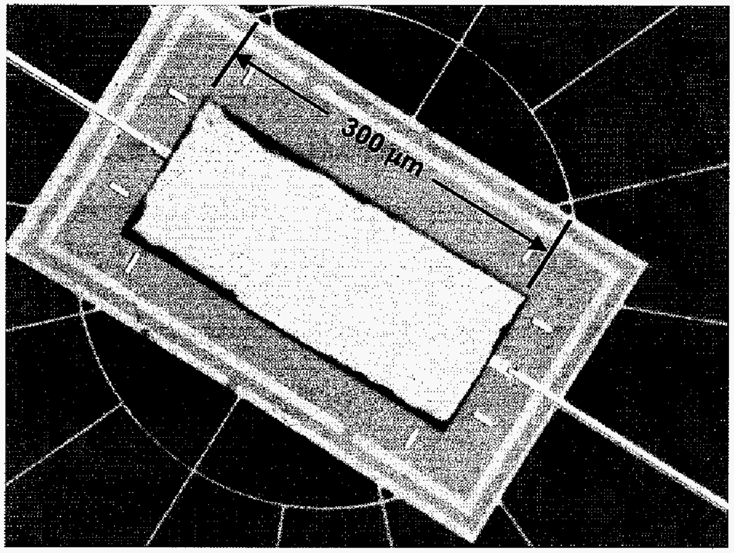
Optical Microscopy

Top View: Center-island device
Magnification: 100X



Web OD = 3.16 mm

Lead length = 4.66 mm

Au lead thickness = 0.3 μm

Lead width = 5.3 μm

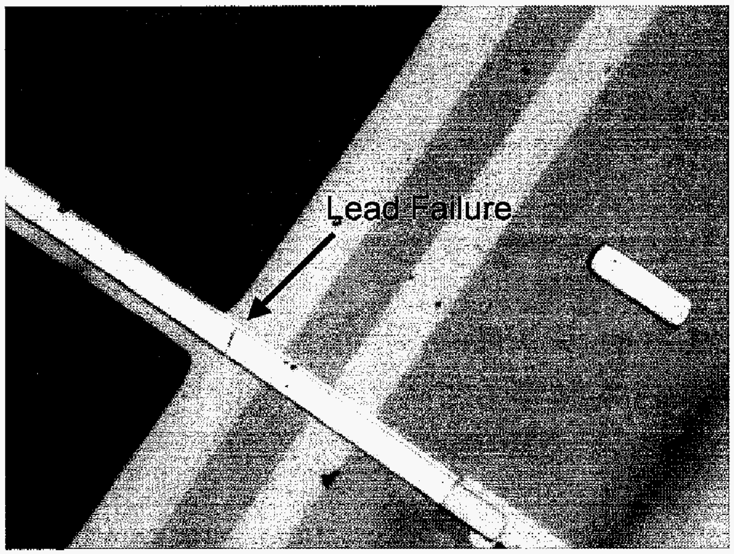
Web width = 3.4 μm

Web thickness = 1 μm

Center chip size: 300 μm x 100 μm x 25 μm
Chip mass: ≈ 4μg

Optical Microscopy -1

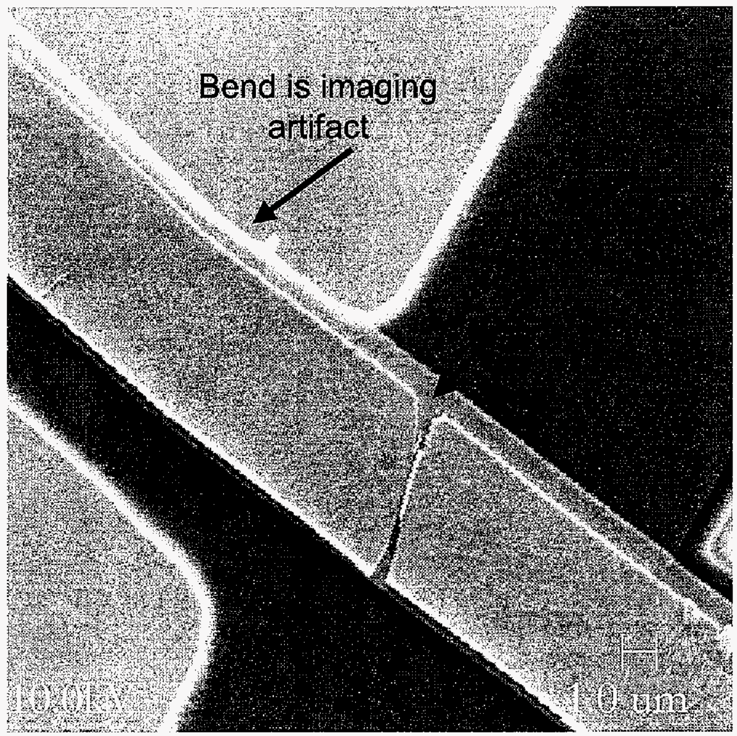
Top View: Center-island device
Magnification: 500X



Open circuit condition reveals defect site in Au lead layer
Failure morphology: fracture

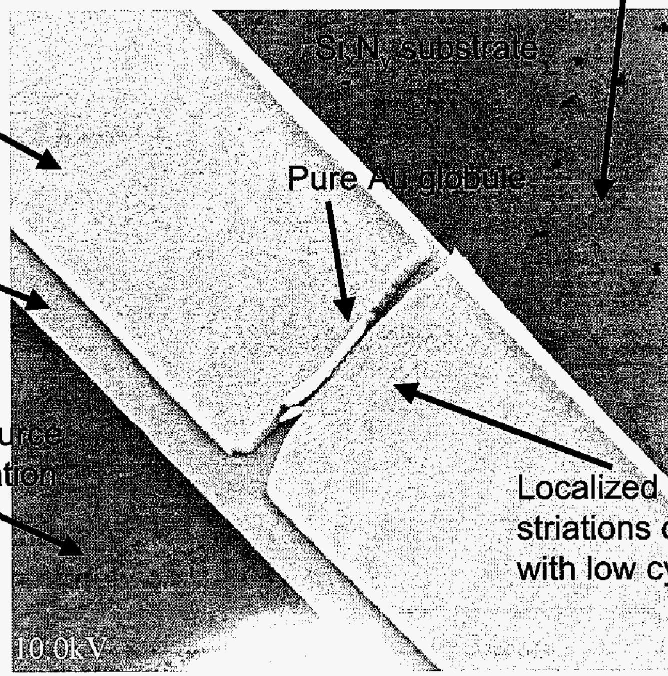
Scanning Electron Microscopy

Magnification: 5000X
Failure mode: tension
Fracture through upper layer
High energy fracture event



Scanning Electron Microscopy - 2

Magnification: 3000X
Plastic zone at front of crack tip, r_y^c < avg. grain size
Fatigue striation spacing $\lambda_s \approx 0.1\ \mu m$, or less



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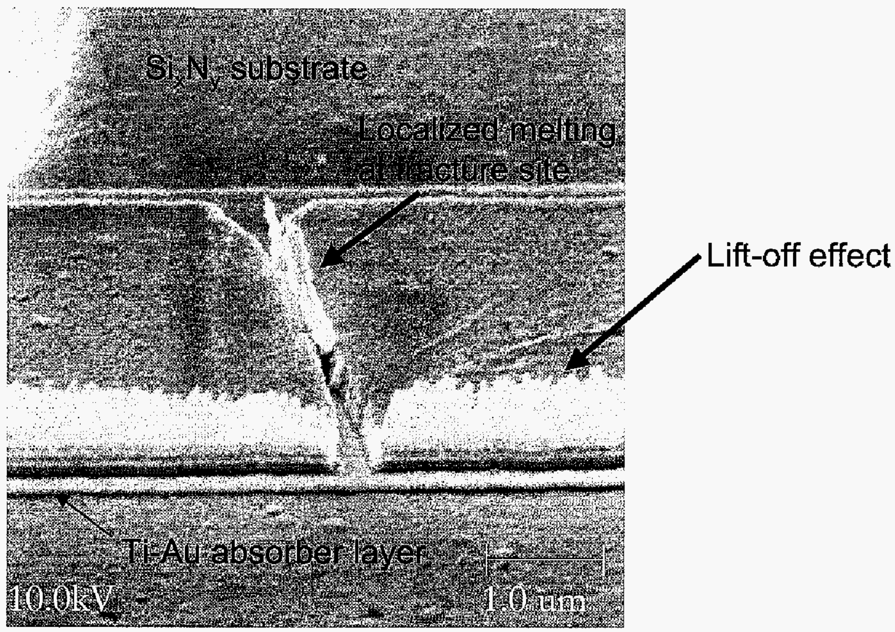
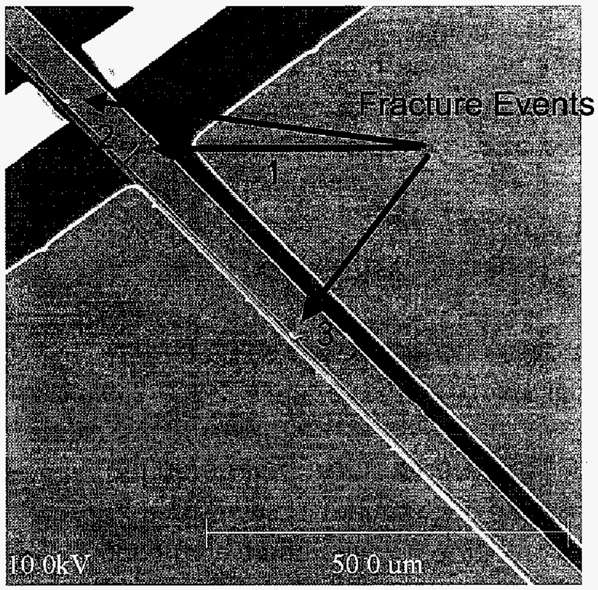
Scanning Electron Microscopy - 3

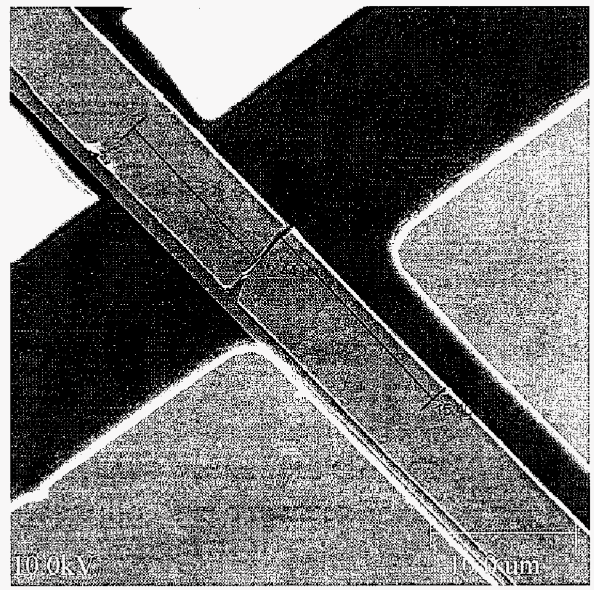
Magnification: 20,000X
Fracture completely through upper Au-layer (0.3 μm)
Localized melting at fracture site



Scanning Electron Microscopy - 4

Magnification: 1500X
Fracture survey shows defects
distributed along lead layer, with periodicity: ≈ 10-12 μm





Discussion of Results

- Crystallography of slip in fcc crystals
  - Slip occurs most often on {111} octahedral planes and in <110> directions parallel to cube face diagonals
  - 12 slip systems (four {111} planes and three <110> slip directions
- Typical crystallographic orientation in Au thin films with submicron columnar grains is <111>
  - average grain size for our films < film thickness
  - Au properties depend on orientation: $E_{<111>}$ = 117 GPa, $E_{<100>}$ = 48 GPa *(Courtney 1990)*
- Fracture morphology
  - ductile failure, with high degree of toughness
  - fracture appears intergranular prior to rapid crack growth
  - Striations/deformation bands perpendicular to tensile axis
  - Bands formed by rotation of grains in response to applied strain
  - Multiple bands formed indicate that tensile loading was uniform
  - Au globules formed by localized adiabatic heating: plastic work converted to localized heating in deformation region
    - Au globules are not due to source spitting
    - Potential source of large adiabatic heating - dislocation avalanche mechanism of Armstrong and Grise
- Elastic limit difference between amorphous substrate and overlying film are source for large plastic response and accumulated energy

Conclusion

- Studies of the dynamic mechanical response and fatigue behavior in nanocrystalline scale Au thin films are reported
  - resonant modes of substrates calculated by hand analysis and Finite Element Modeling (FEM)
  - defect spacings were also found to correlate with resonant modes of the Si_xN_y substrate web
  - SEM images reveal that the metallic films exhibit failure morphologies consistent with low-cycle fatigue
  - close examination of the failed regions show classic fatigue striations
- Results show correlation between nanoscale microstructure and mechanical response
  - ductile failures observed at sub-micron length scales with high degree of toughness
  - localized adiabatic heating is pronounced resulting in localized melting of Au film
- Origins of these observations can be traced, in part, to the large elastic limit differences between the amorphous Si_xN_y substrate, and the over-lying metal film

Acknowledgements

- The authors would like to thank NASA and California Institute Technology
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