A Briefing for Chevron

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Outline

• Missions to research
• Extreme Environments at JPL
• Some current materials research at JPL
  – Phononic damping
  – Nanotube applications
  – Flexible electronics
  – Electronics for extreme high temperatures
  – Electronics for extreme thermal cycles
• Some new research areas of interest
  – Materials for extreme cold
  – Gradient alloys
  – Multifunctional materials
Missions to Research

How do we determine what research to perform?

National Academy of Sciences Decadal survey
→ Recommended Science / Exploration Goals

NASA Science Goals
→ Targeted Robotic Science / Exploration Missions

What are the technical challenges?

→ JPL Strategic Directions
→ Specific mission challenges
  (environments, science detection / return challenges)
→ Identification of particular research issues
  (materials, etc.)
JPL maintains and monitors a set of Strategic Technologies managed by the Chief Technologist

- Critical to JPL’s ability to successfully contribute to NASA’s exploration goals and responding to NASA’s science questions
- Areas where JPL makes a unique or distinguishing contribution
- Require overt JPL or NASA management action to nurture and sustain their development

Updated 2009
- 10 Strategic Technologies

http://scienceandtechnology.jpl.nasa.gov/research/StTechDir/
Overall Technology Description

- Future JPL missions will require operations in environmental extremes that are beyond current technologies. Mechanical and electronic systems need to be developed to survive in these extreme environments.

- The environments may be categorized as follows:

<table>
<thead>
<tr>
<th>Environment / Mission</th>
<th>Radiation</th>
<th>Cold (°C)</th>
<th>Hot (°C)</th>
<th>Thermal Cycling (°C)</th>
<th>Duration (Long Life)</th>
<th>Debris</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa (Orbiter)</td>
<td>~2 Mrads/500-1000 mils</td>
<td>-160</td>
<td>-----</td>
<td>-----</td>
<td>9 Years</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Europa (Lander)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Titan</td>
<td>0.3 Mrads/100 mils</td>
<td>-180</td>
<td>-----</td>
<td>-----</td>
<td>14 Years</td>
<td>Ring Debris Encedus Plume</td>
<td>1.5 bar</td>
</tr>
<tr>
<td>Venus</td>
<td>0.1 Mrads/100 mils*</td>
<td>-------</td>
<td>487</td>
<td>-----</td>
<td>Surface - 1 day 2 yr mission</td>
<td>-------</td>
<td>92 bar</td>
</tr>
<tr>
<td>Moon</td>
<td>0.025 Mrads/100 mils*</td>
<td>-230</td>
<td>130</td>
<td>-230 - +130</td>
<td>20 Years</td>
<td>Dust</td>
<td>--------</td>
</tr>
<tr>
<td>Mars</td>
<td>0.01 Mrad/100mils*</td>
<td>-128</td>
<td>-----</td>
<td>-128 - +20</td>
<td>2+ Years</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Earth Orbit</td>
<td>0.03 Mrads/100mils</td>
<td>-150</td>
<td>-----</td>
<td></td>
<td>20 Years</td>
<td>Orbit Dependant</td>
<td>--------</td>
</tr>
<tr>
<td>Deep Space</td>
<td>0.150 MRads/100mils</td>
<td>3K</td>
<td>-----</td>
<td></td>
<td>10 Years</td>
<td>-------</td>
<td>--------</td>
</tr>
</tbody>
</table>
Sub-Element (Radiation)

• Description: Radiation Environments

• Needed for: Europa (orbiter), Europa (lander) Titan, Moon, Earth Orbit

• Solar Energetic Particle events issues for lunar electronics
SEE in general, Hardening or system mitigation to approximately 1 event/year
Sub-Element (Cold)

- **Description:** Cold temperature operation of electronics and mechanics

- **Needed for:** Titan, Moon, Europa (lander only), Deep Space (astrophysics and planet finding)

- **Performance target(s):** -230°C for lunar operations, -160 for Europa (lander), varies for deep space (10K), -180 for Titan
  - Problems with motor operations (magnetics),
  - Materials phase transitions going cold (nearly all metals)
  - Combined low temperature and radiation unknown,
  - Battery operation
Sub-Element (Hot)

- **Description:** Electronics and mechanical systems for very high temperatures

- **Needed for:** Venus

- **Performance target(s):** Venus 487°C operation for 1 day, 92 bar pressure, supercritical CO₂
  - Mechanical systems
  - Electronics operation and packaging
  - Cables and connectors
  - Sensors
  - Magnets (motors)
  - Pressure vessels
Sub-Element (Thermal Cycle)

• **Description:** operations of wide temperature ranges

• **Needed for:** Mars, Moon

• **Performance target (s):**
  – Extreme cycling between -128 and +20° C causes fatigue issues,
  – Lunar cycling from -230 to +130° C
  – Materials CTE mismatches and materials transitions going cold
  – Electronics performance of wide temperature range
  – Batteries
• **Description:** Reliability of systems for extended lifetimes. Electronics are generally not functional for more than 10 years unless specially designed.

• **Needed for:** Extended Lunar stay, deep space missions and some earth orbiting missions

• **Performance target(s):** 20 year reliable lifetime for extended lunar mission
Sub-Element (Debris/Meteoroids)

- **Description:** Reliability/operation of systems in lunar and terrestrial meteoroid environments and orbital debris during transit

- **Needed for:** Lunar missions--all missions must penetrate orbital debris field

- **Performance target(s):** Survivability during Earth-Moon transit
Sub-Element (Charged Lunar Dust)

- Description: Reliability/operation of systems in lunar dust
- Needed for: Lunar surface missions
- Performance target(s): Extended functionality in lunar dust environment
Sub-Element (Pressure)

- Description: Venus environment is 92 bars at the surface
- Needed for: Venus and Titan missions
- Importance: Critical for Venus mission
- Performance target(s): 92 bar at Venus and 1.5 bar for Titan
Some Materials Research at JPL

1. Phononic damping
2. Nanotube applications
3. Flexible electronics
4. Electronics for extreme high temperatures
5. Electronics for extreme thermal cycles
Phononic Bandgap – Goal
Courtesy Nicholas Boechler and Chiara Daraio - Caltech

- Use nonlinear and discrete phenomena in granular chains to create a tunable broadband vibration damper
- Initial target: 1kHz low pass filter
- Application: small payload vibration isolation
Can Predict Tunable Dispersion Relation (analogy to photonic band gaps):

\[ F_0 = \text{Static Precompression} \]
\[ K_2 = \text{Linearized Stiffness} \]
\[ a = \text{Distance between particle centers} \]
\[ M_1 = \text{Particle Mass 1} \]
\[ M_2 = \text{Particle Mass 2} \]
\[ k = \text{wave number} \]
\[ f = \text{frequency} \]

\[ f^2 = \left( \frac{1}{2\pi} \right)^2 \frac{K_2}{M_1M_2} \left( M_1 + M_2 \pm \sqrt{M_1^2 + M_2^2 + 2M_1M_2\cos(ka)} \right) \]

• 7 polyurethane spheres
• 1.5” diameter
• 10.18 N Precompression
Why Carbon NanoTubes?
Courtesy Abha Misra and Chiara Daraio - Caltech

• Exceptionally strong
• Excellent thermal conductivity
• Ideal ballistic transport (resistance <13 kΩ) \([h/2e^2]\)
• Chemically stable
• Good field emission properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (GPa)</th>
<th>Tensile Strength (GPa)</th>
<th>Resistivity (Ωcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW nanotube*</td>
<td>1054</td>
<td>150</td>
<td>Varies with chirality</td>
</tr>
<tr>
<td>MW nanotube*</td>
<td>1200</td>
<td>150</td>
<td>~10^{-4}</td>
</tr>
<tr>
<td>Steel</td>
<td>208</td>
<td>0.4</td>
<td>~10^{-5}</td>
</tr>
<tr>
<td>Epoxy</td>
<td>3.5</td>
<td>0.005</td>
<td>~10^{15}</td>
</tr>
<tr>
<td>Wood</td>
<td>16</td>
<td>0.008</td>
<td>~10^{7}</td>
</tr>
</tbody>
</table>

* Properties vary with structure

A sheet of Carbon
A Carbon Nanotube

Highly Nonlinear Group

Additional Support
Dr. Harish Manohara
Facilities: Kavli Nanoscience Institute (KNI), Nano fabrication facilities
Mr. Jordan R. Raney
Carbon nanotubes structures for mimicking armors as energy dispersive composites

Dynamic mechanical tests on layered structures: Drop ball tests with velocity 4 m/s

Electro-mechanical actuation capacity for active modulation devices and sensors

Courtesy Abha Misra and Chiara Daraio - Caltech

In-situ visualization of the localization of deformation:

a. Strain dependent changes in shape of a four-layered structure under confined compression showing strain localization.

b. The stress-strain curve with the different stages of strain corresponding to the images in a.

c. Schematic diagram illustrating the recovery and reorganization of the CNTs within the four layer lamellar structure.
Flexible Electronics

Materials Selection

- Based on a theoretical evaluation of available flexible printed circuit board and structural membrane polymers, the following two materials were selected for this evaluation:
  - Liquid Crystal Polymer (LCP) and
  - A commercially available Polyimide (PI)
- Among available thermoplastic printed circuit board materials capable of being used in our lamination process, LCP was selected due to its excellent combination of mechanical and electrical properties.
- PI was selected as a baseline because of its proven space reliability, along with its mature circuit fabrication technology and its superior mechanical properties.

Property Requirements

- Dielectric Constant (\( r \)) Low
- Dissipation Factor/Loss Tangent (\( \tan \delta \)) Low
- Min. Strength to maintain flatness 50 psi
- Tensile Modulus Min. 100 ksi (prefer 300 ksi)
- Coefficient of Thermal Expansion (CTE) – Room
- Temperature
  - As close to Si (8 ppm/°C) as possible w/o delaminating from Cu
  - (16.5 ppm/°C).
- Glass Transition Temperature (Tg) Outside of operating range (application dependent)
- Melt/Decomposition Temperature > Processing temperatures 210-215° C for 63Sn37Pb
- Flex Behavior Dynamic flex (> 1000 cycles)
- Solderability pass

For the embedded assemblies, electrical connections are made through holes in the LCP dielectric to the sides of the traces that were initially in direct contact with the LCP.

Therefore, the active circuitry on the thinned silicon chip and the traces on the flexible substrate are facing the same direction.

A second layer of dielectric is then laminated onto the backside of the assembly, thereby embedding the silicon chip within two layers of flexible LCP material.


Venus Electronics

Objectives:

- The overall objective of this task is to design and demonstrate the functionality of a pre-amplifier circuit for a pressure sensor system that is capable of operating at 460° C (in an inert environment) using commercial components.
  - Screen active and passive components at 460° C.
  - Develop and evaluate a high temperature packaging methodology at 460° C.
  - Design and fabricate a pressure sensor pre-amplifier circuit.
  - Evaluate the pressure sensor electronics for functionality at 460° C.
  - Design and fabricate an updated pressure sensor system, and
  - Evaluate the second set of pressure sensor electronics for functionality at 460° C.
  - Develop methodology/guidelines for 460° C circuit design and packaging.

In this project we are developing the technologies required to enable the construction of small-scale electronic sensing systems that can directly operate at the extremely high temperatures (up to 460° C) of the Venus ground ambient atmosphere. As a demonstration, we propose to build a high temperature sensor system, which includes a commercial pressure sensor and a pre-amplifier (consisting of commercial, high temperature discrete transistors, resistors, and capacitors), and evaluate its functionality at 460° C, in an inert environment. Our work will enable us to establish an infrastructure at JPL for fabrication of high temperature electronics along with a supply chain that can complement this capability.
Packaging Issues

- Following initial testing of the SiC BJT with the Ag-glass die attach in an Al$_2$O$_3$ package, a voltage offset was observed, indicating poor contact to the backside conductor.

- Visual inspection of the die attach material revealed significant porosity.

- Cracking of the passivation on the surface of the BJT was also observed following initial testing.

- This cracking is due to one of the following:
  - Stresses in the passivation due to CTE differences between the die and the passivation, or
  - Stresses resulting from CTE differences between the die and the package.

- Further testing is underway to determine the sources of the failures.

- Au wirebonds on the Au SiC BJT bondpads resulted in a reliable attachment, capable of 460°C operation.
Thermal Cycle Resistance Electronics (TCRE)

Objectives:

- Develop parts selection, design rules and packaging techniques to ensure survivability and operation of MSL electronics
  - Extreme temp range (-120°C to +85°C)
  - Long life (1500 cycles) for 500 Martian Sols x 3 cycles
- Validate electronics and packaging components through modeling, analysis, and environmental/life testing
**TCRE Model and Failure Analysis**

1.) Wire Bond - Break in gold wire at the peak of the wire bond.

A minimization of the potential energy was developed from the geometric function determined by minimizing the bending energy for both splines. The potential energy ($\Pi$) may be written:

$$\Pi = \frac{EI}{2} \int_0^d \kappa_1^2 \left(1 + \left(y_1''ight)^2\right)^{\frac{3}{2}} \, dx_1 + \frac{EI}{2} \int_0^d \kappa_2^2 \left(1 + \left(y_2''ight)^2\right)^{\frac{3}{2}} \, dx_2,$$

where $E$ is Young’s modulus and $I$ is the moment of inertia of the cross section of the wire. The integration of the spline function, $y$, is performed along the span $dx$. The curvature for the two spans is given by:

$$\kappa = \frac{y''}{\left(1 + y'^2\right)^{\frac{3}{2}}}$$

The potential energy can be minimized by finding the coordinate $(d,h)$ where

$$\frac{\partial \Pi}{\partial d} = 0 \quad \text{and} \quad \frac{\partial \Pi}{\partial h} = 0$$

This optimization was performed by Jinka et.al. to find the optimal span length for minimized stress.

Some New Research Areas of Interest

1. Materials for extreme cold
2. Gradient alloys
3. Multifunctional materials
Extreme cold environments are encountered in the exploration of the Europa, Titan and the Moon. These environments could be as cold as -160°C, -180°C and -230°C respectively. We are concerned with ductile-brittle transitions (DBT) in various solders. We would like to gain a fundamental understanding of DBT’s in Sn alloys as a function of various alloying elements including Pb, Au, Ni, Cu, Ag, etc. Toughness, tensile and fatigue properties are of interest. An understanding of fundamentals would be useful to predict behavior of ternary and quaternary alloys. Fatigue for extreme cycles is also of interest, primarily from -130-+85°C.
Applications of gradient structures formed using the laser engineered net-shaped (LENS) process. We are currently studying a transition from Ti to Steel. We are concerned about possible intermetallic structures and their properties. Other gradient structural alloys are of interest.
Multifunctional materials

Modular systems are being evaluated for deploying load-bearing electronics assemblies with built-in heat-transfer and which have the potential to significantly reduce mass overhead. These structures are essentially printed circuit boards with a carbon-composite core which has high planar thermal conductivity and a high structural strength. To succeed, such systems will require reliable interconnect technology for a variety of environments. The available technologies and materials requirements for the connectors need to be evaluated to fully understand current limitations and future development requirements.
Conclusions

- **Fundamental science and engineering research enables breakthrough, unique mission development**
  - Science and technology laboratories must be supported over long time periods
  - Technology development occurs over time scales that can be far greater than mission development time scales