HOTTech Program Overview

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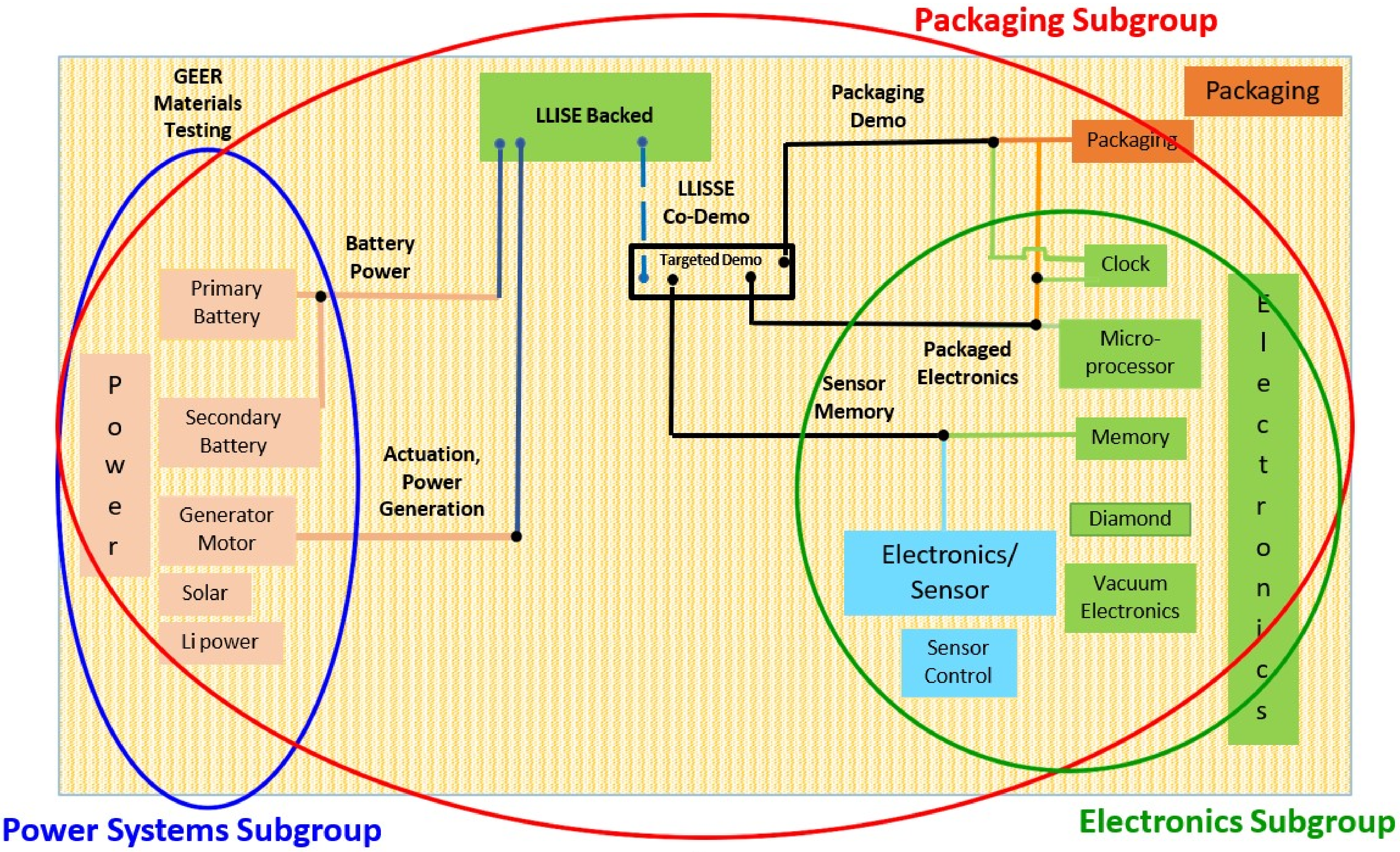
High Operating Temperature Technology (HOTTech) Program Overview

- HOTTech is a ROSES16 Announcement of Opportunity from the Planetary Science Division, Science Mission Directorate, NASA Headquarters
- First time this call was made
- The primary science objective is to develop and mature technologies that will **enable**, **significantly enhance**, or **reduce technical risk** for ***in situ* missions** to high-temperature environments with temperatures approaching 500ºC or higher for the robotic exploration of high-temperature environments such as the Venus surface, Mercury, or the deep atmosphere of Gas Giants.
- HOTTech is limited to high temperature electrical, electronics, electro-mechanical systems that could be needed for potentially extended *in situ* missions to such environments. HOTTech **is not** meant for instrument development
- 29 proposals were submitted and peer-reviewed by a panel of experts in the field:
  - 8+4 proposals were selected to cover a broad portfolio of technologies
  - Approximately $600k/award with a max duration of 3 years

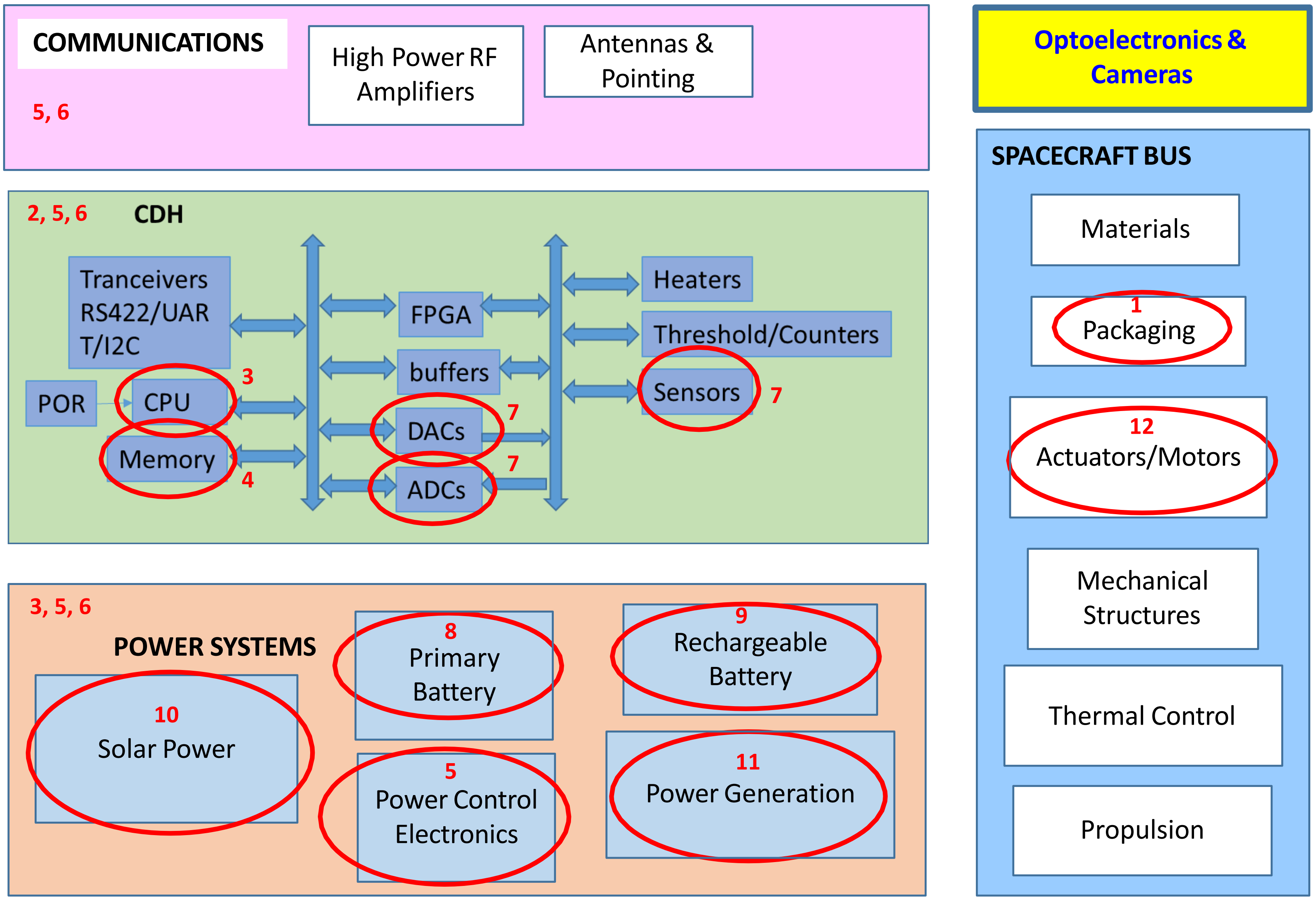
HOTTech Project Technology Areas

	Technology Area	HOTTech Tasks	PI	Organization
1	Packaging	500°C Capable, Weather-Resistant Electronics Packaging for Extreme Environment Exploration	Simon Ang	University of Arkansas
2	Clocks & Oscillators	Passively Compensated Low-Power Chip-Scale Clocks for Wireless Communication in Harsh Environments	Debbie Senesky	Stanford University
3	GaN Electronics	High Temperature GaN Microprocessor for Space Applications	Yuji Zhao	Arizona State University
4	Computer Memory	High Temperature Memory Electronics for Long-Lived Venus Missions	Phil Neudeck	NASA GRC
5	Diamond Electronics	High Temperature Diamond Electronics for Actuators and Sensors	Bob Nemanich	Arizona State University
6	Vacuum Electronics	Field Emission Vacuum Electronic Devices for Operation above 500 degrees Celsius	Leora Peltz	Boeing Corp.
7	ASICs & Sensors	SiC Electronics To Enable Long-Lived Chemical Sensor Measurements at the Venus Surface	Darby Makel	Makel Engineering, Inc
8	Primary Batteries	High Temperature-resilient And Long-Life (HiTALL) Primary Batteries for Venus and Mercury Surface Missions	Ratnakumar Bugga	NASA JPL
9	Rechargeable Batteries	High Energy, Long Cycle Life, and Extreme Temperature Lithium-Sulfur Battery for Venus Missions	Jitendra Kumar	University of Dayton
10	Solar Power	Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration Mission	Jonathan Grandidier	NASA JPL
11	Power Generation	Hot Operating Temperature Lithium combustion IN situ Energy and Power System (HOTLINE Power System)	Michael Paul	JHU/APL
12	Electric Motors	Development of a TRL6 Electric Motor and Position Sensor for Venus	Kris Zacny	Honeybee Robotics, Inc.

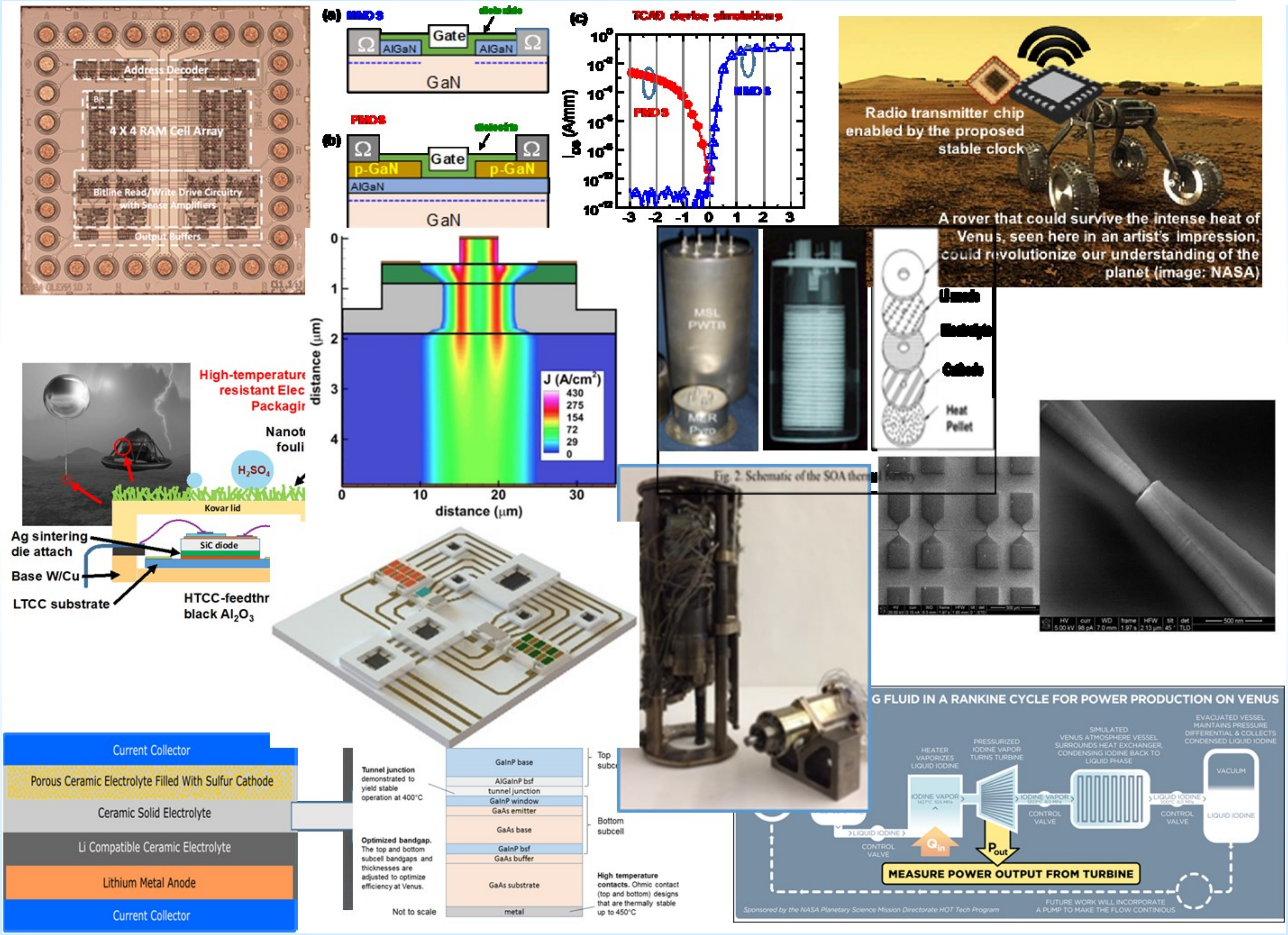
HOTTech Integration Project – Integration Tool



How Technology Areas Map to Spacecraft Systems

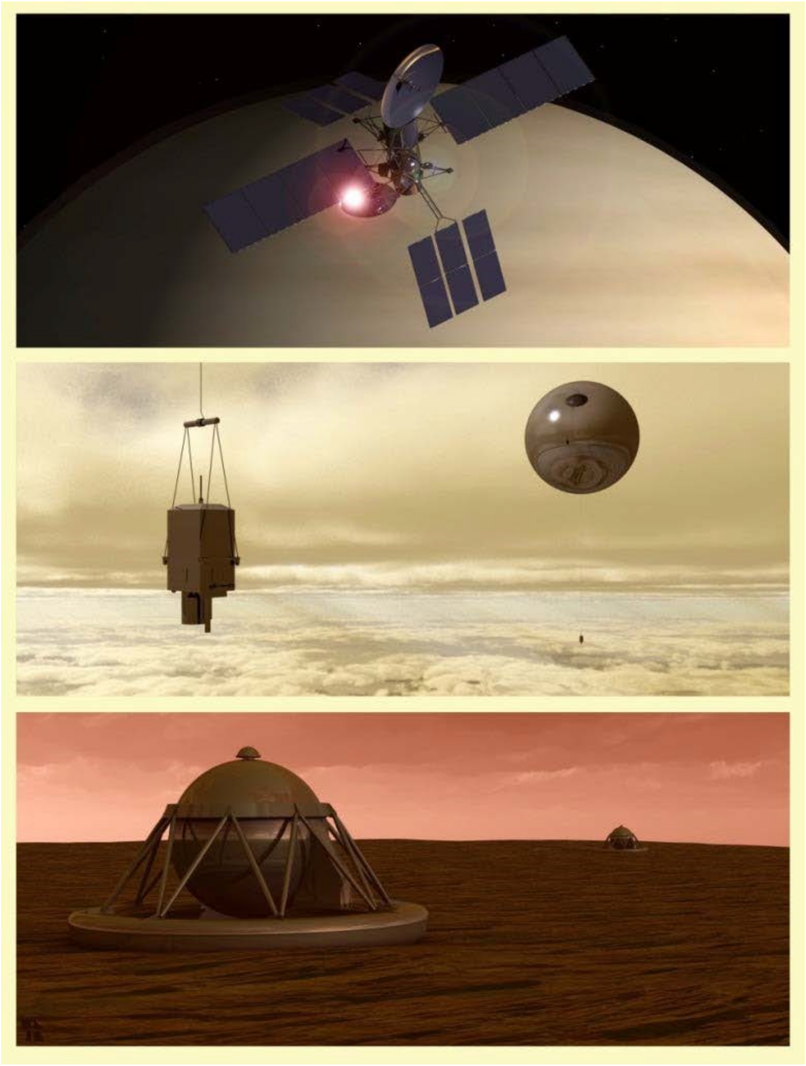


Welcome to HOTTech!



Technology Needs for Future Venus Missions

Motivation



NASA is studying viable approaches to a Venus mission to collaborate with Russia (VENERA-D):

- Surface Platforms utilizing high temperature electronics (HOTTech)
- Aerial Platforms operating in the upper atmosphere using conventional electronics

Strong scientific community interest in proposing these types of missions

Surface Lander

- Focus Areas identified from Aug. 2018 HOTTech Meeting:
  - Power Generation/Storage/Harvesting
  - Sensors (including imaging)
  - Power Electronics (>1 amp capable transistors)
  - RF Signal Electronics (>100Mhz capable switching transistors)
  - Actuators/Motors/Lubrication
  - Packaging & Hermetic Feedthroughs
  - Passive Components (capacitors, inductors, resistors)
  - Heterogeneous Electronics

- Technologies Feed into LLISSE (which feeds into VENERA-D)
  - Currently the **Power Generation** and **Battery Power**, **ASICs and Sensors**, and **Electric Motors** work are directly applicable to LLISSE with a clear path to infusion

Venus Aerial Platforms

- Variable Altitude Balloons are a means of getting higher value science with a lower-risk approach compared to solar aircraft or maneuverable airships and keep the electronics in a conventional temperature range

- Small fixed-altitude Neutrally-Buoyant Drop Sondes also seem attractive if high temperature electronics become available

- **Key Technical Issues:**
    - Maintain 70km to 48km altitude (avoids high temps)
    - Airframe & Materials compatible with acids (PH range -1.3 to 0.5)
    - Power via Solar and/or Batteries
    - Navigation, Guidance & Control
    - Science Instruments (2014 VEXAG Roadmap for Venus Exploration)
    - Lifetime of months to years
    - Pressure range of 80 mbar to 1.3 bar
    - Vertical share of horizontal wind up to 5-10 m/s per km

500°C Capable, Weather-Resistant Electronics Packaging for Extreme Environment Exploration

PI: Simon Ang / Univ. of Arkansas

Target: Extreme environment package providing flexible I/O and related integration processes.

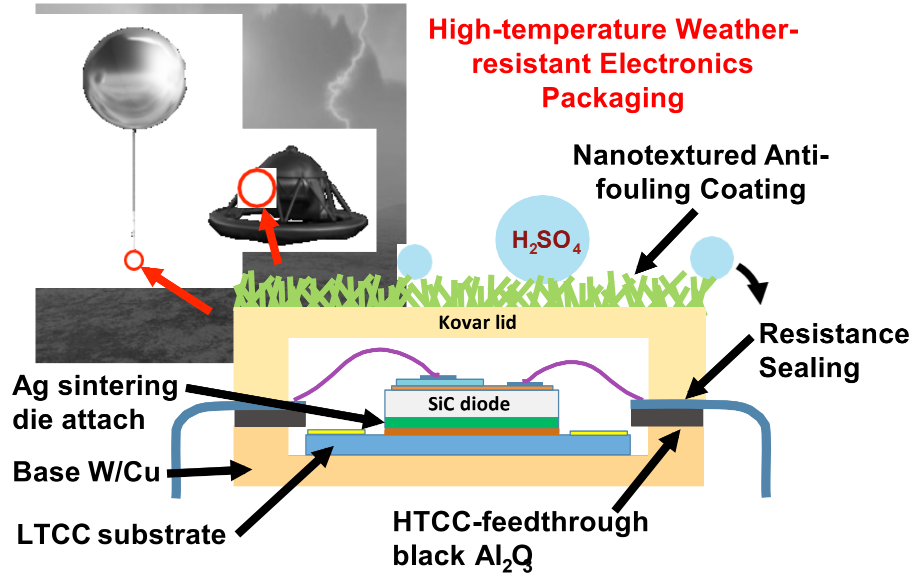
Science:

- *Deeper understanding of survival/degradation behavior of die attach, metal interconnect, and housing materials in extreme conditions (500° C, chemically corrosive conditions)*

Objectives:

- Leverage existing wide bandgap devices (e.g., SiC and GaN diodes) with high-temperature metallization.
- Develop high-temperature packaging using 500° C capable die attach and metal interconnect technology on ceramic substrates.
- Integrate nanotextured anti-fouling films onto housing surfaces.
- Perform thermal and chemical exposure tests on packaging materials and actual packaged devices using high-temperature furnaces (Stanford) and relevant simulation pressure vessels (NASA and University of Arkansas).
- Analyze experimental data and make specific recommendations to NASA for selection of packaging materials and design architectures to realize HOTTech-relevant systems.

CoIs: Stanford; Dr. Debbie Senesky, EXtreme Environment Microsystems Laboratory (XLab)



Key Milestones:

- High temperature die metallization determination
- Anti-fouling coating selection & evaluation
- Chip integration selection & evaluation
- Substrate integration evaluation
- Package construction and environmental evaluation
- Pre-mechanical chip integration analysis
- GEER testing of packaged components
- Post-mechanical chip integration analysis

TRL (2) to (5)

Development of a TRL6 Electric Motor and Position Sensor for Venus

PI: Kris Zacny/Honeybee Robotics

Target: Scientific mission to surface of Venus or similar high temperature, high pressure (HTHP) environment.

Science:

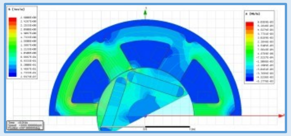
- Regolith sample acquisition and transport.
- Pointing of cameras and antennas.
- Robotic manipulation.
- Mobility.

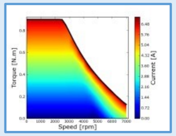
Objectives:

- Design, build and test an electric motor and position sensor compatible with Venus surface environment (CO_2 at 462C, 90 bar pressure).
- Document fabrication and screening test procedure.
- Characterize high temperature reduction in motor torque and efficiency by dynamometer testing. Compare with analytical predictions.
- Perform motor life test.
- Mature HT motor technology from TRL5 to TRL6.

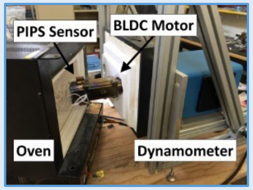
Co-Is: Jeffery Hall, Jay Polk/JPL; Fredrik Rehnmark, Cody Hyman/Honeybee Robotics

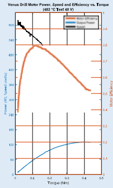
ANALYSIS: Motor simulations performed with Low-Frequency Electromagnetic Field Analysis Software.

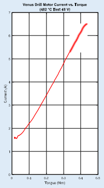




TEST: HT dynamometer testing.







DEMONSTRATION:

H

T

motor and position sensor installed in Venus rock sampling drill (left) and high pressure blower (right).

Key Milestones:

- Month 1-3: Perform analysis to size HT motor.
- Month 4-6: Build HT motor.
- Month 7: Perform dynamometer and life test.
- Month 8-12: Integrated demonstration at VTP.

TRL 5 to 6

Passively Compensated Low-Power Chip-Scale Clocks for Wireless Communication in Harsh Environments

PI: Prof. Debbie G. Senesky (Stanford University)

Target: Utilize 1000° C capable InAlN/GaN electronic device architectures to mature high-temperature stable clock technology.

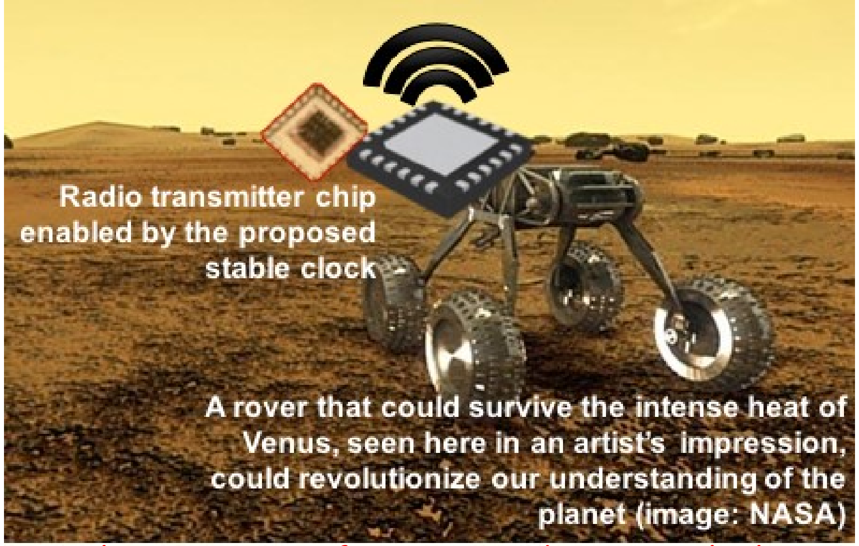
Science:

- Increase the duration and scope of many proposed NASA missions to hot planets and bodies (e.g. Venus, Mercury, or Gas Giants).
- Enable stable collection/transmission of scientific data from any probe, lander, explorer, or sensor to be transferred to main spacecraft.

Objectives:

- Adapt existing AlGaN/GaN and AlN micromechanical bulk-mode resonator designs to the InAlN/GaN platform using multi-physics modeling tools.
- Nanofabricate lattice-matched InAlN/GaN micromechanical resonator arrays with high-temperature metallization, passive temperature compensation, and various film doping concentrations to achieve high-temperature operation.
- Perform in-situ high-temperature laboratory characterization (up to 600° C at various pressures) to quantify temperature-dependent frequency response.

CoIs: Dr. Mina Rais-Zadeh (NASA Jet Propulsion Laboratory)



Schematic image of an envisioned rover on the hot surface of Venus communicating collected scientific data with robust radio transmitter chip.

Key Milestones:

- **Year 1:** 1.) Demonstrate resonator with Q above 2,000
  2.) Achieve temperature stability below 10 ppm
  3.) Perform characterization of discrete resonators and oscillator resonator array
- **Year 2:** 1.) Demonstrate resonator with Q above 5,000
  2.) Achieve temperature stability below 1 ppm
  3.) Perform high-temperature characterization of oscillator resonator array

TRL 2 to 4

Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration Missions

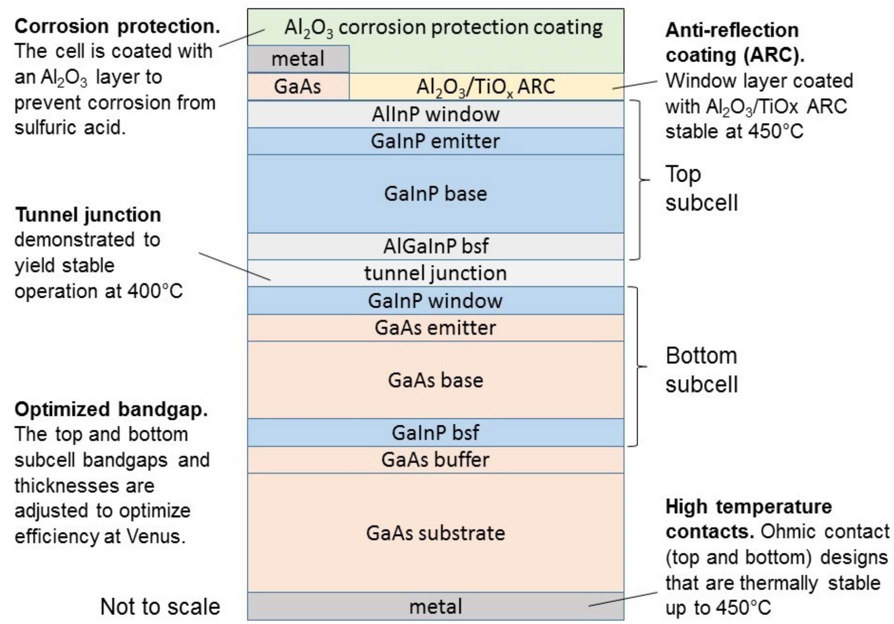
PI: Jonathan Grandidier/JPL

Target: The overall objective is to develop Low Intensity High Temperature (LIHT) solar cells that can function and operate effectively in the Venus atmosphere at various altitudes, and survive on the surface of Venus where the temperature reaches 450-500° C.

Science:
We are developing a dual-junction high-temperature GaInP/GaAs solar cell to satisfy the extreme Venus environmental requirements. The novel features of the proposed cell include:
- high bandgap semiconductor materials (GaInP/GaAs), that are optimized to capture solar irradiance efficiently at Venus.
- high-temperature tunnel junctions.
- high-temperature solar cell contacts.
- anti-reflection coatings.
- Al_2O_3 corrosion protection coatings.
- Adjust size of text box as required

Objectives:
- Demonstrate technical feasibility of a LIHT solar cell
- Fabrication of a LIHT cell and demonstrate LIHT performance goals

CoIs: Alex Kirk, Mark Osowski/Microlink Devices; Minjoo L. Lee/UIUC; Harry Atwater/Caltech



Low Intensity High Temperature (LIHT) Solar Cell. The LIHT solar cell will enable survival and optimize performance in the Venusian environment.

Key Milestones:
- Fabrication of preliminary LIHT solar cell (MicroLink/UIUC)
- Develop LIHT solar cell performance models (CalTech)
- Test data and analysis of advanced LIHT at 300C demonstrating performance under Venus solar spectrum (JPL)

TRL 2 to 4

The HOTLINE Power System

Hot Operating Temperature Lithium combustion for IN situ Energy and Power

PI: Michael Paul, Johns Hopkins Applied Physics Lab
Co-PI: Dr. Alex Rattner, Penn State University

Target: Venus

Science: Long duration surface geology and atmospheric measurements

Objectives:

- Demonstrate Rankine power system designed for Venus surface operating conditions.
- Characterize power levels, efficiencies

Key Milestones

Year 1

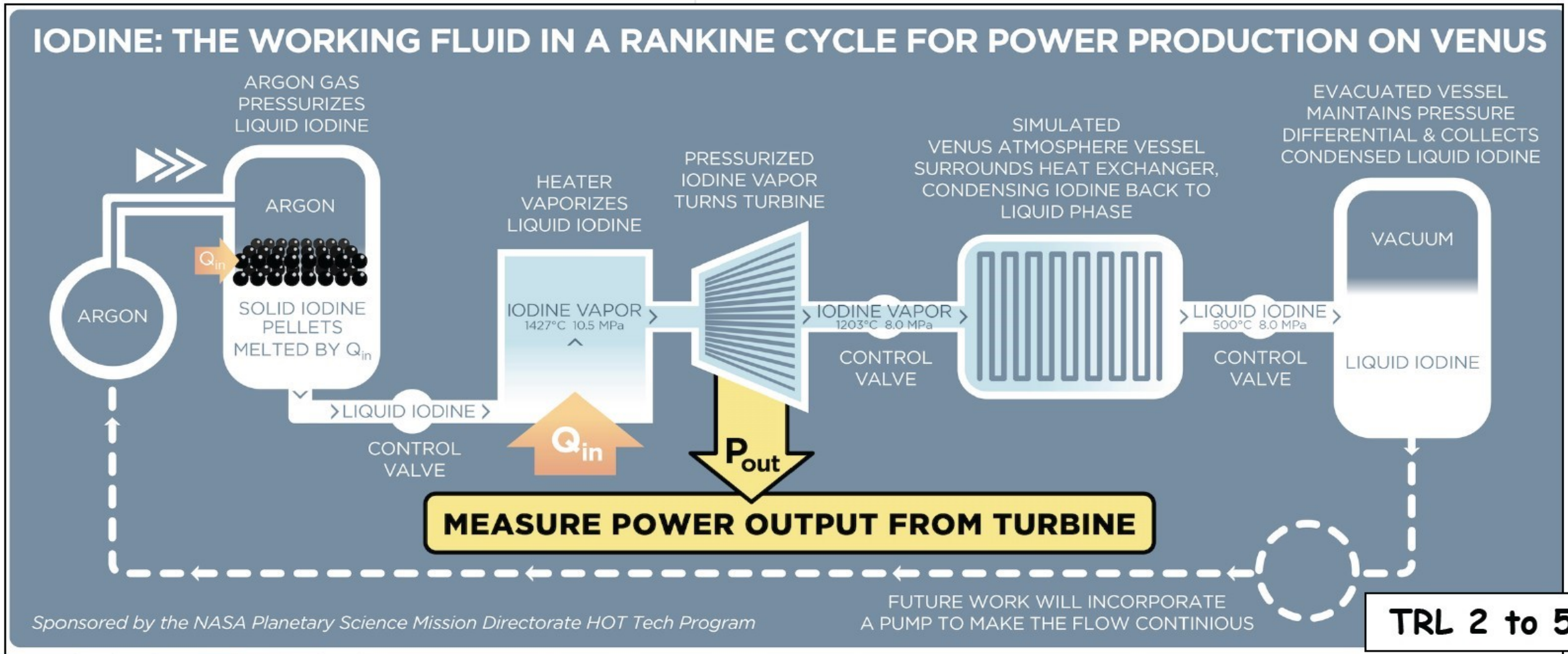
- Flight power system high level definition
- Test system (below) detailed design

Year 2

- Test system fabrication
- Test system checkout

Year 3

- High temperature power tests



TRL 2 to 5

High Temperature Diamond Electronics for Actuators and Sensors

PI: Robert J. Nemanich/Arizona State University

Target: Diamond electronics for actuator and sensor applications at high temperatures (>500° C) for Venus and solar missions.

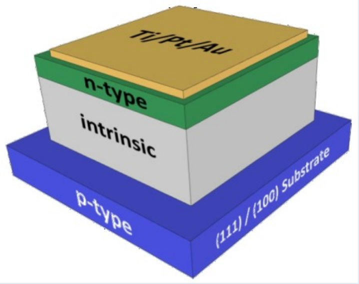
Science:

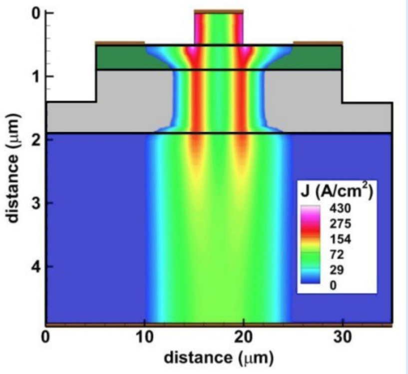
- The Decadal Survey identifies future missions including Mercury/Venus seismic networks and Venus sample-return. Key technological components of such missions include high-temperature (>500° C) survival and long-duration high-temperature subsystems.

Objectives:

- Develop, test and simulate diamond PIN diodes and bipolar junction transistors (BJT) for actuator control and low noise sensor amplification operating >500° C.
- Growth of diamond epitaxial structures eliminating defect structures that degrade device performance.
- Develop strategies for low resistance contacts and stable surface passivation.
- Simulate device operation, stability and degradation for high temperature operation.
- Identify specific mission objectives that would be impacted by the diamond electronics, and develop device specifications.

CoIs: Stephen Goodnick, Franz Koeck, Brianna Eller, James Lyons/Arizona State University; Srabanti Chowdhury/UC-Davis;





Schematic of a diamond PIN diode structure and a simulation of the current density in a diamond BJT operating at 500°C

Key Milestones:

- Diamond PIN diodes for actuator applications operating >500° C with 50V blocking and 1A forward.
- Diamond bipolar junction transistors (BJT) for actuator applications operating > 500° C with 50V blocking and 1A forward.
- Diamond bipolar junction transistors (BJT) for sensor applications with high linearity, low noise at >500° C.

TRL (2) to (4)

Field Emission Vacuum Electronic Devices for Hot Temperature Operations

PI: Dr. Leora Peltz/Boeing Research and Techology

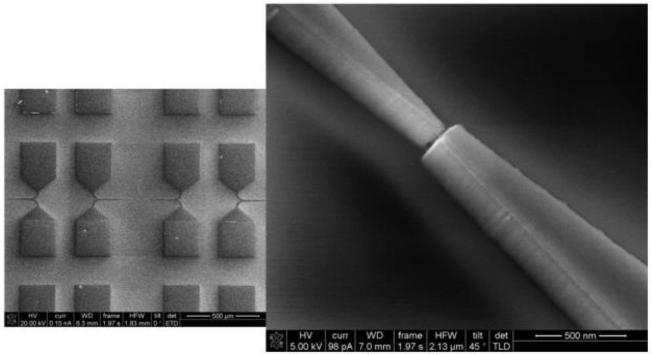
Science and Technology:

- The proposed approach applies nanolithography of 3D silicon structures, followed by modulated etching and then metallization with refractory metals (ex: tungsten). Advanced modulated etching methods will enable sub–50nm 3D geometric profiles, suitable for efficient field emission. Deposition of refractory metals will contribute to the integrity of the metal film for 30 days of device operation at high temperatures of 500° C.
- This creates a new, breakthrough electronics technology that achieves in a miniaturized sub–micron form factor the high temperature performance of vacuum tubes. FEV circuits can help enable a new class of long duration missions to Venus surface, which are not achievable with the existing electronics technologies.

Objectives:

(1)demonstrate *FEV* nanotriodes optimized for 2 to 4 GHz frequency corresponding to S–Band, operating at 500ºC
(2)design and fabricate a small analog integrated circuit (RF preamplifier) and a small digital integrated circuit (oscillator), both operating at S–band (2–4 GHz);
(3) verify operation of *FEV* devices and circuits at 500ºC for 30 days.

CoI: Dr. Axel Scherer/Caltech



Micrograph of prototype FEV device

Key Milestones:

- **Year 1**: (1) process development and characterization for *FEV* devices and circuits for S–band; (2) preliminary circuit design and preliminary Cadence simulation for the analog S–band preamplifier circuit, and digital oscillator circuit; (3) simulation study of metallization at 500ºC.
- **Year 2**: (1) fabrication of preliminary *FEV* circuits (analog S–band preamplifier and digital oscillator); (2) characterization tests.
- **Year 3**: (1) fabrication of *FEV* final circuits (analog S–band preamplifier and digital oscillator); (2) characterization tests of *FEV* circuits at 500° C for 30 days.

Progress: TRL 3 to 5

SiC Electronics to Enable Long-Lived Chemical Sensor Measurements at the Venus Surface

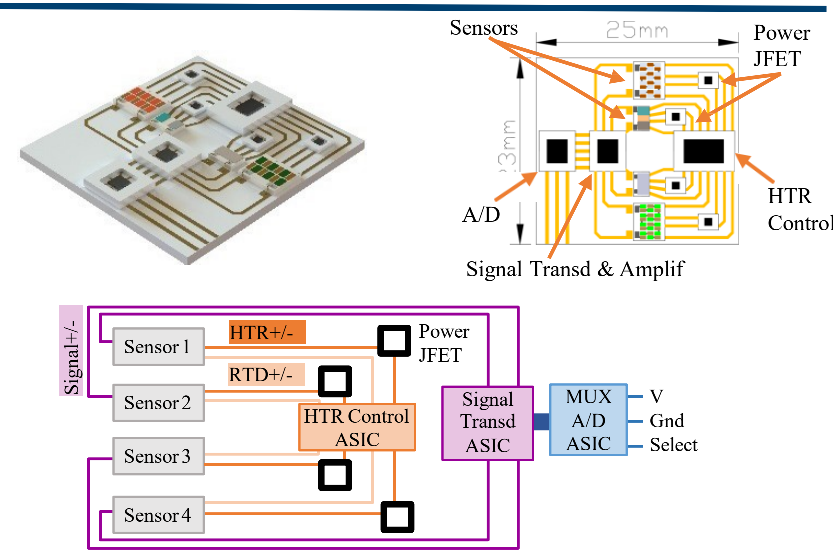
PI: Darby Makel/Makel Engineering, Inc.

Target: Demonstrate high temperature electronics integrated with an array of high temperature chemical sensors for use in extended duration Venus surface measurements.

Science:
- SiC electronics will enable uncooled long lived operation of advanced chemical sensors for trace species including SOx, CO, OSC, HF, HCl, H_2O, NO, H_2, O_2 at 500°C. Such capabilities will allow extended duration characterization of the Venus atmosphere down to the surface.

Objectives:
- Develop silicon carbide (SiC) based electronics capable of operation at 500°C
- Core SiC electronics targeted for amplification, analog control feedback, and analog to digital data to support chemical sensor operation
- Integrate the SiC electronics with an array mature, highly selective chemical microsensors operational at and above 500°C
- Mature the SiC electronics based atmospheric measurement instrument to reduce risk to future missions
- Technology validation by testing at GEER and in volcanic environments

CoIs: Kevin Baines, David Pieri,/Jet Propulsion Laboratory; Gary Hunter/NASA Glenn Research Center



Layout and schematic of close integration of SiC electronics with harsh environment chemical sensors – four-channel system illustrated

Key Milestones:
- Requirements definition – 1st quarter
- SiC analog amplification and control ASICs – 8th quarter
- SiC A/D converter ASIC – 10th quarter
- Design validation testing at GEER – 10th quarter
- Terrestrial volcanic testbed demonstration – 12th quarter

TRL 3-4 to 6

High Temperature-resilient And Long-Life (HiTALL) Primary Batteries for Venus and Mercury Surface Missions

PI: Ratnakumar Bugga / NASA-Jet Propulsion Laboratory

Target: Surface missions to Venus, Missions to Mercury, or the deep atmosphere of gas Giants.

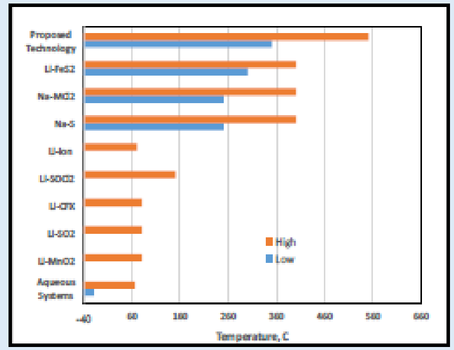
Science:

- Being inherently stable at 500oC and high CO2 pressures (92 bar) and having high specific energy, these batteries will enable a long-term in-situ Venus missions for >30 days (vs <2h with the state of art batteries)
- Venus surface geology, tectonic activity and composition of Venus and Mercury.

Objectives:

- Develop an enabling advanced primary battery technology resilient to the high-temperature environments of Venus surface, Mercury, or the deep atmosphere of gas Giants and operational for 30 days at 500°C (and 92 bar pressure) to enable their robotic exploration.
- Improve the energy densities of these batteries for powering in-situ missions for >30 days.
- The performance targets include: specific energy of >150 Wh/kg, energy density >200Wh/l, long calendar life (>5y) and low self-discharge (<1%/day) at 500°C.
- Batteries will be lightweight (3X vs. SOA) and compact (4X vs. SOA) and will support Venus/Mercury surface missions over long durations (>30 days vs <2h for SOA)

CoIs: i) Michael Pauken (JPL); ii) William West (JPL) iii) Dharmesh Bhakta (Eagle Picher Tech)



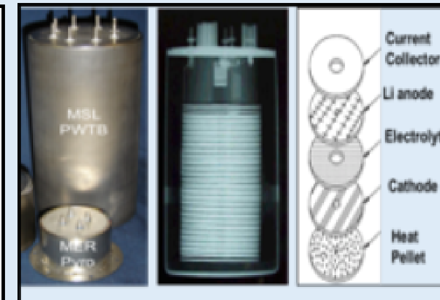


Fig. 2. Schematic of the SOA thermal battery

		Gen 1 Batteries	Gen-2 Batteries
Performance Target		100 Wh/kg and 200 Wh/l (at battery)	150 Wh/kg and >200 Wh/l) (at battery level)
Operational Life at 500C		15 days	>30 days at 500C
Chemistry	High Capacity Anode	Li-Si	Li-rich formulation
	High Energy Cathode	FeS2 or CoS2	FePS3 or CoPS3
	Electrolyte (500C)	Alkali metal halide eutectic	All Li-ternary eutectic (low vapor pressure)
Prototype Batteries (Multi-cell)		No pyro devices and thermal insulation thin-cases	Thick electrodes, thin substrates High energy design

#	Description of Milestone	Due Dat
1	Set up the test bed for battery testing at 500C	End Q1
2	Complete modified cell design for Gen-1 (500C and 100 Wh/kg) battery	End Q2
3	Demonstrate performance enhancement (100 Wh/kg) in Gen-1 500C batteries (with Li-Si/FeS2 chemistry)	End Q4
4	Identification of cell components for 500C and 150 Wh/kg battery	End Q6
5	Fabrication of Gen-2 prototype cells/batteries (500C and 150 Wh/kg) with advanced chemistry	End Q7
6	Demonstration 150 Wh/kg at 500C in Gen-2 high temperature batteries (with advanced chemistry)	End Q8

TRL 3 (entry) to TRL4 (exit)

High Temperature Memory Electronics for Long-Lived Venus Missions

PI: Phil Neudeck/NASA Glenn Research Center

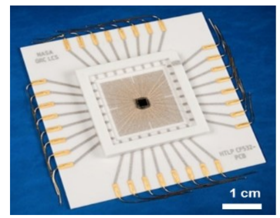
Target: Demonstrate high temperature memory circuits, Random Access Memory (RAM) and Read Only Memory (ROM), operable for extended periods in Venus environments.

Science:
- This development complements on-going high temperature electronics development towards realization of a long-lived Venus surface science station by providing unique memory capabilities that notably change possible mission architectures.

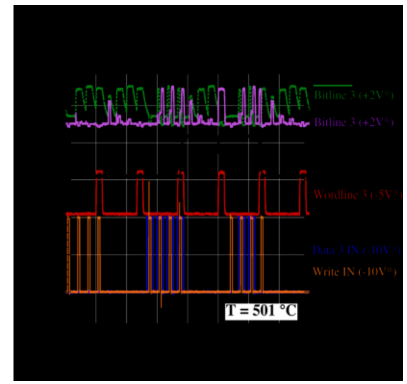
Objectives:
- Develop fully functional 500C memory packaged circuits operating in-situ for long duration Venus missions composed of both RAM (with read/write capability) and ROM (Read Only Memory) chips capable of interfacing with mission control logic and sensors.
- Demonstrate both circuit types with Venus representative data storage in laboratory conditions (at least 3 months) and in simulated Venus environments (GEER) (60 days).

CoIs: D. Spry is Co-I for the circuit design and fabrication. G. Hunter is the Co-I for System Integration and Prototype Testing.

Subcircuits of a prototype high temperature Random Access Memory.



A test assembly of a packaged silicon carbide integrated circuit.



High temperature test waveforms demonstrating ability to read and write a selected RAM cell.

Key Milestones:
- Year 1: First Generation RAM and ROM Memory technology laboratory (oven) demonstrated at 500C for 1.5 months or more.
- Year 2: Second Generation RAM and ROM Memory technology at 500C laboratory demonstrated at 500C for 1.5 months or more. Demonstrate RAM and ROM control circuitry.
- Year 3: Fabricate Prototype RAM and ROM Memory technology with 128 bit and 512 bit capability respectively with control circuitry at 500C. Demonstrate in laboratory and in GEER.

TRL 3-4 to 6

Title: High Energy, Long Cycle Life, and Extreme Temperature Lithium-Sulfur Battery for Venus Missions

PI: Jitendra Kumar/University of Dayton Research Institute (UDRI), Dayton, OH

Target: Venus surface exploration

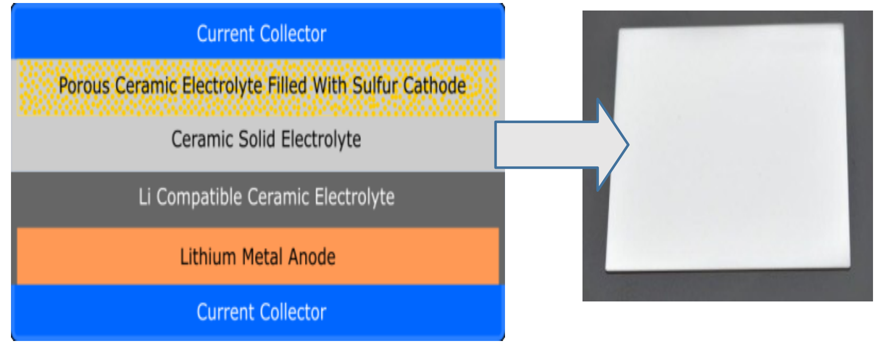
Science:
- In-situ surface studies of rarely explored planet (Venus).
- Understanding high temperature battery materials and interfaces,
- Understanding design and performances of a high temperature rechargeable battery.

Objectives:

Objective is to enable longer and safer NASA Venus mission by developing rechargeable battery with following targeted features:

- Specific energy density = 300 $Wh.kg^{-1}$,
- Cycle life with 100% DoD = 100-150 cycles,
- <10% self-discharge,
- Operation temperature up to 500° C
- High electrical and thermal safety.

CoIs: Priyanka Bhattacharya (UDRI); Yu Zhu (University of Akron), & Guru Subramanyam (University of Dayton).



Proposed Layout of molten Li-S Battery using Li or lithiated Si anode, S cathode encapsulated in 3D ceramic (e.g. LAGP or LLZ, or LGPS) and dense, flat, solid ceramic (e.g. LAGP or LLZ, or LGPS) electrolyte. (UDRI Propriety).

Key Milestones:

- **M1:** Physical (morphology, structure, chemical composition, etc.) and thermal characteristics of LAGP electrolyte interfaced with Li and S compatible materials in presence of Li and S at 25, 180, 400 and 500° C,
- **M2:** Cell design and data on energy density, power density, cycle life of molten LSB based on LAGP at 400-500° C,
- **M3:** Physical (morphology, structure, chemical composition, etc.) and thermal characteristics of LLZ electrolyte interfaced with Li and S compatible materials in presence of Li and S at 25, 180, 400 and 500° C,
- **M4:** Report on cell design and data on energy density, power density, cycle life of molten LSB based on LLZ at 400-500° C.

TRL (entry -3) to (exit - 5)

Title: High Energy GaN Microprocessors for Space Applications

PI: Yuji Zhao / Arizona State University

Target: Venus or Mercury Surface

Science:

- Fundamental science on the high-T properties of GaN materials;
- Physical modeling, basic circuit design, and fabrication of GaN IC logic blocks;
- Operation principle of the GaN microprocessor, which is the first of its kind;
- Basic understanding on the high-T and long-term reliability of GaN technology, ICs and microprocessors

Objectives:

- Fundamental study on the physical degradation mechanisms of GaN FETs at high-T;
- Developing associated mitigation strategies for GaN FETs in device design and fabrication processes;
- Demonstration of GaN FETs, logic building blocks, circuits, and microprocessors, which is the first of its kind;
- Comprehensive electrical characterizations of GaN microprocessors at high-T (300 °C);
- High-T (500 °C) and long-term reliability testing of GaN FETs and microprocessors at NASA GRC lab and GEER facility.

Co-PI: Tomas Palacios/MIT
NASA Collaborator: George Ponchak/NASA GRC

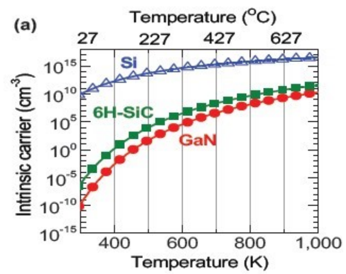


Fig. 1. Theoretical high-T performance of GaN.

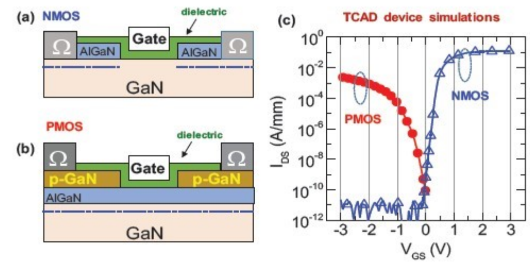


Fig. 2. Proposed GaN N/PMOS FETs and device simulation results.

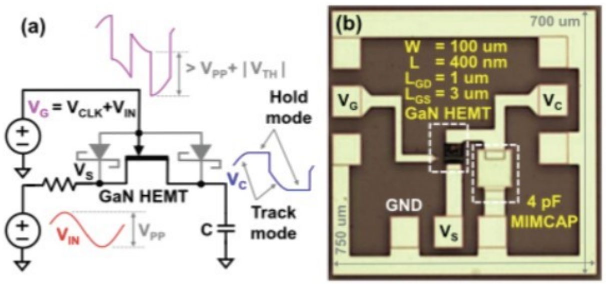


Fig. 3. Example of the GaN circuit developed by MIT team.

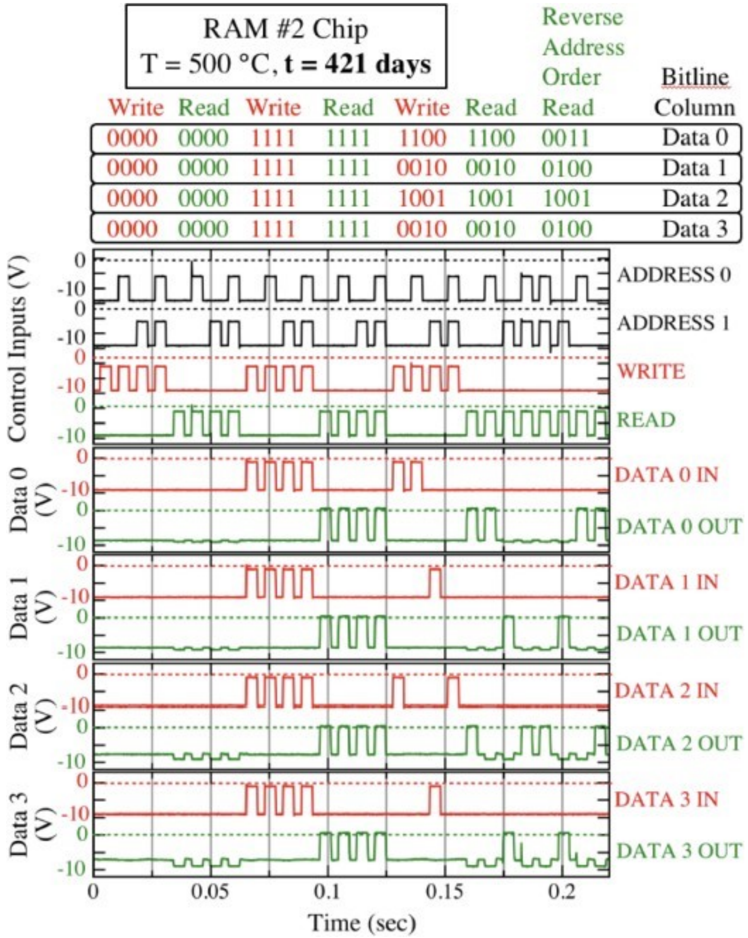
Key Milestones:

- Year 1: Basic high-T study on GaN FETs; IC design and modeling of GaN microprocessors.
- Year 2: GaN FETs under 300°C with no degradation; Demonstration of GaN microprocessors working under RT.
- Year 3: GaN microprocessors working under 300°C; Rigorous testing of GaN chips at NASA high-T facility.

Highlights

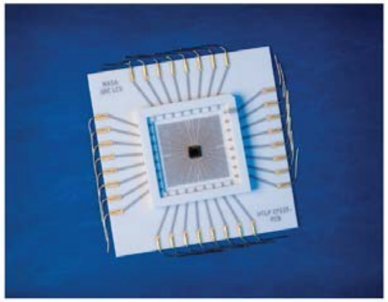
HOTTech Highlights (chart 1)

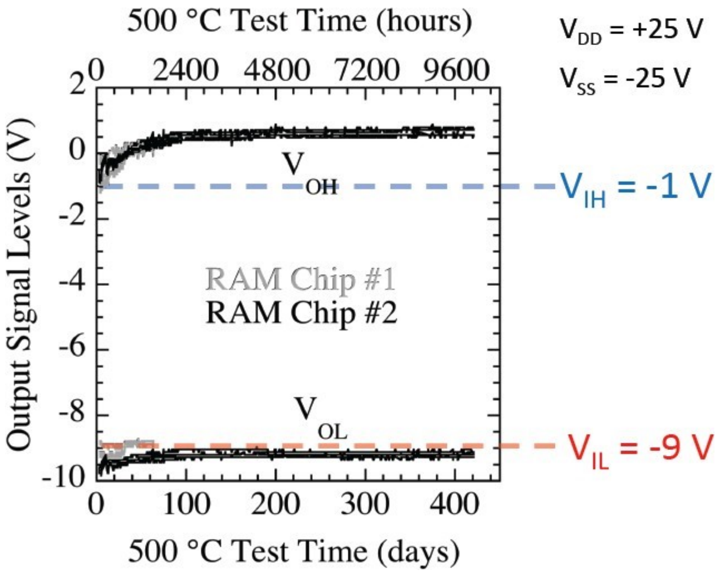
SiC Memory - P. Neudeck Task, GRC



Measured 16-bit waveform

High Temp Packaging





RAM Chip Output Levels vs 500 °C Test Time

- ❑ RAM packages (195 JFETs) are not sealed (open to Venus environment)
- ❑ SiC JFET based memory demonstrated to work at 500C for over 400 days without any degradation in performance

HOTTech Highlights (chart 2)

LIHT Solar Cells - J. Grandidier Task, JPL

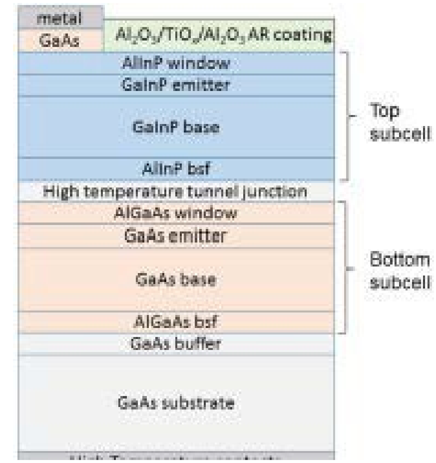
Low Intensity High Temperature Solar Cells for Venus Exploration Mission

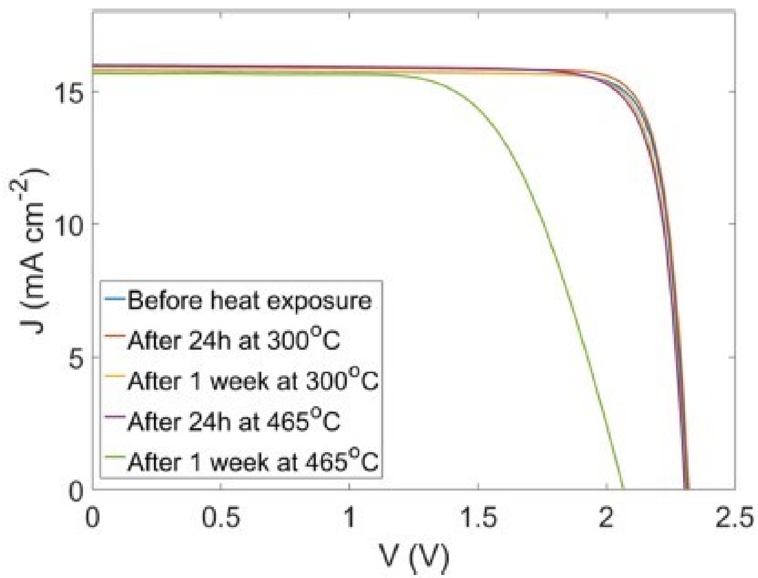
- GaInP/GaAs 2J solar cells have shown promising performance with **no degradation** in the I–V response after **up to 24 h** of exposure to temperatures as high as **465°C**.

- Measurements show that a **power density of 37 W/m²** may be attainable for these solar cells under the Venus solar spectrum at an altitude of **21 km** and a temperature of **300 °C**, provided that the solar cells and modules are properly encapsulated.

- This is encouraging for potential application in a future **long-duration solar-powered mid- to surface-level Venus exploration mission.**

- Work is underway to optimize the grid metal electrodes for better performance after a longer duration (up to 1 month) exposure to a temperature of 465 °C.





24hrs and 1 week exposures at 465°C in vacuum

J. Grandidier, et al., “Low-Intensity High-Temperature (LIHT) Solar Cells for Venus Atmosphere,” *IEEE Journal of Photovoltaics*: 1-6, 2018.

HOTTech Highlights (chart 3)

Packaging Task - S. Ang, Univ. Ark.

Titanium Package Housing

Research Objective:

- New package designed to evaluate the introduction of a new feedthrough idea.

Research Effort:

- Titanium (grade 2) package machined to include a housing slot to incorporate an alumina based feedthrough connector.
- Test feedthrough attached using Ferro's 8835-520C thick film gold paste.
- After gold paste firing process - titanium turns blue.

Titanium Grade-2 bar stock, 50mm x 150mm 6mm.
Total weight 240grams.
Two packages are made from stock. (50 x 75 x 6 mm)
Package weight after milling – 50 grams
Package weight after installing coupons and wirebonding – 54.7g

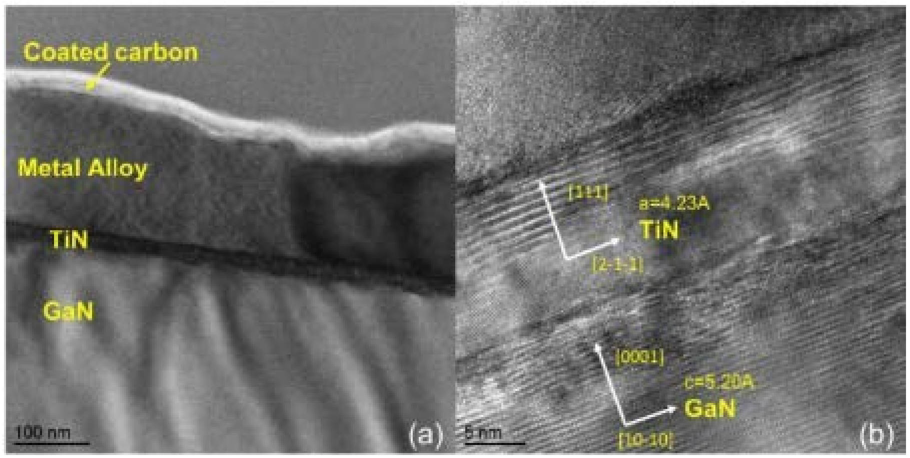
Metal package concept w/ alumina insert after 580c firing.

- ❑ **A new standardized format for electronics packaging in Venus environment has been developed**
- ❑ **Package based on titanium, alumina, and gold structures – tested to 580 C**

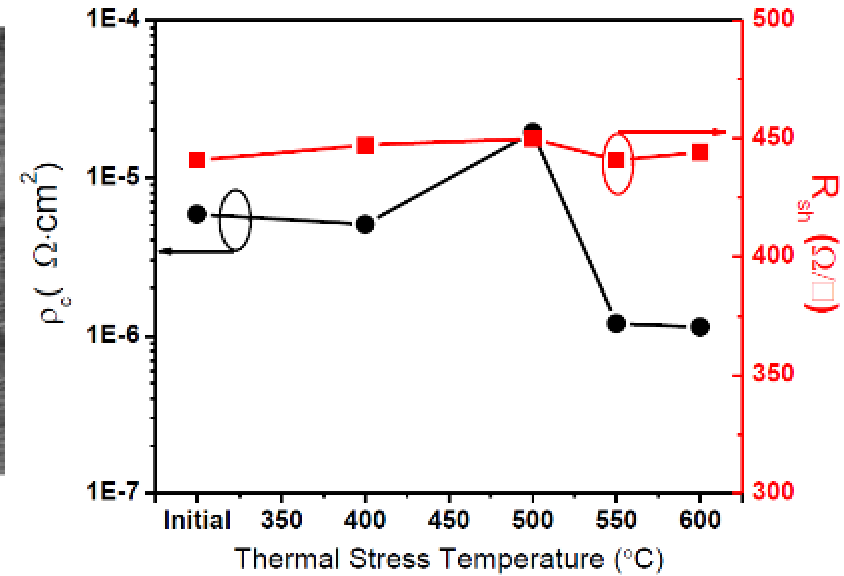
HOTTech Highlights (chart 4)

GaN Electronics Task - Y. Zhao, Arizona State Univ.

Examining the Stability of Metallization Contacts for GaN Electronics



TEM after 600 °C for 4 hours



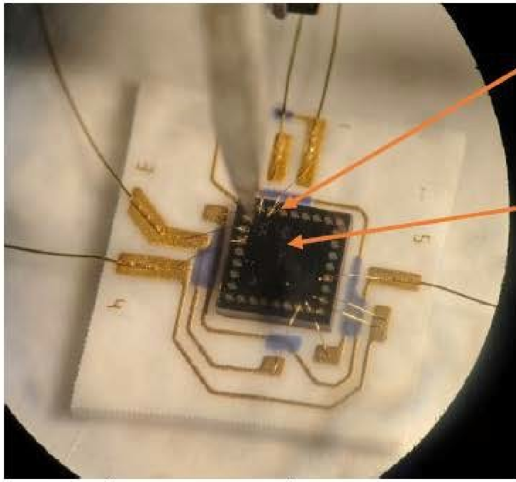
4 hours thermal stress before each measurement

- ❑ **Tested Ni/Au and Ti/Al/Ni/Au (TANG) metallization**
- ❑ **TANG metallization pads show most promise and remain stable after heating up to and past 460 C**
- ❑ **GaN integrated circuits (IC) still under development; durable metallization pads for interconnects and wire bonds are critical for a successful IC**

HOTTech Highlights (chart 5)

Chem. Sensors Task – Makel Engr.

GEN 10 Amplifier Combined with High Temperature Chemical Sensor (SiC Diode for HF)



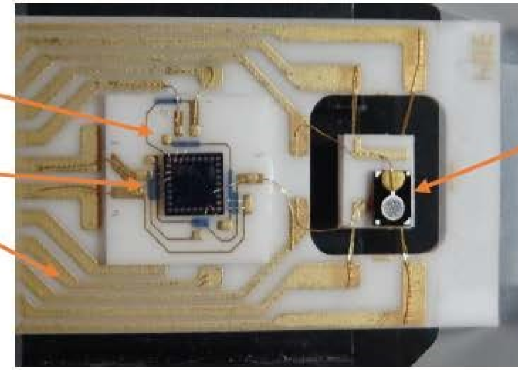
Au Wire Bonds

Au Paste Reinforcement

Gen 10 Electronics

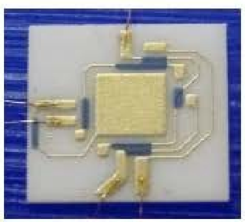
GEER Test Probe

SiC Diode Chemical Sensor

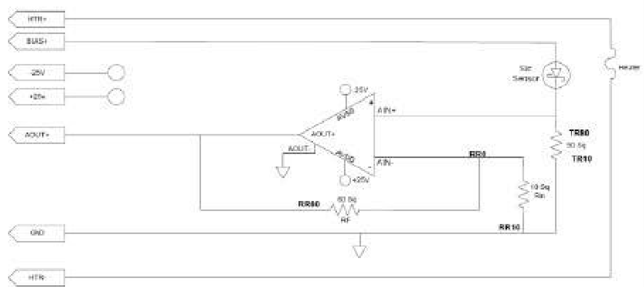


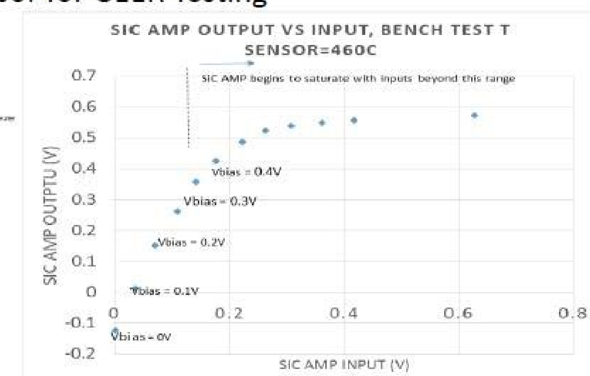
SiC Electronics Packaging

SiC Electronics Combined With Chemical Sensor for GEER Testing



Custom Thick Film Substrate





Test Data Analysis and Post Test Evaluation Underway

- **Gen 10 Integrated SiC circuits and sensors have been developed and tested over 2 months at 460 C**
- **Gen 11 with 2-stage amplifier ASIC is under development and will be tested; 2-stage amplifier provides higher signal gain for better signal to noise ratio**

Summary

- 12 awards currently underway with a broad portfolio of technologies needed for a long-lived spacecraft or surface lander on Venus, or for exploration of the Gas-Giants, and many have shown progress to demonstrate functional operation at realistic environmental conditions.
- The HOTTech Program support office provides a no-cost opportunity for integrated systems-of-systems testing in the Glenn Extreme Environment Rig (GEER) test facility providing chemically-accurate high pressure (90 bar) and temperature (500ºC) environment for possible extended duration testing. A HOTTech Integration Project in GEER will soon be underway
- The Planetary Science Division welcomes HOTTech partnerships with industry and other government agencies to provide additional paths for technology maturation or infusion into terrestrial and space applications
- There have been yearly workshops of all HOTTech awardees, plus outside organizations and industry are encouraged to attend for information sharing and to promote technology transfer.
- HOTTech-2 is pending approval of budget, and if selected, will start in 2021.