

National Aeronautics and
Space Administration



EXPLORE SOLAR SYSTEM & BEYOND

**Microengineering for Space Exploration:
Recent work at NASA Glenn**

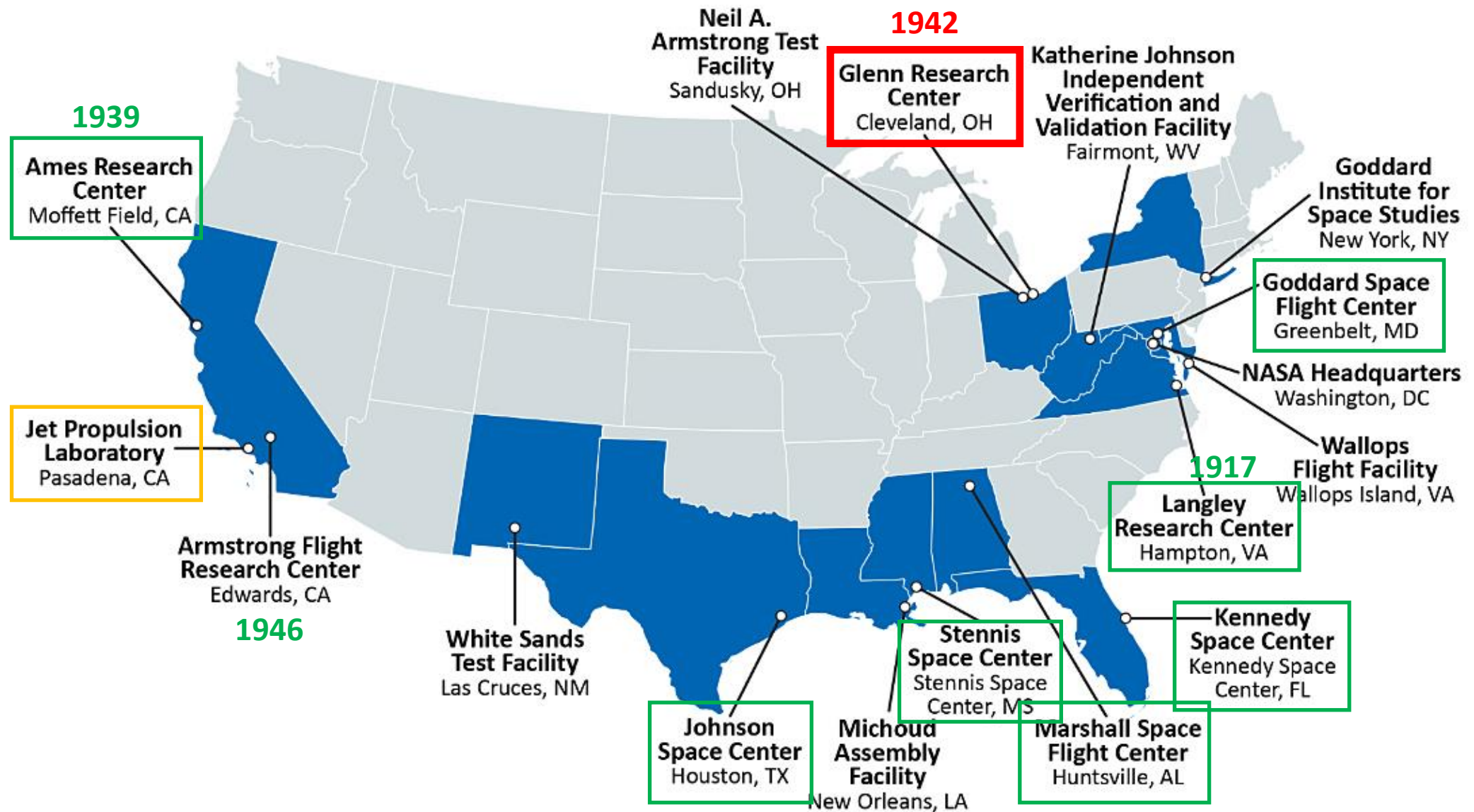
Dr. Hari Rajgopal

**Smart Sensing and Electronics Systems Branch
NASA Glenn Research Center, Cleveland OH 44135**

ANFF-SA Microengineering Winter School, South Australia, July 4, 2024

NASA Glenn Research Center at Lewis Field





NASA Mission Directorates

Aeronautics Research Mission Directorate (ARMD): Generates the innovation, technologies and capabilities needed to enable changes to both the airspace system and aircraft; Focus areas include Supersonics, Advanced Air Mobility, Ultra-Efficient Airlines, Future Airspace and Safety

Exploration Systems Development Mission Directorate (ESDMD): Defines and manages systems development for NASA's Artemis program and planning for NASA's Moon to Mars exploration

Science Mission Directorate (SMD): Leads Agency research in Earth Science, HelioPhysics, Planetary Science and AstroPhysics

Space Operations Mission Directorate (SOMD): Space operations related to human exploration in and beyond low-Earth orbit;

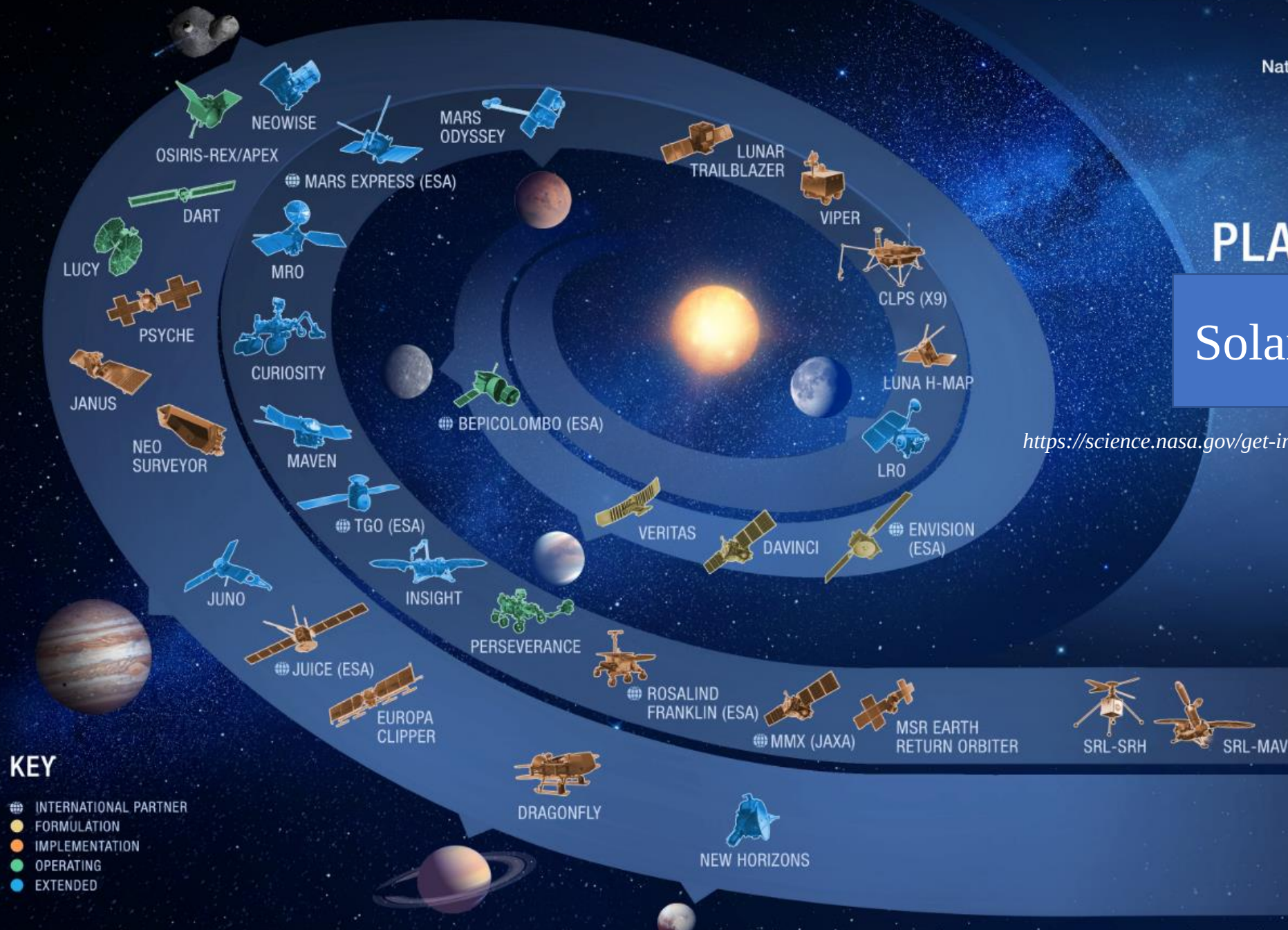
Space Technology Mission Directorate (STMD): Develops, demonstrates, and infuses revolutionary, high-payoff technologies



PLANETARY FLEET

Solar System Missions

<https://science.nasa.gov/get-involved/toolkits/planetary-mission-posters>



NASA TRL

https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

TRL 9

- Actual system “flight proven” through successful mission operations

TRL 8

- Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 7

- System prototype demonstration in a space environment

TRL 6

- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5

- Component and/or breadboard validation in relevant environment

TRL 4

- Component and/or breadboard validation in laboratory environment

TRL 3

- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2

- Technology concept and/or application formulated

TRL 1

- Basic principles observed and reported

Example of a NASA solicitation:

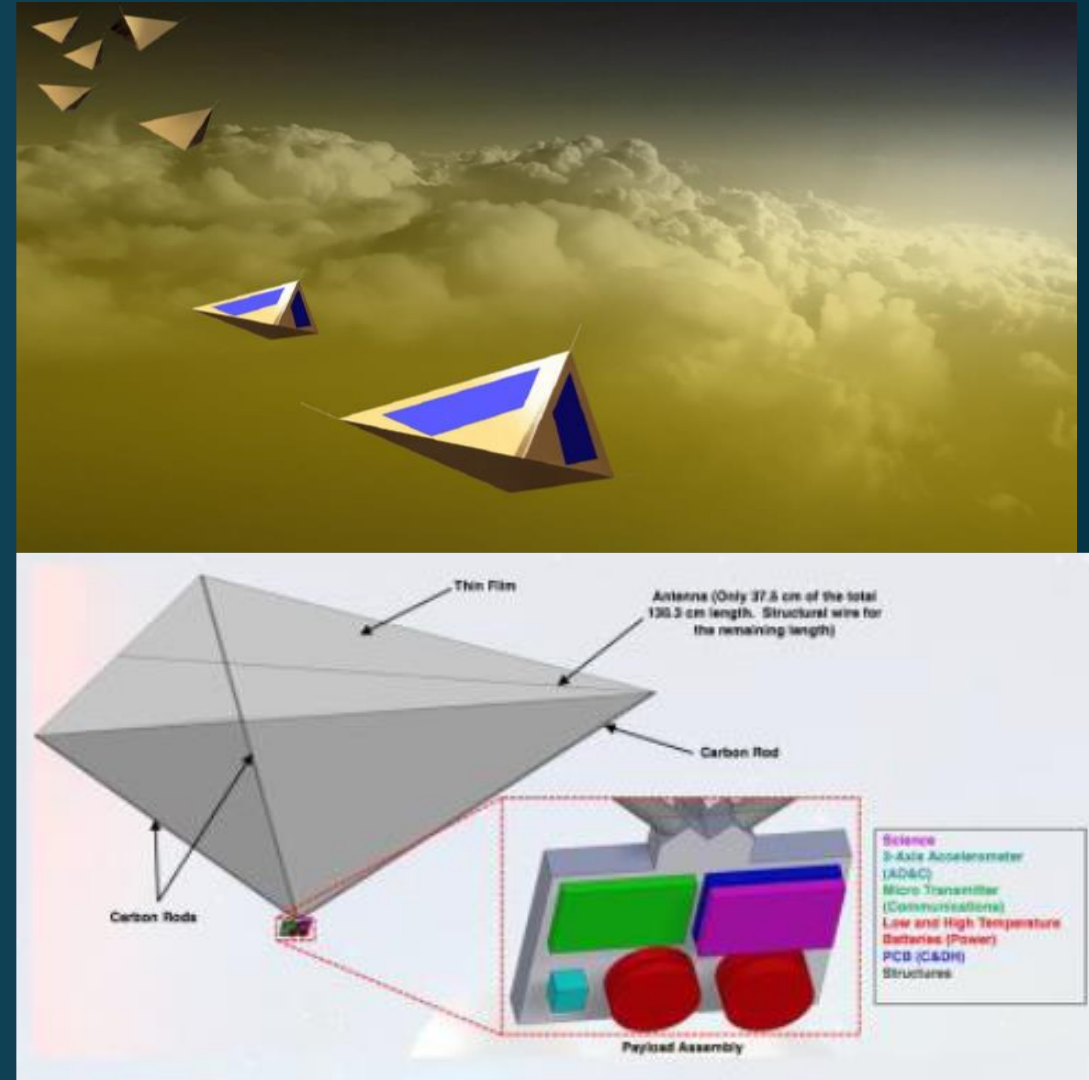
NASA Innovative Advanced Concepts (NIAC) – Phase I

- Phase I proposals for **early stage** feasibility studies of visionary concepts that address national, government, and commercial aerospace goals.
- Concepts solicited from any field of study that offers a radically different approach or **disruptive innovation** that may significantly enhance or enable new human or robotic science and exploration missions.
- Comparatively **high risk and far-term**, NIAC concepts are transformational investments in future NASA and commercial capabilities.
- Concepts must demonstrate an unexplored and highly innovate approach **framed within a representative mission** that clearly identifies scientific or technical advancements and associated benefits compared to current capabilities.
- The entry Technology Readiness Level (TRL) for **Phase I concepts should be TRL 2 or lower**.
- Eligibility: All categories of U.S. organizations may apply. Non-U.S. organizations may partner in, or lead, NIAC studies on a no-exchange of funds basis, and subject to NASA's policy on foreign participation.

Example of a funded NIAC in the Smart Sensing and Electronics Systems Branch:

LEAVES: Lofted Environmental and Atmospheric Venus Sensors

- LEAVES: Extremely light, radar retroreflectors with sensors to probe Venus's atmosphere.
- Conops: Probing the atmosphere at different times by probes with MEMS using a Venus radarsat during its aerobraking stage, activated by atmospheric pressure after “soft” entry.
- Launch: Attached to side of future Venus radarsat, 2020s opportunity.
- Science: Chemical, pressure, temperature MEMS sensors with location data.
- Mechanical: ~120g “leaf” has 1m² drag array that enables deployment in orbit and descent through atmosphere without aeroshell, ~12g loading at atmospheric deceleration over several minutes.

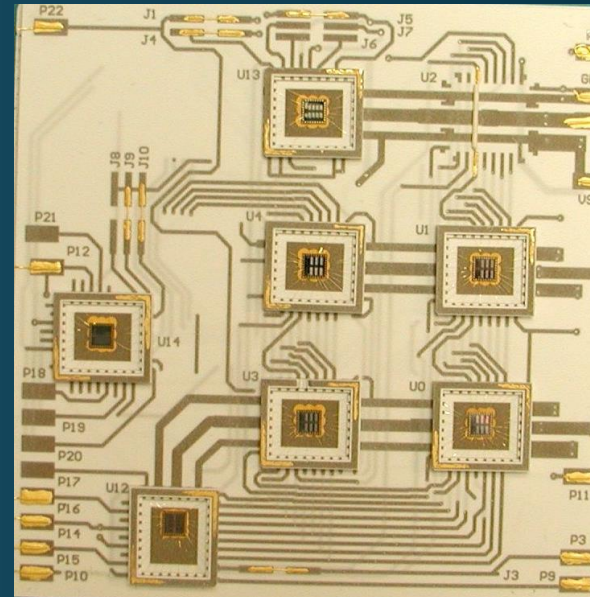


Smart Sensing and Electronics Systems Branch

Emphasis on fundamental & applied research and development of adaptable sensing and electronics systems which incorporate SiC electronics and other capabilities to enable integrated intelligent measurement systems for ongoing and future aerospace and space programs

Core capabilities:

- Silicon Carbide (SiC) - based electronics for extreme (high temp., corrosive/abrasive) environment
- Physical sensors (bulk-, surface-micromachined and thin film) for pressure, stress/strain, heat flux, radiation
- Chemical gas sensors for leak detection, emission, fire/environmental and human health monitoring



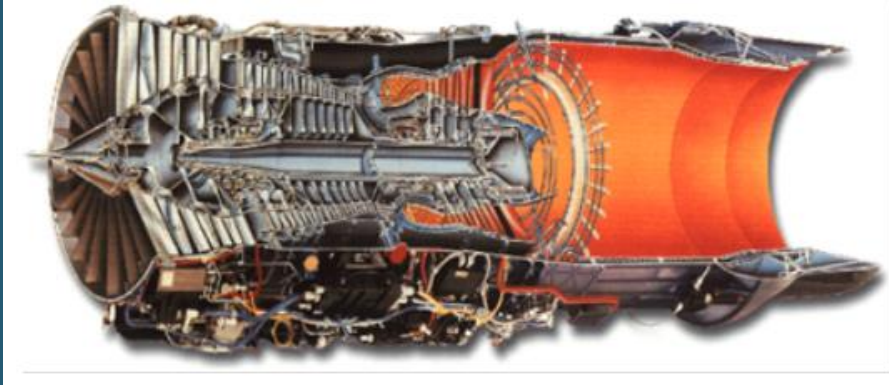
Multi-chip high temperature ceramic circuit board



Heat Flux Thin Film Sensor Array to $T=1000^{\circ}\text{C}$

Research thrusts in branch

Intelligent Propulsion Systems

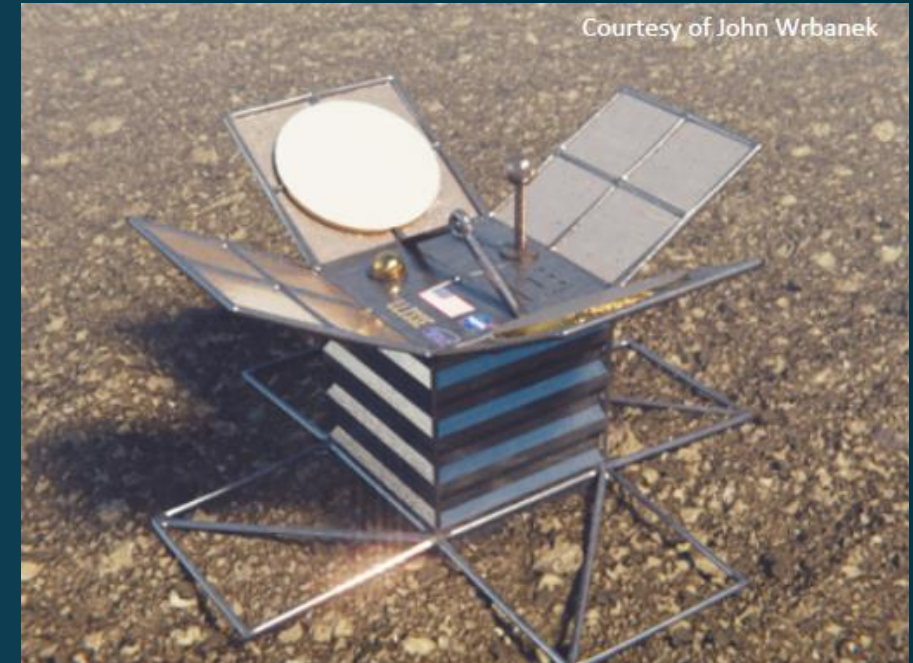


$T > 450\text{ }^{\circ}\text{C}$ sensors with electronics in key engine areas for improving performance

- Thrust to weight ratio
- Fuel efficiency & emissions

Venus Technologies

LLISSE (Long-Life In-Situ Solar System Explorer) Concept



Atmospheric pressure: 9.4 MPa (~ 92 times pressure on Earth)

Temperature: $\sim 460\text{ }^{\circ}\text{C}$

Chemical composition in atmosphere on Venus surface: CO_2 , N_2 , SO_2 , OCS , H_2O , CO , HCl , HF and H_2S

Facilities: Fabrication equipment

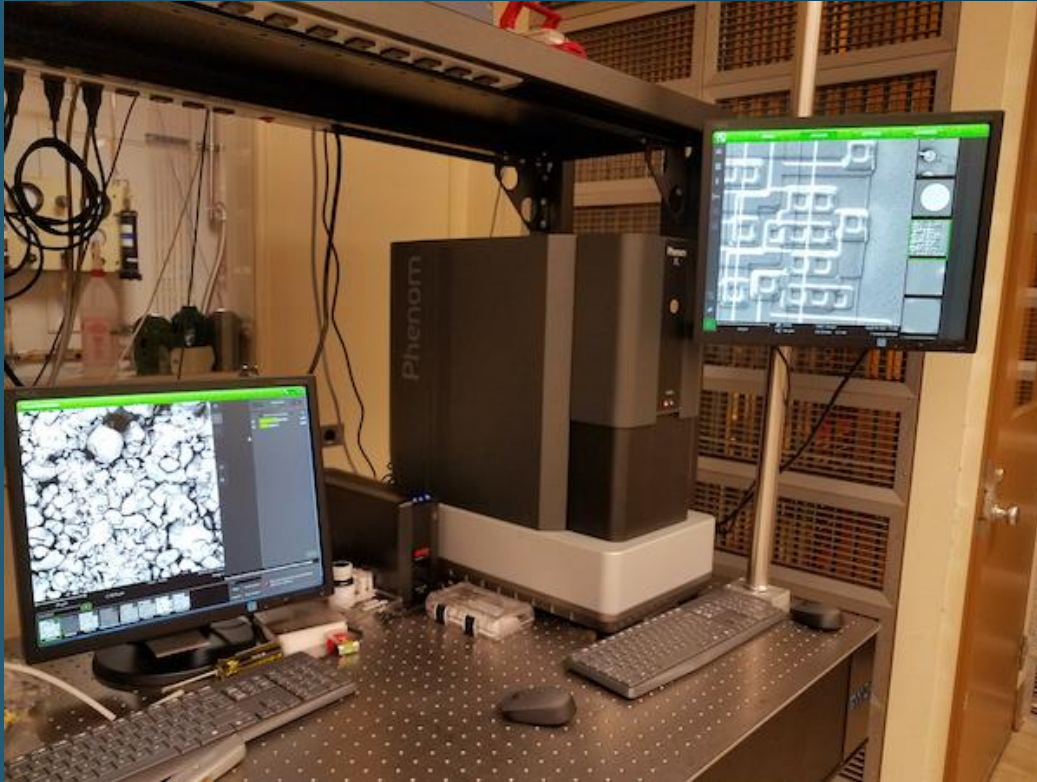


Oxidation and annealing furnaces; Silicon Dioxide Low Pressure Chemical Vapor Deposition System

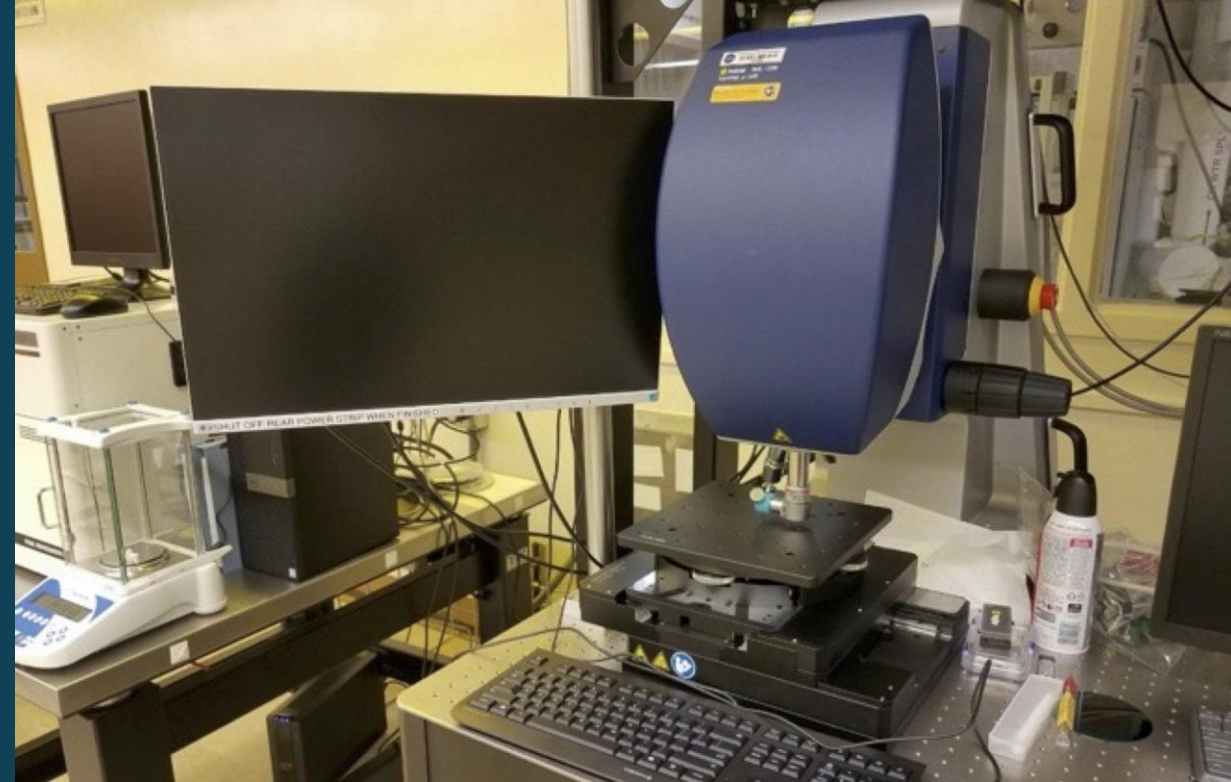


Tantalum Silicide Sputter Deposition System

Facilities: Characterization equipment

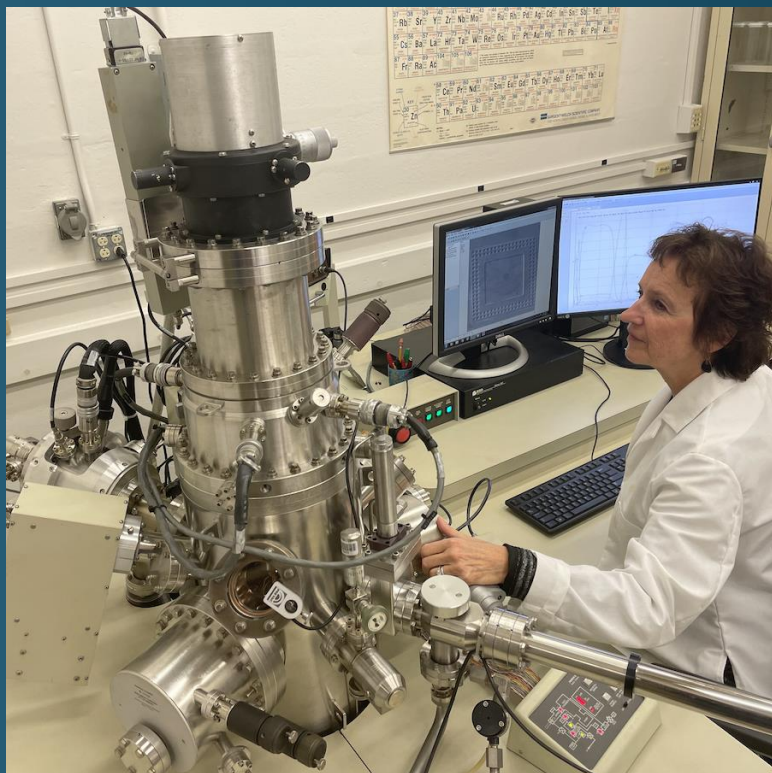


Scanning Electron Microscope

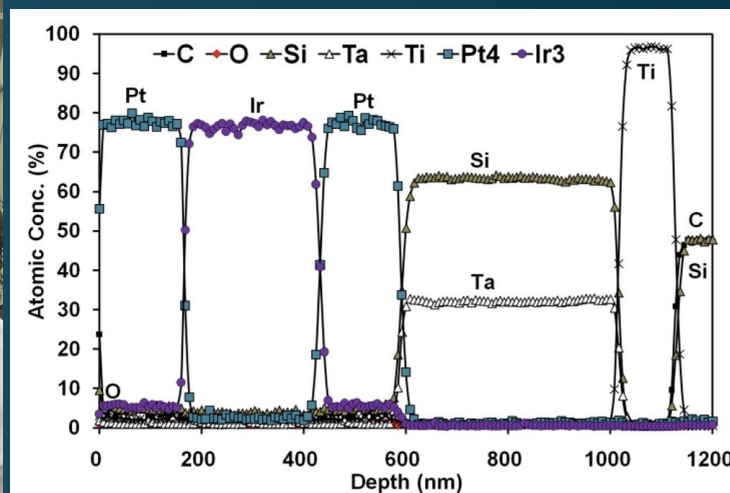


Optical profilometer

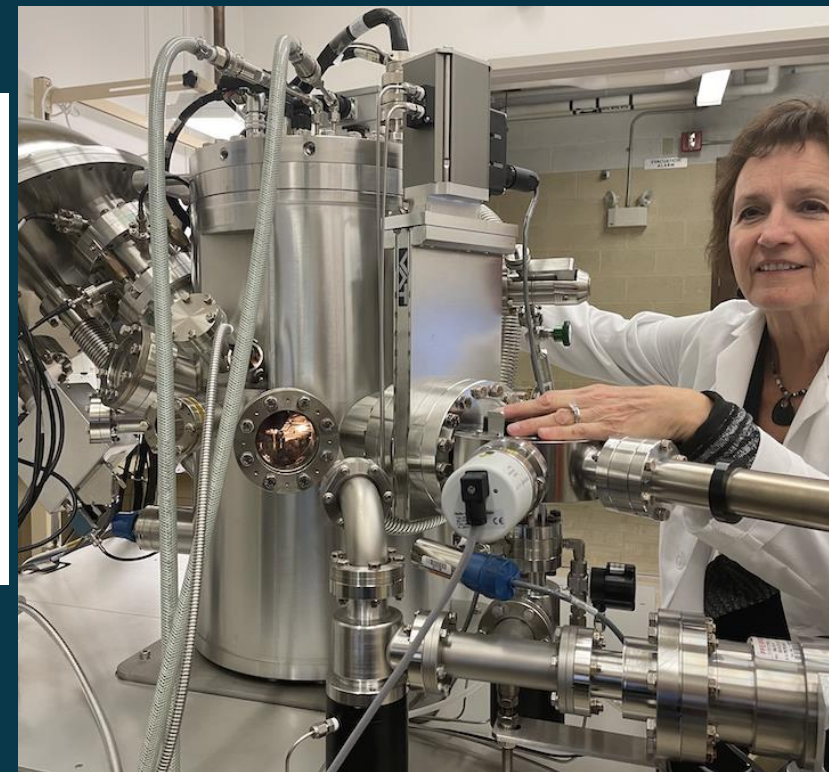
Facilities: Surface analyses



Auger Electron Spectroscopy (AES)
System



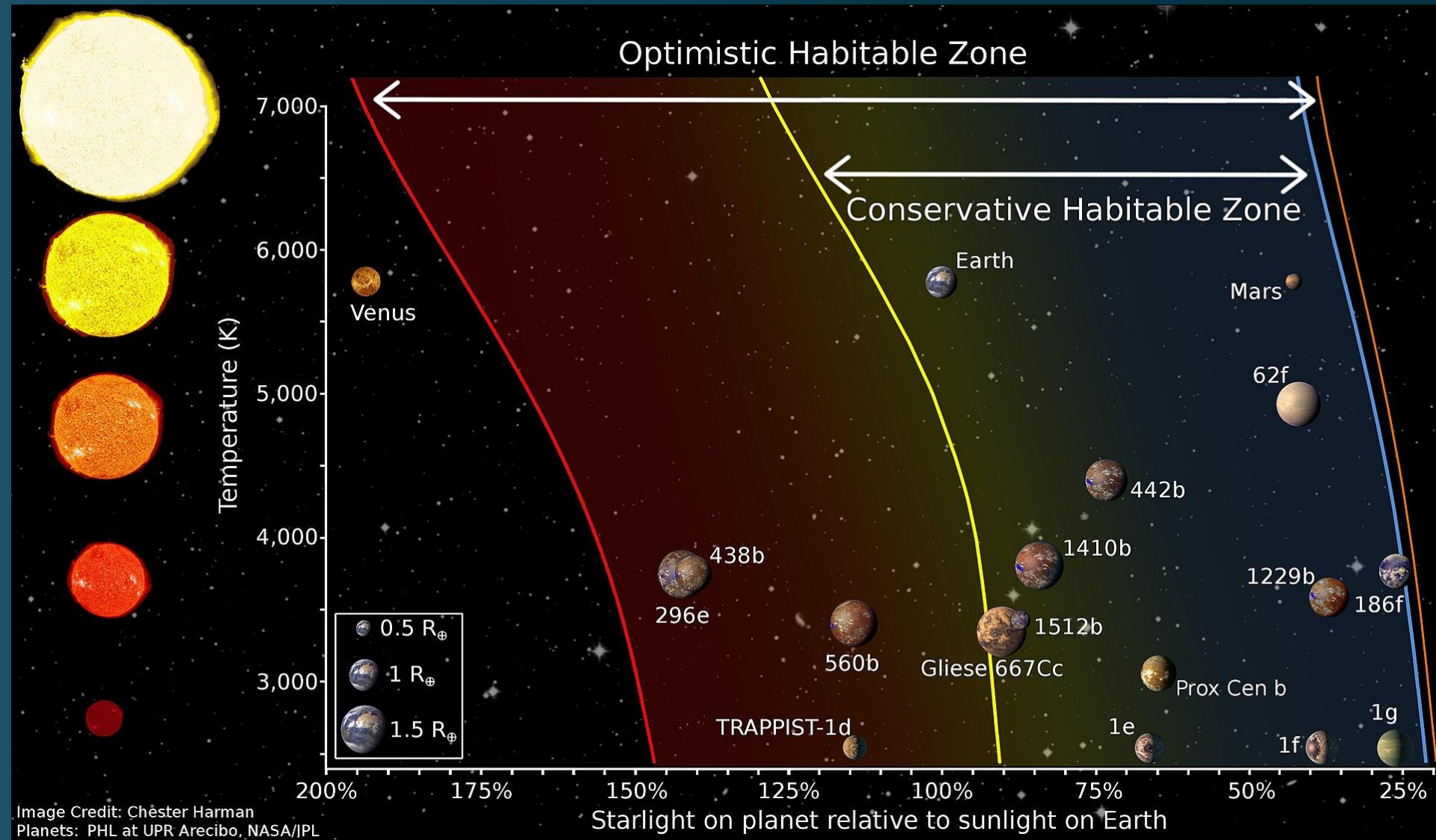
AES depth profile
showing chemical
element and thickness
composition of
vacuum deposited
multi-layer metal stack



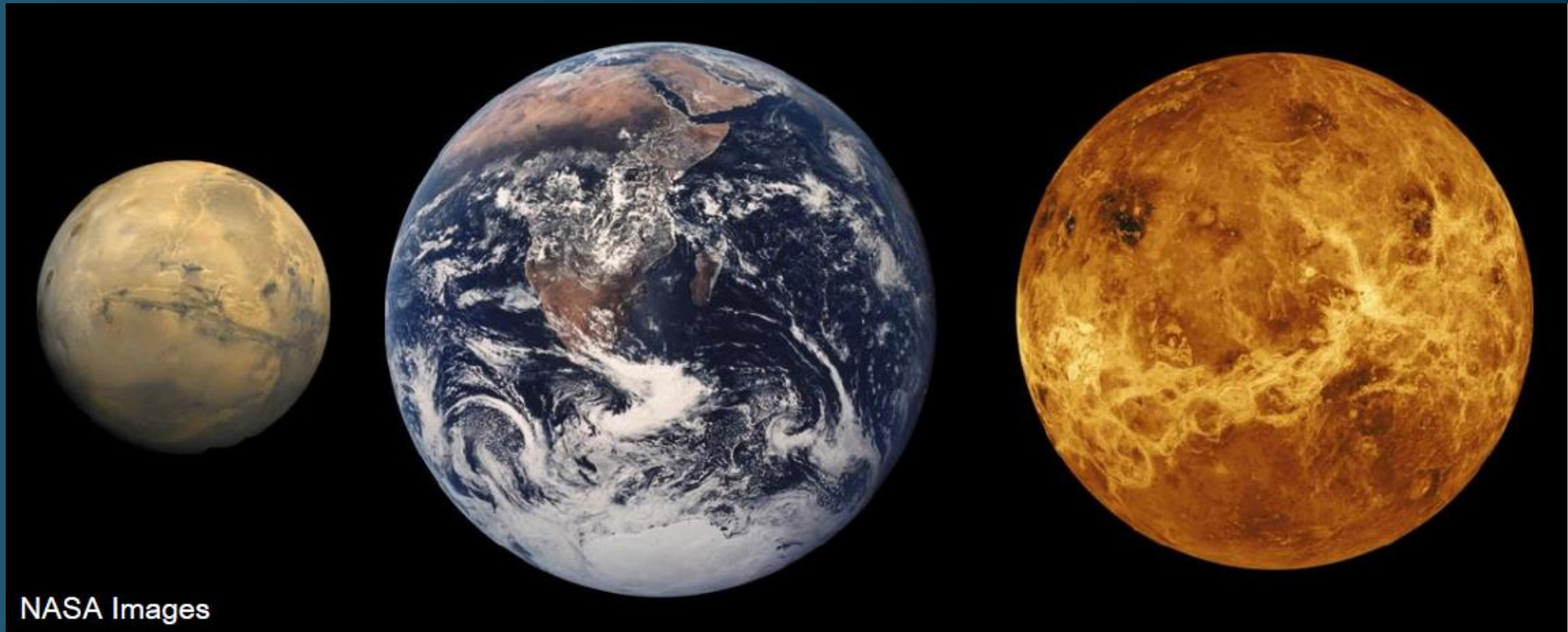
X-ray Photoelectron Spectroscopy (XPS)
System

Circumstellar Habitable Zone

- In astronomy and astrobiology, the circumstellar habitable zone (CHZ) is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure.
- A plot of temperature vs starlight received showing the Habitable zones of different types of stars. Important exoplanets are placed on the diagram, plus Earth, Venus, and Mars
- Whether a body is in the circumstellar habitable zone of its host star is dependent on the radius of the planet's orbit (for natural satellites, the host planet's orbit), the mass of the body itself, and the radiative flux of the host star



Venus comes closest to earth



MARS

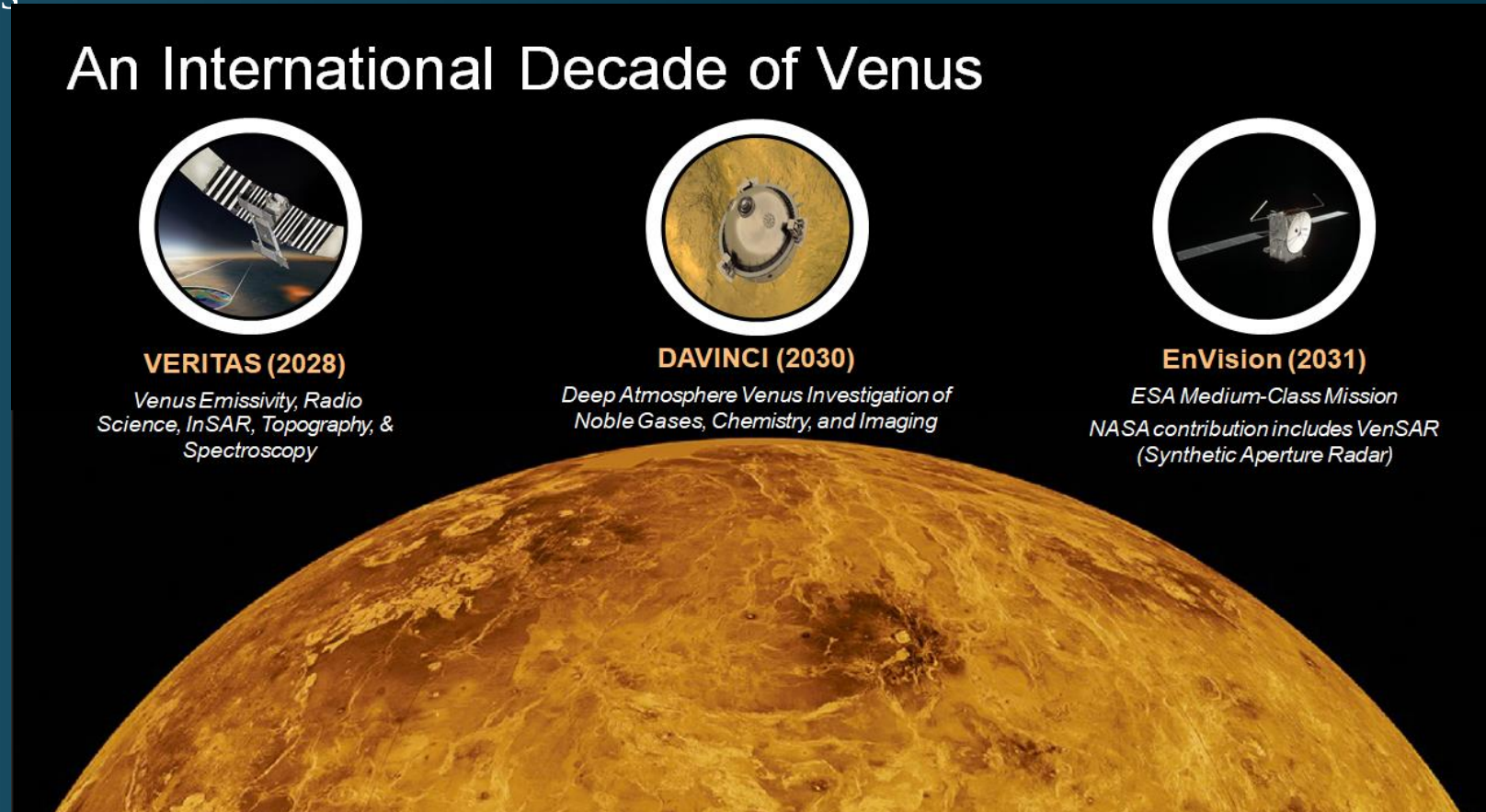
Mass: 10% Earth
Orbit: 150% Earth
T(surface): -143 to +35 °C
Lander missions: Years of data

Venus

Mass: 82% Earth
Orbit: 72% Earth
T(surface): +460 °C
Lander missions: Hours of data

Decade of Venus Exploration

- Three Missions chosen for Venus Exploration in the next decade
- Two orbiters and one descent probe to explore Venus science
 - The DAVINCI⁺ probe descends to the surface but is not a lander mission
 - Development of one orbiter (VERITAS) presently delayed
- Extended duration surface measurements not addressed by these missions
- A number of science questions, e.g., seismology, are best addressed by in-situ measurements



LLISSE Concept Overview

- Probe to acquire and transmit science measurements from Venus surface
- Key attributes:
 - Leverage high temperature electronics initially developed for aircraft engine instrumentation
 - Data captured and transmitted in real time – not stored
 - Powered by battery



The Science behind the LLISSE concept

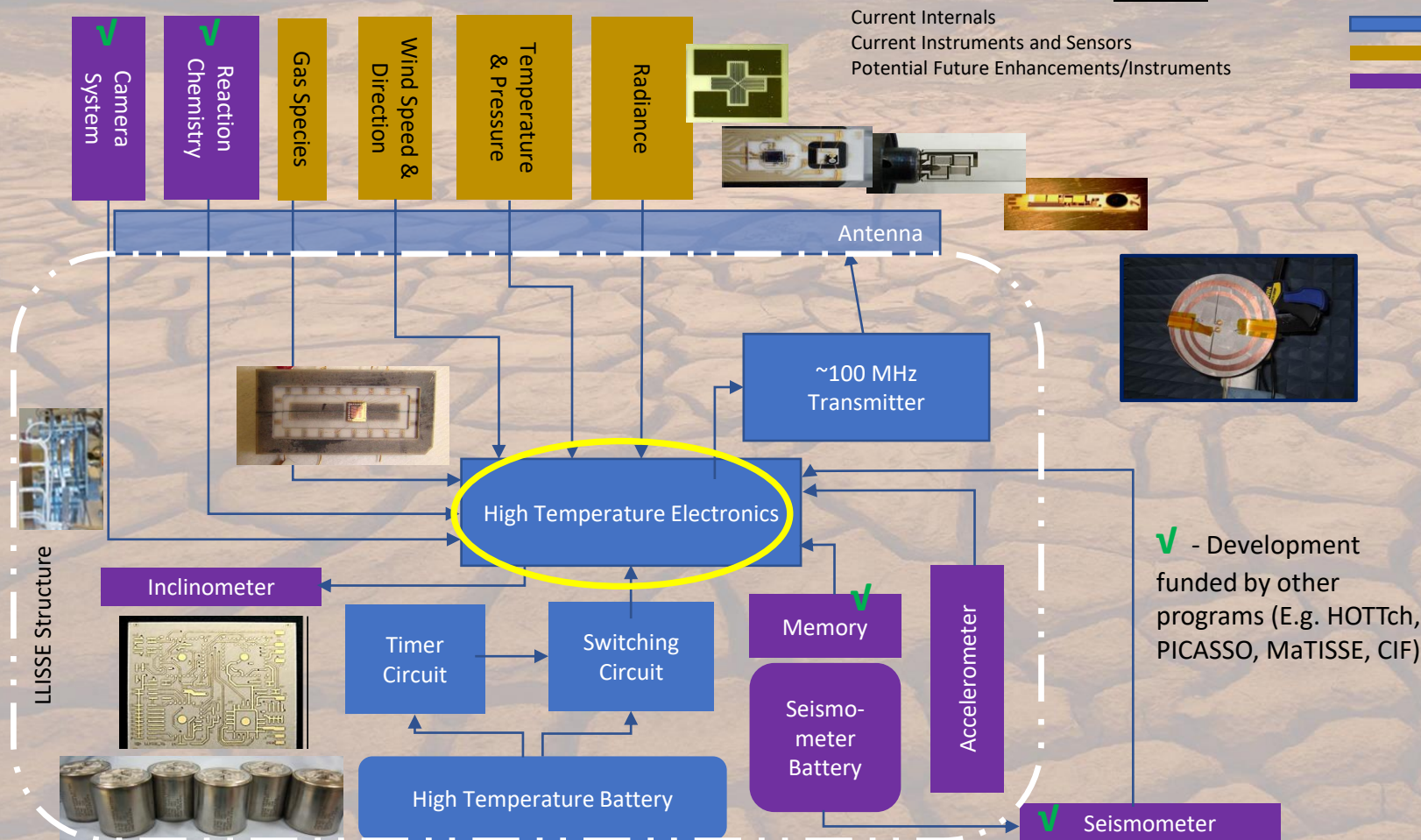
- Objectives
 - Estimate moment exchange between planet and atmosphere
 - Study surface level atmospheric chemistry variation
 - Acquire temporal weather data to update global circulation models
 - Technology demonstration for more capable future lander missions
- Operational goals
 - Operate for a minimum of one Venus “daylight period” and day/night transition (~60 Earth days)
 - Take/transmit measurements periodically – timed for science need and to maximize transfer to orbiter/data relay



LLISSE Concept Block Diagram

Legend

Current Internals
Current Instruments and Sensors
Potential Future Enhancements/Instruments



Approved for Public Release

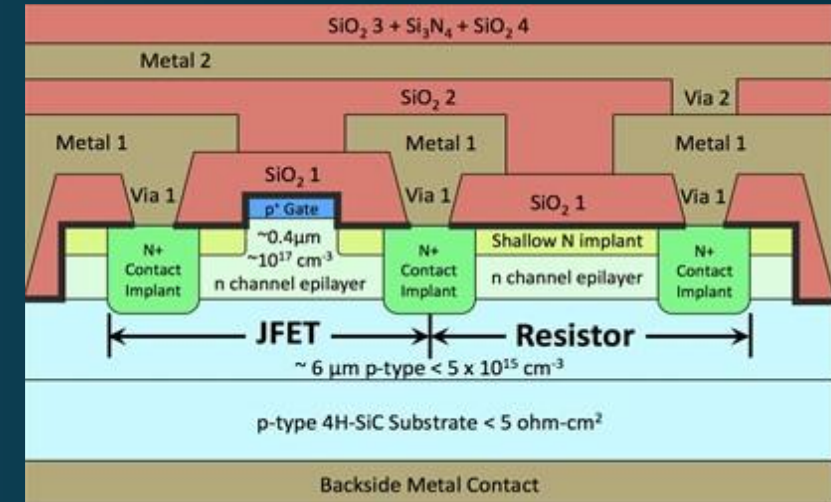
NASA Glenn Extreme Environment Rig (GEER)

- 800-litre test chamber for high-fidelity simulation of Venus atmosphere
- First 10 chemical constituents of Venus atmosphere
- 460 °C, 9.4 MPa capability
- Capability of running for months

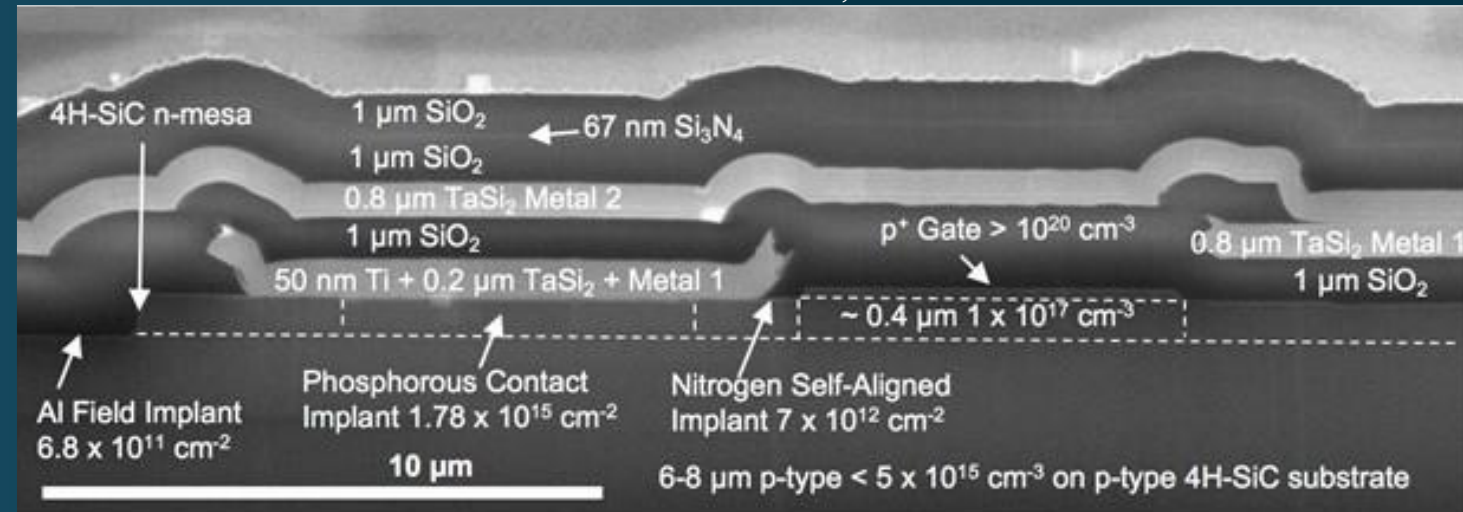


JFET-based Extreme Environment Electronics

- **Junction field effect transistor (JFET)-based electronics**
- **Enabling a wide range of sensing and control applications at High Temperatures**
 - **In-package signal amplification, conditioning and local processing (digitization at the harsh environment source)**
- **Circuits containing 10's to ~1000 JFETs; An order of magnitude upscaling towards ~10000 JFETs/chip currently under development**



Neudeck et al, CS Mantech 2021

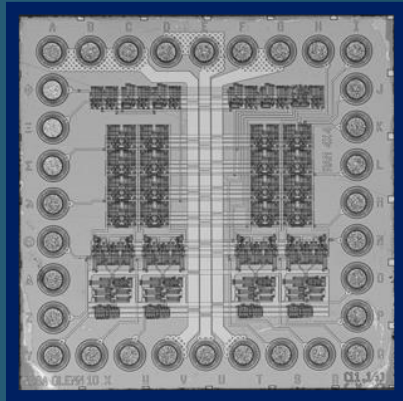


Neudeck et al, ECSCRM 2016

NASA Glenn SiC JFET IC Technology Progress

“IC Gen. 10” (2017)

(16-bit RAM, 195 SiC JFETs)
6 μm gate length, 6 μm resistor width
3 mm x 3 mm

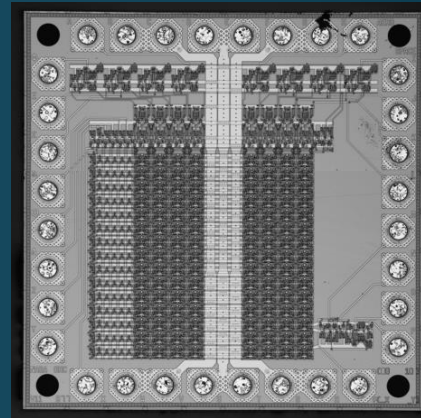


Key IC Version 10 Accomplishments*

- 400+ days stable 500 °C electrical operation
- 60 days stable Venus surface environment electrical operation
- 961 °C electrical operation (short-term)
- -190 °C cryogenic electrical operation
- Radiation immunity through 7 Mrad(Si) ionizing dose and 86 MeV-cm²/mg heavy ions (25 °C)

“IC Gen. 11” (2018)

(120-bit RAM, ~ 1000 SiC JFETs)
6 μm gate length, 3 μm resistor width
4.65 mm x 4.65 mm

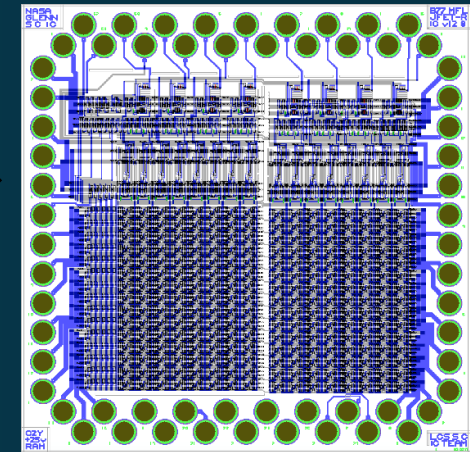


Key IC Version 11 Accomplishments

- 5-fold reduction in logic gate power
- First ICs designed for LLISSE concept
- 500 °C 8-bit Analog to Digital converter
- Few days 500 °C ~1 kbit ROM operation

“IC Gen. 12”

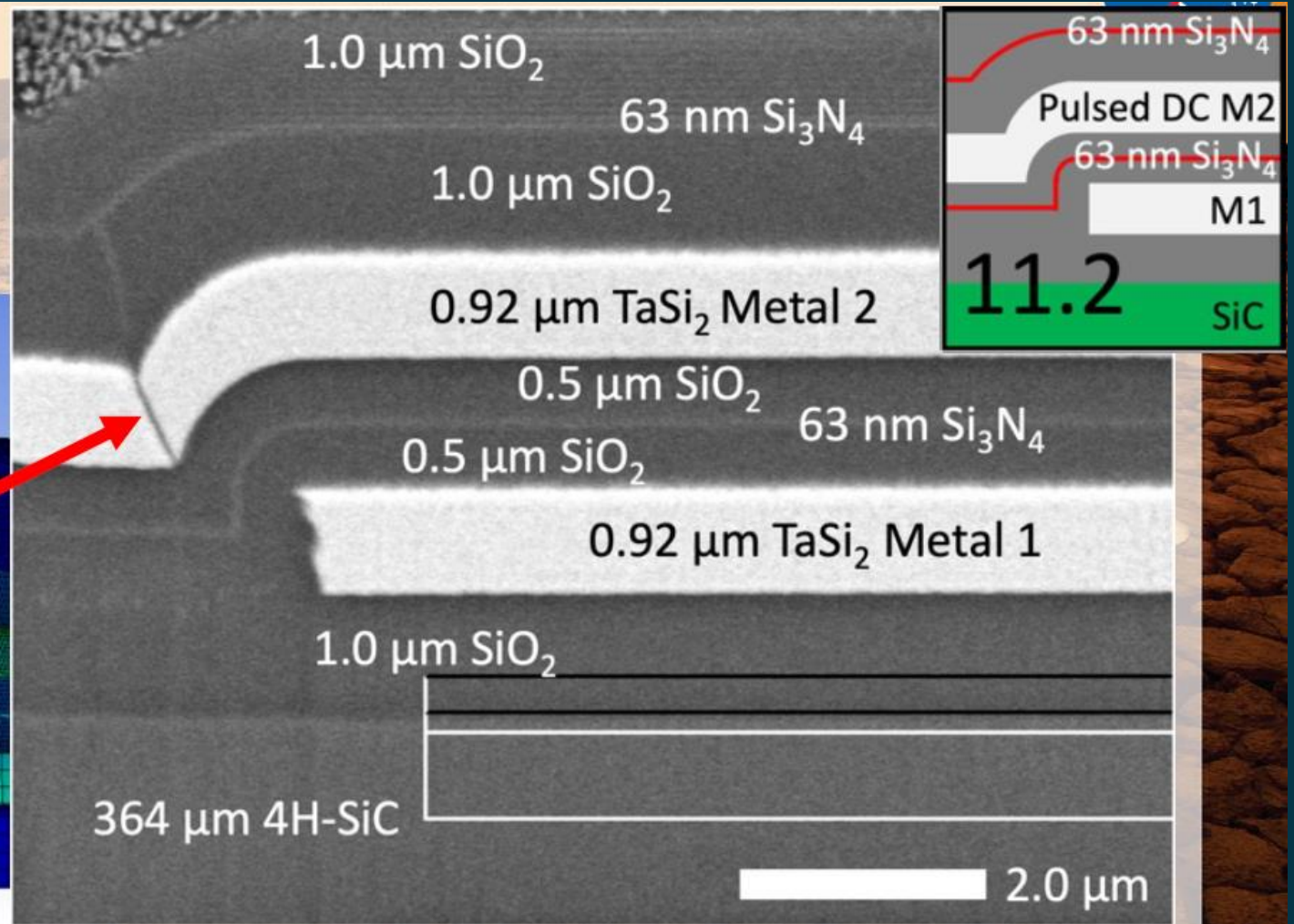
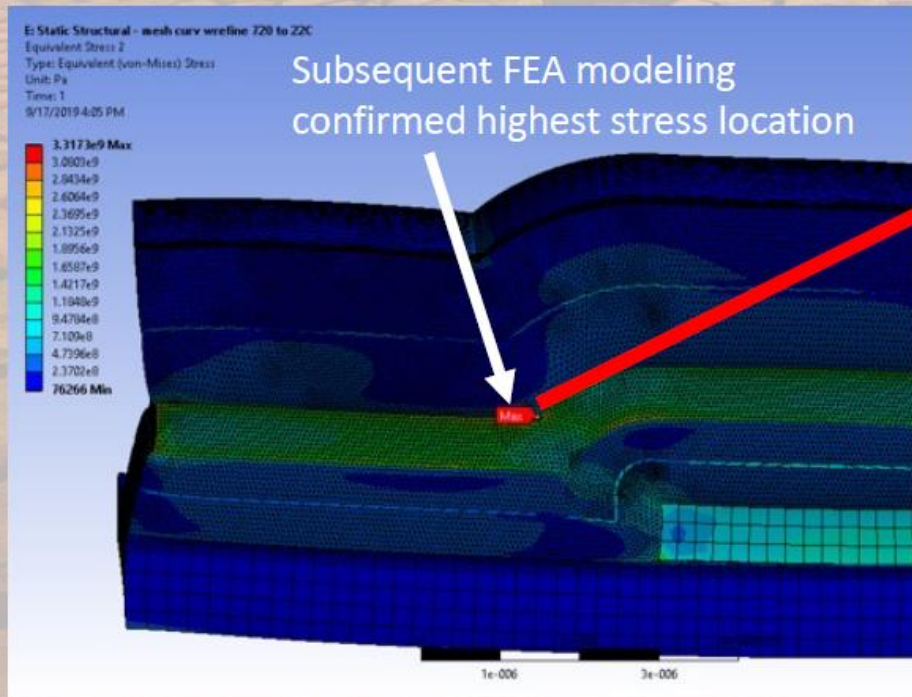
(248-bit RAM, ~ 2000 SiC JFETs)
3 μm gate length, 2 μm resistor width
5 mm x 5 mm



Wafer fabrication in progress

Stress and CTE mis-match effects in IC Gen. 11.2

As seen in the microscopic cross-sections, metal cracks opened in all Metal2 traces running over topology during final Si_3N_4 720 °C deposition, resulting in electrical failure of all the large integrated circuits.



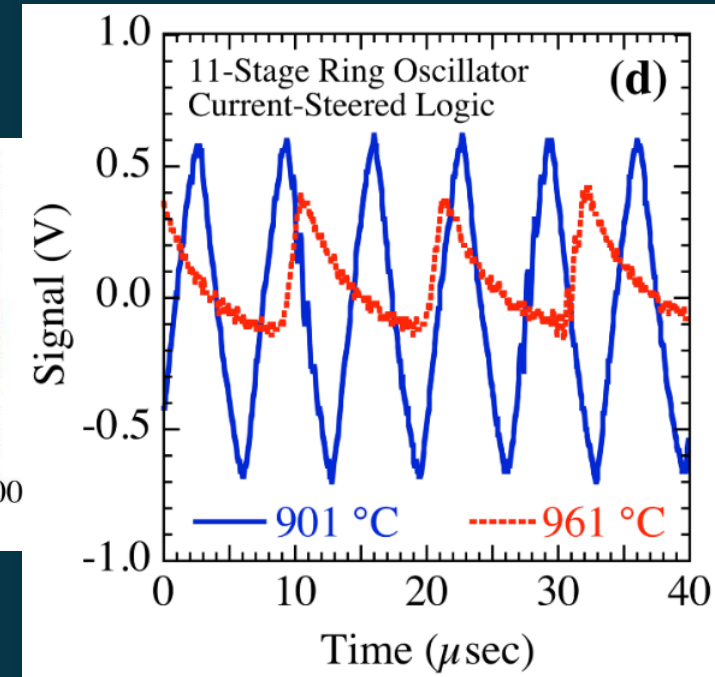
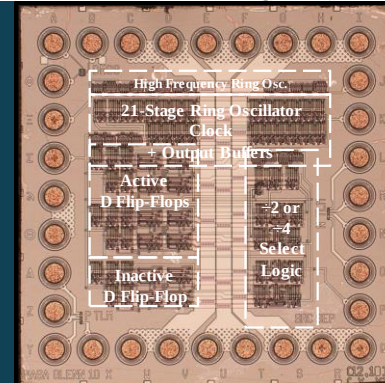
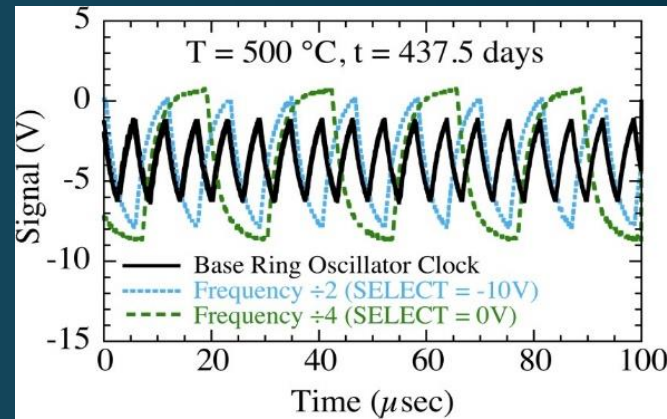
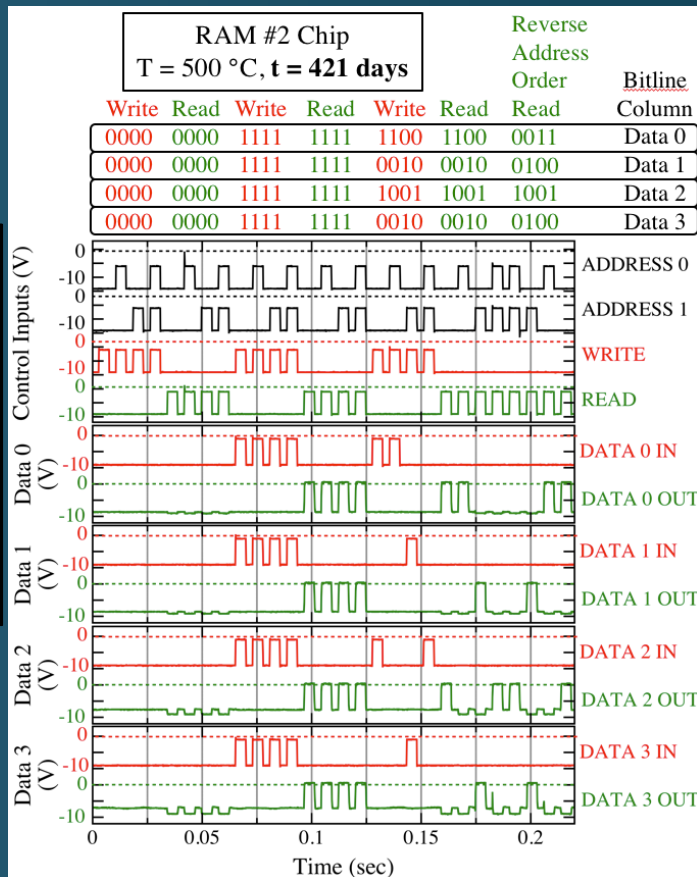
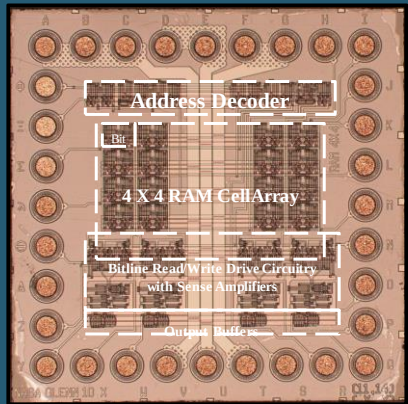
¹ D. Spry, P. Neudeck, C. Chang, Mat. Sci. Forum 1004 pp. 1148-1155 (2020)

Extreme Environment Electronics - Results

Ver. 10 ICs set high temperature durability world records in $T \geq 500\text{ }^{\circ}\text{C}$
Earth-atmosphere oven testing

Complex ICs Operating more that 1 Year at $500\text{ }^{\circ}\text{C}$ ^[1]

ICs Operating at World Record $961\text{ }^{\circ}\text{C}$ ^[2]



[1] 2018 Int. Conf. High Temperature Electronics p. 71

[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017).

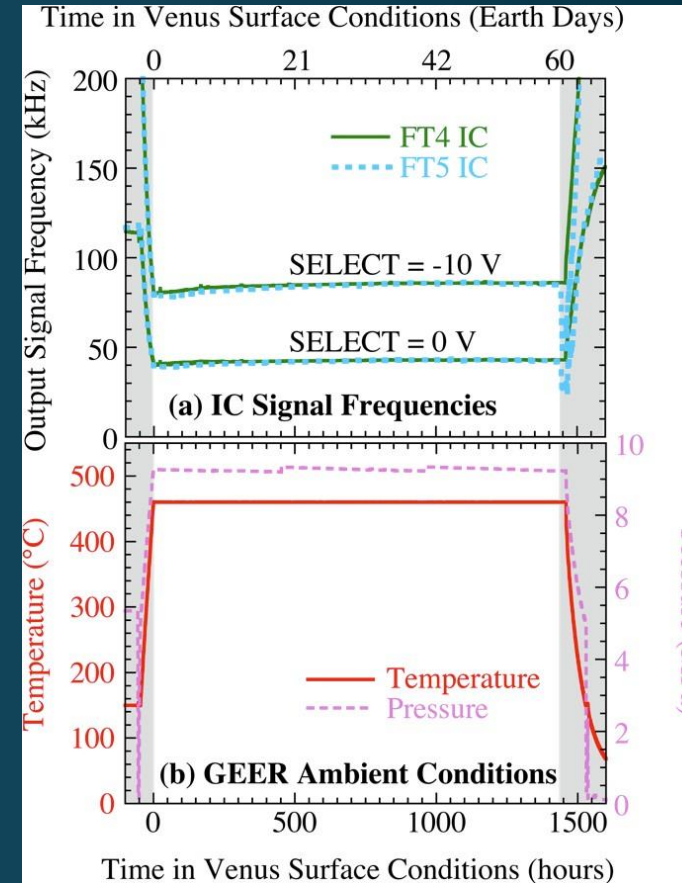
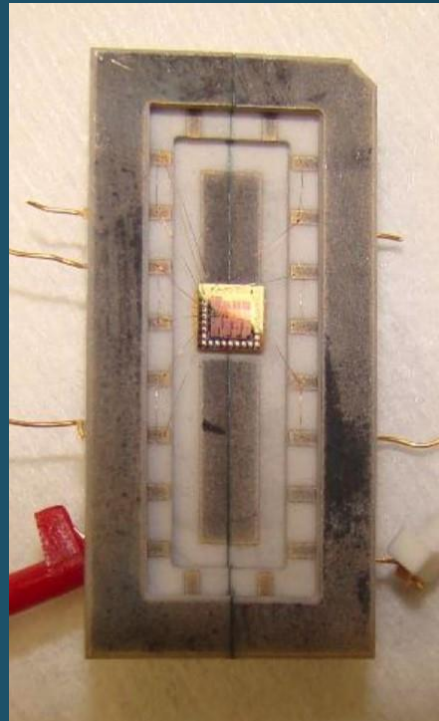
60-Day Venus Environment IC Test (in GEER)^{1,2}

Two IC Version 10 ÷2/÷4 Clock ICs (175 JFETs/chip) successfully operated in GEER Venus surface conditions for 60 days duration.

Before GEER



After 60 days GEER

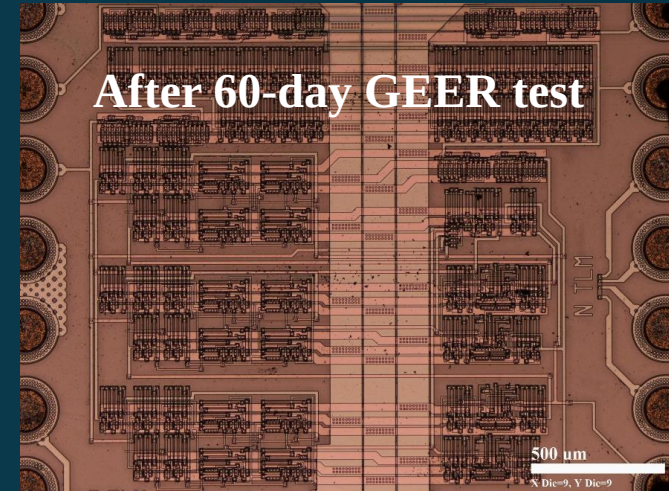
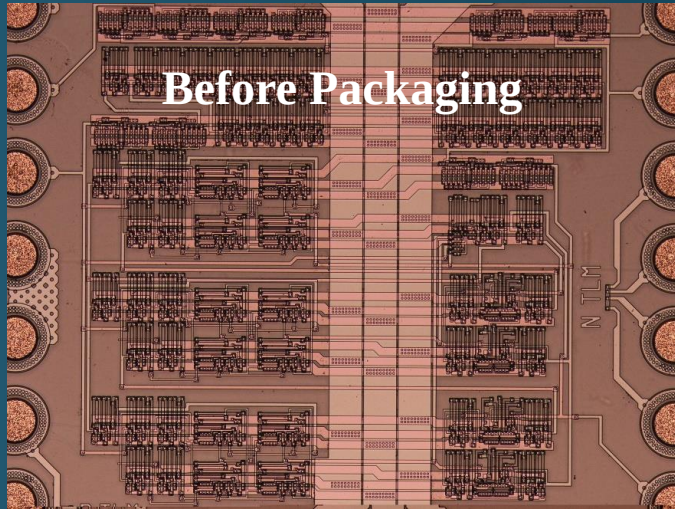


¹Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).

²Chen et al., Proc. 2018 Int. High Temperature Electronics Conf.

GEER testing and Material choice matters

Optical micrographs of SiC oscillator; These circuits are functional - Chip operated for 60 days



Wave guide Before and After 60 days of GEER Testing; These materials react – grow crystals – and will NOT work



Learn by Doing: Materials reactions in Venus surface ambient

Table 1 What works and what doesn't		
Devices	Materials	Outcome
Electronics Packaging	Pb	PbS
	Al ₂ O ₃	No reaction
Insulation	CaO	CaSO ₃ , CaSO ₄
SiC Electronics	Pt	PtS; fibers when present as thin film
	Pt (in the presence of Au)	PtS spheres
	Au	No reaction, but mobile
	Ir	No reaction, but mobile
	SiC	No reaction
	SiO ₂	No reaction
Feedthrough Materials	Cu	Cu ₂ S crystals
	Ni	NiS crystals
	CuBe	Cu ₂ S crystals on surface
SiC Pressure Sensor	Kovar (Ni-Co-Fe)	NiS, Fe _x O _y
	AlN	No reaction
	Ag-Cu Braze	segregation into Cu ₂ S and Ag; Ag mobile
GEER Components	Inconel 625 (Ni-Cr-Mo-Fe)	NiS, Cr _x O _y
	304 SS	Mirror finish, low corrosion rate
	Al foil/Mg doped	MgO on surface, MgF inner layer, Al bulk no reaction

Our own ovens for parallel testing

Improved $T \geq 460^\circ\text{C}$ IC electrical testing statistics data needed for mission infusion

- PXI instrument chassis hardware and software setup for parallel-testing (future 32 ovens capacity)
- First 8 “Mark 1” next-generation small/compact test ovens constructed and installed
 - Rapid heating & cooling (for thermal cycling tests) and power-efficient



Packaged BEOL test chips will be 500°C tested/cycled first, until IC Gen. 12 chips become available.

Acknowledgements

- Dr. Tibor Kremic, GRC Space Science Project Office
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- Facilities: Microsystems Fabrication Laboratory, Glenn Extreme Environments Rig (GEER)

<https://www1.grc.nasa.gov/research-and-engineering/silicon-carbide-electronics-and-sensors/jfet-ic-tech-guide/>



Thank You!

My role(s) as a Subject Matter Expert (SME)

- Fabricate communication circuit technologies for aero and space applications, e.g. Venus lander concept
- Author research publications
- Author proposals for funding from directorates within NASA and external agencies like Defense Advanced Research Projects Agency (DARPA)
- Review NASA Small Business Innovation Research (SBIR) proposals (Phases I and II) and EPSCOR (Established Program to Simulate Competitive Research) proposals
- Contracting Officer Representative (COR) to technically oversee Phase I and Phase II SBIR and EPSCOR contracts
- Maintain existing equipment and acquire new equipment for future technologies/work