Life on Venus, and How to Explore Venus with High-Temperature Electronics

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www.WorkingonVenus.se
Outline

Life on Venus (phosphine in the clouds)
Previous missions to Venus
Life on Venus (photos from the ground)
High temperature electronics
Future missions to Venus, including
Working on Venus (KTH Project 2014 - 2018)
Phosphine gas in the cloud decks of Venus

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Measurements of trace gases in planetary atmospheres help us explore chemical conditions different to those on Earth. Our nearest neighbour, Venus, has cloud decks that are temperate but hyperacidic. Here we report the apparent presence of phosphine (PH\textsubscript{3}) gas in Venus’s atmosphere, where any phosphorus should be in oxidized forms. Single-line millimetre-waveband spectral detections (quality up to -15\sigma) from the JCMT and ALMA telescopes have no other plausible identification. Atmospheric PH\textsubscript{3} at -20 ppb abundance is inferred. The presence of PH\textsubscript{3} is unexplained after exhaustive study of steady-state chemistry and photochemical pathways, with no currently known abiotic production routes in Venus’s atmosphere, clouds, surface and sub-surface, or from lightning, volcanic or meteoritic delivery. PH\textsubscript{3} could originate from unknown photochemistry or geochemistry, or, by analogy with biological production of PH\textsubscript{3} on Earth, from the presence of life. Other PH\textsubscript{3} spectral features should be sought, while in situ cloud and surface sampling could examine sources of this gas.
Phosphine gas in the cloud decks of Venus

Trace amounts of phosphine (20 ppb, PH$_3$) seen by the ALMA and JCMT telescopes, with millimetre wave spectral detection.
Phosphine gas in the cloud decks of Venus

Even if confirmed, we emphasize that the detection of $\text{PH}_3$ is not robust evidence for life, only for anomalous and unexplained chemistry. There are substantial conceptual problems for the idea of life in Venus’s clouds—the environment is extremely dehydrating as well as hyperacidic. However, we have ruled out many chemical routes to $\text{PH}_3$, with the most likely ones falling short by four to eight orders of magnitude (Extended Data Fig. 10). To further discriminate between unknown photochemical and/or geological processes as the source of Venusian $\text{PH}_3$, or to determine whether there is life in the clouds of Venus, substantial modelling and experimentation will be important. Ultimately, a solution could come from revisiting Venus for in situ measurements or aerosol return.
Phosphine gas in the cloud decks of Venus

https://www.nature.com/articles/s41550-020-1174-4
https://www.scientificamerican.com/article/is-there-life-on-venus-these-missions-could-find-it/
Did NASA detect phosphine 1978?

Pioneer 13 Large Probe Neutral Mass Spectrometer (LNMS)
Why Venus?

Our closest planet, but least known
Similar to earth in size and core, has an atmosphere
Volcanoes
Interesting for climate modeling
(ultimate limit of global warming)
Venus Atmosphere

96% CO₂ (Also sulphuric acids)
Pressure of 92 bar (equivalent to 1000 m water)
Temperature 460 °C

→ Difficult to explore
→ Life is not likely
Previous Missions

Venera 1 – 16 (1961 – 1983) USSR
Mariner 2 (1962) NASA, USA
Pioneer (1978 – 1992) NASA, USA
Magellan (1989) NASA, USA
Venus Express (2005 - ) ESA, Europa
Akatsuki (2010) JAXA, Japan
Steps to lunar and planetary exploration:

1. Remote observation (telescope)
2. Fly by or Orbiter
3. Probe (“crash lander”) (Moon, Mars, Venus)
4. Balloons (needs atmosphere)
5. Lander
6. Rover (ok on Mars)
7. Sample return (expensive)
8. Human exploration
9. Colonization
Venus is visible to the naked eye

Morning star
Evening star
CCCP Venera 9 and 10 (1975)

Electronics functional around 1 hour
First B/W images
1560 kg

From Wikimedia Commons, the free media repository
CCCP Venera 13 and 14 (1981)

Lander features for size and color reference

Electronics functional around 2 hours
First color images
No signs of life?

760 kg
More photos from Venera 13: Venus "Scorpion"


Also in http://www.sci-news.com/space/article00156.html
More photos from Venera 14: the Venus ”Fish”

More photos from Venera: the Venus ”Lizard”

VeGa 1 and VeGa 2 - 1985

Combined with Halley comet

https://en.wikipedia.org/wiki/Vega_program
NASA Rovers?

Zephyr

RASC
NASA Venus Flagship Mission Study 2009

Figure 5.6: Thermodynamic Two Stage System for both Power Generation and Cooling on the Venus surface for a Lander. By staging the cooling, the power requirements drop considerably.

NASA Cloudships?

Future Missions to Venus?

- VERITAS - Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy (Orbiter)
- The DAVINCI+ (Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging Plus) mission consists of an orbiter that would, as part of its investigations, dispatch an instrumented probe to the Venusian atmosphere

https://www.scientificamerican.com/article/is-there-life-on-venus-these-missions-could-find-it/
What's left to find out?
High Temperature Electronics

At least 460 °C
Not just for surface exploration of Venus
Terrestrial uses could dominate

Why does silicon electronics fail?
Intrinsic Concentration vs Temperature

\[ n_i = (N_C N_V)^{0.5} \exp\left(-\frac{E_g}{2kT}\right) \]

SiC is the key!
Extreme Environment Applications

SiC (3.2 eV)
Intrinsic Temperature 1000 °C

Automotive

Venus

Turbine Engine

0 °C  100 °C  200 °C  300 °C  400 °C  500 °C  600 °C

Medical

Gas & Oil Drilling

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And beyond Venus...

Fukushima
Shinkansen N700s
Jupiter Moons mission (JUICE)
Working on Venus
KAW Funded 2014 – 2018

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Working on Venus 2014 - 2018

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www.WorkingonVenus.se
Working on Venus – Lander Block Diagram

Uncooled! Compact!
Cleanroom for IC and Device Fabrication

**Electrum Laboratory 1300 m²**
ISO 9001 certified / controlled processes and calibrated characterization tools
100 – 200 mm wafers

**Silicon Technology**
Silicon - IC
Silicon - Microsystems

**Compound Semiconductors**
SiC – Electronics, 100 mm
InP - Opto / electronics
GaAs - Opto / electronics

Part of [myfab] - the Swedish national research infrastructure for micro- and nanofabrication
NASA Glenn test chamber mimics Venus' harsh conditions ("Hell on Earth")

NASA Glenn aerospace engineer Rodger Dyson shows one of the 100-pound bolts that will secure the lid of the new extreme environments test chamber.

http://www.wired.com/2012/01/nasa-venus-chamber/
Testing facilities for electrical characterization

On wafer probing up to 620 °C
Parameter analyzer for DC characteristics
Digital oscilloscope/FFT for AC characteristics
Field Effect Transistor Gas Sensors

(High-temperature operation, 500 °C)

Each sensor chip contains at least one field effect transistor (FET)

The voltage, $V_{GS,ext}$, applied to the gate, $G$, determines the drain current, $I_D$, through the transistor

Certain gas species change the gate voltage (by $V_{GS,int}$) when adsorbing on the gate, altering the I/V-characteristics

High-temperature operation requires:
1) Reliable metallization/Ohmic contacts, 2) Gate material stability, 3) Good high-temperature gas sensitivity

www.WorkingonVenus.se
Accelerometer – Frequency response
Bipolar Process Technology

- SiC Dry Etching
  - Reactive Ion Etching
- Sacrificial Oxidation
  - 1100 °C, 3 hours, in O₂
- Passivation Oxidation
  - 1250 °C, 3 hours, in N₂O
- Contact Salicide
  - Ni, 600 °C, 1 min
- N-type Ohmic Contact
  - 950 °C, 1 min
- P-type Ohmic Contact
  - Ti/Al deposition, patterning and etching
  - > 900 °C, 1 min
- TiW/Al Metal Interconnects
Bipolar Process for T, R and C

www.HOTSiC.se + www.WorkingonVenus.se
Current gain and sheet resistance

- **Current gain β**
  - Y-axis: 100 to 0
  - X-axis: 0 to 500
  - Temperature (T) in °C

- **Sheet resistance Ω/sq**
  - Y-axis: 350 to 0
  - X-axis: 0 to 500
  - Temperature (T) in °C

www.WorkingonVenus.se
Negative Feedback for Analog circuits

www.HOTSiC.se + www.WorkingonVenus.se
SiC Amplifiers

Material aspects of wide temperature range amplifier design in SiC bipolar technologies

A monolithic, 500 °C operational amplifier in 4H-SiC bipolar technology

Silicon carbide fully differential amplifier characterized up to 500 °C
2 A Linear Voltage Regulator

SiC HT Radio Circuits – A challenge to measure

500 °C on chuck but max 200 °C at SMA contacts required LTCC hybrid board for characterization

DOI: 10.1109/LED.2018.2829628

DOI: 10.1109/TED.2018.2804392 (55 MHz, 250 °C)
Noise Margins for Digital circuits

Needs to be measured at every temperature

Electrical Characterization of Integrated 2-input TTL NAND Gate at Elevated Temperature, Fabricated in Bipolar SiC-Technology
M. Shakir et al. ICSCRM 2017

www.HOTSiC.se + www.WorkingonVenus.se
2-input NAND Gate DC-Response at 15 V

VTC vs T

Now also 600 °C operation

NM vs T

www.WorkingonVenus.se
2-input TTL NAND Gate Layout and Micrograph

Schematic

Input Stage

Phase splitter

Output Stage

Layout

Micrograph
Process Design Kit for TTL gate library

LVS - Layout vs Schematic
DRC / Design Rule Check
Hierarchical gate library

DOI:10.3390/electronics8050496
Next steps

- ADC 100 transistors
- Amplifier 25 transistors
- Logic gate 5 transistors
- Microcontroller 6,000 transistors
4 bit TTL CPU

11.4 mm X 13.2 mm = 151 mm$^2$

BJTs = 5911

Integrated Resistors = 3918

Vcc = 15 V, 1 A

2 metal layers

LVS and DRC

Simulated in Spice

Parts characterized up to 600 °C

Test chip also contains ADCs, Amplifiers and UV pixel detector
A 600 °C TTL-based 11-stage Ring Oscillator in Bipolar Silicon Carbide Technology

M. Shakir et al, IEEE Electron Device Letters, vol 39, p 1540, 2018

120 devices
Fabricated Image Sensor

- Schematic and Layout of the digital circuits are from collaborator contributed TTL PDK
- Two 4-to-16 decoders
- One 8-bit counter
- 16x16 pixels
- 1959 transistors
- 68.2 mm²
- Dynamic mode - 7 I/Os
- Static mode – 13 I/Os
Leakage (Dark) Current and optical response of the SiC Photodiodes

- Leakage current density increases at higher temperatures, but it is still low (~1 μA/cm²) even at 550 °C.
- Leakage current density is higher for smaller devices because of surface recombination effect.
Pixel detector in operation

RT

K

T

H

Signal with Shade K

Signal with Shade T

Signal with Shade H

K

T

H
Ferroelectrics for NVRAM (below 660 °C)

Integration and high-temperature characterization of ferroelectric Vanadium-doped Bismuth Titanate thin films on Silicon Carbide
M. Ekström et al. J. Electronic Materials, 2017
DOI: 10.1007/s11664-017-5447-3
Working on Venus - PhD defenses

Juan Colmenares – SiC Power Circuits, 2016
Hossein Elahipanah – HV and HT transistors, 2017
Ye Tian – Readout circuitry for accelerometer, 2017
Shuoben Hou – UV photodetectors (16 x 16 bit array), 2019
Mattias Ekström – CMOS and memory devices, 2019
Muhammad Waqar – RF circuits, 2019
Muhammad Shakir – Process Design Kit for digital ASICs, 2019
Miku Laakso – Accelerometer integration, 2020
Lida Khajavizadeh – Gas Sensors, TBD
Summary and outlook

- Bipolar integrated circuits in SiC can handle 500 °C
- Sensors, Amplifiers, Analog-to-Digital Converters, Microcontrollers, Memory, Radio Transceiver and Power Supply demonstrated (on Earth)
- 5 000+ device level fabricated and tested
- 100 000 device level systems possible for Venus Lander

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