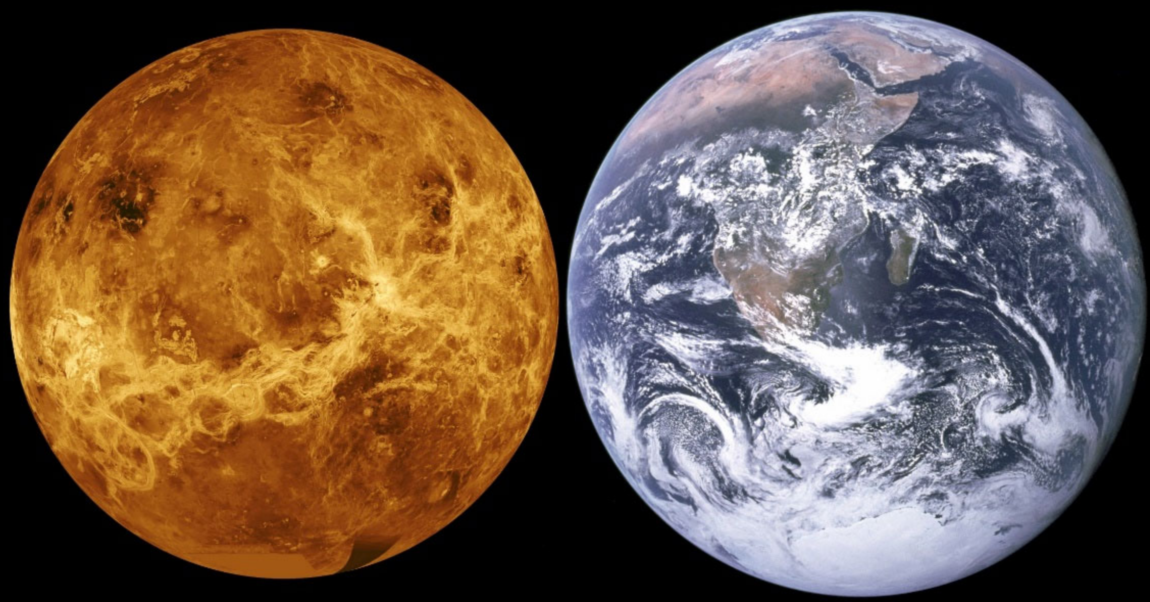
Life on Venus, and How to Explore Venus with High-Temperature Electronics

Carl-Mikael Zetterling bellman@kth.se



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)

nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-020-1174-4

Check for updates

Phosphine gas in the cloud decks of Venus

Jane S. Greaves[1,2], Anita M. S. Richards[3], William Bains[4], Paul B. Rimmer[5,6,7], Hideo Sagawa[8], David L. Clements[9], Sara Seager[4,13,14], Janusz J. Petkowski[4], Clara Sousa-Silva[4], Sukrit Ranjan[4], Emily Drabek-Maunder[1,10], Helen J. Fraser[11], Annabel Cartwright[1], Ingo Mueller-Wodarg[9], Zhuchang Zhan[4], Per Friberg[12], Iain Coulson[12], E'lisa Lee[12] and Jim Hoge[12]

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_3) gas in Venus's atmosphere, where any phosphorus should be in oxidized forms. Single-line millimetre-waveband spectral detections (quality up to ~15σ) from the JCMT and ALMA telescopes have no other plausible identification. Atmospheric PH_3 at ~20 ppb abundance is inferred. The presence of PH_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 subsurface, or from lightning, volcanic or meteoritic delivery. PH_3 could originate from unknown photochemistry or geochemistry, or, by analogy with biological production of PH_3 on Earth, from the presence of life. Other PH_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

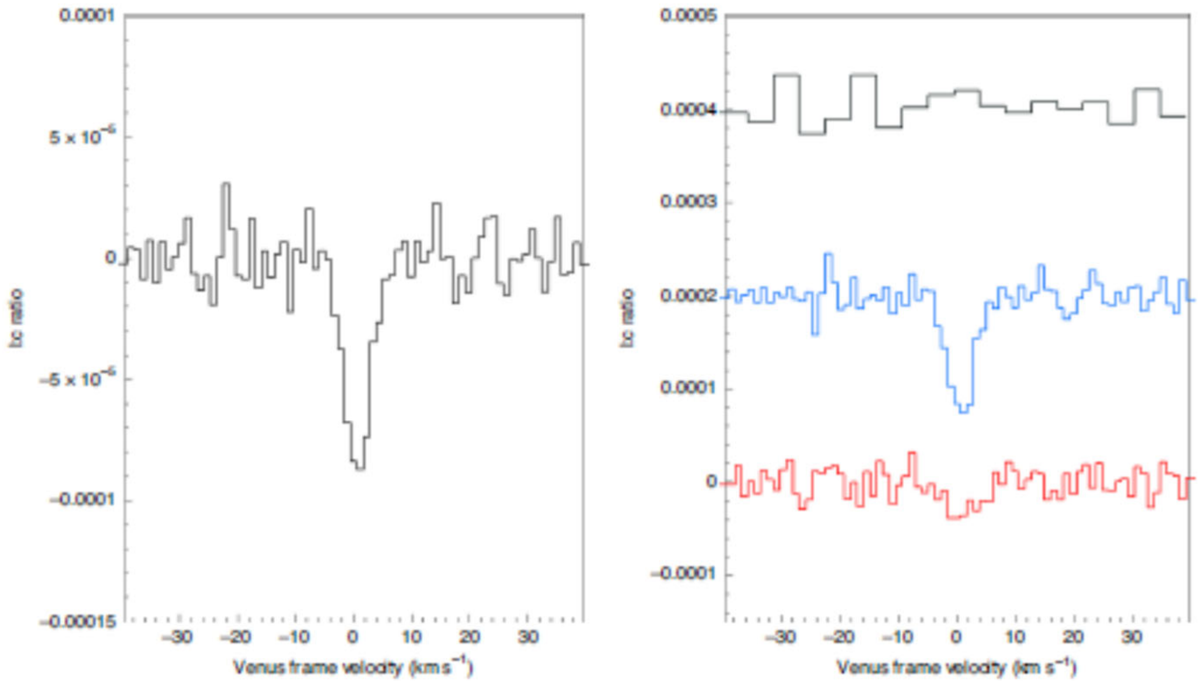


Fig. 2 | Spectra of Venus obtained with ALMA. Left: the PH_3 1–0 spectrum of the whole planet, with 1σ errors (here channel to channel) of 0.11×10^{-4} per 1.1 km s^{-1} spectral bin. Right: spectra of the polar (histogram in black), mid-latitude (in blue) and equatorial (in red) zones, as defined in Table 1. Spectra have been offset vertically for clarity, and the polar spectrum was binned in velocity to obtain a deeper upper limit. Line wings are forced towards zero outside $|v| = 5$ km s^{-1} in these spectra, and only this range was used in characterization (Table 1 and 'ALMA data reduction' in Methods).

Phosphine gas in the cloud decks of Venus

Even if confirmed, we emphasize that the detection of 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 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 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://arxiv.org/pdf/2009.06499.pdf

https://www.nytimes.com/2020/09/14/science/venus-life-clouds.html?smtyp=cur&smid=fb-nytimesfindings

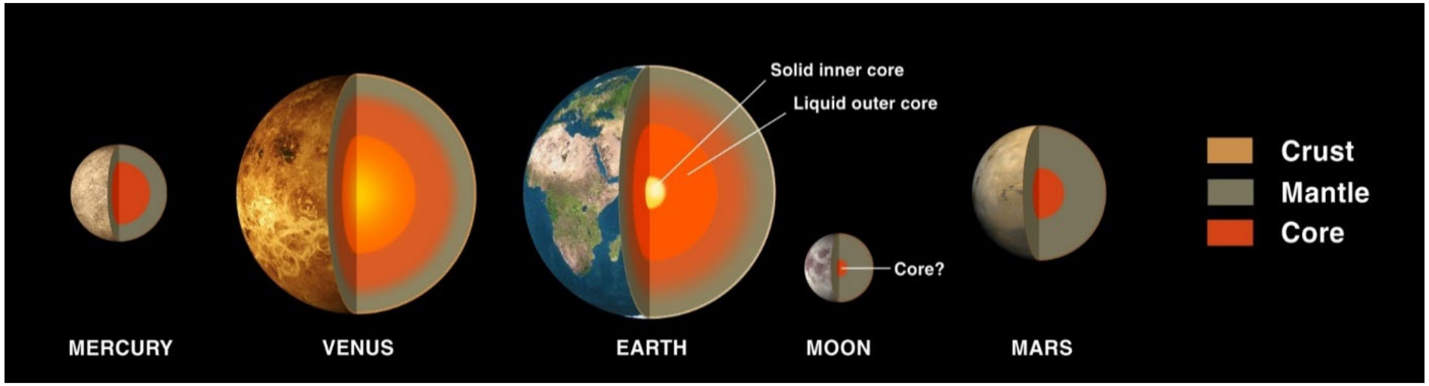
https://www.scientificamerican.com/article/is-there-life-on-venus-these-missions-could-find-it/

Did NASA detect phosphine 1978?

Pioneer 13 Large Probe Neutral Mass Spectrometer (LNMS)

https://www.livescience.com/life-on-venus-pioneer-13.html

Why Venus?



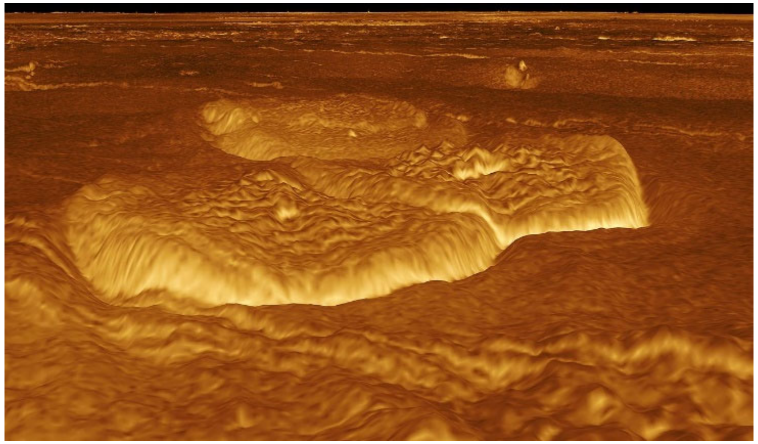
From Wikimedia Commons, the free media repository

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 Long-life Surface Package
C. Wilson, C.-M. Zetterling, W. T. Pike
IAC-17-A3.5.5, Paper 41353
arXiv:1611.03365v1

Venus Atmosphere

96% CO_2 (Also sulphuric acids)
Pressure of 92 bar (equivalent to 1000 m water)
Temperature 460 °C



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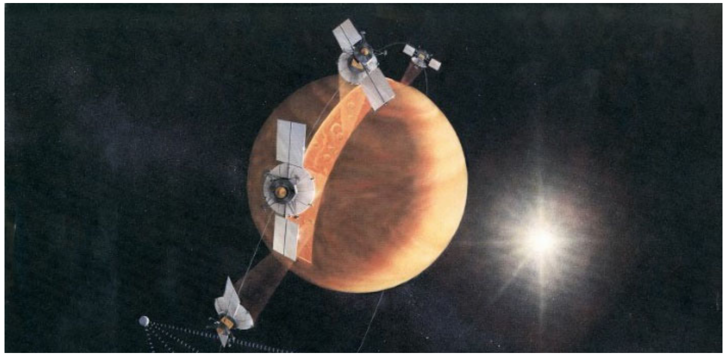
→ Difficult to explore
→ Life is not likely

Previous Missions



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Venera 1 – 16 (1961 – 1983) USSR

Mariner 2 (1962) NASA, USA

Pioneer (1978 – 1992) NASA, USA

Magellan (1989) NASA, USA

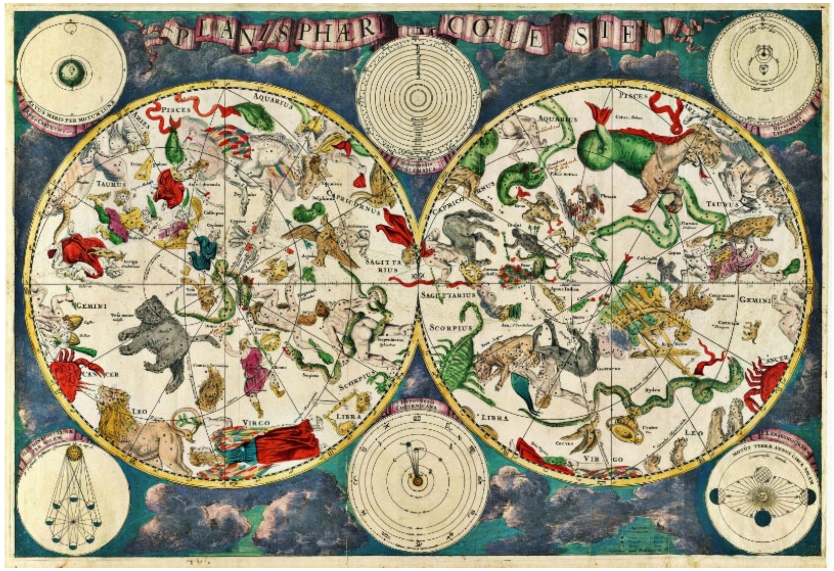
Venus Express (2005 -) ESA, Europa

Akatsuki (2010) JAXA, Japan

Steps to lunar and planetary exploration:

Moon
Mars
Venus

1. Remote observation (telescope)
2. Fly by or Orbiter
3. Probe (”crash lander”)
4. Balloons (needs atmosphere)
5. Lander
6. Rover (ok on Mars)
7. Sample return (expensive)
8. Human exploration
9. Colonization

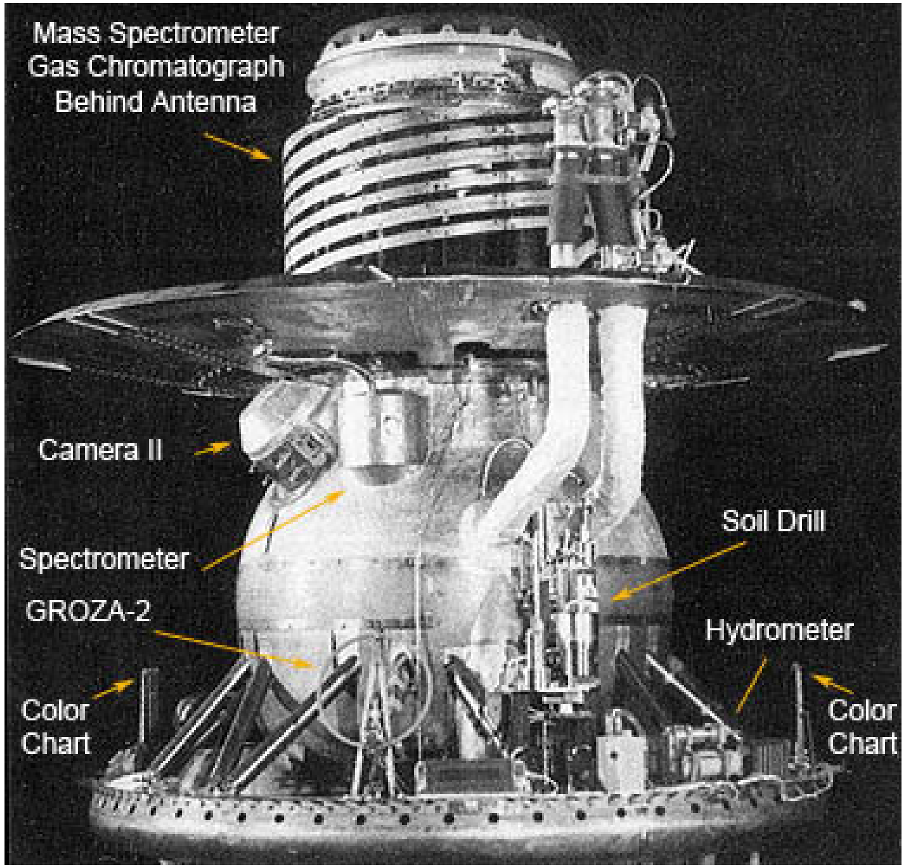


Venus is visible to the naked eye

Morning star
Evening star

CCCP Venera 9 and 10 (1975)

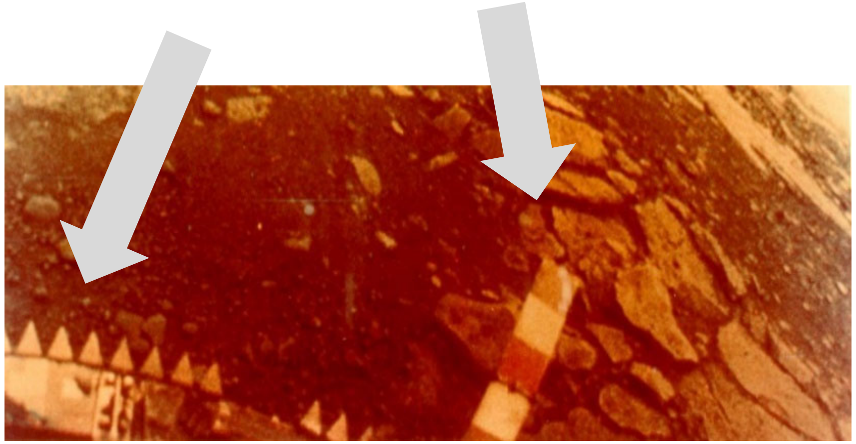
From Wikimedia Commons, the free media repository



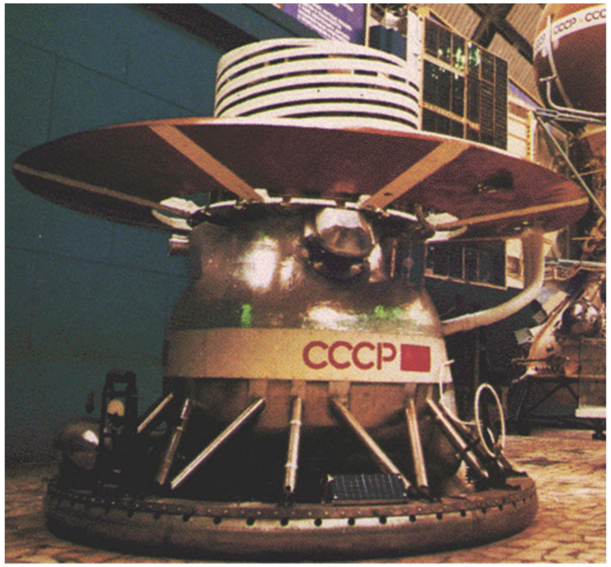
Electronics functional around 1 hour
First B/W images
1560 kg

CCCP Venera 13 and 14 (1981)

Lander features for size and color reference



From Wikimedia Commons, the free media repository

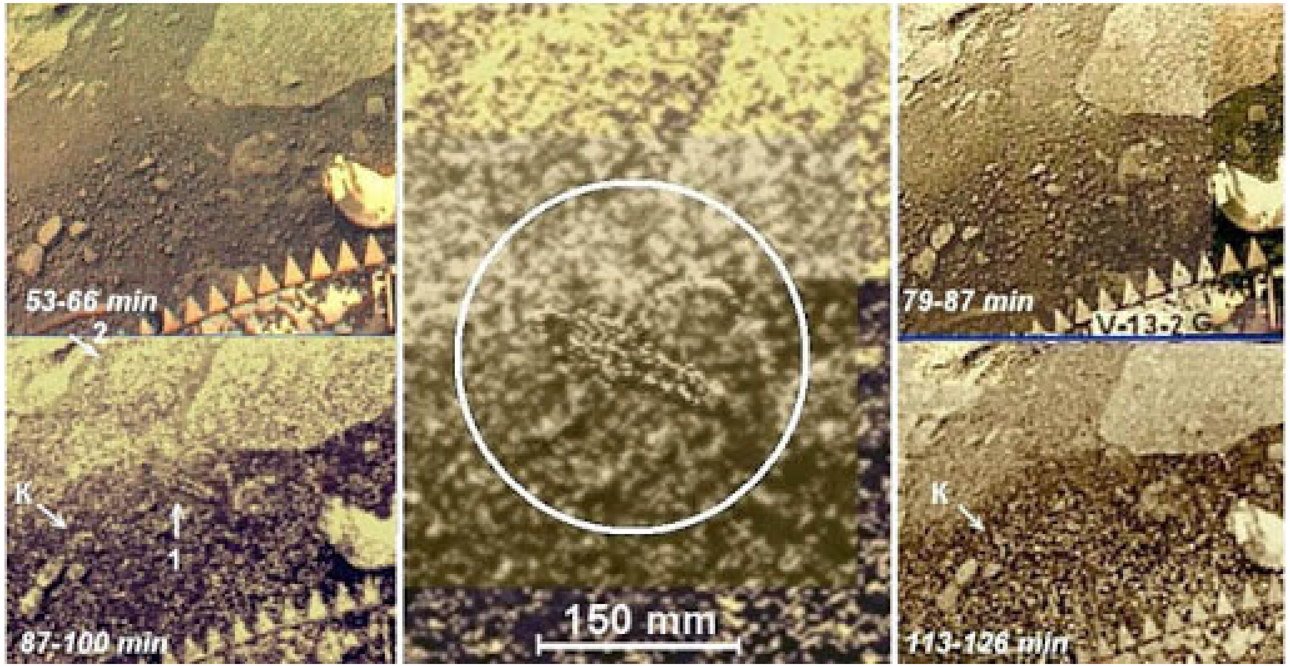


From Wikimedia Commons, the free media repository

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

760 kg

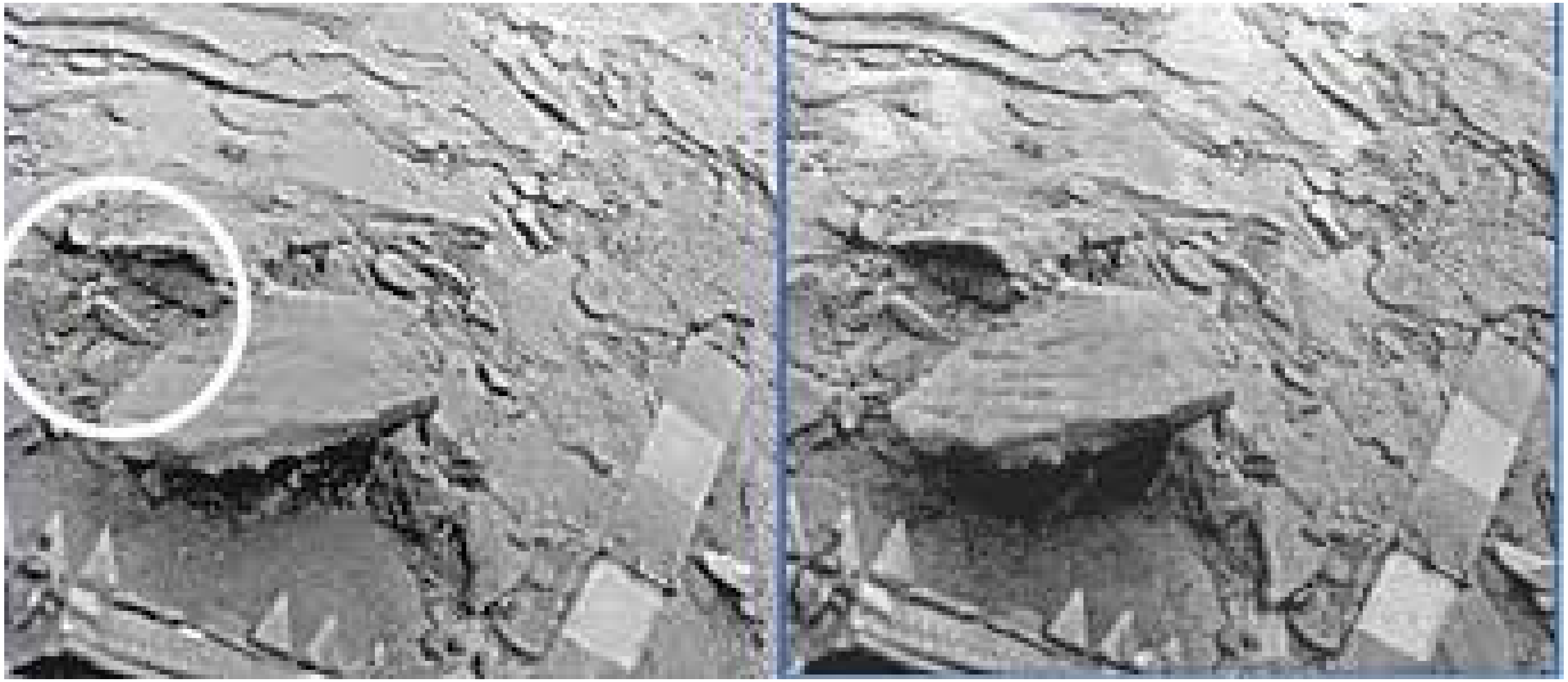
More photos from Venera 13: Venus ”Scorpion”



L. V. Ksanfomality. 2012. Venus as a Natural Laboratory for Search of Life in High Temperature Conditions: Events on the Planet on March 1, 1982. Solar System Research (Astronomicheskii Vestnik) 46, No. 1; doi: 10.1134/S0038094612010042

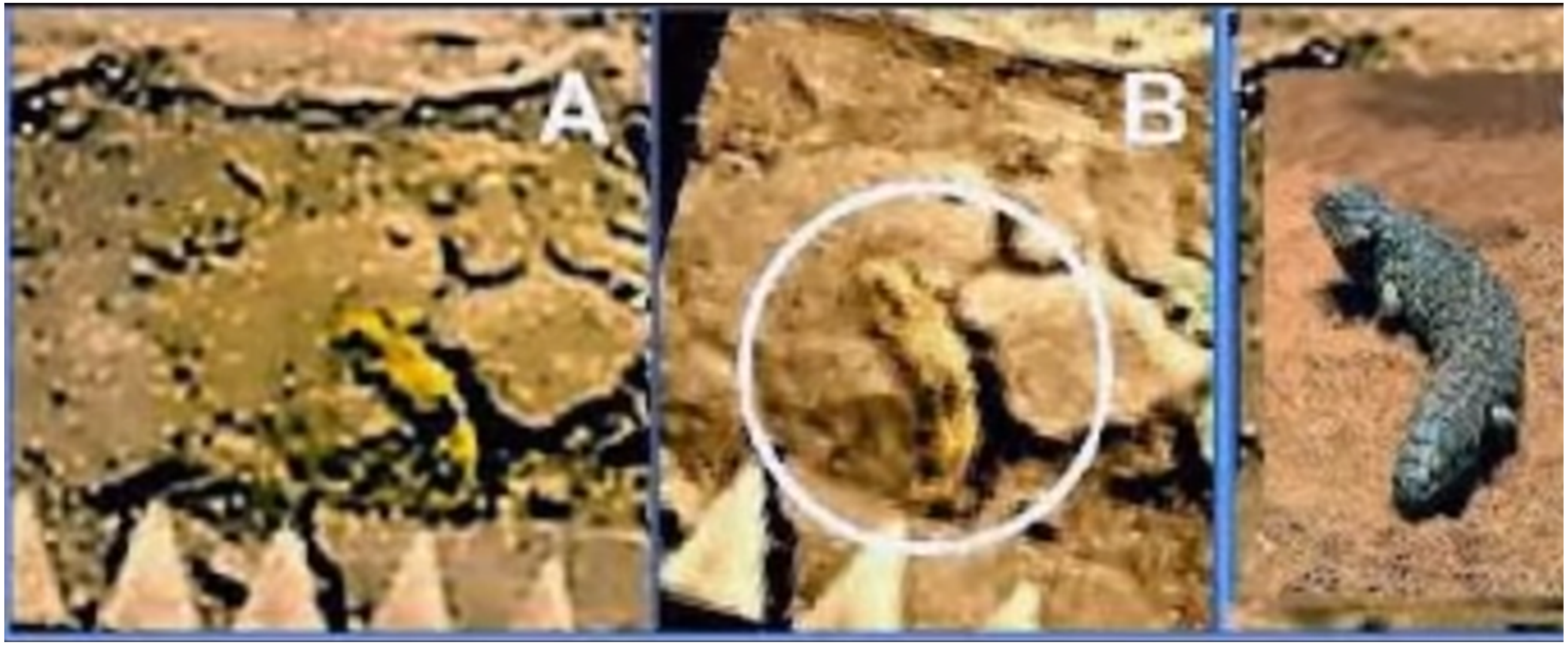
Also in http://www.sci-news.com/space/article00156.html

More photos from Venera 14: the Venus ”Fish”



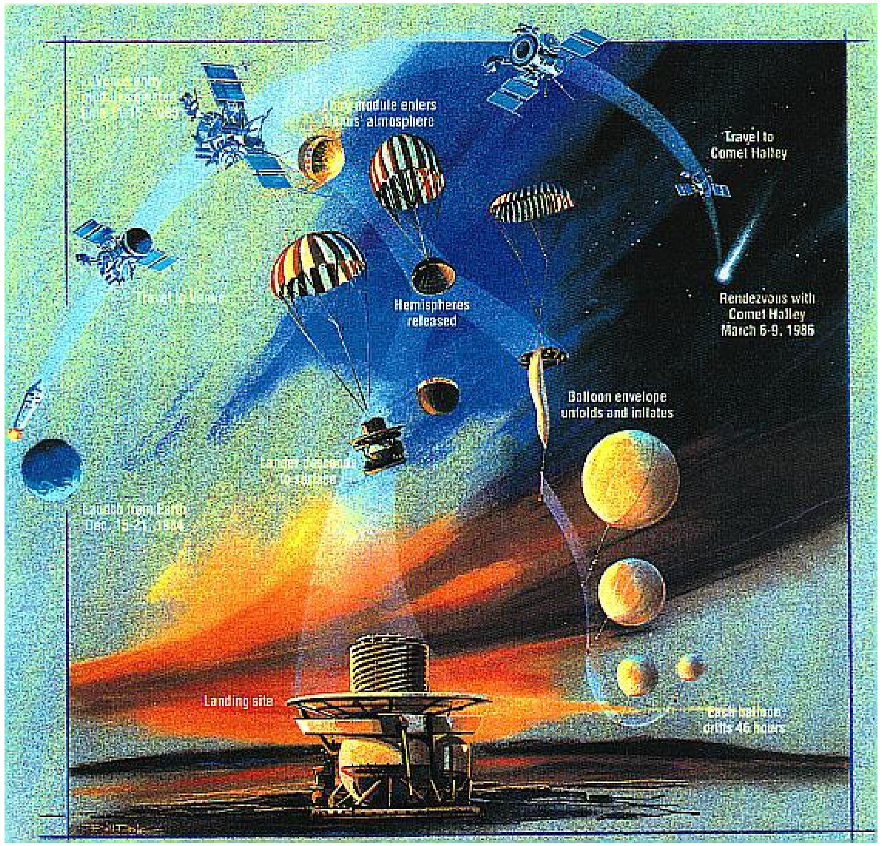
Ksanfomality LV (2014) Amisadas: Hypothetical Venusian Fauna at the Venera-14 Landing Site. Astrobiol Outreach 2: 1000112. doi: 10.4172/2332-2519.1000112

More photos from Venera: the Venus ”Lizard”



https://newsinstact.com/space/russian-scientists-discover-moving-creatures-on-planet-venus/

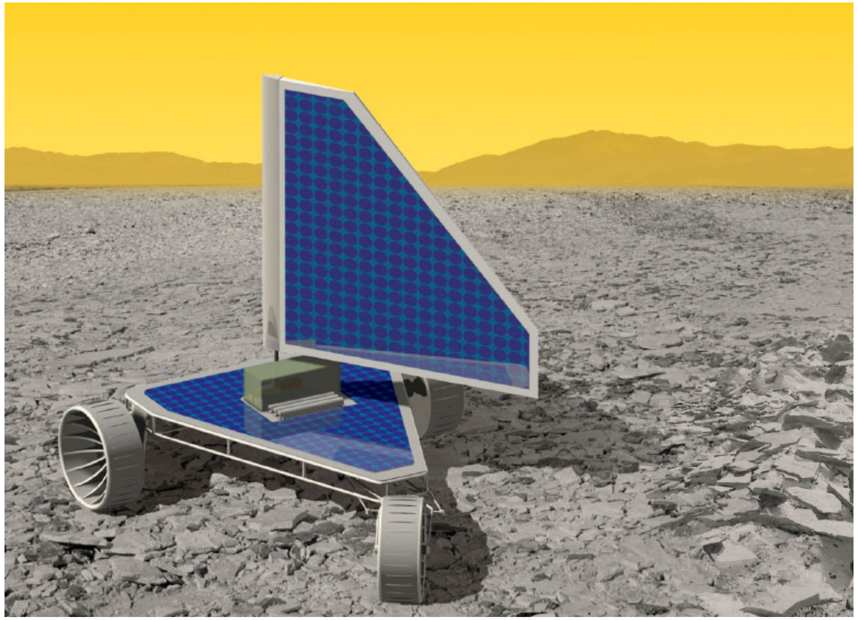
VeGa 1 and VeGa 2 - 1985



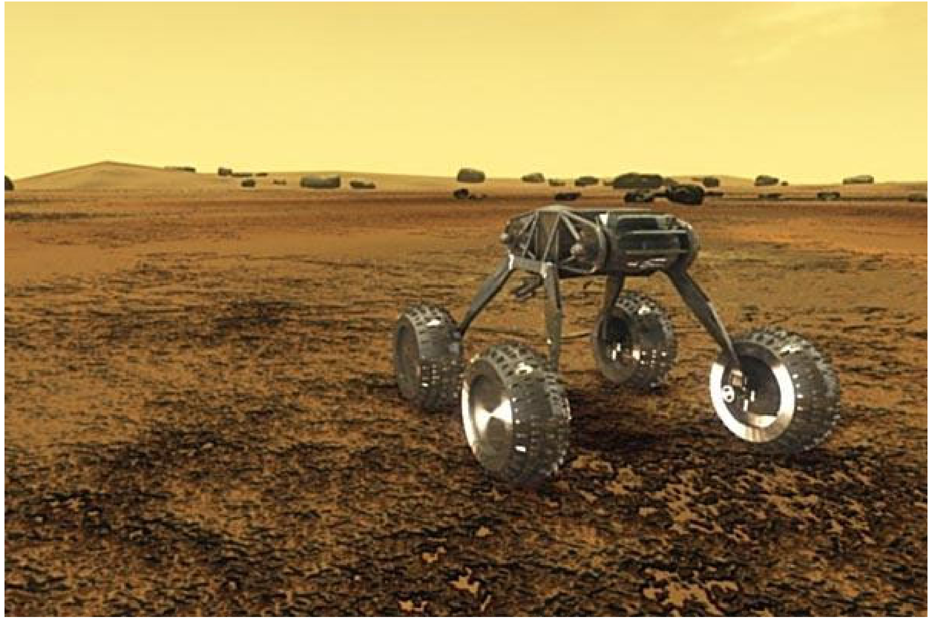
Combined with Halley comet

https://en.wikipedia.org/wiki/Vega_program

NASA Rovers?



Zephyr



RASC

NASA Venus Flagship Mission Study 2009

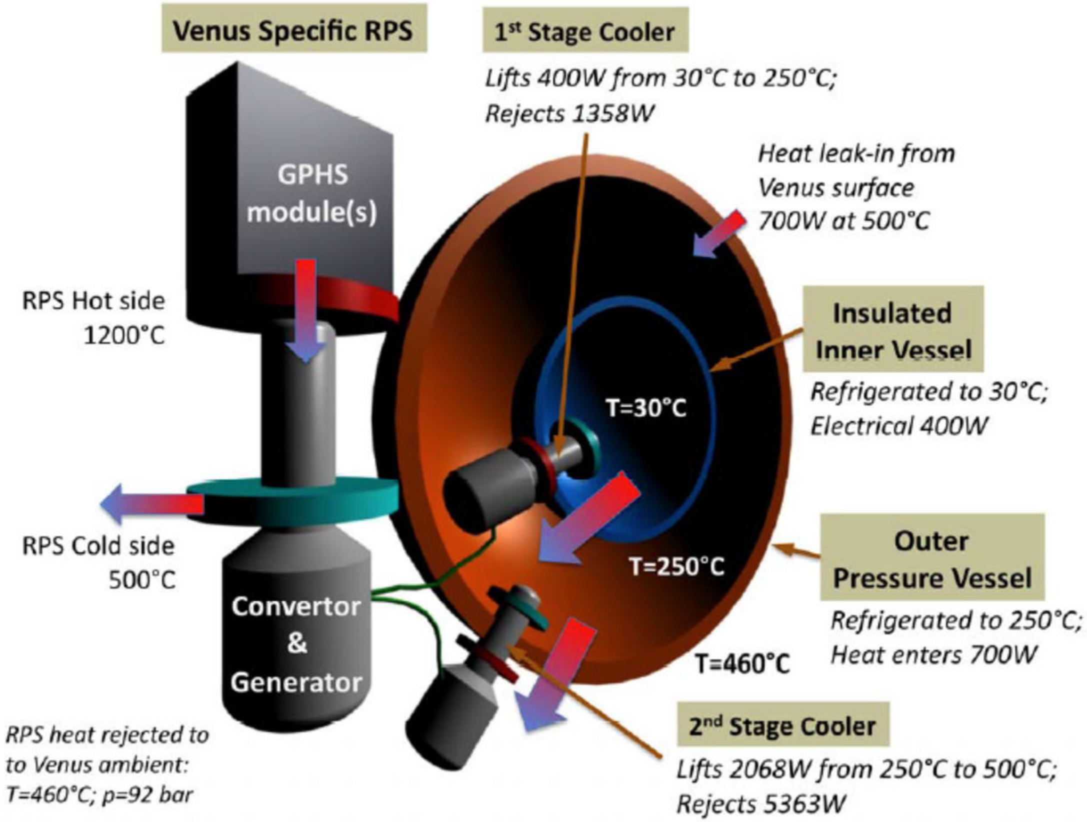
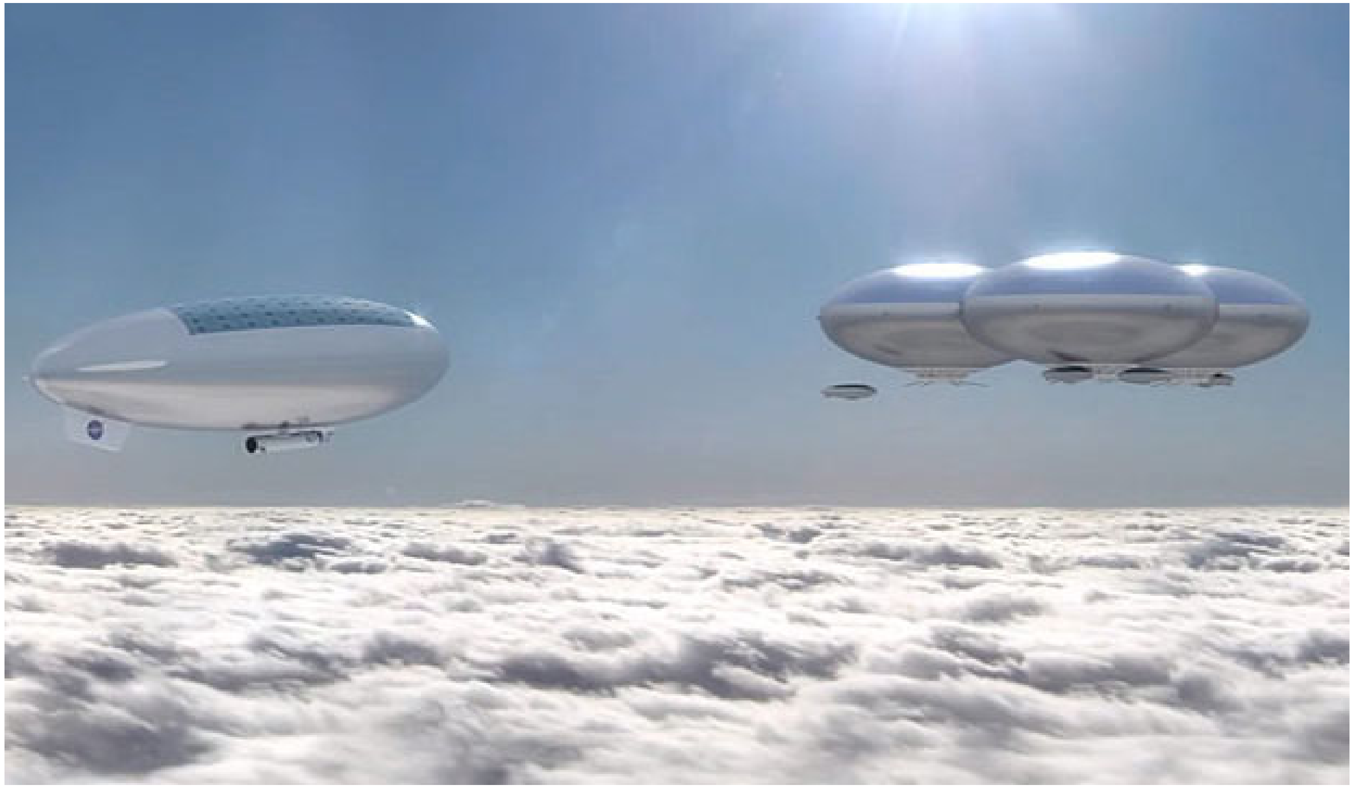


Figure 5.6: Thermodynamic Two Stage System for both Power Generation and Cooling on the Venus surface for a Lander. By staging the cooling, the power requirements drop considerably.

http://vfm.jpl.nasa.gov/files/Venus+Flagship+Mission+Study+090501-compressed.pdf

NASA Cloudships?



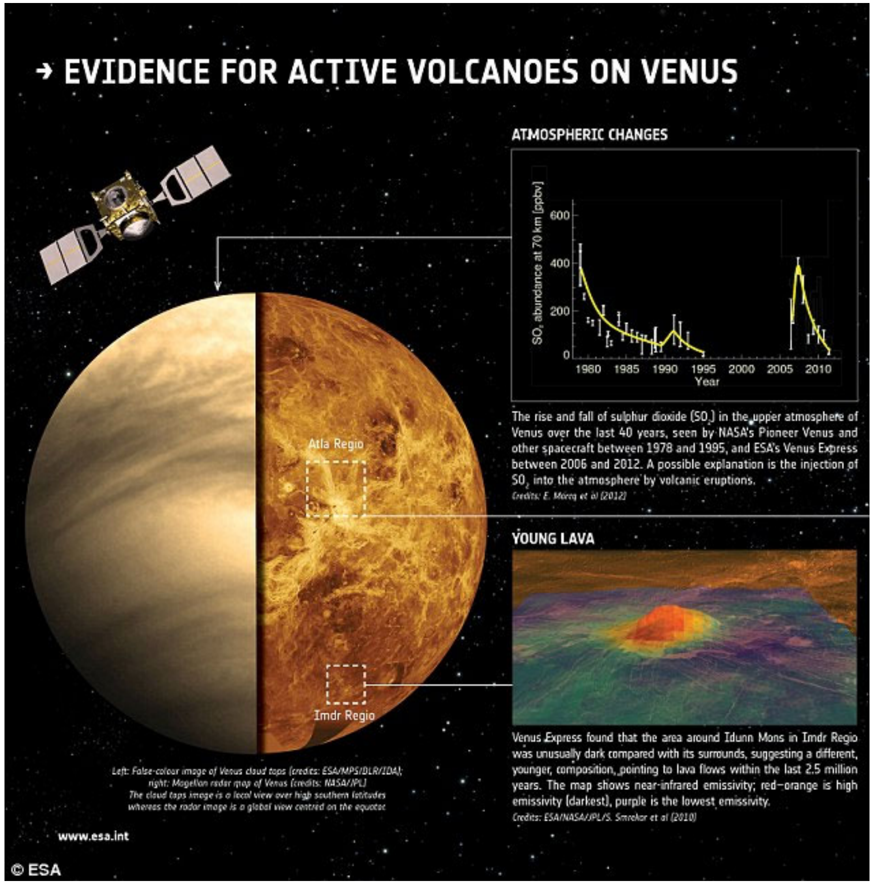
http://spectrum.ieee.org/aerospace/space-flight/nasa-study-proposes-airships-cloud-cities-for-venus-exploration

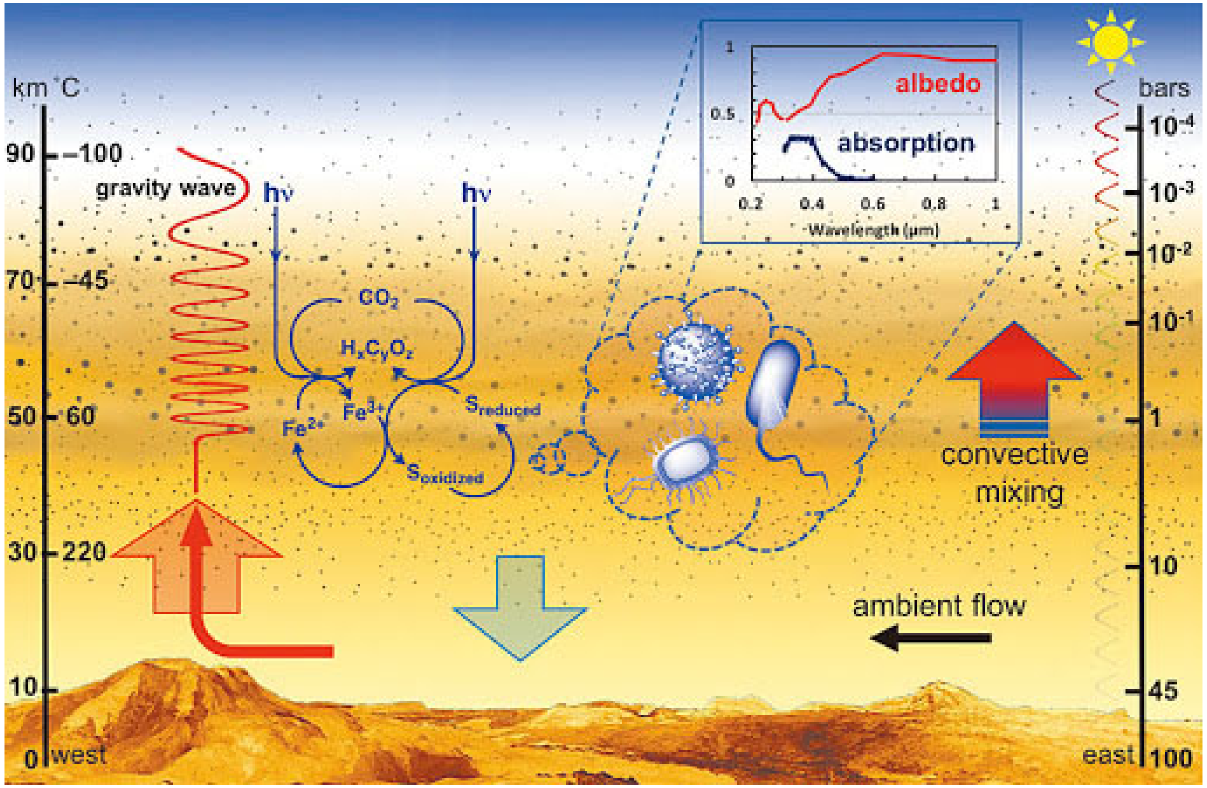
Future Missions to Venus?

- 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

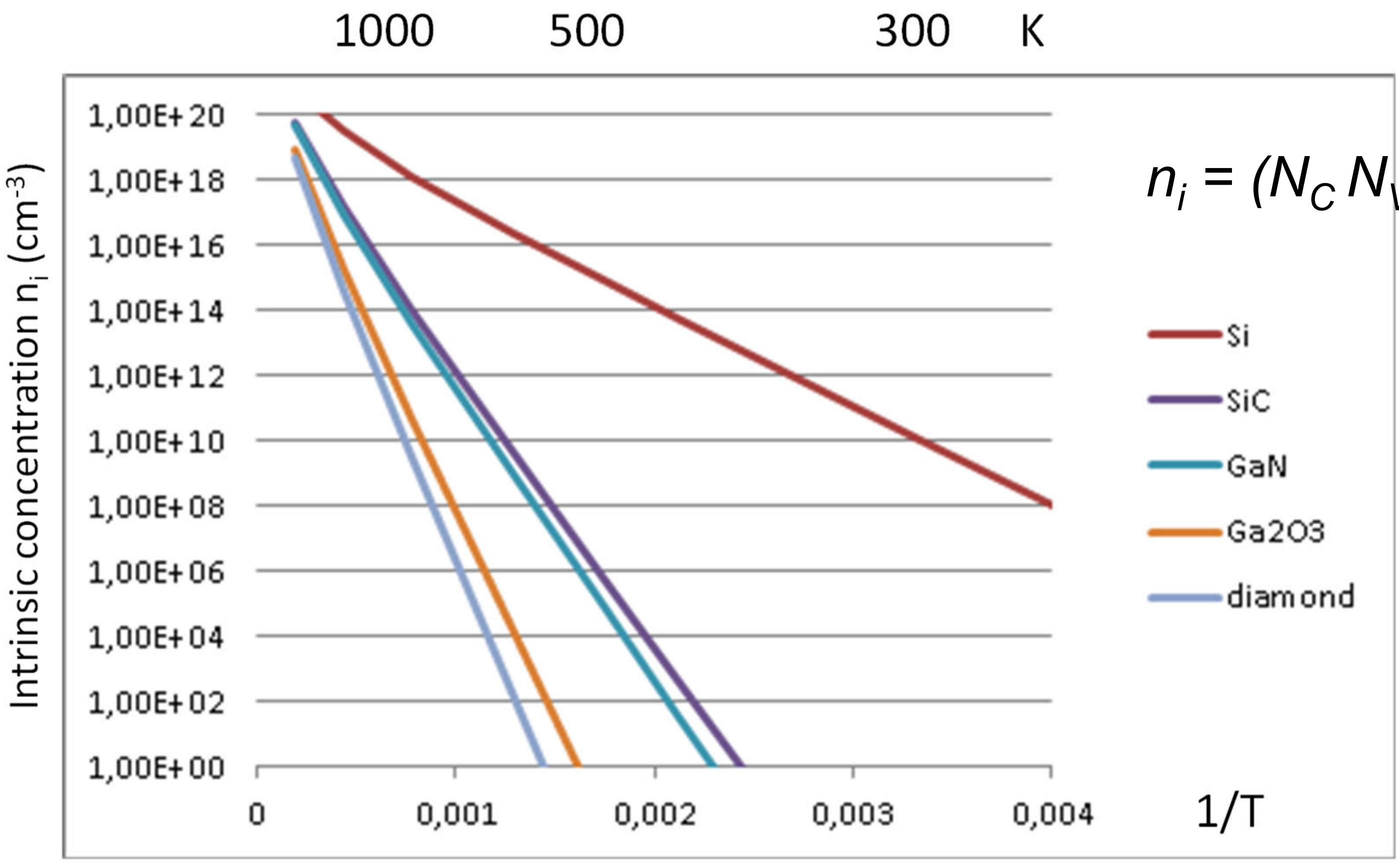
At least 460 °C

Not just for surface exploration of Venus

Terrestrial uses could dominate

Why does silicon electronics fail?

Intrinsic Concentration vs Temperature



$n_i = (N_C N_V)^{0.5} \exp(-E_g / 2\,k\,T)$

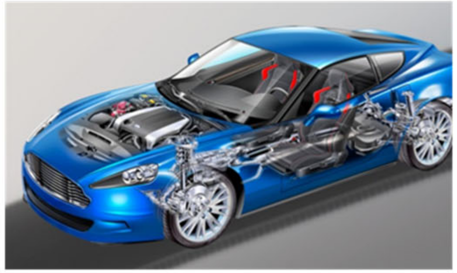
SiC is the key!

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

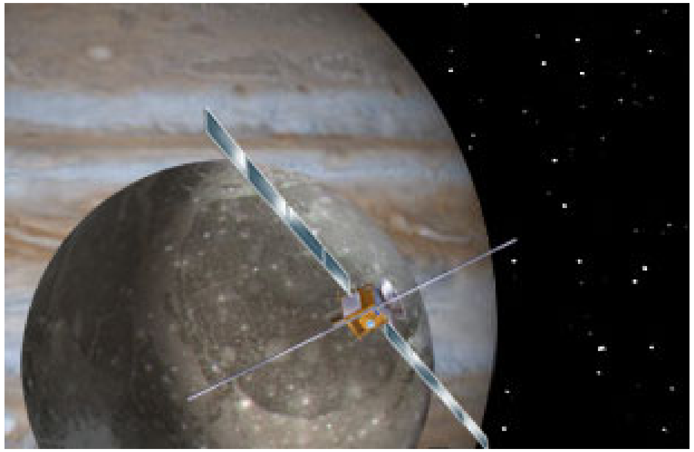
Medical

Gas & Oil Drilling

And beyond Venus...

Fukushima

Shinkansen N700s



Jupiter Moons mission (JUICE)

Working on Venus
KAW Funded 2014 – 2018

Carl-Mikael Zetterling AND Mikael Östling,

Christer Fuglesang, B. Gunnar Malm, Hans-Peter Nee, Frank Niklaus, Ana Rusu, Anita Lloyd Spetz

Mike Andersson, Per-Erik Hellström, Saul Rodriguez

Juan Colmenares, Mattias Ekström, Hossein Elahipanah, Shuoben Hou, Lida Khajavizadeh, Miku Laakso, Muhammad Shakir, Ye Tian, Muhammad Waqar Hussain

KTH and Linköping University

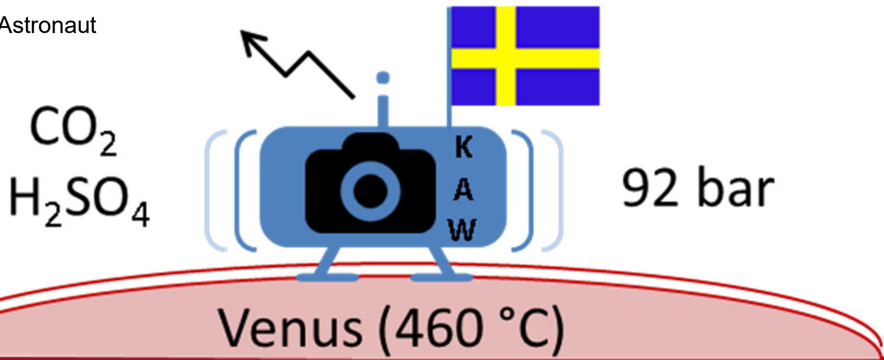
Working on Venus 2014 - 2018

Knut and Alice Wallenberg Foundation

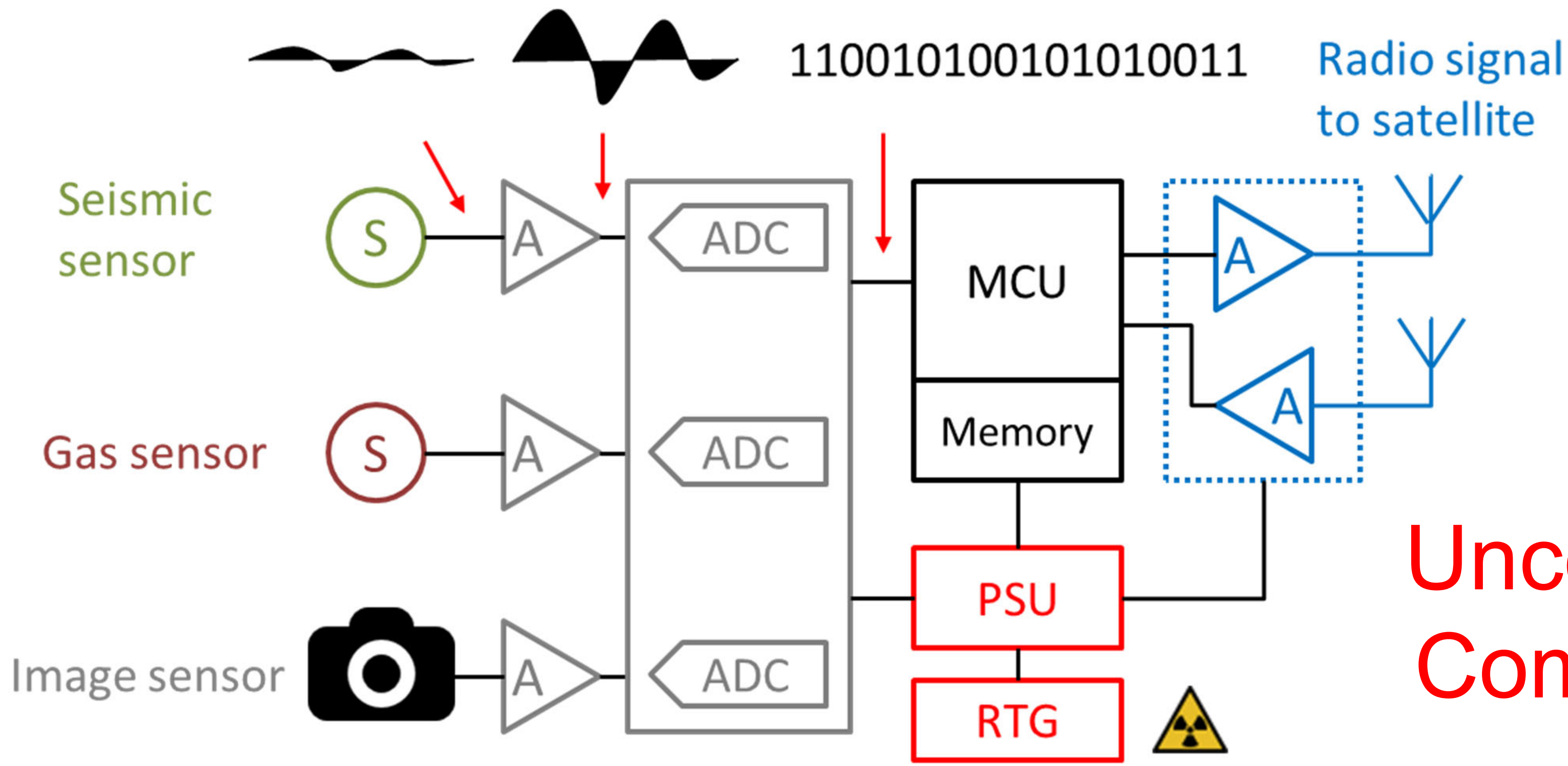
www.WorkingonVenus.se

Prof. Christer Fuglesang

European Astronaut



Working on Venus – Lander Block Diagram



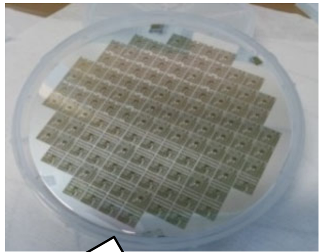
Uncooled!
Compact!

Cleanroom for IC and Device Fabrication

Electrum Laboratory 1300 m^2
ISO 9001 certified / controlled processes and calibrated characterization tools
100 – 200 mm wafers

Silicon Technology
Silicon - IC
Silicon - Microsystems

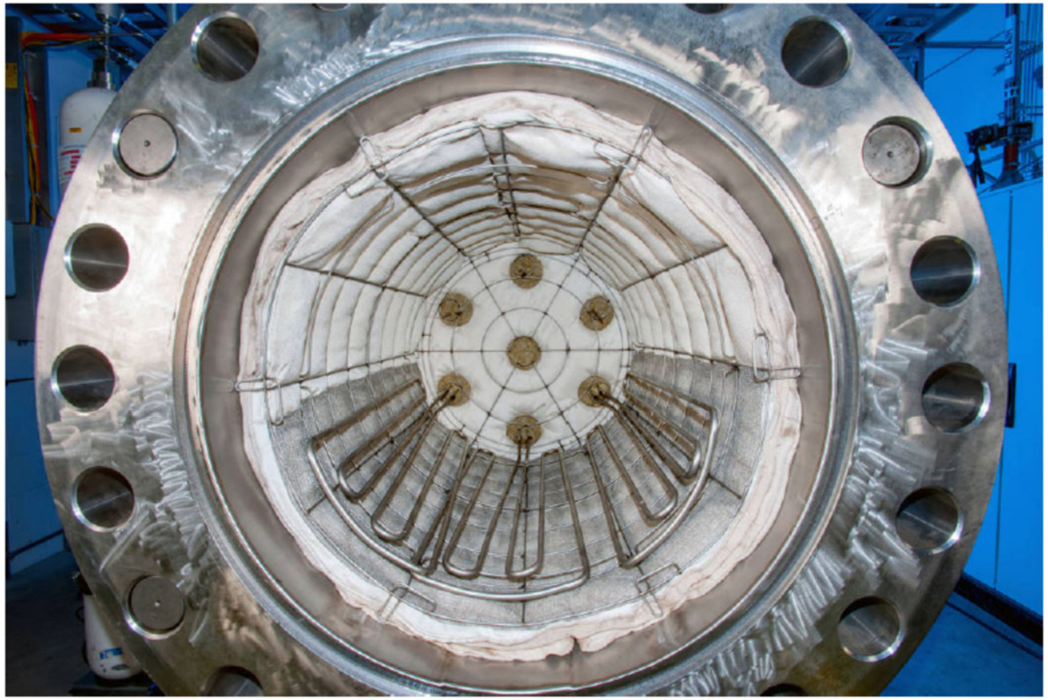
Compound Semiconductors
SiC – Electronics, 100 mm
InP - Opto / electronics
GaAs - Opto / electronics



Phosphine Inside!

Part of myfab - the Swedish national research infrastructure for micro- and nanofabrication

NASA Glenn test chamber mimics Venus' harsh conditions (”Hell on Earth”)



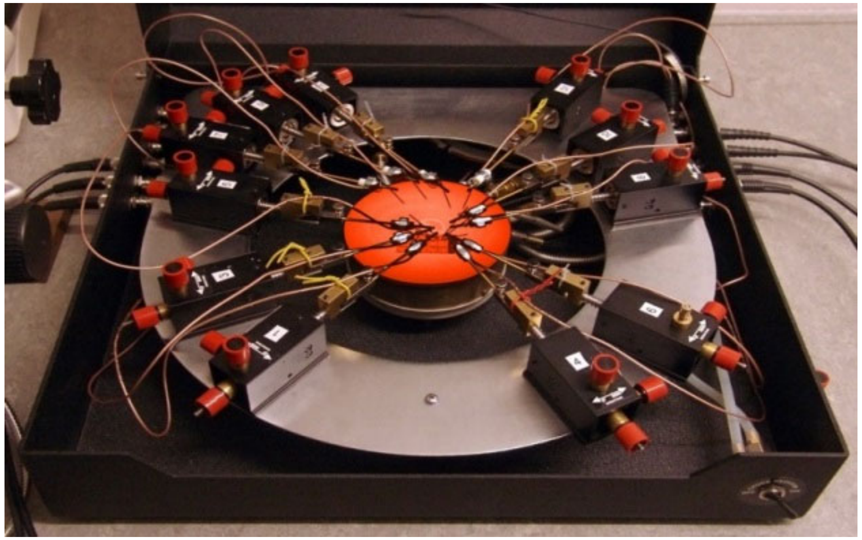
NASA Glenn aerospace engineer Rodger Dyson shows one of the 100-pound bolts that will secure the lid of the new extreme environments test chamber.

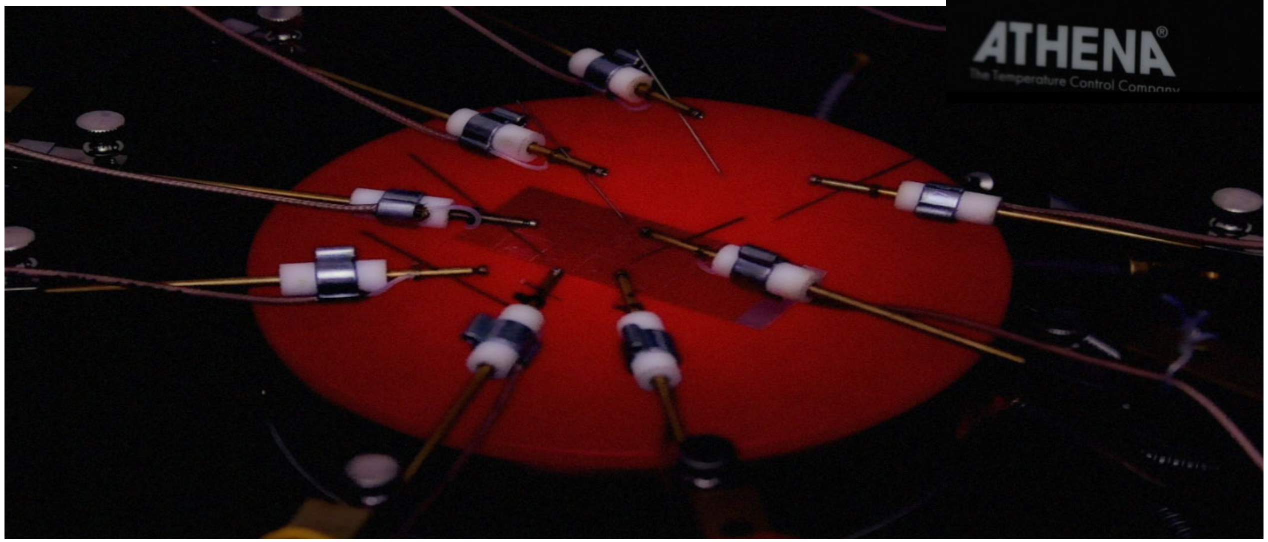
http://www.cleveland.com/science/index.ssf/2012/06/new_test_chamber_at_clevelands.html
http://www.wired.com/2012/01/nasa-venus-chamber/

Testing facilities for electrical characterization

On wafer probing up to 620 °C

Parameter analyzer for DC characteristics
Digital oscilloscope/FFT for AC characteristics

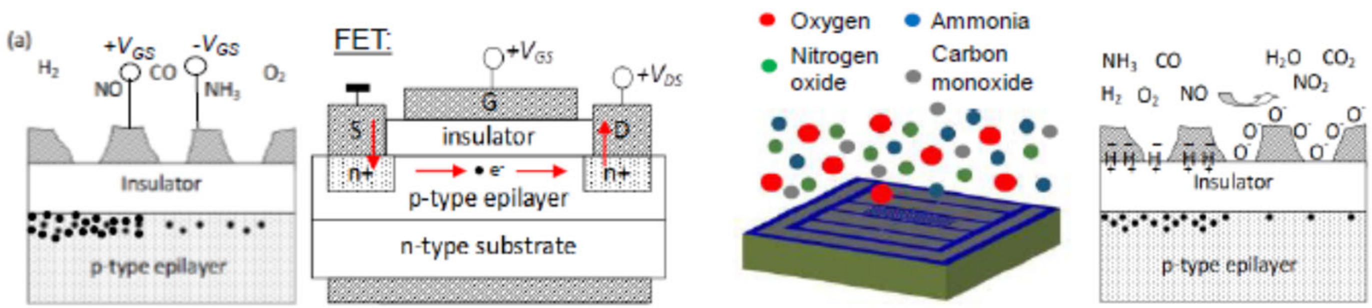




Field Effect Transistor Gas Sensors

(High-temperature operation, 500 °C)

(a)

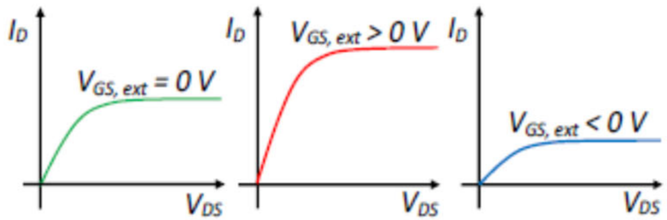


Each sensor chip contains at least one field effect transistor (FET)

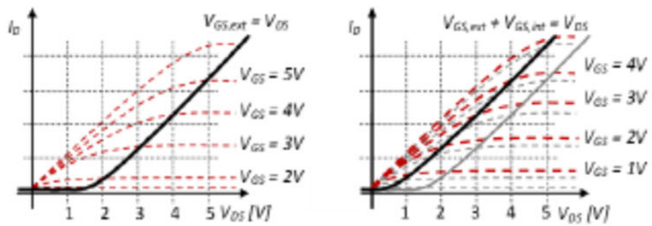
Certain gas species change the gate voltage (by $V_{GS,int}$) when adsorbing on the gate, altering the I/V-characteristics

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

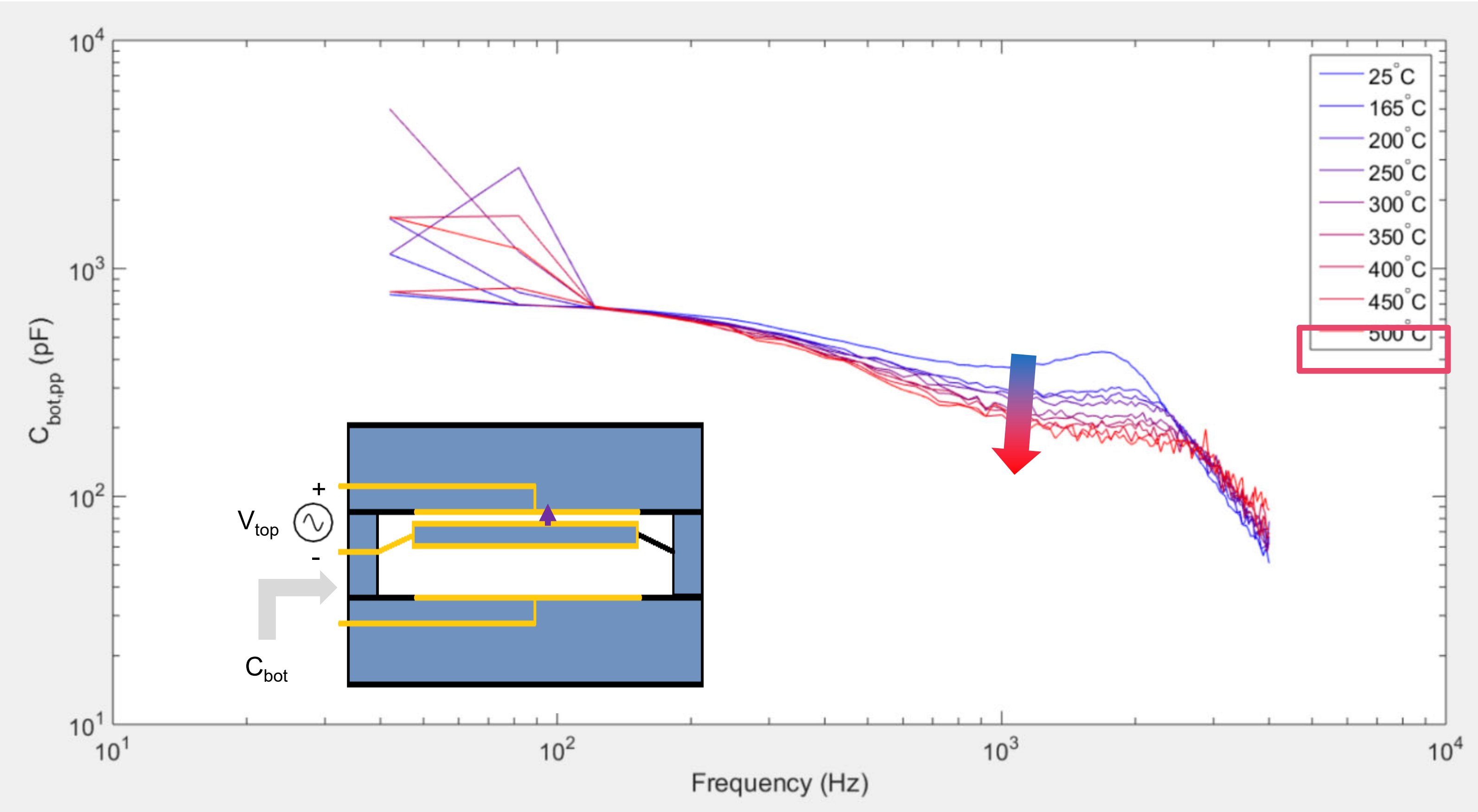
High-temperature operation requires: 1) Reliable metallization/ Ohmic contacts, 2) Gate material stability, 3) Good high-temperature gas sensitivity

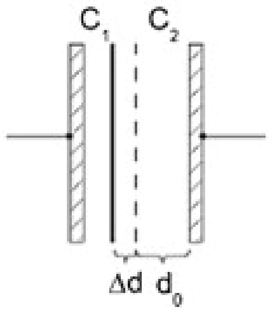


(c)

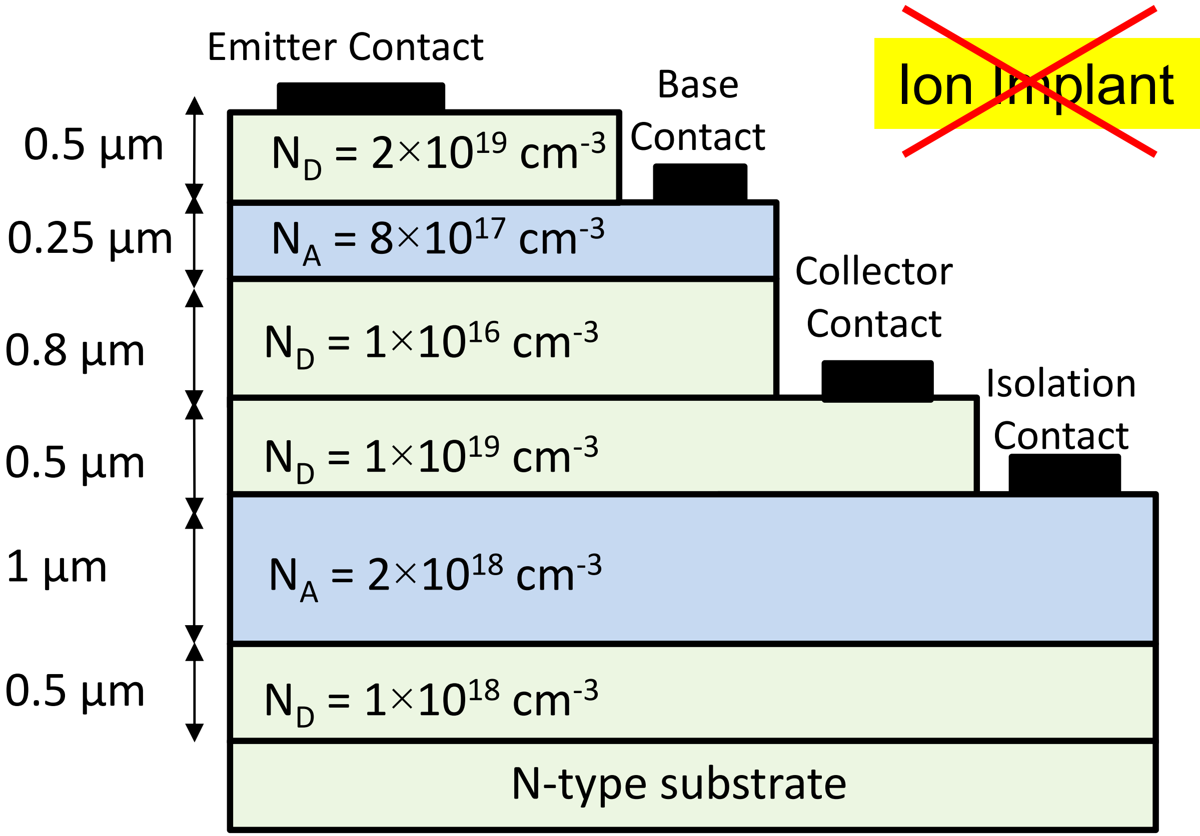


Accelerometer – Frequency response



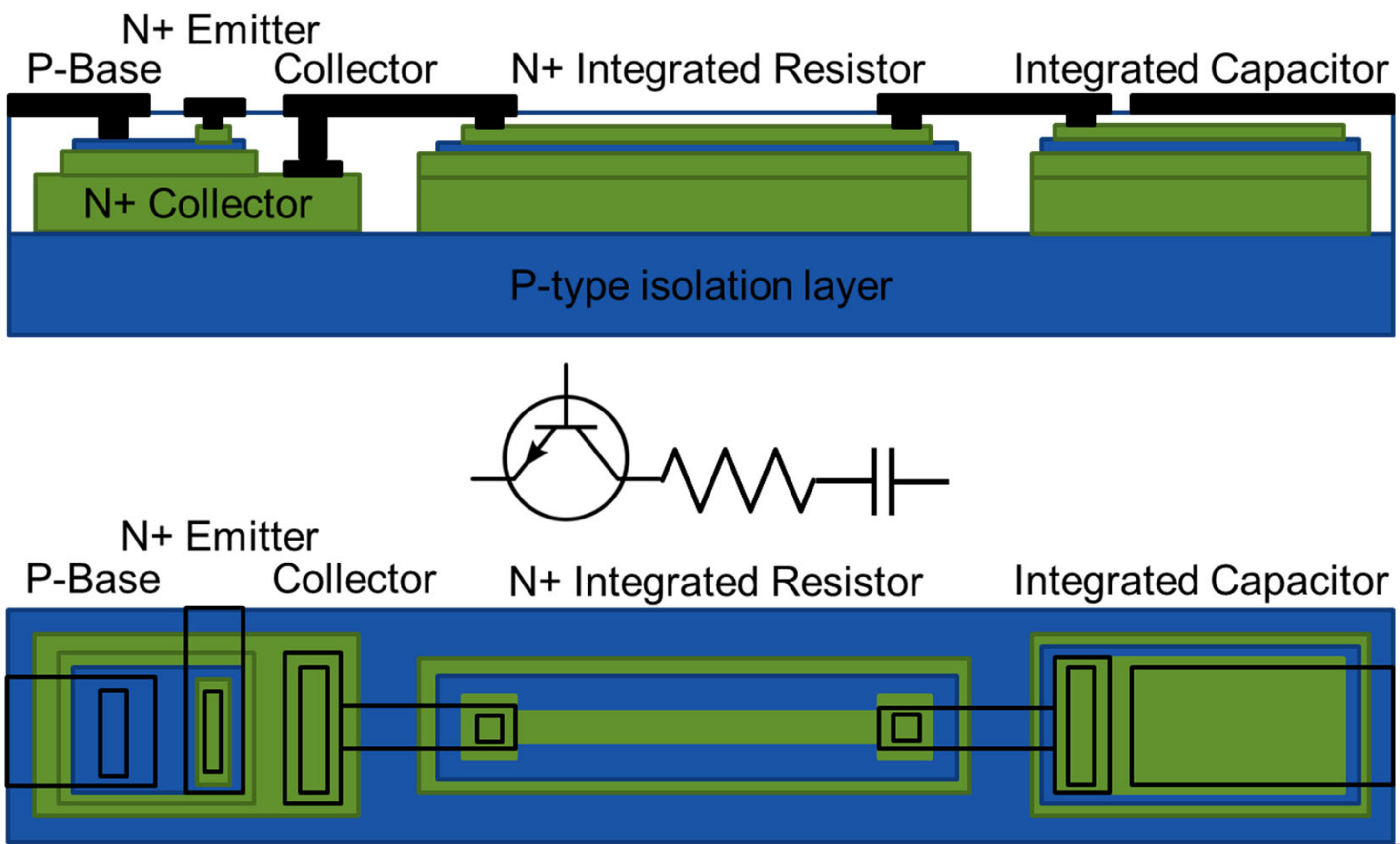


Bipolar Process Technology

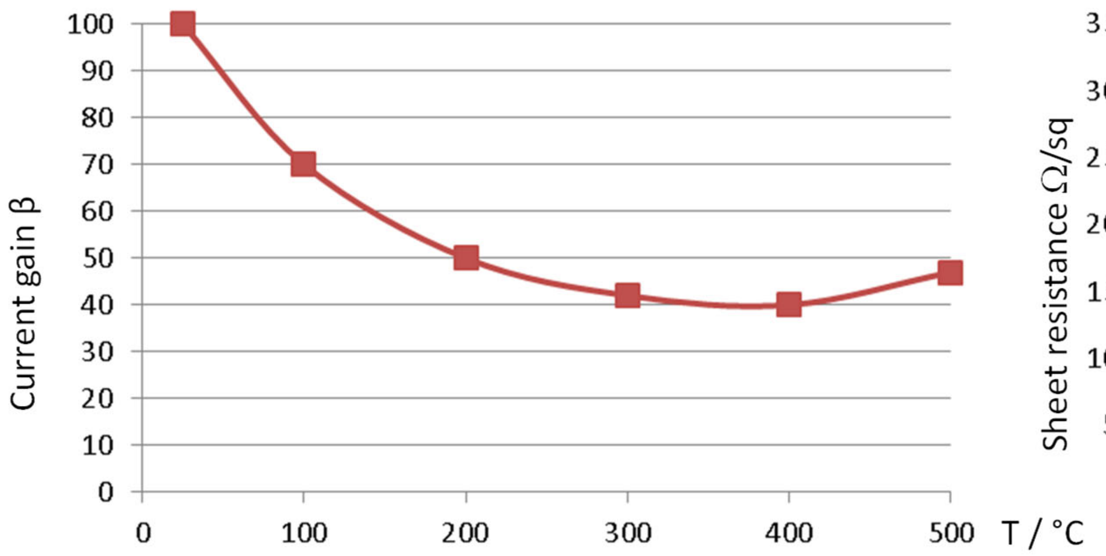


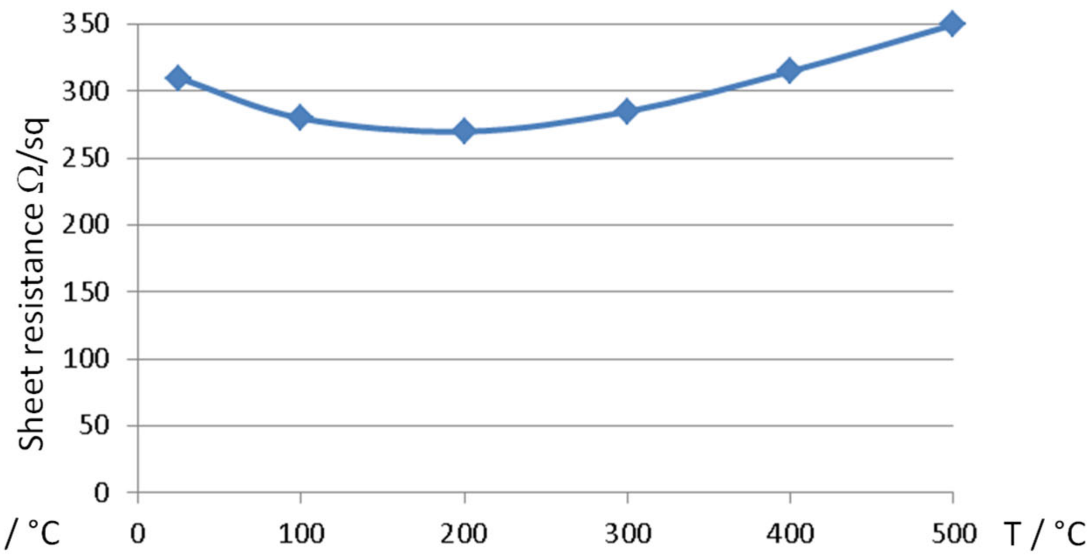
- SiC Dry Etching
  - Reactive Ion Etching
- Sacrificial Oxidation
  - 1100 °C, 3 hours, in O_2
- Passivation Oxidation
  - 1250 °C, 3 hours, in N_2O
- Contact Salicide
  - Ni, 600 °C, 1 min
- N-type Ohmic Contact
  - 950 °C, 1 min
- P-type Ohmic Contact
  - Ti/Al deposition, patterning and etching
  - > 900 °C, 1 min
- TiW/Al Metal Interconnects

Bipolar Process for T, R and C

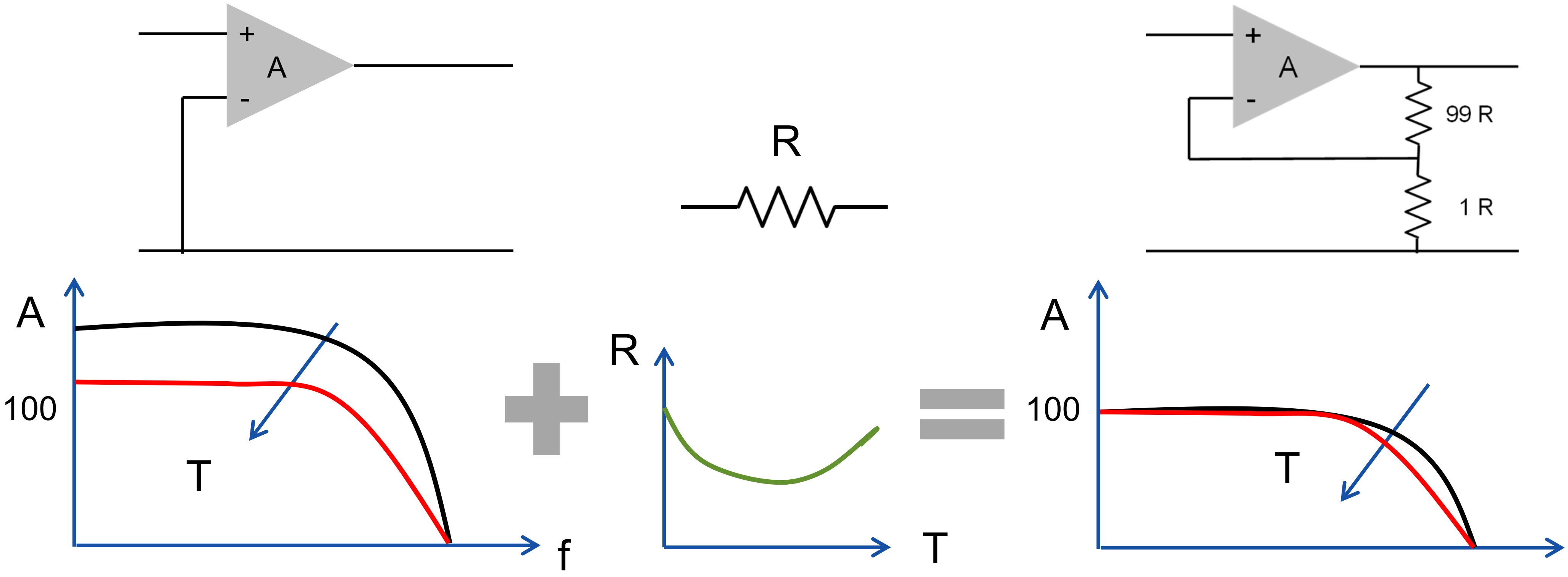


Current gain and sheet resistance



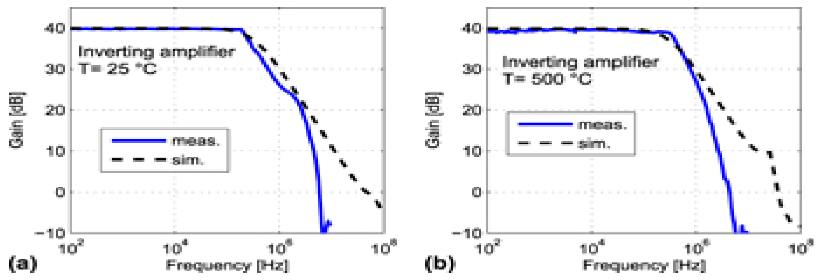


Negative Feedback for Analog circuits

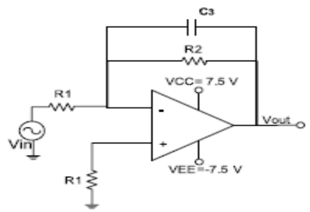


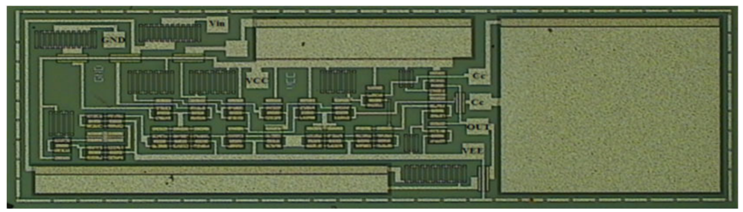
SiC Amplifiers

Material aspects of wide temperature range amplifier design in SiC bipolar technologies
R. Hedayati et al. J. Materials Research 31 (2016) 2928 – 2935 DOI: 10.1557/jmr.2016.321

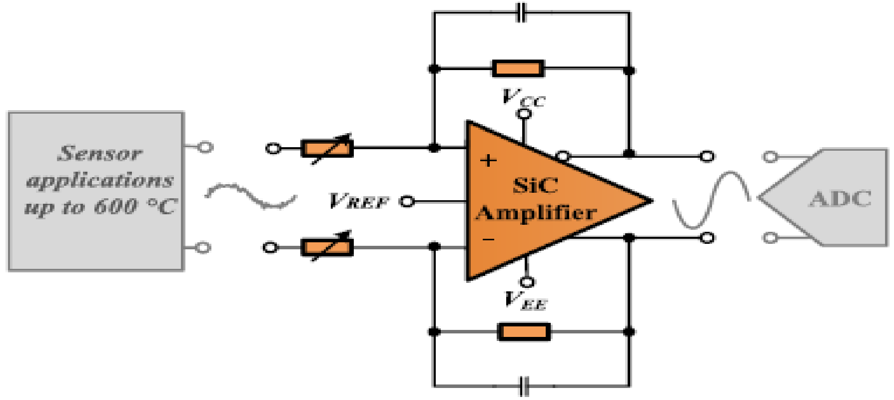


A monolithic, 500 °C operational amplifier in 4H-SiC bipolar technology
R. Hedayati et al. IEEE Electron Dev. Lett. 35 (2014) 693-695 DOI: 10.1109/LED.2014.2322335



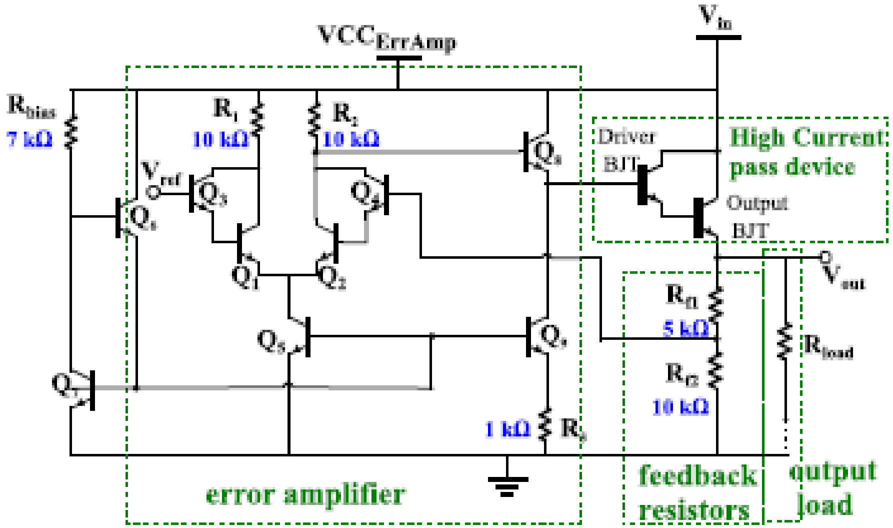


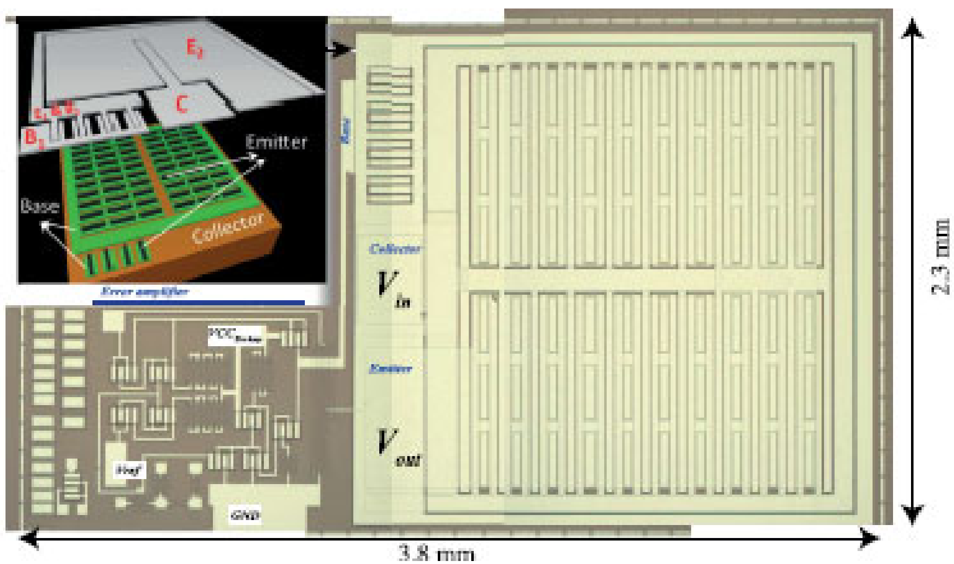
Silicon carbide fully differential amplifier characterized up to 500 °C
Y. Tian et al. IEEE Trans. Electron Dev. 63 (2016) 2242 – 2247 DOI: 10.1109/TED.2016.2549062



2 A Linear Voltage Regulator

500 °C, High Current Linear Voltage Regulator in 4H-SiC BJT Technology, S. Kargarrazi et al., IEEE Electron Device Letters, vol. 39, p. 548, 2018. DOI: 10.1109/LED.2018.2805229



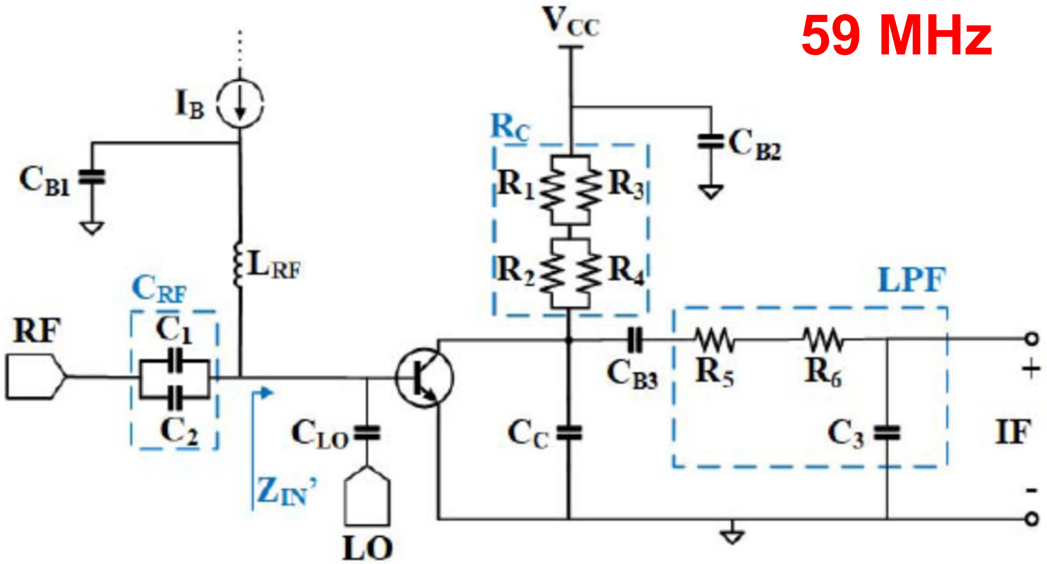


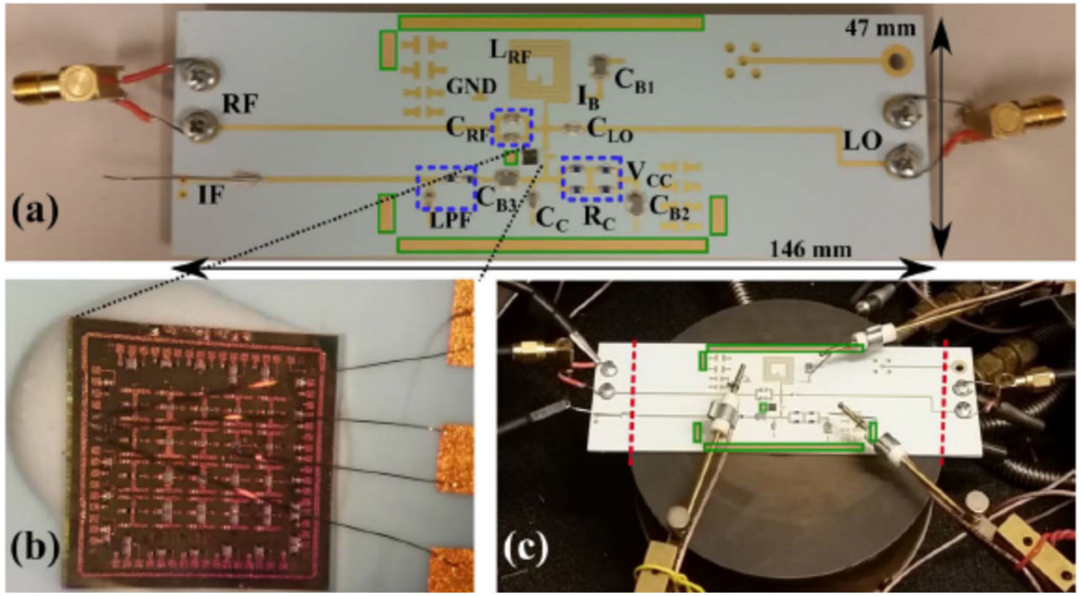
SiC HT Radio Circuits – A challenge to measure

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

A 500 °C Active Down-Conversion Mixer in Silicon Carbide Bipolar Technology,
M. W. Hussain et al., IEEE Electron Device Letters, Vol. 39, p. 855, 2018.
DOI: 10.1109/LED.2018.2829628

59 MHz

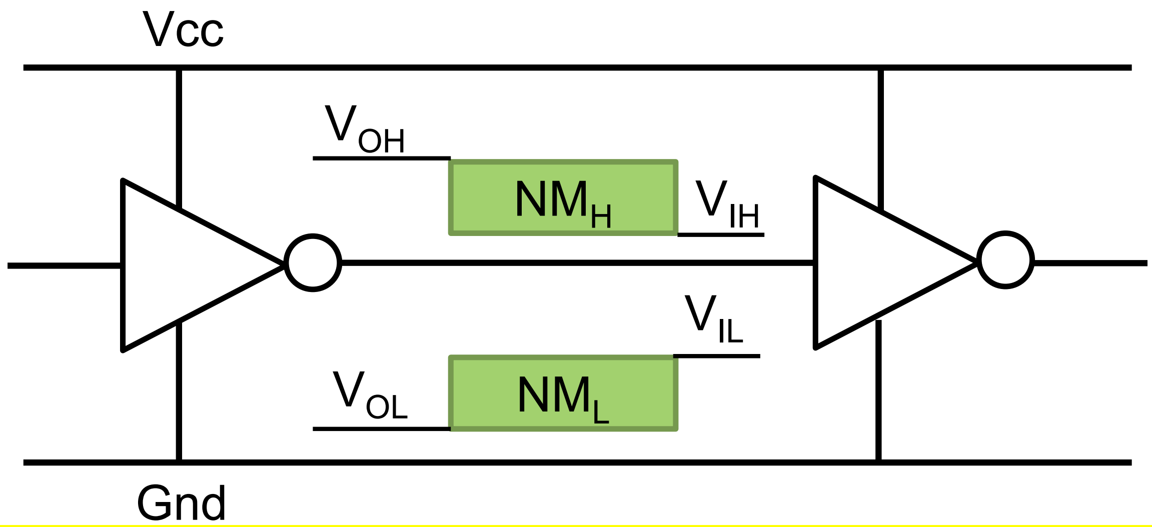




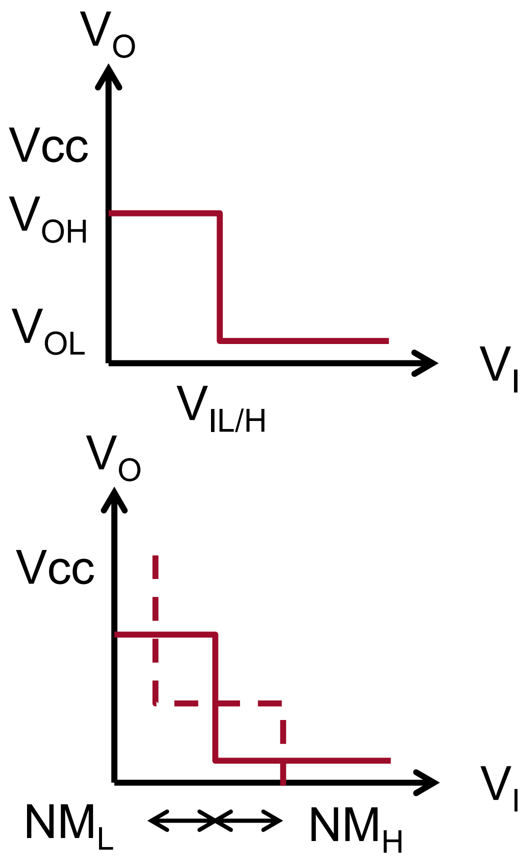
An Intermediate Frequency Amplifier for High-Temperature Applications,
M. W. Hussain et al., IEEE Trans. Electron Devices, vol. 65, p. 1411, 2018.
DOI: 10.1109/TED.2018.2804392 (55 MHz, 250 °C)

Noise Margins for Digital circuits

Needs to be measured at every temperature



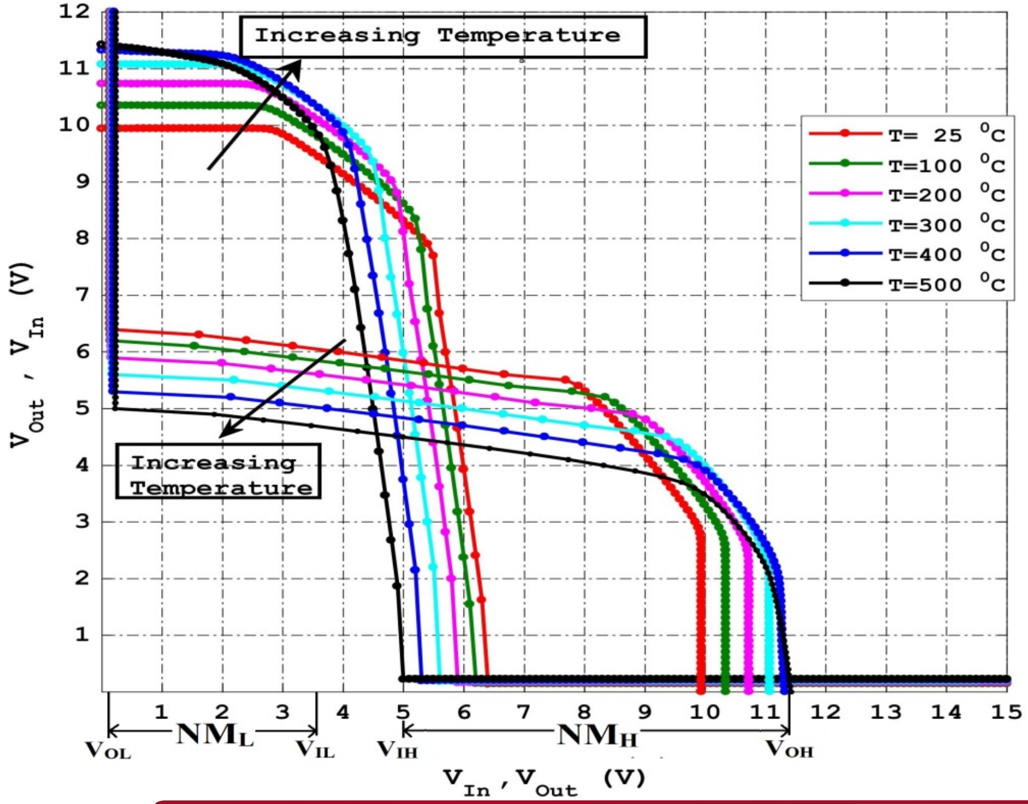
Electrical Characterization of Integrated 2-input TTL NAND Gate at Elevated Temperature, Fabricated in Bipolar SiC-Technology
M. Shakir et al. ICSCRM 2017



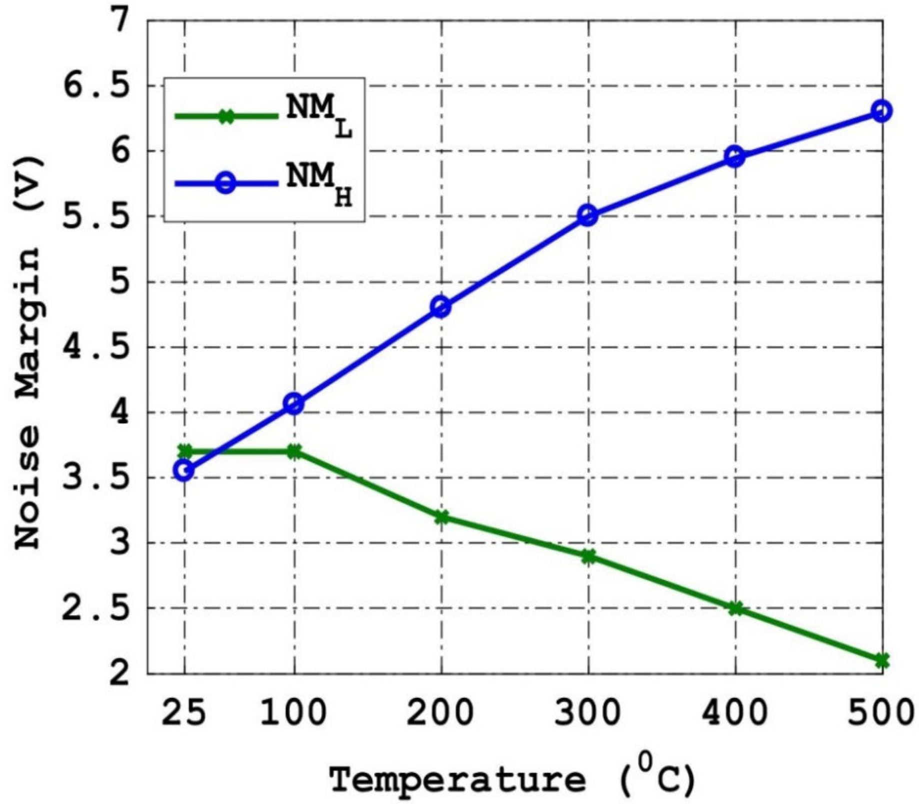
2-input NAND Gate DC-Response at 15 V

Now also 600 °C operation

VTC vs T

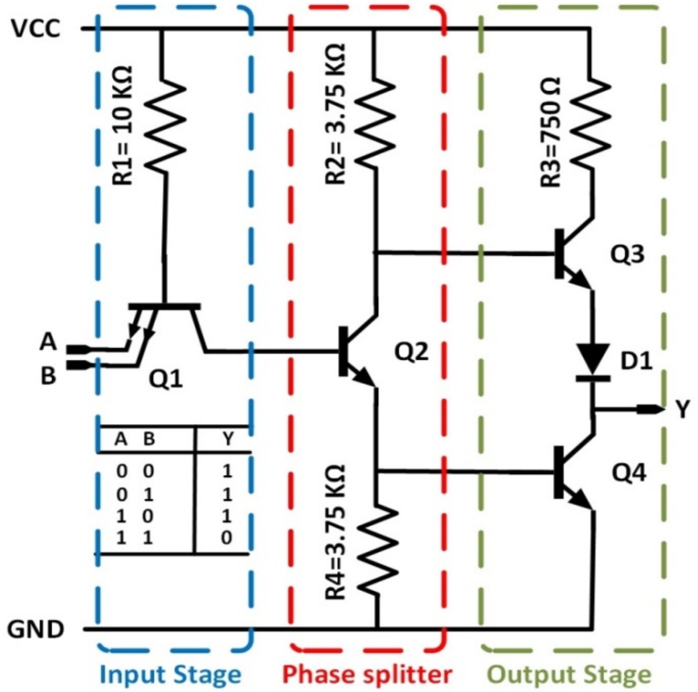


NM vs T



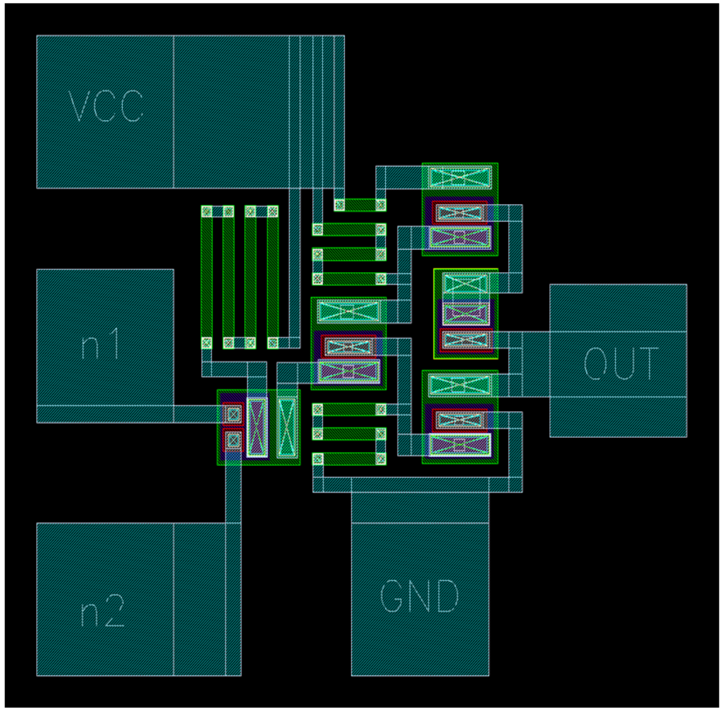
2-input TTL NAND Gate Layout and Micrograph

Schematic

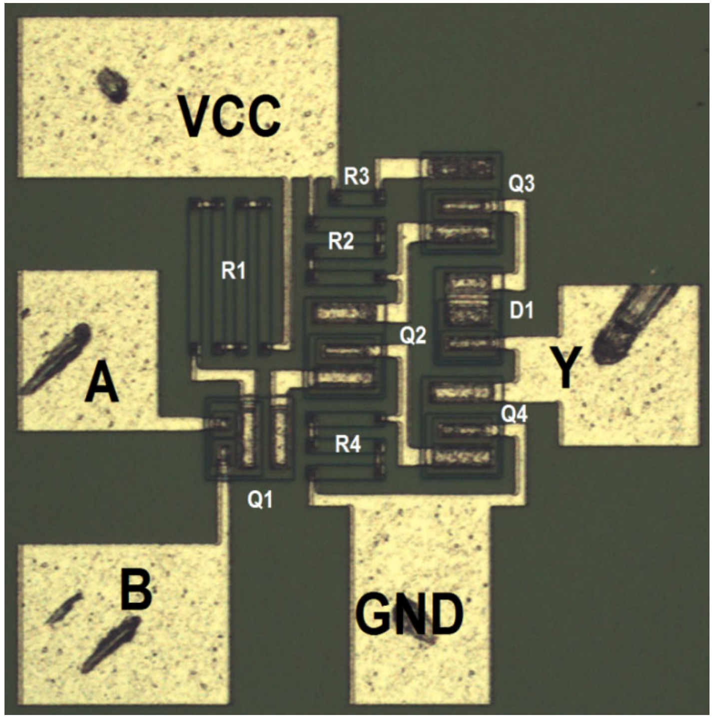


A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

Layout



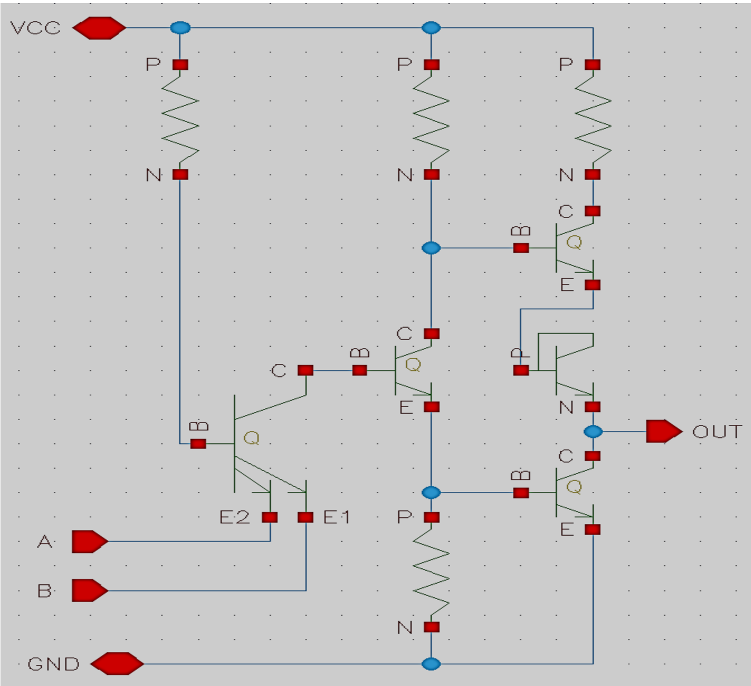
Micrograph

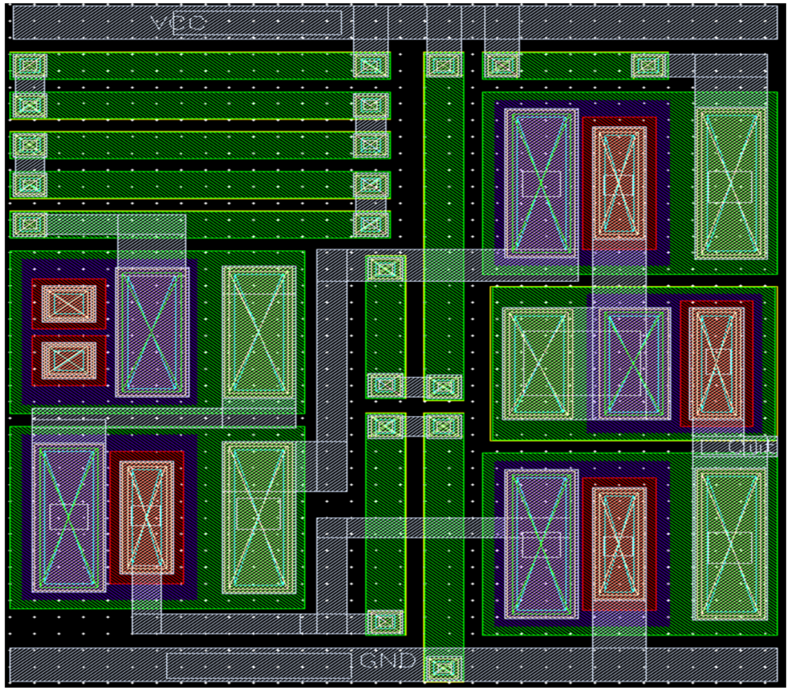


Process Design Kit for TTL gate library

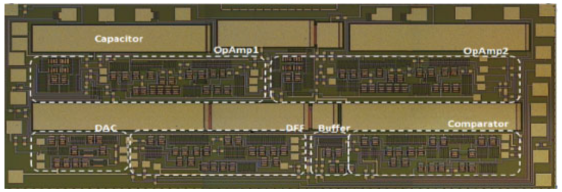
LVS - Layout vs Schematic
DRC / Design Rule Check
Hierarchical gate library

Towards Silicon Carbide VLSI Circuits for Extreme Environment Applications, M. Shakir et al. Electronics 2019 8 (2019) 496
DOI:10.3390/electronics8050496

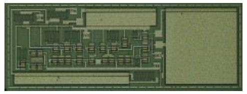




Next steps

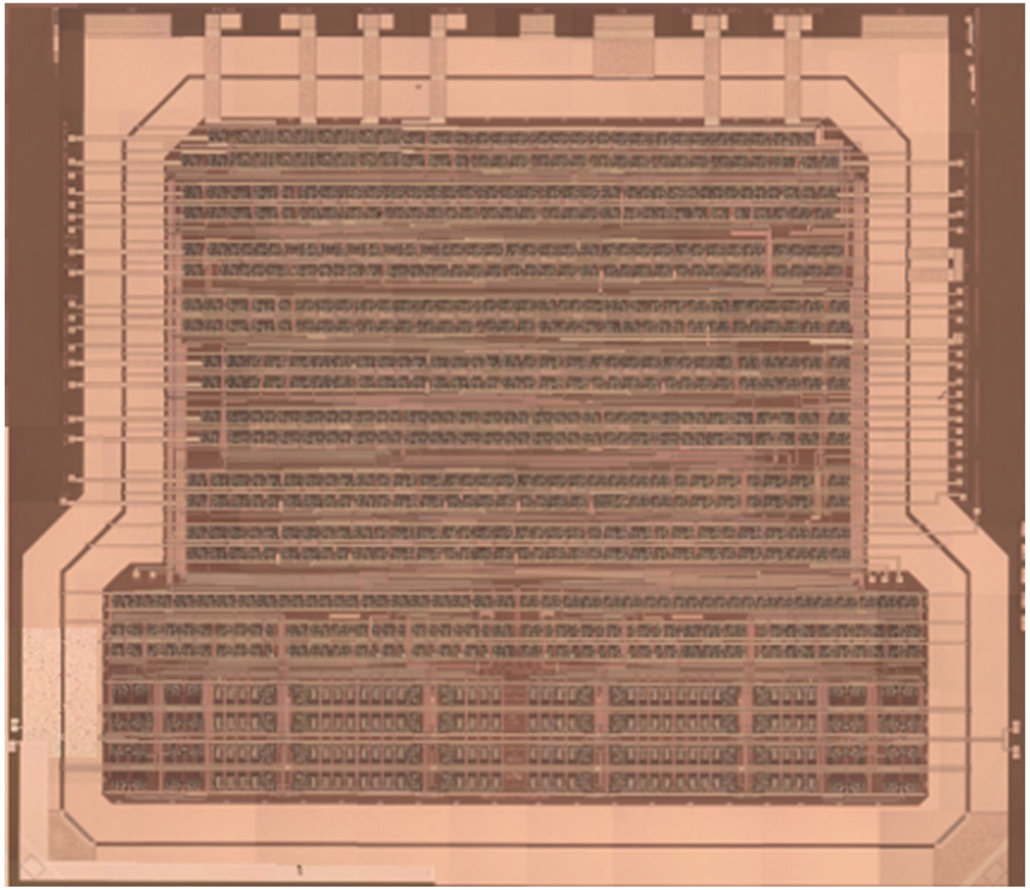


ADC 100 transistors



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

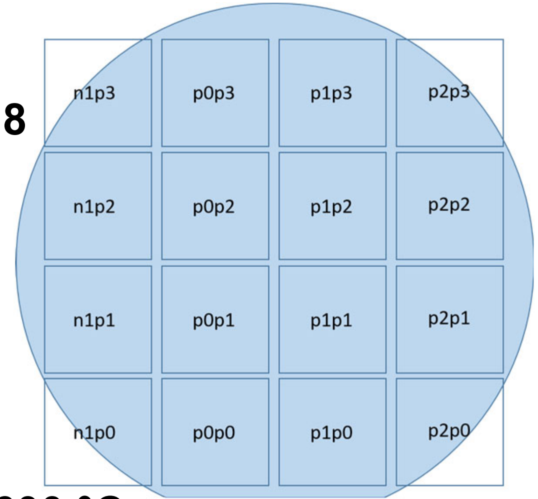
LVS and DRC

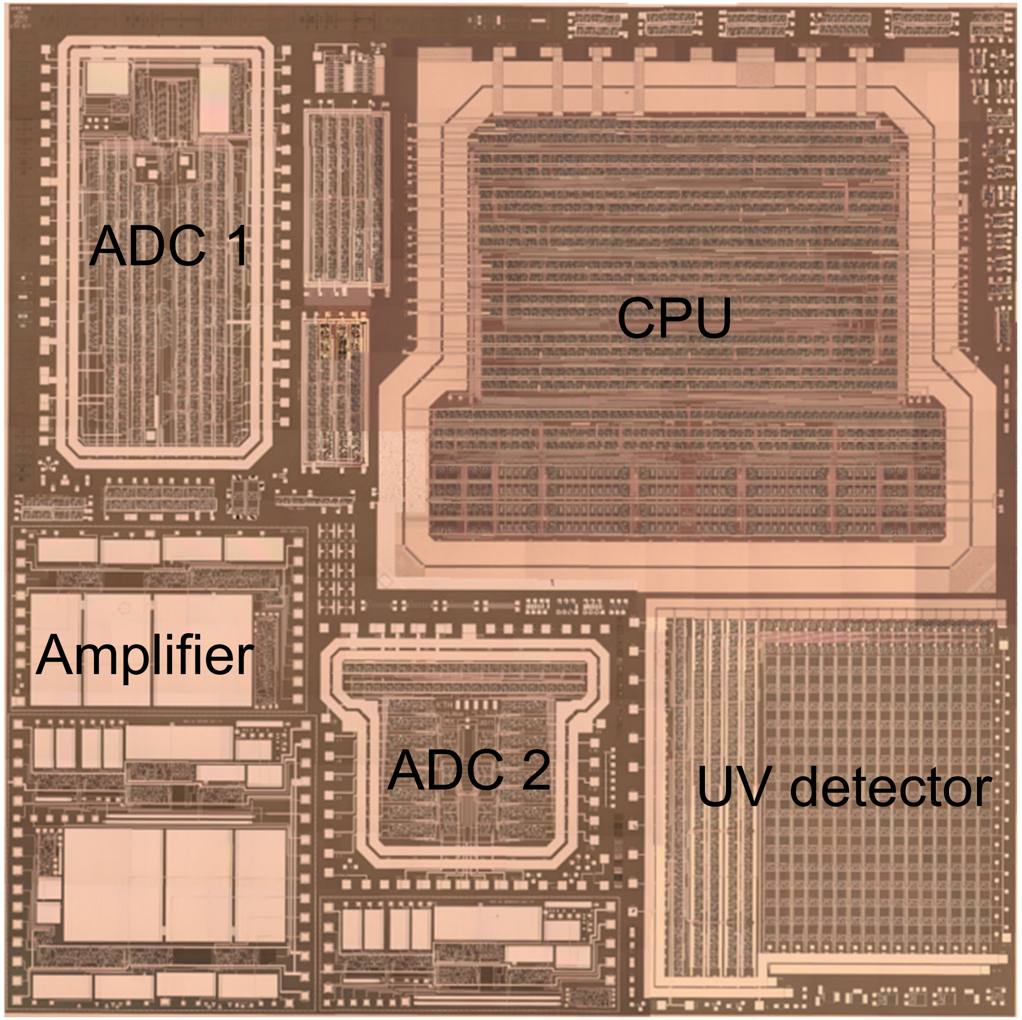
Simulated in Spice

Parts characterized up to 600 °C

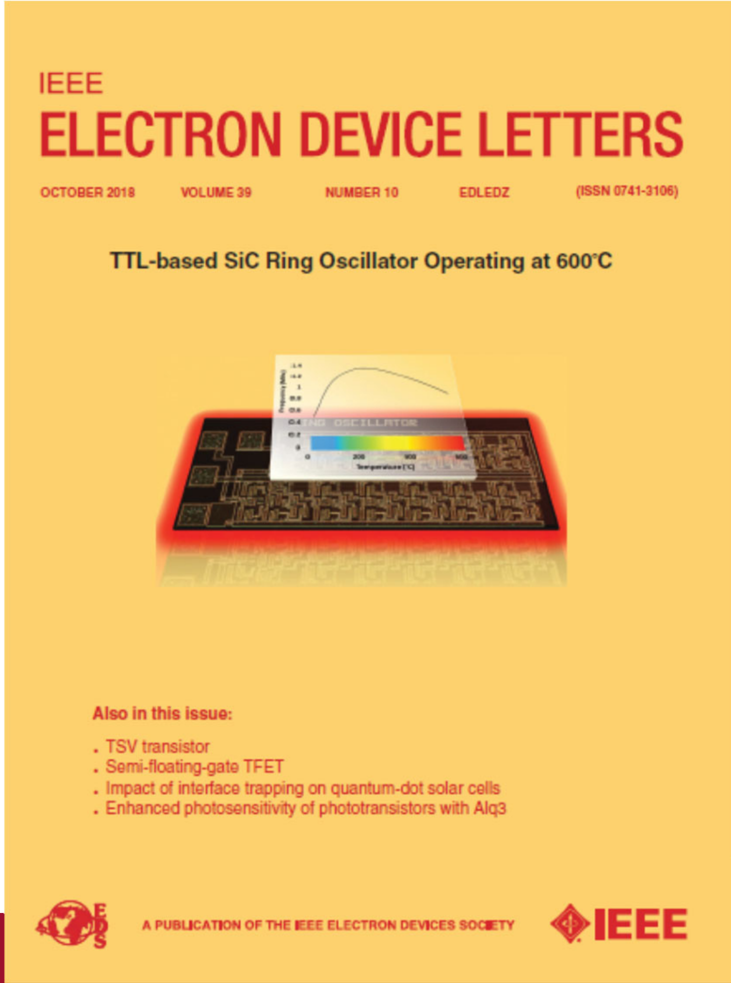
Test chip also contains ADCs,

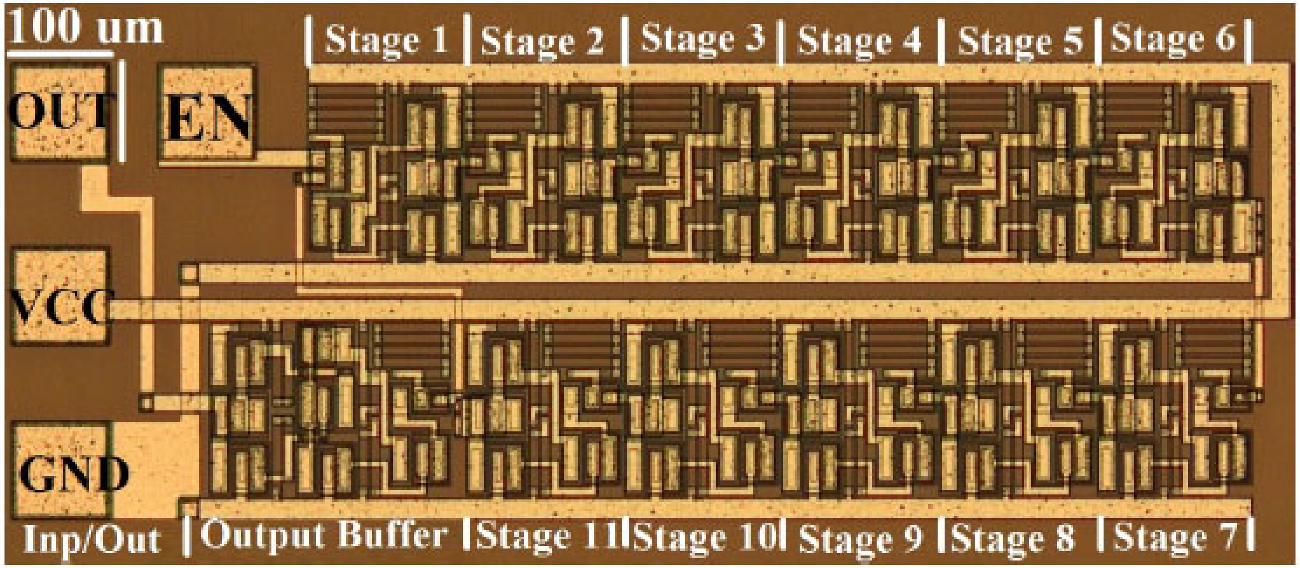
Amplifiers and UV pixel detector





A 600 °C TTL-based 11-stage Ring Oscillator in Bipolar Silicon Carbide Technology

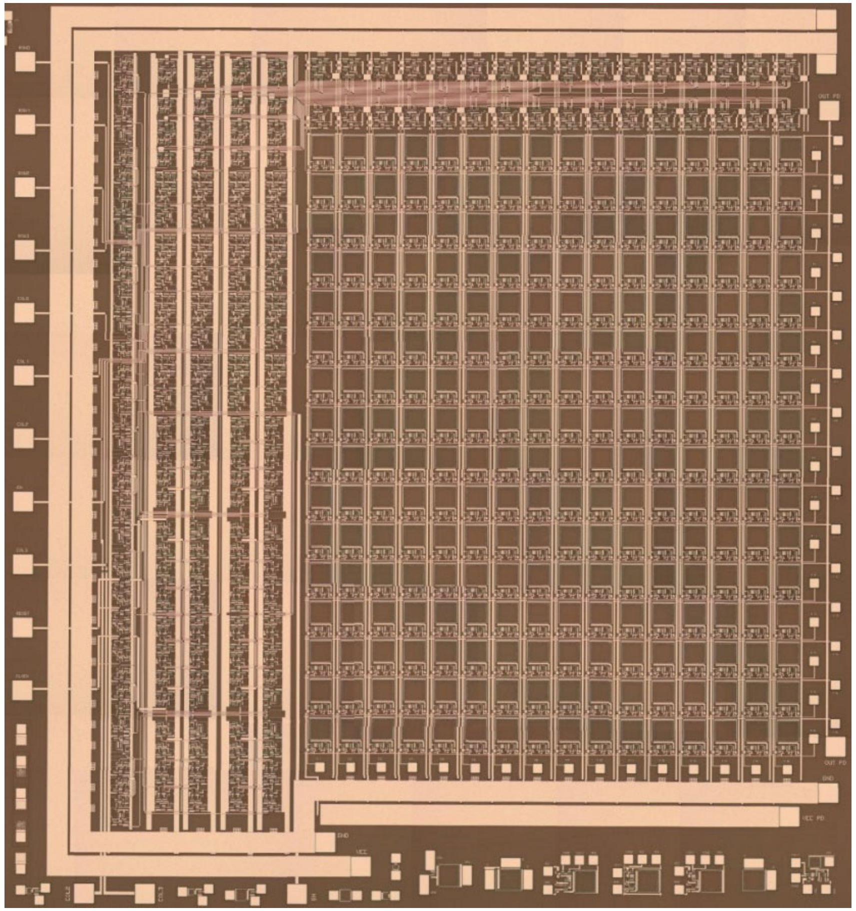




120 devices

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

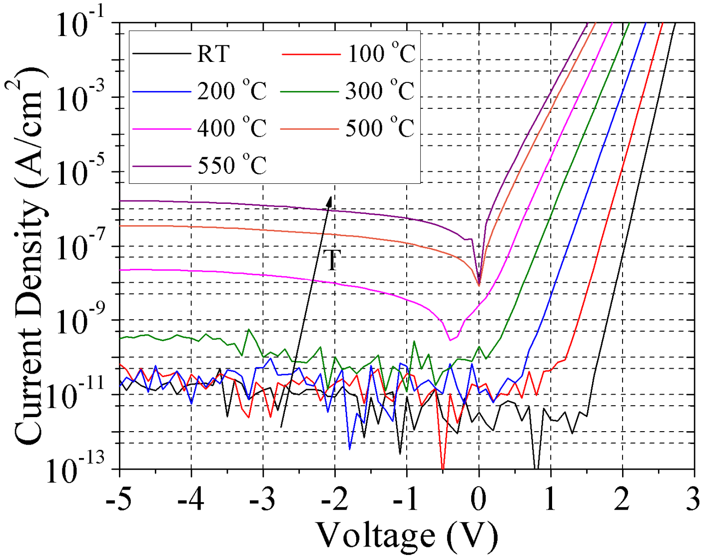
Fabricated Image Sensor

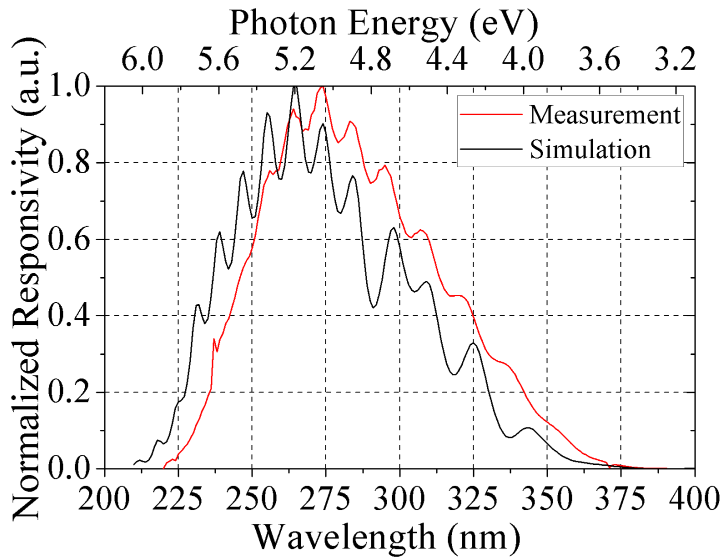


- Schematic and Layout of the digital circuits are from collaborator contributed TTL PDK
- Two 4-to-16 decoders
- One 8-bit counter
- 16x16 pixels
- 1959 transistors
- 68.2 mm^2
- Dynamic mode - 7 I/Os
- Static mode – 13 I/Os

Leakage (Dark) Current and optical response of the SiC Photodiodes

40000 µm²



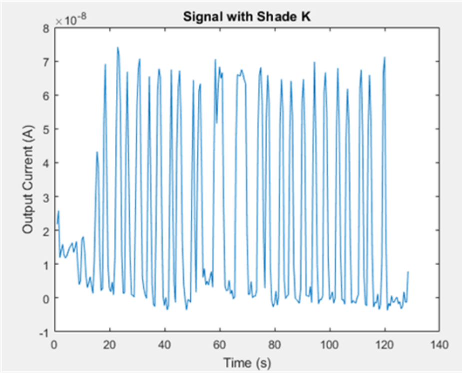


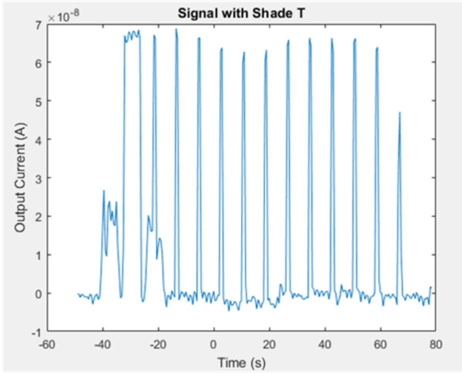
- Leakage current density increases at higher temperatures, but it is still low (~1 μA/cm²) even at 550 °C.
- Leakage current density is higher for smaller devices because of surface recombination effect.

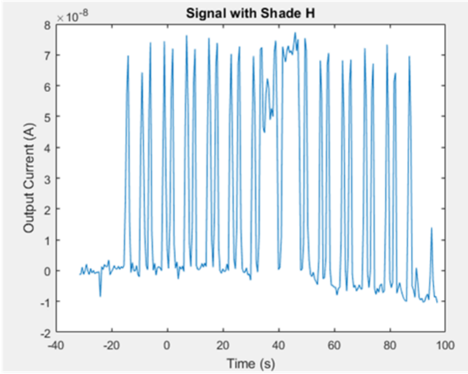
Pixel detector in operation

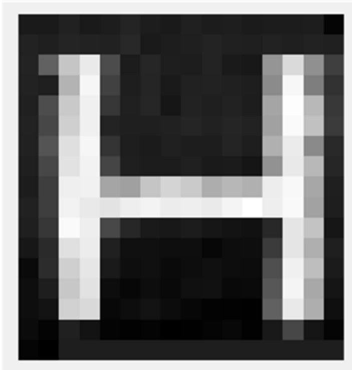
RT

K T H









Ferroelectrics for NVRAM (below 660 °C)

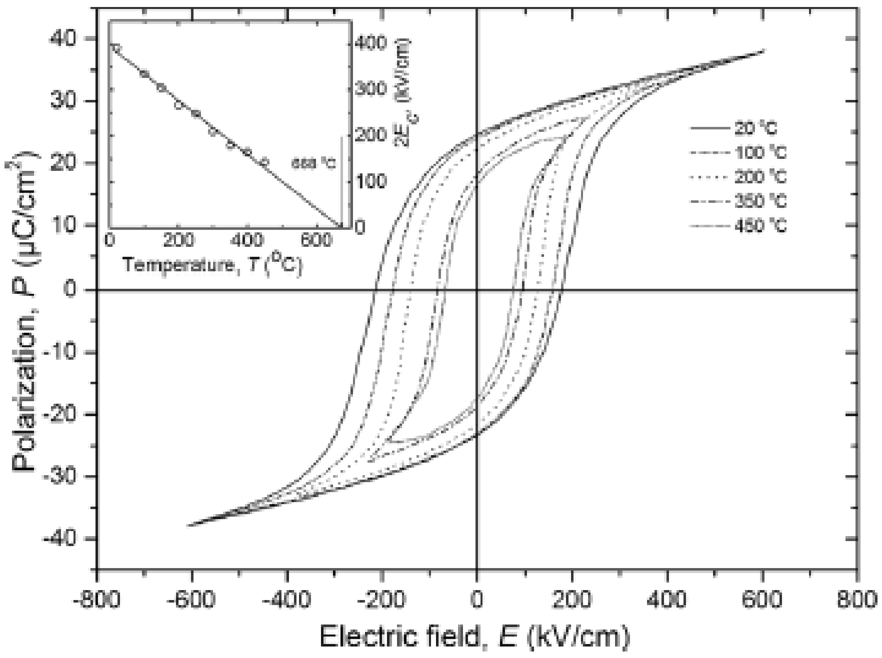
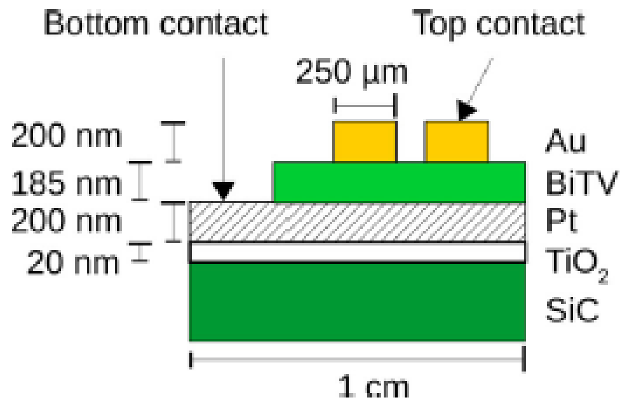


Fig. 9. Hysteresis loop at several different temperatures. Both the coercive field and polarization decrease with increasing temperature. The inset shows the coercive field versus temperature.



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

Acknowledgements

Our sponsors for 25 years of SiC research: Swedish Research Council (VR), Swedish Foundation for Strategic Research (SSF), Swedish Energy Agency, Vinnova, STandUP for Energy

Knut and Alice Wallenberg Foundation

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