SiC semiconductors in space applications: trends, challenges and opportunities

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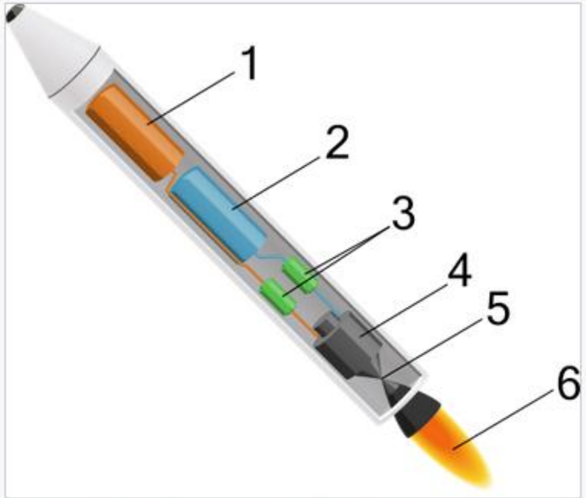
Bodo‘s Wide Bandgap Event 2025

Making WBG Designs Happen

SiC

Liquid-propellant rockets

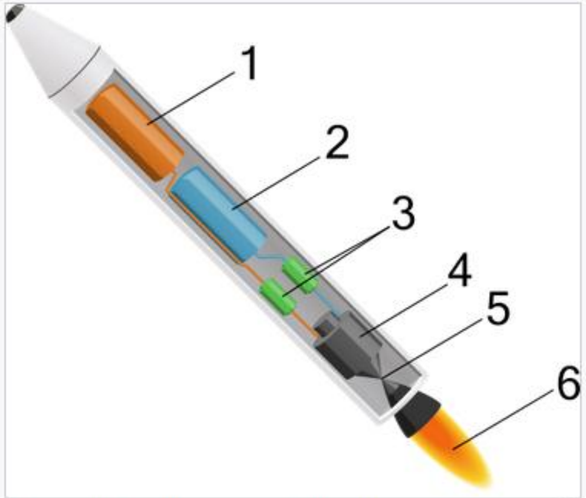


A simplified diagram of a liquid-propellant rocket.

1. Liquid rocket fuel.
2. Oxidizer.
3. Pumps carry the fuel and oxidizer.
4. The combustion chamber mixes and burns the two liquids.
5. Combustion product gasses enter the nozzle through a throat.
6. Exhaust exits the rocket.

Source: https://en.wikipedia.org/wiki/Liquid-propellant_rocket

Liquid-propellant rockets



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Different types depending on…

- Propellant (cryogenic, semi-cryogenic, non-cryogenic)
- Injectors (shower head, self-impinging doublet…)
- Engine cycle (pressure-fed, gas-generator, electric-pump fed…)

TREND: Electric-pump fed cycle

An electric motor (BLDC or PMSM) drives the pump. The motor is powered by a battery pack (that is charged on the ground).

Pro: simple implementation and reduced complexity, **improved accuracy of pressure and mass flow control.**

Contra: extra mass added by the battery pack.

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Power Electronics in Space

Harsh environment

- Temperature extremes and cycles, low or zero pressure, vacuum, partial discharge, radiation, outgassing, pyro-shock, vibration/shock, UV degradation, particle/gas contamination.

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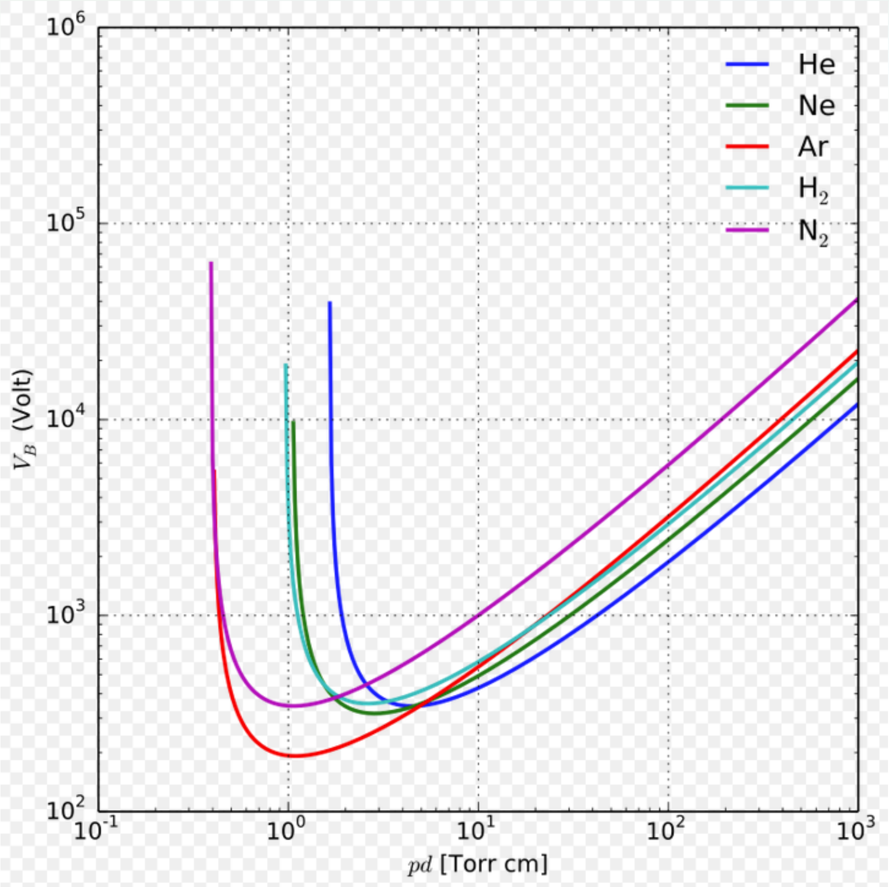
- Above 327 V in the air there is a danger of partial discharge acc. to Paschen's curves.
- Limitations of Paschen's curves: Valid for parallel plates, uniform field, w-out magnetic fields; for dc or 400 Hz only.



Source: https://en.wikipedia.org/wiki/Paschen%27s_law

Radiation aspects of SiC MOSFETs

Radiation resistance/hardness is a challenge.

- Space graded parts in general are approx. 100x more expensive and could have lead time up to 52 weeks.
- Three areas: SEE (single event effects), TID (total ionising dose), DD (displacement damage).
- **Si parts are the best** and **SiC ones are the worst** regarding SEE. The **GaN** is in between.

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- **Si parts are the best** and **SiC ones are the worst** regarding SEE. The **GaN** is in between.
- **Trick:** use automotive grade (Si/SiC) parts then do extra radiation hardness testing/qualification (e.g. protons, neutrons, heavy ions).
- Voltage, current, power **derating for space is significant** (50-80%).
- Typical 1200 V SiC MOSFET can only be used up to 240-360 V dc link!

Cryogenic operation of SiC MOSFETs

Cryogenic temperatures < 120 K (−153 °C)

- The breakdown voltage remains relatively constant.
- Rds_on increasing significantly.
- Switching performance becomes worse.
- Gate threshold voltage increases.

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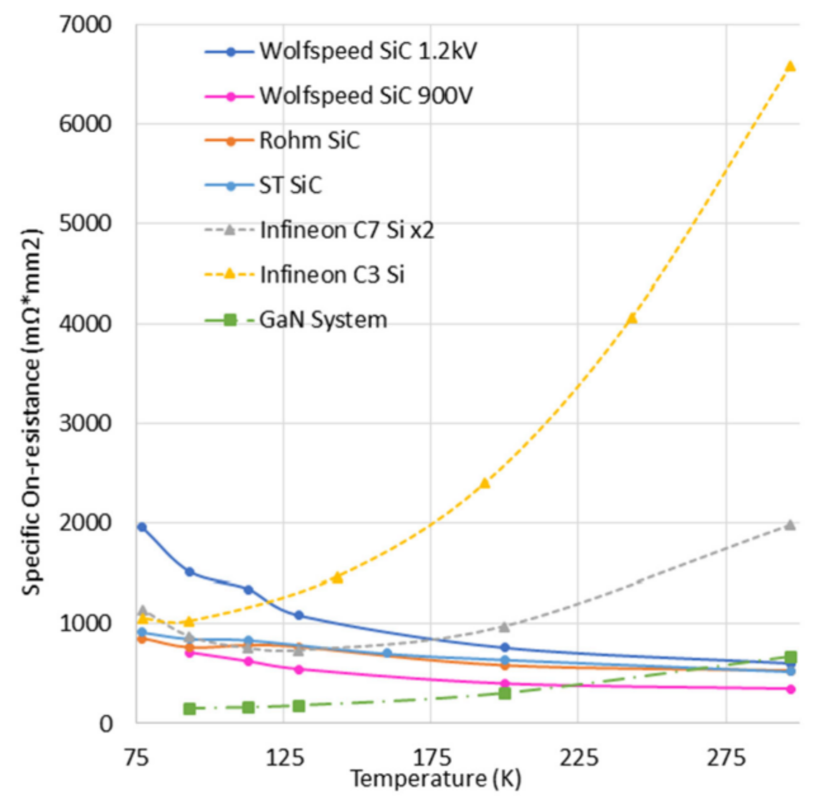
- **NOTE: 1)** gate drivers and respective isolated power supplies have problems at cryogenic temperatures too! **2)** Device packages are not suitable for cryogenics.

Specific on-state resistance versus temperature for SiC, GaN and Si devices



Source: R. Chen and F. F. Wang, "SiC and GaN Devices With Cryogenic Cooling," in IEEE Open Journal of Power Electronics, vol. 2, pp. 315-326, 2021, doi: 10.1109/OJPEL.2021.3075061

System Design Challenges

- Weight and size reduction. →High efficiency and high power density needed.
- In vacuum there is no air convection cooling. → Cryogenic cooling, 120 K (−153 °C).
- Reliability.
- Material selection (*e.g. electrolytic caps are forbidden*). → NASA list of forbidden parts.
- Radiation hardening tests are very expensive (up to 25000 € per part).
- Tin whiskers can grow on PWBs (printed wiring boards).

System countermeasures

- **Conformal coating**
- Potting
- External shielding
- Insulating substrate usage for space-grade ICs are used for preventing failure in (power) electronic devices utilized in space.

Conclusion and Outlook 1/2

- Power electronics and SiC MOSFETs for liquid-rocket engines with electric-pump fed cycle application covered.
- **Challenges:** radiation hardness of semiconductors/ICs, operating voltage limitations due to partial discharge, vacuum operation, cryogenic cooling, etc.
- **SiC is the worst material** for **radiation hardness** and **cryogenic operation.**
- Device **packages not cryogenic friendly**.
- **Trends:** rockets electrification and WBG semiconductors' usage.

Conclusion and Outlook 2/2

- The private-funded **commercial space industry is rising up**.
- **Many start-ups**, but huge investments needed. **Deep Tech!**
- **Many jobs:** power electronics HW/SW, electric machines and drives.
- **Bottleneck:** lack of **skilled workforce** and **SiC parts not yet space-ready/friendly**!

Conclusion and Outlook 2/2

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Opportunities

1) design/produce SiC MOSFETs 1200 V for short missions (e.g. several weeks) that are **hardened for proton radiation only**!

2) Improve device packages to make them cryogenic friendly.

Internet sources

- https://en.wikipedia.org/wiki/Liquid-propellant_rocket
- https://en.wikipedia.org/wiki/Paschen%27s_law
- https://en.wikipedia.org/wiki/Cryogenics
- https://resources.pcb.cadence.com/blog/2023-challenges-for-electronic-circuits-in-space-applications
- C. Leonard, Challenges for Electronic Circuits in Space Applications, Analog Devices, 2017, https://www.analog.com/en/signals/thought-leadership/challenges-for-electronic-circuits-in-space-applications.html

Literature

- J. Kozak et al, “Design, development, and tests of the e-pumps for the Reliance engine,” SPACE PROPULSION 2024, Glasgow, Scotland, 2024

- J. Wang, "Wide Bandgap-Based Power Electronics for Aerospace Applications," in IEEE Power Electronics Magazine, vol. 9, no. 3, pp. 16-25, Sept. 2022, doi: 10.1109/MPEL.2022.3197346 https://ieeexplore.ieee.org/document/9907871

- R. Chen and F. F. Wang, "SiC and GaN Devices With Cryogenic Cooling," in IEEE Open Journal of Power Electronics, vol. 2, pp. 315-326, 2021, doi: 10.1109/OJPEL.2021.3075061 https://ieeexplore.ieee.org/document/9411696

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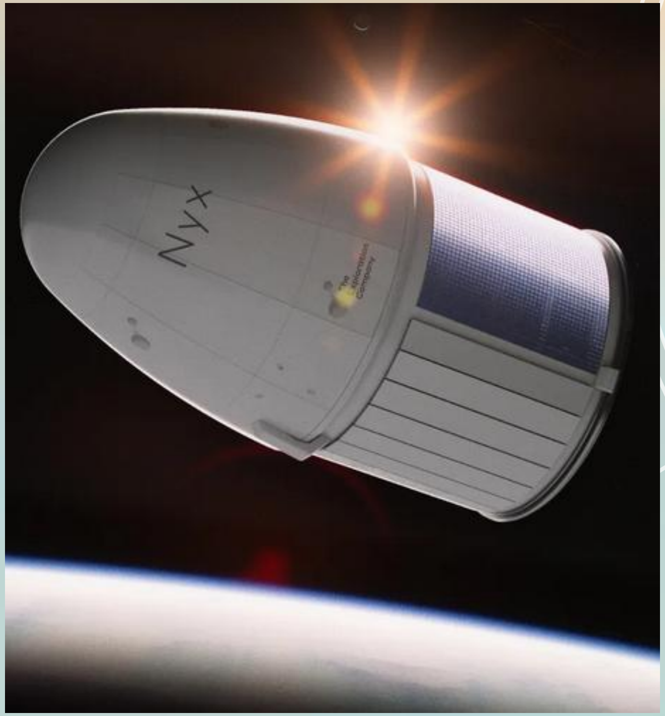

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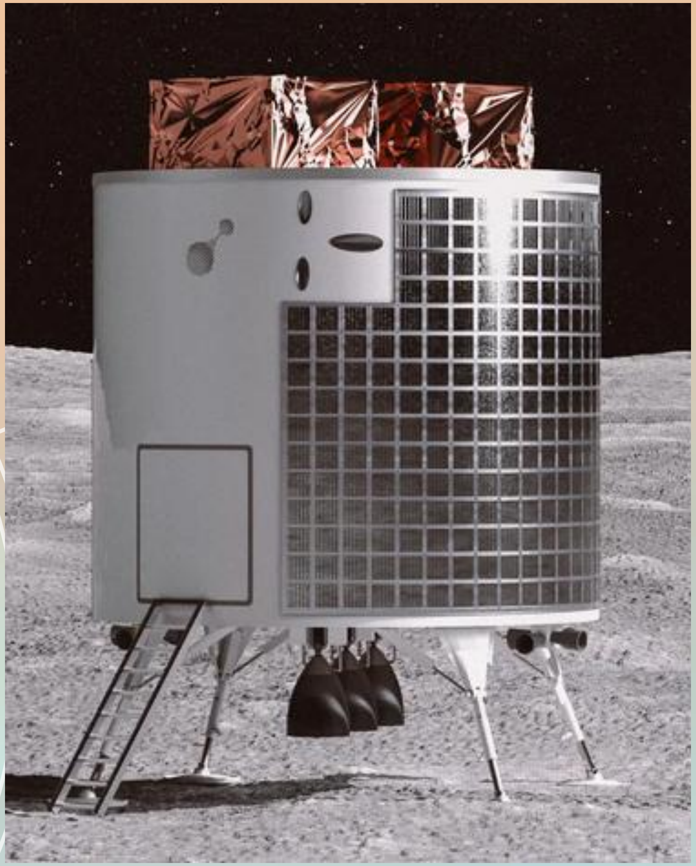
Thank you!



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