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National Aeronautics and Space Administration
Lewis Research Center

INSTRUMENTATION & CONTROL TECHNOLOGY DIVISION

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Silicon Carbide Semiconductor Technology for High Temperature and Radiation Environments

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Nuclear Propulsion
Technical Interchange Meeting

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Figure 1: This talk will describe silicon carbide technology and its potential for enabling electronic devices to function in high temperature and high radiation environments. The talk will be given by Dr. Lawrence G. Matus of the Instrumentation and Control Technology Division, NASA Lewis Research Center.

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SILICON CARBIDE

A Crystalline material with unique properties

- Abrasive
- Structural
- Refractory
- Semiconducting

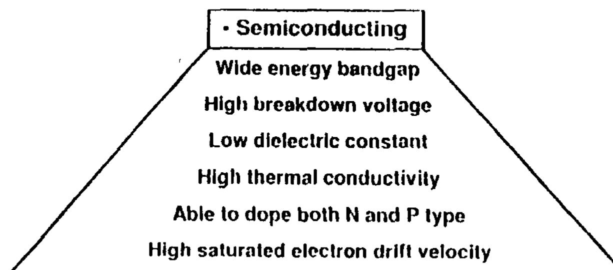

Figure 2: Silicon carbide (SiC) has many unique properties. The LeRC research program is exploring the semiconductor properties of SiC. The wide energy bandgap of SiC allows it to function at high temperatures, the high breakdown voltage and high thermal conductivity of SiC suggests that power devices and radiation hard devices will be possible, and the low dielectric constant and high saturated electron drift velocity of SiC opens the possibility of high frequency devices. SiC can be doped both n- and p-type for electronic device fabrication.

COMPARISON OF SEMICONDUCTORS

Property	Si	GaAs	GaP	3C SiC (6H SiC)	Diamond
Bandgap (eV) at 300 K	1.1	[illegible]	2.3	2.2 (2.9)	5.5
Maximum operating temperature (K)	600	760	1250	1200 (1580)	1400 (?)
Melting point (K)	1690	1510	1740	Sublimes ≥2100	Phase Change
Physical stability	Good	Fair	Fair	Excellent	Very Good
Electron mobility R.T., cm^2/V-s	1400	8500	350	1000 (600)	2200
Hole mobility R.T., cm^2/V-s	600	400	100	40	1600
Breakdown voltage E_b, 10^6 V/cm	[illegible]	[illegible]	[illegible]	[illegible]	10
Thermal conductivity σ_T, W/cm-°C	1.5	.5	.8	5	20
Sat. electron drift vel. v(sat), 10^7 cm/s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dielectric const., K	11.8	12.8	11.1	9.7	5.5

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Figure 3: The properties of the two most common polytypes of SiC (3C-SiC, also called beta or cubic SiC and 6H-SiC, also called alpha SiC) are compared with the properties of commercially available semiconductors and diamond. The commercially available semiconductors were judged unable to meet the 600°C temperature goal the LeRC program, while diamond technology was considered to be too far in the future.

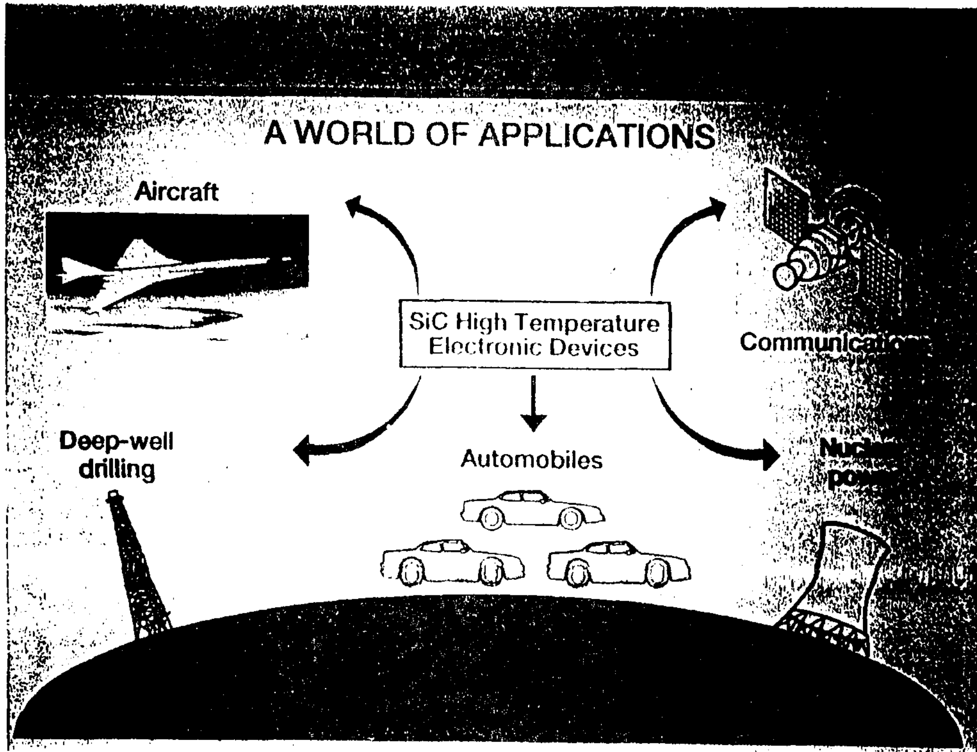

Figure 4: High temperature and/or radiation hard electronic devices fabricated from SiC would have a world of aerospace and terrestrial based applications.

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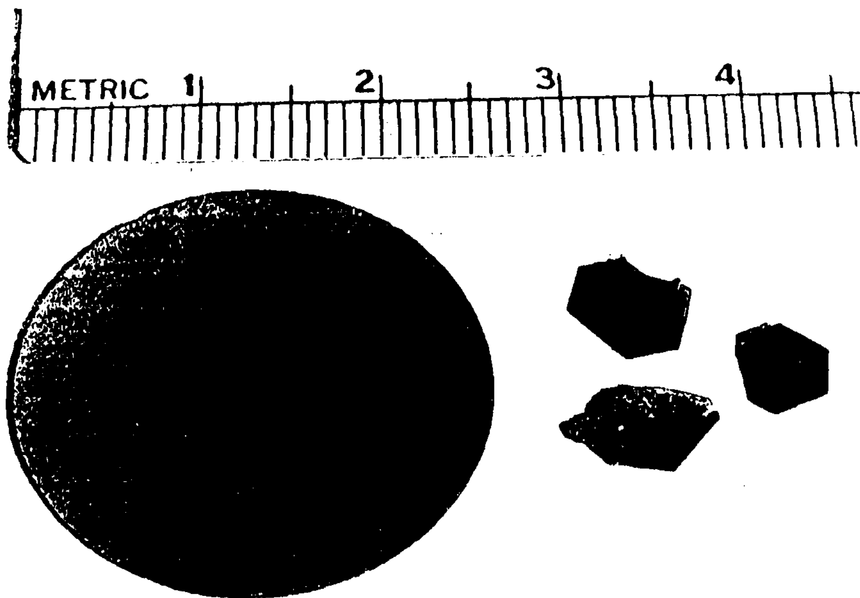

Figure 5: Prior to 1989, SiC researchers had to use small irregular-shaped Lely SiC samples for device studies. Now, Cree Research, Inc., a small company in Durham, North Carolina, has made one inch SiC substrates commercially available.

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SUBLIMATION GROWTH OF 6H-SiC BOULES

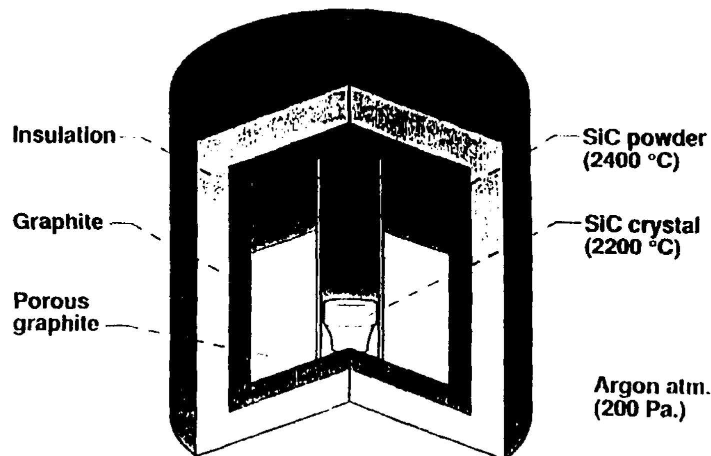

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Figure 6: The difficulty in producing SiC substrates is that SiC does not melt. Therefore, the SiC boule crystal growing technique involves the sublimation of SiC powder. The SiC boule growth is carried out in a high temperature furnace where after the SiC powder sublimes, the SiC vapor is transported along a temperature gradient, and then deposits onto a SiC seed crystal which is at a cooler temperature.

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SiC CHEMICAL VAPOR DEPOSITION REACTION SYSTEM

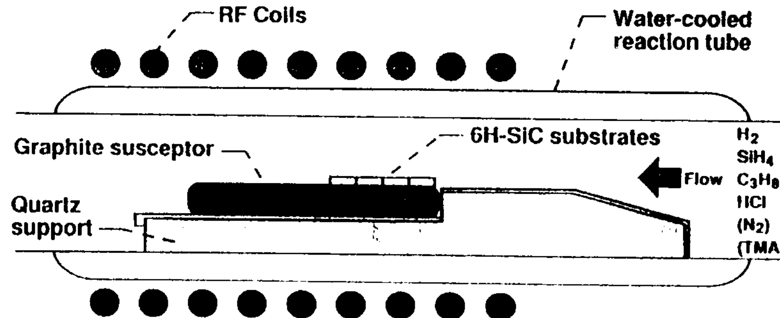

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Figure 7: During the 1980s, the LeRC SiC program developed a chemical vapor deposition technique for the heteroepitaxial growth of 3C-SiC onto silicon substrates. This 3C-SiC material has many defects because of the mismatch in material properties between the SiC and silicon. However, the chemical vapor deposition process works well for the homoepitaxial growth of 6H-SiC onto 6H-SiC substrates. Our process uses silane as the silicon source, propane as the carbon source, and hydrogen as the carrier gas. For doping the SiC epilayers, nitrogen gas produces n-type while trimethylaluminum vapor produces p-type SiC. Hydrogen chloride gas is used during a pregrowth etch. The growth temperature is 1450°C. A radio-frequency generator heats the graphite susceptor. The growth process takes place at atmospheric pressure.

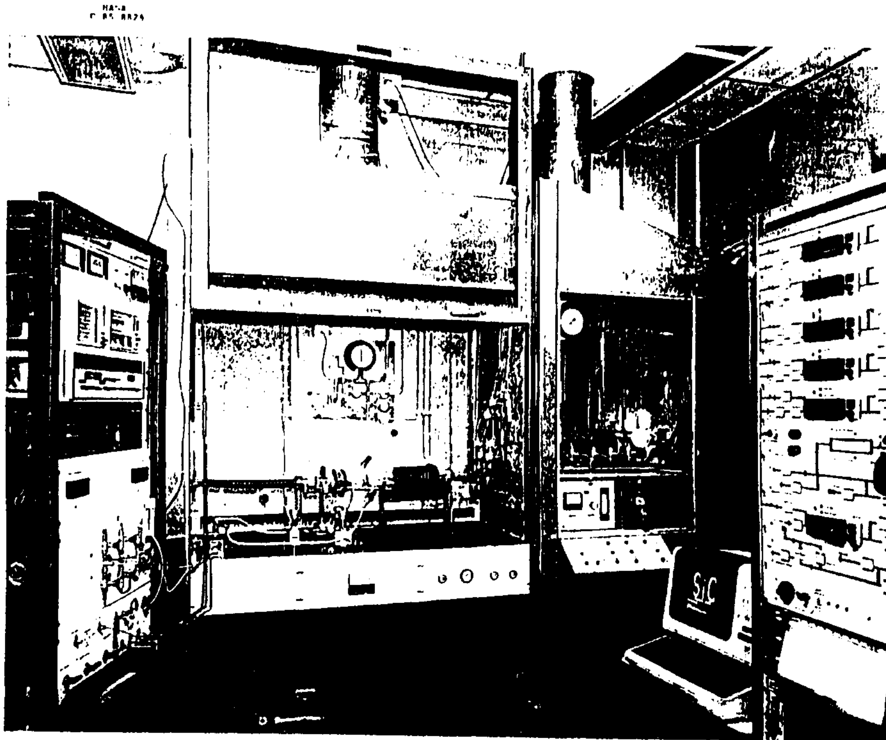
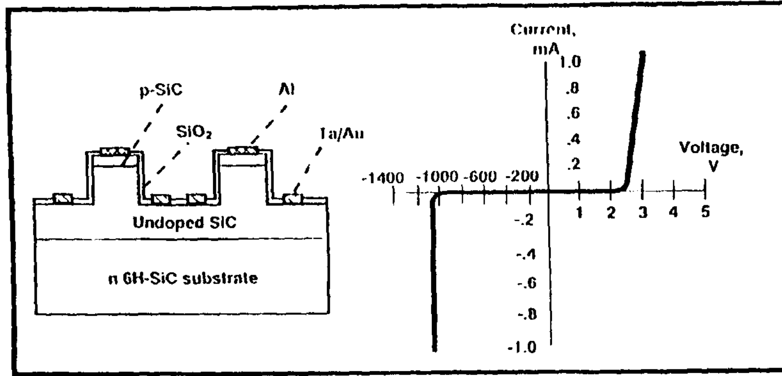


Figure 8: A photo of the LeRC chemical vapor deposition system. The time sequence and flow rates of all process gases are computer controlled.

6H SILICON CARBIDE P-N JUNCTION DIODE



Diode Structure

I-V Characteristics at Room Temperature

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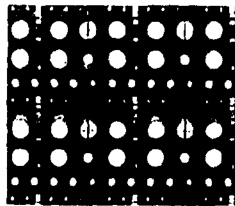
Figure 9: Device structure and room temperature current-voltage characteristics for a 6H-SiC pn junction diode that was fabricated at LeRC. Etching of the SiC to produce the mesa-style pn junction configuration was accomplished by reactive ion etching; there are no known wet chemical etchants for SiC. The reverse diode characteristics demonstrated very low leakage out to the breakdown voltage of around 1000 volts. The forward diode characteristics displayed the rather large turn-on voltage associated with the wide bandgap of SiC.

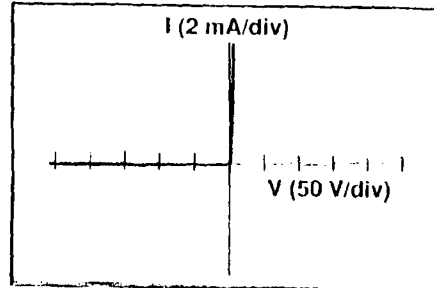
Silicon Carbide Junction Diode

Accomplishment: Highest reported operational temperature (600 °C) for any p-n junction diode device. Significantly improved characteristics above 400 °C. Demonstrates high quality 6H-SiC epitaxial film growth processes.

Diode array



I-V Characteristics at 600 °C



Benefits: Silicon carbide diodes (p-n junctions) are basic building blocks from which all future silicon carbide electronic devices will be developed

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Figure 10. The diode array photo shows SiC diodes of different sizes. The diode sizes range from 50 to 400 microns in diameter. The 6H-SiC diode demonstrated excellent current-voltage characteristics when tested to 600°C. As a semiconductor material, SiC can clearly perform at elevated temperatures. The SiC pn junction is a basic building block from which all future SiC electronic devices will be developed.

Figure 11: A photo documenting the operation of a 6H-SiC pn junction diode at 600°C. One diode, of the many on the chip, is being examined on a probing station equipped with a heating stage. The forward biased diode is emitting blue light while the heating stage is glowing cherry-red at 600°C.

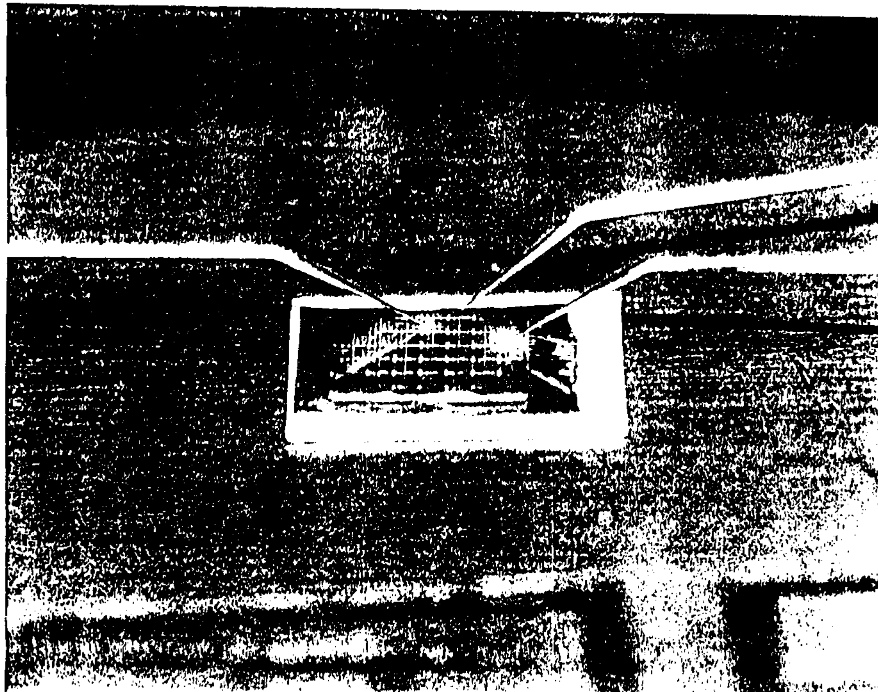

Figure 12: As seen in figure 11, SiC is an LED material. This photo documents for the first time, that both 6H-SiC blue LEDs and 3C-SiC green-yellow LEDs can be produced on a single chip. The ability to fabricate a 3C-SiC LED is an indication of the high quality of the 3C-SiC material.

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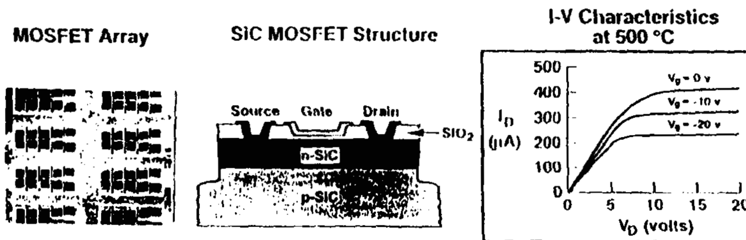
SILICON CARBIDE MOSFET

Milestone: Develop and demonstrate a high temperature, (400 °C), 6H-SiC metal-oxide-semiconductor field effect transistor (MOSFET)



Accomplishments: A depletion-mode silicon carbide MOSFET has been developed and successfully demonstrated at an operational temperature of 500 °C.

Benefits: Silicon carbide MOSFETs (switches) provide the most basic active electronic device from which integrated circuits can be developed.

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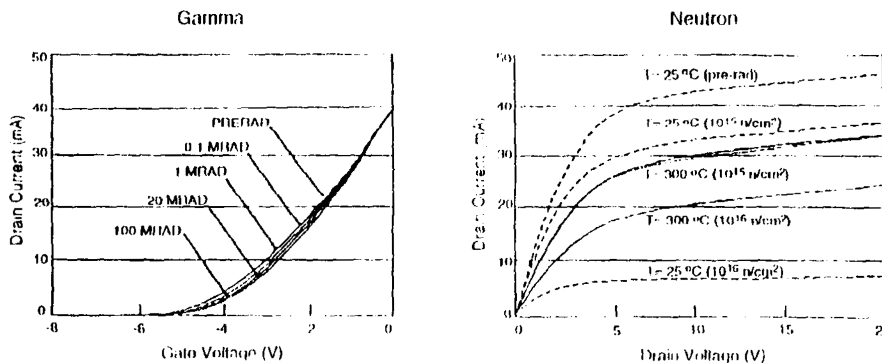
Figure 13: A depletion-mode 6H-SiC Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) was demonstrated to an operating temperature of 500°C. SiC has silicon dioxide as its native oxide, so many of the silicon oxidation techniques are directly importable to the SiC technology. The current-voltage characteristics for this MOSFET are not yet ideal because the device structure and oxide growth processes have not yet been optimized.

Silicon Carbide JFET Radiation Response



Work performed by J.M.McGarrity *et al.*, Harry Diamond Laboratories

To be published in IEEE Trans. on Nuclear Science, 39, No.6 Dec. 1992

Figure 14: SiC is expected to be a radiation-hard semiconductor. Work performed at the Harry Diamond Laboratories demonstrates that, yes indeed, SiC is radiation-hard. 6H-SiC Junction Field-Effect Transistors (JFETs) were exposed to both gamma and neutron radiation. The JFET experienced little effect from the gamma radiation and was still functioning after an exposure of 10^{16} neutrons per cm^2. The JFET also performed better at the elevated temperature of 300°C than at room temperature after the neutron exposure.

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AREAS REQUIRING TECHNOLOGY ADVANCEMENT
(FOR HIGH TEMPERATURE APPLICATIONS)

- Metallization (electrical) contacts
- Passivation and dielectric layers
- Wire attachment
- Packaging
- Circuit board technology

Figure 15: Several areas still require technology advancement before SiC is ready for high temperature and/or high radiation environments. The LeRC program is supporting research in the areas of metallization, passivation and dielectric layers, wire attachment, and component packaging. Ultimately circuit board technology must be developed.

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CONCLUDING REMARKS

- Need for 600 °C electronic devices
- SiC is the semiconductor of choice
- Significant SiC crystal growth progress
- Discrete devices (diodes and MOSFETs) demonstrated
- Several challenging areas await
- SiC is on its way

Figure 16: Concluding Remarks: The LeRC program believes that a need for high temperature (600°C) and/or high radiation-hard electronic devices exists. The semiconductor of choice is SiC because of its many unique properties and the fact that diamond is still far in the future. During the past ten years, significant progress has been made in the advancement of SiC technology. Key progress has been made in the SiC crystal growth process. This progress has allowed device scientists to fabricate prototype SiC electronic devices with exciting characteristics and thus, LeRC researchers feel that SiC, as an electronic material, is definitely on its way. However, as is probably evident, there are still a number of challenging areas of research to be pursued.