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HIGH-TEMPERATURE ELECTRONICS

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ABSTRACT

In recent years, there has been a growing need for electronics capable of sustained high-temperature operation for aerospace propulsion system instrumentation, control and condition monitoring, and integrated sensors. The desired operating temperature in some applications exceeds 600 °C, which is well beyond the capability of currently available semiconductor devices. Silicon carbide displays a number of properties which make it very attractive as a semiconductor material, one of which is the ability to retain its electronic integrity at temperatures well above 600 °C. An IR-100 award was presented to NASA Lewis in 1983 for developing a chemical vapor deposition process to grow single crystals of this material on standard silicon wafers. Silicon carbide devices have been demonstrated above 400 °C, but much work remains in the areas of crystal growth, characterization, and device fabrication before the full potential of silicon carbide can be realized. The presentation will conclude with current and future high-temperature electronics program plans. Although the development of silicon carbide falls into the category of high-risk research, the future looks promising, and the potential payoffs are tremendous.

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HIGH-TEMPERATURE ELECTRONICS

The High-Temperature Electronics Program is aimed at developing silicon carbide as a high-temperature semiconductor material. Research is focused on developing the crystal growth, characterization, and device fabrication technology necessary to produce a family of silicon carbide devices. Such devices would find numerous important applications in aerospace propulsion, space power, and high-temperature, earth-based systems.

HIGH-TEMPERATURE ELECTRONICS

DEVELOP A HIGH-TEMPERATURE FAMILY OF ELECTRONIC DEVICES BASED ON SILICON CARBIDE FOR AEROSPACE PROPULSION APPLICATIONS

- **NEED FOR HIGH-TEMPERATURE ELECTRONICS, BENEFITS OF SILICON CARBIDE**
- **GROWTH OF ELECTRONIC-QUALITY SILICON CARBIDE**
- **DEVICE CHARACTERISTICS**
- **FOCUS OF CURRENT AND FUTURE RESEARCH**

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THE NEED FOR HIGH-TEMPERATURE ELECTRONICS

On the basis of the inherent solid-state properties of silicon, the maximum temperature at which a silicon device could theoretically operate is 300 °C. Gallium arsenide could theoretically operate at 460 °C, but it is not stable at this temperature. However, there is an increasing need for electronics which operate at sustained temperatures above 400 °C. Engine ground-test instrumentation requires multiplexers, analog-to-digital (A/D) convertors, and telemetry systems capable of withstanding hot-section temperatures in excess of 600 °C. Uncooled operation of control and condition monitoring systems in advanced supersonic aircraft would subject the electronics to temperatures in excess of 300 °C. Similarly, engine-mounted integrated sensors could reach temperatures which exceed 500 °C.

THE NEED FOR HIGH-TEMPERATURE ELECTRONICS

COMMERCIAL SILICON DEVICES ARE GENERALLY AVAILABLE FOR USE UP TO 125 °C. SILICON TECHNOLOGY IS LIMITED TO A MAXIMUM TEMPERATURE OF 300 °C. THERE IS AN INCREASING NEED FOR ELECTRONICS WHICH OPERATE AT SUSTAINED TEMPERATURES GREATER THAN 400 °C.

AEROSPACE PROPULSION APPLICATIONS

- **ENGINE GROUND-TEST INSTRUMENTATION**
- **CONTROL AND CONDITION MONITORING SYSTEMS**
- **INTEGRATED SENSORS**

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BENEFITS OF SILICON CARBIDE AS A SEMICONDUCTOR MATERIAL

With the same criteria as applied to silicon, silicon carbide could theoretically be employed at temperatures as high as 1200 °C. A more reasonable, shorter term goal is to produce electronics capable of 600 °C operation. This material is characterized by excellent physical and chemical stability, which make it suitable for long-term use in high-temperature, corrosive environments. The combination of the material's high thermal conductivity and high breakdown field provides the potential for improved power system electronics and for increasing the number of devices per unit area. Those properties, which determine the high-frequency characteristics of semiconductors, appear to be excellent for silicon carbide and superior to those of silicon or gallium arsenide.

BENEFITS OF SILICON CARBIDE AS SEMICONDUCTOR MATERIAL

PROPERTY	BENEFIT
• HIGH OPERATING TEMPERATURE	• 600 °C ELECTRONICS
• EXCELLENT STABILITY	• SUSTAINED USE IN HOSTILE ENVIRONMENT
• HIGH THERMAL CONDUCTIVITY AND HIGH BREAKDOWN FIELD	• IMPROVED POWER ELECTRONICS AND INCREASED DEVICE PACKING DENSITY
• EXCELLENT HIGH-FREQUENCY PROPERTIES	• SUPERIOR HIGH-FREQUENCY DEVICES

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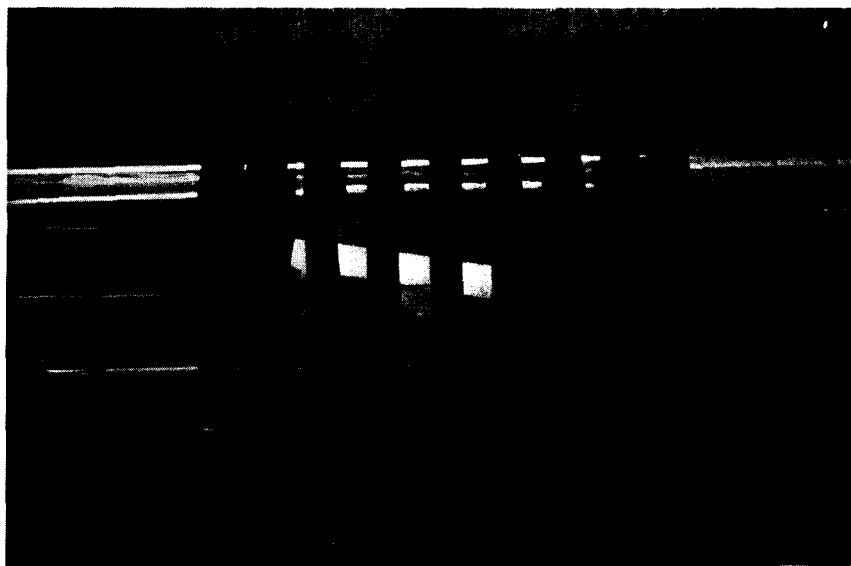
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I-R 100 AWARD

Silicon carbide devices were demonstrated above 400 °C as early as 25 years ago, but most research in the U.S. was terminated in the early 1970's because of an inability to produce the large-area, high-quality crystals required for commercial production. Unlike silicon and gallium arsenide, which are grown from a melt, silicon carbide (SiC) has no liquid phase and must be grown from the vapor state by sublimation. The quality and size of SiC crystals are extremely difficult to control with this process. However, in 1983, researchers at NASA Lewis developed a chemical vapor deposition process which permitted the growth of thin, epitaxial films of SiC on standard silicon semiconductor wafers. For this discovery, an I-R 100 award was presented.

**I-R 100 AWARD
PRESENTED TO NASA LEWIS RESEARCH CENTER
1983**

**FOR THE DEVELOPMENT
OF THE PROCESS FOR
PRODUCING CUBIC
SILICON CARBIDE
DEVICES**

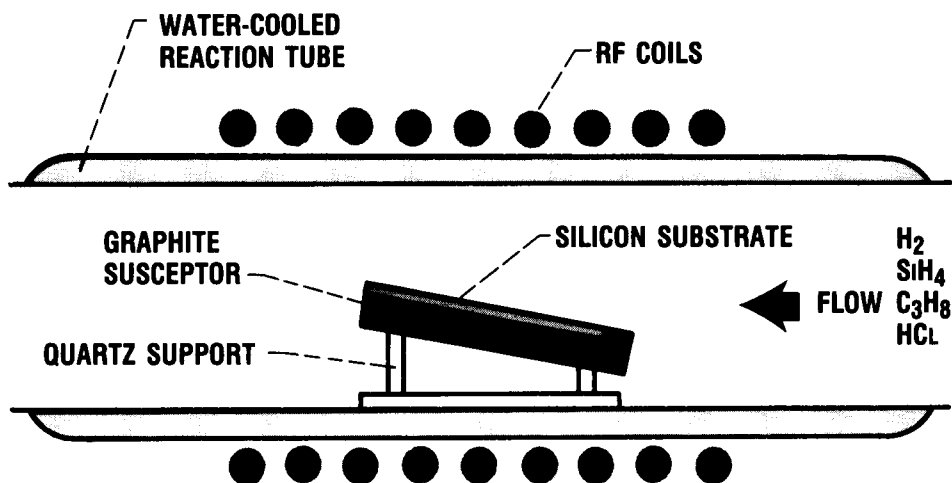


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CHEMICAL VAPOR DEPOSITION REACTION SYSTEM

A diagram of the chemical vapor deposition reaction system is presented. An electronic-grade silicon substrate is placed on a radiofrequency (rf)-heated graphite susceptor. Rapidly ramping the temperature of the silicon (Si) substrate in the presence of silane (SiH_4) and propane (C_3H_8) in a hydrogen carrier gas produces single-crystal silicon carbide (SiC) in spite of a very large mismatch between the lattice parameters (Si-Si and Si-C interatomic distances).

CHEMICAL VAPOR DEPOSITION REACTION SYSTEM



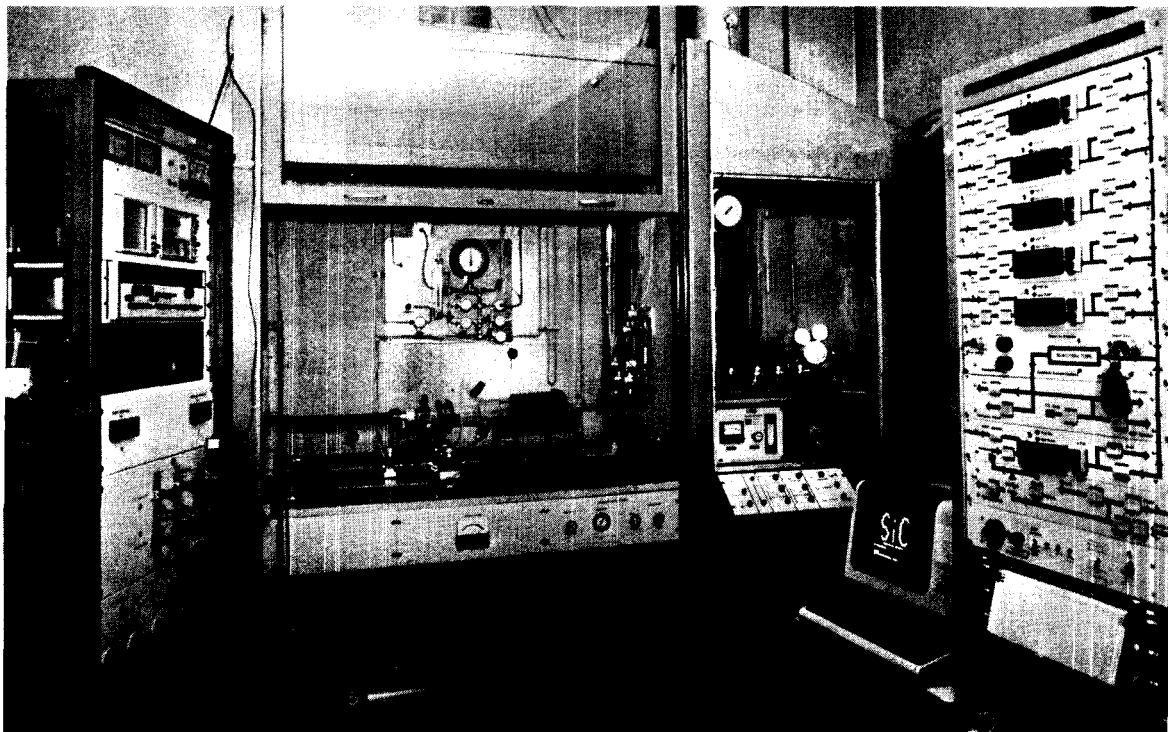
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PHOTOGRAPH OF CHEMICAL VAPOR DEPOSITION SYSTEM

A photograph of the chemical vapor deposition system is shown. The reaction tube and associated plumbing are in the hood (center). The control valves and flow controllers reside in the vented area directly to the right. In the right foreground are the manual and computer control systems, while in the left foreground is a mass spectrometer used to monitor system integrity. The rf generator is not shown.

CHEMICAL VAPOR DEPOSITION SYSTEM

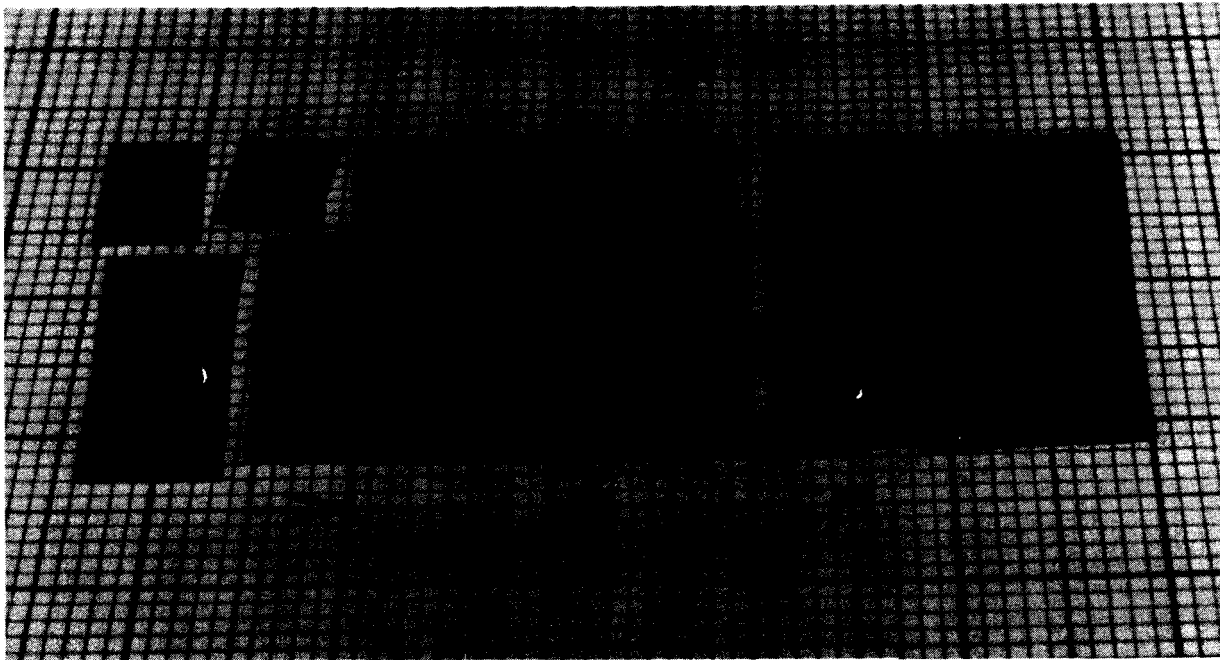


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PHOTOGRAPH OF SILICON CARBIDE CRYSTAL

Silicon carbide (cubic or beta crystal polytype) is a transparent, orange crystal which fractures into regular rectangular pieces. In the photograph, the silicon substrate has been removed from a 16- μ m-thick crystal. Although visually the material appears to be of relatively good quality, in actuality a high density of defects exists in the crystal. Certain defects adversely affect the electrical properties of silicon carbide devices. During the past five years, much progress has been made in understanding problems associated with crystal growth, but much research remains to be done in this area.

SILICON CARBIDE CRYSTAL



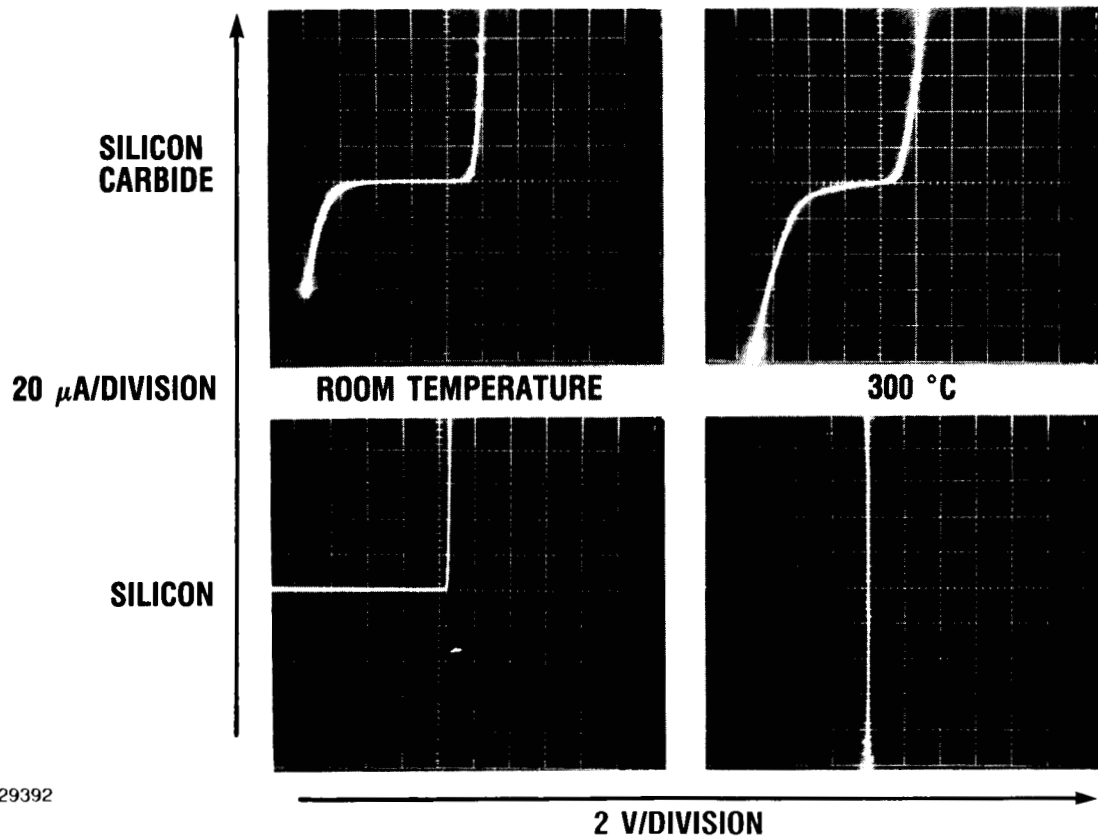
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TEMPERATURE CHARACTERISTICS OF SiC AND Si DIODES

Devices fabricated from NASA Lewis grown silicon carbide (SiC) have been characterized and compared to conventional silicon devices. Here, the current voltage curves are shown for ion-implanted SiC and Si diodes. Note that at 300 °C, the Si diode is rendered useless (shorted), whereas the SiC diode retains its rectification properties. The poorer quality of the SiC diode characteristics at room temperature is due to the unoptimized design of the device, the fabrication process, and the crystal quality. Device fabrication and crystal quality must be improved before the full potential of SiC can be realized.

TEMPERATURE CHARACTERISTICS OF SiC AND Si Diodes



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FOCUS OF CURRENT AND FUTURE SiC RESEARCH

Current and future program plans are outlined. Near-term studies will be performed primarily through in-house and grant research efforts. It should be noted that foreign research programs are more aggressively pursuing the development of silicon carbide technology than are those in the U.S., and although the risks are high, the payoffs are tremendous.

FOCUS OF CURRENT AND FUTURE LEWIS SiC RESEARCH

CURRENT:

- **CONTINUE PRESENT CVD STUDIES TO IMPROVE CRYSTAL QUALITY**
- **STUDY ALTERNATE CRYSTAL GROWTH METHODS**
- **CONTINUE DETAILED CHARACTERIZATION STUDIES**
- **CONTINUE CVD MODELING STUDIES**

FUTURE:

- **STUDY ALTERNATE CRYSTAL GROWTH METHODS**
- **CONTINUE DETAILED CHARACTERIZATION STUDIES**
- **DEMONSTRATE SIMPLE INTEGRATED-CIRCUIT TECHNOLOGY**
- **DEVELOP DEVICE METALIZATION AND PACKAGING TECHNIQUES**
- **DEMONSTRATE INTEGRATED-SENSOR TECHNOLOGY**

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