SiC-Based Gas Sensor Development

G.W. Hunter, P.G. Neudeck, and M. Gray
Glenn Research Center, Cleveland, Ohio

D. Androjna
Cortez III Service Corporation, Cleveland, Ohio

L-Y. Chen
AYT Corporation, Brook Park, Ohio

R.W. Hoffman, Jr.
Ohio Aerospace Institute, Brook Park, Ohio

C.C. Liu and Q.H. Wu
Case Western Reserve University, Cleveland, Ohio

January 2000
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:


- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at (301) 621-0134

- Telephone the NASA Access Help Desk at (301) 621-0390

- Write to: NASA Access Help Desk NASA Center for AeroSpace Information 7121 Standard Drive Hanover, MD 21076
SiC-Based Gas Sensor Development

G.W. Hunter, P.G. Neudeck, and M. Gray
Glenn Research Center, Cleveland, Ohio

D. Androjna
Cortez III Service Corporation, Cleveland, Ohio

L-Y. Chen
AYT Corporation, Brook Park, Ohio

R.W. Hoffman, Jr.
Ohio Aerospace Institute, Brook Park, Ohio

C.C. Liu and Q.H. Wu
Case Western Reserve University, Cleveland, Ohio

Prepared for the
1999 International Conference on Silicon Carbide and Related Materials
sponsored by North Carolina State University
Raleigh, North Carolina, October 10-15, 1999

National Aeronautics and
Space Administration

Glenn Research Center

January 2000
Acknowledgments

The authors would like to acknowledge the contributions of Dr. J.F. Lei, Dr. G. Fralick, Dr. R. Okojie, F. DeAngelo, and Dr. D. Larkin of NASA Glenn and C. Salupo of Cortez III/NASA Glenn. Send correspondences to G. Hunter, E-mail: ghunter@grc.nasa.gov
SiC-BASED GAS SENSOR DEVELOPMENT

G.W. Hunter, P.G. Neudeck, M. Gray
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

D. Androjna
Cortez III Service Corporation
Cleveland, Ohio

L-Y. Chen
AYT Corporation
Brook Park, Ohio 44142

R.W. Hoffman, Jr.
Ohio Aerospace Institute
Brook Park, Ohio 44142

C.C. Liu and Q.H. Wu
Case Western Reserve University
Cleveland, Ohio 44106

Abstract: Silicon carbide based Schottky diode gas sensors are being developed for applications such as emission measurements and leak detection. The effects of the geometry of the tin oxide film in a Pd/SnO₂/SiC structure will be discussed as well as improvements in packaging SiC-based sensors. It is concluded that there is considerable versatility in the formation of SiC-based Schottky diode gas sensing structures which will potentially allow the fabrication of a SiC-based gas sensor array for a variety of gases and temperatures.

1.0 Introduction

Silicon carbide-based gas sensors are of considerable interest since they can be operated at high temperatures and detect gases, such as hydrocarbons (CₓHᵧ) and nitrogen oxides (NOₓ), which are important in various applications such as emission monitoring and leak detection. Our development of SiC-based gas sensors has centered on investigations of gas sensitive Schottky diodes. The major advantage of a Schottky diode in gas sensing applications is its high sensitivity. While a simple palladium (Pd) on SiC (Pd/SiC) Schottky diode structure has the advantage of high sensitivity, these sensors drift with extended heating at high (400 °C) temperature [1]. Efforts are underway to stabilize the Schottky sensor structure for long-term, high temperature operation [2].

One approach incorporates chemically reactive materials such as metal oxides into a SiC-based metal-insulator-semiconductor (MIS) Schottky diode structure. Unlike Si-based electronics, SiC-based devices can be operated at high enough temperatures for these materials, e.g. tin oxide (SnO₂), to be reactive to CₓHᵧ and NOₓ. This results in a metal-reactive insulator-semiconductor (MRIS)
gas sensor structure. Potential advantages of this structure include increased sensor sensitivity and stability. Varying the reactive insulator composition can vary sensor selectivity to various gas species. We previously demonstrated this structure with SnO₂ as the reactive insulator and compared the reactive insulator sensor response to that of a Pd/SiC structure on the same chip (Figure 1a) [2]. The MRIS sensor showed improved stability and different responses than the Pd/SiC sensor.

This approach, combined with metal-alloys directly on SiC [2], potentially yields wide flexibility in the design and operational capabilities of SiC-based gas sensing Schottky diodes. Various reactive oxides and metal alloys can be combined within the Schottky diode structure to tailor the diode response to specific applications. Work is on-going to develop a high temperature electronic nose consisting of an array of appropriately tailored gas sensors based on SiC and other materials [3]. However, this work depends on the ability to package these sensors for the appropriate operating conditions. This paper discusses our on-going development of SiC-based gas sensors. First, the effect of the geometry of the insulator on the MRIS sensor behavior was studied. Second, a prototype sensor package allowing high temperature operation of the sensor in ambient conditions will be discussed.

2.0 Device Fabrication and Testing

The SiC-based sensors are fabricated from chips with a 4-5 μm thick alpha-SiC epilayer grown by chemical vapor deposition on a commercially available off-axis alpha-SiC substrate. A backside contact is achieved by sputtering aluminum onto the bottom of the wafer. The MRIS sensor investigated in this work is shown schematically in Figure 1b. A thin layer of approximately 50 angstroms (Å) of SnO₂ is sputter deposited onto half of the as-grown SiC epilayer surface (layer SnO₂ configuration). On both halves of the wafer, open circular patterns of 200 μm diameter were formed using photoresist. The SnO₂ layer half (left half of Figure 1b) of the wafer was then covered masking off the circular photoresist patterns; on the other half of the wafer 50 Å SnO₂ contacts (diode SnO₂ configuration) were formed by sputter deposition using the same parameters as the first SnO₂ deposition. The layer side was then uncovered and circular palladium (Pd) contacts approximately 400 angstroms (Å) thick were formed on both sides by sputter deposition and the subsequent lift-off. Thus, the SnO₂ is deposited completely across the surface (layered configuration on the left half of Figure 1b) on roughly half the chip while on the other half SnO₂ is deposited only beneath the Pd contact (diode configuration surface on the right half of Figure 1b). The difference between the two sides of the chip is the geometry of the SnO₂ layer beneath the Pd. This is in contrast to the previous tests (Figure 1a) where half the chip had the SnO₂ layer beneath the Pd and the other half had no SnO₂ at all beneath the Pd.

NASA/TM—2000-209653 2
The gas sensor testing facility and sample connections have been described elsewhere [1]. The sample rested on a hot stage whose temperature is controlled from room temperature to 425 °C. Current-time (I-t) measurements were taken to characterize the diode response as a function of time during exposure to a variety of gases, and current-voltage (I-V) measurements were taken to characterize the diode’s electronic properties in a given environment. The forward voltage at which the current is measured is chosen to maximize diode response and minimize series resistance effects.

3.0 Results and Discussion

3.1 Effects of Reactive Insulator Geometry

Heating the structures in Figure 1b at 350 °C for extended periods has shown a difference in behavior between the layer configuration sensors and diode configuration sensors (Figure 2). Both sensors are first exposed to air (10 minutes), nitrogen plus 10% oxygen (15 minutes), nitrogen plus 10% oxygen and 2500 ppm hydrogen, denoted as H2 mix, (15 minutes), followed by nitrogen plus 10% oxygen (5 minutes) and air (10 minutes). The diode configuration sensor has nearly no response to H2 at this concentration while the layer configuration sensor has a significant response. Comparison of the I-V curves of the two configurations is shown in Figure 3. The layer configuration sensor shows exponential behavior at low voltages and series resistance behavior at higher voltages. An increase in the current for a given voltage is noted upon exposure to H2 for this sensor. However, the diode’s H2 sensitivity is less than that noted for the previously investigated Pd/SnO2/SiC sensor with a layer SnO2 configuration [2].

The diode configuration sensor shows complicated behavior as a function of voltage. In air, exponential I-V behavior is noted below 0.4 V. The slope of the exponential changes near 0.4 V and remains nearly constant from 0.4 to 2.5 V. The sensor does not respond to H2 at this concentration below 1.5 V, while between 1.5 to 2.5 volts a small response to H2 is noted. Above 2.5 V, series resistance behavior is noted in both the air and H2 mix curves. This sensor does not have the standard Schottky diode characteristics noted in Pd/SiC diodes previously investigated [1]. In contrast to the results of reference 2, the layer configuration sensor exhibits more standard Schottky diode behavior. Thus, the diode configuration sensor behavior is obviously different than that of the
layer configuration sensor. These results suggest that the geometry of the reactive insulator, i.e. whether the SnO\textsubscript{2} covers the whole region around the sensor or just underneath the diode, affects the behavior of the sensor. The underlying reason for the effect will be investigated in future studies.

These results have some similarities to those seen when comparing the Pd/SiC sensor to that of the Pd/SnO\textsubscript{2}/SiC layer configuration sensor in reference 2. In both cases, increased sensitivity to H\textsubscript{2} is noted for sensors in the layer configuration compared to sensors without the layer. In summary, the diode sensitivity and stability is improved when the SnO\textsubscript{2} layer covers half the chip compared to that of a sensor where a SnO\textsubscript{2} layer does not extend beyond the boundary of the Pd contact.

The difference between the SnO\textsubscript{2} layer configuration sensors discussed in this work (diode 1) and in reference 2 (diode 2) is of interest. Both sensors show exponential behavior followed by series resistance behavior at higher voltages (not shown). The low voltage behavior in air of both diodes is shown in Figure 4 in a linear current scale. At lower voltages, diode 2 shows a linear I-V curve (shunt resistive behavior) until at least 0.6 V. The slope of the I-V curve gives an effective resistance of near 2*10\textsuperscript{6} Ω which is a value consistent with the resistance of a thin SnO\textsubscript{2} film. Above 0.9 V, diode 1 exhibits exponential behavior. In contrast, the I-V curve of diode 2 shows noise current below 0.8 V while above 0.8 V exponential behavior is observed. Thus, the most significant difference in the behavior of the two diodes is the shunt resistance behavior at lower voltages. These results suggest that differences in the deposition of a SnO\textsubscript{2} film can affect the sensor response even if the geometry of the film is the same. Possible differences in the SnO\textsubscript{2} film deposition parameters include thickness of the film and stoichiometry of the SnO\textsubscript{2}.

3.2 Sensor Packaging

The ability to package a sensor for a given environment is of fundamental importance to its eventual application. One difficulty with operating sensors which function at higher temperatures than ambient is that a considerable amount of power (order of several watts) may be necessary to properly heat the sensor. For example, temperatures above 300-400 °C will likely be necessary to optimally measure gases such propylene and methane [1]. The heat power demand to achieve such temperatures may limit sensor use in some applications. Thus, the development of appropriate sensor packaging technology is necessary. Figure 5 shows the schematic of a prototype sensor package.
incorporating a Pd/SiC based sensor, temperature detector, and heater. The sensor resides on a micromachined diaphragm structure; this diaphragm structure minimizes the thermal mass and decreases the amount of power necessary to heat the sensor to appropriate temperatures. It also allows heating of the sensor with minimal heating of the adjoining package components. Temperatures up to 600 °C have been achieved with a heater power of near 1 W. Further, at approximately 500 °C, the packaged Pd/SiC sensor with a built-in heater has measured 5000 ppm of H₂, ethylene, and methane in N₂ (not shown). The methane signal has a longer response time than that of H₂ and ethylene, but has the same general shape of I-t curve. This is in contrast to the results at lower temperatures where the methane response was fundamentally different than the sensor response to H₂ and propylene [1]. However, as would be expected, degradation of the sensor response occurs with continued high temperature operation. This type of packaging can also be used for a variety of other sensors which would constitute the high temperature electronic nose.

![Graph](image)

Fig. 4. The I-V curve in air on a linear current scale at 350 °C of the Pd/SnO₂/SiC diode in this work and in reference 2.

![Diagram](image)

Fig. 5. Schematic drawing of sensor package for SiC-based devices.

### 4.0 Conclusions and Future Plans

The MRIS diode structure shows a dependence on the geometry of the insulator. Further studies with other diode geometries, reactive insulators, and processing conditions are planned. Integration of MRIS and metal alloy-SiC sensors together into an appropriate sensor package is also planned. By integrating SiC-based sensors with various structures into a sensor array, the sensor array can be tailored to meet the detection needs of a range of gas sensing applications.

### 5.0 References

### Title and Subtitle
Si-Based Gas Sensor Development

### Authors
G.W. Hunter, P.G. Neudeck, M. Gray, D. Androjna, L-Y. Chen, R.W. Hoffman, Jr., C.C. Liu, and Q.H. Wu

### Performing Organization
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

### SPONSORING/MONITORING AGENCY
National Aeronautics and Space Administration
Washington, DC 20546–0001

### Abstract
Silicon carbide based Schottky diode gas sensors are being developed for applications such as emission measurements and leak detection. The effects of the geometry of the tin oxide film in a Pd/SnO₂/SiC structure will be discussed as well as improvements in packaging SiC-based sensors. It is concluded that there is considerable versatility in the formation of SiC-based Schottky diode gas sensing structures which will potentially allow the fabrication of a SiC-based gas sensor array for a variety of gases and temperatures.

### Subject Terms
- Gas
- Hydrocarbon
- Emission
- Sensor
- High temperature
- Packaging
- Electronic nose
- Detection
- Silicon carbide

### Limitation of Abstract
Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.