Improved chemical sensors track and control emissions

Anita Lloyd Spetz, Zhafira Darmastuti, Christian Bur, Joni Huotari, Robert Bjorklund, Niclas Lindqvist, Jyrki Lappalainen, Heli Jantunen, Andreas Schütze, and Mike Andersson

Sensitive, low-cost silicon carbide-based gas sensors can detect toxic emissions and hazardous nanoparticulate matter in previously untenable environments.

Controlling combustion and industrial processes requires sensors that can operate in complex, high-temperature environments while remaining selective to specific gases. Silicon carbide field-effect-transistor (SiC-FET) sensor systems can control environmental factors and emissions in a variety of settings, such as power plants. By using appropriate sensing layers and operation temperatures, SiC-FET sensors can monitor and control many types of toxic emissions, such as carbon monoxide, nitric oxides, sulfur dioxide, hydrogen sulfide, volatile organic compounds, and ammonia. However, the selectivity and long-term stability of these sensors must be improved for them to be useful in many applications. To combat these selectivity and stability issues, we developed a new SiC-based sensor.

In addition to monitoring and controlling toxic gases, particulate matter is another important safety concern. Particulate can be hazardous depending on its size, concentration, shape, and chemical content. Unfortunately, current particulate detectors are rather costly and cannot detect chemical content. Thus, we designed a separate new sensor and an accompanying low-cost method to identify dangerous particulate matter.

A SiC-based transistor can be used as a gas sensor when its gate contact is made from a catalytic metal. When using a catalytic metal, gas molecules will decompose and react with the catalytic gate contact, changing the amount of current passing through the transistor. Some gas species, such as hydrogen, can even diffuse to the underlying oxide exposed by the porous catalytic metal. This chemical activity will charge the gate area, also changing the current through the channel of the transistor.

Our newly designed silicon carbide-based sensors (see Figure 1) have greatly improved selectivity, tunability, and long-term stability. While an enhancement-mode transistor needs a certain applied voltage to conduct current, a depletion-mode transistor conducts current without an applied voltage. Ours is a depletion-mode sensor that can be operated at a much smaller gate voltage, improving the structural stability of the catalytic metal. The depletion-mode design allows us to finely tune the current level during operation to change the sensitivity and dynamic range of the sensor for different gases.

Additionally, our new sensor is useful for detecting ammonia in power plants. Earlier results suggested that SiC-based sensors could detect ammonia in diesel engine exhaust by using an iridium gate contact. Thus, these sensors are useful for controlling the rate of urea injection into catalytic converters, a process that reduces nitric oxides in the diesel exhaust into nitrogen gas and water. When we attempted to use the same sensor in a power plant, we found that it could only track carbon monoxide (CO) because of the plant’s low-oxygen atmosphere (about 4% in modern plants compared to 8% in diesel engines). We found that our sensor is selective to ammonia even in a low-oxygen environment with a high level of CO.

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Because SiC/catalytic-metal-gate sensors often respond poorly to sulfur dioxide (SO$_2$), a dangerous power-plant effluent, we used a temperature-cycling operating mode and advanced data evaluation to considerably improve our sensor’s SO$_2$ detection capabilities.\textsuperscript{3,4} Chemical reactions occurring on the surface of the catalytic metal change slightly at different temperatures. Thus, the selectivity of our sensor for a certain gas molecule (or different concentrations of the same molecule) were improved by evaluating the magnitude and speed of the sensor response at selected times during many temperature cycles. By choosing a proper temperature cycle based on these results, we improved the response of our sensor to specific gases, such as SO$_2$.

In addition, we developed a sensor to better detect hazardous particulate. The chemical content of a particle influences its toxicity, but no currently available commercial instruments can detect the chemical content of particulate matter. We developed a method in which our sensor detects the gases emitted from heated particulate.\textsuperscript{4} We studied the detection of fly ash with a known content of ammonia. Once we cycled the temperature of the particles up to 430°C, they released the ammonia to be detected by an ammonia sensor.\textsuperscript{5} The released gas acted as a ‘fingerprint’ for the chemical content of the particulate.

Environmental and health concerns drive the development of both gas and particle sensors. We demonstrated the selective, low-level detection of two toxic gases: ammonia and sulfur, both present in power-plant effluent. We also developed a method to detect the chemical content of particles by heating the particles to high temperatures and detecting the emitted gases, which act as a fingerprint of the chemical content. In the future, we hope to extend this fingerprint method to detect other particles.

**Author Information**

Anita Lloyd Spetz, Zhafira Darmastuti, Robert Bjorklund, and Mike Andersson

Linköping University
Division of Applied Sensor Science
Linköping, Sweden

Anita Lloyd Spetz is a professor of applied sensor science at Linköping University and an FiDiPro professor at University of Oulu in Finland. Her research focuses on harsh environment gas sensors, biosensors, resonators, soot and graphene sensors, and portable nanoparticles detectors.

Zhafira Darmastuti is a PhD student in applied physics. She has an academic and industrial background in energy and environmental engineering. Her main research interest is chemical gas sensors for flue gas cleaning in power generation applications.

Robert Bjorklund finished his PhD in the US and continued as a post-doctorate researcher at Linköping University in Sweden. He is now involved in several industrial projects concerning the applications of the electronic tongue and SiC-FET sensors.

Mike Andersson earned a PhD in applied physics from Linköping University in 2007 and was a post-doctorate researcher in sensor science until 2009. Currently he is a senior researcher at Applied Sensor Science (50%), SenSiC AB (25%), and University of Oulu (25%). His research focuses on chemical and particulate sensors.

Christian Bur and Andreas Schütze

Department of Mechatronics and Measurement Technology
Saarland University
Saarbrücken, Germany

Christian Bur holds a diploma from Saarland University in microtechnology and sensor science. He is currently pursuing a double PhD in the European doctoral program DocMASE between Saarland University and Linköping University. His research includes field-effect-based gas sensors running in dynamic temperature operation as well as signal processing.

Andreas Schütze has a PhD in applied physics from Justus-Liebig-Universität. After spending a number of years in industry, he became a professor at the University of Applied Sciences in Krefeld, Germany, where he stayed for three years. He is now a full professor at Saarland University. His research focuses on microsensors and microsystems, especially for security and environmental applications.

Joni Huotari, Jyrki Lappalainen, and Heli Jantunen

Microelectronics and Material Physics Lab
University of Oulu
Oulu, Finland

Joni Huotari received his MSc degree in electrical engineering from the Microelectronics and Material Physics Laboratories of University of Oulu in 2010. He started as a PhD student at the same laboratory in 2011. His primary research interest is the fabrication and characterization of functional materials for chemical sensors.

Jyrki Lappalainen has a PhD in microelectronics and materials physics from the University of Oulu, and is now a professor of electronics manufacturing technologies. His research includes
the characterization of the structural, electrical, optical, and mechanical properties of functional electroceramic thin films and nanostructures, as well as their applications.

Heli Jantunen has a PhD with honors in microelectronics and materials physics from the University of Oulu. She is currently a full professor and department head, as well as a member of the Academy of Finland. She has been an industrial managing director for ten years. Her research focuses on novel sensors, RF applications, and printed electronics.

Niclas Lindqvist
Center for Development of Air Quality Control
Alstom Power Sweden AB
Växjö, Sweden

Niclas Lindqvist has a MSc in mechanical engineering from Linköping University and has been working in various processing industries for the past 20 years. He currently manages the Center for Development of Air Quality Control Systems for power generation and other industrial applications.

References