NATURAL GAS *brief*

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Stanford | Natural Gas Initiative

School of Earth, Energy & Environmental Sciences and Precourt Institute for Energy

At Stanford University, we have developed the world's first gas sensors that can avoid false positives at low cost and power. These features make them ideal for deployment as part of a continuous leak monitoring IoT network.

Paradigm Shift in Leak Detection—

Identifying and quantifying molecules at low cost and power enables automated monitoring of infrastructure

By Pierre-Alexandre Gross and Ehsan Sadeghipour, Stanford University

According to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, gas pipeline explosions annually cause an average of $74 million in commercial and residential property damage. Over the past decade, more than a hundred people have been killed and hundreds injured from explosions of leaking natural gas pipelines in American residential neighborhoods. Residents often reported smelling gas in the days leading up to these incidents, but it was insufficient to avoid some of the recent major catastrophes. At the same time, the 13 million metric tonnes of methane leaked in the US each year cost $6.3B, which is a significant economic cost pushed to the consumers.

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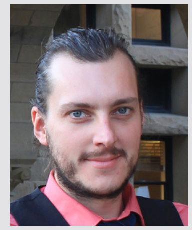
ABOUT THE AUTHORS



Pierre-Alexandre Gross

has a PhD in Physical Chemistry from the University of Strasbourg, where he worked on hydrogen production from water using solar light. He has been a postdoctoral researcher at Stanford University working with Professors Pruitt, Jaramillo, and Kenny, where he invented the world's first chemical sensors able to differentiate various gases at low cost and power. He is the co-founder and CTO of Fullmoon, which is commercializing these sensors.

Ehsan Sadeghipour

has a PhD in Mechanical Engineering from Stanford University, where he designed and fabricated silicon sensors and actuators for studying the mechanical properties of living microtissues. He has been working with Professors Pruitt, Jaramillo, and Kenny on the engineering and fabrication components of the chemical sensor with Pierre. He is the co-founder and CEO of Fullmoon.

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Finally, methane emissions are a much higher potential contributor to the green-house gas effect than CO_2, which is why states like California have recognized it as an environmental pollutant and now mandate the continuous monitoring and reduction of methane emissions. Detecting and reducing methane emissions affects the health, finances, and environment of the average citizen.

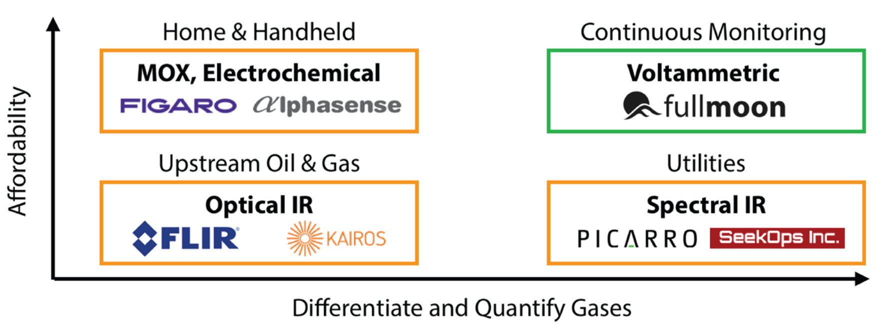
TECHNOLOGY LANDSCAPE

Currently available technologies used to detect methane leaks can be separated on two major axes, depending on the quality of data they provide and their cost. Quality of data refers to the amount of information, identification, and quantification of detected molecules, sensitivity, and resolution. As shown in Figure 1, sensing principles that rely on optical or spectral IR principles are expensive ($10k-$100k). Furthermore, optical IR can only help visualize gas plumes. Spectral IR provides detailed chemical quantification and speciation, albeit at high cost. In addition to the costs of the devices based on these technologies, their deployability is also expensive, as they have to be carried on vehicles (e.g. cars, drones, planes, etc.), and they have to be operated by several engineers in order to collect data.

Because of these shortcomings, IR-based technologies are not suitable for wide deployment as stationary, autonomous units that could continuously report the presence of methane in the air near critical infrastructures prone to leakage.

Less expensive sensing technologies using metal oxide (MOx), electrochemical, galvanic, or nondispersive infrared (NDIR) sensing principles exist, and they have the potential for large deployment. However, these sensors provide low data quality, as they cannot identify molecules, and have poor cross-sensitivity. These devices are intended for the detection of a single type of molecule (methane, carbon-monoxide, hydrogen sulfur, etc.), but are often simultaneously sensitive to several molecules. This poor cross-sensitivity can produce false positives. If these sensors were to be deployed as a sensing network with millions of nodes, even a small rate of false positives can be difficult to resolve.

Figure 1
Landscape of sensing technologies as a function of data quality (ability to differentiate and quantify detected molecules) and affordability.



A NEW SENSING PRINCIPLE

In this technological landscape we have developed a novel sensing principle able to affordably produce high quality data like an IR spectrometer. We have named these devices voltammetric sensors (Figure 2A), based on ▶

how their operational principle relies on Cyclic Voltammetry (CV), and we have founded a company (Fullmoon Sensors) to commercialize them.

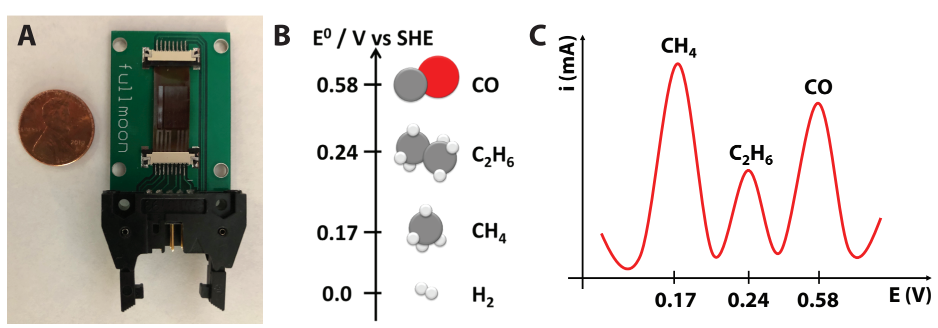
Cyclic voltammetry is a technique that probes for the redox potential of molecules to obtain chemical information. The redox potential is a unique signature of molecules, and it corresponds to the electrical potential required to trigger the oxidation or reduction of that molecule. Figure 2B shows some molecules of interest with their corresponding standard redox potential.

Four components are needed to perform CV: three metallic electrodes (working, counter, reference) and an electrolyte that conducts ions. The electrolyte is usually a salt- containing liquid solution. In the design of our voltammetric sensors we have replaced that liquid electrolyte with a solid-state one. We use Nafion as the solid-state electrolyte. Nafion is a teflon-based proton-conducting polymer that has been used in fuel-cells for more than 70 years. The electrodes of the sensors are made of platinum, which is a great electrocatalyst for the redox reactions of most molecules found in the atmosphere. During operation, molecules present in the air adsorb on the surface of the platinum electrodes. The voltage between the working and the counter electrodes is incrementally ramped between two limits, and the current is measured at each voltage step. In the current vs. voltage (I-V) plots the peaks correspond to the redox reactions of ambient molecules (Figure 2C). The position of each current peak is related to the redox potential of the molecule being oxidized or reduced, which means that it can be used to identify them. The height of the current peak is related to the amount of electrons passed during the oxidation or reduction reactions and can be used to quantify the amount of molecules that are adsorbed. We have used this device to detect methane, carbon monoxide, hydrogen, and oxygen.

CONTINUOUS MONITORING

These sensors have a small footprint, low power use, and they can differentiate and quantify various gases affordably. These features make them ideal for mass deployment as part of an Internet of Things (IoT) network to continuously monitor natural gas infrastructures. Each node in such a system would require not only the voltammetric sensor and the circuitry used to drive it, but also a battery and a wireless radio, ▶

Figure 2
(A) Voltammetric sensor design includes three electrodes: working, counter, and reference, all patterned on the solid electrolyte Nafion. (B) The standard redox potential of four molecules of interest (high to low): carbon monoxide, ethane, methane, and hydrogen. (C) On a current-voltage (I-V) curve, molecules may be differentiated and quantified by the position and height of each peak, respectively.



all housed in a field-deployable housing. The data produced by such a network would not only be valuable for detecting leaks, but also the spatial and temporal richness of this information can be used to drive predictive maintenance and analytics regarding infrastructure integrity. Figure 3 shows how the nodes will transmit information through existing wireless infrastructure to the cloud, where we can determine the proper response using machine learning. Multiple natural gas utilities have been interested in deploying individual nodes at residential meter sets to provide continuous monitoring at these locations.

INDUSTRY AFFILIATION

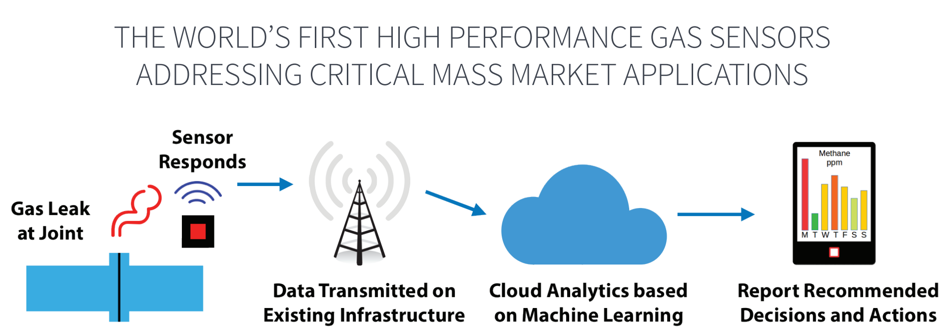
Our results thus far, in addition to the promising capabilities of this novel sensing principle, have gained the interest of many Natural Gas Initiative (NGI) affiliates, especially the California utilities PG&E and SoCalGas. These two companies and the NGI program have provided us with $400k over the last two years to continue the development of voltammetric sensors for detecting natural gas leaks. Very early in the project, PG&E and SoCalGas understood that the ability to differentiate and quantify molecules at low cost and power would revolutionize their efforts to monitor their infrastructures. These companies foresaw the deployment of a widely distributed network of sensing nodes alongside their infrastructures to continuously monitor potential leaks.

When searching for leaks, utilities do not merely look for the presence of methane in the atmosphere, as there are many biogenic sources of methane (i.e. animals, plants, garbage, etc.). In addition to methane, these companies look for ethane, another component of natural gas, which has no biogenic sources. The combination of these two gases, in the right ratio, can be used to ensure that the gas in the atmosphere is from a fossil fuel source, and not any other source. That is why utilities currently rely on IR spectrometers for leak detection, in order to avoid false positives. Using our sensor, which can also differentiate these gases but with much higher deployability, they will be able to continuously monitor their infrastructures.

We have not only benefitted from the financial resources of these NGI affiliates, but also we have been able to interact with them regularly to learn about their pain points. These interactions have allowed us to direct our technology development based on their specific requirements. ▶

Figure 3

These new sensors can be combined with a battery and a wireless radio as part of an IoT network to continuously monitor and recommend maintenance decisions.



Voltammetric sensing allows for the differentiation and quantification of gases at low cost.

For example, much of our effort over the past year has been to design and build more physically- robust versions of our sensor, which were requirements rooted in our conversations about lifetime and deployability. We have also modified the sensor material and added temperature compensation to reduce temperature and humidity variability. These combination of changes allow our latest voltammetric sensors to operate in the field for years without the need for maintenance.

CONCLUSIONS

We have developed the world's first mass deployable sensors that can be used in critical applications. These sensors operate based on a new sensing principle that we developed at Stanford, called voltammetric sensing, which allows for the differentiation and quantification of gases at low cost. These features make voltammetric sensing ideal for deployment as part of an IoT network for continuously monitoring potential leaks. Our work has gained the attention of NGI affiliates, PG&E and SoCalGas. These companies have not only funded our work for the past two years, but also provided valuable insight into industry requirements. The relationships we have built through the NGI program have benefitted our work financially, technologically, and commercially. ▲

THE NATURAL GAS INITIATIVE AT STANFORD

Major advances in natural gas production and growth of natural gas resources and infrastructure globally have fundamentally changed the energy outlook in the United States and much of the world. These changes have impacted U.S. and global energy markets, and influenced decisions about energy systems and the use of natural gas, coal, and other fuels. This natural gas revolution has led to beneficial outcomes, like falling U.S. carbon dioxide emissions as a result of coal to gas fuel switching in electrical generation, opportunities for lower-cost energy, rejuvenated manufacturing, and environmental benefits worldwide, but has also raised concerns about global energy, the world economy, and the environment.

The Natural Gas Initiative (NGI) at Stanford brings together the university's scientists, engineers, and social scientists to advance research, discussion, and understanding of natural gas. The initiative spans from the development of natural gas resources to the ultimate uses of natural gas, and includes focus on the environmental, climate, and social impacts of natural gas use and development, as well as work on energy markets, commercial structures, and policies that influence choices about natural gas.

The objective of the Stanford Natural Gas Initiative is to ensure that natural gas is developed and used in ways that are economically, environmentally, and socially optimal. In the context of Stanford's innovative and entrepreneurial culture, the initiative supports, improves, and extends the university's ongoing efforts related to energy and the environment.

Join NGI

The Stanford Natural Gas Initiative develops relationships with other organizations to ensure that the work of the university's researchers is focused on important problems and has immediate impact. Organizations that are interested in supporting the initiative and cooperating with Stanford University in this area are invited to join the corporate affiliates program of the Natural Gas Initiative or contact us to discuss other ways to become involved. More information about NGI is available at ngi.stanford.edu or by contacting the managing director of the initiative, Naomi Boness, Ph. D. at naomi.boness@stanford.edu.