Planar SiC MEMS flame ionization sensor for in-engine monitoring

D A Rolfe\textsuperscript{1} S Wodin-Schwartz\textsuperscript{1}, R Alonso\textsuperscript{1}, and A P Pisano\textsuperscript{2}

\textsuperscript{1}Department of Mechanical Engineering, University of California, Berkeley, 5101 Etcheverry Hall, Berkeley, California 94720, USA
\textsuperscript{2}Professor of ME and ECE, Dean of Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA, USA 92093-0403

Email: rolfe@berkeley.edu

Abstract. A novel planar silicon carbide (SiC) MEMS flame ionization sensor was developed, fabricated and tested to measure the presence of a flame from the surface of an engine or other cooled surface while withstanding the high temperature and soot of a combustion environment. Silicon carbide, a ceramic semiconductor, was chosen as the sensor material because it has low surface energy and excellent mechanical and electrical properties at high temperatures. The sensor measures the conductivity of scattered charge carriers in the flame’s quenching layer. This allows for flame detection, even when the sensor is situated several millimetres from the flame region. The sensor has been shown to detect the ionization of premixed methane and butane flames in a wide temperature range starting from room temperature. The sensors can measure both the flame chemi-ionization and the deposition of water vapour on the sensor surface. The width and speed of a premixed methane laminar flame front were measured with a series of two sensors fabricated on a single die. This research points to the feasibility of using either single sensors or arrays in internal combustion engine cylinders to optimize engine performance, or for using sensors to monitor flame stability in gas turbine applications.

1. Introduction

Hydrocarbon combustion is still used nearly-ubiquitously in transportation, heating and power generation. Though it is inexpensive and convenient, hydrocarbon combustion is the primary generator of CO\textsubscript{2}, NO\textsubscript{x} and SO\textsubscript{x}: leading contributors to global warming, smog, and acid rain. Though an ultimate solution may come from phasing out such fuels, a more immediate method to mitigate environmental harm may be to improve the efficiency of combustion reactions in internal combustion engines.

A flame is an ionic reaction in which fuel and oxygen are converted into carbon dioxide and water. Flame dynamics are heavily governed by the kinetics of the reaction, which have a highly sensitive dependence on temperature and the initial concentration of the hydrocarbon fuel and oxidizer. Because of this dependence, flame speed can be used to determine engine conditions such as pressure, temperature and air-fuel ratio.
Flame ionization sensors were first developed in 1920, when MacKenze and Honaman installed two ionization probes on an engine’s cylinder head [1]. With the advent of computerized data logging, flame ionization sensors became capable of monitoring combustion in engines on a cycle-by-cycle basis. In the 1970s, spark plug-based sensors, which used a non-firing spark plug with a bias voltage on the order of 100V to detect flame conductivity, began being used in engines [2]. In the 80s and 90s, Douaud (1983), Witze (1993) and Meyers (1993) among others began experimenting with multiple ionization sensors, placed on the gasket head of the engine [1]. Though these sensors provided spatial data including swirl and flame speed, they could not survive for more than a few hours in the harsh environment of an internal combustion engine.

Silicon carbide (SiC) offers an approach for a sensor capable of surviving the heat and soot of an engine cylinder. SiC does not melt, but has a sublimation point of 2830°C [3], and is a functional semiconductor at temperatures up to 800°C [4]. When kept at 300°C on the wall of an internal combustion engine, SiC has been shown to develop an electrically insulating oily residue layer at roughly half the rate of silicon due to its low surface energy [5]. In the past, SiC devices such as pressure sensors [6] have been tested successfully in internal combustion engines.

2. Flame conductivity

A flame, like any plasma, is conductive. When a bias voltage is introduced, current is carried by the charged species of the flame reaction. Electrons are particularly mobile because of their low mass and high mobility. The current density of a flame is given by the equation [7]:

\[ j = -e \sum_k Z_k n_k v_{Dk} \]

where \( n_k \), \( Z_k \), and \( v_{Dk} \) are the number density, charge, and drift velocity, of an ion species, \( k \). For a flame where the relative concentrations of all constituent ions are invariant to the rate and size of the combustion reaction, the current across a flame ionization sensor is proportional to the concentration of ions in the flame.

Chemi-ionization (as discussed above) does not occur in the quenching layer that exists between a flame and a cold surface (such as an engine wall), but electrons and other species scattered out of the flame front can still conduct current some distance away from the flame. Franke proposed a two-zone model for flame ionization conduction shown in Figure 1 [7].

![Figure 1](https://example.com/figure1.png)

**Figure 1.** A schematic of the conduction mechanism of a flame ionization sensor. The flame travels from one electrode, through the flame and boundary layer, toward the other electrode. The boundary layer is roughly four orders of magnitude more resistive than the flame layer, though this varies based on boundary layer thickness.

Because the quenching layer is much less conductive than the flame itself, the flame ionization sensor response can be highly sensitive to the quenching distance. When the quenching distance is much larger than the gap of the flame ionization sensor, conduction occurs primarily though the quenching layer. When the quenching distance is much smaller, current will travel through the flame (chemi-ionization) layer and conductivity improves significantly. This is shown in Figures 2 and 3.
In an internal combustion engine, quenching distances vary from 100µm to 300µm [8], and for a wall at room temperature, a quenching layer of 5mm can be expected [9]. Since all the electrode gap sizes were smaller than the quenching distance, the flame sensor response was not very dependent on the electrode gap size. This has been corroborated by both experimental response (as seen in Section 4) and the experimental results of Witze [1]. The quenching layer could be shortened potentially, if the sensor were heated, as discussed in Section 5.

In the future, the sensor could be constructed with a vacuum insulation layer directly below the sensor’s surface. An insulation layer as thin as 500µm could raise the temperature of the sensor 300°C, increasing the sensor’s sensitivity and further limiting soot formation on the sensor’s surface.

3. Design, fabrication and testing
Flame ionization sensor arrays, consisting of six sensors of varying electrode gap sizes were fabricated on a silicon substrate using a lithography process. A 3µm oxide layer for was deposited using LPCVD on a 6in silicon wafer for electrical isolation. 3µm of SiC was then deposited in a 2-step (to reduce stress) LPCVD process. The SiC was etched using an oxide mask, and a layer of oxide was deposited and patterned to insulate the SiC leads leading from the wire-bonding pads to the electrode gaps. The pads themselves were made of platinum with a chromium adhesion layer. Electrode gaps ranging from 20µm to 4mm were evaluated as well as electrode sizes between 5000µm² and 52000µm².

As electron absorption from flames has been shown to cause signal interference in flame ionization sensors [10], great care was taken to keep any electrical connection isolated from the flame. The sensors were attached to a data acquisition system with a set of electrical probes covered in dielectric epoxy, as shown in Figure 4. The sensor response was measured as the drop in voltage across a 1 MΩ resistor in series with the flame ionization sensor. This voltage divider configuration was used so that the output voltage would intuitively correspond to flame conductivity.
An acrylic “boom tube” was used to expose the sensor to a laminar premixed methane flame. The flame was lit roughly 0.5m from the sensor, and the flame front traveled through the tube perpendicular to the sensor’s surface.

**Figure 4.** a) The sensor is mounted to the surface of an acrylic tube through which a laminar premixed flame propagates. It is connected to a data acquisition system via epoxy-insulated probe tips (b). Each die has six sets of sensors (c) that each consist of a pair of electrode gaps (d) connected to contact pads by SiC electrodes insulated with a layer of SiO$_2$.

### 4. Results and discussion

Flame ionization sensors with varying geometries were tested in the setup shown in Figure 4. Flame resistivity was on the order of $1 \text{M} \Omega$. The sensor response was not sensitive to electrode size or gap size. The insensitivity to electrode size shows that at the quenching distances measured, the resistance of the bulk of the quenching layer is greater than the resistance across the electrode-quenching layer interface. The insensitivity to the electrode gap size is a result of large quenching distance (5mm) relative to the electrode gap of the sensor (as shown in Figures 2 and 3).

Water is a byproduct of any hydrocarbon combustion reaction, and at room temperature the sensor conductivity increases more from water deposition on the surface of the sensor after the flame passes than from the flame’s chemi-ionization. This can be remedied by raising the temperature of the sensor, as shown in Figure 5. At 25°C, the flame ionization conductivity (highlighted in red on Figure 5) is almost imperceptible compared to the moisture conductivity. At 60°C, less water deposits on the sensor, and the chemi-ionization conductivity and moisture conductivity are at roughly the same magnitude. In an engine, the wall on which the sensor would be mounted would be roughly 300°C, and the conductivity of deposited moisture would be significantly limited and the quenching layer would be an order of magnitude smaller, increasing measured ionic conductivity significantly.

**Figure 5.** A comparison of the sensor response to a flame at two different temperatures, 60°C (left) and 25°C (right). At temperatures approach 100°C, the flame ionization peak (highlighted in red) becomes increasingly pronounced compared to the vapour deposition peak that follows it.

Flame speed, which is an important indicator of a variety of engine conditions (as described in Section 1) may be measured two different ways using this sensor. Global flame speed can be
measured by determining the time it takes for a flame to propagate from the spark plug of an engine to a sensor at a known location. Local flame speed can be measured by two sensors mounted to a single die. Figure 6 shows an example of such a measurement with two sensors located 11.1 mm away from each other. Further measurements comparing sensor response to flame images are needed to determine the accuracy of this technique, but preliminary results show that the flame speed measured by the two-sensor arrangement is in agreement with the range of possible local flame speeds.

**Figure 6.** A preliminary demonstration of the response of two sensors (the top and bottom electrode pairs from Figure 4c) on the same die, measured simultaneously. A close up (right) shows how the time difference between the apexes of the ionization peaks may be used to measure the speed of the flame. The broader peak of Sensor 2 owes to the fact that Sensor 2 has an electrode gap 200 times the size of the electrode gap in Sensor 1.

5. Conclusions

Room temperature testing in a constant pressure laminar flame shows that microscale planar flame ionization sensors present a viable approach for measuring flame speeds, even when the electrode gap of the sensor is many times smaller than the quenching layer of the flame. In an engine environment, where quenching distances become two to five times smaller due to the increased temperature and pressure of the flame, which should increase the effectiveness of such a sensor. Though in-engine measurements would require new packaging and wiring, the sensors discussed in this paper should survive an engine environment longer than previous designs due to their SiC construction.

References

[1] Witze P O 1996 *In cylinder diagnostics for production spark ignition engines Unsteady Combustion* ed Culick F et al (New York: Springer) chapter 15 pp 333-368

[2] Eriksson L and Nielsen L 1997 *Control Eng. Practice* 5 pp 1077-1113

[3] Aylward G H et al *SI chemical data* 4th ed (New York: Wiley)

[4] Neudeck P G 2006 *The VLSI handbook* ed Chen W (Boca Raton: CRC Press) chapter 5

[5] Wodin-Schwartz S et al *Proc. PowerMEMS 2008* (Sendai) (London: Imperial College)

[6] Chen L and Mehregany M 2008 *Sensors and Actuators A: Physical* 145-146 pp 2-8

[7] Franke A 2002 Characterization of an electrical sensor for combustion diagnostics *Lund Reports Combustion Physics* 80

[8] Daniel W A 1957 *Proc. Int. Symposium on Combustion* 6 pp 886-894

[9] McAllister S et al 2011 *Fundamentals of Combustion Processes* (New York: Springer)

[10] Xie R et al 2009 *Proc. US Nat. Combustion Meeting* 6 pp 10-13