Wireless Harsh-Environment Oxygen Sensors

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***Abstract*—Surface acoustic wave (SAW) sensors fabricated on high-temperature piezoelectric substrates can be applied as harsh-environment oxygen sensors. In this paper we report recent results on the stability of the response of ZnO/ langasite SAW sensors. We also describe the development of conjugate-matched compact antennas for wireless sensing.**

I. INTRODUCTION

Oxygen sensors are used in many combustion processes is order to improve efficiency and reduce pollution. In oxy-fuel combustion of coal, separated oxygen is used so that the exhaust is nearly pure carbon dioxide suitable for geologic sequestration. In this case, the high cost of separated oxygen provides strong motivation for exhaust gas oxygen sensors.

In this paper we report recent progress toward the development of wireless oxygen sensors suitable for placement in the harsh environment of the combustion system exhaust duct. Wireless sensors are of particular interest because they would facilitate placement of multiple sensors to sample the nonhomogeneous exhaust flow.

We recently reported on a surface acoustic wave (SAW) gas sensor operating up to 700 °C [1]. Wireless interrogration of SAW temperature sensors was also reported [2]. Here we report on the stability of the SAW sensor response when operated at temperatures up to 600 °C. We also report measurements of the input impedance of the SAW sensors and integration of the SAW sensor with a compact antenna.

II. SAW SENSING

Figure 1 shows a schematic diagram of a surface acoustic wave gas sensor. An interdigitated transducer excited with a short RF pulse causes emission of a wave that propagates along the surface of a piezoelectric substrate. The velocity of that wave is influenced by the conductivity of a resistive layer due to the electroacoustic effect [3]. The wave is reflected by a second interdigitated transducer and returns to the emitting transducer, where it is reconverted into an electrical signal. The velocity change is determined by measuring the phase shift between the exciting and return pulse. Changes in the conductivity of the resistive layer due to the gas ambient are therefore reflected in an observed phase change between exciting and return pulses.

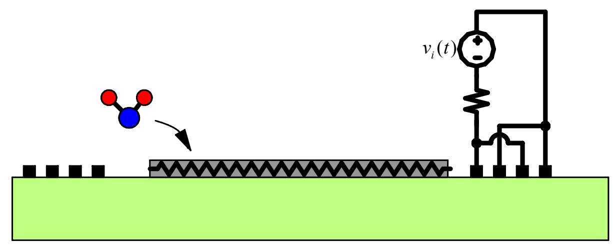

Figure 1. SAW gas sensor.

The SAW sensor is uniquely suited for harsh-environment wireless applications. High-temperature piezoelectric substrates are known that permit operation at least up to 1000 °C, and the cable to the interrogation electronics can be replaced by an RF link, enabling wireless interrogation.

III. SAW SENSOR FABRICATION

SAW sensors with (0, 138.5, 27) Euler angle were fabricated on langasite ($La_3Ga_5SiO_{14}$) substrates. Interdigitated electrodes with 2 µm wide fingers spaced 2 µm were fabricated by a photolithographic lift-off process using 100 nm Pt preceded by a 10 nm Ti adhesion layer. The parameters of the emitting and reflecting IDTs are presented in Table I. These sensors operate at about 325 MHz, corresponding to a wavelength of 8 µm.

TABLE I. SAW DEVICE PARAMETERS

Device ID	Aperture	Transmitter (finger pairs)	Reflectors (distance/finger pairs)
G2	50λ	50	2.56 mm/30, 3.2 mm/30, 3.84 mm/30, 4.48 mm/50, 5.44 mm/50
G3	50λ	50	2.56 mm/20, 3.2 mm/50, 3.84 mm/50

ZnO sensing layers 100 nm thick were deposited on the SAW device by sputtering. For testing, the SAW devices were bonded to a ceramic substrate and connected to a high-temperature cable using conducting ceramic paste. Testing was performed in a furnace with computer-controlled gas flows, using oxygen concentrations ranging from 0.25% to 80% in a nitrogen ambient. Details of the fabrication process and the experimental setup are available in previous reports [1, 4].

IV. SAW Sensor Response Stability

In a previous report, we characterized the SAW oxygen response as a function of temperature. We observed progressive changes in oxygen response as the sensor was exposed to successively higher temperatures up to 700 °C. These changes were attributed to grain growth of the ZnO sensing layer, although reaction between the ZnO and the langasite substrate could also be responsible. In general, one would not expect these changes in sensitivity to occur if the temperature of operation is kept lower than that required to cause the reaction or grain growth. We report here a sequence of experiments intended to test this hypothesis. This is a crucial test as stability of the sensor reponse is essential.

We performed a series of three runs in which the response of the sensor to a stepped oxygen concentration was measured at temperatures between 500 and 650 °C (below the maximum temperature to which the sensor had been exposed of 700 °C). Each run was identical so that drift in the sensor response could be unambiguously detected.

Figure 2 shows an example of the observed sensor response at 600 °C. The three different traces represent the results obtained for the three separate runs. The magnitude of the oxygen response is very consistent from run to run, with a small amount of baseline drift.

Figure 3 compares the phase change resulting from an oxygen concentration change from 0.25% to 40% for the three runs. This shows that there is good reproducibility possible for operation at least up to 650 °C.

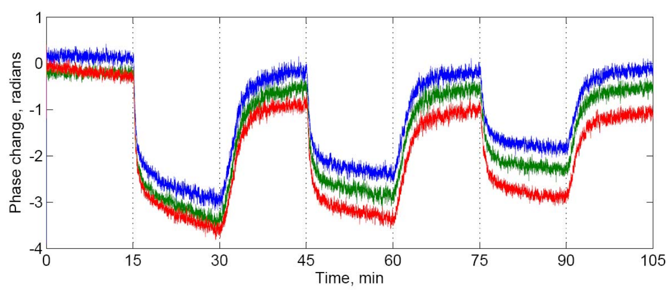

Figure 2. Sensor response to stepped oxygen concentration at 600 °C. (baseline oxygen concentration 0.25%; step increases to 80%, 40%, and 20% at 15, 45, and 75 sec respectively. Blue corresponds to the first test and red the last test of the sequence of three)

The observed dependence of phase change magnitude on temperature is expected based on the theory of the electroacoustic effect. Briefly, the surface wave velocity first increases with layer conductivity and then decreases again [3]. The conductivity of ZnO at fixed concentration of oxygen is thermally activated (1). For higher temperatures than examined here we have observed a decrease in response with temperature, again consistent with the electroacoustic effect.

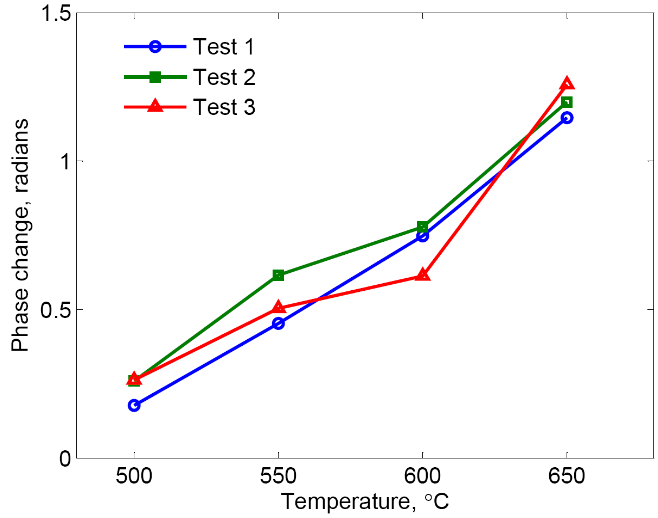

Figure 3. Sensor response to change from 0.25% to 40% oxygen as a function of temperature.

V. SAW Sensor Input Admittance

As noted previously, the high-temperature cable can be replaced with an RF link enabling wireless sensing. This is illustrated schematically in Figure 4. In this mode of operation there is substantial loss associated with the RF link, so it is important to provide for efficient matching of the sensor to the antenna. In order to perform efficient matching it is necessary to determine the input admittance of the SAW sensor. (Note that the antenna is used both to *receive* the exciting pulse and to *transmit* the reflected pulse. By reciprocity an antenna efficient for reception will also be efficient for transmission).

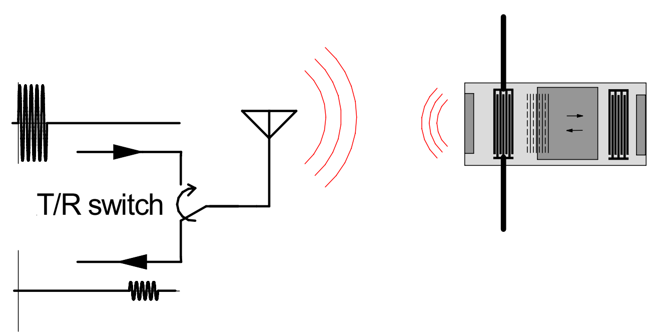

Figure 4. SAW sensor with RF link.

The input admittance of the exciting IDT was measured using a calibrated RF probe and a Rohde and Schwartz ZVB4 network analyzer. Figure 5 shows the real part of the measured admittance as a function of frequency for a large number of IDTs on the same wafer. The data for the particular device shown as a bold line is considered to be "typical." We observe a strong peak at the IDT resonant frequency superimposed on a frequency-independent loss. The peaked conductance represents acoustic radiation, while the frequency-independent loss is caused by resistive losses in the metallization, especially in the fingers. The imaginary part (not shown) is a nearly constant capacitance approximately equal to the geometric capacitance of the fingers. At the resonant frequency the transducer impedance is $Z = 23 - j94\ \Omega$.

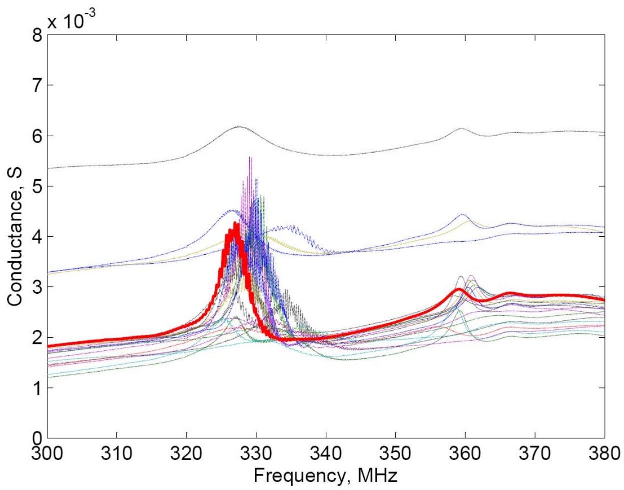

Figure 5. Real part of the input admittance for many interdigitated transducer with 50 pairs and an aperture of 50λ.The transducer corresponding to the heavy line is considered "typical."

This input admittance is predominantly capacitative with a real part somewhat less than the radiation resistance of a half-wave dipole antenna. Consequently attaching the SAW device directly to a dipole antenna will yield a poor match. In the following section we consider the design and fabrication of an antenna with a better match to the SAW sensor.

VI. ANTENNA DESIGN AND FABRICATION

We now consider development of an antenna for a harsh-environment SAW sensor. Requirements for the antenna include (1) good RF efficiency and (2) fabrication from high-temperature materials. In addition a relatively compact design is desirable.

We considered several different antenna designs. A half-wave dipole is relatively large (about 40 cm at the SAW operating frequency). Typically one would use a matching network to improve power transfer between the antenna and the SAW device. However this requires fabrication of both inductors and capacitors from high-temperature materials. While this can be done using thick-film techniques the components obtained, especially inductors, exhibit significant resistive losses [5]. A more attractive approach, at least at high temperatures, is to use an antenna longer than a half wavelength. Such an antenna has an inductive component to its impedance that can be chosen to match the capacitive component of the SAW admittance. Table II compares these two options where the efficiency shown is the ratio of the actual power transferred to the SAW device to the maximum available power into a matched load. This comparison shows that the performance can be improved by increasing the length of the antenna. However the resistive component of the antenna impedance is substantially increased compared to a resonant dipole.

TABLE II. COMPARISON OF ANTENNA DESIGNS

antenna type	length (cm)	series L	Z(antenna)	η(%)
half-wavelength dipole	40.4	0	~ 50 Ω	33
> λ/2 dipole	47.4	0	113+97j Ω	55
λ/4 dipole	20.2	74 nH	8 Ω	7.4
λ/4 dipole (additional L)	20.2	95 nH	8.1+95j Ω	74
meander dipole	20.2	0	21.5+94j Ω	99.9
folded dipole	20.2	0	17+94j Ω	95.7

Also shown in Table II are predictions for two compact antenna designs, a folded dipole and a meander dipole. These two designs are illustrated in Figure 6. The impedance of these antennas was calculated using the rfw (3D electromagnetics) mode of Comsol 3.5a.

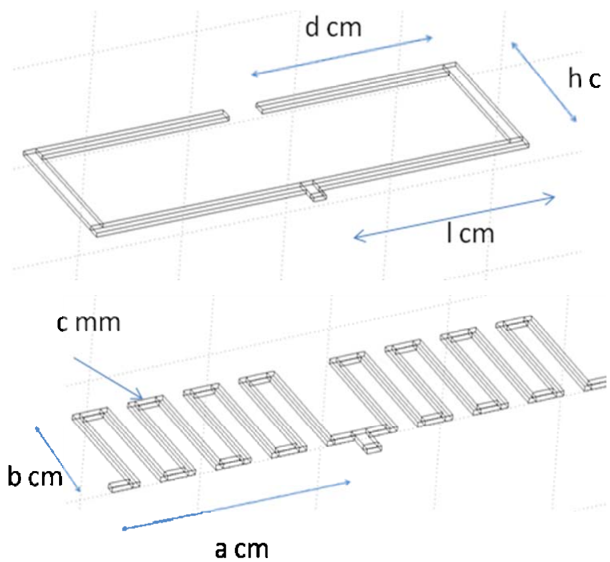

Figure 6. Two compact antenna designs: (top) folder dipole and (bottom) meander dipole,

Both these antenna designs have an impedance with a resistive part less than 50 ohms. As a result it is possible to obtain a near-match to the resistive component of the SAW impedance, and the antenna length can be increased to create an inductive part that cancels the capacitive part of the SAW impedance. This yields a very good match and high predicted efficiency (Table II).

An antenna with the meander dipole geometry was fabricated using high-temperature compatible materials (Figure 7). The antenna conductors were fabricated from 0.8 mm diameter alumel thermocouple wire. The antenna was bonded to a 50 mm square alumina substrate using insulating ceramic paste. A SAW device was attached to the alumina plate using conducting ceramic paste (emitting transducer 50 pairs, 100λ width). The antenna elements were attached to the SAW device terminals using conducting ceramic paste and fine thermocouple wire. These materials have been used in our laboratory for SAW device characterization up to 900 °C.

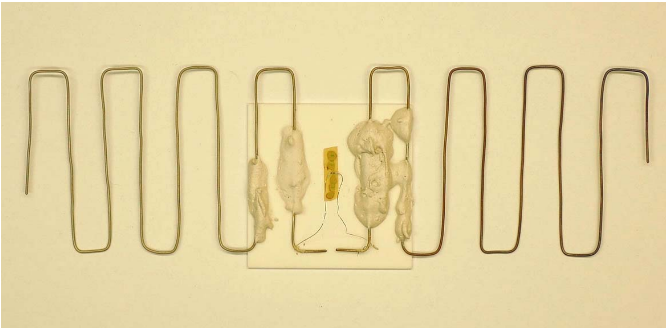

Figure 7. High-temperature antenna with attached SAW device. The alumina substrate and antenna are resting on a vectorboard that is not part of the sensor.

This antenna design was tested at room temperature using the network analyzer attached to a half-wave dipole antenna. In this way the SAW reflections were easily observed at a distance of 225 cm (Figure 8), demonstrating that this design is highly suitable and compact antenna design for wireless sensing. The next step in this work is testing the sensor with attached antenna at high temperature.

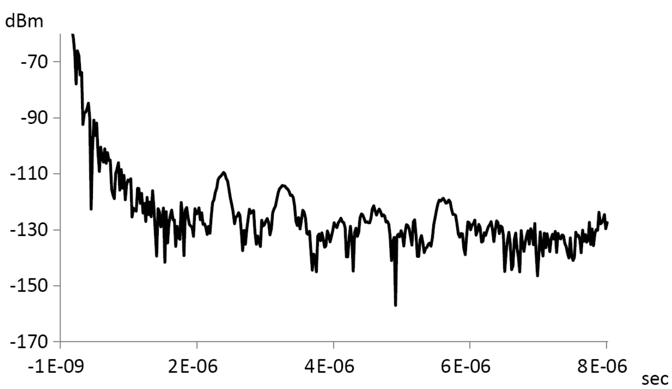

Figure 8. SAW reflections observed wirelessly using the compact antenna design (Data taken at 25 °C with a 225 cm gap between probe antenna and sensor). The first two peaks are from reflectors 3.2 mm and 4.48 mm distant from the emitting transducer.

CONCLUSIONS

We have reported here recent results addressing important aspects of SAW harsh-environment sensing. ZnO/ langasite SAW oxygen sensors have been shown to have good stability of response in repeated testing at temperatures up to 650 °C. Characterization of the SAW sensor input admittance has made it possible to develop efficient antenna designs. The input impedance of the SAW sensor is capacitive with a resistive component is less than 50 ohms, making it necessary to address the impedance match to the antenna. We showed that compact antenna designs provide a closer match to the resistive component and the length can be chosen to provide a conjugate match to the SAW sensor. One antenna design has been fabricated using high-temperature materials and tested. This work makes important progress toward the development of harsh-environment SAW sensors.

ACKNOWLEDGMENT

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VII. REFERENCES

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