Pulse-mode temperature sensing with langasite SAW devices

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***Abstract*— Wired and wireless surface acoustic wave (SAW) sensors with langasite Euler angle (0, 138.5, 27) and (0, 138.5, 117) were fabricated for the purpose of temperature and gas sensing in high temperature combustion process. Their temperature responses were measured in pulse mode both wired to a high-temperature cable and in wireless mode attached to a dipole antenna. The observed surface acoustic wave velocity monotonically decreases above 200 °C with multiple reflections observable in wired measurements up to 900 ºC and in wireless mode up to 700 °C. Temperature resolution better than ± 0.5 C was achieved for wired and wireless measurements from 200 °C to 600 ºC.**

I. Introduction

Temperature and gas sensing in harsh environments is increasingly important for many industrial processes, such as control of oxy-fuel combustion. In this application, high temperature exhaust gas composition and temperature sensors make it possible to control the combustion process so as to achieve a nearly pure carbon dioxide exhaust suitable for geologic sequestration. In order to eliminate power and signal transmission cables, wireless sensing is preferred in these situations. However, very few technological options are available for wireless sensing in the temperature range of interest here (500 ºC ~ 1000 ºC). Wireless passive sensing based on surface acoustic wave (SAW) devices is a promising technique for high temperature wireless sensing [1, 2].

SAW devices use an interdigitated transducer (IDT), consisting of thin metal electrode with equal spacing and width, to generate and receive surface acoustic waves in piezoelectric materials [3, 4]. In wireless SAW sensors, an IDT is connected to an antenna which receives the RF sensing request signal from interrogation equipment. The received RF pulse is then converted into surface acoustic wave by IDT and propagates on the piezoelectric substrate. The surface acoustic wave is reflected back to IDT by reflectors. The reflections are then reconverted to RF signal and sent back to interrogation equipment. Perturbations of the piezoelectric substrate, including variation of temperature, surface conductivity, and surface mass, change the surface acoustic wave velocity. We can therefore use SAW device as a wireless sensor by detecting the change of propagation time or phase of reflected pulse.

Among various piezoelectric materials for SAW devices, langasite ($La_3Ga_5SiO_{14}$) has been shown to be a promising substrate for high temperature sensing [5,6]. The electromechanical coefficient of langasite is about 0.4%, comparable to quartz. It has no phase transition and decomposition below its melting temperature (1470 °C) [5]. In addition, langasite SAW sensors have been reported in several papers with wired gas and temperature sensing demonstrated up to 1000 ºC [7-11], and wireless temperature sensing up to 750 °C [12,13]. However, most of the previous work on wireless langasite SAW sensor is done in continuous wave mode by measuring *S* parameters using a network analyzer. The measurement resolution and wireless transmission range is limited by the network analyzer in this method. The conductivity based langasite SAW gas sensor requires a very high measurement resolution to detect a surface acoustic wave velocity change around 0.01% due to the low electro-mechanical coefficient. Pulse mode measurement with an RF signal generator and signal analyzer offers better resolution by measuring the phase change of SAW sensor reflections. It also provides larger wireless transmission distance. The disadvantage of phase measurement is the phase ambiguity, which can be resolved by designing a SAW sensor with multiple reflections. In this paper, we reported a pulse mode measurement of the langasite SAW temperature sensors, with multiple reflections observable in wired configuration up to 900 ˚C, and in wireless configuration up to 700 ºC. Temperature measurement resolution better than ± 0.5 C was achieved in this work.

II. Experiment

A. SAW Devices

SAW devices were fabricated on 76 mm diameter, 0.5 mm thick langasite wafer (Roditi International, UK). The Euler angles of the surface acoustic wave propagation were (0, 138.5, 27) and (0, 138.5, 117), which use the same wafer cut but different propagation directions. Interdigitated transducers

(IDTs) were fabricated using a lift-off technique and E-beam sputtering. 50 nm platinum, on top of a 10 nm titanium adhesion layer, was used as the metallization.

SAW sensors with the several different combinations of transmitting and reflecting IDTs were designed. Figure 1 shows one typical design, where the transmitter was located in the center, and four reflectors were located on two sides at center-to-center separations of 0.72 mm, 1.44 mm, 2.16 mm and 2.88 mm. The transmitter and reflectors had 2 µm finger widths, 1:1 mask to space ratio, yielding an 8 µm surface acoustic wave length. The number of electrode finger pairs in different SAW designs varied from 10 to 50 for transmitters, and 3 to 60 for reflectors. The transmitter and reflector had the same aperture, 50 or 100 wavelengths. Shorted lines connected two terminals of each IDT to avoid pyroelectric charge accumulation during fabrication. The shorted lines were broken after fabrication giving an open reflector design. Since the reflectors had the same structure as the transmitter, they can be used as transmitter to excite and receive surface acoustic wave reflections as well.

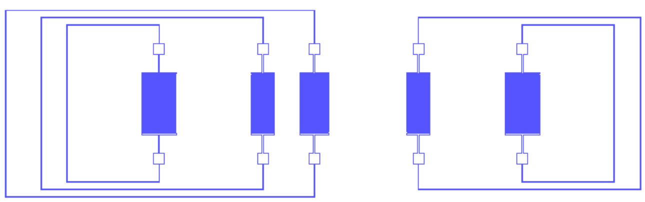

Figure 1. Sensor mask design.

B. *Sensor Packaging*

The langasite SAW devices were first wirebonded in side-braze ceramic packages for room temperature characterization. A variable capacitor and an inductor were used to provide an *L* section impedance matching network. For high temperature characterization, the langasite SAW devices were bonded on 5 cm by 5 cm alumina ceramic substrate using high temperature platinum/silver pastes (9595-A ESL ElectroScience). A sheathed mineral-insulated thermocouple wire (Omega, Super OMEGACLAD XL) was used as the high temperature RF cable for wired sensor measurement (Figure 2). Thermocouple wire of this type is convenient because it can tolerate high temperatures and exhibits a characteristic impedance near 50 ohms. The platinum/silver conductor paste was painted on ceramic substrate to connect the high temperature RF cable with the SAW IDT transmitter terminals. For the wireless sensor measurements, two stainless steel tubes were bonded to a ceramic substrate with high temperature cement acting as a $\lambda/2$ dipole antenna (Figure 3). The dipole antenna is then connected to langasite SAW IDT transmitter terminal using painted platinum/silver conductor paste. No impedance matching circuit was used in the high-temperature experiments to simplify the package design.

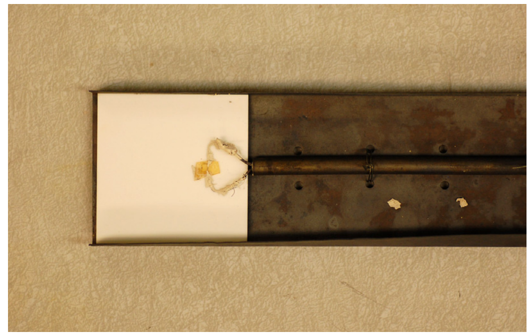

Figure 2. Langasite SAW device connected for wired measurement.

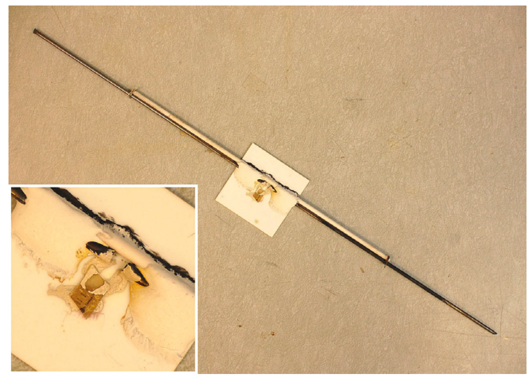

Figure 3. Langasite SAW devicewith dipole antenna connected for wireless measurements.

C. *Measurement Setup*

The wired and wireless sensors were placed in a tube furnace for high temperature measurement. A RF vector signal generator (NI PXI-5670) was used to generate a 0.2 µsec windowed pulse around the resonant frequency of SAW IDT transmitter. The excitation pulse was then directed to the antenna or high temperature cable through a T/R switch to excite the langasite SAW sensor. A vector signal analyzer (NI PXI 5661) was used to receive the reflections from SAW sensor and the attenuated excitation. It then performed the non-coherent phase detection on the reflections and the excitation pulse. The ratio of in phase component to quadrature component was averaged to give better resolution of phase measurement. The phase difference between reflections and the excitation pulse was measured as a function of temperature. The change of phase difference $\Delta\Phi$ is related to the time of arrival change Δt through $\Delta t = \Delta\Phi/2\pi f$, where f is the excitation frequency. The surface acoustic wave velocity change $\Delta\nu$ is then calculated $\Delta\nu = \nu_0\, \Delta t/t$, where ν_0 is the surface acoustic wave velocity at room temperature, t is the total traveling time of the reflection. Based on the above measurement setup, we are able to measure the surface acoustic wave velocity change as a function of temperature up to 900 °C.

III. RESULTS&DISCUSSION

The S_{11} parameter of the IDT transmitter was measured with a network analyzer (Rhode and Schwartz ZVB 4) at room temperature. The langasite SAW device with Euler angle (0, 138.5, 27) had a resonant frequency at 340 MHz, yielding a surface acoustic wave velocity of about 2720 m/sec, while the langasite device with Euler angle (0, 138.5, 117) had a resonant frequency at 325 MHz, yielding a surface acoustic wave velocity of about 2600 m/sec.

The langasite SAW sensors with two different Euler angles were tested using the high temperature RF cable up to 900 ºC. Figure 4 shows the reflections from a SAW sensor with a langasite Euler angle (0, 138.5, 27) at 750 °C, 800 °C, and 850 °C. The excitation pulse had 340 MHz frequency and 15 dBm power. An IDT with 50-pair fingers, 100 wavelength aperture was the transmitter and 3 reflections were observed arriving at 0.54, 0.98, and 1.62 µsec. Figure 5 shows the surface acoustic wave velocity change as a function of temperature for SAW sensor with both Euler angles. The surface acoustic wave velocity monotonically decreases from room temperature to 900 °C for langasite (0, 138.5, 27), while the surface acoustic wave velocity first increases from room temperature to 200 °C, and then decreases above 200 °C for langasite (0, 138.5, 117) . The wired langasite SAW sensors survived over an hour above 800 ºC and the reflections disappeared shortly after heating to 900 °C.

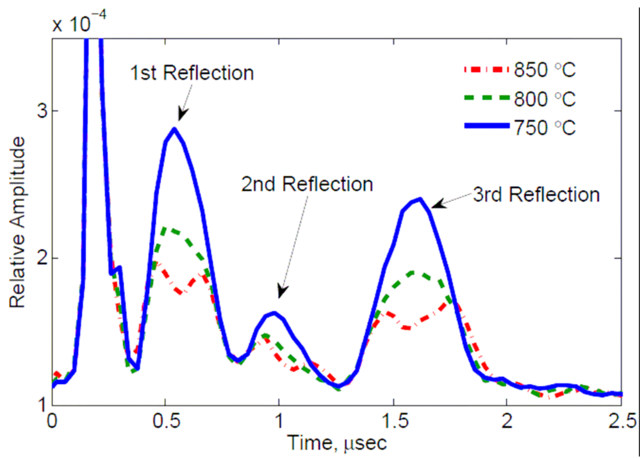

Figure 4. Wired langasite (0, 138.5, 27) SAW sensor reflections at 750 °C, 800 °C, and 850 °C. Three reflections were at 0.54, 0.98, and 1.62 µsec. The peak at 0.2 µsec is leakage from the T/R switch.

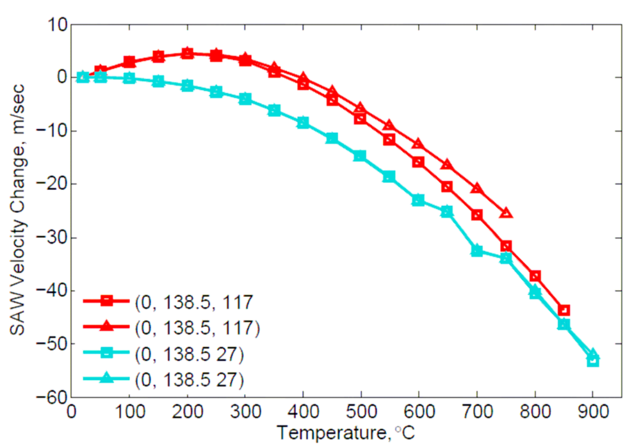

Figure 5. Surface acoustic wave velocity change as a function of temperature in the wired langasite SAW sensor measurement. The square data points are from measurement of the phase difference between the first and the second reflection. The triangle data points are from measurement of the phase difference between the third and the first reflection.

Langasite SAW sensors with both Euler angles were tested in wireless mode up to 700 °C. Figure 6 shows the multiple reflections from the wireless SAW sensor with a langasite Euler angle (0, 138.5, 27). The excitation pulse had a frequency 335 MHz and 17 dBm power. An IDT with 50-pair fingers, 50 wavelength aperture was the transmitter and 3 reflections were observed arriving at 1.12, 2.22, and 2.66 µsec. A monopole antenna was used to drive the wireless sensor at 50 cm distance outside the tube furnace. An aluminum shielding box was used to confine the radiation. Figure 7 shows the surface acoustic wave velocity change as a function of temperature for wireless SAW sensor with both Euler angles. The trend is similar to the measurements obtained on the wired langasite SAW sensor. The surface acoustic wave velocity decrease at 700 °C of wireless langasite (0, 138.5, 27) sensor was 45 m/sec, while for the wired langasite sensor with the same Euler angle was 34 m/sec. This difference could be due to the use of two different wafers for these devices with possibly different misalignment. The measurement result of langasite(0, 138.5, 27) sensor is in fair agreement with previous work on langasite temperature

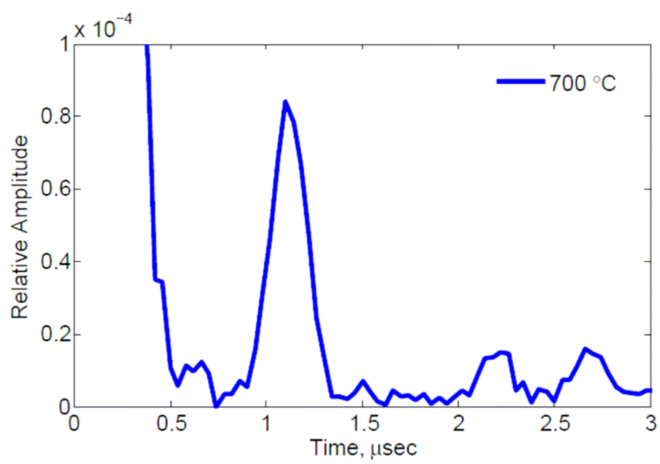

Figure 6. Wireless langasite (0, 138.5, 27) SAW sensor reflections at 700 °C. Three reflections were observed arriving at 0.54, 0.98, and 1.62 µsec.

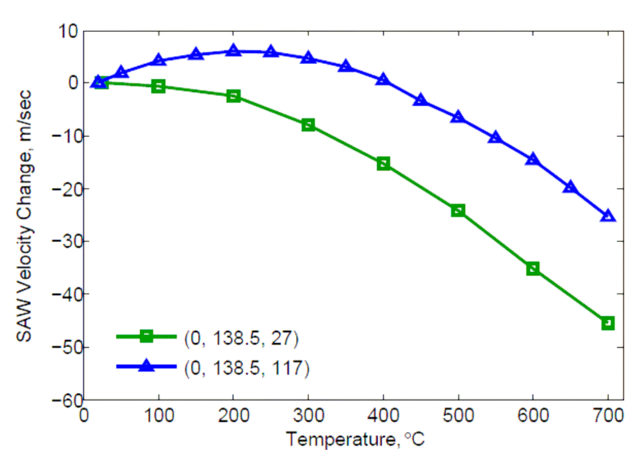

Figure 7. Surface acoustic wave velocity change as a function of temperature in the wireless langasite SAW sensor measurements for two different propagation directions. The phase change was evaluated in different ways (▲ between first reflection and excitation pulse; □ between first and second reflections).

sensors, where the surface acoustic wave velocity decrease at 700 ºC was about 50 m/sec for langasite (0, 138.5, 26.6) in Ref [5], and 45 m/sec for langasite with an unspecified Euler angle in Ref [12].

Finally, we have determined the resolution of the temperature measurement based on the RMS deviation from the average of many sequential temperature measurements. This deviation was calculated from 5 minutes of data where each measurement is obtained from the average of 1000 samples. The temperature measurement resolution was calculated for wired and wireless langasite (0, 138.5, 27) SAW sensor. Figure 8 shows that a measurement resolution better than ± 0.5 ºC was achieved from 200 ˚C to 600 ºC. Both the wired and wireless sensors had poorest resolution around 100 ºC, because the surface acoustic wave velocity dependence on temperature is smallest at this temperature.

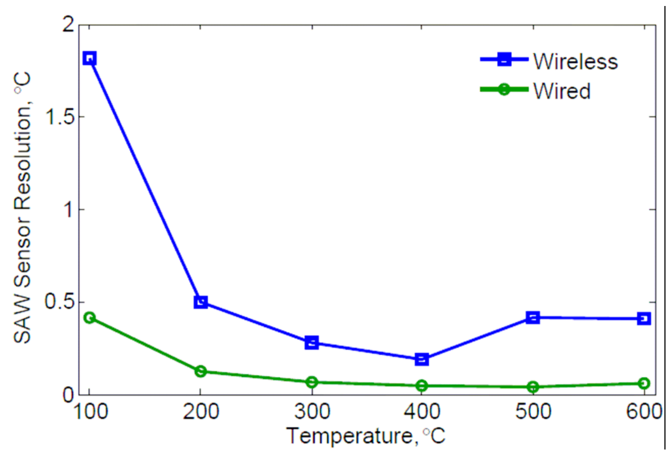

Figure 8. Temperature measurement resolution of wired and wireless langsite (0, 138.5, 27) sensor.

IV. CONLUSION

Wired and wireless SAW sensors with langasite Euler angle (0, 138.5, 27) and (0, 138.5, 117) were fabricated for the purpose of temperature and gas sensing in high temperature combustion process. Their temperature responses were measured in a tube furnace both wired to a high-temperature cable and in wireless mode attached to a dipole antenna. An RF signal generator and analyzer were used to measure the surface acoustic wave velocity change from phase measurements in pulse mode. The observed surface acoustic wave velocity monotonically decreases above 200 °C with multiple reflections observable in wired measurements up to 900 ºC and in wireless measurement up to 700 °C. Temperature resolution better than ± 0.5 C was achieved for wired and wireless sensors from 200 °C to 600 ºC.

ACKNOWLEDGMENT

This work was performed in support of research on carbon storage at NETL under RES contract DE-FE0004000.

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