Langasite Surface Acoustic Wave Sensors for High Temperature Nuclear Reactor Monitoring Applications

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Introduction

There is a significant need for harsh environment sensor materials and sensor systems that can provide reliable, long-term structural health monitoring (SHM) and prognostic capabilities for advanced micro-reactors and high temperature gas reactors (HTGRs) [1],[2]. In addition to being tolerant to high gamma radiation (e.g., > 10 Gy/s) and neutron flux levels (> 10^{12} n/(cm^2·s)), in-core sensors must also be able to withstand the high operating temperatures (> 700°C) that are typically required to achieve the desired high energy conversion efficiencies for these reactors. Such harsh environment constraints limit the type and number of sensor technologies that can be successfully implemented in these reactor systems. For example, there is currently a lack of commercially available in-core neutron flux sensors that can reliably function at temperatures above 550°C [2].

To address these sensor needs for high temperature advanced reactors, researchers at the University of Maine recently demonstrated a langasite (LGS)-based surface acoustic wave resonator (SAWR) sensor technology that is capable of measuring total neutron flux levels up to 2×10^{12} n/(cm^2·s) while operating at 800°C [3]. The SAWR sensor frequency responses were measured in-situ during irradiation exposure and under high temperature conditions at the Ohio State University Nuclear Reactor Laboratory (OSU-NRL) facilities, and supported by the Nuclear Science User Facilities (NSUF) program. The effects of gamma heating on SAWR sensor frequency responses were accounted for by using a controlled furnace that kept the SAWR sensors at a fixed high temperature when exposed to different reactor powers/neutron flux levels. The measured variations in sensor frequency responses could then be primarily attributed to neutron flux induced material softening of the SAWR devices' elastic moduli [4],[5]. As such, this material softening produced frequency variations at a rate of approximately 3 kHz per 0.4×10^{12} n/(cm^2·s), or per 100 kW of reactor power, while operating at 800°C.

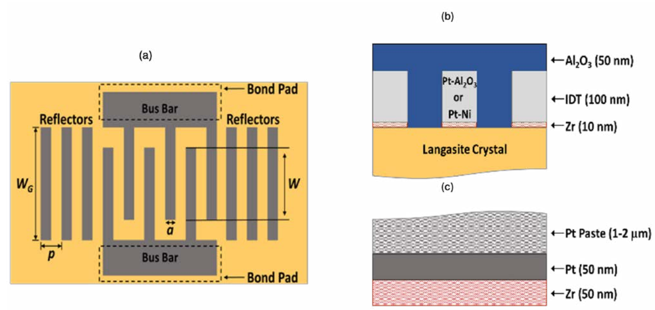

Fig. 23. (a) Top-view schematic of the SAWR sensor device. (b) Cross section of the device at the electrode region. (c) Cross section of the bond pad electrode on top of the bus bar region used for field coupling to the bus bars/interdigital transducer electrodes. Reproduced from [3].

Sensor Fabrication and Packaging

For the work described here, a total of seven LGS SAWR sensors were designed, fabricated, packaged, and calibrated for high temperature operation using UMaine cleanroom fabrication and sensor testing facilities, and were characterized under nuclear radiation and high temperature conditions at OSU-NRL. Fig. 23a-c shows a top-view and side profile diagrams of the general SAWR layout and thin film stack utilized in this work. Five of the devices were fabricated with co-deposited Pt-Al_2O_3 electrodes, and two of the devices were fabricated with alloyed Pt-Ni electrodes, both of which were nominally 100 nm thick. The Pt-Al_2O_3 and Pt-Ni electrode-based SAWRs operated at 331 MHz and 285 MHz resonant frequencies, respectively. These electrode configurations were chosen due to their known stability when operated at temperatures up to the 800°C to 1000°C range under prior testing [6],[7]. In addition, the testing of SAWR sensors with different high-temperature electrode materials (Pt-Al_2O_3 and Pt-Ni) enabled investigations on the influence of material-dependent irradiation softening for the different electrodes, which can impact the overall sensor sensitivity under different reactor power levels and high temperature conditions.

Fig. 24a shows a fabricated LGS SAWR sensor mounted and electronically connected to a high-temperature Inconel coaxial cable using 4 mil and 1 mil platinum (Pt) bond wire, respectively. To further protect the exposed SAWR sensors during transport and testing at OSU-NRL,

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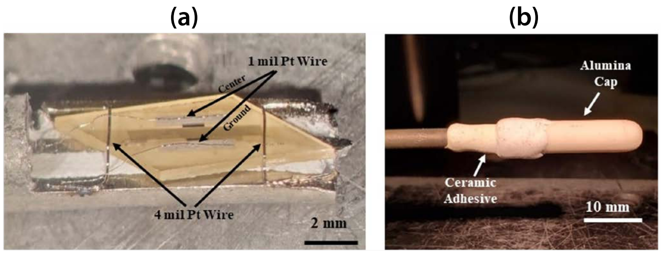

Fig. 24. (a) Top-view of a LGS SAWR sensor device attached and electronically connected to a high temperature Inconel cable. (b) The same device shown in (a) packaged/protected with an alumina cap using a high temperature ceramic adhesive. Reproduced from [3].

high temperature alumina caps were used to cover and package the sensors as shown in Fig. 24b. These UMaine developed wire bonding and device packaging techniques have been successfully tested under a variety of high temperatures and harsh environments [8], and are a critical aspect for successful SAWR sensor testing in advanced high temperature reactors.

High Temperature Reactor Facility Used for Sensor Testing

Fig. 25 shows the OSU-NRL high-temperature test rig furnace and the pool-based reactor facility utilized in this work for in-situ monitoring of the LGS SAWR frequency responses as a function of reactor power/neutron flux and high temperature. The fabricated sensor probes shown in Fig. 24 were initially inserted into the furnace (Fig.25a), which is capable of maintaining fixed high temperatures. Once loaded into the furnace, the sensors were then connected to low temperature RF coaxial cables that were externally routed to a data acquisition system for obtaining in-situ sensor measurements. Two separate type-K thermocouples were included with the sensor bundle and positioned immediately next to the sensors for local temperature measurement feedback. Once the seven SAWR sensors were installed into the furnace, the entire rig shown in Fig. 25a was lowered into a movable vertical ex-core steel dry tube shown in Fig. 25b and positioned next to the reactor core as shown in Fig. 25c.

High temperature irradiation testing of the LGS SAWR sensors took place over five days at OSU-NRL. During this test period, all seven sensors were exposed to a total neutron fluence of approximately 10^{17} n/cm^2; and maximum neutron and gamma flux rates of 2×10^{12} n/(cm^2·s) and 21 Gy/s, respectively, which occurred at the reactor's maximum power of 461 kW. The test temperatures ranged from room temperature to a maximum of 800°C during irradiation.

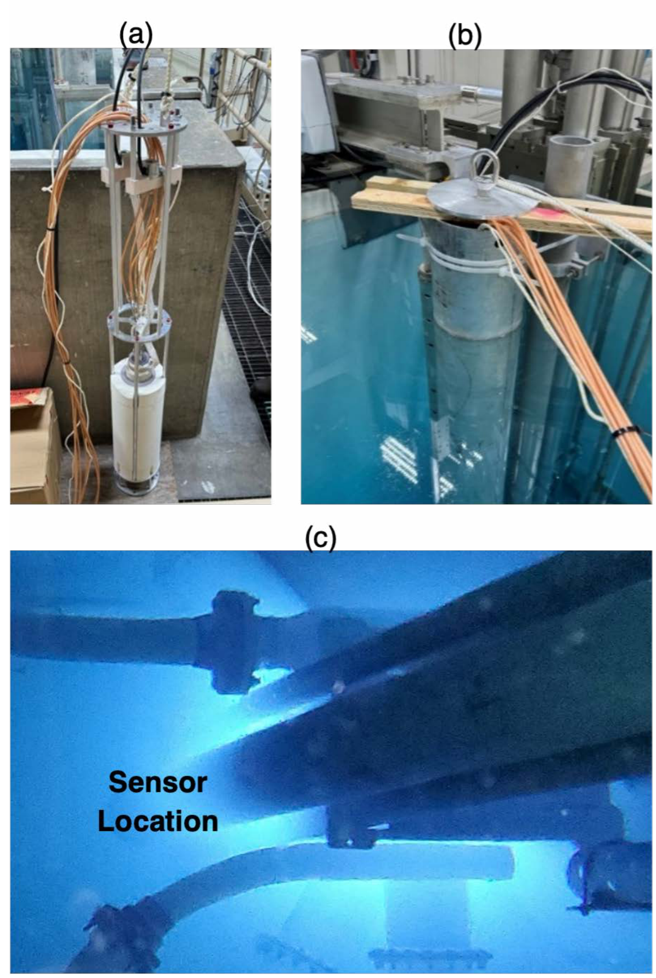

Fig. 25. (a) High temperature test rig loaded with a set of seven LGS SAWR sensor probes. (b) Vertical steel dry tube in the reactor pool, showing low temperature RF cables extending from the tube. The RF cables connect the sensor probes located in the furnace at the bottom of the dry tube to a DAQ system located on a nearby benchtop for in-situ sensor monitoring. (c) A view looking down into the reactor pool during high temperature / high irradiation LGS SAWR sensor testing. Reproduced from [3]

Current Status and Highlights

All seven LGS SAWR sensors tested at OSU-NRL remained functional during testing. In addition, once the sensor radioactivity levels were deemed safe for transport and handling i.e., < 1 µC, all seven SAWR devices were returned to UMaine facilities for post-irradiation analysis. Measurements of the sensors showed no signs of degradation with respect to their pre-irradiation resonant frequencies and signal strengths.

Regarding the exposure to radiation, the tests at OSU-NRL revealed that, in general, the Pt-Al_2O_3 electrode sensors were more sensitive to detecting neutron flux than the devices with Pt-Ni electrodes. In addition, measurements conducted at room temperature showed that significant

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gamma heating of the LGS SAWR devices occurred over the range of reactor powers tested (e.g., up to 90°C at 300 kW), and in general must be accounted for when measuring SAWR frequency shifts that are only due to neutron flux induced material softening.

Fig. 26a shows a representative sensor frequency response overlaid with the reactor power levels used to irradiate the sensor probes at 800°C. Use of the furnace temperature controller ensured a constant sensor temperature during these measurements, meaning the frequency variations shown in Fig. 26a were primarily due to variations in neutron flux and not significantly influenced by variations in gamma heating. As shown in Fig. 26a, the sensor frequency response shifts to lower frequencies when exposed to different reactor powers, which is consistent with a softening in the elastic constants of the SAWR electrodes.

Fig. 26a also shows that larger shifts in reactor power corresponded to larger frequency shifts. Specifically, the LGS SAWR sensors produced linear frequency shifts at an approximate rate of -3 kHz / 100 kW. As such, this approach shows the feasibility of using LGS SAWR technology for monitoring in-core neutron flux rates at temperatures up to 800°C.

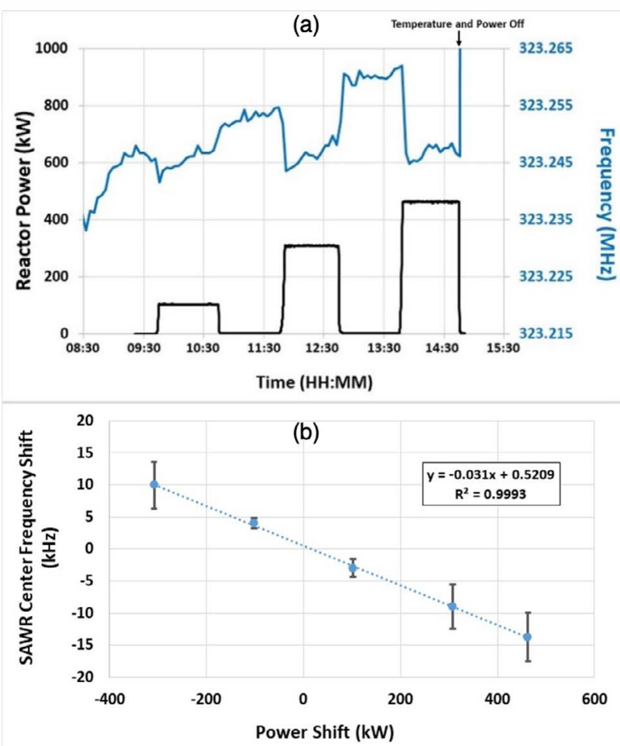

Fig. 26. (a) Representative LGS SAWR sensor with Pt-Al2O3 electrodes showing frequency response at 800°C versus different reactor power levels. (b) Average frequency shift versus reactor power shift. Reproduced from reference 3.

Conclusion and Future Work

The proof-of-principle work described here is an important step towards the development of much needed sensor technologies capable of providing monitoring and prognostic capabilities in harsh environments present within advanced high temperature nuclear reactors. Future work will focus on continued testing of the LGS SAWR sensor platform at higher reactor powers and over longer test periods for technology maturation, and for use in various advanced reactor applications.

Acknowledgements

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