Sensors and Actuators A 224 (2015) 6–13

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

High temperature packaging for surface acoustic wave transducers acting as passive wireless sensors

Bruno François[a,*], Jean-Michel Friedt[b], Gilles Martin[a], Sylvain Ballandras[c]

[a] FEMTO-ST, Time and Frequency Department, UMR6174 CNRS-Univ., Franche-Comté, Besançon, France
[b] SENSeOR SAS, c/o FEMTO-ST Time & Frequency, Besançon, France
[c] frec|n|sys, Temis innovation, Besançon, France

ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form
19 December 2014
Accepted 30 December 2014
Available online 8 January 2015

Keywords:
Packaging process
Surface acoustic wave
Sensor
High temperature
Quartz

ABSTRACT

Numerous developments have been dedicated these passed years to demonstrate the use of surface acoustic wave (SAW) devices as passive sensors probed through a wireless radio-frequency link. Giving access to physical parameter variations without embedded power supply, recent works have shown that SAW sensors can be used under harsh environments such as temperatures in excess of 300 °C and much more. The purpose of this paper is to present a new packaging process for SAW sensors operating under temperature environments up to 600 °C. The robustness of this packaging process is first validated at the above-mentioned temperature using a classical temperature probe via wired connection. The reliability of this process applied to differential SAW sensors then is demonstrated by wireless interrogation of a quartz-based SAW differential sensor from room temperature to 480 °C. The sensor operation has been validated for several tens of hours without major failure nor significant deviation, although the measurement distance dynamic range is observed to be dramatically reduced with operating on such a wide temperature range.

1. Introduction

Surface acoustic wave (SAW) are widely used for telecommunication and on-board signal processing. Their parametric sensitivity also allows one for the development of accurate sensors either based on resonators or delay lines. SAW [1] transducers are therefore considered for probing physical parameters such as temperature in sensing application. Being intrinsically radiofrequency devices compatible with remote powering using RADAR-like measurement strategies, these devices can be used without on-board power supply [2] and as such, the resulting sensors are compatible with harsh environments provided a packaging process adapted to such operation conditions. SAW propagation requires the chip surface to remain stress-free, preventing the use of any kind of material completely surrounding the chip. The most common packaging process for high temperature is based on a mechanical holder for wired measurement [3–5]. The electrical connections between the chip and the housing are done by wire-bonding using bonding wire material resistant to the targeted operating temperature of the sensor. In [6], a bench dedicated to operating gas sensors in a high temperature environment has been developed, here again with the use of a mechanical holder with high temperature-compatible wires for the electrical connection between the sensor and the measurement setup. Although allowing for an effective characterization of SAW sensors, these approaches are poorly suited to a compact conditioning compatible with actual implementation of the sensor for real environment applications. In the EC/Russia co-funded SAWHOT project (NMP4-SL-2009-247821), SAW sensors have been developed for wireless measurements of temperature up to 700 °C [7]. In this context, a dedicated packaging process was developed for achieving the targeted sensor capabilities.

One of the principal motivation of the packaging approach developed in the frame of the SAWHOT project was to propose a low cost and simple process to simultaneously achieve the electrical and mechanical connection between the SAW chip and the antenna required for the wireless communication between the reader and the sensor. The considered solution relies on the use of a refractory cement paste covering the whole sensor structure and preserving standard tin soldering from liquefaction and therefore connection defect. The principle of this approach has been first validated using a wired standard Pt-100 thermal probe submitted to 600 °C. This packaging process then has been applied to SAW quartz-based sensor for testing its reliability, robustness and reproducibility. As the target of the packaging process was

* Corresponding author. Tel.: +33 381402841.

http://dx.doi.org/10.1016/j.sna.2014.12.034
0924-4247/

to operate above 600 °C, quartz-based sensors are unsuitable for such high temperatures since the Curie temperature characterizing the onset of the α to β crystalline orientation is 573 °C [8,9]. However, some experiments have been done [10] to demonstrate the possibility to use quartz substrates as an alternative solution to pure synthetic substrates i.e. langasite family (LGS) [11,12] or gallium orthophosphate ($GaPO_4$) [13] for temperature from 25 °C until 480 °C.

The paper first briefly recalls the principle of wireless SAW sensors. In order to use SAW sensors built on quartz up to 500 °C, the system needs to be assembled and therefore the packaging process developed in this work is discussed. The final sections are devoted to effective temperature measurements in the above-mentioned ranges, assessing the evolution of a sensor chip after temperature cycles, and to the evolution of the physical parameters characterizing the SAW resonator with respect to temperature. The radiofrequency link budget is analyzed in terms of SAW resonator property evolution with temperature: the drop of the quality factor is related to the interrogation range drop, while the coupling coefficient is observed to remain constant. Due to the large resonance frequency shift observed over the extended temperature range, a differential sensor optimizing the use of the radiofrequency spectrum requires overlapping frequency ranges for the two resonances needed for a measurement. The signal processing algorithm used in the wireless reader electronics is flexible enough to allow for the identification of both resonances within an extended frequency band ranging from 430 to 450 MHz. A dedicated algorithm is implemented to get rid of the resonance frequency location within preset radiofrequency sub-bands, providing the flexibility to track each acoustic mode despite crossing frequency curves as temperature evolves, and allowing for the measurement of temperature as long as modes do not overlap. As a conclusion, the capability of differential SAW sensors on quartz to measure temperature up to 500 °C is discussed.

2. Surface acoustic wave interrogation principle

SAW sensors are broadly classified either as delay lines [14] or resonators [15], depending on their spectral characteristics, matching at best the requirements of the industrial, scientific and medical (ISM) frequency band they are designed for. Delay lines exhibit a link budget directly related to the electro-mechanical coupling coefficient and are hence often fabricated on lithium niobate well known for the strength of its piezoelectric properties. The bandwidth required for operating a delay line – typically several tens of megahertz for radiofrequency pulses shorter than 100 ns – confines their operation in the ISM band centered in 2.45 GHz. An alternative approach is the use of narrowband devices (i.e. resonators) which offers access to lower frequency ISM bands. Particularly, the 434 MHz European ISM band is often considered as a tradeoff between antenna dimensions (the quarter electromagnetic wavelength is 17 cm at such a frequency), dice overall dimensions (typically smaller than $3\times3\ mm^2$) and cleanroom processing lithography resolution (6–9 μm acoustic wavelength for most of the available piezoelectric single crystals).

The link budget of a delay line is determined by the electromechanical coupling coefficient (K_s^2) of its surface mode whereas the quality factor Q is the most relevant parameter for a resonator. Indeed, in the former case, the RADAR cross-section in the RADAR equation [16], which defines the ratio of the returned power on the incoming power when a target is illuminated, is replaced with the magnitude of the insertion losses IL, magnitude of the S_{11} coefficient in the time domain of the echo considered, multiplied by the square of the electromagnetic wavelength ($IL \times \lambda^2$), representative of typical antenna area intersecting the sphere over which incoming energy spreads. Since the incoming energy is first converted from electromagnetic to acoustic energy through the electromechanical coefficient K_s^2 and then from acoustic to electromagnetic energy through the reverse principle involving the same coefficient, K_s^2 is the relevant quantity for a constant acoustic path length, *i.e.* a constant acoustic propagation loss. On the other hand, in a resonator probing approach, the sensor is first loaded with energy by an incoming monochromatic radiofrequency pulse. The energy storage time constant is Q/π periods and therefore conditioned by resonance quality. Once the loading pulse stops, a fixed time delay must be kept before listening to the returned signal to get rid of clutter. Typical durations for unloading passive radiofrequency components and getting rid of clutter are in the microsecond range. The exponential decay with time t of the returned signal is of the shape $\exp(t/\tau)$ with $\tau = Q/(\pi \cdot f)$, f being the resonance frequency of the sensor. Since $20 \cdot \log_{10}(e) \simeq 8.7$ dB, the losses associated with exponentially decaying signal returned from the resonator is about $8.7 \cdot f \cdot \pi/Q$ dB/μs. When working at $f \simeq 434$ MHz, and considering quality factors of the order of 10,000 for quartz resonators, the time constant is $\tau \simeq 7.3$ μs. Recording the signal 1 μs after switching from emission to reception yields losses of 1.2 dB on the RF link balance. The linear dependence of this logarithmic-loss with Q is obvious and will be the core issue discussed in Section 6 of the present paper. As mentioned above, quartz-based and langasite-based resonators exhibit Q factors in excess of 10,000 at 434 MHz taking advantage of the limited viscoelastic properties of these materials. To conclude this paragraph, quartz-based and langasite-based resonators exhibit Q factors compatible with wireless sensor application because of their low acoustic losses and moderate coupling coefficient (smaller than 1%), which on the other hand make such materials hardly usable with a delay line approach.

In our embodiment of the pulsed-RADAR like interrogation strategy, the monostatic reader unit emits a radiofrequency signal lasting 5τ for the spectral width of the emitted pulse to be narrower than the width at half height of the resonator at a variable central frequency which is swept over the ISM band. After each emitted pulse, the returned signal is sampled by a radiofrequency power detector one microsecond after switching from emission to reception, and a total delay of 5τ including the signal processing duration is waited for before sending the next pulse to make sure that the resonator was fully unloaded and hence make sure that successive probing pulses provide independent samples. The maximum returned signal is associated with the resonance frequency f of the resonator and is related, through a preliminary calibration step, to the physical quantity under investigation. A differential approach in which at least two resonances are probed using this approach is mandatory to get rid of the effects of the transmission channel, local oscillator drift and aging, or sensor aging.

The underlying physical principle of the sensing mechanism is based on the conversion of the incoming electromagnetic energy to acoustic energy using the inverse piezoelectric effect. As piezoelectricity is linear, the finite spectral width of the incoming pulse is defined as a product with the transfer function of the resonator and the returned power is transmitted as an electromagnetic signal through the direct piezoelectric effect. The identification of the resonance frequency allows for recovering the physical quantity under investigation via conversion coefficients and physical relations. A parabolic frequency-temperature law is generally used to derive the temperature to which the sensor is submitted [17], whereas linear relations are used for determining torque [18] or pressure [19] via SAW stress sensitivity coefficients. Assuming a properly designed transducer, our investigation focuses on the packaging of the sensor to be operated in a high temperature environment.