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Surface acoustic wave electronic tongue for robust analysis of sensory components

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ABSTRACT

A robust approach is presented here for the rapid identification of the different human tastes. Novel two-port resonator-based shear-horizontal surface acoustic wave (SH-SAW) sensors have been designed that operate on a purely physical detection principle. The devices were fabricated on a 3″ 36° YX $LiTaO_3$ wafer and found to resonate at the designed wireless ISM frequency of 434 MHz. They have been also designed to be low loss when operated in aqueous media and without the need for taste-specific coatings. The successful identification of six different tastes was achieved: not only the four common tastes of saltiness, sweetness, sourness, and bitterness but also solutions representing the umami and metallic tastes. 100% separation between samples of the same taste class (e.g. caffeine and quinine hydrochloride of the bitter class) was also demonstrated, as well as a detection and classification of samples of the same substance with different concentrations. Furthermore, the identification of binary taste mixtures and separating them from original component solutions was investigated and confirmed experimentally. We believe that the sensor's response to the mixtures can be described by a simple model based upon combinations of their characteristic physical properties; amongst which electrical conductivity, density and viscosity appear to have the most significant influence. Uncoated taste sensors offer the potential for robust liquid sensors that can be manufactured in volume at low unit cost.

1. Introduction

The extreme versatility of piezoelectric (acoustic wave) sensors is a key quality that underpins their commercial application. The largest consumer is the telecommunications industry that accounts for about 3 billion acoustic wave filters annually – primarily in mobile phones and base stations. Among the emerging areas of application is the food and beverages industry, with potential for applications in process monitoring, quality control, and freshness evaluation. There have been several reviews published recently on applications of different sensing systems in food analysis, especially concentrating on quality and safety of food products [1–4].

Taste sensors are sometimes referred to as e-tongues and are emerging as very promising tools for scientists in a variety of applications in the food industry. In the last few years these systems have been used in food process monitoring, food freshness evaluation and shelf-life investigation, foodstuff recognition, quantitative analysis of food, and food quality control studies. The most common types of sensors in e-tongue applications reported to date are based on electrochemical principles, such as potentiometry and voltammetry [5–9] and other methods include optical and acoustic principles [10–13]. A comprehensive review on the different types of sensing technologies used in electronic tongue systems has been reported in Ref. [3].

The aim of this study is to assess the potential of acoustic devices to complement (or even replace) the human sensory test panels that are frequently employed for flavour assessment, but whose subjective judgements can often lead to variations between panels of up to 50% in terms of flavour units. It is evident that the development of both superior and 'objective' tools in order to detect taste is highly desirable.

In the majority of applications, different types of ion selective electrodes/membranes are employed to convert information about taste substances into an electrical signal. The sensors generate different output patterns for chemical substances that have different taste qualities, such as saltiness and sourness. Based on this principle the taste of some beverages, such as beer, coffee, mineral water, wine, milk, have been quantitatively assessed [7]. Taste sensors using artificial-lipid membranes based on the observation of their global selectivity and high correlation with human sensory scores

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have shown promise in taste evaluation of food and beverages and food quality control as reported in Ref. [14]. Recent analysis of drinking water [15] has demonstrated the potential of using voltammetric e-tongues for the identification of compounds such as NaCl, $NaHSO_3$ and NaOCl and the prediction of their concentrations but using only pure solutions rather than mixtures. Electronic tongue based on pulse voltammetry has recently been employed to assess the quality of black tea samples obtained from the gardens of north and north-east India [16]. The application of piezoelectric quartz crystal sensor arrays, with molecularly imprinted polymer coatings, to determine the presence of quinine and saccharine in bitter drinks has also been reported and the results compared to taste assessment from a human panel [17]. In another study two types of electronic tongues were used as rapid techniques to classify tomato cultivars based on their taste profile [18]. To quantify individual sugars, acids and minerals in a complex mixture, a system based on the potentiometric principle was developed at the University of Saint-Petersburg and has proved highly appropriate, but this system could not predict general sweetness and umami taste as evaluated by the sensory panel. The commercial ASTREE electronic tongue (Alpha M.O.S., France) was able to quantify glutamic acid and NaCl, but the sensor readings were poorly correlated to the sweetness, sourness, saltiness and umami in tomato as tasted by the sensory panel. In another recent study the αAstree e-Tongue from Alpha M.O.S. was used for *umami* taste evaluation of MSG, disodium inosinate and guanylate [19]. However, these instruments are expensive and often desktop with dedicated PCs.

The work described in this paper is based on the design and application of shear-horizontal surface acoustic wave (SH-SAW) devices for indirect taste measurements. A published review [20] of the commonly used acoustic wave sensors argues that the high sensitivity of the electrical perturbation is a significant advantage of the SH-SAW sensors; this makes them very attractive for applications based on electro-acoustic interactions, such as in the food industry and for environmental monitoring. SAW devices that support a horizontal-polarized mode of vibration have been selected in order to reduce the acoustic loss in the liquid. They too usually employ analytical coating films to enhance the chemical selectivity of the sensors. The problem in using biological and organic coatings is that they generally have a short life and so not robust for particular application. However, as stated above we employ devices without bio-chemical layers, thus relying on a purely physical, rather than electrochemical, principle of operation. Such a principle of operation makes the sensors more robust and durable compared to electrochemical sensors. More specifically this paper explores the application of SH-SAW resonator-based configurations for identification of taste solutions. The majority of SAW resonators reported to date have been used in gaseous phase applications [21–23] and very few applications of SAW resonators have been reported for liquid phase measurements [24]. Commercially-available SAW-resonators on a $LiTaO_3$ piezoelectric substrate employing a SiO_2 guiding layer have been used in aqueous media [25] where the study investigated the possibility of increasing the sensitivity of the devices through the application of an optimized wave-guiding layer. Research on one-port resonators [26] showed that the resonance frequency and the Q-factor value depend on the viscosity of the liquid sample; while the conductivity and the square root product of the density and viscosity of the liquid influence the response of two port resonators [27].

Previous work has been reported on the analysis of several taste solutions and results are presented [28]. The sensor proved successful in the identification of six liquid samples: alongside the four classical tastes – saltiness, sweetness, sourness, and bitterness – test samples included aqueous solutions simulating the umami and metallic tastes. Similar devices have been previously used on real complex drinks where 100% discrimination was observed [29].

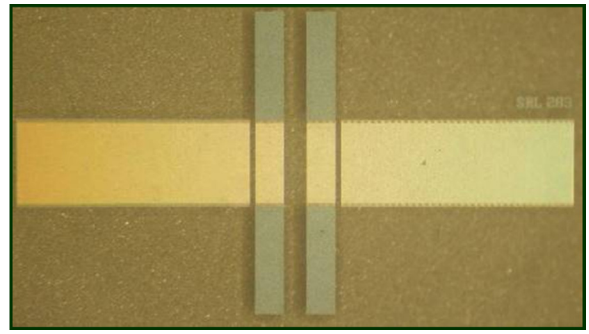

Fig. 1. Photograph of the two-port resonator with the overall dimensions of 4600 μm × 3000 μm. The outer rectangular blocks are the reflectors.

Here we report that SAW sensors are not just able to separate between solutions of the same taste class (e.g. caffeine and quinine hydrochloride of the bitter class) but are also successful in detecting and classifying samples with different concentrations such as 0.5%, 1%, 3% and 5% of sodium chloride. The sensors were also exposed to binary mixtures of taste solutions and they proved successful in discriminating them and separating them from original solutions.

2. SH-SAW two port resonator sensor – theory and design

Our devices were designed with both ports having identical parameters: 25 solid finger pairs forming inter-digitated transducers (IDTs) of 2.4 μm pitch and a 384 μm acoustic aperture. The IDTs form a cavity of 192 μm (20λ) wide; the reflectors on each side of the cavity consist of 400 strips in a positive and negative reflector arrangement with the same 2.4 μm pitch. However, from a traditional resonator design perspective our device is non-ideal because it has a smaller number of finger pairs per IDT than normally recommended [30] in order to reduce its footprint. The condensed resonator fits within a die with overall dimensions 4600 μm × 3000 μm. A photograph of a single two-port resonator sensor is shown in Fig. 1.

The resonator sensor configuration has a free cavity, thus the sensor output is a complex combination of both acousto-mechanical and acousto-electric effects. Electrical measurements were performed with a network analyser (Agilent 8753ES) and amplitude and phase information have been recorded for each measurement. This two-port resonator has been used in a similar experimental set-up to that of a delay line sensor described in Ref. [31]. Generally, the sensor's amplitude A and phase response Φ can be expressed as a complex function of the liquid physical properties, e.g. viscosity η, density ρ, electrical conductivity σ, dielectric permittivity ε and temperature T as:

$$A, \Phi = f(\eta, \rho, \sigma, \varepsilon, T) \tag{1}$$

The derivation of the acousto-electric interaction parameters can be obtained by means of an equivalent circuit model [32], which treats the near surface currents induced by the acoustic wave. The elements G, C_l, C_s in Fig. 2 can be obtained by considering the current flows caused by the varying surface potential φ. $G = k\sigma$, $C_l = k\varepsilon_l$ and $C_s = k\varepsilon_s$, represent the conductance and capacitance of the liquid per unit area and the capacitance of substrate per unit area, respectively. In the absence of ions in the solution, the decay of electric potential ϕ a distance y into the liquid can be found by solving Poisson's equation, which yields

$$\nabla^2\phi = 0 \Rightarrow \phi(y, x, t) = \phi_0 e^{-ky} e^{j(\omega t - kx)} \tag{2}$$

in which k is the unperturbed wave number of the wave travelling in x direction, and ϕ_0 is the potential at the solid/liquid interface.