Sensors and Actuators B 204 (2014) 50–56

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Dynamics and response of a humidity sensor based on a Love wave device incorporating a polymeric layer

Jiansheng Liu*, Lijun Wang

Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form 11 July 2014
Accepted 22 July 2014
Available online 30 July 2014

Keywords:
Surface acoustic wave
Love wave
Humidity
Viscoelastic
Adsorption

ABSTRACT

In this study, we investigate the dynamics and response of a humidity sensor based on a polymer-coated Love wave device. A review is presented for the theoretical model of Love waves in a layered structure with a viscoelastic layer on a piezoelectric substrate. Numerical illustrations are executed for the mass velocity sensitivity and mass loss sensitivity of a polymer-coated device. The BET equation and its improved equation are introduced to describe the adsorption mechanism of gas on the detector surface. A method is introduced for calculating the surface area of the polymer layer, which is proved a porous material. An experiment is performed for a humidity sensor based on a Love wave device consisting of two 28 μm-periodic interdigital transducers, a 0.47 μm-thick PVA layer, and an ST-90°X quartz substrate. The operation frequency and insertion loss of the Love wave device are measured by using a network analyzer; the relative surface area of the PVA layer is calculated through comparing the fitted and the theoretical frequency shift caused by the monolayer of water molecules. The frequency shifts and insertion loss increments are shown as functions respect to the relative humidity; the theoretical curves agree well the experimental results.

1. Introduction

In the past few decades, surface acoustic wave (SAW) sensors [1–3] have been attracting the interest of many researchers because of their high sensitivity, small size, low cost, and easy fabrication. SAWs are excited and received by the interdigital transducers (IDTs) deposited on the surface of a piezoelectric substrate. Due to the surface energy concentration, SAWs are very sensitive to the disturbance acting on the substrate surface. Using this feature, SAWs have broad prospects in many sensing areas such as temperature [4], pressure [5], strain [6], acceleration [7], mass loading, etc. Wherein SAW gas sensors [8,9], a type of sensor for mass loading, are often coated with sensing films to achieve higher sensitivities and the selective adsorption of a target gas. Because of their simple coating and good selectivity, polymers are often used as sensitive films for SAW gas sensors.

Humidity is of great importance in varieties of commercial and industrial applications, so humidity sensors have been attracting the interest of many researchers [10]. For a humidity sensor based on SAW technology, one of the most important design considerations is the choice of sensitive film. The most common sensitive films are polymers [11–14] with strong hygroscopicity, which is helpful to obtain a larger output response. However, the insertion loss of the detector will also increase due to the polymer's viscoelasticity.

Love wave is a kind of SAW which propagates in a layered structure. The substrate of a Love wave device supports a purely (or predominantly) piezoelectric shear horizontal (SH) acoustic wave which is faster than the transverse wave in the upper layer. Because of the particle polarization only existing in the SH direction, almost no energy is coupled into the liquid above the layer, thus Love waves are also suitable for detection in liquids. Different from a commonly used Rayleigh type SAW device, the performance of a Love wave device depends on its guiding layer rather than on IDT structures and substrate characteristics. A suitable guiding layer is the key to implement a Love wave sensor with high mass sensitivity, good temperature stability, and acceptable insertion loss. Due to its low acoustic loss and excellent abrasion resistance, SiO_2 is the most used guiding layer material for Love wave devices. Unfortunately, a Love wave sensor incorporating a SiO_2 layer cannot achieve a very high sensitivity, because of the fast transverse acoustic waves in SiO_2. Due to their low shear waves, polymers are often adopted as guiding layers for Love wave sensors to get a higher sensitivity.

The shortcoming of polymeric layer is the large loss caused by the viscosity of polymers. To analyze the effect of the viscosity, many theoretical models have been developed for SAW devices

* Corresponding author. Tel.: +86 1082547803.
E-mail addresses: liujs98@hotmail.com, liujiansheng@mail.ioa.ac.cn (J. Liu).

http://dx.doi.org/10.1016/j.snb.2014.07.095

incorporating polymeric layers. Based on perturbation approach, Martin et al. [15] investigated the dynamics and response of polymer-coated SAW devices with acoustically thin and thick layers. They committed that the changes in velocity and attenuation caused by the viscoelastic film were related to the surface mechanical impedances contributed by the film. By expanding the complex dispersion equation into Taylor series, Kielczynski [16] analyzed Love wave devices incorporating a low loss guiding layer. By adopting Maxwell model to describe the viscoelasticity of polymer layers, McHale et al. [17] developed a method for describing Love wave sensors incorporating viscoelastic guiding layers. In our previous works [18,19], the authors reported a method for Love wave devices consisting of a polymeric layer on a piezoelectric substrate by adopting a Maxwell–Weichert model to describe the viscoelasticity of the guiding layer.

For gas sensors, another key element is the adsorption mechanism of gas on detector surface, which describes the relationship between the adsorption amount and the gas concentration. In past decades, many experimental studies [11,20–22] were carried out to measure the curves of SAW velocity (or oscillation frequency) changes versus different gas concentrations. However, theoretical research was rarely reported on the gas adsorption mechanism in the field of SAW sensors. In our recent paper [23], the gas adsorption mechanism was described by adopting a Brunauer–Emmett–Teller (BET) equation and its improved form. Combined the Wohljent's theory, a theoretical method was developed for the response mechanism of SAW gas sensors based on surface adsorption. By using a commercial SAW gas chromatography (GC) analyzer, the method was verified by an experimental measurement of the frequency shifts caused by different concentrations of dimethyl methylphosphonate (DMMP).

In this study, we investigate the dynamics and response of a humidity sensor based on a polymer-coated Love wave device. Firstly a theoretical model is reviewed for Love wave device consisting of a polymeric layer and a piezoelectric substrate. The mass velocity sensitivity and the mass loss sensitivity are introduced for polymer-coated devices. Numerical illustrations are presented for a Love wave device with a polymeric layer on an ST-90°X quartz substrate. Secondly the BET adsorption equation is introduced to describe the physical adsorption of gas on solid surfaces. Anderson equation, a improved form of BET equation, is presented to expand the suitable scale of the adsorption equation. A method is introduced for calculating the surface area of the polymer layer. The response of SAW devices caused by gas adsorption is analyzed. In the experiment section, a humidity sensor is implemented based on a Love wave device consisting of a polyvinyl alcohol (PVA) layer on an ST-90°X quartz substrate. The response curves are measured for changes in operation frequency and insertion loss as functions respect to relative humidity (RH). Theoretical curves are also predicated by the developed method and they agree well with the experiment results.

2. Theoretical analysis on Love wave sensors

2.1. Dispersion equation and mass sensitivity

In this section, a review is presented on Love waves in a piezoelectric layered structure [24,25]. Fig. 1 displays the schematic of a Love wave device and the coordinate system used in this work. The propagation direction is parallel to the x_1-axis; the particle displacement is parallel to the x_2-axis, which is in the SH direction. The piezoelectric substrate occupies the lower half space of $x_3 < 0$; the non-piezoelectric layer occupies the internal space of $0 < x_3 < h$; the upper half space of $x_3 > h$ is occupied by the air which is assumed none mechanical touch on the layer surface. Material constants of the piezoelectric substrate must be in some special forms [26] to support pure SH acoustic waves coupled with electric fields.

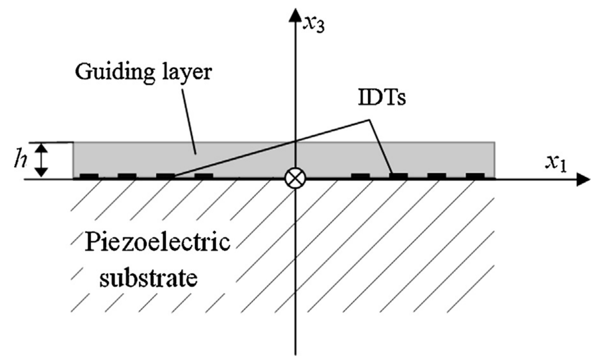

Fig. 1. Schematic and the coordinate system of a Love device.

In the piezoelectric substrate, the particle motion is coupled with the electric field, thus the particle displacement and the electric potential must satisfy the following equations:

$$c_{jk2l}\frac{\partial^2 u_2}{\partial x_k \partial x_l} + e_{k2l}\frac{\partial^2 \varphi}{\partial x_k \partial x_l} = \rho\frac{\partial^2 u_2}{\partial t^2}, \quad j = 1, 2, 3; \quad k, l = 1, 3 \tag{1}$$

$$e_{k2l}\frac{\partial^2 u_2}{\partial x_k \partial x_l} - \varepsilon_{kl}\frac{\partial^2 \varphi}{\partial x_k \partial x_l} = 0, \quad k, l = 1, 3 \tag{2}$$

where c, e, and ε are elastic, piezoelectric, and dielectric constants of the substrate respectively, ρ is the mass density, u_2 is the particle displacement in the x_2 direction, φ is the electric potential. Solutions of the shear acoustic wave and electric field in the substrate are:

$$u_2 = [M_1 A_1 \exp(k\beta_1 x_3) + M_2 A_2 \exp(k\beta_2 x_3)] \exp\{i(\omega t - kx_1)\} \tag{3}$$

$$\varphi = [M_1 \exp(k\beta_1 x_3) + M_2 \exp(k\beta_2 x_3)] \exp\{i(\omega t - kx_1)\} \tag{4}$$

where ω is the angular frequency, k is the wave number, β is the amplitude decaying factor in the $-x_3$ direction, M is the undetermined coefficient to be decided by the boundary conditions.

In the isotropic layer, the SH acoustic wave is uncoupled with the electric field and their solutions are in following forms:

$$u_2^L = [M_3 \exp(ik\beta_L x_3) + M_4 \exp(-ik\beta_L x_3)] \exp\{i(\omega t - kx_1)\} \tag{5}$$

$$\varphi^L = [M_5 \exp(kx_3) + M_6 \exp(-kx_3)] \exp\{i(\omega t - kx_1)\} \tag{6}$$

where $\beta_L = \sqrt{v^2/V_L^2 - 1}$, v is the propagation velocity of Love waves, $V_L = \sqrt{\mu_L/\rho_L}$ is the velocity of the transverse acoustic wave in the layer, and μ_L and ρ_L are the shear modulus and mass density of the layer medium respectively.

In the space above the layer, only the electric field exists and it can be described as:

$$\varphi^0 = M_7 \exp\{-k(x_3 - h)\} \exp\{i(\omega t - kx_1)\}. \tag{7}$$

The acoustic waves and electric fields must obey the following boundary and continuity conditions:

(1) At the interface of $x_3 = 0$, the continuity conditions for particle displacement, electric potential, normal stress and normal electric displacement for the electrically open case are:

$$\begin{cases} u_2(x_3 = 0) = u_2^L(x_3 = 0) \\ T_{23}(x_3 = 0) = T_{23}^L(x_3 = 0) \\ \varphi(x_3 = 0) = \varphi^L(x_3 = 0) \\ D_3(x_3 = 0) = D_3^L(x_3 = 0) \end{cases} \tag{8}$$