TLM Modeling for Analysis and Design of SAW Hydrogen Sensor

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1. Introduction

Basically SAW sensors[1-4] for the detection gas consists of a pair of transducers, an input interdigital transducer (IDT) and an output IDT, provided on the surface of a piezoelectric substrate over which the waves propagate, as shown in Fig. 1. The sensing film between two transducers is chosen for the gas detection. The Palladin film is usually used for detection of hydrogen gas.

The characteristics analysis of the SAW sensors have been evaluated using the equivalent circuit model, finite element method and etc[3-4]. In the present paper, we propose alternative modeling, a Transmission Line Matrix (TLM) modeling [5-6] for the SAW sensor analysis. The TLM modeling provides time domain characteristics evaluation. The results using TLM modeling are compared with one with the equivalent circuit model.

2. TLM Modeling of Acoustic Wave Propagation

To implement the acoustic wave propagation on the piezoelectric substrate, we considered two factors - electromechanical coupling coefficient $K^2$ and the propagation velocity variation - in the TLM modeling. In the non-electroded region with the surface acoustic impedance $Z_s$, waves travels at the velocity $v_f$ and, in the electroded region with the surface acoustic impedance $Z_e$, waves travels at the velocity $v_e$. The electromechanical coupling coefficient $K^2$ due to the piezoelectric substrate is defined by

$$K^2 = 2 \frac{v_f - v_e}{v_f}$$  \hspace{1cm} (1)

For the waves incident to the electroded region, the reflection coefficient $R$ is given by

$$R = \frac{Z_e - Z_f}{Z_e + Z_f} = \rho_f \rho_e \frac{\rho_f v_e - \rho_f v_f}{\rho_f v_e + \rho_f v_f}$$  \hspace{1cm} (2)

where, $\rho_f$ and $\rho_e$ are respectively the equivalent surface mass density of the free region and that of the electroded region.

Fig. 1  A typical SAW gas sensor.

An one-dimensional minute wave field can be described by a line TLM element (length=$\Delta l$), consisting of two transmission branches with a node at its center as shown in Fig. 2. Each branch has the surface characteristic impedance $Z_0=\rho v$, where $\rho$ is the equivalent medium density and $v$ is the propagation velocity of the surface wave.

![TLM elements for acoustic wave propagations](image)

(a) One-dimensional \hspace{1cm} (b) One-dimensional with damping and variable velocity

Fig. 2  TLM elements for acoustic wave propagations.

The propagation velocity may be changed by the introduction of branches at the node. The introduction of the 3rd branch of length $\Delta l/2$ with the characteristic impedance $Z/\eta$ provides the variable propagation capability, with which one has

$$v_f = \sqrt{\frac{2}{\eta + 2}} v$$  \hspace{1cm} (3)

The 3rd branch is short-circuited at the end. The velocity depends on parameter $\eta$ chosen, which is the specific admittance of that branch measured in terms of $Z_0$[6]. The 4th branch is introduced to include the damping for the two IDTs. The loss is thus considered. The damping depends on parameter $\zeta$ of the branch of infinite length, which is the specific admittance measured in terms of $Z_0$.

The scattering at the node is partly damped due to the energy to the infinite long branch, and
the scattering matrix is defined as follows
\[
\begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix}_{\omega,\eta} = \frac{1}{\eta + \zeta + 2} \begin{bmatrix}
-\eta - \zeta & 2 & 2\eta \\
2 & -\eta - \zeta & 2\eta \\
2 & 2 & -\eta - \zeta - 2
\end{bmatrix}\begin{bmatrix}
P_1 \\
P_2 \\
P_3
\end{bmatrix},
\]
where \(P\) and \(S\) are respectively the incident and scattered pulses. The TLM network is illustrated in Figure 6, for a pair of the electrodes (2 fingers) in the IDT, which consists of \(40\Delta l (=\lambda_0)\).

3. Numerical Demonstrations

For the simulation, it is assumed that the input IDT consists of twenty and a half pairs (41 fingers) and the output IDT consists of twenty pairs (40 fingers). The central frequency is \(f_0=4\text{MHz}\) or \(\lambda_0=872\mu\text{m}\). The surface acoustic velocity is \(v=3488\text{ m/s}\). For the substrate material, YZ-lithium niobate is taken. The electromechanical coupling coefficient is assumed to be \(K^2=4.6\%\) for \(\eta=0.09527\) and \(\zeta=0.0046\). As each electroded region is consisted of 10 division, so that \(\zeta=K^2/10\). The distance between two IDTs is 20 \(\lambda_0\).

At first, we demonstrated the surface acoustic wave propagation without the sensing film between two transducers. We didn’t describe about the equivalent circuit model and its performance, but for the comparison, we just referred our previous paper [7]. Figure 5 is impulse responses in the equivalent circuit model and the TLM modeling. Figure 6 is the corresponding frequency characteristics Fourier-transformed, for a single impulse excitation. The results from TLM modeling is shown to be resembled in comparison with the equivalent circuit model.

Next, we considered the sensing film with Palladin. We referred the velocity profile with their thickness from the reference 8. According the data, \(\eta\) were calculated 0.07822 for thickness 2.038(\(\mu\text{m}\)), 0.44193 for thickness 2.19(\(\mu\text{m}\)). Figure 7 shows the simulation results. From above, there are no sensing film, 2.038(\(\mu\text{m}\)), and 2.19(\(\mu\text{m}\)). The first arrival time respectively were delayed 16(\(\Delta t\)), 85(\(\Delta t\)) from the result of Fig. 5.

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References