Sensitivity Comparison between Surface Acoustic Wave and Lamb Acoustic Wave Hydrogen Gas Sensors

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Introduction

- Several applications for hydrogen gas sensors
  - Automation
  - Transportation
  - Environment
  - Health
  - Agriculture
  - Resulting in an increasing demand on more sensitive and more reliable hydrogen gas sensors

- Currently, acoustic technology based on Rayleigh mode (SAW) is often used
  - Reliable
  - Passive
  - Robust
  - Low fabrication cost

- Explore new technology based on Lamb waves
  - Sensitivity comparison with technology based on Rayleigh wave

- Sensitive layer: Palladium (Pd)
  - High capability to interact with hydrogen
Methodology

Selected mode characteristics

- Low frequency
- Symmetric
- Compression or extension along the propagation direction

- High frequency
- Anti-symmetric
- Shearing in the thickness direction

- High and Low frequencies
- Elliptic displacement in the sagittal plane and is evanescent in the thickness of the medium

- \( S_0 \) Lamb mode
- \( A_1 \) Lamb mode
- SAW mode
Methodology

Sensitivity comparison method

Parametric study with Comsol based on simultaneous variations of Palladium sensitive layer properties

Density variation of $\pm 5\%$

Young’s modulus variation of $\pm 20\%$

Frequency determination for each study

Relation determination between $f$, $E$ and $\rho$

$$f = f_0 \left( 1 + b \left( \frac{E - E_0}{E_0} \right) + c \left( \frac{\rho - \rho_0}{\rho_0} \right) + d \left( \left( \frac{E - E_0}{E_0} \right) \left( \frac{\rho - \rho_0}{\rho_0} \right) \right) \right)$$

3% hydrogen concentration

Curve fitting method

Reduced equation to compare relative sensitivities
Methodology

Finite Element Model

- Models used
  - Piezoelectric
  - Linear elastic
  - Electric
  - Multiblock
  - Conformal
  - Floquet periodic

- Mesh

- Boundary conditions

a) Lamb mode

- Multiblock
- Conformal

b) SAW mode

- Multiblock
- Conformal
Methodology

- Frequency Band Identification
  
  Sensitivity study in ISM bands:
  
  Dispersions curves of Lamb waves in 2 µm ZX AlN plate

<table>
<thead>
<tr>
<th>Modes Selected</th>
<th>ISM Band (MHz)</th>
<th>Period (µm)</th>
<th>Wavelength (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>433.05 – 434.79</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>A1</td>
<td>902 – 928</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>SAW</td>
<td>433.05 – 434.79 or 902 - 928</td>
<td>4 or 1.5</td>
<td>8 or 3</td>
</tr>
</tbody>
</table>
Results and discussions

Reduced equation for sensitivity study:

\[
f = f_0 \left(1 + b \left(\frac{E - E_0}{E_0}\right) + c \left(\frac{\rho - \rho_0}{\rho_0}\right) + d \left(\frac{E - E_0}{E_0}\right)\left(\frac{\rho - \rho_0}{\rho_0}\right)\right)
\]

### Sensitivity comparison

**Between \( S_0 \) and Rayleigh mode**

<table>
<thead>
<tr>
<th>Mode sensitivity</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_0 )</td>
<td>0.0321</td>
<td>-0.1529</td>
<td>0.0027</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>0.0421</td>
<td>-0.1070</td>
<td>0.0071</td>
</tr>
</tbody>
</table>

430 MHz ISM Band

**Between \( A_1 \) and Rayleigh mode**

<table>
<thead>
<tr>
<th>Mode sensitivity</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>0.0293</td>
<td>-0.1941</td>
<td>0.0195</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>0.0774</td>
<td>-0.2130</td>
<td>0.0078</td>
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</tbody>
</table>

920 MHz ISM Band

### Sensitivity comparison table

<table>
<thead>
<tr>
<th>Mode</th>
<th>( f_0 ) (MHz)</th>
<th>( f ) with 3% hydrogen concentration (MHz)</th>
<th>Frequency shift (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_0 )</td>
<td>476</td>
<td>476</td>
<td>0</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>442</td>
<td>440</td>
<td>0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>( f_0 ) (MHz)</th>
<th>( f ) with 3% hydrogen concentration (MHz)</th>
<th>Frequency shift (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>1154</td>
<td>1155</td>
<td>0.09</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>1082</td>
<td>1075</td>
<td>0.65</td>
</tr>
</tbody>
</table>
To a 3% hydrogen concentration

- Rayleigh mode is more sensitive to changes in Pd stiffness than the $S_0$ mode.
- $S_0$ mode is more sensitive to the mass loading effect than the Rayleigh mode.
- Rayleigh mode is more sensitive to the simultaneous stiffness and mass variations than the Lamb waves.

- Explore other acoustics modes.
- Other comparisons to determine the influence of hydrogen concentration.
- Validation of theoretical results by experiments.
Thank you !!!