Digital phase detection approach and its application for AlN dual-mode differential surface acoustic wave sensing

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Received 4 January 2007; received in revised form 9 January 2008; accepted 18 January 2008
Available online 31 January 2008

Abstract

Performance of a conventional phase detector implemented using analog circuitry is affected by, among other factors, the parameter value drifting of the analog components with environment (e.g., temperature) and time (i.e., aging). It is also adversely impacted by electromagnetic interferences likely existing in the analog circuits when the detector operates in a high frequency range. More importantly, such a detector is inflexible to compensate various nonlinear characteristics of sensors and is very difficult to realize sophisticated signal processing strategies desired for practical applications. To address issues like these, we have developed a digital system approach that uses the zero-crossing algorithm for phase detection. The phase detection limit and dynamic phase response of the system were assessed using surface acoustic wave (SAW) sensors. Our preliminary evaluation involved aluminum nitride (AlN) dual-mode differential sensors, which were fabricated on an AlN(0001)/Al\textsubscript{2}O\textsubscript{3}(1\overline{1}20) thin film structure, with the SAW and shear horizontal SAW (SH-SAW) operating at approximately 243 MHz and 256 MHz, respectively. Due to the hardware constraints, the digital phase processing was carried out in an off-line fashion. Our baseline experiments without sensor indicate that the system can achieve a lower level of phase noise with the standard deviation being about 0.005\textdegree. Experiments with the differential sensors running in the SAW and SH-SAW modes exhibit that the system can reach a phase detection limit of 0.02\textdegree. The differential system showed small temperature coefficient at ppm level measured by varying the sensor temperature using a thermal control oven. Finally, our use of the system in measuring the response of the SH-SAW sensor to sodium chloride (NaCl) solution conductivity shows that the system is capable of performing microanalysis of liquid properties. We conclude that a real-time fully digital phase detection system can be practically achieved.

Keywords: Digital phase detection; AlN; SAW; SH-SAW; Conductivity

1. Introduction

In the area of surface acoustic wave (SAW) sensing, there exist two fundamental approaches to construct the signal processing system: (1) the phase detection approach that measures the perturbation altered phase velocities by tracking the phase change between the input and output of the SAW sensor; (2) the oscillator loop approach by which the sensor, together with amplifiers, are placed in a feedback loop, to generate oscillation at a fixed frequency so that the perturbation mechanisms can be correlated to the oscillation frequency change. The former approach is more favorable in aqueous sensing applications for its good tolerance to large change in insertion loss of SAW sensors [1]. The key element of the conventional hardware solution for phase detection is an analog phase detector. Analog elements are known to be prone to environment change (e.g., temperature) and aging, and are not flexible to handle nonlinear characteristics existing in the system. Analogy system is also susceptible to harmonic, noise, and electromagnetic interferences [2]. Therefore, performance of this type of systems is not ideal. The specification of a phase detector is largely device dependent, resulting in poor hardware shareability among different SAW sensor systems.

In this work, we propose a flexible and higher resolution digital phase detection system as part of our efforts to develop a novel piezoelectric aluminum nitride (AlN)-based SAW sensor system. As compared to the conventional phase detector-based system that simply monitors the phase and amplitude information, this system utilizes the built-in analog-to-digital (A/D) converters of an off-the-shelf digital oscilloscope to record

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complete waveform information, a merit that enables easy application of digital signal processing methods for phase detection, harmonic suppression, and noise reduction. Such system can be virtually adopted by any SAW sensor with proper choice of sampling rate to retain the fidelity of SAW waveforms.

The digital phase detection system is tested on an AlN dual-mode (SAW and SH-SAW) differential sensor platform. Piezoelectric AlN is promising for miniaturized SAW sensor applications due to its fast acoustic velocity and relative high mass sensitivity [3–5]. Recent studies showed that a SAW mode and a SH-SAW mode can be excited simultaneously along Al2O3[1 1 0 0] on an AlN(0001)/Al2O3(1 1 2 0) structure [6]. The SH-SAW mode was shown to have high mass sensitivity as does the SAW mode and thus it can be utilized for aqueous sensing as its SH wave component radiates little energy into surrounding fluid [1].

We will first describe the principle of the digital phase detection system and investigate its phase detection resolution with and without sensors in the loop. The dynamic phase response of the system is then tested by producing the temperature variation on the AlN dual-mode sensors in a controlled fashion. To further evaluate the system performance in an actual sensing environment, we expose the AlN SH-SAW sensors to sodium chloride (NaCl) solutions and their response to solution conductivity change are analyzed by the digital phase detection system and compared with theoretical calculation.

2. Experiment setup

2.1. Digital phase detection system

Several digital methods, such as zero-crossing [7], sine-wave fitting [8], and fast Fourier transform (FFT) phase detection [2], have been reported in the literatures for general-purpose phase discrimination. However, little work has been done to explore their potential for fully digitized SAW sensor data acquisition and signal processing systems. In our prior work, the FFT phase detection, sine-wave fitting, and zero-crossing phase detection methods were comprehensively investigated under the presence of harmonics and added noises in SAW sensors [9]. The zero-crossing method yielded the smallest standard deviation of phase noise, which was 0.21 mdeg for purely sinusoidal waves and 5.1 mdeg for sinusoidal waves with additive noise and harmonic frequencies. It had less computational complexity than sine-wave fitting, and was not subject to the limited frequency resolution as in the FFT method due to the limited sampling length [10]. As a result, the zero-crossing method is implemented in our digital phase detection system (Fig. 1).

A signal source provides a high-frequency sinusoidal signal that matches the operating frequencies of two identical SAW delay line sensors. The SAW, excited by the sinusoidal signal at each sensor input, travels to the output with certain phase delay and is converted back to electrical signal by the output interdigital transducers (IDTs) [1]. Two sensor output signals are digitized by the A/D converters and the phase difference between two sensors is calculated by the signal processing software.

The zero-crossing method is the core of the signal processing software and its principle is now briefly described. The sinusoidal waves from sensors 1 and 2 can be expressed, respectively, as:

\[
y_1(t) = V_1 \sin(2\pi f t + \varphi_1)
\]

\[
y_2(t) = V_2 \sin(2\pi f t + \varphi_2)
\]

where \(V_1\) and \(V_2\) are the wave amplitudes, \(f\) is the operating frequency of the SAW sensors, and \(\varphi_1\) and \(\varphi_2\) are the instant phases of the two signals. The sampled digital signals of \(y_1(t)\) and \(y_2(t)\) are given as:

\[
y_1(nT_s) = V_1 \sin(2\pi fnT_s + \varphi_1)
\]

\[
y_2(nT_s) = V_2 \sin(2\pi fnT_s + \varphi_2), \quad n = 1, \ldots, N
\]

where \(T_s\) and \(N\) are the sampling period and the length of the sampling sequence, respectively.

Linear interpolation is employed to calculate the sampling time related to the zero-crossing points [11]. In Fig. 2, \((t_{m}, y_{m})\) and \((t_{m+1}, y_{m+1})\) are the sample points on sinusoidal wave 1 that are most adjacent to the time axis (i.e., \(0\) V) at times \(t_m\) and \(t_{m+1}\); \((t_n, y_n)\) and \((t_{n+1}, y_{n+1})\) are the sample points on sinusoidal wave 2 closest to the time axis at times \(t_n\) and \(t_{n+1}\). \(T_m\) and \(T_n\) are the time values estimated from the linear interpolation algorithm:

\[
T_m = \frac{|y_n| t_{m+1} + |y_{m+1}| t_m}{|y_n| + |y_{m+1}|}
\]

\[
T_n = \frac{|y_n| t_{n+1} + |y_{n+1}| t_n}{|y_n| + |y_{n+1}|}
\]

The time difference between the sinusoidal waves 1 and 2 can be expressed as \(\Delta t_k = T_m - T_n\), where \(k\) is defined as the smaller value of \(m\) and \(n\). The number of zero-crossing points is dependent on the sampling rate, sampling length, and signal frequency. Averaging all these points, we derive the averaged...
instant phase difference between the two sinusoidal waves:

\[ \Delta \phi = \frac{\sum_{k=1}^{L} (\Delta \phi_k)}{L} \times f \times 360^\circ, \]  

(4)

where \( L \) is the total number of the zero-crossing points.

In actual phase detection process, the existence of DC offset and harmonic frequencies can bring unwanted errors to the measurement. To deal with this problem, a digital finite impulse response (FIR) bandpass filter with linear phase response is utilized to remove the harmonic frequencies. The FIR filter introduces an additional fixed phase delay [12]. But when two signals are processed with the same filter, such phase delay will be cancelled out, leading no appreciable change to the actual phase difference between the two signals [13]. The DC offset, on the contrary, can be largely eliminated by subtracting the mean value of each sequence of the signal from its original values.

The corresponding insertion losses of the SAW and SH-SAW modes are −30.6 dB and −42.2 dB, respectively.

Fig. 3. Implementation of the digital phase detection system.
2.3. Experiment setup for testing the baseline resolutions of the digital system

The baseline resolutions of the digital system, with and without sensors in loop, were measured at room temperature \((T = 24 \, ^\circ\text{C})\) by inputting a sinusoidal signal from the signal generator. The sinusoidal signal was set at 250 MHz, which was close to the operating frequencies of the AlN SAW and SH-SAW modes. The baseline responses were measured multiple times, each for a duration of 10 min.

2.4. Experiment setup for testing the dynamic phase response of the digital system

In order to evaluate the performance of the digital phase detection system in response to dynamic phase shift of the AlN dual-mode sensors, the sensors were mounted onto the circuit board and placed in a thermal control oven (Isotemp 10-750-14 from Fisher Science Inc.), which produced temperature variation from 30 °C to 90 °C at a 10 °C interval with temperature stability of ±1 °C. The oven was maintained at each temperature setting point for 20 min to reach the thermal equilibrium on the sensors. The temperature-induced phase shifts of the differential sensors were recorded by the digital system for both the SAW and SH-SAW modes.

2.5. Liquid conductivity measurement experiment using the digital system

To evaluate the digital phase detection system in a SH-SAW sensing application, a liquid conductivity measurement experiment was carried out using the AlN SH-SAW differential sensors. The SH-SAW mode is suitable for fluid-based sensing since its shear horizontal displacement component ideally does not couple energy into fluid. In this experiment, propagation characteristics of the SH-SAW loaded with conductive solutions was monitored by the digital phase detection system. Propagation of the SH-SAW is accompanied by an evanescent electric field, which extends into the adjacent liquid. The acoustoelectric interaction of the electric field with ions or dipoles in the conductive liquid would conversely perturb the wave velocity and amplitude [16,17]. Differential sensing structure was utilized in this experiment with one sensor as the sensing sensor and the other as the reference sensor. Unlike the sensing sensor, which had a free AlN surface between input and output IDTs, an aluminum thin film was evaporated onto the inner IDT region of the reference sensor so that the surface was electrically shorted and was no longer susceptible to acoustoelectric interaction. The signal changes in responses to liquid viscosity, density, mass loading, etc. should therefore be cancelled out in the phase difference, leaving only the changes resulting from acoustoelectric interference. To manage the injection and confinement of liquid, two acrylic flow cells shown in Fig. 5 were glued onto the inner IDT region of the two sensors by UV curable epoxy (Dymax 1186-M). The open area for liquid loading is 2.9 mm × 2.8 mm with a unit volume of 2 µl. Deionized (DI) water and sodium chloride (NaCl) solutions with different concentrations were injected into the flow cells alternatively. The phase shifts induced by the liquid alteration were sampled and calculated by the digital phase detection system when the fluid was standing still on the surface. The solution conductivity was monitored by a conductivity meter (Oakton pH/CON 510) at the same time.

3. Experiment results and discussion

3.1. Phase resolution without sensor in loop

The upper panel of Fig. 6 shows the typical phase detection results before applying the moving average filter. The system yields a random phase noise pattern with a standard deviation of 0.018°, which is larger than the standard deviation of 0.0051° achieved in our simulation study [9]. This is because, in the real sensing process, the phase difference calculation depended not only on the algorithms but also on the hardware factors such as synchronization between sampling channels [18], time base nonlinearity [19], and sampling jitters of A/D converters of the oscilloscope [20]. Fortunately, this standard deviation of phase noise (0.018°) could be reduced by a moving average filter. The lower panel of Fig. 6 presents the standard deviation of the phase noise with respect to the number of data points \((M)\) used in the moving average filter. By raising \(M\) from 0 to 50, one can substantially cut down the standard deviation from...
0.018° to 0.0065°. Such trend eases off and a reduction of only ~0.002° occurs to the standard deviation as \( M \) increases from 50 to 250. The selection for \( M \) is a tradeoff between the computing time and the desired phase noise suppression level. In this regard, we selected \( M = 200 \) and a standard deviation as small as ~0.005° was achieved by the system. This result is comparable to the reported 0.006° phase noise obtained with a much higher sampling frequency of 20 GHz when using a digital storage oscilloscope to measure the phase shift in an electron storage ring for synchrotron radiation applications [2].

### 3.2. Phase detection limit with the AlN sensors in loop

Fig. 7 shows a typical measurement of the phase difference between two sensors for both the SAW and SH-SAW. The peak-to-peak values of the phase difference were within the range of 0.01–0.016° for the SAW and SH-SAW, respectively. It showed that the digital phase detection system with the differential sensor configuration was effective in reducing the common-mode interference. The corresponding standard deviations of phase noise were 0.006° and 0.008° for the SAW and SH-SAW, respectively. If we adopt the definition of the detection limit as three times the standard deviation of noise [1], this AlN dual-mode digital phase detection system could reach a detection limit of around 0.02°.

### 3.3. Phase response of the digital system induced by temperature variation

By stepping up the oven temperature, we produced sensor temperature variation from 30°C to 90°C at a 10°C interval. The corresponding phase shift results for SAW and SH-SAW modes are shown in Fig. 8a and b, respectively. For both modes, the sensors exhibit a reverse linear relationship between the phase shift and temperature. The temperature coefficient of frequency (TCF), for the film thickness-to-wavelength ratio of 0.08 in our case, was estimated as the slope of the fractional frequency change vs. temperature:

\[
TCF = \frac{1}{f_0} \times \frac{\Delta f}{\Delta T}
\]

Fig. 8. Phase response of the digital phase detection system with respect to temperature change imposed on the AlN differential sensors: (a) SAW mode; (b) SH-SAW mode. The phase response of one of the two differential sensors is not shown. It is almost identical to the one shown, which can be inferred from the phase difference.
where $f_0$ is the operating frequency at room temperature ($T = 24^\circ C$). Here the simple relation $\Delta v/v_0 = \Delta f/f_0 = -\Delta \varphi/\varphi_0$ is used to calculate the TCF, with $\Delta v/v_0$, $\Delta f/f_0$, and $\Delta \varphi/\varphi_0$ being the fractional change in velocity, frequency, and phase, respectively [1].

The derived values for single AlN sensor were around $-56$ ppm/$^\circ C$ and $-61$ ppm/$^\circ C$ for the SAW and SH-SAW, respectively. Since the measured intrinsic phase shift of the circuit board only accounted for 1% of the overall phase shift in the observed temperature range, we hereby ignored the temperature effect of the circuit board. The measured TCFs of SAW and SH-SAW are slightly smaller than the reported values of $-59$ ppm/$^\circ C$ and $-63$ ppm/$^\circ C$ for the SAW and SH-SAW modes, respectively [6]. Such differences may arise from the nonconformity in the AlN film thickness-to-wavelength ratios.

Using the differential configuration, the temperature-induced phase difference change between the two sensors was much smaller than the phase shift of the individual sensors. The average TCF of the differential sensors was dramatically reduced to 0.78 ppm/$^\circ C$ for the SAW and 2.2 ppm/$^\circ C$ for the SH-SAW. Apparently, this differential system is effective in cancelling out the temperature effect on the SAW sensors.

### 3.4. Liquid conductivity measured by the digital system

The system’s response to alternative loading of DI water and NaCl solution was studied. Solutions with five different concentrations were used in the test and the corresponding conductivities monitored by the conductivity meter were 0.42 S/m, 0.62 S/m, 1.08 S/m, 1.67 S/m, and 2.7 S/m, respectively. Fig. 9 shows the phase shift of the differential sensors when the liquid was switched from water to 1.08 S/m NaCl solution. At any instance of time, two sensors were loaded with the same type of liquid and the phase difference between the two sensors was plotted as a function of time. As is apparent in the figure, good reproducibility of the phase shift pattern is achieved in the repetition cycle. Since the reference sensor had a metallized wave path, the $\sim 1.2^\circ$ phase shift that occurred upon the NaCl solution loading could be solely attributed to acoustoelectric interference from the solution.

Fig. 9. Phase shift of AlN SH-SAW differential sensors for the 1.08 S/m NaCl solution.

By repeating the DI water/NaCl solution injection cycles, the phase shift data were measured with respect to the solution conductivities. The data were then translated to the fractional velocity change of the SH-SA by the simple relation:

$$\frac{\Delta v}{v_0} = \frac{\Delta \varphi}{\varphi_0} = \frac{\Delta \varphi}{2\pi f_0 l}$$

where in our case $f_0 = 256.05$ MHz and $v_0 = 6145$ m/s were the unperturbed SH-SA frequency and velocity, respectively, and $l = 2.9$ mm was the wave path under liquid perturbation. We herein assume that the effect of acoustoelectric perturbation is uniform along the entire wave path. The calculated $\Delta v/v_0$ was plotted as a function of solution conductivity $\sigma$ in Fig. 10. For the range of the solution conductivity examined, increased conductivity slows down the SH-SA velocity as a consequence of the coupling between ions in solution and the evanescent electric field accompanying the wave propagation [16]. To investigate the validity of the experiment results, a solid curve is plotted in Fig. 10, representing the fractional velocity change of the AlN SH-SA mode based on the following reported theoretical model [21]:

$$\frac{\Delta v}{v_0} = \frac{K^2}{2} \frac{2\varepsilon_S}{\varepsilon_S + \varepsilon_L} \frac{\sigma^2}{\varepsilon_S + \varepsilon_L}$$

Fig. 10. Conductivity measurement—experimentally measured by the digital sensor system vs. theoretically calculated.

where $K^2$ is the electromechanical coupling coefficient, $\omega$ is the angular frequency of the SH-SA, $\varepsilon_S$ and $\varepsilon_L$ are the dielectric constants of the substrate and solution, respectively. In our calculation, $K^2$ is experimentally determined to be 0.05% from piezoelectric shorting effect – $K^2 = -2\Delta v/v_0$, where $\Delta v/v_0$ is the fractional velocity change due to Al coating on the inner IDT region [1,15]. The dielectric constant of AlN is $\varepsilon_S = 11\varepsilon_0$ [22]; for both water and NaCl solutions, $\varepsilon_L = 79.3\varepsilon_0$ is used, assuming ions in the diluted solution have no significant effect on the dielectric constant. As shown in Fig. 10, the measured phase shift points are in good agreement with the trend of the calculated curve. The slight differences may be attributed to the level of accuracy in the estimated $K^2$ value. In addition, the presence of ions in the solution also tends to perturb the dielectric constant from that of the pure water [17,21].

\[\text{Fig. 10. Conductivity measurement—experimentally measured by the digital sensor system vs. theoretically calculated.}\]
4. Conclusion

We described a digital phase detection approach to SAW sensing applications. The system relied on the zero-crossing algorithm for phase measurement. It offers flexible choice of diverse digital signal processing algorithms to achieve stable phase response. The system had a baseline resolution of $\sim0.005^\circ$ without outliers in loop. When interfaced with the AIN differential SAW sensors, the system could achieve a phase detection limit of $\sim0.02^\circ$. The response of the digital phase detection system with the AIN-based SAW and SH-SAW, operating at 243.325 MHz and 256.050 MHz respectively, was measured in the temperature range from 30°C to 90°C. Linear TCF of around $-60$ ppm/$^\circ$C was derived for individual SAW and SH-SAW modes. With the use of the differential sensor configuration, the temperature effect was reduced by around 60 times for the SAW mode and 30 times for the SH-SAW mode. The system was also used to measure the response of the AIN SH-SAW sensors to solution conductivity change. The results showed distinctive phase shift with respect to the conductivity change of NaCl solutions, which conformed to the trend of the theoretical calculations.

In conclusion, the feasibility of using the digital phase detection system for SAW sensing has been established. Although due to the hardware constraints our system processed the signals in an off-line manner, the concept is readily adapted to real-time applications that interrogate SAW sensors or general acoustic wave sensors working at various frequency bands. If standalone A/D converters are used instead of those in a digital oscilloscope, the entire digital phase measurement system can be built as a portable device suitable for many real-time sensing applications.

Acknowledgements

This work was supported in part by NIH grant 1RO1EB00741-01, DoD grant DAAE07-03-C-L140, and the Smart Sensors and Integrated Microsystems program at Wayne State University.

References


Biographies

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Gregory W. Auner is a professor of electrical and computer engineering, biomedical engineering, and material science at Wayne State University in Detroit, MI. He is the founder and director of the Smart Sensors and Integrated Microsystems (SSIM) program at WSU which encompasses 5 interconnecting laboratories with over 11,000 sq. feet of space involving 35 participating faculty, 30 graduate students, 20 staff scientists/engineers, and 15 undergraduate researchers. In partnership with Delphi Research and Development and NASA, the SSIM program has established a 5000 sq. foot class 100/10 clean room facility. Dr. Auner has developed an array of instruments, sensors and microsystems for federal institutions, research institutions, and industry. Approximately 80%
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Joseph Smolinski is a research professor associated with the Smart Sensors and Integrated Microsystems group in Electrical and Computer Engineering Department at Wayne State University. He has worked at the LTV Steel and Ford Motor Company Research labs prior to receiving his PhD in chemical engineering for Wayne State University in 1994. His previous research areas include machining and cutting fluids, polymer rheology, and super critical gas systems. For the past 5 years his research has concentrated on the development of sensors for the detection and analysis of biological and chemical agents.

Hao Ying received his PhD degree in biomedical engineering from The University of Alabama, Birmingham, Alabama, in 1990. He is a professor at Department of Electrical and Computer Engineering, Wayne State University. He is also a Full Member of its Barbara Ann Karmanos Cancer Institute. He was on the faculty of The University of Texas Medical Branch at Galveston between 1992 and 2000. He was an adjunct associate professor of the Biomedical Engineering Program at The University of Texas at Austin between 1998 and 2000. He has published one research monograph entitled Fuzzy Control and Modeling: Analytical Foundations and Applications (IEEE Press, 2000), 86 peer-reviewed journal papers, and over 115 conference papers. Dr. Ying is an associate editor for five international journals and is on the editorial board of two other international journals.