Feasibility Study for the Evaluation of Chicken Meat Storage Time Using Surface Acoustic Wave Sensor

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Abstract
Purpose The objectives of this study are to provide the detailed information of designing, fabrication process, and performance test results of a surface acoustic wave (SAW) sensor for evaluating chicken meat storage time (up to 15 days).

Methods The aldehyde gas generated from chicken meat was selected as the reactive material, and Love wave was used among various SAWs due to its high sensitivity of the aldehyde gas particles. The SAW sensor was fabricated on the surface of LiNbO₃ piezoelectric wafer with a cross-linked polydimethylsiloxane (PDMS)-sensitive layer using standard photolithographic techniques. To analyze the fabricated SAW sensor characteristics, the S₂₁ parameters and base line noise were acquired by a vector network analyzer. Before measuring chicken meat gas samples, a reference gas (a mixture of 25, 50, 75, and 100 ppm acetaldehyde (a functional group with the structure –CHO, CH₃CHO) and nitrogen (N₂) gas) was measured to verify the reactive performance of the SAW sensor. Among the VOCs from chicken meat gas, CH₃CHO was selected as an intrinsic biomarker due to its harmful effects on the human body. Then, aldehyde gas from chicken meat samples was measured and the phase changes of the response signals with increasing the chicken meat storage time were obtained by the SAW sensor.

Results About −4 dB insertion loss occurred due to the PDMS coating and the high electromechanical coupling factor of used substrate. The phases of the response signals decreased linearly with increase of both the reference gas concentration and the storage time of the chicken meat samples. The determination coefficients of the reference gas and the storage time were over 0.9. The results show that the developed SAW sensor can provide valuable information about evaluating the chicken meat storage time.

Conclusion The newly developed SAW sensor clearly demonstrates that chicken meat storage could be evaluated by detecting aldehyde gas. This opens a promising research avenue to explore.

Keywords Aldehydes · Chicken meat · Cross-linked polydimethylsiloxane · Love wave · Surface acoustic wave sensor

Introduction

Chicken meat is one of the most commonly consumed meats around the world, and it should be kept cold during distribution to retail stores to prevent the growth of bacteria and to increase its shelf life (Igene et al. 1979; Silva and Glória 2002; Soyer et al. 2010). The quality of chicken meat varies with several factors during the slaughtering process, storage, and distribution. Therefore, technology for sensing the quality of chicken meat has become important in various food industries.
The deterioration of the freshness of meats usually begins with the breakdown of protein and fat, which are caused by enzymes secreted by microorganisms. Thus, a variety of volatile organic compounds (VOCs) are released by the microorganisms that live in meat and they can typically be analyzed using solid-phase microextraction (SPME). SPME is an effective sample preparation technique that involves several operations such as sample collection, extraction, analyte enrichment, and isolation from sample matrices and has been used to extract analytes (including both volatile and nonvolatile) from different kinds of gaseous, liquid, and solid phase. Microorganisms such as *Salmonella enteritidis*, *Escherichia coli*, *Klebsiella pneumonia*, and *Enterobacter cloacae* are the primary causes of the VOCs that can be found in pork, goose, and duck meats, as well as in chicken meats (Arnold and Senter 1998; Du et al. 2000; Eišamotu et al. 1998; Soncin et al. 2007). In addition, because an aldehyde is a compound including a functional group with the structure –CHO, acetaldehyde can also be classified as aldehyde gas. Among the VOCs, acetaldehyde, an organic chemical compound with the formula CH₃CHO in aldehyde group and a result of ethanol metabolism, is one of the most important factors considered in sophisticated packaging systems regarding contamination from packing. Numerous studies on the correlation between aldehydes in the human body and specific illnesses have recently been conducted (Bicanic et al. 2003; Fromme et al. 2008; Nanto et al. 2000; You et al. 2009). Thus, it is classified as a carcinogen and its maximum permitted concentration is 25 ppm per 8 h, as defined by the American Conference of Governmental Industrial Hygienists (ACGIH) (Giberti et al. 2012; Mitsubayashi et al. 2005). Its inhalation can cause serious health problems related to the central nervous system such as headache, paralysis, respiratory disorders, and a comatose state (Jun et al. 2011; Yamashita et al. 2010).

Therefore, in this study, CH₃CHO was selected as the reference gas for evaluating aldehydes from chicken meat in relation to storage time. Recently, a number of sensing methods have been developed (such as spectroscopy, gas chromatography, chemo-resistivity, chemo-capacitance, field effect gas sensors, amperometry electrochemical cells, and electronic nose systems) that are useful for detecting aldehydes in air and liquid phases (Calestani et al. 2011; Giberti et al. 2012; Jun et al. 2011; Mitsubayashi et al. 2005; Yamashita et al. 2010). Among these methods, electronic nose systems have been widely studied for evaluating the freshness and a quality of food by analyzing VOC components (Fitzgerald et al. 2017; Loutfi et al. 2015). They can be used to assess the changes in quality and thus, how long meats have been in cold storage (according to the type of food) (Boothe and Arnold 2002; Di Natale et al. 1997; Olafsdottir et al. 2005). The application of electric nose techniques, with respect to the freshness levels of fish species and meats, accounts for a large area of VOC analysis. However, to the best of our knowledge, studies on the rapid evaluation of aldehyde gas from chicken meat have rarely been conducted using a non-destructive testing method (Loutfi et al. 2015). For the rapid and precise detection of VOCs, surface acoustic wave (SAW) devices have drawn a substantial attention for biosensing applications. Their advantages include simple sensing structure, cost-effective capabilities, relatively small size, fabrication reproducibility, and fast output. These qualities make them attractive choices for various VOCs and liquid sensors (Biswas et al. 2004; Leonte et al. 2006; Liu et al. 2011; Shen and Liou 2008; Wen et al. 2007). Accordingly, we selected the SAW sensor for the evaluation of aldehyde gas from chicken meat. For SAW gas sensing, its surface is coated with a chemically active membrane (sensitive layer), which can absorb specific gas molecules. The sensitive layer responds to mass changes on its surface with a frequency shift and can be used for gas-phase sensing applications (Horriollo et al. 2004; Pan et al. 2014). Therefore, a chemically selective layer should be used to collect and concentrate target molecules on its surface. To accomplish this, cross-linked polydimethylsiloxane (PDMS)-based sensing techniques have been selected because of its being inexpensive, flexible, and nontoxic, and exhibit a swelling effect upon absorbing volatile aldehyde molecules (Horriollo et al. 2004; Lin et al. 2008; Ning et al. 2016; Weng et al. 2009). In addition, the PDMS-based sensitive layer can easily be achieved using a spin-coating method on a SAW inter-digital transducer (IDT) (Almenar et al. 2007; Joo et al. 2007; Lee et al. 2013; Weng et al. 2009; Wyszynski et al. 2010).

Among various SAWs, the Love wave was selected due to its excellent ability for detection of specific molecular interactions between its sensitive layer and piezoelectric substrate. Based on the above techniques, the SAW sensor was designed to respond to changes in the phase when it is exposed to aldehyde gas. Before measuring the aldehyde, gas generated from chicken meat samples, a reference material (a mixture of CH₃CHO and N₂ gas) was measured using the SAW sensor for verifying its reacting performance and aldehyde gas from actual chicken meat was evaluated.

**Materials and Methods**

**Analysis of Gas Components from Chicken Meat in Relation to Its Time of Storage**

Fresh chicken meat from a slaughterhouse was purchased and sliced. Samples (150 g) of the chicken meat were put into glass bottles that were sealed with a cap. These were then stored at 4 °C for intervals from 1 to 15 days. Differences in the gaseous components of the chicken meat samples stored
for different intervals were analyzed using the SPME method. With the gas chromatography-mass spectrometry (GC-MS Saturn 2000, Varian Inc., CA, USA) technology associated with this method, it is possible to detect and identify volatile compounds. The analysis involved the use of an HP-5 capillary column (Cross-linked 5% PHME siloxane, Hewlett-Packard Co., CA, USA). The temperatures of the column and of the injector were set to 260 °C, and helium was used as the carrier gas. The thickness of the fiber that collected the gas components was 50 μm, and the fiber was coated with divinylbenzene (DVB)/carboxin (CAR)/PDMS. Chicken meat samples (5 g) were each put into a vial and sealed with a septum. After incubating a vial with the chicken meat sample at 37 °C for 20 minutes, the gases from the headspace were allowed to adhere to the fiber for 3 minutes, after which their spectra were analyzed by software included with the GC-MS device.

**SAW Sensor Design and Fabrication**

The SAW sensor was designed to detect aldehyde gas in order to evaluate the time chicken meat had been stored. The SAW sensor consisted of input and output IDTs, a sensitive layer, acoustic absorbers to reduce triple transit echo, and a piezoelectric substrate. Fig. 1 shows a conceptual diagram of the structure of the SAW sensor.

In Fig. 1, the acoustic waves are generated by supplying a voltage to the input IDTs on the piezoelectric substrate and they travel along both x-directions. When propagating both x-directions on the surface of the piezoelectric substrate, one passes under the sensitive layer and the other reaches to the acoustic absorber. The output IDT receives and converts the acoustic waves into electrical signal (voltage), and the acoustic absorber attenuates the unnecessary mechanical energy.

The IDTs consist of a pair of electrodes and many of repeated parallel fingers are connected to each other. When excitation voltage is applied to produce a potential acoustic energy, the piezoelectric substrate is deformed and changes the electrical energy into the acoustic energy. The nature of the acoustic wave depends on the sound speed of the used piezoelectric substrate \( v = f \times \lambda \) (\( v, f, \) and \( \lambda \) are sound velocity, operating frequency, and wavelength of piezoelectric substrate). The width between the fingers is typically calculated to be a quarter wavelength of the sound speed of the piezoelectric substrate (LiNbO₃ wafer, about 4000 m/s) (Lee et al. 2011, 2012).

In this study, single IDT pattern design was used due to its advantages of simple structure and high sensitivity. Although double IDT design can provide effective resolution and decrease signal distortion characteristics generated between the IDT electrodes, single IDT design was used, because high sensitivity is one of the most important factors for biosensing application. In addition, more precise control for fabricating double IDT pattern requires high cost as well as increases error rate for the entire SAW sensor system. The operating frequency of the newly fabricated SAW sensor, the finger width of the IDT, the number of finger pairs, the length of each finger, and the distance between the IDTs were 160 MHz, 6 μm, 25, 1.2 mm, and 2 mm, respectively.

SAW is produced by piezoelectric effect which converts the mechanical energy into electrical energy, and vice versa. To select an appropriate piezoelectric material for SAW application, electromechanical coupling coefficient \( (k_2) \), temperature coefficient of delay (TCD), and temperature coefficient of frequency (TCF) should be considered (Gizeli et al. 2003; Lee et al. 2012), because chicken meat is transported under cold packaging and gas sensing requires high sensitivity. In general, Quartz, LiNbO₃, and LiTaO₃ have been widely used for the piezoelectric substrate for SAW sensor applications. Among them, 128° cut YX-LiNbO₃ wafer was selected because it satisfied the above conditions.
The area of the sensing layer was 2.4 (2 × 1.2) mm². For the IDT patterns, 1000-Å-thick Au and 200-Å-thick Ti layers were deposited onto each piezoelectric substrate using a sputtering method. The mixture of 25 μm tungsten powder (W006021, Good Fellow Inc., LDN, UK) and epoxy resin (Araldite GY509, Huntsman Co., TX, USA) was used for the acoustic absorber because of high acoustic impedance of tungsten (about 100 kg/m²s). Moreover, the tungsten powder scatters the acoustic waves as well as attenuates ultrasonic energy.

The substance selected for use in the sensitive layer for aldehyde detection was PDMS. It was selected because of its high sensitivity to aldehyde gas (Firpo et al. 2015; Joo et al. 2007; Lachenmeier et al. 2006; Ning et al. 2016; Staginus et al. 2013; Torino et al. 2017). Love waves propagate near the surface of a piezoelectric substrate supporting shear horizontal waves. Because of this perturbation effect between the sensitive layer and piezoelectric substrate, the acoustic energy of the Love wave can be concentrated in the thin sensitive layer deposited on the surface of a LiNbO₃ wafer. The Love wave SAW sensor can respond to the aldehyde gas particles that are adsorbed to the sensitive layer (Jakoby and Vellekoop 1998; Saha et al. 2003). Therefore, among various options for SAWs, the Love wave was selected for use in aldehyde sensing. Theoretically, considering the change in displacements with increase of the thickness of the sensitive layer, high mass sensitivity can be obtained in layer-guided acoustic wave systems. When the first mode of a Love wave begins, and the thickness of the sensitive layer is increased from zero, the displacement pattern takes the form of a plane wave in the substrate. Then, the sensitive layer assumes a quarter-wavelength pattern. Additional increases in the thickness of the sensitive layer will further restrict its displacement, but this is not consistent with higher sensitivity (Gizeli et al. 2003; McHale et al. 2002). Hence, the optimal thickness of the PDMS layer was calculated based on theoretical considerations (Lee et al. 2011, 2012; McHale et al. 2002). The measured sound propagation speed of a PDMS specimen was about 1068 m/s. The sensor was mounted on a Teflon-jig with a semi-precision coaxial RF connector to prevent electrical noise. Fig. 2 shows the fabrication process of the SAW sensor with the PDMS-sensitive layer added using a spin-coating method.

**Experimental Set for SAW Sensor**

In this study, the experiments of the SAW sensor were performed by two stages: the reference gas and chicken meat gas sensing. The reference gas sensing was performed to verify the sensing ability of detecting CH₃CHO gas and a gas mixture of CH₃CHO (purity 99.99%) and N₂ (99.99%) was used as the reference gas and the concentration levels of the mixed gases were 25, 50, 75, and 100 ppm, respectively. Two experiments were performed in a room with controlled humidity and temperature (25 °C) by the experimental setup shown in Fig. 3. The following figure shows the experimental setup for the measurement of the reference aldehyde gas.

The experimental setup consisted of a mass flow controller (MFC 5850E, Brooks Inc., PA, USA) to control the flow rate of the mixed gases, a flow and pressure controller (GMC1220, ATOVAC Co. Ltd., Yongin-si, Rep. Korea) to let the gases be mixed at different concentrations, and a vector network analyzer (HP 8520D, Agilent Technologies Inc., CA, USA) connected to a laptop computer via a USB/GPIB interface. While mixing N₂ gas with CH₃CHO gas, the vector network analyzer activates the SAW sensor and the mixed gas is provided into the SAW sensor and the S₂₁ parameters of the SAW sensor were acquired. S-parameters describe the relationship of input-output between ports in an electrical system and S₂₁ parameter represents the power transferred from port 1 to port 2. The network analyzer generates broadband frequency. Then, the SAW sensor receives and excites its mechanical vibration. Before measuring the mixed gas, the N₂ gas was inserted into the SAW sensor for 300 s for the stabilization of the SAW sensor. The same stabilization process was performed when measuring each different concentration level, and the mixed gas sensing was also conducted for 300 s. After sensing the mixed and stabilization gases, the used gases were ventilated through the hood system. Then, the operating frequency and phase changes of the SAW sensor were measured and analyzed. For the aldehyde gas sensing experiment of chicken meat, the gas data based on the phase changes of the SAW sensor in relation to the number of days with the samples had been stored were measured using the same experimental setup as in Fig. 3 without the gas mixing stage. The storage interval over which the chicken meat samples had been stored was evaluated by detecting aldehyde gas.

Among the components of the SAW sensor, the IDT pattern and sensitive layer are the most important parts for determining the repeatability and reproducibility of the sensor system because operating frequency and phase of the SAW sensor are changed according to the mass of target molecule (CH₃CHO) on the sensitive layer and IDT produces the acoustic waves affected by the sensitive layer. Therefore, in this study, to protect the sensing part from external inflow gas, a small acrylic chamber (volume 50 mm³) was constructed around the sensing area and sealed using epoxy resin (Araldite GY509, Huntsman Co., TX, USA) to prevent leakage of the chicken gases. The gases were collected by syringe from the glass sample bottles and injected onto the PDMS-sensitive layer through a 1.6-mm Teflon tube connected to the small chamber of the SAW sensor. The changes in the phase of the SAW sensor were measured according to changes in the
The phases of the SAW sensor are described in Eq. 1 (Ballantine Jr et al. 1996).

$$\frac{\Delta \phi}{\phi} \propto \frac{\Delta f}{f_0} = f(\Delta m)$$ (1)

where $\phi$, $\Delta \phi$, $f_0$, $\Delta f$, and $\Delta m$ are the phase in radians, the phase change, the resonant frequency in Hz, the frequency change, and the mass loading of the target material, respectively.

**Results and Discussion**

**Chicken Meat Gas Analysis**

The concentrations of the gas components in the chicken meat samples (e.g., alcohols, ketones, esters, hydrocarbons, aldehydes, sulfur compounds) varied according to the storage period, and the results are shown in Fig. 4. In general, the amounts of these gases increased with increase in the storage interval. In particular, the amounts of alcohols and aldehydes increased rapidly after 5 days and the amounts of esters, ketones, and sulfur compounds increased rapidly after 10 days. The target gas component selected for evaluating the freshness of chicken meat was aldehyde. This is a group of organic compounds produced after microbial consumption of alcohol, which shows a rapid increase after 5 days of storage.

In Fig. 4, the concentrations of sulfur compounds and hydrocarbons account for about 90% among VOCs. However, these gases could not be the major indicators for evaluating chicken meat gas because sulfur is a mineral that the body uses for various functions, including making and repairing DNA. Lots of foods and beverages contain sulfur. Especially,
fermented food such as beer, cheese, and wine also produces volatile sulfur compounds (Landaud et al. 2008). Food is composed of many kinds of hydrocarbon. Esters occur naturally in fruits and can enhance their flavors and the major ingredient in alcoholic beverages. Ketones are water-soluble molecules that are produced by the liver and have been considered as a carrier of energy to peripheral tissues for exercise (Newman and Verdin 2014). Therefore, we selected aldehydes because of their harmful effects (Giberti et al. 2012; Mitsubayashi et al. 2005).

**S21 Parameter Response and Base Line Noise**

As mentioned above, although the amount of the aldehyde gas was the third lowest in terms of dominance in the headspace in Fig. 4, it was selected due to the extremely harmful effects on the human central nervous system (e.g., allergic hypersensitivity diseases, respiratory allergies, and idiosyncratic drug toxicity). Before sensing aldehyde gas, the frequency responses of the newly developed SAW sensor were measured using a vector network analyzer, by which its S21 parameters were acquired in air at room temperature. To analyze the effects of the PDMS coating, we compared the sensitivity before and after PDMS coating, and measured the insertion losses. Fig. 5 shows the results of the comparison.

In Fig. 5a, the red line and black dashes are the frequency responses of before and after PDMS coating, respectively. An insertion loss of about –4 dB and a center frequency shift of 0.34 MHz were found due to the mass loading effect of the PDMS layer. If the insertion loss is relatively large in the results without and with the PDMS layer, the sensitivity of the SAW sensor may be low, but in this study, the insertion loss of –4 dB is relatively small because the performance of the piezoelectric material was determined using the electromechanical coupling factor ($k_p$), the efficiency of converting mechanical energy into electrical signals. The LiNbO3 wafer possessed good stability of its electromechanical properties in the temperature range between 0 and 100 °C (Chen et al. 2019).

In Fig. 5b, after the PDMS coating, the phase was measured to analyze the baseline noise for about 1000 s. Baseline noise is the short time variation of the baseline after chemical response caused by electric signal fluctuations, chemical reaction, temperature fluctuations, and other factors. Usually, the stability of the SAW sensor signal can be achieved by measuring the baseline noise of the sensor system and the effective
SAW sensors should be three times from the baseline noise. The obtained baseline noise (phase variation) is about $81 \pm 0.25^\circ$ in Fig. 5b, and the phase change according to chicken meat storage time was about 73 to $77 \pm 0.5^\circ$. From the experimental results, the difference of amplitude between two response signals is much more than 3 times.

As mentioned above, the optimum thickness (quarter wavelength) of the sensitive layer is one of the most critical parameters for minimizing insertion loss (Gizeli et al. 2003) and, in this study, the ideal thickness was calculated to be about 1.69 $\mu m$. However, the measured thickness of the PDMS coating was about 1.8 $\mu m$. Because of mismatching the optimal thickness of the sensitive layer, the insertion loss was also increased. Even if the optimal thickness was not exactly achieved, the operating frequency and its bandwidth (about 60%) could be obtained, and this will be controlled by the rotating speed (rotation per minutes) in future study.

**Reference Gas Sensing**

In Fig. 4, even though aldehyde gas has relatively low concentration among the other gases generated from the chicken meat, it was selected due to adverse effects on the central nervous system of human. After measuring the $S_{21}$ parameter, the reference gas sensing was conducted, and its outcome is shown in Fig. 6.

Fig. 6a shows the real-time phase changes of the SAW sensor with increasing concentration of a reference gas sample. At the first $N_2$ stabilization stage, the phase was dramatically increased and located near $-146.5^\circ$. This result is much different from the baseline noise of the air stabilization in Fig. 5b. The phase shift might be strongly affected by $N_2$ gas and other gas components in air. The measured real-time phases of the SAW sensor at about 25, 50, 75, and 100 ppm are about $-146.2^\circ$, $-147.5^\circ$, $-148.8^\circ$, and $-150.4^\circ$, respectively. The maximum phase variation is approximately 4°, almost 2.5 times more than the air stabilization. While the baseline noise of the air stabilization is fixed within 1°, the baseline noise of the $N_2$ stabilization changes at every concentration level from $-146.5^\circ$ to $-148.5^\circ$. The baseline noise variation is about 2°. The measured phases of the SAW sensor decrease as the
CH₃CHO concentration increases. For a more precise analysis, the least squares approximation method was performed. Fig. 6b shows the linear relationship between the phase changes and the CH₃CHO concentrations. The determination coefficient of the linear regression equation is about 0.98. The measurements of CH₃CHO were repeated 10 times per sample. Consequently, it can be seen that, as the concentration of CH₃CHO increases by 1 ppm, the measured phase decreases by about 0.52°.

**Chicken Meat Gas Sensing**

The condition of chicken meat samples stored for 1, 5, 10, and 15 days after being slaughtered was evaluated. The number of chicken meat samples was 10 per each storage day and total 40 samples were measured by 10 different SAW sensors. These data were compared with the detection results for the reference CH₃CHO gas samples. To accomplish this, the experimental setup shown in Fig. 4 was used and the VOCs (including aldehyde gas) generated from chicken meat samples were measured using the SAW sensor. The measured real-time phase changes over 300 s of the SAW sensor in relation to the number of days the chicken meat samples had been stored. Because the collected gas from chicken meat samples was a much smaller amount than the reference gas, the sensing was conducted for about 100 s per each storage day. Considering the real-world environment, the stabilization of the SAW sensor was conducted in air for about 60 s. Fig. 7 shows the results for the detection of aldehyde gas in relation to the storage time of the chicken meat samples.
In Fig. 7, the phase change is the average values of the response signals per 10 chicken meat samples, each storage day. After the stabilization, the base line noise was about 75.5° and this is a very similar result with that of the base line noise experiment in Fig. 5. The measured real-time phases of the SAW sensor according to storage time are about 77°, 76°, 75°, and 73.5° for 1, 5, 10, and 15 days, respectively, after being slaughtered. The same linear regression analysis was conducted as in the analysis of the detection of the reference CH₃CHO gas samples. Ten experiments were done per storage day. In Fig. 7b, a linear relationship between the phase changes and the number of storage days of the chicken meat samples is shown, and its determination coefficient was 0.989. In addition, the measured phase of the SAW sensor decreases by 0.26° every day. To obtain high sensitivity, LiNbO₃ was used. From the linear regression equations of the two experiments, it was determined that 0.5 ppm of aldehyde gas was released from the chicken meat every day. Thus, the storage time of the chicken meat samples could be evaluated quantitatively using the SAW sensor results. In addition, if we determine day-criteria for the freshness of chicken meat during its distribution, evaluating the freshness of chicken meat would be possible using the SAW sensor with the PDMS-sensitive layer fabricated in this study. This opens a promising research avenue to explore.

Conclusions

An aldehyde gas was selected as an indicator of the freshness of chicken meat due to its hazardous effects. The amounts of aldehyde gas increased rapidly after 5 days of storage, thereby indicating that the freshness of the chicken meat had decreased. A simple device for detecting aldehyde gas to evaluate the storage time of chicken meat was developed using a SAW sensing technique. A SAW device with a center frequency of 160 MHz was fabricated on a LiNbO₃ wafer. Then, PDMS polymer was coated onto a sensitive line of the SAW device as a sensitive layer for detecting aldehyde gas. To evaluate the feasibility of using the SAW sensor for freshness measurements of chicken meat, various concentrations of CH₃CHO mixed with N₂ gas were measured using the reactive phase changes of the newly developed SAW sensor and the measured phases decreased linearly as the CH₃CHO concentrations increased. After the measurement of CH₃CHO gas, aldehyde gas generated from chicken meat was measured and the phase differences could be distinguishable from those after 1 to 15 storage days. Consequently, the determination coefficient between aldehyde gas and chicken meat storage time was about 0.989. From the experimental results, the freshness of chicken meat can thus be evaluated using the SAW sensor developed in this study.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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