Passive Wireless Surface Acoustic Wave CO₂ Sensor with Carbon Nanotube

Nanocomposite As An Interface Layer

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Abstract— A passive wireless CO₂ sensing system based on surface acoustic wave (SAW) device and carbon nanotube nanocomposite thin film was studied. The electrical resistance change of the carbon nanotube nanocomposite thin film was examined first, and about 10% resistance increase was observed when the thin film is exposed to pure CO₂. The frequency change for SAW sensor coated with nanocomposites film was around 0.03% when the device is exposed to pure CO₂. However, the performance of the CO₂ SAW sensor is severely influenced by environmental humidity. With additional ultrathin parylene film packaging, the SAW sensor frequency change from relative humidity of 0% to 100% at room temperature decreased from over 0.1% to less than 0.01%. It was found that the lowest detection limit of the CO₂ SAW sensor is 1% CO₂ concentration, with 0.0036% frequency change. Wireless module was tested and showed promising transmission distance at preferred parallel orientation.

Key words: Wireless SAW Sensors, CO₂ gas sensor, carbon nanotube polymer composite

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1. INTRODUCTION

CO₂ sensors are widely used in various military, industry and civil applications. For example, carbon emission control through geological carbon dioxide sequestration [1, 2] needs close monitoring of CO₂ leakage on the ground around the injection wells. Commercially available non dispersive infrared (NDIR) CO₂ sensor[3] operated based on laser detection is one of the most widely used CO₂ sensor in mining industry and building monitoring. However, such sensor suffers from its high power consumption.

The other major CO₂ sensors on the market are mostly operated based on chemical reaction. Like any other gas sensor, the major functions in the CO₂ gas sensor are recognition of the CO₂ gas molecule and transduction of that recognition into a useful signal. The recognition of CO₂ gas is essentially the reaction between the CO₂ gas and the sampling module of the sensor, such as aqueous solution or polymer membrane. The reaction produces a change in parameter such pH, resistance, conductivity, or capacitance based on the exchange of ion reactions between the analyte and surface material. Among them, CO₂ sensor based on surface acoustic wave (SAW) shows great potential.

Equipped with a comb-shape transmitting inter digit transducer (IDT) and a receiving IDT on a piezoelectric substrate, the SAW sensor generates SAW after receiving agitation signal either through wireless antenna or from direct connected power source. The SAW signal then travels along the substrate surface and is intercepted by the receiving IDT and then transferred to the measuring instrument or sent over the wireless antenna. The physical change on the SAW travelling path, such as change in mass or conductivity, will cause the change in SAW velocity and amplitude, thus the change of sensor resonant frequency and attenuation.

There are a lot of SAW sensor on different gases, such as H₂[4, 5], H₂S[6] or VOC[7]. Most of the SAW gas sensor utilizes a sensitive film between the transmitting IDT and receiving IDT, and the sensor response changes accordingly when the sensitive film reacts with target gases. For CO₂ detection, many of the SAW sensor uses gas absorption thin films and measures the resonant frequency change due to the mass change of the film. For example, SAW sensor with ZnO film will have 0.03% frequency change with 10ppm CO₂[8]. SAW sensor with PVA film[9], PAPP/PAPO film[10], SiO_x and Teflon fi[11], Teflon

1 film[12, 13], polyimide film[14], and many other types of films are reported. These SAW CO₂ sensors have
2 different sensitivities, depending on the choice of resonant frequency and sensitive film. They are mostly
3 compact and have low power consumption. However, the mass loading type of sensor suffers from long
4 term drift and false alarm caused by absorption of unwanted gases.

5 Since SAW signal changes not only with the change of mass loading, but also with the change of the
6 conductivity, permittivity, mobility of the charge carrier and other parameters of the sensitive film[15],
7 there are also SAW gas sensors that respond to the change of conductivity change of the sensing film. For
8 example, PbPc[16] film changes conductivity after reaction with CO₂ and causes considerable amount of
9 frequency change of SAW sensor. Among the SAW CO₂ sensors that make use of conductivity changes of
10 the sensing film, nanotube and insulator (such as polymer) composite attracts more attention due to the
11 large surface to volume ratio of nanotubes, thus higher possible sensitivities. These nanotube composites
12 include SnO₂ [17] and carbon nanotube (CNT)-SiO₂ [18] and many other compositions. By far CNT and
13 polyethyleneimine (PEI) composite proves to be one of the most promising combinations due to its ease of
14 fabrication and low cost. There are some researches on CNT-PEI CO₂ sensing from industry (Honeywell
15 [19] and Nanomix [20]) and academic institutions [21]. Due to the nature of CNT-PEI composite, the CO₂
16 sensor performance will be greatly influenced by humidity. However, most of the past researches omitted to
17 address the impact of humidity on sensor performance. Some built a reference sensor for humidity sensing
18 so as to compensate the humidity effect. Since the response to humidity change is normally much greater
19 than the response to CO₂ concentration change, such sensor will suffer from unstable sensing performance
20 in real applications.

21 It's thus vital to find a suitable packaging method for SAW CO₂ sensor based on conductivity change.
22 Parylene, a material long been used in electronic packaging industry, proved to be good candidate for
23 humidity resistant [22]. Parylene film is water vapor repelling and gas permeable when the film is thin
24 enough. So a thin parylene layer will allow CO₂ molecules to go through while stopping water vapor from
25 getting contact with sensing film.

2. THEORETICAL ANALYSIS AND PERFORMANCE EVALUATION OF SAW CO₂ SENSOR

A. SAW Dependence on sensing film conductivity

A SAW propagating in X direction (in the case of ST cut Quartz) has a surface electrical potential ϕ which can be expressed as [16]:

$$\phi(x, t) = \phi_0 e^{j(\omega t - kx)} \quad \text{Eq. 1}$$

where ω is the angular frequency of the SAW and k is the wave number (For ST cut quartz with a period of 60um, the wave number is 52.35E+3).

And considering the relationship between the current density J_x in the conductive sensing film and the surface potential through the continuity equation [16]:

$$\frac{\partial J_x}{\partial x} = -\frac{\partial}{\partial t} \left(\frac{\rho_s}{d} \right) \quad \text{Eq. 2}$$

where d is the thickness of the film.

When neglecting the diffusion current and considering only the anisotropic SAW substrate, the complex power flow into carrier can be calculated. The fractional velocity perturbation and the attenuation per wave number can be finally calculated as [16]:

$$\frac{\Delta v}{v_0} \cong -\frac{\beta}{k} = -\frac{K^2}{2} \frac{(\sigma d)^2}{(\sigma d)^2 + v_0^2 (\epsilon_0 + \epsilon_1)^2} \quad \text{Eq. 3}$$

$$\frac{\alpha}{k} \cong \frac{K^2}{2} \frac{v_0 (\epsilon_0 + \epsilon_1) \sigma d}{(\sigma d)^2 + v_0^2 (\epsilon_0 + \epsilon_1)^2} \quad \text{Eq. 4}$$

Here β is the imaginary part of the propagation factor $\gamma = \alpha + j\beta$, k is the wave number, σ is the film conductivity, K^2 is the electromechanical coupling factor, $v_0 = \omega/k$ is the unperturbed SAW velocity (3158m/s for ST cut quartz, 3295m/s for LiTaO₃ and 4000m/s for LiNbO₃), ϵ_0 is the permittivity of the region above the substrate and ϵ_1 is that of the substrate, d is the thickness of the film.

Equation 3 and 4 describe the velocity and acousto-electric attenuation change due to the change of the film conductivity on SAW propagation path. When considering the total surface wave velocity, we know from perturbation theory that [16]:

$$\frac{\Delta v}{v_0} = \frac{1}{v_0} \left(\frac{\partial v}{\partial m} \Delta m + \frac{\partial v}{\partial c} \Delta c + \frac{\partial v}{\partial \sigma} \Delta \sigma + \frac{\partial v}{\partial \epsilon} \Delta \epsilon + \frac{\partial v}{\partial T} \Delta T + \frac{\partial v}{\partial p} \Delta p \right) \quad \text{Eq. 5}$$

Here m is the variables mass, c is the stiffness, T is the temperature and p is the pressure. Together with unperturbed wave velocity v_0 , conductivity σ and dielectric coefficient ϵ , these are the major components that can cause SAW velocity change, thus frequency shift.

Equation 5 can be exploited to design high efficient SAW gas sensor based on parameters other than mass loading and conductivity change for future research.

Based on equation 3, the relationship between the sensing film conductivity and SAW sensor performance can be plotted as shown in Fig. 1(a). From the figure, it can be seen that the best choice of SAW substrate is LiNbO_3 with the highest frequency shift over composite conductivity change.

From equation 3, the sensitivity of the SAW sensor over conductivity change can also be calculated by taking first order derivative of the equation over conductivity, i.e. $d(\Delta f/f)/d\sigma$. From the results plotted in Fig. 1(b), it can be easily seen that the most sensitive region for LiNbO_3 is around 1.6S/m.

B. SAW CO_2 Sensor Performance Evaluation

Based on preliminary test of the composite, as shown in Fig. 2, and the relationship from equation 3, the sensor performance can be estimated as shown in Fig. 3.

3. SURFACE ACOUSTIC WAVE SENSOR DESIGN, FABRICATION AND TEST SETUP

A. Piezoelectric Substrate Material Selection

The properties of common used piezoelectric materials can be seen from Table 1.

Table 1. Common used Piezoelectric Material Properties.

Substrate	Cut	Propagate Direction	Wave Speed(m/s)	Coupling Coeff K^2 (%)	Temperature Coefficient (ppm/°C)	Transmission Loss(dB/cm)
Quartz	Y	X	3159	0.23	-22	0.82

	ST	X	3158	0.16	0	0.95
LiNbO ₃	Y	Z	3485	4.5	-85	0.31
	131°Y	X	4000	5.5	-74	0.26
	128° Y	X	4000	5.5	-72	
LiTaO ₃	Y	Z	3230	0.74	-37	0.35
	X	112° Y	3295	0.64	-18	

Considering the coupling coefficient and transmission loss, LiNbO₃ is the best candidate for wireless communication. The conductivity dependence analysis above also shows that LiNbO₃ works best with sensing film of 1.6S/m sheet conductivity.

B. CNT-PEI Composite Fabrication

The CNTs are commercially available through Aldrich® (2g, St. Louis, Mo, USA) with 1-2nm outer diameter and 5-30um length. Dimethylformamide (DMF) is used to disperse CNT. DMF is believed to be good candidate for CNT dispersion because of their chemical compatibility. CNT is mixed with DMF with 1:1000 weight ratio. The mixture is then agitated by ultrasonic convertor (Misonix® ultrasound liquid processors). The CNTs are well dispersed in the DMF solution after 90 minutes ultrasound at 70W. PEI is purchased from Aldrich with mean molecular weight of 25000. Starches are mixed with water using magnetic stir bar at elevated temperature around 100°C. The solution is then mixed with PEI. It's known that the mixture of PEI with starch will have better response to CO₂ compared to pure PEI, due to the hygroscopic nature of starch.

The CNTs solution is drop coated on the sensing film region of the SAW sensor using pipette and let dry. The PEI-Starch solution is then applied onto the CNT film area and then washes away using deionized (DI) water so the CNTs will be surrounded by a thin layer of PEI and starch. The calculated volume conductivity of the resulted composite thin film based on resistance measurement proves to be within the optimum working zone of the SAW sensor, i.e. around 1.6S/m.

C. Design and fabrication of SAW Sensor

Two methods are adopted in sensor fabrication: photo lithography and shadow mask technology. 128° YX cut LiNbO₃ are selected for its excellent coupling coefficient (5.5% compared to 0.16% of ST cut

quartz) and low transmission loss (0.26dB/cm compared to 0.95dB/cm of ST cut quartz). Surface acoustic wave velocity on LiNbO_3 is 4000m/s.

During photo lithography process, 1500Å thick gold is coated on the LiNbO_3 substrate. Micro posit S1805 is used as photo resist. After spin-coating at 4000rpm for 45s, the photo resist is 0.6µm thick. After patterning, the substrate is then immersed in metal etchant and the metal not covered by photo resist is removed completely. The remaining photo resist on IDT is then removed in RIE (reactive-ion-etching), with 48sccm O_2 , 2sccm CH_4 . The power of plasma is kept at 200 watts and the pressure is 250 mTorr. The RIE process lasted for 120s. With IDT finger width and spacing of 15µm, the synchronous frequency of the SAW sensor is about 60 MHz, which limits the highest frequency of operation of SAW devices to a few GHz, since a typical SAW sensor can be operated at multiple of its resonant frequency, such as 3x, 5x or even higher frequencies.

The other approach of IDT fabrication is shadow mask process. A shadow mask is a thin metal sheet with opening of IDT. The opening is normally achieved by laser cutting or chemical etching. During the IDT fabrication process, the LiNbO_3 substrate is covered by the shadow mask and exposed in metal coating system. Only the opening area is coated with metal. This method is relatively simple and cost effective, except that the feature size is relatively big compared to photo lithography. The estimated resonant frequency of the sensor is 6.45MHz.

The fabricated SAW sensors from both processes are shown in Fig. 4. The 60MHz sensor has 70 pairs of input and output IDTs that are 3 mm apart. The IDT width and IDT spacing are both 15µm. The IDT height and aperture height are 2.5mm and 2.4mm respectively. The whole sensor is constructed on a $30 \times 30 \times 0.5$ mm substrate, and the two IDTs are located symmetrically on the center of the substrate. The 6.45MHz sensor has 15 pairs of input and output IDTs that are 3mm apart. The IDT width is about 160µm while the IDT spacing is about 150µm. The IDT height and aperture height is 11.7mm and 11.4mm respectively. The whole sensor is constructed on a $30 \times 30 \times 0.5$ mm substrate, and the two IDTs are located symmetrically on the center of the substrate.

1 *D. SAW Gas Testing System Setup*

2 As shown in Fig. 5 (a), the gas testing system comprises of gas sources (Compressed Air gas tank and
3 compressed CO₂ gas tank), flow controllers, one quartz gas testing flow chamber with oven, one sink
4 connected with exhaust gas pipe, one current source measurement unit for thin film conductivity
5 measurement (can be replaced by network analyzer in later characterization process), one computer
6 connected to the current source unit for automatic data collection.

7 As shown in Fig. 5 (b), the system contains flow control module, quartz gas test tube in oven,
8 resistance measurement module, from left to right. Gas cylinders are connected to flow control module
9 from back. The test samples are fixed in the fixture inside the test tube, the pads of the test samples are
10 connected to the connectors on the fixture. The connectors are electrically connected out of the cap in the
11 gas exit side of the measurement module.

12 The test tube has an inner diameter of 4.8cm, length of 96cm, with the total volume of around 1.7L
13 (1700cc). Experiments contains three major steps: flush – the test tube is flushed with compressed air at
14 150sccm, 50% CO₂ – the test tube is flushed by 30sccm CO₂ mixing with 30sccm compressed air, and
15 100% CO₂ – the test tube is flushed by 30sccm CO₂.

16 *E. SAW Sensor Humidity Test Setup*

17 There are commercialized humidity testing system available with high accuracy humidity reading and
18 multiple humidity level manipulation. Such system is perfect candidate for sensor humidity performance
19 characterization. However the system is not readily available due to the cost. As an alternate, the sensor can
20 be tested at several fixed humidity level. It's a common practice that in enclosed container with certain
21 chemical solution, if the solution is over saturated at room temperature, the humidity level of the
22 atmosphere above the solution will remain constant.

23 Such saturated solution provides an accurate relative humidity environment at fraction of the cost of
24 humidity control system. As shown in Tab. 2, the relative humidity of each saturated solution depends on
25 the temperature of the solution. Since the lab where the experiments are conducting has very stable

temperature control system, the temperature fluctuation is less than 2°C. In another word, the relative humidity fluctuation is less than 1%, so the testing environment can be assumed to have constant relative humidity.

Table 2. Relative Humidity above saturated solutions in different temperatures (from Omega).

Relative Humidity (RH%)	LiCl	MgCl ₂	NaBr	CaCl ₂	NaCl	KCl	K ₂ SO ₄
20°C	11.31	33.07	59.14	32.3	75.47	85.11	97.59
25°C	11.30	32.78	57.6	31	75.29	84.34	97.30
30°C	11.28	32.44	56.0		75.09	83.62	97.00

It should be noted that due to the different solution heat (Enthalpy change of solution) of the salt, the dissolving process might generate a lot of heat or need certain heating environment. The temperature change of the solution can be calculated and shown in Tab. 3. It can be seen that LiCl, MgCl₂ and CaCl₂ will have drastic temperature increase so their dissolving process needs to be slow and the salts need to be added to solution step by step every time after the solution temperature stabilize.

Table 3. Solution heat and Temperature increase during saturated solution preparation process.

	LiCl	MgCl ₂	NaBr	CaCl ₂	NaCl	KCl	K ₂ SO ₄
Solution Heat (KJ/mol)	37.4	155	0.6	81.3	-3.9	-17	-23.8
Salt Quantity (g)	460	300	330	350	150	180	72
Molecular Weight (g/mol)	42.4	95.3	102.9	111	58.5	74.6	174
Water Quantity (g)	500	500	300	300	400	400	400
Temperature Increase (°C)	193.9	233.1	1.5	204.1	-5.97	-24.5	-5.9

4. EXPERIMENT RESULTS AND DISCUSSION

A. SAW Gas Sensor Performance

The fabricated SAW sensor with sensitive thin film is tested with network analyzer as measurement instrument. The sensor is tested under Air (about 400ppm CO₂), and CO₂ concentrations of 0.1% (about twice of CO₂ concentration in the air), 0.5%, 1%, 5%, 10%, 20%, 35%, 50%, 75%, 90% and 100%. The CO₂ concentrations of 1% and below are achieved by mixing compressed dry air and compressed dry 1% CO₂ in air. CO₂ concentrations above 1% are achieved by mixing compressed dry air and compressed dry

pure CO₂. The SAW sensor performance is shown in Fig. 6 with linear and log scale of gas concentration respectively.

After comparing test results from Fig. 6 with prediction from Fig. 3, it can be seen that test results basically agree with prediction under 20% CO₂ concentration, while the predicted response based on resistance measurement is slightly higher than the real frequency measurement results, with over twice difference under pure CO₂. This might be caused by the slight difference in the fabrication process. In resistance measurement experiments, the test samples are immersed in starch-PEI solution for overnight and washed by DI water. While in frequency test experiments, the sensor is not immersed in the solution since the IDT might be contaminated during this process, and the starch-PEI solution is simply dropped onto the sensor and let dry or washed by DI water right away. The difference in preparation leaves the frequency test samples with less PEI-starch, thus the response to CO₂ saturates at lower concentration.

Even the sensor response to CO₂ concentration higher than 20% is not as high as predicted, the fabricated sensor still shows reasonable response, with 0.003% frequency change under 1% CO₂. Since the CO₂ concentration in the air is around 400ppm, and occasional wild fire and other natural activities might further increase this concentration, 1% is safe for not to trigger false alarm and good enough for leakage monitoring.

B. SAW Sensor Humidity Response

The SAW sensor is then placed in the enclosed container above the saturated salt solution for testing. The measurements are conducted generally one hour after the sensor put in the container, when the signal has been stable for long time. After testing, the sensor is placed in an enclosed container with dry P₂O₅, a strong desiccant for at least 20 minutes under the signal gets stable.

Fig. 7 shows the sensor response under different relative humidity condition. It's noted that under high humidity, the resonant frequency of the sensor even vanished and the response around the resonant frequency changes dramatically. At 84.3%RH, the measurement curve starts to deform, and the local peak at the resonant frequency completely vanishes at 97.3%RH.

1 C. Packaging Impact on SAW Sensor Humidity Response and Gas Sensing Performance

2 Parylene layer is coated by Specialty Coating Systems® PDS 2010. 1g parylene polymer powder is
 3 used and the resulted thin film is about 500nm thick. As seen in Fig. 8, coated SAW sensor shows an order
 4 of magnitude smaller frequency shift compared with uncoated SAW sensor, with less than 0.01% frequency
 5 change under saturated water vapor condition.

6 Fig. 9 (a) and Fig. 9 (b) show the sensing performance comparison between uncoated and coated
 7 sensor in linear and log scale respectively. It can be seen that coated sensor also respond to CO₂
 8 concentration as low as 1% and the frequency change at 1% is 0.0036%, which is similar to the uncoated
 9 one. With the increase of CO₂ concentration, the frequency shift of coated sensor also shows similar trend
 10 while the response is generally slightly lower than that of the uncoated sensor. This proves that the coated
 11 parylene layer is gas permeable and does not hinder the sensing performance while improving the humidity
 12 resistance.

13 5. WIRELESS MODULE DESIGN, CONSTRUCTION AND TESTING

14 MEMS type antenna normally works at high frequency since the resonant frequency of the LC circuit
 15 can be calculated as $f_{resonant} = \frac{1}{2\pi\sqrt{LC}}$. So for lower resonant frequency, either the capacitance or the
 16 inductance of the circuit needs to be sufficiently large. Thus MEMS type antenna is not recommended for
 17 system with resonant frequency lower than 400MHz. Due to fabrication limit, the maximum resonant
 18 frequency in current sensor design is below 100MHz, which means planar antenna is not the best choice so
 19 small scale macro size antenna is used.

20 The inductor we used in the project is 132-20SM_LB from Coilcraft®. The inductor has 20 turns of
 21 coils with 538nH conductance. And the coil can be connected to a capacitor in parallel to be used as
 22 resonant circuit. Two coils can be connected in series to double the inductance. The required capacitance
 23 for the wireless module can be calculated accordingly.

For gas sensor with IDT from shadow mask, the design frequency is 6.45MHz. And the real measurement of one prepared sensor gives a resonant frequency between 6.114MHz and 6.116MHz, depending on the gas concentration. It can be calculated that for the design frequency, the desired capacitance is 1131.7uF. For the specific sensor, the desired capacitance is between 1258.7uF and 1259.5uF. For sensors with IDT from photolithography process, the design frequency is 66.7MHz, while the measured resonant frequency is 60.6MHz. The corresponding capacitance in the system is therefore 10.6uF and 12.8uF.

Due to the nature of the fabrication process, the fabricated IDT electrodes will have certain error for each batch of sensors. So the resonant frequency will have slight change between the sensors, which require tunable LC circuit, in this case, tunable capacitor. The capacitor is from McMaster®. The size for 540-648uF capacitor is 2.75”H×1.44”D, and the size for 30-36uF capacitor is the same. The transmission losses of the sensors vary between 30dB and 40dB. Since the network analyzer currently used in this project can measure signal that has transmission loss up to 90dB. So the total transmission loss caused by wireless module needs to be limited to about 60dB.

Depending on antenna orientation, the wireless module is tested under two circumstances, series and parallel. The change of insertion loss versus the distance between the antennas can be seen from Fig. 10 with series configuration on top. It can be seen from Fig. 10 that the parallel configuration has lower antenna loss compared to the series configuration. It can also be seen that for a sensor with 23.633dB insertion loss, as observed for the fabricated SAW gas sensor, the maximum loss the antenna can have is about 68dB. In another word, that means the antenna range can be over one foot if properly oriented.

6. CONCLUSION

A SAW CO₂ sensor was developed based on conductivity change upon gas concentration change. Gas test of sensor shows 0.03% frequency change under pure CO₂. Sensor test results basically agree with theoretical prediction of sensor performance. The impact of humidity, however, is more than two times larger than the gas response. After application of parylene coating, the humidity response is reduced to be

less than 0.01% for saturated water vapor, while the gas sensing performance is not compromised. Wireless module is also built on coil and variable capacitor and the prelim results show the sensor capable of sensing over one foot distance.

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Caption of Figures

Fig. 1. SAW sensor performance theoretical calculation.

Fig. 2. Relative resistivity change of CNT-PEI nanocomposite thin films under air, 1%, 5%, 10%, 20%, 50% and pure CO₂ respectively.

Fig. 3. SAW sensor response prediction at different CO₂ concentration.

Fig. 4. Fabricated SAW gas sensor.

Fig. 5. SAW gas sensor testing system setup.

Fig. 6. SAW gas sensor performance.

Fig. 7. SAW sensor response to humidity.

Fig. 8. SAW Sensor Humidity Response comparison after Parylene Coating.

Fig. 9. SAW sensor gas performance comparison.

Fig. 10. The wireless module performance summary with series configuration on top.

(a) SAW frequency shift corresponding to the thin film conductivity.

(b) SAW sensor conductivity sensitivity corresponding to the thin film conductivity.

Fig. 1. SAW sensor performance theoretical calculation.

Fig. 2. Relative resistivity change of CNT-PEI nanocomposite thin films under air, 1%, 5%, 10%, 20%, 50% and pure CO₂ respectively.

Fig. 3. SAW sensor response prediction at different CO₂ concentration.

(a) LiNbO₃ sensor from photo lithography process.

(b) LiNbO₃ sensor from shadow mask process.

Fig. 4. Fabricated SAW gas sensor.

(a) Gas tesing system overview.

(B) Near view of flow controller and gas testing chamber.

Fig. 5. SAW gas sensor testing system setup.

Fig. 6. SAW gas sensor performance.

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Fig. 7. SAW Sensor Response to humidity.

Fig. 8. SAW Sensor Humidity Response comparison after Parylene Coating.

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(a) SAW sensor performance comparison with gas concentration in linear scale.

(b) SAW sensor performance comparison with gas concentration in log scale.

Fig. 9. SAW sensor gas performance comparison.

Fig. 10. The wireless module performance summary with series configuration on top.