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Implementation of Surface Acoustic Wave Vapor Sensor Using Complementary Metal–Oxide–Semiconductor Amplifiers

Chia-Sung Chiu[1,3], Ching-Chun Chang[2], Chia-Lin Ku[2], Kang-Ming Peng[2],
Erik S. Jeng[2], Wen-Lin Chen[1], Guo-Wei Huang[1], and Lin-Kun Wu[3]

[1] *National Nano Device Laboratories, No. 26, Prosperity Rd. I, Science-based Industrial Park, Hsinchu, Taiwan 30078, R.O.C.*
[2] *Chung Yuan Christian University, Department of Electronic Engineering, 200, Chung Pei Rd., Chungli, Taiwan 32023, R.O.C.*
[3] *National Chiao Tung University, Department of Communication Engineering, 1001 University Road, Hsinchu, Taiwan 300, R.O.C.*

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A surface acoustic wave (SAW) vapor sensor is presented in this work. A SAW delay line oscillator on quartz substrate with the high gain complementary metal–oxide–semiconductor (CMOS) amplifier using a two-poly–two-metal (2P2M) 0.35 μm process was designed. The gain of the CMOS amplifier and its total power consumption are 20 dB and 70 mW, respectively. The achieved phase noise of this SAW oscillator is −150 dBc/Hz at 100 kHz offset. The sensing is successfully demonstrated by a thin poly(epichlorohydrin) (PECH) polymer film on a SAW oscillator with alcohol vapor. This two-in-one sensor unit includes the SAW device and the CMOS amplifier provides designers with comprehensive model for using these components for sensor circuit fabrication. Furthermore it will be promising for future chemical and biological sensing applications.

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1. Introduction

The commercial market has rapidly grown for demanding various sensitive sensors in areas including chemistry, medicine and biology. Although surface acoustic wave (SAW) filters have seen much use in telecommunication, SAW-based sensors have recently emerged for many attractive features in medical and chemical applications.[1,2] The use of acoustic microsensor to detect the physical properties, such as mass loading and viscosity, provides the benefits of real-time electronic readout, compact size, robustness, and low cost. Monolithic integration of biosensors with existing microelectronics will allow biochemical detection system to be further miniaturized in mass production and enhanced with software-definable functions. Chemical sensing through the use of acoustic wave devices has long been available using ST-quartz as the piezoelectric material for generating acoustic wave. Vapor and gas sensors based on SAW oscillators have been progressing since Wohltjen reported the first studies in 1979 due to their high sensitivity and low production cost.[3] A SAW chemical or biological sensor is commonly realized by a polymer-coated delay-line resonator as the frequency control element in the feedback loop of an oscillating circuit.

Relative to sensing applications, using monolithic integration technology, have been demonstrated.[4–7] These studies developed to date only have a sensor system without any sensing experiments. Although these studies have developed a sensor system using silicon or GaAs process, these sensing performances lack some experiments to show its feasibility. Therefore, in order to modulize and miniaturize the sensing system, it is of great interest to develop chemosensor or biosensor systems by taking advantages of matured IC processing technologies and validate the sensor with sensing experiment in this research.

In this work, the fabrication of SAW devices and the related oscillating circuit using two-poly–two-metal (2P2M) 0.35 um complementary metal–oxide–semiconductor (CMOS) process are investigated. Their electrical characteristics are evaluated as well as vapor sensing results. The SAW sensor with the CMOS circuitry is a potential candidate for the development of highly sensitive and low power microsensors.

2. Basic Sensing Mechanism

Although the acoustic wave detects any change of the mechanical or electrical boundary conditions on the piezoelectric substrate surface, it is mainly the mass loading effect that is used in chemical sensors. In this case, an appropriate measure for sensing is the fractional frequency shift $\Delta f/f_0$ caused by a change in the mass loaded onto the surface, where f_0 is the operation frequency of oscillator without vapor adsorption. This fractional frequency shift can be given by[8]

$$\frac{\Delta f}{f_0} = C f_0 h \Delta\rho, \qquad (1)$$

where C is a frequency-independent constant, h denotes the thickness of the coating film that incorporates vapor molecules, and $\Delta\rho$ is the mass density change due to absorption.

The phase noise measurement is a typical way to determine whether the signal of oscillator that was designed as sensor is stable or not. High signal stability in the oscillator is important for differentiating sensing result. Phase noise is defined to quantify the fluctuations of signal in frequency domain, and expressed as the ratio of the single side-band power at a frequency offset $\Delta\omega$ from the carrier with a measurement bandwidth of 1 Hz to the carrier power. The phase noise can be theoretically expressed in the following equation:

$$L\{\Delta\omega\} = 10\log\left[\frac{2FkT}{P_{\text{carrier}}}\left(1+\frac{\omega_0}{2Q\Delta\omega}\right)^2\left(1+\frac{\Delta\omega_{1/f^3}}{|\Delta\omega|}\right)\right], \qquad (2)$$

where k is the Boltzmann's constant, T is the absolute temperature, F represents an empirical parameter, P_{carrier} is the output power of carrier, Q is the quality factor of the SAW device,[9] ω_0 is the oscillation frequency, $\Delta\omega$ is the offset frequency from the oscillation frequency and $\Delta\omega_{1/f3}$ is the corner offset frequency between the $1/f^3$ and the $1/f^2$ regions in the phase noise response.[15] Equation (2) is simplified considerably in our case because SAW devices have an exceptional performance regarding flicker noise ($1/f$ noise).[10] Only if the amplifier is the dominant noise source will an increase in Q result in reduced oscillator

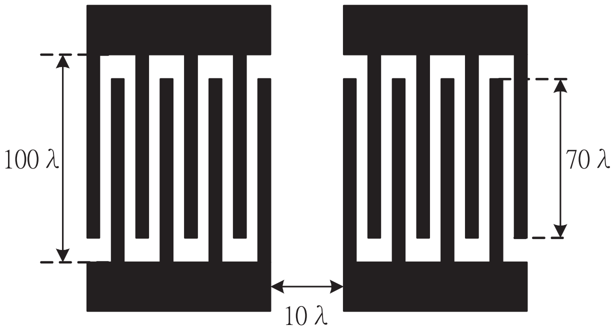

Fig. 1. A diagram of the sensor device.


(a) (b)

Fig. 2. (Color online) The photo of SAW device: (a) without cap and (b) with cap.

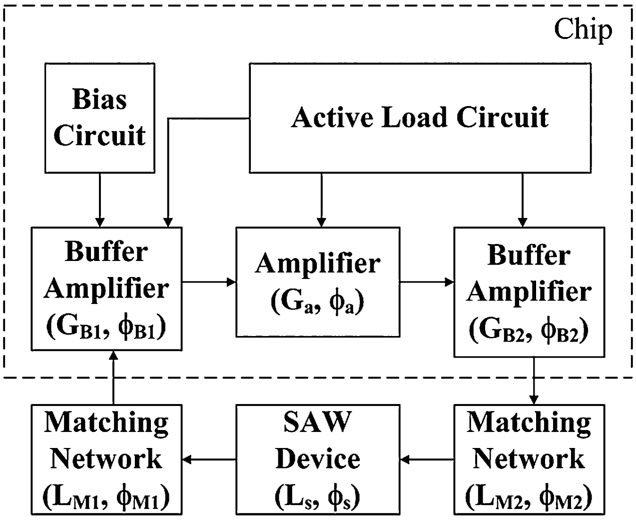

Fig. 3. The schematic of sensor system.

flicker noise. Base on eq. (2), improving the Quality factor of SAW device and increasing the power of oscillator appropriately will lower the phase noise to obtain an ideal oscillator for sensing purposes.

3. Oscillator Design and Experiments

3.1 SAW device design

A SAW device having inter-digital transducers (IDT) on the quartz substrate in this study is a key component in the sensing circuit. When an electrical signal of a certain frequency is applied to the input IDT, the SAW is excited on the surface of the substrate because of its piezoelectric effect, and then the SAW propagates across the surface of the substrate toward the output IDT. Figure 1 shows the schematic layout of a two-port SAW device in this work. Two single-finger interdigitated transducers were fabricated on an ST-quartz substrate with a propagation direction perpendicular to the x-axis of the quartz. The electrodes were 1/4 wavelength wide and separated by 1/4 wavelength at the target center frequency. A predetermined 157 MHz SAW device whose λ is approximately 20 µm was then designed with a delay path length of 10λ, and IDT length of 100λ, and uniform aperture width of 70.[11] A wire-bonded SAW device in the metal can package is shown in Fig. 2(a). The SAW device with a metal cap is used to prevent gas disturbance from the ambient as shown in Fig. 2(b).

3.2 Sensing circuit design

Early reported sensing experiments were conducted to measure the center frequency shift or phase shift of a SAW device using the vector network analyzer (VNA) to directly monitor the frequency response on the SAW device.[12] However, these sensing results by reading the VNA have shown less sensitivity and complicated VNA calibration in gas sensing. In this study, a CMOS-based oscillating circuit for a vapor sensor was accomplished. Before full circuit implementation, a summary of circuit design scheme is presented in Fig. 3. For an oscillator to be used in biochemical detection, a MOS amplifier with a feedback loop through the SAW delay line is designed. In order to meet Barkhausen criteria, the amplifier must provide sufficient gain at the target oscillator frequency to overcome the SAW insertion loss as well as the phase difference. Thus the oscillator successfully oscillates as long as the following conditions are satisfied:

$$G_a + (G_{B1} + G_{B2}) + L_s + (L_{M1} + L_{M2}) \geq 0, \tag{3}$$

$$\phi_a + (\phi_{B1} + \phi_{B2}) + \phi_s + (\phi_{M1} + \phi_{M2}) = 2n\pi. \tag{4}$$

In the above equations, G_a, G_{B1}, and G_{B2} are the gain of the amplifier and buffer amplifiers as shown in Fig. 3; L_S, L_{M1}, and L_{M2} are the losses of the saw device and match circuits respectively; ϕ_a, ϕ_{B1}, and ϕ_{B2} are the phases of the amplifier and buffer amplifiers; ϕ_s, ϕ_{M1}, and ϕ_{M2} are the phases of the saw device and match circuits respectively. As changes occur due to mass loading or temperature, the oscillating frequency will change to maintain a multiple of 360° phase shifts in the oscillator loop. In the amplifier design, the enhancement load amplifier is chosen to avoid resistors. Therefore, the lowest phase noise will be achieved easily. Furthermore, the cascade buffer amplifier improves the isolation between input and output of an enhancement load amplifier. Thus an improved stable and stable gain will be obtained. Figure 4 illustrates the schematic of CMOS amplifier circuits and measurement result. The open-loop gain of the amplifier is above 20 dB at 157 MHz in Fig. 4(b).

The flow to accomplish a SAW sensing circuit is shown in Fig. 5. There are three major parts in the SAW sensing system including a SAW delay line sensor, a CMOS amplifier and matching networks. First, the SAW device has been designed and fabricated based on the required electrical properties as discussed in the previous section. After completing the SAW device, an amplifier was designed and tuned based on the center frequency and insertion loss of the SAW device. Next, the circuits of phase matching should be considered to compensate the SAW

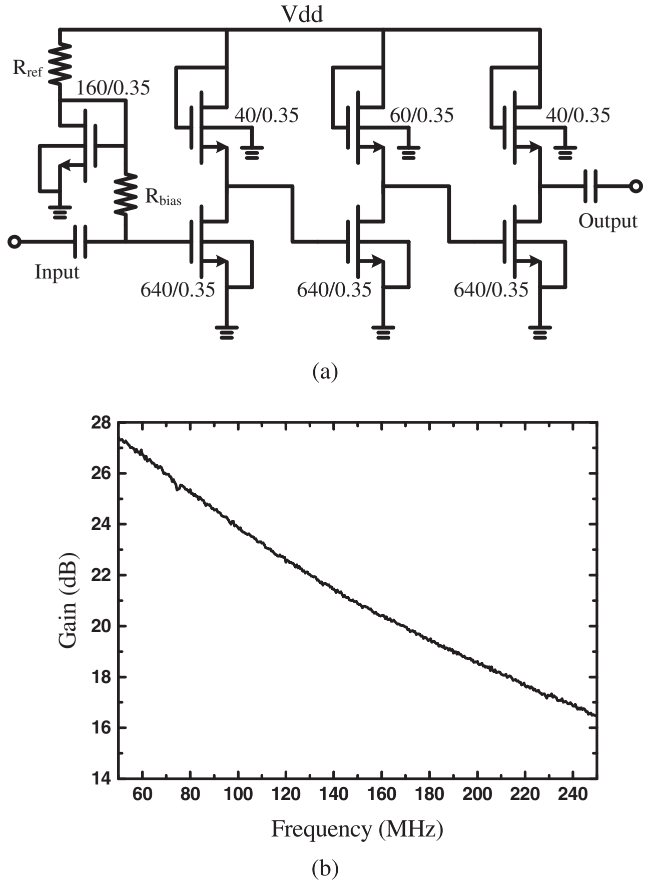

Fig. 4. Two port amplifier: (a) circuit schematic and (b) measurement result.

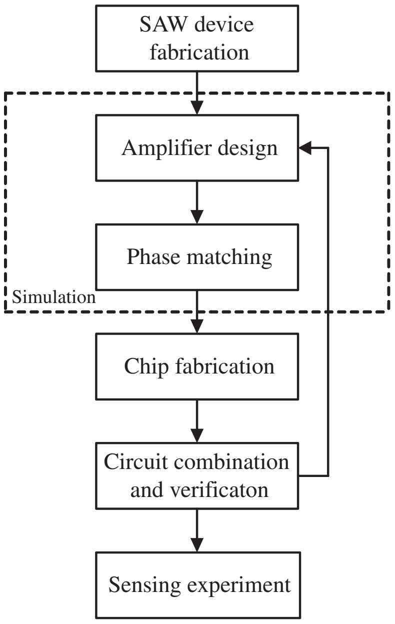

Fig. 5. The design flow of sensor circuit.

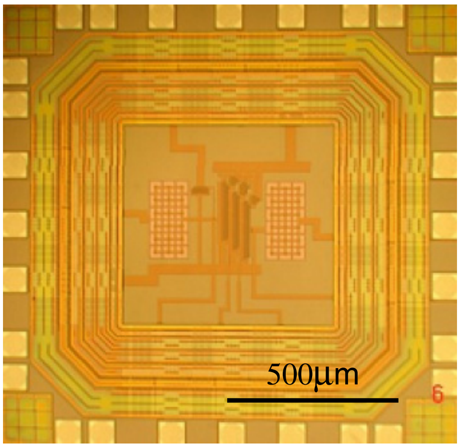

Fig. 6. (Color online) The photo of the circuit.

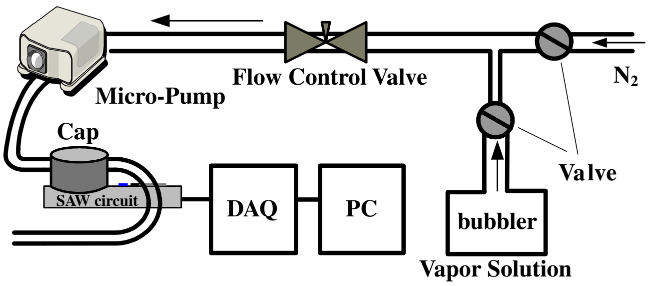

Fig. 7. (Color online) Experimental sensing system in this study.

device and CMOS amplifier. For various sensing experiments and conditions, additional passive components were needed to achieve proper phase matching. While the chip process was completed, the SAW device was wire-bonded with the amplifier in a PCB or metal-can package. The SAW delay line and amplifier were initially characterized by a network analyzer, respectively. A picture of the processed CMOS chip ($1.3 \times 1.3\,\mathrm{mm}^2$) is shown in Fig. 6.

3.3 Sensing system

Sensing systems with closed chambers were proposed in some studies.[12)] The chemical sensor was reported to successfully detect ethanol in previous literature.[13,14)] Figure 7 shows the schematic of a simple sensing system in this study. The SAW device was hermetically sealed in the metal can package, as indicated in Fig. 2(b) to minimize the residual gas volume and reduce the reaction time. Alcohol vapor was diluted by dry nitrogen and flowed into the metal can package when the flow control valve in this system was turned on. Furthermore, the alcohol concentration was detected by infrared spectrophotometer (IR) system. When the valve was turned off, only pure dry nitrogen flowed into the metal can package. The gas flow rate was 100 sccm. All measured data, including those of the frequency shift, were acquired by data acquisition modules (DAQ), and then analyzed by a personal computer (PC).

4. Results and Discussion

4.1 Sensor circuit performance

In order to acquire the repeatable sensing results, it is important to analyze the quality of signal by phase noise measurement. The SAW oscillator was tested with a commercial spectrum analyzer with $V_\mathrm{d} = 3\,\mathrm{V}$. The phase noise of the oscillator was measured by Agilent E5052A signal source analyzer. The operating frequency of the oscillator is 157.2 MHz as shown in Fig. 8. The phase noise of this oscillator is shown in Fig. 9. The achieved phase noise of the oscillator with SAW device is $-150\,\mathrm{dBc/Hz}$

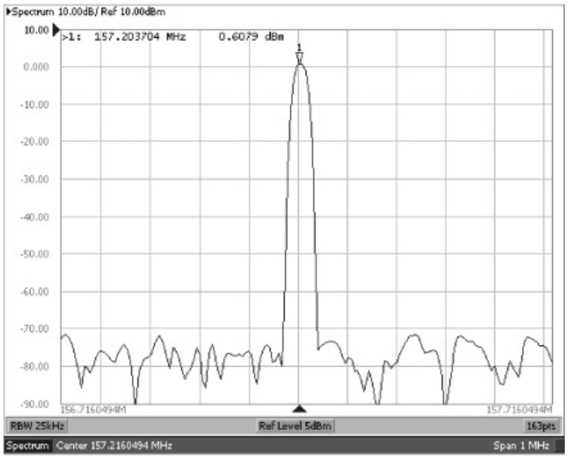

Fig. 8. The power measurement of oscillator.

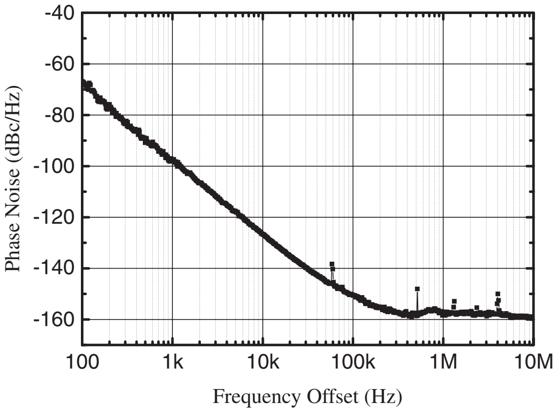

Fig. 9. The phase noise measurement of oscillator.

at 100 kHz offset. Comparing to the traditional oscillator design with inductance–capacitance (LC) tank, the oscillator with SAW device in this study has well phase noise value at 100 kHz due to the high-Q in SAW devices.[15] The excellent phase noise would stabilize the peak frequency drift in the oscillator. The power consumption was 70 mW and expected to be reduced if the SAW device is properly matched in its impedance and the RF amplifier is further optimized. A lower insertion loss in the SAW would be desirable for a low gain amplifier. In this work, the insertion loss of SAW device was about −20 dB.

4.2 Sensing result

After completing the SAW oscillator, the SAW device was tested in a gas sensing system. The sensor was exposed to 50×10^3 ppm of alcohol. A 600-s exposure time was used for each alcohol pulse. The alcohol sensing results by a thin polyepichlorohydrin (PECH) polymer film on a SAW device are demonstrated in Fig. 10. The alcohol molecules are absorbed into the PECH film on the SAW device. As alcohol molecules gradually diffuse into the PECH film, the SAW oscillating frequency shifts because of mass loading effect. Consequently, the maximum oscillation frequency shift between gas on and off is approximately 10 kHz.

5. Conclusions

In this paper, the monolithic integration of a SAW delay-line sensor and a 0.35 μm CMOS amplifier has been demonstrated for the organic vapor sensing application. The circuit scheme and design flow of the oscillator with a SAW device are also presented in this study. The gain and total power consumption of the amplifier are 20 dB and 70 mW, respectively. The phase noise of the SAW oscillator achieves −150 dBc/Hz at 100 kHz offset. The sensing experimental results show that the maximum oscillation frequency shift between gas on and off is approximately 10 kHz with 50×10^3 ppm alcohol vapor concentration. This compact integrated microsensor will be promising for future chemical and biological sensing applications.

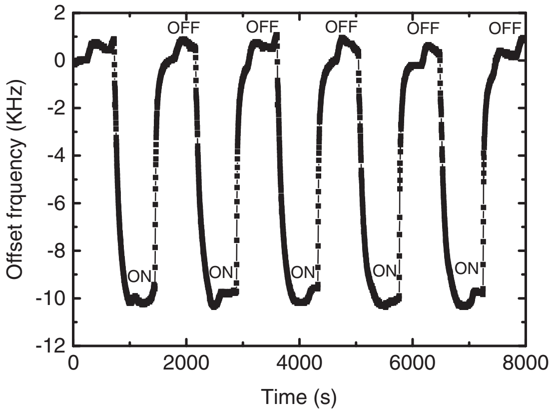

Fig. 10. Typical response of PECH film exposed to alcohol in pure N_2.

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