Optical and Acoustical Methods in Science and Technology

New Approach to SAW Gas Sensors Array Response Measurement

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Majority papers concerning surface acoustic wave sensors technology is devoted to the analysis of self-oscillating circuits with surface acoustic wave device and its basic frequency changes in particular. Such circuits are widely used mainly due to their relative simplicity. Unfortunately the price of the simplicity is such drawbacks like frequency instability, sensitivity to unwanted factors, surface acoustic wave surface load limit etc. A new approach to the analysis of surface acoustic wave gas sensors response is proposed in the paper. The approach significantly eliminates the disadvantages of commonly used so far methods of analysis.

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1. Introduction

Typical approach to response measurement of a surface acoustic wave (SAW) gas sensors is based on basic frequency changes observation of self-oscillating circuits (overtones are usually neglected). Such an approach is most often presented in many papers concerning the topic mainly due to its relative simplicity [1–5]. However, the cost of simplicity are such drawbacks like frequency instability, oscillation fading, significant limitations of SAW surface load, dependence on signal and environment parameters changes etc. The assumption that the information on gas concentration in the environment is contained only in the basic frequency change of SAW device is commonly accepted in the case of self-oscillating SAW circuits.

The theory described in [5, 6] shows that the assumption may not always be true especially in the case of sensors with viscoelastic (polymer) chemisensitive layers. It can be concluded from the mentioned papers that the information concerning the response of such a SAW sensor is included not only in its basic frequency but also in harmonic frequencies changes. Moreover, an important part of the response is included also in the shapes of amplitude and phase characteristic changes of the sensor as well.

Some attempts to use the SAW higher harmonics for sensor response measurement are described in [7], however the self-oscillating circuits still were used there. The circuits presented in the paper enable to observe the changes close to the one harmonic frequency only.

In order to observe the SAW gas sensor response in a much wider frequency range the traditional self-oscillating approach seems not to be suitable and a new approach is needed.

2. New approach description

Instead of self-oscillating circuits a system with short-term ultrastable frequency source (of the order of 0.01 ppm) with linear or stepped frequency modulation (LFM/SFM) working in about 1 GHz wide band is proposed. The signal incites sequentially the set of SAW sensors and tests their responses in the wide spectrum of the frequency bandwidth. The output signal spectrum is analyzed with very high resolution (≈ 0.001 Hz) using digital signal processor. The method is well known in radar signal processing technology and many procedures may be adapted from the field to the SAW response measurement (e.g. adaptative complex signal processing, pattern recognition). Instead of frequency change measurement the system is able to provide the information about the whole spectrum changes inside the operating frequency band as well as changes of SAW velocity and dispersion. Moreover, it may be easily extended to multisensor device that allows preceding complex mathematical operation on the output signal to extract some additional information.

The block diagram of the proposed system is shown in Fig. 1.

The ultrastable signal source generates harmonic signal with frequency increasing in a linear way from $f_0 - \Delta f$ up to $n(f_0 + \Delta f)$, where f_0 is the basic SAW device frequency, Δf — maximum of possible device detuning and n — overtone number. The signal passing through the multiplexers (MUX) is sequentially sampling the individual SAW sensors. The responses are detected and compared to original version of the signal. The products of the detection after analog-digital conversions (ADC)

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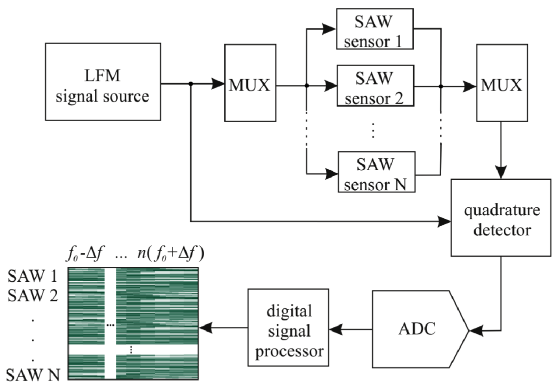

Fig. 1. The block diagram of the system.

are next sent to the digital signal processor where information about sensors characteristic changes under environment detected factors influence is extracted. The results of the processing may be finally represented in the matrix form (e.g. bitmap) that allows applying the pattern recognition procedures. Such the new approach has many basic advantages. It may use different kinds of SAW devices (resonators, delay lines etc.). Moreover, it is much more stable in the frequency than the self--oscillating version and as a result it greatly increases the measurements accuracy. Similar attempts to construct front–end SAW measurement device has been described recently in [8].

In the version proposed here not only frequency changes can be observed but also amplitude and characteristic shapes as well. In order to eliminate high frequency components of the signal the quadrature detection of measured channel changes is proposed. This kind of detection gives opportunity to eliminate unwanted parts of the signal spectrum without loss of the information contained in the signal structure. In addition such a detecting procedure is simple to implement in the modern programmable electronic technology.

3. Detection principle

The signal from ultrastable source passing the reference and measurement channels with SAW devices can be represented in the following two forms for measurement and reference patches, respectively:

$$x_M(t) = x_{IM}(t)\cos(\omega t) - x_{QM}(t)\sin(\omega t)\,, \tag{1}$$

$$x_R(t) = x_{IR}(t)\cos(\omega t) - x_{QR}(t)\sin(\omega t)\,, \tag{2}$$

where subscripts I and Q describe the amplitudes of in phase and quadrature amplitudes, the subscripts M and R concern the measurement and the reference channels, respectively. The information about changes in measurement channel of interest is included in phase difference between both signals. The measurement of the difference can be carried out using the following procedure:

$$S(t) = [x_M(t) - x_R(t)]^2. \tag{3}$$

As a result one can obtain the signal in the form as follows:

$$\begin{aligned}S(t) &= x_{IM}^2\cos^2(\omega t) - 2x_{IM}x_{QM}\sin(\omega t)\cos(\omega t)\\ &- 2x_{IM}x_{IR}\cos^2(\omega t) + 2x_{IM}x_{QR}\sin(\omega t)\cos(\omega t)\\ &+ x_{QM}^2\sin^2(\omega t) + 2x_{QM}x_{IR}\sin(\omega t)\cos(\omega t)\\ &- 2x_{QM}x_{QR}\sin^2(\omega t) + x_{IR}^2\cos^2(\omega t)\\ &- 2x_{IR}x_{QR}\sin(\omega t)\cos(\omega t) + x_{QR}^2\sin^2(\omega t)\,.\end{aligned} \tag{4}$$

Using a simple trigonometric identities it can be converted into the following formula:

$$\begin{aligned}S(t) &= \frac{1}{2}x_{IM}^2[1+\cos(2\omega t)] - x_{IM}x_{QM}\sin(2\omega t)\\ &- x_{IM}x_{IR}[1+\cos(2\omega t)] + x_{IM}x_{QR}\sin(2\omega t)\\ &+ \frac{1}{2}x_{QM}^2[1-\cos(2\omega t)] + x_{QM}x_{IR}\sin(2\omega t)\\ &- x_{QM}x_{QR}[1-\cos(2\omega t)] + \frac{1}{2}x_{IR}^2[1+\cos(2\omega t)]\\ &- x_{IR}x_{QR}\sin(2\omega t) + \frac{1}{2}x_{QR}^2[1-\cos(2\omega t)]\,.\end{aligned} \tag{5}$$

It is easy to notice that operation (3) moves some part of resulting signal spectrum into doubled frequency range and the part can be simply eliminated by low-pass filtering procedure without significant distortions of the low frequency spectrum components.

After low-pass filtering (LPF) the terms of (5) containing doubled frequencies vanish and the resulting signal can be approximated by

$$\begin{aligned}S_{LPF}(t) &= \frac{1}{2}\left(x_{IM}^2 + x_{QM}^2 + x_{IR}^2 + x_{QR}^2\right) - x_{IM}x_{IR}\\ &- x_{QM}x_{QR}\,.\end{aligned} \tag{6}$$

The function contains information about phase difference between signals from measurement and reference channels that is the measure of SAW velocity changes in the measurement channel. Because of orthogonality of I and Q components the formula (6) can be written in the more comprehensive form

$$S_{FDP}(t) = \frac{1}{2}\left(A_M^2(t) + A_R^2(t)\right) - \cos(\varphi)\,, \tag{7}$$

where $A_M(t)$ i $A_R(t)$ describe the signals complex amplitudes in the channels, and φ — phase difference between the signals where $\varphi \in \langle -\pi, \pi\rangle$.

4. Conclusions

The circuit and detection procedure described above allow us very precise monitoring of measured channel changes in a wide-band range of the SAW device spectrum. Such a system gives a more complete spectral characterisation of the device instead of one spectrum component description. It makes the analysis of gas concentration much more exhaustive and accurate. In this case one can obtain the result in a form of a function depending on 3 variables instead of a function of 2 variables only.

The results described commonly in many papers may be then considered as cross-sections of the first one taken for the basic resonant frequency. In consequence the results of measurement using proposed method can easily be reduced, if necessary, to the common one making the cross-section on the basic frequency only. The measurement system proposed here changes the 2D function into the 3D one representing the gas concentration changes in a graphical form of a matrix (picture) that can be analysed using neural network approach, for instance.

When the SAW sensor array is used (as in Fig. 1) the resulting matrix represents the environment chemical composition and can interpret as a graphical odour representation.

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