A MICROELECTRONIC HUMIDITY–FREQUENCY TRANSDUCER WITH HUMIDITY-SENSITIVE CAPACITIVE ELEMENTS

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Abstract

A microelectronic transducer with capacitive elements implementing the principle of humidity to frequency conversion has been developed. Experiments has been conducted for samples of P14 Rapid humidity-sensitive capacitors (Wired and SMD) of Innovative sensor technology company, HCH-1000 humidity-sensitive capacitors of Honeywell company, and humidity-sensitive MOS capacitor of Helium Research Institute ((Vinnytsya, Ukraine). The essential effect of the physical and chemical properties of the humidity-sensitive layer of the capacitive element on the sensitivity of the humidity–frequency transducer has been experimentally proved. In a range of 18–99% of humidity, the transducer with a humidity-sensitive MOS capacitor based on amorphous silicon has the highest sensitivity of 3500 Hz/%. The range of change in the oscillation frequency is 320 kHz.

1. Introduction

Humidity sensors are an integral part of measuring equipment in today's world. The need for humidity control in industry and everyday life requires novel approaches to the development and research of various types of humidity sensors, whose operation is based on changes in the physical and electrical parameters.

Microelectronic sorption humidity sensors are found to be of great practical interest among a great variety of humidity sensors [1–4]. Humidity absorption or liberation by the sorbent is accompanied by changes in the mass and physical and electrical characteristics (conductivity, permittivity, etc.) in adsorption and absorption sensor types [5–8].

The application of primary humidity sensors in frequency devices converting humidity to frequency enhances sensitivity and accuracy, reduces the cost of information processing systems, and improves metrological performances of the transducers. In this case, it is necessary to use a capacitor as a humidity-sensitive element having the most optimal parameters. It allows obtaining smaller overall dimensions of the sensitive element and constructing special integrated circuits for processing of signal on the crystal [9, 10].

A promising trend in the development and construction of microelectronic humidity transducers is the research of humidity–frequency transducers on the basis of semiconductor transistor structures with negative resistance. The study in this area has shown n inseparable relation between reactive properties and negative resistance. Simplicity and multifunctionality of frequency transducers on the basis of semiconductor transistor structures with negative resistance make it promising to measure of physical values in the application. The principle of humidity to frequency conversion excludes analog-to-digital transducers and amplifiers from designs of transducers, makes it possible to reduce the cost of monitoring and control systems, to increase sensitivity and accuracy of transformation of informative signal into frequency, and to improve metrological performances of the transducers [11–14].

Therefore, the development and implementation of these transducers in actual practice is one of the urgent tasks.

2. Theoretical and Experimental Research

The study is intended to develop a new microelectronic humidity–frequency transducer with humidity-sensitive elements, having high sensitivity to measuring parameters and wide measuring humidity range. The microelectronic frequency–humidity transducer is designed as a hybrid integrated circuit. The self-sustained oscillator is a circuit with negative resistance consisting of a VT1 dual gate MOS-transistor and a VT2 bipolar transistor. The equivalent capacity of the impedance on these electrodes as drain of dual gate MOS field-effect transistor VT1 and collector of bipolar transistor VT2 forms the capacity of the oscillating circuit. The inductance of the oscillating circuit is implemented using inductor *L*.

Resistors R1, R2, and R3 form the voltage dividers and provide voltage supply for transistors VT1 and VT2. The limiting capacitor *C* prevents the current flow through the voltage supply source. Negative resistance emerges on electrodes of the drain of MOSFET transistor VT1 and the collector of bipolar transistor VT2 with increasing voltage supply to a certain required value. It provides an excitation of oscillations in the circuit. The effect of humidity on the humidity-sensitive capacitor produces a change in the negative component of the impedance on the drain of field-effect transistor and on collector of bipolar transistor. It causes an effective change of the circuit oscillation frequency.

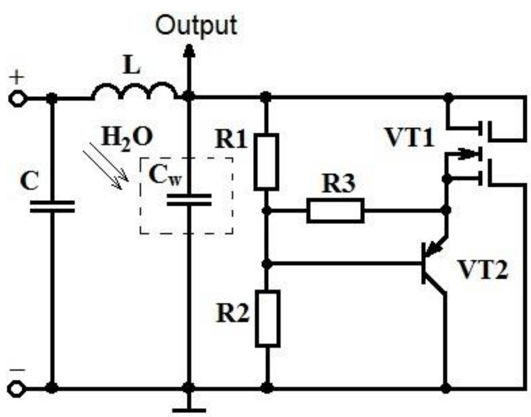

Fig. 1. Circuit of a microelectronic humidity–frequency transducer with a humidity-sensitive element.

The following humidity-sensitive samples were used as experimental:
– a humidity-sensitive MOS capacitor developed by Helium Research Institute (Vinnitsa, Ukraine);
– an HCH-1000 humidity-sensitive capacitor (Honeywell company);
– humidity-sensitive capacitors P14 Rapid (Wired and SMD) of Innovative sensor technology company.

The humidity-sensitive layers of the studied capacitors of Honeywell and Innovative sensor technology companies are composed of a porous polymer.

To determine the transfer function and the dependence of sensitivity on humidity, an equivalent high-frequency nonlinear circuit of the humidity–frequency transducer with a humidity-sensitive element has been developed (Fig. 2).

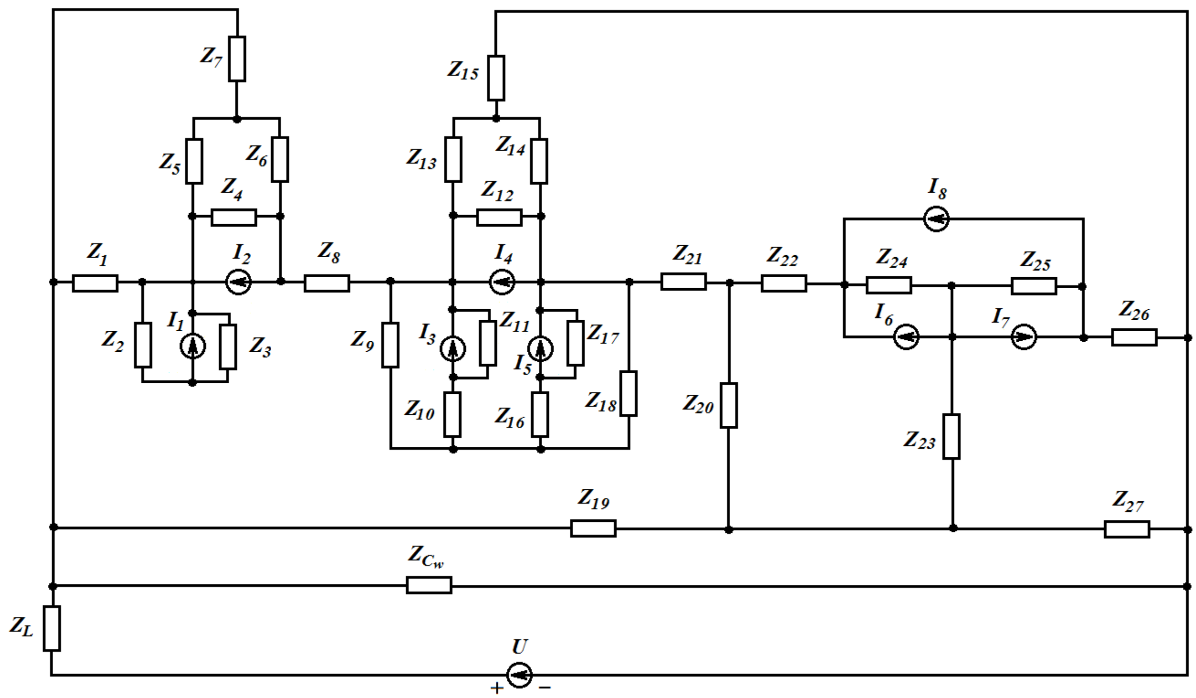

Fig. 2. High-frequency nonlinear circuit of a humidity–frequency transducer with humidity-sensitive elements.

The symbols are used in the equivalent circuit (Fig. 2) are defined as follows:

$$Z_L = j\omega L, \quad Z_{C_w} = \frac{1}{j\omega C_w}, \quad Z_1 = R_{d1} + R'_{d1} + j\omega L_{d1}, \quad Z_2 = R_{bd1} - j\frac{1}{\omega C_{bd1}}, \quad Z_3 = \frac{1}{j\omega C_d},$$

$$Z_4 = R_{ds1}, \quad Z_5 = \frac{1}{j\omega C_{gd1}}, \quad Z_6 = \frac{1}{j\omega C_{gs1}}, \quad Z_7 = R_{g1} + R'_{g1} + j\omega L_{g1}, \quad Z_8 = R_{ds1}, \quad Z_9 = \frac{1}{j\omega C_{bd2}},$$

$$Z_{10} = R_{bd2}, \quad Z_{11} = \frac{1}{j\omega C'_d}, \quad Z_{12} = R_{ds2}, \quad Z_{13} = \frac{1}{j\omega C_{gd2}}, \quad Z_{14} = \frac{1}{j\omega C_{gs2}},$$

$$Z_{15} = R_{g2} + R'_{g2} + j\omega L_{g2}, Z_{16} = R_{bs3}, \ Z_{17} = \frac{1}{j\omega C_s}, \ Z_{18} = \frac{R_{b2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2} - j\frac{R_{b2}^2 \omega C_{bs2}}{1+\omega^2 R_{b2}^2 C_{bs2}^2},$$

$$Z_{19} = R_1, \quad Z_{20} = R_3, \quad Z_{21} = R_{s2} + R'_{s2} + j\omega L_{s2}, \quad Z_{22} = R_e + R'_e + j\omega L_e, \quad Z_{23} = R_B + R'_B + j\omega L_B,$$

$$Z_{24} = \frac{1}{j\omega C_e}, \ Z_{25} = \frac{1}{j\omega C_c}, \ Z_{26} = R_c + R'_c + j\omega L_c, \ Z_{27} = R_2.$$

where L is the external inductor; C_w is the humidity-sensitive capacitor; R_1, R_2, R_3 are the resistances of voltage divider; R_d is the resistance of the drain; R'_d is the ohmic resistance of the drain; L_d is the inductance of the drain; C_{bd} is the capacity of the body-drain; R_b is the resistance of the body; C_{bs} is the capacity of the body-source; R_{bd1}, R_{bd2} are the bulk resistances of the body–drain junction; R_{bs3} is the bulk resistance of the body–source junction; C_d, C'_d are the capacities of the *p–n* junction of the drain; C_s is the capacity of the *p–n* junction of the source; R_{ds} is the resistance of the drain-source; C_{gs} is the capacity of the gate-source; C_{gd} is the capacity of the gate-drain; R_g is the resistance of the gate; R'_g is the ohmic resistance of the gate; L_g is the inductance of the gate; I_{bd} is the current of the junction of the body-drain; I_{sd}, I'_{sd} are the currents of the source-drain; I_{bds} is the current of the junction of the body-drain-source; I_{bs} is the current of the junction of body-source; R_{ds1} is the common resistance of drain-source of the first gate of dual-gate transistor VT1; R_s is the resistance of the source; R'_s is the ohmic resistance of the source; L_s is the inductance of the source; R_B is the resistance of the base; R'_B is the ohmic resistance of the base; L_B is the inductance of the base; C_e is the capacity of the *p–n* junction of the emitter; C_c is the capacity of the *p–n* junction of the collector; R_e is the resistance of the *p–n* junction of the emitter; R'_e is the ohmic resistance of the emitter; L_e is the inductance of the emitter; R_c is the resistance of the *p–n* junction of the collector; R'_c is the ohmic resistance of the collector; L_c is the inductance of the collector; I_{eB} is the current of the junction of the emitter-base of transistor VT2; I_{cB} is the current of the junction of the collector-base of transistor VT2; I_{ec} is the current of the junction of the emitter-collector of transistor VT2.

The dependence of oscillation frequency on humidity (transfer function) is determined by the circuit reverse current in accordance with the equivalent circuit (Fig. 2) based on the Lyapunov stability theory [15]. The transfer function of the humidity transducer is described by the formula

$$F_0 = \frac{C_w(W)C_{gd1}C_{gd2}C_cC_{gs1}C_{gs2} \pm \sqrt{H1+H2+H3+H4+H5+H6+H7}}{4\pi LC_w(W)C_{gd1}C_{gd2}C_cC_{gs1}C_{gs2}}, \quad (1)$$

where $H1 = C_w^2(W)C_{gd1}^2C_{gd2}^2C_c^2C_{gs2}^2C_{gs1}^2$; $H2 = 4LC_w^2(W)C_{gd1}^2C_{gd2}^2C_c^2C_{gs2}C_{gs1}^2$;

$$H3 = 4LC_w^2(W)C_{gd1}^2C_{gd2}C_c^2C_{gs2}^2C_{gs1}^2;\quad H4 = 4LC_w(W)C_{gd1}^2C_{gd2}^2C_c^2C_{gs1}^2C_{gs2}^2;$$

$$H5 = 4LC_w^2(W)C_{gd1}^2C_{gd2}^2C_cC_{gs1}^2C_{gs2}^2;\quad H6 = 4LC_w^2(W)C_{gd1}C_{gd2}^2C_c^2C_{gs1}^2C_{gs2}^2;$$

$$H7 = 4LC_w^2(W)C_{gd1}^2C_{gd2}^2C_c^2C_{gs2}^2C_{gs1}.$$

Dependences of oscillation frequency on humidity calculated by (1) and determined experimentally for microelectronic humidity–frequency transducers with humidity-sensitive capacitive elements of Innovative sensor technology and Honeywell companies are shown in Fig. 3; those with the humidity-sensitive capacitor developed by Helium Research Institute are shown in Fig. 4. The plots show that an increase in humidity W leads to a decrease in the generation frequency (Figs. 3, 4). The ranges of change in transducer generation frequency have the following values:

– 103 kHz (humidity-sensitive capacitor P14 Rapid (WIRED), $W = 1 \div 100\%$);
– 92 kHz (humidity-sensitive capacitor P14 Rapid (SMD), $W = 1 \div 100\%$);
– 74 kHz (humidity-sensitive capacitor HCH-1000, $W = 0 \div 100\%$);
– 320 kHz (humidity-sensitive MOS capacitor, $W = 18 \div 99\%$).
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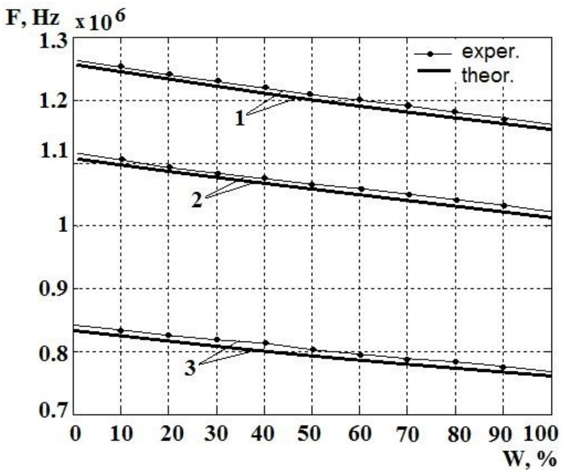

Fig. 3. Experimental and theoretical dependences of oscillation frequency on the relative air humidity for the transducer with humidity-sensitive capacitors: (*1*) P14 Rapid (WIRED), (*2*) P14 Rapid (SMD), and (*3*) HCH-1000.

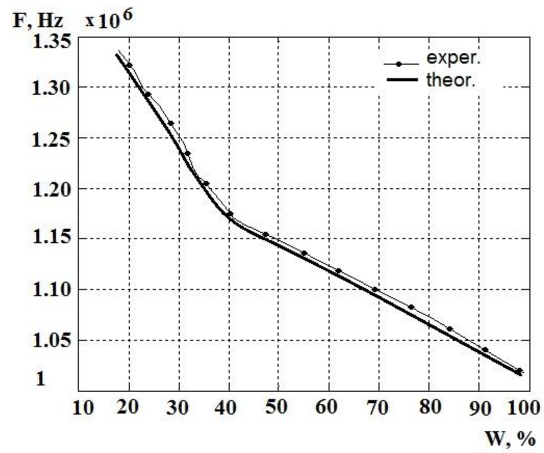

Fig. 4. Experimental and theoretical dependences of oscillation frequency on the relative air humidity of the transducer with a humidity-sensitive MOS capacitor.

The formula for sensitivity of the frequency transducer was calculated using equation (1):

$$S_W = -\frac{C_w(W)C_{zc1}C_{zc2}C_kC_{zb1}C_{zb2} \pm \sqrt{H1+H2+H3+H4+H5+H6+H7}\left(\frac{\partial C_w(W)}{\partial W}\right)}{4\pi L C_w^2(W)C_{zc1}C_{zc2}C_kC_{zb1}C_{zb2}} +$$

$$+\frac{\left(\frac{\partial C_w(W)}{\partial W}\right)G1 \pm \frac{G2\left(\frac{\partial C_w(W)}{\partial W}\right)+G3\left(\frac{\partial C_w(W)}{\partial W}\right)+G4\left(\frac{\partial C_w(W)}{\partial W}\right)}{2\sqrt{H1+H2+H3+H4+H5+H6+H7}}}{4\pi L C_w(W)C_{zc1}C_{zc2}C_kC_{zb1}C_{zb2}} +$$

$$+\frac{\left(\frac{\partial C_w(W)}{\partial W}\right)G1 \pm \frac{G5\left(\frac{\partial C_w(W)}{\partial W}\right)+G6\left(\frac{\partial C_w(W)}{\partial W}\right)+G7\left(\frac{\partial C_w(W)}{\partial W}\right)+G8\left(\frac{\partial C_w(W)}{\partial W}\right)}{2\sqrt{H1+H2+H3+H4+H5+H6+H7}}}{4\pi L C_w(W)C_{zc1}C_{zc2}C_kC_{zb1}C_{zb2}}, \tag{2}$$

where $G1 = C_{zc1}C_{zc2}C_kC_{zb1}C_{zb2}$; $G2 = 2C_w(W)C_{zc1}^2C_{zc2}^2C_k^2C_{zb1}^2C_{zb2}^2$;

$$G3 = 8LC_w(W)C_{zc1}^2 C_{zc2}^2 C_k^2 C_{zb2} C_{zb1}^2; \quad G4 = 8LC_w(W)C_{zc1}^2 C_{zc2} C_k^2 C_{zb1}^2 C_{zb2}^2;$$
$$G5 = 4LC_{zc1}^2 C_{zc2}^2 C_k^2 C_{zb1}^2 C_{zb2}^2; \qquad G6 = 8LC_w(W)C_{zc1}^2 C_{zc2}^2 C_k C_{zb1}^2 C_{zb2}^2;$$
$$G7 = 8LC_w(W)C_{zc1} C_{zc2}^2 C_k^2 C_{zb1}^2 C_{zb2}^2; \quad G8 = 8LC_w(W)C_{zc1}^2 C_{zc2}^2 C_k^2 C_{zb2}^2 C_{zb1}.$$

The theoretical and experimental dependences of sensitivity on changes in air relative humidity for transducers with a WIRED, SMD, HCH-1000 and MOS capacitor are shown in Figs. 5 and 6. The plots (Figs. 5, 6) show that the sensitivity of the transducer with humidity-sensitive capacitors is as follows:

- P14 Rapid (WIRED, Innovative sensor technology company) changes from 1304 to 1000 Hz/% within a measuring range of $W = 1 \div 100\%$;
- P14 Rapid (SMD, Innovative sensor technology company) changes from 1077 to 822 Hz/% within a measuring range of $W = 1 \div 100\%$;
- HCH-1000 (Honeywell company) changes from 835 to 570 Hz/% within a measuring range of $W = 0 \div 100\%$;
- MOS-capacitor (Helium Research Institute) changes from 5730 to 1917 Hz/% within a measuring range of $W = 18 \div 99\%$.

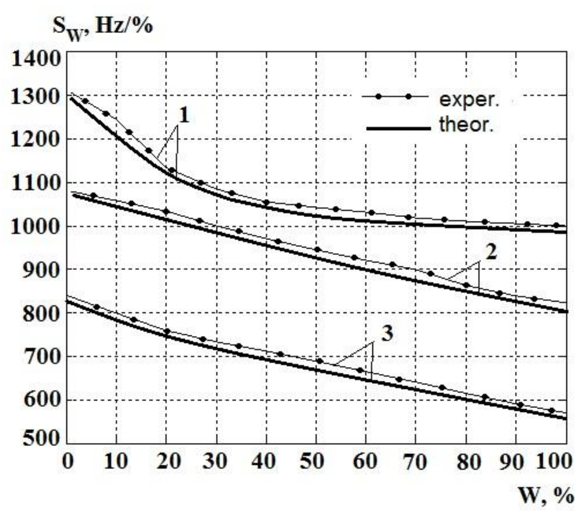

Fig. 5. Experimental and theoretical dependences of sensitivity on the air relative humidity for the transducer with humidity-sensitive capacitors: (*1*) P14 Rapid (WIRED); (*2*) P14 Rapid (SMD); and (*3*) HCH-1000.

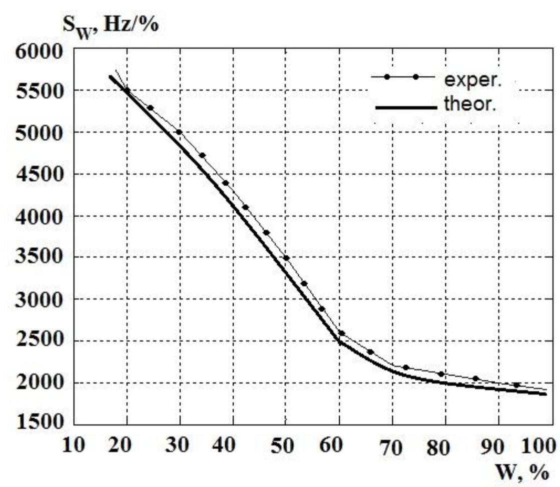

Fig. 6. Experimental and theoretical dependences of sensitivity on the air relative humidity for the transducer with a humidity-sensitive MOS capacitor.

3. Conclusions

The microelectronic humidity transducer with capacitive elements implementing the principle of humidity to frequency conversion has been developed. Analytic expressions for the transfer function and sensitivity equation have been derived using a high-frequency nonlinear circuit of humidity–frequency transducer. The electrical parameters of the frequency transducer have been studied experimentally; theoretical dependences of the parameters have been calculated.

It has been determined that the average values of sensitivity of the developed transducer with humidity-sensitive capacitors are as follows:

- 1040 Hz/% within a measuring range of $W = 1 \div 100\%$ for P14 Rapid (WIRED, Innovative sensor technology company);
- 944 Hz/% within a measuring range of $W = 1 \div 100\%$ for P14 Rapid (SMD, Innovative sensor technology company);
- 689 Hz/% within a measuring range of $W = 0 \div 100\%$ for HCH-1000 (Honeywell company);
- 3500 Hz/% within a measuring range of $W = 18 \div 99\%$ for a MOS-capacitor (Helium Research Institute).

The significant effect of the physical and chemical properties of the humidity-sensitive layer of the capacitive element on the sensitivity of the transducer has been proved experimentally. In a humidity range of 18–99%, the transducer with a humidity-sensitive MOS capacitor based on amorphous silicon has the highest sensitivity of 3500 Hz/%.

Analysis of the theoretical and experimental results has shown that the theoretical values agree with the experimental data to an accuracy of better than 3%.

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