Angular displacement sensor based on oscillistor effect

A I Cheredov, A V Shchelkanov

Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

1E-mail: aicher@mail.ru
2E-mail: shchelkanov@omgtu.ru

Abstract. The development of angular displacement sensors with a frequency output signal based on the oscillistor effect in electronic germanium is considered. The experimental results of the dependence the oscillistor oscillation frequency on angular displacement are described in the paper. Angular displacement sensors sensitivity is 1.0 kHz/deg at temperature of 295 K. With decreasing temperature the sensitivity increases and reaches 40 kHz/deg at 77 K. The design of the oscillistor-based sensor is presented.

1. Introduction

Measuring the linear and angular displacement of physical objects is essential for many applications: industrial, transport, robotics, military, etc. The resistive based displacement sensors (potentiometers) [1] are contact-type sensors. The non-contact type angular displacement sensor are based on optical [2], capacitive [3], and inductive [4] methods. The output signal of such sensors is an analog value. The sensor described in this article is a non-contact type sensor. Its advantage is the frequency output. The frequency output provides high noise immunity and can be easily integrated into digital circuits. The sensor can operate in a very wide temperature range.

2. Theory

In 1958 Ivanov and Ryvkin discovered the phenomenon of current oscillation flowing through a semiconductor rod placed in parallel electric $E_0$ and magnetic $B_0$ fields. The discovered phenomenon was called the oscillistor effect.

Later M. Glicksman [5] explained this phenomenon on the basis of the helical instability theory of Kadomtsev-Nedospasov. The most clearly physical mechanism of the appearance of current oscillations is shown in [6]. The helical disturbance arising in the cylindrical rod of n-semiconductor in cylindrical coordinates is expressed by the formula:

$$\Delta n = F(r)e^{i\omega t - ikr - im\varphi},$$

where $F(r)$ is determined by the boundary conditions on the cylinder surface; $\omega$ is angular frequency; $k$ is wave vector; $m$ is harmonic; $t$ is time.

The electric field along the sample splits helical disturbance of negative and positive charges, which leads to the occurrence of azimuthal $E_\varphi$ and radial $E_r$ electric fields. These fields, in combination with the longitudinal magnetic field, cause the appearance of radial ($E_r \times B$) and azimuthal ($E_\varphi \times B$) fluxes of charge carriers (figure 1). The flows have a direction that there is an increase of carriers in the place of their excess and a decrease in the place of their insufficiency. At the same time, the initial disturbance is amplified. Simultaneously with the amplification due to diffusion and
recombination, the disturbance is attenuated. The flows amplifying the initial disturbance depend on the strength of electric $E$ and magnetic $B$ fields and grow with their increase. There are some threshold values of $E_T$ and $B_T$, below which the disturbance is attenuated and above which it is amplified.

For a given value of magnetic field induction $B$, the value of the threshold electric field strength $E_T$, at which instability occurs, is determined by the expression: $E_T = C/B$, where $C$ is the coefficient determined by the physical parameters of the electron-hole plasma and the size of the sample.

In addition, the disturbance under the action of the electric field moves along the rod in the direction of the minority charge carriers drift with the velocity:

$$V_a = E \frac{\mu_n \mu_p (n - p)}{\mu_n n - \mu_p p} = E \mu_a = 0,$$

(2)

where $\mu_a$ is ambipolar mobility; $n$ and $p$ is electron and hole concentration respectively; $\mu_n$ and $\mu_p$ is the mobility of electrons and holes.

Thus, at values of electric $E$ and magnetic $B$ fields exceeding the threshold values of $E_T$ and $E_F$, the disturbance of the quasi-neutral plasma density increases and simultaneously moves along the sample. In addition, the helical disturbance is rotated during the longitudinal movement. The total motion of the helix is a composition of two motions: 1) the disturbance transfer in the direction of drift of the non-basic carriers; 2) the rotation of the helix. Hence, the occurring instability of the electron-hole plasma flow will have a helical character. For the extrinsic semiconductor ($\mu_a > 0$), the disturbance propagation along the sample will prevail, and for the intrinsic one ($n = p$, $\mu_a = 0$) the motion will be purely rotational.

At low ambipolar drift rates (or at very fast disturbance growth) the carrier concentration disturbance grows faster than it decreases. At field strengths above some critical ones the disturbance amplification will change to self-excitation. In this mode the semiconductor sample can be used as an alternating voltage generator. This mode of helical instability of semiconductor plasma is called “oscillistor”.

The frequency of oscillistor oscillations depends on many factors and can be approximately described by the expression:

$$f = \frac{0,18 \mu_a}{a} E + \frac{0,71 D_a (\mu_n - \mu_p)}{a^2} B,$$

(3)
where $D_a$ is ambipolar diffusion ratio; $a$ is sample transverse size; $E$ – electric field strength; $B$ – magnetic field induction.

From expression (1) it can be seen that a change in the electric and magnetic field strengths and electron-hole plasma parameters of the oscillistor leads to a change in the frequency of oscillistor oscillations. This property of the oscillistor effect can be used to build frequency sensors of various physical quantities. The papers [7, 8] describe measuring transducers of voltage, magnetic field induction, and linear motion based on the oscillistor effect in electronic germanium.

A change in the angle between the electric and magnetic fields (at fixed values of these fields) leads to a change in the frequency and amplitude of the oscillistor oscillations. At specific angles the oscillations are canceled. This is due to the influence of the transverse component of the magnetic field and the Sul's magnetoconcentration effect on the behavior of the helical instability.

In this paper we consider the possibility of building frequency angular displacement sensors based on the oscillistor effect in electronic germanium.

3. Experimental results

For experimental research of sensors based on the oscillistor effect, the sensitive element (oscillistor) was made of electron germanium of GES40, GES45 grades in the form of a square cross-section rod of $(1 \times 1 \times 5)$mm$^3$ size. To create electron-hole plasma, the injecting contacts were made of indium (In), and ohmic contacts were made of tin (Sn).

A necessary condition for the oscillistor effect to occur is the presence of an electron-hole plasma in the volume of the oscillistor, which can be created in various ways. One way is to create semiconductor plasma with the help of an injecting contact. The oscillistor effect occurs in the form of the generation of low-frequency transverse potential oscillations. When there is a small imbalance between the electric and magnetic fields, oscillations of the current flowing through the oscillistor occur. The oscillations frequencies of potential and current are equal. Hence, it is possible to make several variants of electrodes (contacts) on the oscillistor and include them in the measuring circuit when creating an angular displacement sensor.

![Figure 2](image1.png)

**Figure 2.** Electron-hole plasma is created by injection from the end contacts and the oscillistor is rotated in a magnetic field.

![Figure 3](image2.png)

**Figure 3.** Electron-hole plasma is created by injection from the end contacts and the oscillistor is fixed in a magnetic field.

![Figure 4](image3.png)

**Figure 4.** Electron-hole plasma is created by injection from the side contacts and the oscillistor is fixed in a magnetic field.

A version (figure 2) provides mechanical connection of the oscillistor to the moving object. The schemes in figure 3, figure 4 provide mechanical connection of the moving electrode of the variable resistor with the object.

The oscillistor was placed in the magnetic field created using two permanent magnets made of NdFeB alloy in the form of rectangular plates 4 mm thick. Figure 5 schematically shows the magnetic system with the oscillistor located in it for the variant of figure 3.
Figure 5. Schematic view of the sensor with rotation oscillistor. 1 – case; 2 – permanent magnets made of NdFeB alloy; 3 – oscillistor; 4 – oscillistor holder; 5 – contact pads; 6 – power leads; 7 – output signal leads.

Figure 6 shows experimental dependences of the sensor output frequency on the oscillistor rotation angle in the magnetic field at temperatures of 295 K and 77 K.

Figure 6. Frequency-angle characteristics, T=295K.

Figure 7. Frequency-angle characteristics, T=77K. 1 – 20 V; 2 – 40 V.

To exclude heating of the oscillistor by the current, it was powered by single or repeated rectangular voltage pulses with a frequency of 10 Hz and a duration of one to ten milliseconds. At a temperature of 295 K the pulse amplitude was 50 volts, at a temperature of 77 K the amplitude decreased to 20 volts. The output signal was taken from the side ohmic contacts of the oscillistor. Amplitude of output alternating voltage reached (0.8-1.2) V.

Experimental studies of oscillistor angular displacement sensors showed that sensitivity in the range (0-8) degrees at a temperature of 295 K is (0.8-1.0) kHz/deg. With decreasing temperature the sensitivity increases and reaches 40 kHz/deg at 77 K.

As can be seen from the presented results, the output frequency of oscillistor-based sensors significantly depends on its temperature. Thus, for practical use of sensors based on germanium
oscillator, it is necessary to use them at a constant temperature, for example, in cryogenic environments, calibrating the sensor for each operating temperature, or to carry out its thermostatting.

The frequency of electrical oscillations in oscillator depends on the value of applied voltage. The frequency increases when the voltage is increased. This property can be used to compensate for temperature errors. When a thermistor whose resistance changes with the ambient temperature is included in the sensor supply circuit, the temperature error is compensated by the change in voltage applied to the sensor element.

Above we considered angular displacement sensor, in which the measured quantity is directly converted into the frequency of the sensor output signal. From the formula (1) it follows that it is possible to change the frequency of oscillator oscillations by changing the supply voltage and the density of the injected electron-hole plasma. The density of injected plasma depends on the injection current. Thus, by including in the oscillator circuit an element controlling supply voltage or injected current, frequency sensors of various physical quantities can be built. Figure 3, 4 shows two circuits of angular displacement sensor with preconversion of angular motion into change of resistance. In these circuits, the ohmic resistance of the variable resistor $R(\alpha)$ determines the oscillator voltage (figure 3), or the current through the side injection contact (injection current) (figure 4).

In the circuit of figure 3, the oscillator voltage $U_o$ depends on the resistor resistance $R(\alpha)$ and is determined by the expression:

$$U_o = \frac{UR}{R(\alpha) + R'},$$  \hspace{1cm} (4)

where $R$ is oscillator resistance.

For the research, a variable resistor (potentiometer) with a maximum knob rotation angle of 250 deg and a nominal resistance of 10 kOhm was chosen as a resistor $R(\alpha)$. The initial position of the knob was taken as 15 deg, and the $R(\alpha)$ resistance was equal to 600 Ohm.

During the study, the knob's rotation angle varied from 15 degrees to zero. An oscillator of germanium grades HES30 with dimensions $(1 \times 1 \times 5)$ mm$^3$ was placed in the gap of magnetic system with magnetic field induction of 0.4 T. Power was supplied by single pulses with duration of 10 ms, amplitude 60 V.

In figure 8 shows the dependence of oscillator frequency on voltage. Figure 9 shows the static characteristic of the sensor as a function of the potentiometer knob rotation angle.

![Figure 8](image1.png)  \hspace{1cm} ![Figure 9](image2.png)

**Figure 8.** Frequency-voltage characteristics, $B=0.4T$.

**Figure 9.** Frequency-angle characteristics, $B=0.4T; U=40$ V.
It was obtained that the sensitivity of the studied angular displacement sensor reaches 0.75 kHz/deg. Linearity error of the static characteristic reaches 8%.

Figure 10 shows the dependence of the oscillistor oscillations frequency on the current through the injecting contact on the side edge of the oscillistor. The dependence of the frequency on the injection level is the basis for the angular displacement sensor shown in figure 4. The same potentiometer was used as a resistor as for the circuit of figure 3. A value of 0 deg was taken as the initial position of the knob. Figure 11 shows the characteristic of the sensor. The injection current is generated from a stable voltage generator 1V. The average sensitivity of the sensor in the range (0-15) deg is 2 kHz/deg.

![Figure 10. Dependence of oscillistor frequency on injecting current, B=0.4T; U=40 V](image1)

![Figure 11. Frequency-angle characteristics, B=0.4T; U=40 V.](image2)

As was noted above, the operation of oscillistor sensors is greatly affected by temperature. One of the effective methods to reduce the temperature error of oscillistor sensors is differential coupling. The design of the described sensors allows to place another oscillistor in the magnetic system, which is not affected by the measured, but it is in the same conditions as the working one. Since both oscillistors are in the same conditions (in the working gap of the same magnetic system), the differential mode also allows to reduce errors caused by changes in magnetic induction value and supply voltage.

4. Conclusion

The results presented in this paper show the possibility of creating angular displacement sensor with a frequency output signal based on the oscillistor effect in electronic germanium, characterized by high sensitivity, simple design, and the possibility of adjusting the characteristics of sensors without additional elements and changing the circuit.

References

[1] Eren H., Webster J. G., Measurement Instrumentation and Sensors Handbook: Spatial, Mechanical, Thermal, and Radiation Measurement, CRC Press, 2014.

[2] Golebiowski, J., Milcarz, S., Rybak, M. Optical fibre angle sensor used in MEMS, (2014) Journal of Physics: Conference Series, 494 (1), № 012013.

[3] Fan, X., Yu, Z., Peng, K., Chen, Z., Liu, X. A Compact and High-Precision Capacitive Absolute Angular Displacement Sensor, (2020) IEEE Sensors Journal, 20 (19), № 9097866, pp. 11173-11182.

[4] Zhang, L., Wang, K., Zheng, S. Design and experimental study of a novel self-inductance displacement sensor for active magnetic bearings, (2018) Yi Qi Yi Biao Xue Bao/Chinese
Journal of Scientific Instrument, 39 (1), pp. 100-109.
[5] Gliksman M. Instabilities of a cylindrical electron-hole plasma in a magnetic field // Phys. Rev. – 1961. Vol 124. P. 1655 – 1664.
[6] C. E. Hurwitz , A.L. Mc Whorter, Drawing helical density waves in semiconductor plazmas, Physical Review. A., vol. 134A, 1964, pp. 1033-1050.
[7] A. I. Cheredov, A. V. Shchelkanov, Metrological characteristics of measuring converters based on oscillistor effect, Dynamics of Systems, Mechanisms and Machines (Dynamics) Proceeding, 2016, DOI:10.1109/Dynamics.2016.7818993.
[8] A. V. Shchelkanov, A. I. Cheredov. Photodetectors based on oscillistor effect, Journal of Physics: Conference Series, 2019, vol. 1210, pp. 012029-1–012029-5, DOI:10.1088/1742-6596/1210/1/012029.