Oscillistor-based force sensor

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Abstract. The development of an oscillistor based force sensor with a frequency output is introduced. Sensor can operate in a wide temperature range from room to cryogenic. Experimental studies were carried out at temperatures of 77 and 295 K. Force sensor sensitivity is 0.9 kHz/N in the force range (0–10)N at temperature 295K. A decrease temperature to 77K leads to increase sensitivity to 15 kHz/N. The design of the oscillistor based force sensor is presented.

1. Introduction
Force measuring problems exist in various industrial and technical fields. In the modern sensors, the most commonly used method is the measuring the strain produced in an elastic member by the unknown force. The sensor is comprised of a spring and linear variable differential transformer displacement sensor. Within the linear range of the spring, the linear variable differential transformer sensor produces voltage, which is proportional to the applied force [1]. A feature of the described sensor is frequency output. Frequency output provides very high noise immunity and a simple way of connecting to digital circuits [2]. One of the demands for any sensors is to be capable of operating in a wide temperature range. The sensor described in this paper can operate in a temperature range from room to cryogenic temperatures.

The paper is organized as follows. First, a description of the oscillistor effect theory is given. Next, the materials and design of the sensor are analyzed. This part of the paper describes the process technology of the specimen to obtain the necessary characteristics of the sensor. Then an optimal construction of the force sensor is designed. Finally the experimental results are presented.

2. Theory
An oscillistor is a long semiconductor diode fabricated by using a special technology. Oscillistor is placed in longitudinal electric and magnetic fields. In practice, the electric field is produced by electric voltage applied to face end contacts of the oscillistor. One of the contacts has p-n junction properties and the other is ohmic contact. When the values of the electric field strength $E$ and magnetic field induction $B$ exceed some thresholds values $E>E_T$ and $B>B_T$, the self-generated oscillations of current in the oscillistor are onset [3]. This effect, called oscillistor effect, is caused by the occurrence of the absolute helical instability in the semiconductor specimen electron-hole plasma [4].

There is a rotational motion of the electron-hole plasma helical disturbance in the intrinsic semiconductor. The current oscillation frequency is determined by the frequency of the helical disturbance rotation.
In non-intrinsic semiconductor, the helical disturbance is moving towards the action of the electric field with speed $V_a$:

$$V_a = E\mu_a,$$

(1)

where $\mu_a$ – ambipolar mobility of charge carrier.

The helical disturbance moving is equivalent to an azimuthal rotation and frequency is determined by the moving speed of the disturbance.

Frequency value could be found as [5]:

intrinsic semiconductor:

$$f_i = \frac{-20D_a}{9\pi a^2} (\mu_n - \mu_p) B_T,$$

(2)

where $\mu_n$ and $\mu_p$ is the mobility of electrons and holes; $D_a$ is the ambipolar diffusion coefficient; $a$ is the oscillistor transverse size.

non-intrinsic semiconductor:

$$f_n = \frac{K}{2\pi} \mu_a E_T,$$

(3)

where $K$ is the wave number.

It should be noted that as longitudinal current oscillations occur, transverse electric potential oscillations occur simultaneously. In addition, the frequencies of these oscillations are equal.

As can be seen from the equations (2) and (3), the absolute value of the oscillations frequency is determined by the specimen size, electron-hole plasma parameters, condition of the specimen surface and values of the electric and magnetic field strength. Changing the value of any of these values leads to a change in frequency. This allows using of oscillistor effect for constructing frequency sensors of the various physical quantities [6].

In real semiconductor the helical disturbance rotates and simultaneously drifts in the electric field direction and frequency will be determined by both the helical disturbance native rotation and its drift in an external electric field. And ambipolar drift makes the main contribution to the frequency value.

In the case of the electrons $n$ and holes $p$ concentration are equal ($n = p$), the ambipolar mobility becomes equal to zero and the drift of the helical disturbance is absent:

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

(4)

where $n$ and $p$ is electron and hole concentration respectively.

Generally, the expression for the ambipolar drift can be written as

$$\mu_a = \frac{n\mu_n \mu_{p\perp} \{n \left[ K_\parallel^2 + \mu_{n\parallel} \mu_{p\perp} K_\perp^2 \right] - p \left[ K_\parallel^2 + \mu_{p\parallel} \mu_{p\perp} K_\perp^2 \right] \}}{n \mu_{n\parallel} \mu_{p\parallel} K_\parallel^2 + p \mu_{p\parallel} \mu_{p\perp} K_\parallel^2},$$

(5)

where $\mu_{n\parallel}$, $\mu_{p\parallel}$, $\mu_{n\perp}$, $\mu_{p\perp}$ is electrons and holes mobility along and across the electric field respectively; $K_\parallel$, $K_\perp$ is wave numbers characterizing the inhomogeneity of the density and potential distribution in the quasineutral disturbance region.

In multivalley crystals, uniaxial deformation causes an intervalley redistribution of charge carriers, and the ambipolar mobility (even if $n = p$) becomes nonzero. The current oscillation frequency determined by the disturbance ambipolar drift will depend on the uniaxial deformation of the system. However, this is observed for crystals cut in certain directions. For silicon that is the direction <100>, for germanium – <111>. 


The multivalley semiconductor model in which all charge carriers belong to two classes was considered in [7]. In the first class the electron mobility in valleys elongated perpendicular to strain is $\mu_{n\parallel}$ and $\mu_{n\perp}$. In the second class the electron mobility is $\mu_{n\parallel\text{ef}}$ and $\mu_{n\perp\text{ef}}$, and has the following form:

$$\mu_{n\parallel\text{ef}} = \frac{8}{9} \mu_{n\perp} + \frac{1}{9} \mu_{n\parallel}, \quad \mu_{n\perp\text{ef}} = \frac{4}{9} \mu_{n\perp} + \frac{5}{9} \mu_{n\parallel},$$

(6)

In this case, the ratio of electron concentrations at strain can be written as:

$$\frac{n_1}{n_2} = \frac{1}{3} e^{\frac{4\Sigma_{ij} P}{kT C_{44}}},$$

(7)

where $n_1$ and $n_2$ is electrons concentration in valleys along the deformation axes and the other valleys, respectively; $\Sigma_{ij}$ is deformation potential constant; $C_{44}$ is elastic constant; $k$ is Boltzmann constant; $T$ is temperature; $P$ is pressure.

As follows from (7) a change in the pressure affecting the crystal lead to an intervalley redistribution of charge carriers, in particular electrons. This leads (even with relatively small deformations of the crystal) to a significant change in the helical disturbance ambipolar drift and to a change of the electric oscillations frequency.

Dependence of the frequency against uniaxial strain can be used to make force sensors with frequency output.

3. Design, fabrication and materials

In order to develop sensors based on helical instability it is necessary to take into account several parameters:

- the material of the sensitive element (oscillistor);
- magnetic system into the working gap of which an oscillistor is placed.

Currently, there are several semiconductor materials in which the absolute helical instability of electron-hole plasma is excited. These include indium antimonide ($\text{InSb}$), silicon ($\text{Si}$) and germanium ($\text{Ge}$).

In indium antimonide it is possible to excite absolute helical instability at relatively low values of the electric and magnetic fields strength. However, the oscillations frequency is unstable due to the strong influence of external factors. In silicon, it is difficult to excite an oscillistor at room temperature due to the rather low carrier mobility and a sufficiently high magnetic field strength is required to excite oscillations. Germanium is the most suitable material for creating frequency sensors. In germanium oscillistor, current oscillations can be excited at a magnetic field induction of a 0.3T. It is functional in the range from room temperature to liquid helium temperature.

N-type germanium grade $\text{GES}$ with a specific resistance of 0.4 to 0.5 Ohm·m is used as a material of the sensitive element. The sensitive element was fabricated on the basis of technology [8]. The monocrystalline germanium standard ingots oriented in the required crystallographic direction were cut to plates by a diamond-edged saw blade with an internal cut. To remove the damaged layer, the cut specimens were ground on a glass with a water suspension of grinding powder M28. Then specimens were finally polished to the required size on M10 and M5 powders. Specimen dimensions were controlled with a micrometer and microscope. Then the specimens were further polished on a diamond paste ASM3.

At the second stage, the specimens were degreased three times in boiling tetrachloromethane and washed in alcohol. Then the surface is chemically etched in 5% and 30% boiling hydrogen peroxide for five and one minutes respectively. Hydrogen peroxide makes it possible to obtain a low value of surface recombination rate. The specimens were thoroughly washed in distilled water and then dried in dry air at a temperature of (80-100) °C for three hours.

At the three stage, the contacts were made on the germanium specimen surface. There are two types of the contacts: injecting and ohmic. Injecting and ohmic contacts were made from indium ($\text{In}$)
or In+0.5%Ga and from pure tin (Sn) or Sn+1%Sb respectively. It has been found experimentally that no significant influence of the contacts material on the oscillistor characteristics. Contacts were made by fusion in a vacuum of 10⁻⁵ mm Hg at a temperature of (450 – 500) °C for (10 – 15) minutes. After fusion, the specimens were slowly cooled in vacuum at a rate of (15 – 20) degrees per minute.

With a threshold magnetic induction (0.3-0.4) T, for reliable generation of oscillistor oscillations, it is required to create an electric field strength E≥4·10³ V/m. The voltage applied to injecting contacts produce the electric field in oscillistor. Operating in a continuous mode, this value of electric field strength leads to a significant overheating of the oscillistor, which in turn causes changes in its threshold and frequency characteristics. A decrease of the electric field strength E can be achieved by increasing the external magnetic field induction, which complicates the task of creating a magnetic system. To avoid excessive heating, the oscillistor is fed in a pulsed manner. The pulse duration is (1-10) ms.

The connection of the oscillistor to an external circuit may be realized in several ways. In this study, we use the connection with two lateral ohmic contacts located of 1 mm from the end ohmic contact (figure 1).

As was noted above, an important task is to create a magnetic system. The magnetic system must provide the necessary magnetic induction in the working gap (at least 0.3 T) and be small. The most optimal design of a magnetic system is a tube type system.

![Figure 1. The oscillation output into an external circuit](image1)

![Figure 2. A schematic view of the force sensor](image2)

Figure 2 presents a schematic view of the force sensor based on helical instability electron-hole plasma. The sensitive element of measuring converter (oscillistors) 1 was manufactured from n-type germanium (GES-40) in the form of parallelepipeds with size (1x1x5) mm. Oscillator 1 is placed in a magnetic field created by neodymium permanent magnets 2 and 3. Permanent magnets are made in the form of tablets with diameter of 6 mm, thickness of 3 mm and are located in the tube type case 4 and 5. Oscillistor 1 is attached to a plexiglas bushing 6 using a copper strip 7. Socket 8 is soldered to the strip 7. The second end of oscillistor 1 is fastened to a phosphor bronze strip 10 using socket 9. The measured force is transferred to oscillator 1 using a force transfer system. The force transfer system consists of a top bar 10 and rods 11 and 12 and a stainless steel bar 13. Silvered wires are soldered to the sensor contacts connected to copper leads 14. Bars 7 and 10 are separated from the permanent magnet by a layer of dielectric material.
4. Experimental results
Figures 3 and 4 show the experimental studies of the force sensor at temperature 295K and 77K.

**Figure 3.** Frequency-force characteristics, T=295K. 1 – 50 V; 2 – 40 V.

**Figure 4.** Frequency-force characteristics, T=77K. 1 – 50 V; 2 – 40 V; 3 – 30 V.

Figures 3 and 4 show that the force sensor average sensitivity is 0.9 kHz/N in the force range (0–10)N. A decrease temperature to 77K leads to increase sensitivity to 15 kHz/N. Moreover, the sensitivity increases not only with decreasing temperature, but also with increasing supply voltage. It should be noted that with decreasing temperature, the threshold magnetic field strength decreases. This simplifies the task of creating a magnetic system and allows to significantly reduce the supply voltage and operate in a continuous mode.

The main disadvantage of the presented sensor is a strong influence of the ambient temperature on the sensor output frequency. Thus, for practical use of the sensor in case of wide temperature range, it is necessary to either thermostat the sensor or calibrate it for each operating temperature. In practice, these methods are difficult to implement. It is more practical to compensate for the temperature changes in frequency by using an oscillistor identical to the main one. The second oscillistor is placed in the same magnetic system, but is not affected by the measured force.

5. Conclusion
Carried out experiments show that there is possibility of development frequency output force sensors based on oscillistor. Sensors have a high sensitivity, especially at low temperatures and can operate in a wide temperature range from room to cryogenic. The experimental results showed that the use of force sensor at cryogenic temperature is possible and reasonable.

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