Photodetectors based on oscillistor effect

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Abstract. Semiconductor photodetectors are widely used in devices of radio electronics, automation, computer and measuring technology. This paper describes the capability of constructing position sensitive photodetectors and displacement sensors with frequency output signal based on oscillistor effect in semiconductor. The experimental results of the dependence the oscillistor oscillation frequency on radiation intensity and moving of the light beam are described in the paper. The schematic view of the displacement sensor with frequency output based on oscillistor is presented in the paper.

1. Introduction
In the general set of means of radio electronics, automation, computer engineering and measurement technology the various photoelectric devices, in particular, semiconductor photodetectors, have been made widespread.

Photodetector is sensor of light that converts optical radiation into electric output signal. Most of the photodetectors operate on the principle of extrinsic and intrinsic photoeffect. The photodetectors based on extrinsic photoeffect are the vacuum photocells, gas-filled phototubes, photomultipliers, etc. Semiconductor photodetectors based on intrinsic photoeffect are the photoresistors, photodiodes, phototransistors and widely used at present.

In intrinsic photoeffect the creation of pairs of charge carriers – electrons and holes – occurs under the action of light. These additional carriers change the electrical conductivity. The change of the conductivity under the action of photons is called photoconductivity. A semiconductor resistor, whose resistance changes under the action of light, is called photoresistor. In some cases through photogeneration of the electrons and holes an electromotive force is generated.

If a pn-junction of the photodiode is exposed to light, the diode conductivity and reverse current increases. The different types of photodiodes are avalanche photodiodes, Schottky diodes. In the avalanche photodiode a high reverse bias voltage is applied to achieve avalanche multiplication. Schottky diodes are constructed from a metal to semiconductor contact.

Also, photodiodes can operate as electromotive force generator.

In phototransistors, the light affects the transistor base. In this case, the base generates pairs of carriers of electrons and holes, which diffuse to the collector junction. Finally, this process leads to an additional increase in the collector current. The phototransistors can to provide current gain, resulting in a much higher sensitivity.

Most of the currently existing photodetectors have the change of the amplitude as the information parameter of the output signal. However, such signals have a number of shortcomings: 1) low interference immunity, especially, for the long-distance transmission; 2) low output signal level, which
requires amplification; 3) connection of the photodetectors to a digital data acquisition system requires conversion of the analog signal into digital.

Photodetectors, whose information parameter is the change of the frequency, have a higher characteristics. Such photodetectors are represented by: high noise immunity of the output signal including the long-distance transmission; frequency output signal can be easy converted into digital; high accuracy of frequency measurements; possibility of the direct connection to microcontroller system.

These advantages of the photodetectors with frequency output help to determine high actuality of researching and developing the new types of the photodetectors with frequency output, characterized by high sensitivity and reliability.

There are different ways that to construct the photodetectors with frequency output: 1) by conversions of the measured value to a voltage or current with the subsequent conversion to a frequency; 2) by conversions of the measured value to other value, e.g. resistance, with the subsequent conversion to a frequency; 3) by direct conversions of the measured value to frequency.

The first two methods require the use of different circuit devices (e.g. voltage-to-frequency converters, oscillation circuits, etc.) to obtain the frequency output.

2. Theory
Most physical effects and phenomenon, at the present time, don't allow constructing the photodetectors with direct conversions of the measured value to frequency.

In the middle of the 20th century a number of new physical phenomenon and effects in solid have been opened. These effects may be observed under certain conditions in the form of the onset of spontaneous electric oscillations. Examples of such effects are Josephson and Gunn effects, domain electric instability in semiconductors etc. On the basis of these effects, it is possible to develop various measuring sensors with direct conversion of the measured value to the electric oscillations frequency [1, 2]. Oscillistor effect is one of the effects that allow designing measuring sensors with a frequency output signal. Oscillistor effect is the spontaneous oscillations of current in a semiconductor (oscillistor) placed in parallel magnetic and electric fields [3].

The basis of the oscillistor effect is the helical instability of the electron-hole plasma of the semiconductor specimen placed in magnetic and electric fields [4]. The disturbance of the electron-hole plasma arising in the semiconductor sample under the action of electric and magnetic fields rotates and simultaneously moves along the sample. Two scenarios of the electron-hole plasma disturbance evolution are possible. In the first case, the amplitude of the initial disturbance increases with time and the instability moves in space, remaining finite in amplitude at each point of the semiconductor sample. This type of instability occurs at a high ambipolar drift velocity and is called convective instability. This can be used to build amplifiers. In the second case, the amplitude of the helical disturbance arising at some point of the sample increases asymptotically at the same point to an arbitrarily large value, until the nonlinear effects limit the growth of the amplitude. In this mode the spontaneous oscillations of electric current are generated and the oscillations frequency is determined by a number of the different factors. This type of instability occurs at a low ambipolar drift velocity is called an absolute instability (oscillistor effect). This kind of instability can be used for constructing the generators and the measuring converters of physical values to frequency.

A necessary condition for the oscillistor effect is the excess of the electric and magnetic field strengths of certain threshold values and the presence of an electron-hole plasma in the oscillistor.

The electric field with required strength can be created by applying an electric voltage to the oscillistor, and the magnetic field by means permanent magnets.

There are different ways of generating electron-hole plasma, e.g. injection of electrons and holes from contacts, oscillistor lateral side illumination etc. Injection from contacts is the most common method. Injection can be realized by various circuit, e.g. double injection of electrons and holes from contacts on face side (figure 1(a)) or injection from lateral side contacts (figure 1(b)).
**Figure 1.** Methods of electron-hole plasma generation by (a) face side contacts, (b) lateral side contacts, (c) entire lateral side illumination, (d) part of the lateral side illumination.

Based on excitation process of the absolute helical instability, the oscillations frequency is defined by rotation frequency of helical disturbance in electric and magnetic fields, by ambipolar drift of helical disturbance under the action of longitudinal electric and magnetic fields [6]. In a real semiconductor, there will exist both a rotation of helical disturbance under the action of a magnetic field and a drift under the action of an electric field. In this case frequency of oscillistor oscillations is determined by both drift disturbance velocity and rotation frequency of helical disturbance. Neglecting different nonlinear effects, using an expression, obtained in [6], it is possible to write an approximate expression for frequency:

\[ f = 0.18 \mu_a \frac{E}{a} + 0.71 D_a (\mu_n - \mu_p) B, \]

where \( \mu_a \) – ambipolar mobility of charge carrier; \( D_a \) – ambipolar diffusion ratio; \( \mu_p \) and \( \mu_n \) – holes and electrons mobility; \( a \) – sample transverse size; \( E \) – electric field strength; \( B \) – magnetic field induction.

When the injected plasma is generated, e.g. by illumination of the oscillistor lateral side, in a semiconductor volume additional electrons \( \Delta n \) and additional holes \( \Delta p \) are created. At that, from the electrical neutrality condition, it follows that \( \Delta n \approx \Delta p \). Taking into account an equilibrium background, density of electrons \( n \) and holes \( p \) are equal:

\[ n \approx n_0 + \Delta n; \ p \approx p_0 + \Delta p \]

In case of the injected plasma, values \( \mu_a, D_a \) can be found from the expression:

\[ \mu_a = \frac{\mu_n \mu_p (n_0 - p_0)}{\mu_n (n_0 + \Delta n) + \mu_p (p_0 + \Delta p)} \]

\[ D_a = \frac{\mu_n D_p (n_0 + \Delta n) + \mu_p D_n (p_0 + \Delta p)}{\mu_n (n_0 + \Delta n) + \mu_p (p_0 + \Delta p)} \]

where \( D_n \) and \( D_p \) – diffusion coefficient of electrons and holes accordingly.
The impact of the light on plasma can be made in different ways: by illumination of the entire surface of the oscillistor lateral side (figure 1(c)); by fixed or moving light beam illumination of the part of the oscillistor lateral side (figure 1(d)).

When plasma is generated by illumination of the oscillistor lateral side (figure 1(c)), light beam with intensity \( J \) creates excess concentration of electrons \( \Delta n_j \) and holes \( \Delta p_j \), which can be found from the expression:

\[
\Delta n_j = \frac{\beta \alpha \tau_n}{h \nu} J; \quad \Delta p_j = \frac{\beta \alpha \tau_p}{h \nu} J,
\]

where \( \beta \) – quantum yield; \( \alpha \) – absorption factor; \( \tau_n \) и \( \tau_p \) – electrons and holes lifetime; \( h \) – Planck constant; \( \nu \) – frequency.

Equations (1), (3) and (4) demonstrate that when the additional charge carriers are generated in the oscillistor volume, the oscillistor oscillation frequency decreases. In optical generation of charge carriers (electrons and holes) in the specimen volume, with increasing the optical radiation intensity, the semiconductor plasma density increases. At a high value of the light intensity, when concentration of the nonequilibrium charge carriers generated by light is much more than equilibrium plasma density, the dependence of the frequency on the light intensity is defined by:

\[
 f \approx K_T \Phi^{-1},
\]

where \( K_T \) – coefficient depending on the oscillistor material, size and applied voltage.

3. Experimental results

The oscillistors were fabricated from high-resistance n-type germanium grade GES-40. Samples were cut in the form of parallelepipeds 0.8×0.8×5 mm\(^3\). In figure 2 the results of experimental studies of the oscillistor oscillations frequency as a function of the light radiation intensity is shown. The impact of the light on plasma was realized by illumination of the oscillistor lateral side.

The impact on the frequency of oscillistor oscillations can also be realized by a narrow light beam, illuminating a part of the lateral side and moving along the specimen. When plasma is created by injecting charge carriers from the end contacts, moving a light beam of constant intensity causes a displacement of the origin place of the helical instability. The density of the electron-hole plasma at the origin point of the helical instability will be change. In figure 2 dependence of the frequency on the light beam position on the lateral side of the oscillistor with a size (1×1×10) mm is shown.

Thus, frequency dependence of the light radiation intensity can be used to construct photodetectors with frequency output based on the oscillistor. The photodetector sensitivity depends on the supply voltage, increasing with its increase.

![Figure 2. Dependence of frequency against radiation intensity.](image1)

![Figure 3. Dependence of frequency against moving of the light beam.](image2)
4. Conclusion

The dependence of the frequency on the position of the light beam on the oscillistor surface shows the possibility of using it, in the case of a constant intensity of the light beam, for the construction of position sensitive photodetectors and displacement converters with a frequency output signal. In figure 4 shows one of the possible variants of constructing a frequency converter based on the oscillistor. The sensitivity of such converter reaches ones kHz / mm. The sensitivity can be increased by increasing the initial frequency of the current oscillations in the oscillistor. This is achieved by reducing the transverse size of the oscillistor and increasing the electric and magnetic fields strength.

Carried out research is sure to make a conclusion that there is possibility of development the high sensitivity photodetectors with frequency output signal based on oscillistor effect in n-type germanium.

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