Chemistry for Sustainable Development **9** (2001) 79–82

Opto-Capacitive Transducer

VALERY A. VASILIEV

Penza State University, Ul. Krasnaya 40, Penza 400017 (Russia)

E-mail: paspen73@hotmail.com

Abstract

An opto-capacitive transducer is proposed which is able to transform optical energy into electric signal through the changes of the capacitance of a solid structure. The transducer involves the semiconductor's feature to change surface resistance under the action of optical radiation. The capacitance of the solid structure is changed due to the change of the surface resistance of gallium arsenide (GaAs). Opto-capacitive transducer allows detecting optical radiation, measuring the changes of capacitance depending on the changes of the width of light spot, radiation power, radiation frequency. Along with the possibility to control, record and transform optical radiation into electric signal, it allows recording metal bodies and measuring distance from them. On the basis of the opto-capacitive transducer, it is possible to develop various devices to detect and record the light signal, to measure the optical radiation power; it is also possible to develop transformers of optical energy into electric signal, various sensors for shift, force, pressure, *etc.*

Different types of the transducers of physical and mechanical values are known [1–4]. The operation principle of the major part of them is based on physicochemical properties of materials. The use of semiconductor materials in various transducers is a very promising direction.

To transform optical energy into electric signal, photodiodes, photoresistors, bolometers, opto-acoustic transformers and others are used [5]. However, the listed transformers of optical energy into the electric signal are not always convenient for use.

An opto-capacitive transducer is proposed which is able to transform optical energy into the electric signal through the changes of the capacitance of a solid structure. It is based on the ability of semiconductors to change the surface resistance under the action of optical radiation. The capacitance of the solid structure changes due to the change of the surface resistance of semiconductor.

The opto-capacitive transducer (Fig. 1) is a solid structure composed of the dielectric substrate *1*, two metal plates *2* and *3* (situated in one and the same plane), dielectric layer *4* and semiconductor layer (plate) *5*. Ceramics or glass can be used as dielectric substrate *1*. Metal plates *2* and *3* are formed on the substrate *1* and are coated with a thin dielectric layer (it is reasonable to use silicon monoxide SiO). Semiconductor layer *5* (for example, that composed of gallium arsenide GaAs) is deposited onto the dielectric layer *4*. Instead of the semiconductor layer *5*, a thin semiconductor plate can be used (fixed at the dielectric layer *4*). Electric outputs *a* and *b* serve to connect the opto-capacitive transducer to the unit transforming capacitance into electric signal.

An excess concentration of free charge carriers is formed in the surface layer of the semiconductor during its irradiation with the light having wavelength more than the width of the forbidden gap. This causes the decrease of the surface resistance of the semiconductor. The conductivity of the surface layer increases. The surface layer with the excess concentration of free charge carriers starts to play the role of

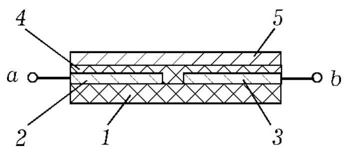

Fig. 1. Solid structure of the opto-capacitive transformer: *1* – dielectric substrate; *2* and *3* – metal plates; *4* – dielectric layer; *5* – semiconductor layer.

the third conducting plate located parallel to the first two metal plates *2* and *3*. Deep-lying regions of the semiconductor material play the part of a dielectric. The permittivity of semiconductors is known to be rather large (ε ~11–14); the capacitance is directly proportional to the permittivity. As a result, the capacitance between the two metal plates changes substantially.

To transform the capacitance of a solid structure (see Fig. 1) into electric signal, it is convenient to involve the comparison of the capacitance to be transformed C_x with the reference value C_0. It is reasonable to select the capacitance comparable to that of the solid structure as the reference value.

It is possible to achieve high sensitivity of capacitive transducer using the bridge measuring schemes; the sensitivity that can be thus achieved is $\Delta C/C$ up to $1 \cdot 10^{-9}$–$1 \cdot 10^{-13}$.

The structural principles of operational transducers are listed in [6]. Figures 2–4 show different electric schemes of the operational transducers that transform capacitance into electric signal. Each of these schemes can be used in

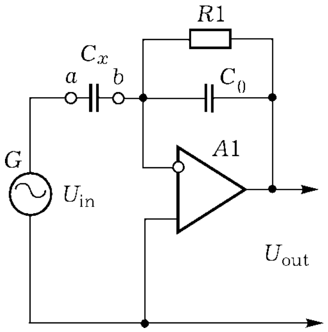

Fig. 4. A scheme of the unit transforming the capacitance into electric signal with the bypassing resistor in the feedback circuit.

combination with the opto-capacitive transducer shown in Fig. 1.

The electric scheme of the transformer of the capacitance of a solid structure into electric signal, shown in Fig. 2, belongs to auto-compensation schemes. It is a circuit with balancing counter-phase currents through the measuring branch that contains the capacitance to be measured C_x and the reference branch with the reference capacitance C_0. The output voltage of this measuring circuit is determined by the equation

$$U_{\text{out}} \cong U_{\text{in}} \frac{C_x}{C_0} \frac{1}{1 + \dfrac{1}{k}\left(1 + \dfrac{C_0}{C_x} + \dfrac{C_{c2}}{C_x}\right)} \qquad (1)$$

where U_{out} and U_{in} are the output and input voltage of the measuring circuit, k is the amplification coefficient of the operational amplifier at the carrier frequency, C_{c2} is the capacitance of the screened conductor.

The analysis of the eq. (1) shows that the measuring circuit under consideration may be conveniently used to transform into voltage because it is practically linear for large k. The capacitance of the screened conductors C_{c1} and C_{c3} has only a weak effect on the transformation. The effect of screened conductors decreases with decreasing the output voltage of the generator of input signal and the operational amplifier. Thanks to profound negative feedback embracing the operational amplifier, its input voltage, and thus the voltage at its inverting input, is very small. This circumstance allows to leave unchanged the measuring circuit independently of the length of the screened connection line and consequently of the ca-

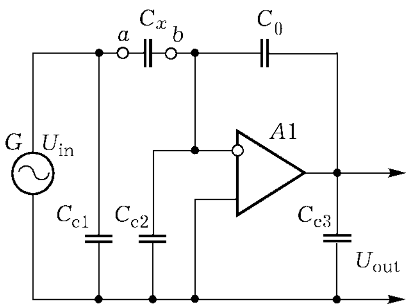

Fig. 2. A scheme of the unit transforming the capacitance of the solid structure into electric signal.

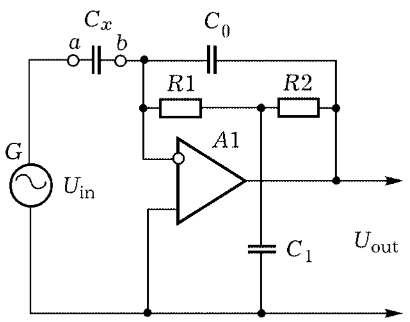

Fig. 3. A scheme of the unit transforming the capacitance into electric signal with a T-shaped R–C–R feedback circuit.

pacitance C_{c2}. However, it is necessary to use the operational amplifier with rather fast operation and large amplification coefficient.

It is convenient to use the electric circuit shown in Fig. 2 for measurements within a broad temperature range. This circuit allows to place the solid-phase structure (opto-capacitive transducer) with the capacity C_x and the reference capacitor with capacitance C_0 at some distance from the unit transforming capacitance into electric signal. A similar solid structure placed in shadow can be used as the C_0 capacitor.

One of the shortcomings of the electric circuit, shown in Fig. 2, is the difficulty to provide the stability of the operational amplifier and stabilization of its mode over direct current at large amplification coefficient k. This disadvantage may be eliminated by increasing the internal resistance of the operational amplifier. For example, this can be achieved by increasing the time constant of the operational amplifier with the help of the correcting circuit, or by switching an additional resistor sequentially with its output.

Figure 3 shows the electric circuit of the unit transforming the capacitance of the solid structure into the electric signal with T-shaped correcting circuit composed of the resistors R1, R2 and capacitor C_1. T-shaped circuit provides stabilization of the direct-current mode of the operational amplifier. A feature of this circuit is that it has a resonance peak of amplification at the frequency of $f_0 = \frac{1}{2\pi R}\sqrt{C_1 C_0}$. In order to minimize the dynamic error, it is necessary that $f_{inp} >> f_0$, $f_0 >> f_p$ where f_{inp} is the frequency of input voltage, f_0 is the frequency of resonance of the measuring circuit, f_p is the frequency of measuring process.

From the viewpoint of broadening the transmittance band, advantage is exhibited by the circuit with negative feedback as a bypassing resistor $R1$ (see Fig. 4) between the inverse input and output of the operational amplifier A1. In this case, it is necessary that the condition $f_{inp} >> 1/(2\pi R_1 C_0)$ is fulfilled; the value to be selected from this relation is $R1 >> 1/(2\pi f_{inp} C_0)$. The introduction of the bypassing resistor leads to the shift of the output voltage along constant level and thus to the decrease of the range of the output voltage of operational amplifier. As a result, the sensitivity of the transducer decreases.

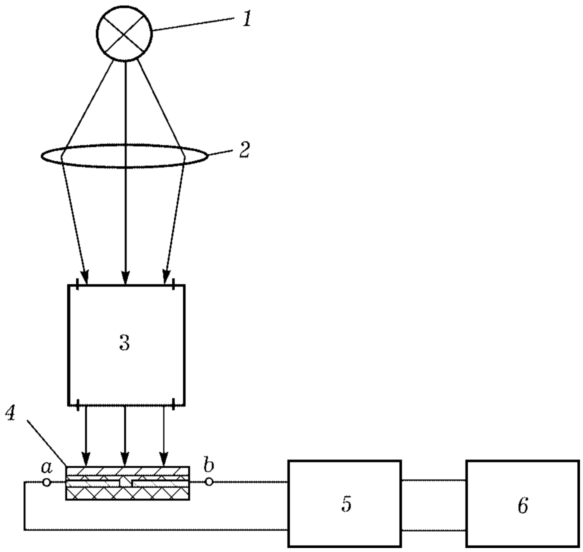

Fig. 5. A scheme of the set-up for experimental investigations of the opto-capacitive transducer: *1* – the source of optical radiation; *2* – optical system; *3* – monochromator; *4* – solid structure of the opto-capacitive transducer; *5* – unit transforming capacitance into electric signal; *6* – recording unit.

Experimental investigations of the opto-capacitive transducer were carried out using the set-up shown schematically in Fig. 5. Optical radiation from the source *1* within a broad spectral range was let through the optical system *2* onto monochromator *3*. Monochromatic radiation from its output was directed at the solid structure *4* of the opto-capacitive transducer. Electric outputs a and b of the solid structure *4* were connected to the input of the unit transforming capacitance into electric signal *5*. The change of capacity was monitored and recorded by the device *6*. A voltmeter may be used as a recording device in the simplest case.

Figure 6 shows spectral dependence of the relative change of the capacitance of solid structure (see Fig. 1) measured at 300 K. The semiconductor layer *5* (see Fig. 1) was gallium arsenide GaAs (area: 35 mm^2, thickness: 0.4 mm), with the following characteristics: orientation, [100]; specific resistance, $1.7 \cdot 10^7$ Ω cm; mobility of charge carriers, $\mu = 22.15$ $cm^2/(V\ s)$. Within the range of photon energies 1.3 to 1.45 eV (see Fig. 6), the edge of inherent absorption is clearly exhibited; within the range 0.75 to 1.1 eV, the extrinsic absorption band is observed.

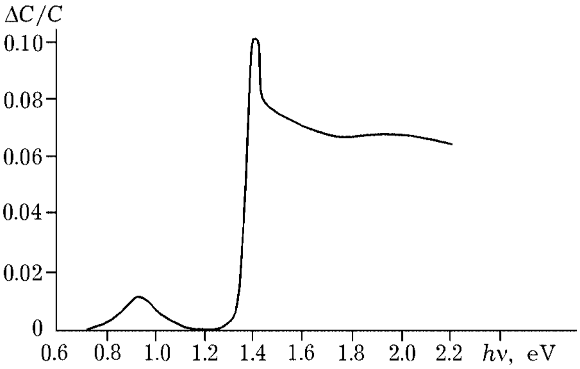

Fig. 6. The dependence of the relative change of the capacitance of solid structure (opto-capacitive transducer) on photon energy.

It is known that the optical properties of semiconductors, in particular GaAs, are determined by their zone structure. The zone structure of GaAs is shown in Fig. 7 [7]. The edge of inherent absorption in GaAs corresponds to vertical transitions between the extremal points of the two zones at $k = 0$. The width of the forbidden gap at $T = 300$ K is ~1.43 eV, which is in good agreement with the experimental results (see Fig. 6).

Crystals and epitaxial layers of GaAs with high specific resistance (~10^7 Ω cm) can be obtained by doping gallium arsenide with iron (Fe) or chromium (Cr). Fe and Cr create low-lying energy levels of acceptor type thus functioning as efficient recombination traps. Ionization energies of these impurities are: Fe − 0.52 eV, Cr − 0.79 eV [7]. One can see from the spectral dependence of the relative change of capacitance (see Fig. 6) that Cr impurity is present in the semiconductor layer of the investigated solid structure. Its presence explains the absorption in the region 0.75−1.1 eV. The ionization energy of Cr is shown in Fig. 7; it is in the forbidden gap between the bottom of the conductance band and the top of the valence band.

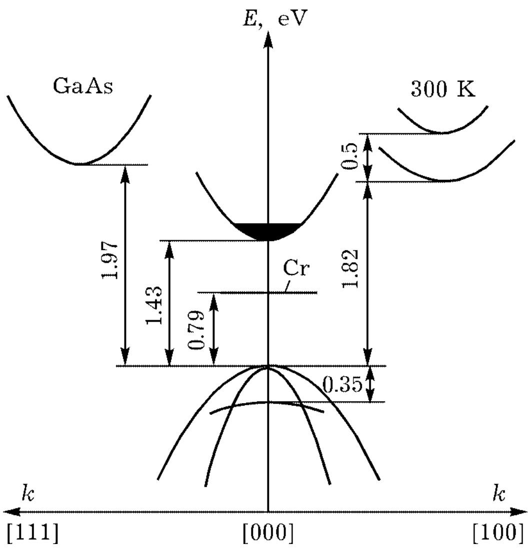

Fig. 7. Energy zone diagram of GaAs.

Experimental studies of the opto-capacitive transducer showed that the capacitance of the structure is rather sensitive to the changes of the width of light spot *s* and the radiation power *P*. Opto-capacitive transducer allows to detect the presence of optical radiation, to measure the changes of capacitance depending on the changes of the width of the light spot, radiation power, frequency of optical radiation.

An advantage of the opto-capacitive transducer is that it can be manufactured using the planar technology of microelectronics. It is possible to use semiconductor layers (plates) with the thickness less than the diffusion length of the free charge carriers.

A substantial advantage of the opto-capacitive transducer is its broadened functional ability. Along with the possibility of controlling, recording and transforming optical radiation into electric signal, it allows to register and control the distance from metal bodies.

On the basis of the opto-capacitive transducer, it is possible to develop various devices for detection of light signal and recording it, for controlling the power of optical radiation, and also the devices for the transformation of optical energy into electric signal, as well as various sensors of shift, force, pressure, *etc.*

REFERENCES

1 V. A. Vasiliev, E. M. Zaitsew, A. I. Tikhonov, *Izv. vuzov, Priborostroyeniye*, 10 (1984) 47.
2 V. A. Vasiliev, *Ibid.*, 11 (1987) 34.
3 Inventor's certificate 1420407 SSSR, 1988.
4 V. A. Vasiliev, Tr. konf. "Informatsionnye tekhnologii v nauke, obrazovanii, telekommunikatsii, biznese, Yalta−Gurzuf, 2000, p. 182.
5 V. A. Vasiliev, Metodicheskiye ukazaniya k laboratornym rabotam po kursu "Optoelektronika i integral'naya optica", Penza, 1995.
6 V. S. Gutnikov, Integral'naya elektronika v izmeritel'nykh ustroystvakh, Energoatomizdat, Leningrad, 1988.
7 Spravochnik po elektrotekhnicheskim materialam, Pod red. Yu. V. Koritskogo, V. V. Pasynkova, B. M. Tareyeva, vol. 3, Energoatomizdat, Leningrad, 1988.