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Optoelectronic Transimpedance Converter Based on MOS Photovaricap for High Resistive Gas Sensors

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Abstract. The gas detectors consist of two parts: metal-oxides gas sensor and transducer. The sensing material is made of a thin semiconductor layer. The transducer is responsible for converting the change in the several physical parameters of the thin sensitive layer into a measurable signal. Due to the high output resistance of high resistive gas sensors and the low input currents of amplifiers, electrometric cascades are employed, followed by the conversion of the gas sensors small direct current into an active current signal using a mechanical modulator (dynamic capacitor) to enhance sensitivity and stability. The aim of this research is to analyze the main characteristics of a novel type of dynamic capacitor that utilizes a surface metal-oxide-semiconductor (MOS) photovaricap (PV) as the regulating element when detecting signals from high resistive gas sensors. For the creation of surface MOS PVs, samples of p-Si with varying resistivity were chosen. A thin layer of SiO_2 was deposited on these samples, onto which a translucent metallic electrode was applied. Modulation of the PV capacitance was achieved by illuminating it with a gallium arsenide LED. As a result, the capacitance of the PV is changed, producing a variable voltage across the load resistor, which was then amplified and recorded. It was observed that the settling time of the useful signal is determined by two factors. The first is the *RC* chain composed of the load resistance of the gas sensor and the input capacitance of the PV, and the second is slow relaxation phenomena in the structure of the MOS PV that lead to the screening of the induced charge. Characteristics of the MOS PV as a dynamic capacitor and the features of the photo capacitance as a semiconductor element, in turn, determine the transimpedance conversion coefficient. The conducted research showed that MOS PVs can be applied to register small DC currents and voltages from high resistive gas sensors. In this case, ordinary narrowband or wideband amplifiers with relatively low input resistance can be used instead of electrometric amplifiers with mechanical dynamic capacitors. The considered circuit has been experimentally tested with commercial resistors.

Keywords: gas sensors, resistivity, MOS photo varicap, transimpedance converter scheme

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1. Introduction

All types of sensors convert specific physical quantities into a form suitable for further processing. In each case, the electrical signals at the output of the sensors are proportional to the physical quantities they monitor. In recent years, thin-film gas sensors based on metal oxide materials sensitive to various toxic and explosive gases have been the subject of intensive research [1, 2 and 3]. Metal oxides have a wide bandgap and exhibit insulator properties with high resistivity. Therefore, changes in their resistance (which underlie the operation of gas sensors) are primarily achieved through heating [4].

Various gas detectors and gas analyzers also widely employ high resistive gas sensors with resistance $R_{GS} < 10^{12}$ Ohm. Some chemical sensors, as metal-oxides sensors, according analyte gas substance concentration, strongly vary their resistance, from tens of kiloohms to hundreds of gigaohms. So, their signal conditioning systems currently are of a special interest [5, 6]. When designing measurement devices based on these sensors, their peculiarities must be taken into account, such as high output resistance and low working currents. Consequently, in these sensor systems, electrometric transimpedance matching devices are typically used at the input of amplifiers. To enhance sensitivity and stability, the gas sensors DC is converted into an amplitude-modulated signal using mechanical dynamic capacitors. Subsequently, synchronous detection is performed [7, 8].

The significant drawbacks of these mechanical dynamic capacitors include their low modulation frequency (typically in the hundreds of hertz range), low durability, and large size and weight. Moreover, due to the low modulation frequency, the input stage of the low-frequency amplifier becomes electrometric.

The aim of this study is to investigate the fundamental characteristics of a semiconductor voltage modulator (i.e. dynamic capacitor) of a new type that uses a surface MOS PV as the regulating element when detecting signals from the high resistive gas sensors.

Theoretical analysis and some experimental results of the physical phenomena that determine the operation of MOS PVs are presented in previous works [9, 10]. Semiconductor dynamic capacitors improve the essential parameters of gas analytical recording equipment.

2. Measurement methodology

Samples of p-type silicon with different resistivity ($\rho = 10^2 \div 10^4$ Ohm·sm) were selected. The surface of the samples was etched in a polishing etcher, after which a thin layer (~ 1000 Å) of SiO_2 was sprayed. A translucent metal electrode was deposited onto the SiO_2 dielectric layer [11, 12]. In the manufacture of PV, special attention was paid to ensuring the initial surface potential of silicon in the region of strong exhausting bending zones. At the same time, the $C - V$ characteristic of the MOS structure has the maximum steepness [13, 14]. A LED from GaAs carried out by the modulation of the PV capacitance [15].

If considering the structure of a MOS with a p-type semiconductor. Suppose a constant positive voltage is applied to the translucent electrode, and we assume that the depth of the near-surface region of the spatial charge in the dark is equal to d_d.

If the PV is not illuminated, then a small dark current I_d goes through it. In this case, the voltage on the PV U_1 is equal to

$$U_1 = E - I_d R_{L1} \quad (1),$$

where R_{L1} is the load resistance. If the PV is illuminated, then the photocurrent I_F is added to the dark current. In this case, the voltage on the PV U_2 is equal to:

$$U_2 = E - (I_d + I_F) R_{L1} \quad (2).$$

Thus, when the PV is illuminated, the voltage on it changes by

$$U_1 - U_2 = I_F R_{L1} \quad (3).$$

In this case, the capacity of the MOS structure also changes from the voltage value U_1 to the value U_2 [16].

Illumination of the MOS structure causes the development of nonequilibrium electrons and holes. They are generated in space charge region (SGR), as well as in a quasineutral volume. The nonequilibrium carriers arising during illumination in the near-surface layer are separated by a field of SGR. The non-basic carriers are pulled up to the surface and participate in the formation of a conduction channel or the refilling of surface electronic states. In this case, the electric field created by an external source is shielded. The main charge carriers are output by the field into a quasineutral volume [17, 18].

The process of charge redistribution continues with the establishment of a stationary state. It corresponds to the equality of generation and recombination flows. The depth of the near-surface SGR decreases to value d_F, which is accompanied by an increase in the capacity of the MOS capacitor. In the inversion channel mode, the capacitance value is almost independent of temperature.

The principle of operation of an optoelectronic transimpedance converter of this type is as follows. When the PV is illuminated with sinusoidal modulated light, its capacitance changes, and an alternating voltage is released on the load resistance, which is then amplified and recorded (Fig.1).

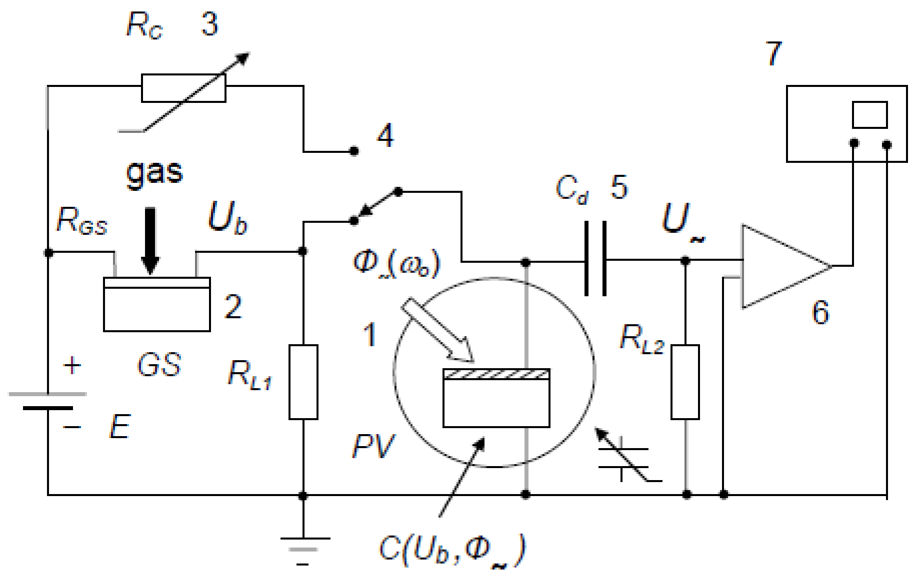

Fig. 1. The block diagram of HRGS measuring unit: (1) MOS PV, (2) gas sensor, (3) calibration resistance, (4) switch, (5) decoupling capacitor, (6) operational amplifier, (7) recording device.

The overlap coefficient (modulation of the PV capacitance) $K_C = \frac{\Delta C_{max}}{C_0}$, which determines the efficiency of the MOS capacitor as a varicapacitance, depends on the limiting capacity of the oxide and the design. With weak illumination, the PV is described by the light sensitivity coefficient K_Φ. It is related to the nonlinearity coefficient $K_n = (1/C)\,(\partial C/\partial U)$ by the ratio $K_\Phi = K_n(\frac{\partial U}{\partial \Phi})$.

A constant voltage (or a low frequency variable) is supplied to the input of the PV through the switch S either from a gas sensor loaded with a high resistive resistance R_{L1} or (for calibration) through a resistance $R_k \sim 10^9 \div 10^{12}$ ohm, simulating the internal resistance of the gas sensor.

The use of semiconductor PV as dynamic capacitors has its own characteristics, since in this case the problem of decoupling the circuits of the modulating voltage and the converted signal is simply solved [16]. Semiconductor photocapacities are of various types. The structural photocapacitance has high dielectric qualities; however, it is not sensitive to bias voltage U_b [15, 19]. Photocapacitance based on metal - semiconductor or p - n junction contact, are sensitive to bias voltage U_b, but have a relatively low input impedance ($\sim 10^6 \div 10^8$ Ohms) [15, 21]. MOSs PV using modulation of the capacitance of the isolated region of the near surface spatial charge under illumination have high parameters. Resistance of the dielectric layer determines the input resistance of such photocapacities, therefore it can be made high. This ensures high Q-factor and sufficiently low noise.

With a sinusoidal effect of LED illumination on the MOS PV, its capacitance is equal to

$$C = C_0 + \Delta C_{max} sin\omega t. \tag{4}$$

The photo capacitance modulator, depending on the value of the time constant of the RC circuit, can operate in the mode of a given voltage - U_c or a given charge - Q.

In the first case, i.e. when $\omega R_{L1}C << 1$, we will have $U_c \approx U_b$, and

$$Q \approx (C_o + \Delta C_{max} sin\omega t)U_b, \tag{5}$$

or

$$I = \frac{dQ}{dt} = U_b \omega \Delta C_{max} cos\omega t. \tag{6}$$

The output value of the capacitive modulator in this case will be an electric current, the value of which is proportional to the constant bias voltage.

In the second case, when $\omega R_{L1}C >> 1$, at a sufficiently high modulation frequency (f_0 = 25 kHz), the capacitance of the dynamic capacitor according to the sinusoidal law, such that during one period the charge in the circuit does not have time to change, i.e.

$$Q \approx C_0 U_b = const,$$

then

$$U_c = \frac{Q}{C} = C_0 \frac{U_b}{C_0 + \Delta C_{max} sin\omega t} = U_b \left(1 - \frac{\Delta C_{max}}{C_0} sin\omega t\right) = U_b - U_{\sim}, \tag{7}$$

under condition

$$\frac{\Delta C_{max}}{C_o} \ll 1.$$

The output value is the variable component of the voltage U_c, which is recorded after the decoupling capacitor C_d,

$$U_{\sim} = U_b \cdot \frac{\Delta C_{max}}{C_0} sin\omega t. \tag{8}$$

The experimental dependences of the useful signal voltage $U_{\sim}$ on the constant bias voltage U_b have been obtained, which are presented in Fig.2.

Consider the optoelectronic transimpedance conversion coefficient K_T of the voltage of the modulator, which determines the ratio of the maximum amplitude of the modulated signal to the value of the constant bias voltage applied to the PV (i.e., the output signal from the gas sensor), if $K_c \ll 1$, then

$$K_{\text{т}} \approx K_{\text{c}} = \frac{\Delta C_{max}}{C_0}. \tag{9}$$

It follows that it is necessary to increase the modulation coefficient of the capacitance (by light) $K_c = \frac{\Delta C_{max}}{C_0}$ and reduce C_0.

In the MOS PV, the value of the maximum capacitance is limited by the capacitance of the dielectric. Series resistance of the dielectric capacitances C_0 and the spatial charge region determined the minimum capacitance. In general, the capacity of surface traps can also be taken into account [19, 20].

In order to increase the efficiency of the PV, it is necessary to use a high resistive material with the minimum possible thickness of the dielectric, taking into account the requirements of minimality of the leakage current.

If a positive voltage is applied to the gate of the ideal MOS of the PV capacitance with a p-type substrate (N_A = 10^{16} sm^{-3}), then the maximum width of the SGR is estimated to be $\sim 0{,}3\,\mu m$ [4].

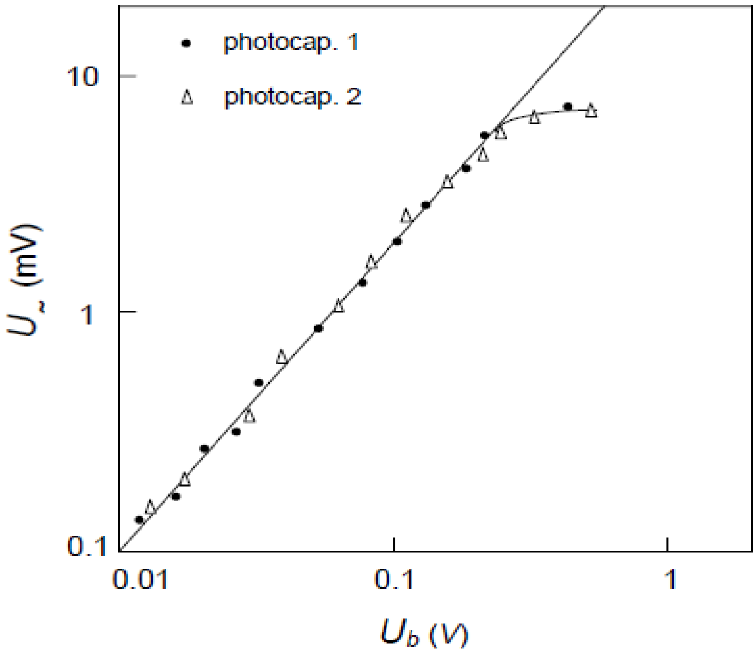

Fig. 2. The experimental dependences of the useful signal voltage $U_\sim$ on the constant bias voltage U_b for two MOS PVs.

With "exhausting" bending of the zones, the capacity of the SGR is much smaller than the capacity of the dielectric. At voltages corresponding to the formation of an inverse layer, the course of the dependence of $C(U_g)$ (the capacitance of the PV on the gate voltage) of the characteristics is different for electron and hole silicon. This is due to the different times of establishing thermodynamic equilibrium in these materials. With weak quasistationary depletion, the light overlap coefficient of capacitance is a function of the rate of surface recombination, charge redistribution during illumination, and linearly depends on the intensity of illumination.

3. Results

Two factors influence the establishment time τ_{est} of test the useful signal $U_\sim$: electrical chains consisting of the load resistance gas sensor - R_{L1} and the input capacitance of PV - C.

The dark capacitances of the investigated MOSs PV usually lie in the range of 5÷50 pF. With load resistances GS - R_{L1} of the order 10^{10}÷10^{11} Ohm, the setting time reaches 0.5÷5 sec.

Slow drift phenomena were observed in the studied samples of the MOS PV and reached 10% of the amplitude of the useful signal $U_\sim$, during the relaxation time of the order of 10 seconds.

The above analysis shows that the optoelectronic transimpedance conversion coefficient K_T value is determined by the characteristics of the MOS PV, which serves as a dynamic capacitor ($C_0, \Delta C/C_0$) and the features of the photo capacity as a semiconductor element.

To increase the K_T conversion factor, it is necessary to obtain the greatest possible modulation depth at the minimum initial capacitance.

The choice of the optimal value, i.e. the area of the electrodes and the configuration must be made taking into account the necessary requirements. For example, an unjustified increase may be undesirable, since the inertia of the transimpedance measuring converter will increase. On the other hand, when developing specific PV, there is no need to reduce the size of the electrodes, since it is possible to reduce while increasing C_0 and maintaining $\Delta C/C_0$ constant, R_{L1} and R_{L2} can be reduced.

The K_T values in most samples were in the range of $(3\div8)\cdot10^{-3}$.

Semiconductor dynamic capacitors based on MOS structures are sensitive to the total density of surface traps, since the accumulation of charge on them leads to a decrease in the voltage applied to the dynamic capacitor.

On the other hand, it is necessary to strive to obtain the maximum dielectric capacitance to increase the modulation depth of the effective capacitance of the system.

In order to achieve significant values of the capacitance modulation coefficient K_C and the steepness of the volt-capacitance characteristic in the MOS PV, it is necessary to further use dielectric materials with high permittivity values.

The operation of the gas sensor with the MOS PV during gas analytical measurements showed that the parameters of this semiconductor dynamic capacitor in the atmosphere of various gases do not change. Fig.3 shows the operation of the MOS PV together with two gas sensors.

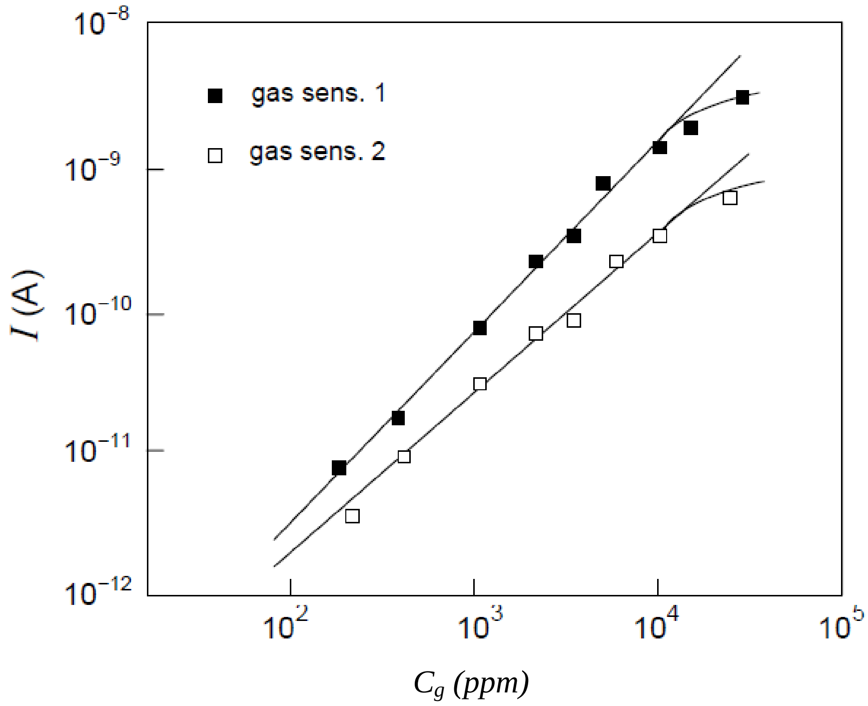

Fig. 3. Experimental dependences of the output current I on the analyte gas (acetone) relative concentration C_g for two high resistive gas sensors recorded using the MOS PVs.

When the concentration of analyte gas (acetone) changes by $3\div4$ orders of magnitude $(5\cdot10^1\div5\cdot10^4\ ppm)$, the output characteristic of the PV is almost linear. The deviation from linearity begins at high concentrations of analyte gas ($>5\cdot10^4\ ppm$), probably due to a decrease in the input resistance of the PV. The minimum voltage $U_b\sim0{,}15\ mV$ is registered.

4. Conclusions

The expression for the dependence of useful signal voltage $U_{\sim}$ on the MOS PV voltage U_b has been appreciated. MOS PV, as follows from the above, can be used to register small DC currents and voltages from high resistive metal-oxide gas sensors. Therefore, photocapacitance and conventional narrowband or broadband amplifiers with relatively low input impedance can be used as an alternative to electrical amplifiers with mechanical capacitors.

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