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Specialities of Optical FET with Tin-Doped Junction Channel

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Abstract—This paper deals with researches of phototransistor based on gallium arsenide with tin-doped channel. It is experimentally shown, that in contrast to usual phototransistors with tellurium-doped channels, gate photocurrents are constant, i.e. independent on blocking voltage, and these currents grow with light intensity increase. At that time total photo sensitivity is smoothly controlled by working voltage and it achieves high values, current sensitivity achieves 8.26×10^2 A/W, voltage sensitivity achieves 1.3×10^8 V/W.

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Field effect transistors (FET) with controlling junction find an application for optical and microelectronics devices. There are developed very high frequency both low-powered and high-powered FETs, begining to substitute bipolar transistors according to many parameters. An application for their construction materials with high movability, in particular, gallium arsenide heterostructures allows to expand their functionality. New technology application and perfection of FET construction give an opportunity to use it as an amplifier of electrical and light signals and also for magnetic sensitive elements. Last time different optic FETs and magnetotransistors appear [1, 2]. An information about photo sensitivity of FET with controlling homo *p-n*-junction based on gallium arsenide appears in papers [3, 4]. Here optical FET was illuminated by integrated light (light intensity changes from 400 to 8500 lux) with maximum wavelength 0.55 μm. High photo sensitivity (400 A/W) was obtained due to channel can be illuminated directly and its width (0.5–0.7 μm) was selected less than light penetration depth from proper domain and also due to high output resistance. Photocurrents and photovoltages was maximal in saturation region in current characteristic. Photocurrent dependently on blocking voltage also achieved maximal value (at 1 V) and then it was three and more times decreased, when voltage values (2.5 V) tended to cut-off voltage (3 V). High sensitivity region position at narrow working voltages interval (1–1.5 V) can be related to growing character of tellurium impurities in channel width [5].

In this paper we present researches results of photosensitivity specialties of optic FET with *p-n* junction, whose channel is tin–doped.

Investigated structures were created according to criteria, stated in certificate of recognition [6] with intermediate epitaxial *p*-layer between channel and p^+GaAs gate. Correspondingly,

$$h_{\text{int}} = h_{\text{ch}}(N_{\text{ch}} / N_{\text{int}})^{0.5},$$

where N_{ch}, N_{int} are carrier concentration in channel and intermediate *p*-layer, h_{int}, h_{ch} are thickness of intermediate layer and channel correspondingly. In particular, epitaxial channel of *n*GaAs, tin-doped up to concentration of 3×10^{16} cm^{-3} is grown by means of liquid epitaxy on the top of intermediate epitxial *p*GaAs layer with concentration of 3×10^{17} cm^{-3} and with thickness of ~0.1 μm, which is grown on heavily p^+GaAs (2×10^{19} cm^{-3}) substrate. Epitaxial layer—channel thickness is 0.32 μm and its width is 700 μm. Distance between source and drain contacts (channel length) is 50 μm. Light sensitivity area of channel is 3.5×10^{-2} mm^2. Tin selection as a dopant was determinate by two factors. At first tin in epitaxial layer compensates internal stresses and it reduces amount of gallium inclusions, captured by grown epitaxial layer, while tellurium promotes their growth [7]. Gallium inclusion presence leads to back current growth due to tunnel effect appearance [8]. At second, while tellurium carrier concentration in epitaxial layer grows along its thickness [5], whereas tin provides diminution carriers concentration, that increase efficiency of FET channel cut-off.

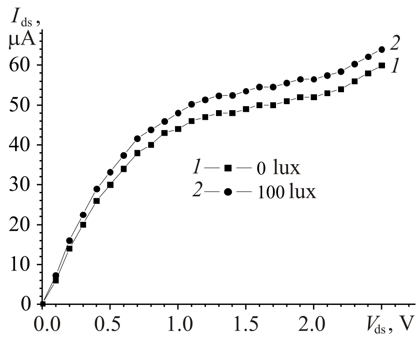

Fig. 1.

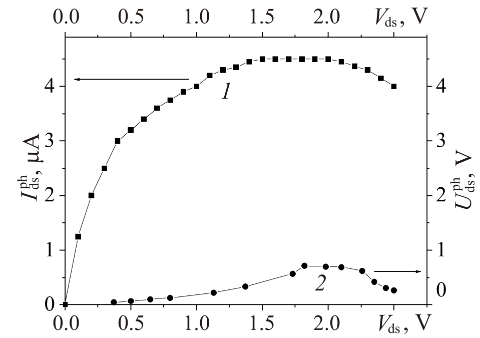

Fig. 2.

Obtained structures of optic FET volt-ampere characteristics in the dark has explicit drain current saturation. Drain current grows with drain-source voltage (V_{ds}) increase, becomes saturated, achieves maximal value 150 μA, when fixed blocking voltage gate-source grows, drain current decreases and achieves minimal values, comparable with back gate current. In Fig. 1 drain volt-ampere characteristics are represented, when V_{gs} = –0.8 V (curve *1* corresponds to dark characteristic, curve *2* corresponds to light characteristic at 100 lux). Cut-off voltage, defined using transfer characteristic is 1.7 V, calculation data [9] give a value 1.75 V, then we can say both values are practically identical.

$$V_{gs}^{cut} = \frac{N_{ch} q a^2}{2\varepsilon\varepsilon_0}\left(1 + \frac{N_{ch}}{N_g}\right) - V_D; \quad V_D = \frac{kT}{q}\ln\frac{N_{ch} N_g}{n_i^2},$$

where $q = 1.6\times10^{-19}$ coulomb is an electron charge, a is a channel width, $\varepsilon_0 = 8.85\times10^{-14}$ F/cm is vacuum permittivity, $\varepsilon = 11$ is a permittivity of GaAs, $n_i = 10^7$ cm^{-3} is intrinsic charge carriers concentration in GaAs, $V_D = 1.03$ eV is a contact potential of gate *p-n* junction.

Channel illumination by visible light leads to drain current (i.e. current between drain and source) change (Fig. 1, curve *2*) and gate current (between gate and source). When drain voltage grows at fixed gate voltage and illumination photo currents $I_{ds}^{ph} = I_{ds}^{light} - I_{ds}^{dark}$ and photo voltages $V_{ds}^{ph} = V_{ds}^{dark} - V_{ds}^{light}$ between source and drain are changed non-linearly.

Dependences of photo current (*1*) and photo voltage (*2*) on drain–source voltage are represented in Fig. 2.

Drain photo current grows with drain voltage increase (at fixed gate voltage –0.8V), then it becomes saturated (Fig. 2, curve *1*), photo voltage achieves maximal value (0.71 V) and it stays at this level (1.82 V) up to drain voltage is 2.25 V (Fig. 2 curve *2*), whereas character of drain resistance on voltage increase changes its sign (saturable character of drain current substitutes by growing), Fig. 1. It means that given voltage interval provides maximal output signal. Current photosensitivity at 100 lux for optimal voltage 1.82 V is

$$S_{I-ds} = \left.\frac{\partial I_{ds}^{ph}}{\partial \Phi}\right|_{V_{ds}} = \frac{4.5\times10^{-6}}{100\times3.5\times10^{-8}} = 1.28 \text{ A/lumen or } 8.26\times10^2 \text{ A/W}$$

($\Phi = E \times S$, where E is illumination (lux), S is photosensitive channel area (m^2)), voltage sensitivity is

$$S_{V-ds} = \left.\frac{\partial V_{ds}^{ph}}{\partial \Phi}\right|_{V_{ds}} = \frac{0.71}{100\times3.5\times10^{-8}} = 2.10^5 \text{ V/lumen or } 1.3\times10^8 \text{ V/W}.$$

These photosensitivity is twice greater in comparison to FET with tellurim-doped channel [3]. It should be noted, that when channel is illuminated then modulation channel factor is light radiation. It creates photo

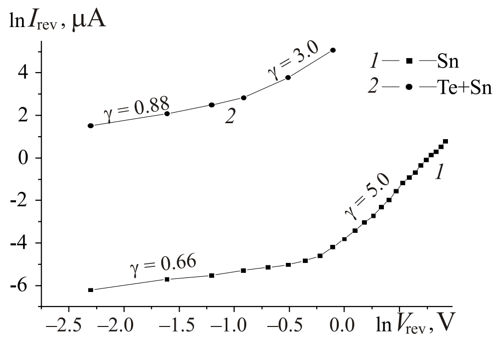

Fig. 3.

current in gate *p-n* junction $I_{gs}^{ph} = I_{gs}^{light} - I_{gs}^{dark}$ (see Table 1) and corresponding change of blocking voltage value $\Delta V_{gs} = R_{s.g}\Delta I_{gs}$ that leads to drain current change $\Delta I_{ds} = S_I \Delta V_{ds}$.

Photocurrent relation to incident power of luminous flux characterizes its diode photosensitivity

$$S_{I-gs} = \left.\frac{\partial I_{gs}^{ph}}{\partial \Phi}\right|_{gs} = \frac{0.077 \times 10^{-6}}{100 \times 3.5 \times 10^{-8}} = 0.022 \text{ A/lumen.}$$

Correspondingly, transistor gain factor is a triode photo sensitivity relation to diode photo sensitivity [10]

$$K_I^{ph} = \left.\frac{\partial I_{ds}^{ph}}{\partial I_{gs}^{ph}}\right|_{V_{ds}} = \frac{S_{I-ds}}{S_{I-gs}} \approx SR_{s.g} = \frac{4.5 \times 10^{-6}\text{ A}}{0.077 \times 10^{-6}\text{ A}} = 58.44.$$

Photo electrical gain factor is related to transistor gain factor. This relation is characterized by quantum efficiency η_{eff}

$$K_I^{ph} = \eta_{eff}(\Delta I_{ds} / \Delta I_{gs}).$$

We suppose, high values of drain photo current is provided by properties of tin-doped channel, grown on intermediate epitaxial *p*-layer. Current characteristics of tin-doped *p-n* junction and combined tin and tellurium doped *p-n* junction are represented in Fig. 3, where curve *1* corresponds to Sn doped junction, curve *2* corresponds to Te+Sn doped junction. As it is shown the first transistors have lower values of dark current (2...22×10^{-9} A).

At that dependence $I \sim V^{\gamma}$ exponent (0.66) is near theoretical value (0.5), which is typical for step junction, determined by generation-recombination processes in *p-n* junction volume charge layer area.

Observed behavior of photo electrical characteristics of researched FET can be explained by lattice defect of gallium arsenide tin-doped channel rearrangement. In particular, tin in epitaxial layers provides internal stresses compensation and reduces amount of gallium arsenide inclusions in growing layers. In epitaxial tellurium-doped layers appearing internal stresses creates defects, comparable with substrate material [7]. Another specificity of tin-doped channel is absence of negative-going zones [3] at photocurrent characteristic in wide voltage range (0–2.5 V) in contrast to tellurium-doped transistors. Moreover, gate photocurrent dependences on blocking voltage illumination intensity has growing character (Table 1).

Thus, specialties of photosensitivity of gallium arsenide FET with epitaxial *p-n* junction and with open tin-doped channel of GaAs are constancy of gate photocurrents dependently on blocking voltage and photocurrent growth dependently on illumination intensity, beginning from small values of illumination intensity (100 lux). Reverse currents are small, current and voltage photosensitivity is smoothly controlled by working voltages and achieves high values 8.26×10^2 A/W and 1.3×10^8 V/W correspondingly. Due to

Table 1 Gate light and photo currents

V_{gs}, V	I_{gs}^{dark}, μA	I_{gs}^{light}, μA			I_{gs}^{ph}, μA		
		200 lux	600 lux	1000 lux	200 lux	600 lux	1000 lux
0	0	0.08	0.38	0.83	0.08	0.38	0.83
0.1	0.002	0.085	0.4	0.85	0.083	0.398	0.848
0.3	0.004	0.096	0.42	0.9	0.092	0.416	0.896
0.6	0.0065	0.1	0.43	0.94	0.093	0.423	0.933
0.9	0.015	0.11	0.45	0.99	0.095	0.435	0.975
1.2	0.048	0.145	0.48	1.06	0.097	0.432	1.012
1.5	0.14	0.245	0.58	1.2	0.105	0.44	1.06
1.8	0.4	0.5	0.83	1.47	0.1	0.43	1.07
2.1	0.9	1.013	1.336	2	0.113	0.436	1.1
2.4	1.68	1.798	2.12	2.81	0.118	0.44	1.13

high values of photosensitivity tin-doped optic FET can be used for optic signal receive and processing in microwave and optic devices.

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