Phototransistor utilizing a GaAs–AlAs heterojunction

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The results are given of an investigation of the electrical and photoelectric characteristics of an n-GaAs–p-GaAs – n-$Al_xGa_{1-x}As$ phototransistor. The use of a wide-gap III–V semiconductor as the transitor material made it possible to reduce considerably the dark current and raise the range of working temperatures. The presence of a wide-gap emitter considerably extended the spectral sensitivity region. Phototransistors of this type were prepared by epitaxial growth from the liquid phase and had the following characteristics: dark current $I_t \sim 10^7$ A/cm^2 under a voltage V_{ec} = 1.0 V; integrated sensitivity S = 100 A/W; gain K = 300; constant sensitivity region from 1.4 to 2.0 eV.

Continuous development of optical information transmission and processing methods makes it necessary to develop high-efficiency fast-response optical detectors with internal amplification. One of such detectors is the phototransistor. The existing phototransistors based on germanium and silicon have a number of important disadvantages compared with photodiodes: Their thermal stability is lower, the dark current and the noise levels are higher, and the maximum operating frequency is lower. All these disadvantages are common to detectors with internal amplification. These disadvantages can be minimized very considerably by the use of III–V wide-gap semiconductors with the direct band structure. However, the advantages of these semiconductors have not yet been utilized. This is due to technological difficulties encountered in the preparation of crystals sufficiently pure and with a sufficiently long minority-carrier diffusion length.

The gain of a phototransistor [1] is given by $K \approx 2(L_{p,n}/W_b)^2$, where $L_{p,n}$ is the diffusion length of the minority carriers and W_b is the thickness of the base. It is clear from this expression that the base thickness must be very small in order to obtain K > 100 for a minority-carrier diffusion length of several microns. Moreover, the effective depth of penetration of light into a direct-gap semiconductor is very small in the fundamental absorption region and almost all the carriers generated by the incident light recombine near the surface. This imposes additional requirements on the thickness of the emitter or collector regions which must be penetrated by the incident light flux. The use of a heterojunction in a phototransistor allows us to avoid this difficulty and to extend the spectral sensitivity region. The present paper reports the results of an investigation of phototransistors based on heterojunctions in the GaAs–Al As system.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the energy band diagram of an n-GaAs–p-GaAs–n-$Al_xGa_{1-x}As$ phototransistor. The base was made of p-type gallium arsenide, in spite of the considerably poorer separation of photocarriers[2] at the emitter junction because of the conduction-band discontinuity ΔE_c. This was done because L_n in p-type GaAs is almost an order of magnitude longer than the diffusion length of holes in n-type GaAs.

The transistors were prepared by epitaxial growth of n- and p-type GaAs and n-type $Al_xGa_{1-x}As$ films from the liquid phase. These films were deposited on n-type GaAs substrates ($n \approx 10^{16}$ cm^{-3}). The type of conduction, the doping level, and the composition of the films were gov-

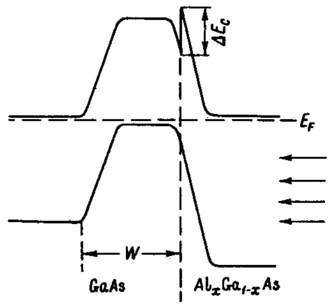

Fig. 1. Energy band scheme of a phototransistor with a wide-gap emitter.

erned by varying the amount and type of the dopant during growth and by altering the concentration of aluminum in the melt. Usually the collector and the emitter regions were doped with Te to concentrations not exceeding 10^{17} cm^{-3} and the base was doped with Ge up to $p \sim 10^{16}$ cm^{-3}. The thickness of the space-charge layer in the collector junction was increased by ensuring that the concentration in the base at the interface with the collector was $\sim 10^{15}$ cm^{-3}, rising to 10^{16} cm^{-3} over a distance of 1 μ.

We investigated transistors with bases 1-3.0 μ thick. The capacitance of the structure C_0 in the emitter–collector configuration was 10-30 pF. The phototransistor area was 0.2-1 mm^2.

Figure 2 shows the current–voltage characteristic of one of the samples obtained at different illumination levels. The characteristic in darkness could be described by $I = I_{k_0}(V)/(1-\alpha)$. Therefore, the initial part of the dark characteristic was governed by the current across the collector junction and obeyed a power law $I \propto V^n$. The current rose strongly with the applied voltage because of an

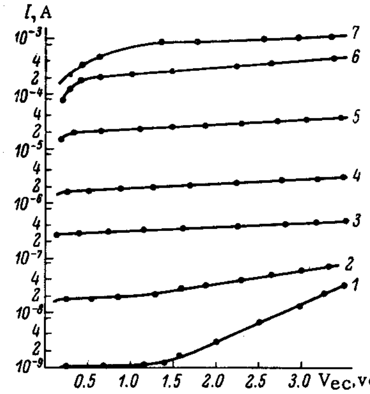

Fig. 2. Current–voltage characteristics obtained at different illumination levels. Incident light flux $P \cdot 10^6$ (W): 1) 0 (dark characteristic); 2) 2.0; 3) 3.2; 4) 4.1; 5) 1.08; 6) 4.0; 7) 10.

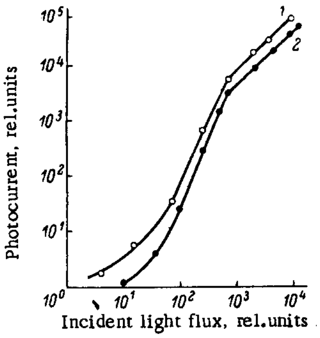

Fig. 3. Dependence of the photocurrent on the relative illumination intensity. V_{ec} (volts): 1) 1.0; 2) 0.5.

increase in the gain. The voltage corresponding to the onset of the rapid rise of the current increased with increasing thickness of the base region.

The integrated sensitivity $S = \Delta I/\Delta P$ (A/W) was determined from the rise of the phototransistor current resulting from an increase in the incident light flux. The sensitivity of the best samples was S = 100 A/W. This could be expressed in terms of the number of incident quanta for which the gain factor was K = 300. The high value of the gain was due to small effective thickness of the base because of the large thickness of the space-charge layer W_0 at the collector junction. In our samples the zero-bias thickness of this space-charge layer was $W_0 \approx 1.0\ \mu$ for a total base thickness $W_b \approx 1.4\ \mu$. An estimate of the diffusion length L_n of electrons in p-type GaAs, deduced from the equation for the gain, was $L_n \approx 5$-$6\ \mu$. When the base thickness was increased to 2-3 μ, the gain fell strongly to ≈50-12.

Figure 3 shows the dependence of the photocurrent (proportional to the gain) on the intensity of the light flux for two values of the voltage V_{ec} = 0.5 and 1.0 V. The photocurrent was not a linear function of the illumination. At low illumination levels the dependence $I_{ph} = f(P)$ was

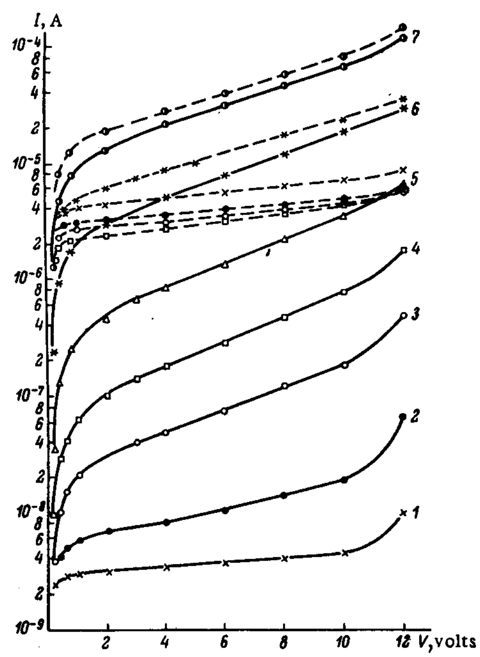

Fig. 4. Current–voltage output characteristics in darkness (continuous curves) and during illumination (dashed curves) recorded at a constant illumination level but at different temperatures T(°K): 1) 296; 2) 332; 3) 369; 4) 392; 5) 416; 6) 450; 7) 497.

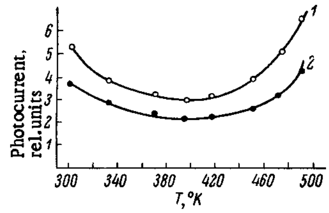

Fig. 5. Temperature dependences of the gain (in relative units). V_{ec} (volts): 1) 6.0; 2) 0.8.

weak, probably due to the influence of accidental surface leakage currents. At higher illumination levels the dependence became quadratic. This quadratic region was probably associated with the recombination in the space-charge layer of the emitter junction. At still higher illumination levels the dependence $I_{ph} = f(P)$ was linear over three orders of magnitude of the illumination intensity above the quadratic region. This indicated a constancy of the gain. The measurements were carried out by a pulse method. The observed behavior of the gain resulted from the independence of the injection efficiency in the investigated range of currents up to $\sim 5 \cdot 10^2$ A/cm.

The emitter efficiency of our transistors $\gamma = I_n/(I_p + I_n)$ can be written in the following form by the application of the diffusion theory:

$$\gamma = \frac{\frac{qD_n}{L_n} n_n e^{\frac{\Delta E_c}{kT}}}{\frac{qD_n}{L_n} n_n e^{\frac{\Delta E_c}{kT}} + \frac{qD_p}{L_p} p_p}.$$

It follows that if $\Delta E_c \gg kT$ (in our case $\Delta E_c = 0.5$ eV), the first term in the denominator is considerably larger than the second for any reasonable carrier density in the base and this ensures the constancy of the injection efficiency in the investigated range of currents.

The influence of temperature on the current–voltage characteristics in darkness and during illumination can be judged from the curves in Fig. 4. Figure 5 shows the temperature dependences of the gain (in relative units). An analysis of the energy band diagram of our phototransistors shows that if $W_b < L_n$, i.e., if the probability of photocarrier separation at the collector junction is high, the long-wavelength edge of the spectral sensitivity is governed by the forbidden-band width in the base and the short-wavelength edge is governed by the "window," i.e., by the forbidden-band width of the emitter (n-type $Al_xGa_{1-x}As$). Figure 6 gives the spectral sensitivities of two photo-transistors with different forbidden-band widths of the wide-gap emitter (the sensitivity was determined at room temperature). Thus, simple variation of the forbidden-band width of the emitter makes it possible to control the spectral sensitivity in the photon energy range 1.4-2.0 eV. (It is important to note the constancy of the gain throughout the spectral sensitivity region.)

The sensitivity of our phototransistors matched well

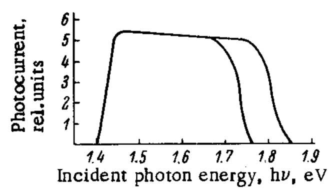

Fig. 6. Spectral sensitivity of two transistors with different forbidden-band widths of the wide-gap emitter.

the sensitivity of $Al_xGa_{1-x}As$ light-emitting diodes. The current gain of such an optron pair (a light-emitting diode separated by ~1 mm from a phototransistor) was found to be 0.1. Therefore, the transient characteristics were investigated employing GaAs–AlAs light-emitting diodes as sources of an alternating light flux. The energy of the photons emitted from these diodes at room temperature was $h\nu_m = 1.46$ eV, the external quantum efficiency was $\eta_e = 0.8\%$, the lifetime was ~5 nsec, and the luminescence decay time was ~30 nsec.

The situation was much less satisfactory in the case of frequency and pulse characteristics of the investigated phototransistors. The expression for the gain $K \approx \tau_n/t_{tr}$ was used to calculate the electron lifetime in the p-type base. This lifetime was 20-50 nsec, in agreement with the measurements carried out on a single emitter junction. Since the phototransistors were used in the common-emitter configuration, the maximum frequency at which useful gain was obtained $\omega_\beta \approx 1/\tau_{nb}$ was governed only by the minority-carrier lifetime in the base and it should be $\sim 10^7$ Hz. However, the actually measured values of ω_β were much lower. The pulse characteristics were investigated by two methods:

1) applying voltage pulses to a phototransistor and using a constant illumination flux;

2) using light pulses and a constant voltage across a transistor.

In both cases the excess charge accumulated in the base disappeared solely because of recombination. However, the conditions for the disappearance of the charge were different. In the first case the phototransistor signal followed exactly the applied light pulses with leading and trailing edges of 100 nsec. In the second case the shape of the current pulses across the collector load depended on the light flux. The leading edge amounted to several tenths of a microsecond. When the duration of the light pulses was longer than the leading edge, the current pulses were exactly of the same duration as the light pulses. The trailing edge of the current pulses varied with the incident light flux from microseconds to tens of microseconds. It was likely that this slow decay of the photocurrent was mainly due to the low value of the dark current and the high value of the gain. If we assumed that the charge accumulated in the base during illumination was proportional to the current, the relaxation time was

$$t = \tau_{nb} \ln \frac{I\left(\frac{\tau_n}{t_{np}}\right)}{I_d},$$

where I_d is the dark current ($\sim 10^{-9}$ A) and the factor $\tau_n/t_{np} = K$ allows for the fact that some of the carriers cannot recombine in the base during the transit time. Estimates indicated that if $I = 0.1$ A, $K = 300$, $I_d = 10^{-9}$ A, and $\tau_n = 50$ nsec, then $t = 1.2$ μsec.

Obviously, the presence of a base terminal should make it possible to reduce considerably the decay time and to study in greater detail the pulse characteristics.

The wide region of photon energies in which the sensitivity is constant, the broad working temperature range, the high sensitivity, and the constancy of the gain at high illumination levels lead us to expect extensive practical applications of the phototransistors described above.

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