The temperature dependence of the photocurrent in doped sillenite-type crystals is investigated in the temperature range 80-300 K. In the region of low temperatures thermally activated photocurrent is observed, while at high temperatures quenching is observed. In a number of specimens the temperature quenching section is absent. The results are explained within the framework of a multilevel recombination model involving slow and fast recombination centers as well as capture levels.

Sillenite-type crystals exhibiting simultaneously linear electrooptical effect and photosensitivity are widely applied in the processing of transparencies whose parameters vary under the action of optical and electrical signals. In this case the magnitude of the photoconductivity of the crystals at temperatures below room temperature is very important. The temperature dependence of the photocurrent in specially undoped \( \text{Bi}_2\text{GeO}_4 \) and \( \text{Bi}_2\text{SiO}_4 \) crystals was investigated previously in [1, 2], but such crystals have low photosensitivity. It was found that in \( \text{Bi}_2\text{GeO}_4 \) the stationary photocurrent \( I_{ph} \) increased monotonically in the temperature range 153-293 K, while in \( \text{Bi}_2\text{SiO}_4 \) lowering of the temperature also led to the growth of \( I_{ph} \) (up to 250 K), and then to its temperature quenching. However, no detailed investigation of this phenomenon was carried out.

In the present communication the stationary photocurrent is investigated in doped \( \text{Bi}_2\text{GeO}_4 \) and \( \text{Bi}_2\text{SiO}_4 \) crystals in the temperature range 80-300 K. On the basis of the results obtained, a model of recombination processes in these materials is proposed involving, in addition to fast recombination centers, slow sensitizing recombination centers and "slave" capture centers for the majority charge carriers (electrons).

High-resistivity (more than \( 10^{16} \Omega \cdot \text{cm} \)) single crystals, grown by the Czochralski method, specially nondoped, annealed in vacuum, and doped with \( \text{Bi}_2\text{FePO}_4 \), \( \text{Bi}_2\text{FeVO}_4 \), \( \text{V}_2\text{O}_5 \), \( \text{CdO} \), \( \text{ZnO} \), \( \text{Ga}_2\text{O}_3 \), \( \text{CaF}_2 \), \( \text{Al}_2\text{O}_3 \), and others by the introduction of the doping elements in the composition of the batch were investigated. Slotted specimens with aluminum contacts were used in the measurements illuminated with light in the fundamental absorption region whose intensity was controlled by means of neutral filters. The temperature of the specimens was varied automatically in the range 80-300 K according to a linear law at a rate of 0.015 K sec\(^{-1}\), the photocurrent was amplified by a U5-7 electrometer amplifier and recorded on a PDP4-002 x-y recorder with the application to the specimen of a voltage of 200 V.

Under identical illumination, the photocurrent at any temperature was two or more orders of magnitude smaller in nondoped \( \text{Bi}_2\text{SiO}_4 \), \( \text{Bi}_2\text{GeO}_4 \), and \( \text{Bi}_2\text{TiO}_4 \) as well as in \( \text{Bi}_2\text{FePO}_4 \), \( \text{CdO} \), \( \text{Fe}_2\text{O}_3 \), \( \text{Ga}_2\text{O}_3 \), \( \text{Bi}_2\text{FeVO}_4 \) doped specimens than in structures based on materials subjected to annealing in vacuum.

The temperature dependence of the stationary photocurrent in specially nondoped crystals at various illumination levels is shown in Fig. 1. In the low-temperature region, already above 80 K, the photocurrent is seen to rise with increasing temperature in all specimens. In \( \text{Bi}_2\text{SiO}_4 \) specimens it is characterized by the presence of exponential sections with the exponents 0.07-0.09 and 0.15-0.2 eV (in \( \text{Bi}_2\text{GeO}_4 \) 0.07 and 0.15, in \( \text{Bi}_2\text{TiO}_4 \) 0.07 and 0.1 eV), depending on the light intensity \( L \) [with increasing \( L \) the slope of the \( I_{ph}(T) \) curves decreases]. The temperature at which the activation of the photocurrent ends is 167, 159, and...
Fig. 1. Temperature dependence of the photocurrent in sillenite-type nondoped crystals at various illumination levels \( L \):
\[ L_1 > L_2 > L_3 > L_4 \]. 1-4) \( \text{Bi}_{122}\text{SiO}_{20} \); 5) \( \text{Bi}_{122}\text{TiO}_{20}-L_3 \); 6) \( \text{Bi}_{122}\text{GeO}_{20}-L_3 \).

Fig. 2. Temperature dependence of the photocurrent in Si-sillenite crystals doped with: 1) \( \text{Bi}_{122}\text{FePO}_{40} \); 2) \( \text{V}_{20} \); 3) \( \text{ZnO} \); 4) annealed in vacuum.

153 K for \( \text{Bi}_{122}\text{SiO}_{20} \), \( \text{Bi}_{122}\text{GeO}_{20} \), and \( \text{Bi}_{122}\text{TiO}_{20} \), respectively, and increases with the illumination intensity. The temperature quenching of the photocurrent (TQP) begins above these temperatures \( T_m \). At the same time, the values of the photocurrents at \( T_m \) are comparable. The \( I_{\text{ph}}(T) \) curve obtained is satisfactorily explained within the "band–recombination level" or "capture level–recombination level" type multilevel recombination model for a monopolar semiconductor in which there are fast \( s \)-centers and slow sensitizing \( r \)-centers, as well as \( t \)-type capture levels for the majority charge carriers lying at various depths which lead to the redistribution of electrons and holes under the action of temperature and illumination [3].

At low temperatures (=80 K) and low illumination levels the occupation of the \( r \)-centers in sillenite-type crystals is no longer determined by the \( t \)-type capture levels because of their low concentration and small depth (=0.07 eV). The probability of thermal ejection of electrons to \( r \)-type recombination centers leading to the lowering of their hole population, the increase of the electron lifetime \( \tau_n \), and the growth of the photocurrent (thermal activation) which has an exponential character [3] having a slope \( E_{t} \) /2:

\[
I_{\text{ph}} \propto n \sim \left( \frac{L N_{c}^{1/2}}{N_{t}} \right) e^{-E_{t}/2K_{B}T}.
\] (1)

Here \( E_t \) is the depth of the capture levels with respect to the bottom of the conduction band; \( N_c \) is the effective density of electron states in the conduction band; \( N_t \) is the concentration of the \( t \)-levels. In sillenite-type crystals, before the onset of the TQP, two shallow capture levels are manifest whose electron capture function \( \varphi_t \), described in the region of photocurrent activation by the expression

\[
\varphi_t = \frac{N_t}{N_c} e^{-E_t/K_{B}T},
\] (2)

decreases exponentially with increasing temperature.

The photocurrent activation process in the crystals ends at the temperatures \( T_m \) determined by the conditions

\[
N_t = N_c e^{-E_t/K_{B}T_m}.
\] (3)

Making use of the experimental values of \( E_t \), \( T_m \), and \( N_c = 10^{17} \ T^{2/2} \ m \) [4, 5], the values of \( N_t \) were derived, which were found to be 1.9•10^{13}, 1.2•10^{13}, and 7.3•10^{12} cm^{-3} in \( \text{Bi}_{122}\text{SiO}_{20} \), \( \text{Bi}_{122}\text{GeO}_{20} \), and \( \text{Bi}_{122}\text{TiO}_{20} \), respectively. At the same time, the thermal transitions of elec-