ELECTRIC AND PHOTOELECTRIC INVESTIGATIONS ON GaP SINGLE CRYSTALS

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Density and activation energy of local levels in GaP:Cu and $GaAs_xP_{1-x}$ ($x=0.26$ and 0.48) single crystals have been investigated by long wavelength probing of the centres and by measuring thermally stimulated currents. The results indicate the presence of the Cu level having a broad activation energy near 0.6 eV. Some results connected with current-voltage characteristics are summarized and the condition of the onset of induced impurity breakdown oscillations has been derived.

In previous papers [1—3] we have dealt with the specific behaviour of the photoconductivity and of the current-voltage characteristics in highly compensated vapour-grown GaP:Cu single crystals. Some of the results led to conclusions concerning the existence of localized impurity levels above the principal (indirect) band gap. In the present article we wish to give an account of some results, on one hand, about further investigations of photoelectronic type (long wavelength probing of the impurity levels, LWP, and the measurement of thermally stimulated currents, TSC) and, on the other hand, about some recent experiments and results on current-voltage characteristics and instability phenomena.

Long Wavelength Probing of Impurity Levels

Samples used in these experiments were similar to those described in [1]. The experiments were performed using a slight modification of the original arrangement described by RYVKIN [4] (Fig. 1). The light from an infrared monochromator (IR Spectrophotometer, type ИКС – 12 was chopped by a rotating disc and, by the help of the shutter Sh_1, it was focussed together with the light ($\lambda < 530$ nm) of the lamp L onto the surface of the sample S. The photodetector system to measure the incident photon flux consisted of the PbSe photoresistance D (Zeiss) and the corresponding measuring system MS (preamplifier, EMG-1594, and selective measuring receiver, TELMES, type TT-1301). This system enabled us to adjust properly the photon fluxes of both light beams. The sample holder was similar to that described by URE [5] and made possible to perform measurements at various temperatures. The wavelength interval of the measurements was from 0.6 to 16 μm, but levels having measurable concentration were found to have activation energy between 0.8 and 1.6 μm.

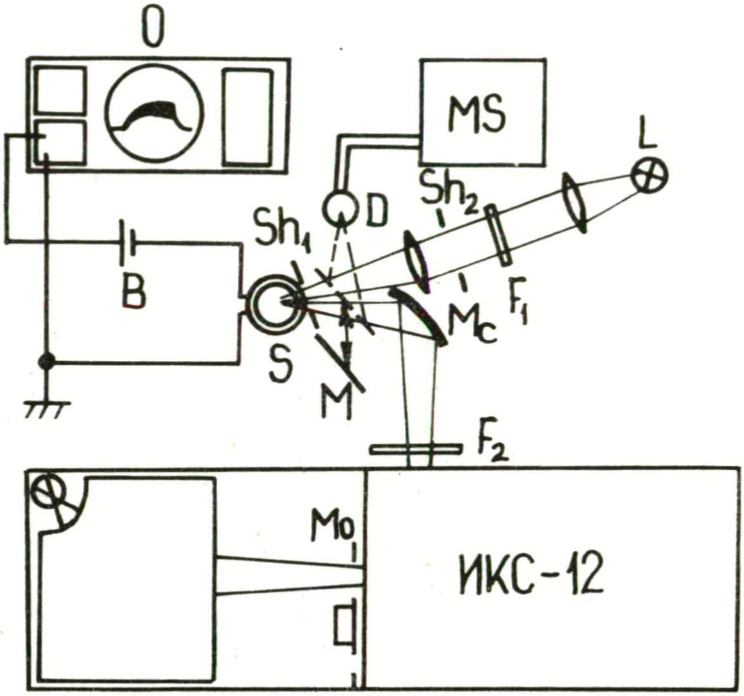

Fig. 1 Experimental arrangement for LWP measurements. *O:* oscilloscope (Solartron, type 1400), *Mo:* chopper, Sh_1, Sh_2*:* shutters, *S:* sample, *B:* battery, *D:* PbSe photoresistance (Zeiss), *MS:* measuring system, F_1,*:* Schott filter (transparent for $\lambda < 440$ nm) and grey wedge, F_2*:* grey wedge, *L:* incandescent lamp, *M:* movable mirror, M_c*:* concave mirror.

Fig. 2*a* and *b* show two typical examples of the filling-up and the emptying of the $0.85\,\mu\text{m} = E_c - h\nu = 1.46$ eV (*a*) and the $1.2\,\mu\text{m} = E_c - h\nu = 1.03$ eV (*b*) deep levels. Here E_c denotes the energy of the conduction band and $h\nu$ the photon energy in electronvolts.

In order to calculate trapped electron concentrations, we had to measure the

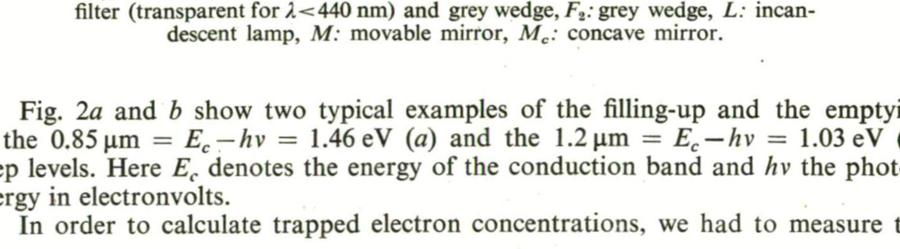

Fig. 2 Time scale: 0.2 sec/div. Temperature: *a)* 122 °K, *b)* 296 °K

response time (τ_0) for the rise (r) and decay (d) transients connected with the probing light beam, too [4]. Using the relation

$$\frac{1}{\tau_0^r}-\frac{1}{\tau_0^d}=QS,$$

where Q denotes the absorbed photon flux and S the photon capture cross-section of the centres, we could calculate S (Table I). These values, together with the excess carrier concentration n' (due to IR photons) in the LWP experiment, enabled us to determine the trapped carrier concentration n_t by the following formula [3]

Table I

λ (μm)	0.9	1.0	1.1	1.2
S (cm^2)	2.1×10^{-15}	9.2×10^{-15}	2.6×10^{-14}	1.0×10^{-14}

$$n' = n_t QS.$$

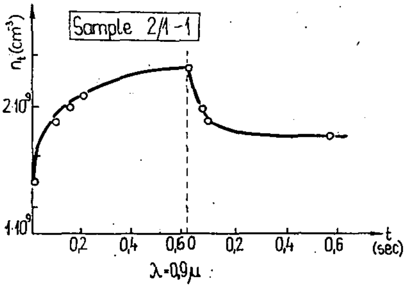

Fig. 3a

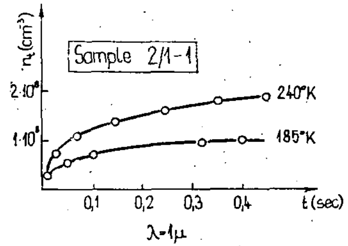

Fig. 4a

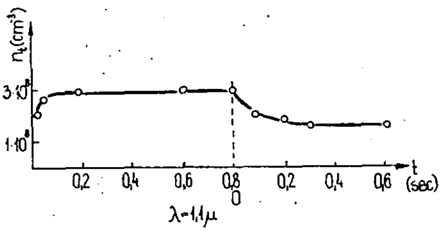

Fig. 3b

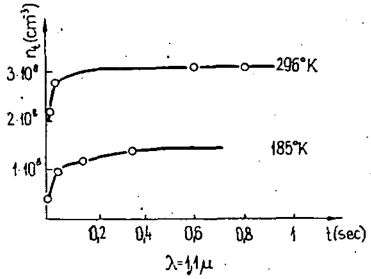

Fig. 4b

Figs. 3a and b show typical results for two IR wavelengths, while Figs. 4a and b, those for two different wavelengths and temperatures (these latter contain only the filling-up of the centres). The photon flux was held constant for every wavelength $Q_{IR} = 1.1\times10^{18}$ photon/sec cm^2. (Similar results were obtained with copper compensated GaAs$_x$P$_{1-x}$ crystals, $x=0.26$ and 0.48.)

Thermally Stimulated Currents in GaP and $GaAs_xP_{1-x}$ Crystals

In these experiments we used the same Dewar to maintain the desired temperature rise. The illumination at 90 °K was produced by the light of an intensive microscope lamp. Currents were measured by a d.c. measuring amplifier (Atlas, type DC 60). The constant rate (*b*) of temperature rise was ensured by the controlled heating of the sample holder.

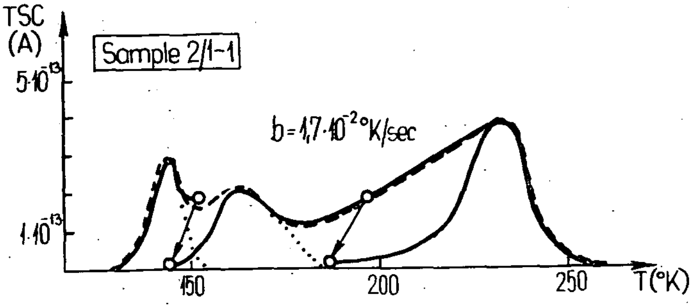

Fig. 5

Fig. 5 shows results on a compensated GaP crystal. The results of direct measurements are shown by broken line, while the full line represents curves using thermal cleaning [6]. Extrapolation was used in drawing the contours of the individual maxima (dotted lines).

Using the expressions connecting trap parameters with the TSC experimental data [7], the calculated trap depth values (E_t) and the densities (N_t) in sample 2/1—1, are summarized in Table II.

Table II

E_t (eV)	0.39	0.41	0.64
N_t (cm^{-3})	1.1×10^{15}	3.5×10^{14}	2.6×10^{14}

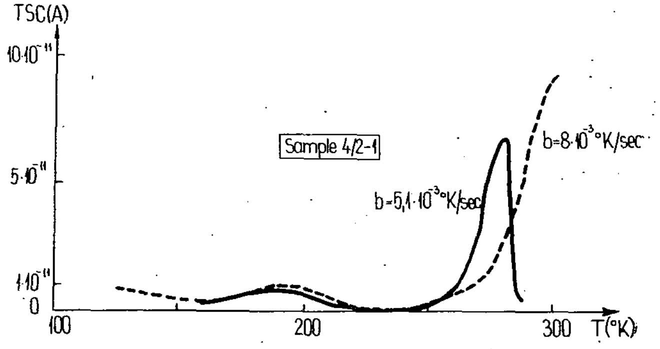

Fig. 6

The trap having an activation energy of 0.64 eV may be attributed to the Cu centres [8], the origin of the other levels could not been identified. Samples from different growing cycles mainly showed the 0.64 eV maximum only. In curves obtained with $GaAs_{0.26}P_{0.74}$ crystals the same maximum appeared prominently (Fig. 6, $N_t = 1.4 \times 10^{16}\ cm^{-3}$).

Some Effects of a High Electric Field in GaP

In previous publications [2, 3] we have described some of our results connected with the current density — voltage (i—V) characteristics of thin (200—500 μm) GaP monocrystal slices (faces perpendicular to the [111] direction), which led to the conclusions that *i)* the $i - V$ characteristics reflect the effect of trapping on an Ashley and Milnes type [9] double injection and *ii)* the dependence of the light induced impurity breakdown oscillations on exciting photon energy provided evidence of the presence of discrete trapping centres well above the principal conduction band edge.

In the present article we present some further details of the above experiments.

a) Using a high voltage pulse generator (Fig. 7) triggered by a laboratory pulse generator (EMG-1154), we have measured the dependence of current density on voltage (Fig. 8) and, using d.c. voltage, on sample thickness l (Fig. 9). The shape of the curves is in accordance with the $i \propto l^{-[2(T_c/T)+1]}$ law, where T is the ambient temperature and T_c is the distribution parameter of the centres having an exponential distribution in energy [10]. The calculated value $T_c/T = 1.1 \times 10^3$ (using the two minor sample thicknesses) is in good agreement with those calculated on the basis of Fig. 8 [3].

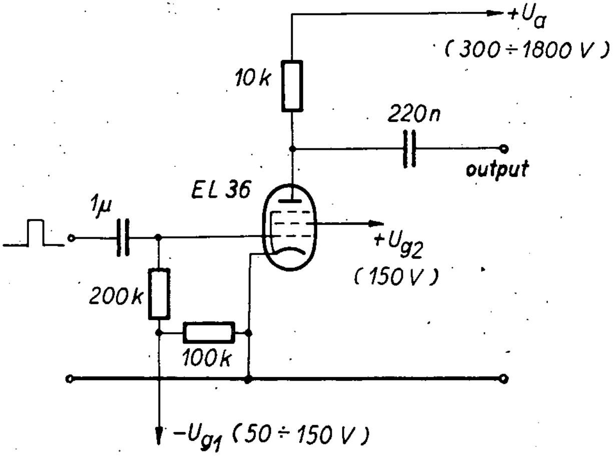

Fig. 7

b) Concerning the detailed investigation of the light induced impurity breakdown oscillations, we present some previously unpublished results.

Figs. 10*a* and *b* show the dependence of the repetition frequency of the above oscillations on exciting photon flux. The clearly linear relations, as well as the repeti-

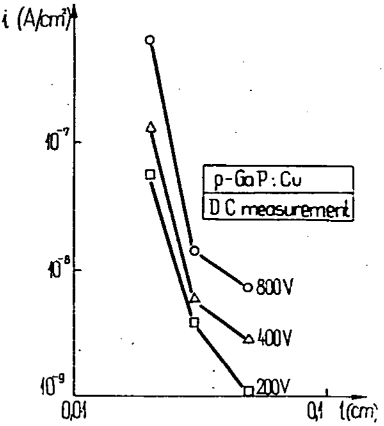

Fig. 9

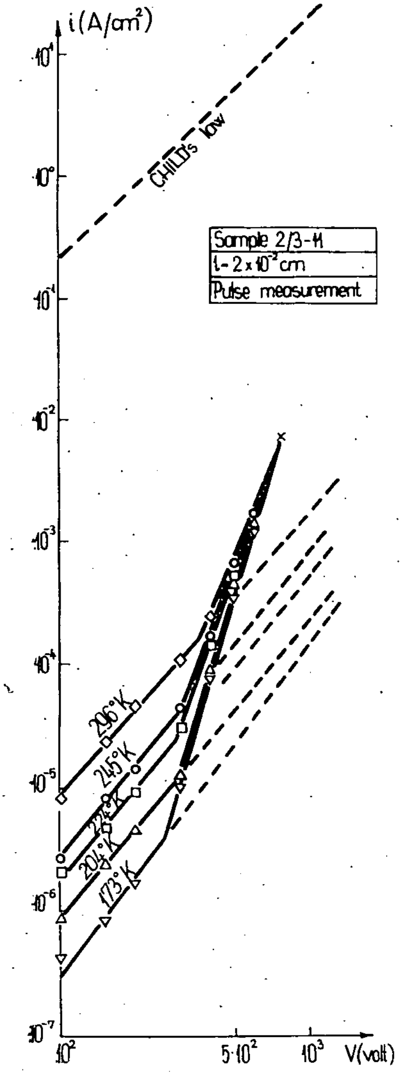

Fig. 8

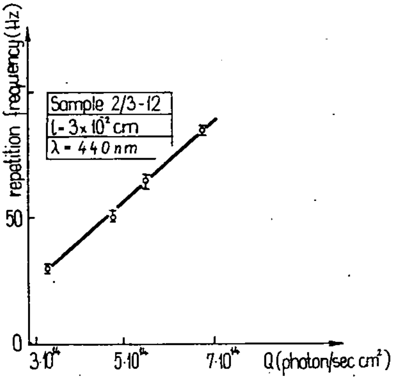

Fig. 10a

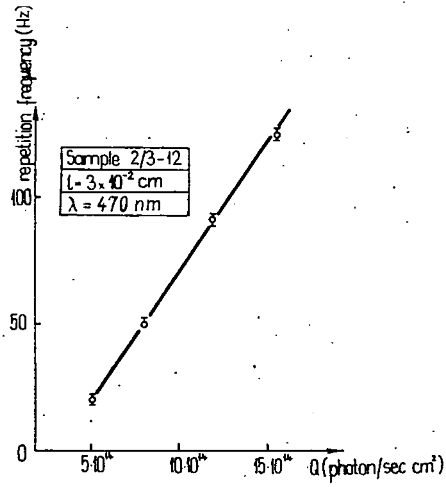

Fig. 10b

tion frequency *vs* field strength dependence, showing a saturation character (Fig. 11), are in accordance with our proposed explanation [2].

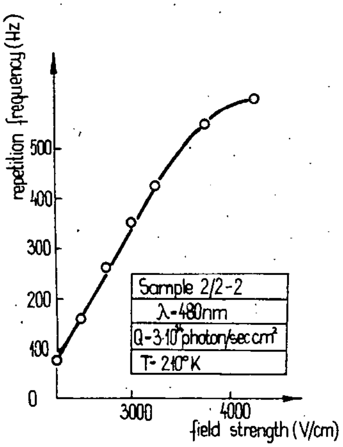

Fig. 11

Taking into consideration our findings on the dependence of the repetition frequency on photon energy, which point to the presence of centres having higher energy than the [100] conduction band minimum, and using the model proposed in [2], we can determine the condition of the onset of these oscillations. To the analogy of the treatment of YAMASHITA [11], the stationary state between the processes shown in Fig. 12, can be expressed as follows:

$$\frac{dn_1}{dt} = S_{t1} v \alpha_t^* Q N_{c1} + S_{t1}^i v n_1 \alpha_t^* Q - S_r v n_1 (N_r - n_r) = 0,$$

where α_t^* denotes the light absorption coefficient connected with the centres, S_{t1}^i and S_{t1} the cross sections of the induced and thermal transitions from traps to the *1* conduction band minimum, v is the velocity of the electrons, S_r the cross section of the recombination centres for electrons, and N_{c1} the effective density of states in the minimum *1*. From this equation we obtain

$$n_1 = S_{t1} \alpha_t^* Q N_{c1} [S_{t1}^i \alpha_t^* Q - S_r (N_r - n_r)]^{-1}.$$

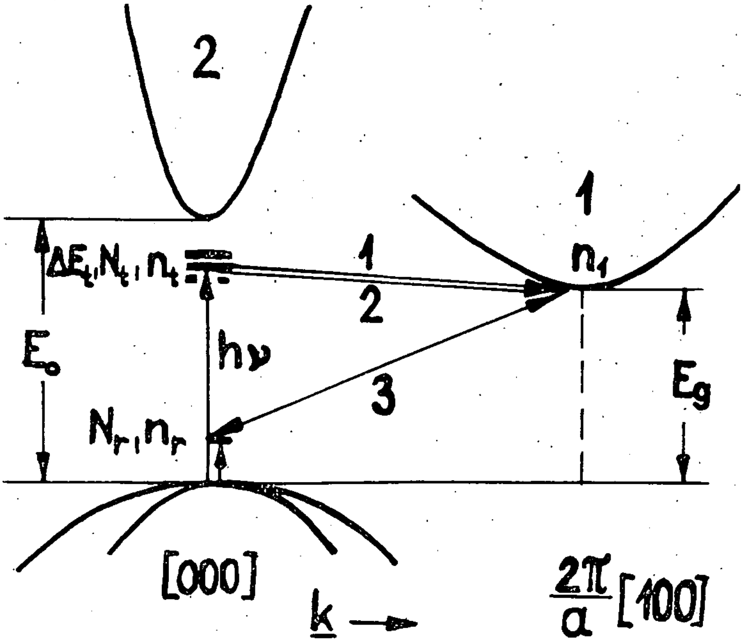

Fig. 12 Proposed level scheme. The processes denoted by arrows: 1) $S_{t1} v \alpha_t^* Q N_{c1}$, 2) $S_{t1}^i v n_1 \alpha_t^* Q$, 3) $S_r v n_1 (N_r - n_r)$

Then the condition of the breakdown has the following form

$$S^i_{t1}\alpha^*_t Q = S_r(N_r - n_r), \quad \text{or} \quad S^i_{t1} = \frac{(\tau_n v)^{-1}}{S n_t Q},$$

where τ_n is the lifetime of the electrons. Using our present and previously published data [1], we obtain as an estimate $S^i_{t1} \approx 10^{-14} - 10^{-16}$ cm^2, a value which seems to be in accordance with our proposed model.

* * *

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ЭЛЕКТРИЧЕСКИЕ И ФОТОЭЛЕКТРИЧЕСКИЕ ИССЛЕДОВАНИЯ НА МОНОКРИСТАЛЛАХ ФОСФИДА ГАЛЛИЯ

Й. Гьюлаи и Й. Яраи

Плотность и энергия локалных состояний в GaP:Cu и $GaAs_xP_{1-x}$ (x=0,26 и 0,48) монокристаллах было исследовано с помощью метода длинноволновых зондированных центров и измерением термически стимулированных токов. Результаты показывают наличие медных центров с энергией активации около 0,6 эв. Были описаны результаты связаных с вольт-амперным характеристикам кристаллов и вычислено условие начала индуцированных светом колебаний примеси пробойа.