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Investigation of contact exclusion in p-Ge long samples

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Abstract. Spatial carrier concentration distributions with a region of very rapid variation in the carrier density were investigated in germanium samples under the contact exclusion effect. The studies were in a range of sample temperatures from 299 to 320 K, under sample illumination with a strongly absorbed light and under various treatments of the sample's lateral faces. The results obtained are in good agreement with results of an analytical theory.

1. Introduction

Pioneering investigations on the contact exclusion phenomenon were carried out [1] during 1954 and 1955. In [1], low-level exclusion was merely studied, when the contact region was not fully excluded. For this case the qualitative electron–hole pair concentration distribution is depicted in figure 1 by curve 1. For low-level exclusion the exclusion factor of the contact region is small and the excluded region extends approximately over one diffusion length from the contact. The current–voltage characteristic is almost ohmic. High-level exclusion, when the contact region is excluded almost fully in a high electric field, was investigated later (see the review in [2] of the studies carried out up to 1984). The electric current in the excluded region is conveyed by extrinsic carriers. This case is illustrated by curves 2–4 in figure 1. In the case of high-level exclusion the excluded region extends over a few diffusion lengths from a contact and with increase in the voltage applied the whole bulk of the sample becomes excluded. Then the current–voltage characteristic differs drastically from the ohmic characteristic.

For high-level exclusion the appearance of a sharply non-uniform ('step-like') distribution of electron–hole pairs was a qualitatively new result that was predicted and preliminarily investigated in recently undertaken studies [3–6]. The distributions are governed by both the diffusion and the drift of carriers in an electric field. The concentration varies drastically over a distance (the 'compressed' length) which is much less than the ambipolar diffusion length. Aronov *et al* [2] did not know about these distributions; they supposed that the diffusion made no substantial contribution to the formation of carrier density distributions in the contact region. These 'step-like' distributions were obtained by the numerical solution of the transport equations for a narrow-band semiconductor by White [3]. The analytical solution of the problem for a wide-band semiconductor and estimations of the value of the carrier concentration jump and the region of its extent were presented in [4]. In [5] a continuity equation for a wide-band semiconductor has been numerically solved and results confirming the analytical

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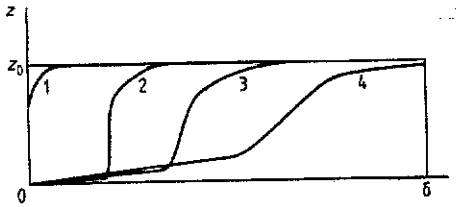

Figure 1. The schematic outline of the spatial distribution of the electron–hole pair concentration for different current ranges: curve 1, low-level exclusion $i < i_1 = \frac{1}{2}(z_0 + \frac{1}{2})$; curves 2 and 3, high-level exclusion, spatial carrier density distribution with a concentration 'step', $i_1 < i < i_2 = (z_0 + \frac{1}{2})^2$; curve 4, high-level exclusion, distribution without a concentration 'step', $i > i_2$. The p^+–p contact is on the left and the ohmic contact on the right.

calculations [4] have been obtained. The existence of such a stepwise distribution was experimentally confirmed [4] by the measurement of the potential distribution along a sample. The above-depicted pattern of the phenomenon is more well defined in 'pure' semiconductors, when the electron–hole pair concentration greatly exceeds (by a factor of 10 or more) the concentration of the extrinsic carriers.

The results from the optical probing of a 'step' (a measurement of the CO_2-laser light transmission beyond the fundamental absorption edge in Ge) are presented here. In particular, the surface generation and photogeneration of excess carriers (exposure of the sample to the strongly absorbed light) as well as the temperature variations (the thermal generation of electron–hole pairs) will be discussed with respect to their effect on such characteristics of the step as steepness and its extent along the crystal. In the same way as in most studies devoted to the exclusion effect, germanium is chosen as the model material.

2. Background theory

Since the exclusion effect in the p^+–p–p^+ structure is under consideration, let us cite the solution of the continuity equation in the base p region which has been performed in the quasineutrality approximation: $n_e + n = p$, where n and p are the concentrations of electrons and holes, and n_e is the concentration of ionized acceptors. The following basic results were obtained in [4].

The following notation is used: n_0 and p_0 are the equilibrium electron and hole concentrations, $z_0 = n_0/n_e$, D is the diffusion coefficient which is assumed to be the same for electrons and holes, τ is the lifetime which is assumed to be the same for electrons and holes and not to depend on concentration, $L = \sqrt{D\tau}$ is the bipolar diffusion length, $j = j_p - j_n$, j_n and j_p are the hole and electron fluxes, and $i = jL/4Dn_e$ is the dimensionless current in the flux units.

At currents smaller then $i_1 = \frac{1}{2}(z_0 + \frac{1}{2})$ the current–voltage characteristic of the structure is ohmic, and electron–hole pairs are not completely carried away from the near-contact region; exclusion in this region is small and extends approximately to the diffusion length from the contact by the exponential law (see figure 1, curve 1). At $i_1 < i < i_2 = (z_0 + \frac{1}{2})^2$ near the contact a region of almost complete sample exclusion occurs; the concentration in the excluded region slowly increases from the value $z_1 = z_0/16i^2$ on the contact to $z_2 = i/(z_0 + \frac{1}{2}) - \frac{1}{2}$. The excluded region length can amount to some diffusion lengths. The carrier distribution is governed in the region by the drift only.

While approaching the second contact the excluded region in the sample is substituted by the region of the abrupt (stepwise) concentration increase on the compressed length

$$l_{cp} \simeq Li^{1/2}/(z_0 + \tfrac{1}{2}) \ll L \qquad \delta_{cp} = l_{cp}/L \tag{1}$$

at $z_0 \gg 1$; the concentration increases from the value z_2 to the value $z_3 = i^{1/2} - \frac{1}{2}$ and the electric field falls off by a factor of

$$N \simeq (z_0 + \tfrac{1}{2})/i^{1/2}. \tag{2}$$

The drift and the diffusion play equal parts in the formation of the carrier distribution in the region. A region of stepwise concentration rise is followed by a region of smooth concentration growth over a length approximately equal to the diffusion length from the value z_3 to the equilibrium value z_0. The carrier distribution is governed here by diffusion only and the region is separated from the preceding region by a point of inflection, where the spatial derivative W of the density distribution has its maximum:

$$W_m = z_0 + \tfrac{1}{2} - i^{1/2}. \tag{3}$$

The other part of the sample is occupied by equilibrium concentration carriers close to the opposite contact, if this contact is ohmic. However, if this contact is a p^+–p contact, an accumulation layer with a high concentration of electron–hole pairs and a thickness of the order of the bipolar diffusion length forms near it. Curves 2 and 3 in figure 1 illustrate the pattern of the carrier concentration distribution within the current range $i_1 < i < i_2$. In this case the current–voltage characteristic takes the form

$$\varphi = eU/kT = 2i\delta/(z_0 + \tfrac{1}{2}) + 4(z_0 + \tfrac{1}{2})[i^2/(z_0 + \tfrac{1}{2})^2 - \tfrac{1}{4}] \tag{4}$$

(where U is the voltage on the sample, φ is its dimensionless value, l is the sample length between contacts and $\delta = l/L$). At $2i \ll \delta$, the current–voltage characteristic is ohmic and, if $2i \gg \delta$,

$$i \simeq \tfrac{1}{2}(z_0 + \tfrac{1}{2})^{1/2}\varphi^{1/2}. \tag{5}$$

The length l_{ex} of the excluded sample part is determined as

$$l_{ex} \simeq L[2i/(z_0 + \tfrac{1}{2}) - 1] \tag{6}$$

and decreases with increase in z_0 when the current through the sample is the same.

At currents $i > i_2$ the jump in the concentration distribution disappears and a smooth concentration growth from the exclusion contact to the opposite contact is observed in the sample (curve 4 in figure 1). When the current through the sample increases, the distribution remains smooth with a simultaneous decrease in the pair concentration in the whole sample. At currents $i > i_3 = \delta(z_0 + \frac{1}{2})$ the sample conduction is mainly determined by the concentration of the holes neutralizing the ionized acceptors and the current–voltage characteristic has the form

$$\varphi = 4i\delta - \delta^2 z_0. \tag{7}$$

All the above discussion becomes more apparent, the better the inequality $z_0 \gg 1$, and is valid for $l \gg L$.

3. Experimental results

The samples investigated were p-type germanium plates about 3 cm long with an impurity concentration n_e of about 8×10^{11} cm^{-3} and an electron and hole lifetime τ of about

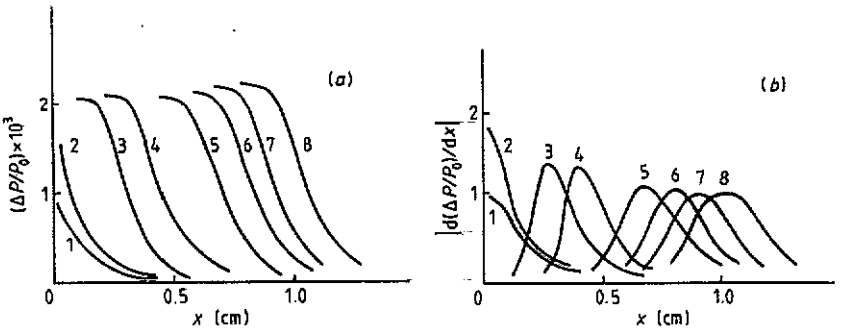

Figure 2. (*a*) The longitudinal distribution of CO_2-laser light transmission through the p-Ge sample (2.92 cm × 0.28 cm × 0.37 cm) at $T = 299$ K and various voltages U: curve 1, 0.5 V; curve 2, 1 V; curve 3, 5 V; curve 4, 10 V; curve 5, 20 V; curve 6, 30 V; curve 7, 40 V; curve 8, 50 V. (*b*) Derivatives of the spatial transmission distribution along the coordinate for the curves in (*a*).

540 μs at $T = 300$ K. The p^+–p contacts were produced by indium fusion into the end sample faces etched in H_2O_2. Then the wide lateral sample faces were polished and the whole structure was etched in boiling hydrogen peroxide. The sample was stuck onto the copper heater produced as a frame with an internal diaphragm measuring 0.3 cm × 5.0 cm (see the inset in figure 4 later). The distribution of the carrier concentration was studied using light absorption by free carriers. The emission of a CO_2 laser with a wavelength of 10.6 μm was used as the probing radiation. The light passed through the sample and the diaphragm about 140 μm wide was recorded with the Ge(Au) detector. A signal from the photodetector was applied to the selective voltmeter and then to the recorder. The heater together with the sample moved by means of a micrometer connected with a coordinate sensor, whose signal was applied to the recorder as well. So, a dependence of the signal proportional to the sample transmission on the longitudinal coordinate was automatically recorded.

The voltage was applied to the sample as rectangular pulses 1.7 μs long with a frequency of 358 Hz and an amplitude as high as 80 V. The signal proportional to the laser emission modulation ΔP due to the periodic exclusion along the sample length was measured. The modulated signal value at each point was normalized to the transmission signal P_0 recorded without a voltage using mechanical beam chopping.

4. Results

Figure 2(*a*) shows the spatial dependence of the light transmitted through the sample at a temperature of 299 K, when the equilibrium carrier concentration is $n_0 = 2.36 \times 10^{13}$ cm^{-3}. The parameter z_0 is approximately equal to 30 and all characteristic properties of the spatial carrier density distribution are well defined. (It is noteworthy that the greatest transmission is in the excluded region.) The results obtained were averaged (the curves depicted are averaged curves) and differentiated numerically. The curves presented in figure 2(*b*) show the spatial derivatives of the carrier concentration distribution in a sample.

The excluded region length, defined as the distance from the exclusion contact to the point of inflection of the carrier density distribution, is shown as a function of current in

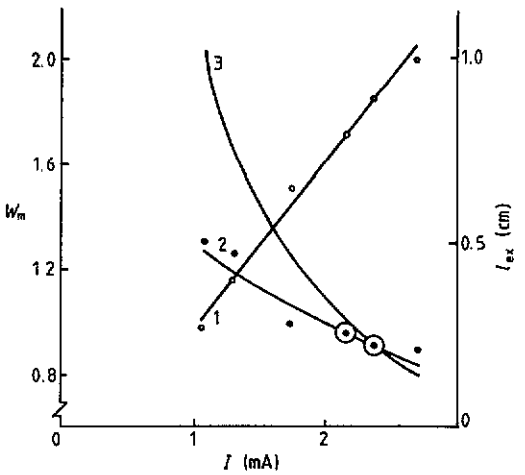

Figure 3. The dependence of the exclusion length (curve 1) and the maximum value of the transmission spatial distribution derivative as a function of current: curve 2, theory [4] which takes into account diffusion; curve 3, theory [2] which takes no account of diffusion; ●, experimental.

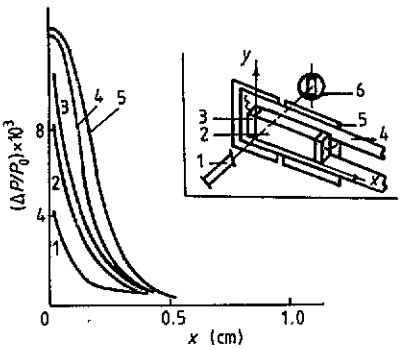

Figure 4. The same as in figure 2(*a*) at $T = 316$ K for various voltages: curve 1, 1 V; curve 2, 5 V; curve 3, 10 V; curve 4, 20 V; curve 5, 50 V. The experimental set-up is shown in the inset: 1, CO_2 laser; 2, sample; 3, p^+–p contact; 4, diaphragm of the copper heater; 5, a slot 140 μm wide; 6, photodetector.

figure 3, curve 1. The plot is linear according to equation (6). The spatial derivatives of concentration density distributions are asymmetrical about their maxima according to the theoretical prediction that the rise in the carrier density concentration in the 'step' is more rapid than exponential. The experimental dependence of the derivative maximum value against the current is shown by full circles in figure 3. The theoretical plot of equation (3) is shown by curve 2. At the encircled dots the parameters describing curve 2 were determined with the aid of equation (3). There is good agreement between the experimental results and the theory. For the comparison we have depicted here in curve 3 the plot of the derivative that was obtained from a theory which takes no account of diffusion. For this case the derivative maximum value is inversely proportional to the current.

Figure 4 shows the spatial dependence of the light transmission at $T = 316$ K, when the intrinsic carrier concentration is equal to 5.5×10^{13} cm^{-3}. The parameter z_0 has a value greater than 68; so the concentration 'step' is much steeper in this case. Estimates using equations (1) and (2) show that over a distance $0.16L$ there is a sixfold rise in the concentration at an applied voltage of 20 V. The rise for the same voltage and at $T =$ 299 K is $N \simeq 4$ over a distance $\delta_{cp} \simeq 0.26$ (curve 5 in figure 2(*a*)). The above-mentioned asymmetry of the carrier density derivative is also observable at a temperature T of 316 K. It should be noted that curves 1–3 in figure 4 correspond to low-level exclusion and the contact region is not fully excluded. Exposure of the sample to strongly absorbed light yielded results similar to those obtained when the temperature was increased. Although the light was absorbed and electron–hole pairs formed at distances of the order of 10 μm from the light-exposed wide sample face only, the results obtained (see figure 5, full curves) can be treated as an increase in z_0 by illumination. An increase in the illumination intensity caused a sharper distribution of the pair concentration and a decrease in the excluded region length.

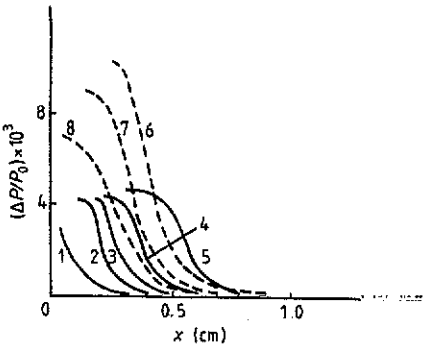

Figure 5. The same as in figure 2(*a*) at $T = 302$ K with external exposure to strongly absorbed light for various voltages U: curve 1, 1 V; curve 2, 5 V; curve 3, 10 V; curve 4, 20 V; curve 5, 50 V. The same as in figure 2(*a*) at $T = 311$ K and $U = 40$ V for various values of the surface recombination rate S: curve 6, 100 cm s^{-1}; curve 7, 300 cm s^{-1}; curve 8, 500 cm s^{-1}.

The dependence of the steepness of the rapid density concentration variation on the rate of surface carrier generation on the lateral faces is of interest. As follows from figure 5 (broken curves), the highest steepness, the largest length of the excluded region and the lowest concentration of the electron–hole pairs in it are observed with the lowest surface generation rate. This follows from the fact that in the excluded region, the higher the surface generation rate, the more important is the role that the carrier fluxes originating on the faces play. However, in the region of the equilibrium concentration there are no such fluxes. Therefore, it is the excluded region where the total number of electron–hole pairs increases and because of this the abruptness of the density concentration 'step' and the full length of the excluded region decrease. So, the validity of the concept developed [4] was confirmed by the direct optical measurements. There is close agreement between the theoretical predictions [4] and the experimental results obtained in this work.

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