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Charge-Carrier Capture and Its Effect on Transition Capacitance in GaP–Cu Diodes*

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The induced photovoltaic effect and the change in transition-layer capacitance in alloyed GaP–Cu diodes have been investigated. Both effects can be explained by hole capturing in acceptor levels with large binding energy. The holes can be released by ir illumination which generates a transient shortcircuit current and quenches the change in capacitance. The spectral sensitivity of the transient photoeffect and of the capacity change is in agreement with other experimental results obtained in homogeneous material. Due to the large binding energy, thermal ionization of acceptor levels is very small at room temperature. Finally, the voltage dependence of the transition-layer capacitance is compared with theoretical considerations, taking into account not only deep lying acceptor levels but also donor levels with large binding energy.

I. INTRODUCTION

In recent years, several papers have been published on copper-doped GaP with respect to photoconductivity[1–5] and photovoltaic effects.[4,6] These investigations indicated that high-resistivity GaP could easily be produced by copper diffusion and that these samples show large photoconductivity gains. Furthermore, it has been observed that the intensity dependence of the photoconductivity in high-resistivity GaP is often supralinear,[3,5] and that the photoconductivity can be quenched rather effectively by ir light.[3] Both effects have been explained[3] by optical charge exchange[7] between two impurity centers with large binding energies. At least one of these centers is probably caused by copper, namely the one that has a low electron-capture cross section and is responsible for the hole capture. These assumptions have been further supported by photo-Hall measurements[5] and storage effects[8] in homogeneous material. That hole capture can also play an important role in photovoltaic effects has been shown by the supralinear dependence of the shortcircuit current on intensity in Cu-doped GaP diodes[6] and by the spectral sensitivity of the photocapacitance of surface barrier junctions.[4,9]

The purpose of this paper is to give direct support for capture of charge carriers in the transition layer of Cu-doped GaP diodes by investigating the induced photovoltaic effect. Furthermore, how these captured charge carriers affect the diode capacitance is discussed. It is shown that a considerable concentration of holes can be stored in the transition layer and that due to the storage of holes, the transition-layer capacitance of the diode can be switched optically or electrically.

II. MATERIAL AND EXPERIMENTAL PROCEDURE

As starting material for the Cu-doped gallium phosphide samples, *n*-type GaP has been employed, made by causing gallium to react with phosphorous hydride. Copper has been incorporated into these samples by annealing them at 400°C in contact with metallic copper, as described in Ref. 3. Most of the resulting material had a resistivity between 1 and 10 Ω·cm and was still *n* type. These *n*-type GaP–Cu samples have then been used for the fabrication of diodes by alloying.[10] Because of the partial compensation of the copper-doped GaP, it is assumed that the positive space-charge region of the junction is much larger than the negative space-charge region.

Three main types of measurements are discussed, those of shortcircuit current (photovoltaic effect), capacitance and charge. Shortcircuit currents have been determined by measuring the voltage drop over a sufficiently small resistance in series with the diode. A Boonton capacitance bridge (type 75D) has been employed for capacitance measurements at 1 MHz. For frequencies below 1 MHz another transformer bridge built at the Institute has been used. Charges have been measured with an operational amplifier and a Tektronix storage oscilloscope type 549. The latter has also been used for the registration of transient effects. As light sources, either a Leiss monochromator or focused Reuter lamps in conjunction with interference filters have been used.

III. EXPERIMENTAL RESULTS

The current–voltage characteristic of the diode used for the investigations reported here is of the type as illustrated in Fig. 1 for diode B18 and discussed

* This work has been supported by the Swedish Council for Technical Research.

[1] J. W. Allen and R. J. Cherry, J. Phys. Chem. Solids **23**, 509 (1962).
[2] D. N. Nasledov and S. V. Slobodshikov, Sov. Phys.—Solid State **4**, 2315 (1963).
[3] H. G. Grimmeiss and H. Scholz, Philips Res. Reps. **20**, 107 (1965).
[4] B. Goldstein and S. S. Perlman, Phys. Rev. **148**, 715 (1966).
[5] D. L. Bowman, J. Appl. Phys. **38**, 568 (1967).
[6] H. G. Grimmeiss and H. Scholz, Philips Res. Reps. **21**, 246 (1966).
[7] See, for instance, S. M. Ryvkin, *Photoelectric Effects in Semiconductors* (Consultants Bureau, New York, 1964).
[8] H. G. Grimmeiss and G. Olofsson, Phys. Status Solidi **28**, 547 (1968).
[9] Y. Furukawa, Japan J. Appl. Phys. **6**, 675 (1967).
[10] H. G. Grimmeiss, W. Kischio, and H. Scholz, Philips Techn. Rsch. **10/11**, 386 (1963/64).

in Ref. 11 for GB 18. It is therefore assumed that the current through the diode is caused by recombination–generation processes in the space-charge region of the junction. The current in reverse direction at -2.5 V was less than 5×10^{-11} A at room temperature. No correlation, however, has been observed between the storage effect and the current–voltage characteristic of a diode. Diodes with completely different I–V characteristics can exhibit the same amount of storage effect.

In order to check whether a diode is exhibiting a storage effect or not, the following procedure was adopted using no external voltage sources: first the diode was illuminated with ir light only (1.2 μ) for a time t_s and the current in the external circuit was registered as a function of time [Fig. 2(a)]. If the small peaks at the beginning and the end of the illumination are neglected, no appreciable current was observed and neither expected because the energy of the ir photons was too small even for a two-step excitation.[12] That nevertheless sometimes a photoeffect is observed also for photon energies $h\nu<\frac{1}{2}Eg$, is discussed elsewhere. When the diode then is illuminated with extrinsic (0.7 μ) light (pumping) for a time t_p, the shortcircuit current increases rather slowly, and it takes considerable time before steady state is obtained [Fig. 2(b)]. If the diode is illuminated again with 0.7 μ light, the steady state of the shortcircuit current is reached much faster [Fig. 2(c)]. Similar but less pronounced effects have also been observed by pumping with intrinsic light (0.5 μ). After a fixed waiting time t_w in darkness (typically 15 sec), the diode was illuminated for a time t_s with ir light again. A transient shortcircuit current could now clearly be observed [Fig. 2(d)]. This transient shortcircuit current was not influenced by shortcircuiting the diode during the excitation with either intrinsic or extrinsic light and/or during the waiting time t_w. Furthermore, the charge Q represented by the transient shortcircuit current and defined as

$$Q=\int^{t_s} i_{sc}(t)\,dt$$

is not changed by varying the resistance in series with the diode between 10^2 and $10^6\,\Omega$. This clearly shows that we are not dealing with high Ohmic photoeffects and that the storage effect is not caused by an ordinary capacity effect. Q values up to 10^{-8} A·sec have been observed in diodes that had an area of about 2×10^{-3} cm^2.

An explanation of the induced shortcircuit current can be given using the results obtained in homogeneous material.[8] Because of the special geometry of the diode, electron–hole pairs are mostly created on the n side of the junction. This part of the diode, however, is to a certain degree compensated by deep lying acceptor levels (probably copper), having a large cross section with respect to free holes.[3,6] This means that the free holes created during pumping and responsible for the shortcircuit current, are captured by the acceptor levels until most of the levels are empty. This corresponds to an increase in lifetime and the shortcircuit current is therefore increasing until steady state is obtained. After the source of excitation has been removed, the captured holes will stay in these levels at room temperature because of the high binding energy. This is the reason why repeated illumination exhibits a fast increase of the shortcircuit current when most of the acceptor levels are already empty. If the diode now is illuminated with ir light of sufficient energy to excite electrons from the valenceband into the empty acceptor levels, free holes are created that can take part in the shortcircuit current. Consequently, the smallest ir photon energy that can create holes for a transient shortcircuit current, should be determined by the binding energy of the acceptor level. Plotting Q as a function of the ir photon energy for constant t_p, t_w, t_s and excitation density (Fig. 3), a sensitivity edge is clearly observed at photon energies between 0.6 and 0.7 eV. This value is in good agreement with the corresponding curve for homogeneous GaP–Cu material,[8] the "relative quenching" of photoconductivity[3] and the ir stimulated and quenched photoeffect.[6] Although Q is constant for ir photon energies larger than 0.75 eV, the decay time of the transient shortcircuit current depends considerably on the photon energy of the ir light (Fig. 4). As in homogeneous material, the decay time is shortest for light energies of about 1 eV and increases with smaller and larger photon energies. Due to the long decay time at low photon energies, the

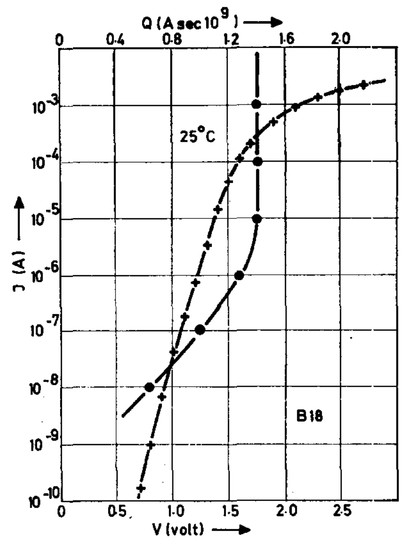


FIG. 1. Current–voltage characteristic of diode B 18. ●—● denotes the stored charge Q as a function of forward current.

[11] G. Bjorklund and H. G. Grimmeiss (unpublished).

[12] H. G. Grimmeiss, W. Kischio, and H. Koelmans, Solid-State Electron. 5, 155 (1962).

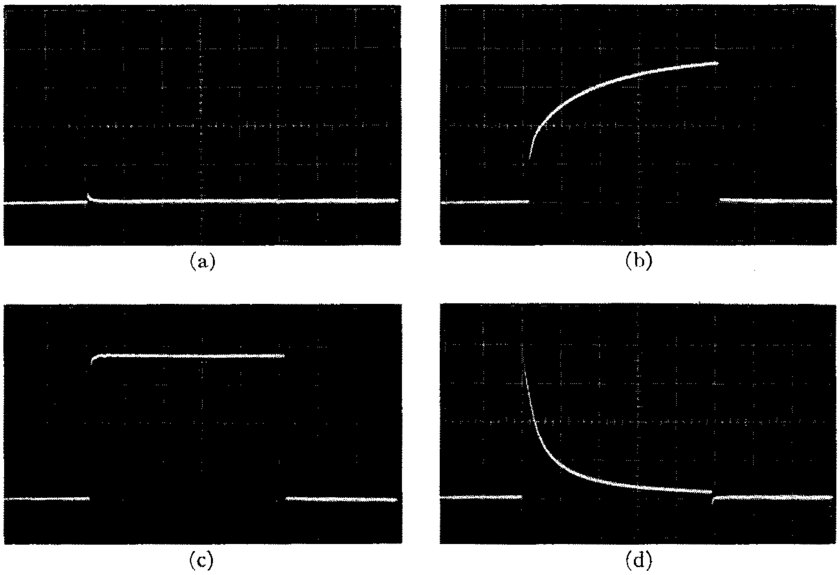


FIG. 2. Time dependence of the shortcircuit current i_{sc} for diode $Q2$ due to illumination with (a) ir light ($1.2\ \mu$), when the diode has not been excited previously; (b) extrinsic light ($0.7\ \mu$), when the diode has been illuminated with ir light ($1.2\ \mu$) previously; (c) extrinsic light ($0.7\ \mu$), when the diode has been illuminated with extrinsic light ($0.7\ \mu$) previously; (d) ir light ($1.2\ \mu$), when the diode has been illuminated with extrinsic light ($0.7\ \mu$) previously. Vertical scales 5 nA/div; horizontal scales 0.2 sec/div.

experimental difficulties for the determination of Q in Fig. 3 increase with decreasing photon energies. Nevertheless, it was clearly observed that there is no sensitivity for photon energies smaller than 0.55 eV. The constant Q value for ir photon energies larger than 0.75 eV, indicated that Q is mainly determined by acceptor levels with binding energies in a rather small energy range. The variation in decay time of the transient shortcircuit current with ir photon energy might therefore be caused by the valenceband structure.

From this explanation, it is clear that a faster rise-time of the shortcircuit current can be obtained with extrinsic light, directly after ir illumination, when hole capturing is made less likely. This is achieved by simultaneous illumination with ir light during pumping (Fig. 5).

From the spectral distribution of the shortcircuit current, it is known[6] that even photons with energies less than the bandgap can create electron–hole pairs in GaP. If a plot of Q against the photon energy of the pump light used to empty the acceptor levels is compared with the spectral sensitivity of the shortcircuit current (Fig. 6), the same low-energy sensitivity edge is found at about 1.5 eV. Although this value nearly corresponds to the distance of the acceptor level from the conduction band edge, the value is somewhat too low to exclude the possibility that also other levels are involved in the excitation of free electron–hole pairs with extrinsic light.

Because of the large binding energy of the acceptor levels responsible for the hole capture, long storage times are observed in our diodes. The stored charge Q decreases typically 30% after 1 h in darkness at room temperature (Fig. 7). From measurements of Q as a function of the waiting time t_w the order of magnitude of the thermal release factor γ of the acceptor levels involved in the hole capturing can be estimated. If the assumption is made that only one level is present and that

$$da^0(t)/dt = -\gamma a^0(t),$$

where $a^0(t)$ is the concentration of the empty acceptor levels at the time $t=t_w$, a plot of $\log Q$ as a function of the waiting time t_w should give a straight line. Experimentally, this is more or less confirmed at larger waiting times giving a value of about 5×10^{-6} sec^{-1} for γ.

The results described hitherto are also obtained when instead of light a forward bias is used for excitation. This is illustrated in Fig. 1 where Q is plotted as a function of the current flowing through the diode a time $t_p=10^4$ sec in order to avoid incomplete excitation. These results indicate that Q saturates for currents in excess of 5×10^{-6} A. This current value corresponds to a forward bias of about 1.3 V as it is seen from the I–V curve. Apart from the arguments presented later, it

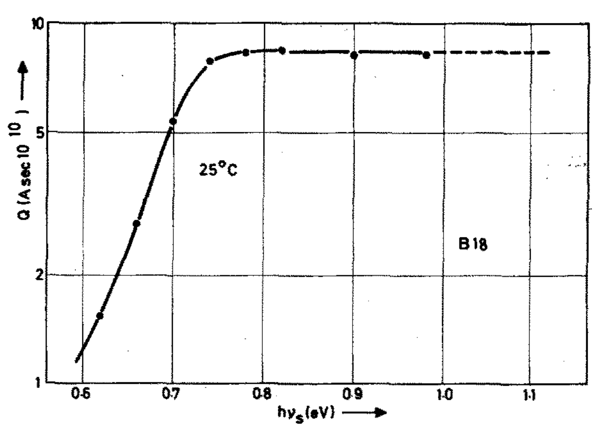
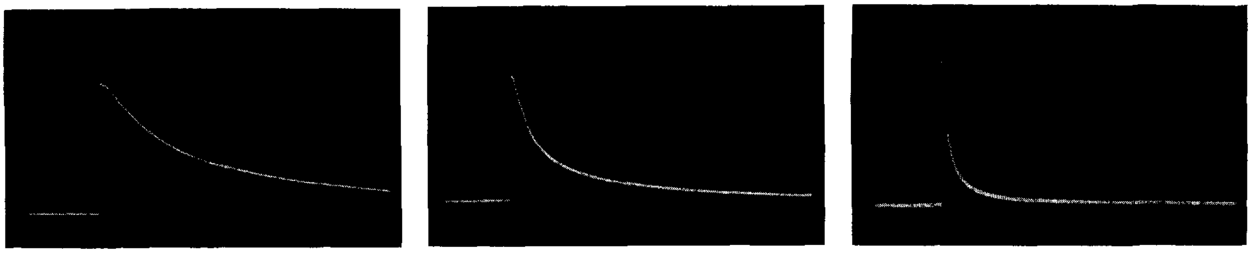
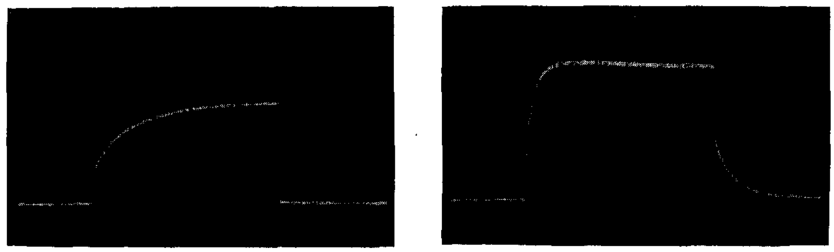


FIG. 3. Stored charge Q as a function of the ir photon energy $h\nu_s$. $t_p=15$ sec, $t_w=30$ sec, $t_s=100$ sec (see text).



(a) (b) (c)

FIG. 4. Time dependence of the shortcircuit current ($Q2$) for three different ir photon energies $h\nu_s$: (a) $h\nu_s=0.8$ eV, vertical scale 0.3 nA/div; (b) $h\nu_s=0.88$ eV, vertical scale 1.1 nA/div; (c) $h\nu_s=1.0$ eV, vertical scale 5 nA/div. Horizontal scales 0.5 sec/div.



(a) (b)

FIG. 5. Time dependence of the shortcircuit current i_{sc} ($Q2$) caused by extrinsic light (0.79 μ) (a) without and (b) with simultaneous ir (1.2 μ) illumination. Vertical scale 1 nA/div, horizontal scale 1 sec/div.

might be expected that hole capture is more effective with minority carrier injection than with extrinsic light because in the latter case, a certain refilling of the acceptor levels with electrons from the valence band cannot be avoided, for if no refilling took place, there could not be any extrinsic steady state shortcircuit current. A comparison between Figs. 1 and 3 shows indeed that the Q values obtained with current excitation are larger than those with extrinsic light. Furthermore, when the diode after being biased in the forward direction with $V>1.3$ V is illuminated with photon energies 1.5 eV$<h\nu<$2 eV, this refilling causes a transient shortcircuit current that is superimposed on the total current (Fig. 8).

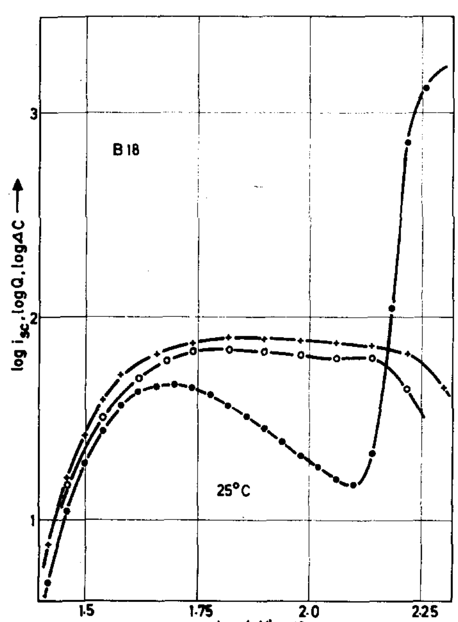


FIG. 6. Logarithm of the capacitance change ΔC (○—○) and logarithm of the stored-charged Q (+—+) both as a function of the extrinsic photon energy $h\nu_p$ used for pumping. ●—● denotes the spectral sensitivity of the logarithm of the shortcircuit current i_{sc}.

It has already been pointed out that the creation of a shortcircuit current demands both free holes and free electrons.[13] By illuminating the diode with ir light after pumping, not only free holes but also free electrons have to be excited. In the neutral n region this can in principle be achieved by simultaneous excitation of electrons from donor levels. In our case, however, where the Fermi level in the n region is situated relatively close to the conduction band, the electrons stored

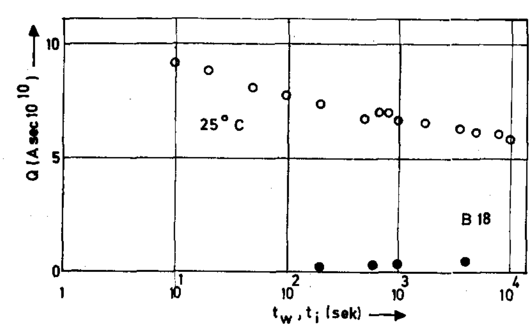


FIG. 7. Stored charge Q (○) as a function of the logarithm of the waiting time t_w ($t_p=15$ sec). ● denotes the charge Q obtained at room temperature a time t_i after ir illumination.

[13] See, for instance, R. Wiesner, *Halbleiterprobleme III* (F. Vieweg & Sohn, Braunschweig, 1956), p. 59; T. S. Moss, *Semiconductors and Semimetals* (Academic Press Inc., New York, 1966), p. 205.

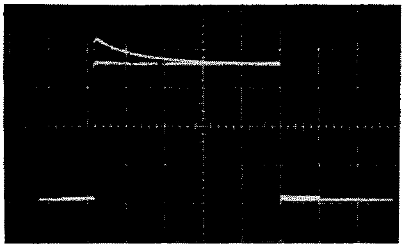


FIG. 8. Time dependence of the shortcircuit current ($Q2$) obtained with extrinsic light ($0.65\ \mu$) without any bias (lower curve) and when the diode has been biased with 1.3 V previously (upper curve).

due to the charge exchange would be thermally released and no long storage times can be expected in contrast to the experimental results. If however, hole capturing takes place in the positive space-charge region, two effects can become apparent. Either charge exchange happens with no change in charge density, or the excited electrons will be trapped outside the positive space-charge region causing a change in the charge density in this region. The first case is rather unlikely because, among others, the low concentration of deep donor levels[3] could not account for the large Q values observed. In the second case, a change in the diode capacitance should be found after illumination, because the charge density of the space-charge region is directly correlated to the transition-layer capacitance of the diode. This is in agreement with experimental results. A clear change in the transition layer capacitance is observed before and after illumination of the diode with photon energies larger than about 1.5 eV, showing at the same time that charge exchange in the positive space charge region obviously does not play a dominant role. According to this explanation, $\Delta C = C_a - C_0$ should be correlated with Q, where C_0 is the diode capacitance before pumping and C_a the capacitance in darkness after the source of excitation has been removed. Plotting ΔC against the photon energy of the (pump) light used for excitation, it is clearly seen (Fig. 6) that this indeed is the case and that the same low-energy sensitivity edge as for the shortcircuit current is obtained. Furthermore, if ΔC is plotted as a function of the ir photon energy after the diode has been excited with photon energies $h\nu > 1.5$ eV, a decrease in ΔC is found for photon energies where Q increases (Fig. 9). It is also observed that ΔC is not affected by photon energies less than 0.55 eV and that ΔC is rather small already for photon energies of 0.8 eV, thus indicating that the junction capacitance is nearly returned to the value of thermal equilibrium. This shows that ΔC, Q, and i_{sc} are generated by the same excitation processes giving rise to hole capturing that cause a change in the transition-layer capacitance after the source of excitation has been removed, and that can be returned to thermal equilibrium by illuminating the diode with ir light, whereby a transient shortcircuit current is caused.

Assuming an abrupt p–n junction, these experimental results can be readily explained using a simple model that takes into account the presence of acceptor levels in the transition region in the bulk of the junction, as due to the compensation of the starting material with copper. The energy band diagram of the p^+–n junction used in the present analysis is illustrated in Fig. 10(a). From previous investigations of the bulk material, it is known[3,5,8] that besides deep-lying acceptor levels, further impurity levels with large binding energy have to be taken into account, although their concentration is rather low. These levels have been assumed to be donor levels. Restricting ourselves to one acceptor level E_a and one donor level E_k, the transition region of the junction can be divided in three regions by the boundaries x_a and x_k according to different charge densities. x_a and x_k are determined from the interception of the Fermi level and the acceptor and donor levels, respectively. In thermal equilibrium, the charge densities in the three regions are $\rho(0<x<x_a)=e(N_d+N_k)$, $\rho(x_a<x<x_k)=e(N_d+N_k-N_a)$ and $\rho(x_k<x<W)=e(N_d-N_a)$, where N_d is the concentration of the ionized shallow donor levels, responsible for n-type conductivity in the starting material and N_k and N_a the electrically active concentration of the deep donor levels and acceptor levels, respectively [Fig. 10(b)]. Assuming that after illumination with photon energies $h\nu > 1.5$ eV, all acceptor levels in the space-charge region are empty, only two regions are left with net charges $\rho(0<x<x_k')=e(N_d+N_k)$ and $\rho(x_k'<x<W')=eN_d$, thus causing a decrease in the width of the space-charge region [Fig. 10(c)]. Because of the large binding energies of both the donor and acceptor levels, the capacitance of the junction in thermal equilibrium at sufficiently high frequencies is given by[14]

$$C_0 = F \cdot \epsilon / W, \tag{1}$$

where F is the area of the junction. Using $C_a = F \cdot \epsilon / W'$

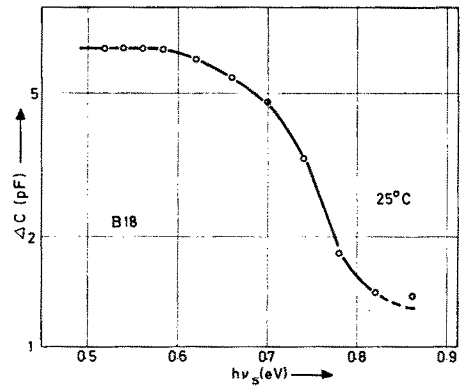
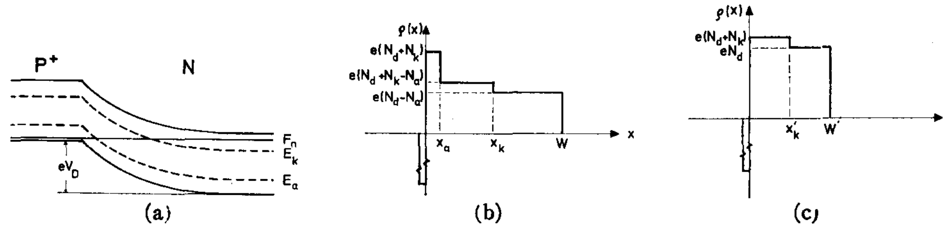


FIG. 9. Capacitance change ΔC as a function of the ir photon energy $h\nu_s$ (see text).

[14] C. T. Sah and V. G. U. Reddi, IEEE Trans. Electron Devices **ED-11**, 345 (1964).

FIG. 10. (a) Energy-band model; (b) charge distribution in thermal equilibrium; (c) charge distribution after pumping.



it follows that $\Delta C=C_a-C_0=F\cdot\epsilon[(1/W')-(1/W)]>0$ because of $W>W'$, which agrees with the experimental results. Refilling all the empty acceptor levels by illuminating the diode with ir photon energies $E_a<h\nu<E_g-E_k$ a transient shortcircuit current is created representing a charge

$$Q=F\cdot e\cdot N_a\cdot W', \tag{2}$$

whereby the junction capacitance is changed. Both ΔC and Q can be calculated and compared with experimental results if W and W' are known. A relation between the applied voltage V and the width W of the junction is however, readily obtained from the solution of the Poisson equation using the simple charge distribution shown in Fig. 10(b) and equalizing the junction width W with the positive space charge region. The solution is

$$V_D-V=(e/2\epsilon)[N_ax_a^2+N_kx_k^2+(N_d-N_a)W^2], \tag{3}$$

where

$$W-x_k=[2\epsilon\phi_k/e(N_d-N_a)]^{1/2}=\beta, \tag{4}$$

$$W-x_a=[1/(N_d-N_a+N_k)][2\epsilon\phi_k/e(N_d-N_a)]^{1/2}\{N_k+[(N_d-N_a)^2(\phi_a/\phi_k)+N_k(1-N_a)(\phi_a/\phi_k)-N_k(N_d-N_a)]^{1/2}\}$$
$$=\beta\cdot\gamma, \tag{5}$$

$$\phi_a=(E_{F_n}-E_a)/e,$$
$$\phi_k=(E_{F_n}-E_k)/e.$$

From Eqs. (3), (4), and (5), the wanted voltage dependence of the junction width W can be calculated, giving

$$W=[\beta/(N_d+N_k)](N_a\gamma+N_k+\{(N_a\gamma+N_k)^2+(N_d+N_k)[(2\epsilon/e\beta^2)(V_D-V)-N_a\gamma^2-N_k]\}^{1/2}). \tag{6}$$

By inserting Eq. (6) in Eq. (1), the voltage dependence of the junction capacitance is obtained:

$$C_0=\frac{F\cdot\epsilon\cdot(N_d+N_k)}{\beta[N_a\gamma+N_k+((N_a\gamma+N_k)^2+(N_d+N_k)\{[(N_d-N_a)/\phi_k](V_D-V)-N_a\gamma^2-N_k\})^{1/2}]}. \tag{7}$$

For $N_d\gg N_k$, this can be transformed to:

$$C_0=C_0'\cdot\{[\phi_k(N_a\gamma+N_k)^2/N_d(N_d-N_a)(V_D-V)]^{1/2}$$
$$+[1+\phi_k(N_a\gamma+N_k)^2/N_d(N_d-N_a)(V_D-V)-(N_a\gamma^2+N_k)\phi_k/(N_d-N_a)(V_D-V)]^{1/2}\}^{-1}, \tag{8}$$

where

$$C_0'=F[e\epsilon N_d/2(V_D-V)]^{1/2},$$

and is the capacitance of the junction without deep-lying levels. Similar to the one-level case calculated by Sah and Reddi,[14] C_0 decreases with increasing concentration of acceptor levels because of the increase in W. Consequently when the diode is illuminated with photon energies $h\nu>1.5$ eV and the electrically active concentration of acceptor levels is reduced, the junction capacitance will increase. This increase in capacitance is also observed when the source of excitation is removed, because the captured holes will stay in the acceptor levels due to the large binding energy, in agreement with the experiment. It is also clear from Eq. (7) that this rise in capacitance should increase with the degree of compensation. Although the compensation was probably rather low in our diodes and therefore the change in capacitance after illumination quite small (at most 15%), it is nevertheless evident from Eq. (7) that a large increase can be expected with properly doped junctions.

The results given in Eq. (7) can be readily proved experimentally by measuring the junctions capacitance as a function of the applied voltage in darkness (Fig. 11). In contrast to junction without deep levels,[15] and in agreement with Eq. (7), no linear relationship has been found between C_0^{-2} and V, in all those diodes, in which storage effects have been observed. In the case of diode B 18, the best fit between Eq. (7) and the experimental results has been obtained when $N_d=6\times10^{16}$ cm^{-3}, $N_a=4\times10^{16}$ cm^{-3} and $N_k=10^{15}$ cm^{-3}, assuming $\phi_k=0.5$ V (solid line in Fig. 11). These values clearly correspond to the series resistance of the diode

[15] W. Shockley, Bell System Tech. J. **28**, 436 (1949).

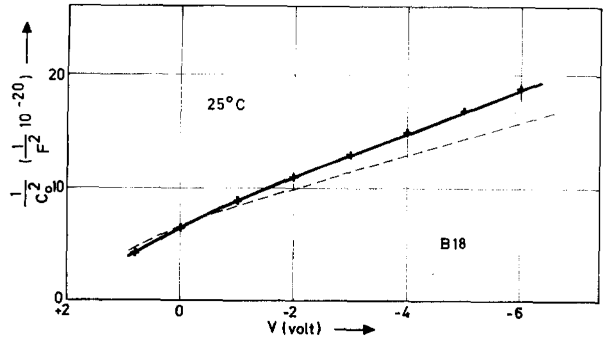


FIG. 11. Plot of C_0^{-2} against bias. + denotes experimental and —— calculated values using Eq. (7) in the text. The dotted line corresponds the best fit of Eq. (10b) in Ref. 14 for the one-level case.

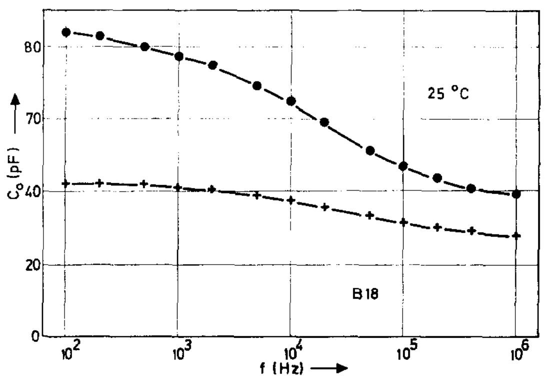


FIG. 12. Transition-layer capacitance C_0 of diode B 18 as a function of frequency with -2.5 V (+—+) and without (●—●) reverse bias.

and agree with previous investigations which indicated that the concentration of the deep donor levels is only small. Furthermore, the N_a/N_d value for the degree of compensation is not in contradiction to the observed ΔC values.

The N_a value obtained from this experiment can be employed for an estimation of Q. If it is assumed that all acceptor levels are emptied during excitation and that at the same time all deep lying donor levels are filled, Eq. (9) can be used to calculate W' in order to estimate the lower limit of Q. Taking $F=1.5\times10^{-3}$ cm^2 and inserting $N_a=4\times10^{16}$ cm^{-3} in Eq. (2), this gives $Q_{\text{cal}}=2\times10^{-10}$ A·sec which is lower than the experimental results, as expected. Somewhat higher calculated Q-values are obtained when no assumption is made on the filling up of the deep lying donor levels.

Using Eq. (2), we tacitly assumed that all acceptor levels in the region $0<x<W'$ are filled by electrons with ir illumination. This means, however, that thermal equilibrium is not obtained immediately after ir illumination, because in thermal equilibrium acceptor levels in the region $0<x<x_a$ are empty. It should therefore be expected that the junction capacitance is somewhat smaller directly after ir illumination than in thermal equilibrium. This is in agreement with experimental results. The capacitance of diodes showing storage effects increases in darkness after the source of ir illumination is removed, until thermal equilibrium is reached. On the other side the capacitance in thermal equilibrium decreases after ir illumination.

That thermal equilibrium is not reached after ir illumination is also confirmed by transient photoeffects without pumping. With repeated ir illumination the diodes do not show any photoeffect as long as the time t_i between ir illuminations is short. This ceases to be the case for sufficiently large t_i values. Figure 7 illustrates the increase in charge represented by a transient short-circuit current obtained by thermal pumping at room temperature as a function of t_i.

In conclusion we only want to add that the low frequency capacitance C_{dc} for a junction with two deep levels has been calculated using the method of Sah and Reddi[14] giving

$$C_{\text{dc}}=\frac{F\cdot\epsilon\cdot(N_d+N_k)}{\beta\{(N_a\gamma+N_k)^2+(N_d+N_k)[(N_d-N_a)/\phi_k](V_D-V)-N_a\gamma^2-N_k\}^{1/2}}. \tag{10}$$

As in the one-level case, C_{dc} is always larger than C_0 for all applied voltages. This is illustrated in Fig. 12 where the junction capacitance is plotted as a function of frequency. A closer inspection of Eqs. (7) and (10) reveals that the difference between C_0 and C_{dc} decreases with increasing reverse bias. Because both values decrease with reverse bias this means that C_{dc} decreases faster than C_0 as illustrated in Fig. 12. Calculating

$$[C_0/(C_{\text{dc}}-C_0)]^2=[(N_d+N_k)(N_d-N_a)/(N_a\gamma+N_k)^2\phi_k](V_D-V)-[(N_a\gamma^2+N_d)(N_d+N_k)/(N_a\gamma+N_k)^2]+1, \tag{11}$$

it is seen that the above ratio should be linearly dependent on the applied voltage. This has been found independent, whether saturation has been obtained at low frequencies or not. In agreement with Auth[16] it is therefore not convincing that such a linear dependence is really a sensitive check.[14]

IV. CONCLUSIONS

Previous investigations indicated that acceptor levels with large binding energy and hole-capture coefficient

[16] J. Auth, Phys. Status Solidi **27**, 653 (1968).

exist in copper-doped GaP. In this paper, it has been shown that these acceptor levels can be used for charge storage in the transition region of alloyed diodes made of GaP–Cu. Charge storage is achieved by hole capture in the acceptor levels. Holes are created either by illumination or electrical injection of the forward biased junction. The charge stored in the acceptor levels amounts typically to 10^{-9} A·sec, at junction areas of $c{:}a$ 10^{-3} cm^2 and can be released by ir illumination causing a transient shortcircuit current without any externally applied voltage. In contrast to photoconductors, these storage effects are easily detected in diodes because normally a shortcircuit current is not generated with photon energies less than half the bandgap. The lowest ir photon energy exhibiting a transient photoeffect corresponds to the binding energy of the acceptor level. At room temperature, the stored charge is therefore only little affected by thermal ionization processes during the first hour. Due to the hole capturing also the charge density in the transition layer and therefore the diode capacitance is changed. This change in capacity has the same time constant as the stored charge Q and can be quenched by the same ir photon energies that cause the transient photoeffect. The experimental voltage dependence of the transition layer capacitance of selected diodes is in agreement with theoretical considerations taking into account both acceptor levels and donor levels with large binding energies.

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Studies of the Early Afterglow in Helium and Argon Plasmas*

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Spatially resolved measurements of parameters during the early afterglow of helium and argon plasmas are presented. The investigated plasmas were contained in a vessel with a wall temperature much less than the electron temperature at the center of the plasma. All measured parameters developed nonuniformly. In spite of the high thermal conductivity of the free electrons, a temperature gradient was supported; the electron temperature being highest in the center of the vessel. The mechanism by which these gradients were supported is discussed. Both the electron and neutral gas temperatures remained elevated at several thousand degrees for at least 200 μsec into the afterglow. Attention is also focused on the effect of spatially nonuniform plasma parameters on transport processes as well as the dependence of the net decay on the cold walls.

I. INTRODUCTION

The results of spatially and temporally resolved measurements of parameters are presented for helium and argon afterglow plasmas. The plasmas studied were contained in a vessel with a wall temperature much less than that of the electrons and neutral atoms at the center of the tube. The results show that in such plasmas all the measured parameters are spatially nonuniform and serve to illustrate the importance of spatial resolution in investigations of similar plasmas. It is shown, for example, that in spite of the high thermal conductivity of the free electron gas, a gradient of electron temperature is supported throughout the time of observation. The mechanism by which this gradient is supported is discussed. Attention is focused on the effect of spatial gradients of plasma parameters on transport phenomena and on the role played by the cold vessel walls in controlling the afterglow plasma. Also discussed is the effect of spatially nonuniform parameters on atomic spectral emission and how the study of this phenomenon can lead to useful information about the plasma.

II. PLASMA FORMATION

The plasma investigated is here in many ways similar to the plasma studied in Ref. 1, where the first known mention was made concerning the support of electron temperature gradients in afterglow plasmas in spite of

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[1] M. A. Gusinow, J. B. Gerardo, and J. T. Verdeyen, Phys. Rev. **149**, 91 (1966).