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High-Field Recombination Domains in Semiconductors with Two Types of Carrier

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An analytic theory of recombination domains in semiconductors with mobile electrons and holes is developed making allowance for hole trapping. The theory applies to "band-band" illumination and to double injection. It is shown that holes may increase strongly the velocity of domains and the thickness of their walls even at low illumination levels when the density of free electrons is close to the value in darkness. Since holes are not generated by illumination with light whose frequency is less than the forbidden band width, the influence of illumination on the domain parameters is determined not only by the intensity but also by the frequency of light.

1. INTRODUCTION

HIGH-FIELD recombination domains, associated with the field-dependent carrier trapping, have already been observed in many materials: gold-doped n-type Ge,[1] copper-doped n-type Ge,[2] GaAs doped with various impurities,[3-5] CdS,[6] etc. As a rule, recombination domains are observed during illumination and the velocity of these domains may increase by several orders of magnitude when the intensity of illumination is increased. An analytic theory of recombination domains developed in [7,8] explains the dependence of the velocity and the shape of recombination domains on the illumination level, the lattice temperature, and the parameters of a sample in the case when mobile carriers of only one sign (specifically, electrons) exist in a sample. (References to earlier theories of recombination domains can be found in Volkov and Kogan's review.[9]) However, if the frequency of the incident light exceeds the forbidden band width, mobile holes may be generated. We shall show that the presence of holes may increase strongly the velocity of domains and the thickness of their walls even at low illumination levels when the density of electrons in the conduction band is almost equal to the density in darkness. In the absence of holes such a low illumination level would not change the domain parameters. This means that the influence of illumination depends strongly not only on the intensity but also on the frequency of the incident light because holes are formed when the frequency exceeds the forbidden band width.

2. BASIC EQUATIONS AND FORMULATION OF THE PROBLEM

We shall use the following equations, which are written in a coordinate system $z = x - ut$ moving at a velocity u equal to the domain velocity:

$$env_n(E) + eD_n\frac{dn}{dz} - u\rho_n = en_1v_n(E_1) \equiv j_n(E_1), \quad (1)$$

$$u\frac{dn}{dz} + \frac{u}{e}\frac{d\rho_n}{dz} = \frac{n}{\tau_r(E)} - \frac{n_1}{\tau_r(0)} + \frac{1}{e}[\alpha(E)n + g]\rho_n, \quad (2)$$

$$\frac{d}{dz}\left\{p\mu_pE - D_p\frac{dp}{dz} - p_1\mu_pE_1 - u(p-p_1)\right\} = -\nu_p(p-p_1), \quad (3)$$

$$-u\,dN_p/dz = \nu_p(p-p_1), \quad (4)$$

$$\frac{dE}{dz} = \frac{4\pi}{\varepsilon}\rho \equiv \frac{4\pi}{\varepsilon}[e(p-p_1) + e(N_p - N_{p1}) + \rho_n]. \quad (5)$$

Here, $j_n(E)$ is the density of electrons in a homogeneous sample; $v_n(E)$ is the average drift velocity of electrons; E is the electric field; ρ_n is the electron space charge; ρ is the total space charge; $\alpha(E)$ is the electron trapping coefficient of the centers present in a sample; N_0^0 is the concentration of vacant electron-trapping centers in a homogeneous sample; $\tau_r(E) = [\alpha(E)N_0^0]^{-1}$; n and p are the densities of electrons and holes; D_n and D_p are the diffusion coefficients of electrons and holes; ϵ is the permittivity; g is the reciprocal time of liberation of electrons from the trapping centers; μ_p is the mobility of holes; ν_p is the frequency of hole trapping by the centers whose concentration is N_p. The subscript 1 represents the values outside a domain. In the absence of holes, the system (1)–(5) reduces to the standard system of equations employed in the description of recombination domains (see, for example, [7-10]). In deriving Eq. (2) we have assumed that $n \ll N_0^0$ because the trapping is postulated to occur in a compensated semiconductor.

For the sake of simplicity we have derived Eq. (3) on the assumption that the recombination of holes at the trapping centers is a linear process, which is justified if the concentration of the hole-trapping centers is high compared with the density of free holes. We have also assumed that holes and electrons are captured by different centers. The charge in a domain is determined almost completely by the deviation of the concentration of the occupied centers from its equilibrium value (the relevant estimates are given in [7]). Moreover, since oscillations of the electron charge ρ_n are small compared with the value of eN_0^0,[7] it follows that the system (1)–(4) can be solved by iteration if it is assumed that $\rho_n = \rho_n^{(0)} + \rho_n^{(1)}$ and $n = n^{(0)} + n^{(1)}$. In the zeroth approximation we can ignore the displacement current and the diffusion current of electrons in Eq. (1). Then the system (1)–(4) can be rewritten in the form

$$n^{(0)}v_n(E) = n_1v_n(E_1), \quad (6)$$

$$\frac{4\pi u}{\varepsilon e}\rho_n^{(0)}\frac{d\rho_n^{(0)}}{dE} = \frac{n^{(0)}}{\tau_r(E)} - \frac{n_1}{\tau_r(0)}. \quad (7)$$

The charge of holes is ignored in Eqs. (6) and (7) but it will be included in the higher approximations. The exact criteria of the smallness of the hole charge will be derived later.

The solution of Eqs. (6) and (7) is of the form

$$[\rho_n^{(0)}(E)]^2 = \frac{\varepsilon en_1}{2\pi u\tau_r(0)}\int_{E_1}^{E} dE'\left[1 - \frac{j_n(E_1)}{j_n(E')}\right], \quad (8)$$

where

$$j_n(E)=ev_n(E)n_1\tau_r(E)/\tau_r(0).$$

It follows from Eq. (8) that, depending on the sign of u, we can have either high-field or low-field domains. If $u<0$ (this corresponds to the motion of a domain from the cathode to the anode), only the high-field domains can exist, whereas if $u>0$, only the low-field domains can form (Fig. 1). The extremal field E_m in a domain (the maximum field in a high-field domain and the minimum field in a low-field domain) is found from the equal-areas rule for the reciprocal of the current, corresponding to the condition $\rho^2(E_m) = 0$:[7]

$$\int_{E_1}^{E_m} dE\left[\frac{1}{j_n(E_1)}-\frac{1}{j_n(E)}\right]=0. \tag{8a}$$

The velocity of a domain can be determined by solving the system (1)–(5) in the next approximation. The solution (8) is of the same form as the solution which describes a recombination domain in the absence of holes (cf. Eq. (15) in [7]). However, since the value of u in a sample which contains only electrons may differ considerably from the velocity of a domain in the presence of holes, the electron charge oscillations may also be greatly affected (compared with the case of a sample containing electrons only), in spite of the fact that the hole charge is small.

In the first approximation Eqs. (1) and (2) are of the form

$$en^{(1)}v_n(E)=n\rho_n^{(0)}-\frac{4\pi e}{\varepsilon}D_n\rho_n^{(0)}(E)\frac{dn^{(0)}}{dE}, \tag{9}$$

$$\frac{4\pi u}{\varepsilon e}\frac{d}{dE}(\rho_n^{(0)}\rho_n^{(1)})=-\frac{4\pi u}{\varepsilon e}\rho_p\frac{d\rho_n^{(0)}}{dE}+\frac{n^{(1)}}{\tau_r(E)}+\frac{1}{e}\rho_n^{(0)}(\alpha n^{(0)}+g), \tag{10}$$

where $\rho = e(p+N_p-p_1-N_{p1})$ is the hole charge. Eliminating $n^{(1)}$ from Eqs. (9) and (10) and substituting $n^{(0)}$ from Eq. (6), we obtain

$$\frac{4\pi u}{\varepsilon e}\frac{d}{dE}[\rho_n^{(0)}\rho_n^{(1)}]=-\frac{4\pi u}{\varepsilon e}\rho_p\frac{d\rho_n^{(0)}}{dE}+\frac{1}{e}\rho_n^{(0)}(E)\Big[g+\frac{n_1v_n(E_1)}{v_n(E)}\alpha(E)+\frac{u}{v_n(E)\tau_r(E)}+\frac{4\pi uen_1v_n(E_1)}{\varepsilon v_n^2(E)}\frac{dv_n(E)}{dE}+\frac{4\pi eD_nv_n(E_1)n_1}{\varepsilon\tau_r(E)v_n^3(E)}\frac{dv_n(E)}{dE}\Big]. \tag{11}$$

If we integrate Eq. (11) and use Eq. (8), we find that

$$\frac{4\pi u}{\varepsilon e}\rho_n^{(0)}\rho_n^{(1)}=-\frac{4\pi u}{3\varepsilon e^2n_1}\left[\frac{u}{v_n(E_1)}+\frac{n_1}{N_0^0}\right][\rho_n^{(0)}(E)]^3+\frac{1}{e}\int_{E_1}^{E}dE'\rho_n^{(0)}(E')\Big\{\frac{4\pi u}{\varepsilon}\frac{d\rho_p(E')}{dE'}+g+\frac{1}{\tau_r(0)}\left[\frac{n_1}{N_0^0}+\frac{u}{v_n(E_1)}\right]+\frac{4\pi uen_1v_n(E_1)}{\varepsilon v_n^2(E')}\frac{dv_n(E')}{dE'}+\frac{4\pi D_nn_1v_n(E_1)e}{\varepsilon\tau_r(E')v_n^3(E')}\frac{dv_n(E')}{dE'}\Big\}-\frac{4\pi u}{\varepsilon e}\rho_p(E)\rho_n^{(0)}(E). \tag{12}$$

At the point E_m the following relationship should be satisfied to within terms of the first order:

$$\rho^{(0)}(E_m)+\rho^{(1)}(E_m)=0. \tag{12a}$$

Since the function $\rho^{(0)}(E)$ is double-valued, Eq. (12a) represents effectively two conditions because it should be written for both walls of a domain. These two conditions determine the domain velocity and the first-order correction to the maximum field in the domain. However, if $\rho^{(0)}(z)$ is an odd function of z (the origin of coordinates is assumed to lie at the domain peak), as in the case we are considering, and the function $\rho^{(1)}(z)$ is an even function of z, it follows from the two conditions of Eq. (12a) that $\rho^{(1)}(E_m) = 0$ and in the first approximation the maximum field in the domain remains constant. It is evident from Eq. (12) that when ρ_p and $d\rho_p/dE$ are even functions of z, the function $\rho^{(1)}(z)$ is also even. This situation occurs, for example, if ρ_p depends only on E, which is true of all the cases we shall be considering in calculations of the domain velocity. It then follows from Eq. (12a) that $\rho^{(1)}(E_m) = 0$ and Eq. (12) leads to the following integral relationship:

$$\int_{E_1}^{E_m}dE\rho_n^{(0)}(E)\Big\{u+v_n(E_1)\left[\frac{n_1}{N_0^0}+g\tau_r(0)\right]+\frac{4\pi eun_1v_n^2(E_1)}{\varepsilon v_n^2(E)}\frac{dv_n(E)}{dE}\tau_r(0)+\frac{4\pi u}{\varepsilon}\tau_r(0)\frac{d\rho_p(E)}{dE}v_n(E_1)+\frac{4\pi eD_nn_1\tau_r(0)v_n(E_1)}{\varepsilon\tau_r(E)v_n^3(E)}\frac{dv_n(E)}{dE}\Big\}=0. \tag{13}$$

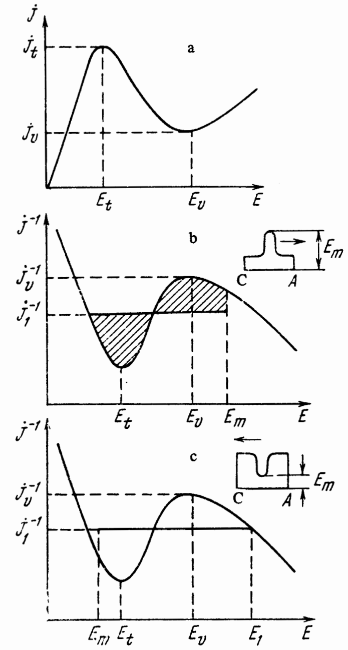

FIG. 1. Equal-areas rule for the reciprocal of the current: a) dependence j(E); b) equal-areas rule for reciprocal currents in the case of high-field domains ($u<0$); c) equal-areas rule for reciprocal currents in the case of low-field domains ($u>0$). The field distributions along a sample with a high-field and a low-field domain are shown schematically on the right in Figs. 1b and 1c. The arrows show the direction of motion of these domains. C is the cathode, A is the anode, and E_m is the extremal field in a domain.

Equation (13) determines the domain velocity. In the absence of holes, Eq. (13) reduces to the expression for the domain velocity derived in [8]. The dependences of the domain velocity and of the amplitude of the electron charge oscillations on the electron density can be obtained in an explicit form if we determine the charge of holes ρ_p from Eqs. (3) and (4).

We shall consider two limiting cases: 1) the case of fast hole trapping when the hole density in a sample is practically equal to the steady-state value p_1; 2) the reverse case when the characteristic times are short compared with ν_p^{-1} and the trapping of holes can be completely ignored.

3. FAST TRAPPING OF HOLES

In this case the total charge of holes ρ_p (the charge of free holes and of those localized at the trapping centers) is

$$\rho_p(E) = \frac{e}{u} p_1 \mu_p (E - E_1). \quad (14)$$

Equation (14) is obtained by adding Eqs. (3) and (4) and making allowance for the fact that $(p - p_1)/p_1 \ll 1$. Substituting Eq. (14) into Eq. (13), we obtain

$$\int_{E_1}^{E_m} dE\, \rho_n^{(0)}(E) \Big\{ u + v_n(E_1) \Big[\frac{n_1}{N_0^0} + \tau_r(0) g + \frac{4\pi e n_1 v_n(E_1)}{\varepsilon v_n^2(E)} \frac{dv_n(E)}{dE} \tau_r(0) + \frac{4\pi}{\varepsilon} e p_1 \mu_p \tau_r(0) \Big] + \frac{4\pi e D_n n_1 \tau_r(0) v_n(E_1)}{\varepsilon \tau_r(E) v_n^3(E)} \frac{dv_n(E)}{dE} \Big\} = 0. \quad (15)$$

We shall now consider in more detail the limiting case when the diffusion of electrons can be ignored and we can use the lowest approximation in respect of n_1/N_0^0 (the contribution of the omitted terms to the domain velocity is discussed in [8]). Then, the domain velocity can be written in the explicit form:

$$u = -v_n(E_1) \Big[\frac{n_1}{N_0^0} + \tau_r(0) \Big(g + \frac{4\pi e}{\varepsilon} p_1 \mu_p \Big) \Big]. \quad (16)$$

It follows from Eq. (16) that the presence of holes accelerates the motion of a domain. If the hole density is sufficiently high, the domain velocity becomes

$$u = -\frac{4\pi e}{\varepsilon} \mu_p p_1 v_n(E_1) \tau_r(0) \equiv -v_n(E_1) \frac{\tau_r(0)}{\tau_{mp}}, \quad (17)$$

where τ_{mp} is the Maxwellian (dielectric) relaxation time of holes.

If we substitute Eq. (17) into Eq. (8), we obtain the field dependence of the electron charge in the limiting case under consideration:

$$\rho^2(E) = \frac{\varepsilon^2 n_1}{8\pi^2 p_1 \mu_p v_n(E_1) \tau_r^2(0)} \int_{E_1}^{E} dE' \Big[\frac{j_n(E_1)}{j_n(E')} - 1 \Big]. \quad (18)$$

An estimate of the upper bound of the integral in Eq. (18) gives

$$\rho_{max}^2 < \varepsilon^2 n_1 E_v / 8\pi^2 p_1 \mu_p \mu_n E_1 \tau_r^2(0), \quad (19)$$

where μ_n is the weak-field mobility of electrons and E_V is the "valley field" which corresponds to the minimum in the current-voltage characteristic (Fig. 1).

If we use the estimate given by Eq. (19), we can derive the criteria of validity of our approximation. First of all, we find that the fast trapping approximation is valid if the inequality $(p - p_1)/p_1 \ll 1$ is satisfied, which is equivalent to the condition

$$4\pi\rho\mu_p / \varepsilon\nu_p \ll 1. \quad (20)$$

Substituting the estimate of ρ from Eq. (18) into Eq. (20), we obtain

$$\nu_p \tau_r(0) \sqrt{\Big| \frac{u}{u_0} \Big|} \gg \sqrt{\frac{8\pi e \mu_1{}^2 E_v}{\varepsilon \alpha(0) \mu_n E_1}}, \quad (21)$$

where $u_0 = n_1 v_n(E_1)/N_0^0$.

Next, substituting Eq. (17) into Eq. (21), we obtain

$$p_1 / n_1 \gg 2\mu_p E_v / \mu_n E_1 [\nu_p \tau_r(0)]^2 \quad (22)$$

or

$$\nu_p \tau_r(0) \gg (2\mu_p E_v n_1 / \mu_n E_1 p_1)^{1/2}. \quad (23)$$

In deriving Eqs. (18)–(23) we have assumed that Eq. (17) is valid and, as is evident from Eq. (16), this is true if

$$p_1 / n_1 \gg \varepsilon\alpha(0) / 4\pi e \mu_p \quad (24)$$

[the inequality (22) applies to the case when $\alpha n \gtrsim g$, which corresponds to $N_0^0 \lesssim N_0^-$].

The second criterion of the validity of our approximation follows from the fact that the hole charge should be small compared with the electron charge. It follows from Eqs. (8) and (14) that

$$\frac{2\pi e p_1^2}{\varepsilon u n_1} \mu_p^2 \tau_r(0) E_v \ll 1. \quad (25)$$

If the hole density p_1 is sufficiently high [see Eq. (24)], so that the velocity u is given by Eq. (17), it follows from Eq. (25) that

$$\mu_p p_1 E_v / 2\mu_n n_1 E_1 \ll 1. \quad (26)$$

Moreover, we have assumed that the displacement current is small compared with the conduction current. The relevant criterion can be obtained from Eqs. (6) and (8):

$$\varepsilon u E_v / 2\pi e n_1 \tau_r(0) \mu_n^2 E_1^2 \ll 1. \quad (27)$$

If the hole density is sufficiently high so that u is given by Eq. (17), we find that the inequality (27) becomes identical with the inequality (26).

It follows from our criteria that the range of values of the ratio p_1/p_n in which our theory is valid and the domain velocity is given by Eq. (17) lies within the limits

$$\max\Big(\frac{2\mu_p E_v}{\mu_n E_1 [\nu_p \tau_r(0)]^2}, \frac{\varepsilon\alpha(0)}{4\pi e \mu_p} \Big) \ll \frac{p_1}{n_1} \ll \frac{2\mu_n E_1}{\mu_p E_v}. \quad (28)$$

The conditions for the existence of this range are of the form:

$$\nu_p^{-1} \ll \tau_r(0) \mu_n E_1 / \mu_p E_v, \quad (29)$$

$$\varepsilon\alpha(0) E_v / 4\pi e \mu_n E_1 \ll 1. \quad (30)$$

The inequality (28) is identical with the criterion of validity of our theory even in the absence of holes and this criterion has a large "safety' margin" (see [7]). If we consider GaAs and assume that $\mu_p \sim 400\ cm^2 \cdot V^{-1} \cdot sec^{-1}$, $\mu_n \sim 8000\ cm^2 \cdot V^{-1} \cdot sec^{-1}$, $E_1 \sim 200$ V/cm, $E_V \sim 10^4$ V/cm, $\epsilon = 12.5$, $\alpha(0) \sim 5 \times 10^{-10}\ cm^3/sec$, we find that Eq. (28) yields $10^{-5} \ll p_1/n_1 \ll 0.8$. It is evident from this estimate that even when the hole density is low compared with the electron density, the domain velocity, the charge distribution in a domain, and its dimensions may change considerably.

The hole trapping frequency ν_p can vary considerably from one sample to another. Therefore, we shall estimate the value of ν_p^{-1} at which the fast-trapping approximation is valid and we shall do this on the basis of the criterion (29). In the case of GaAs with the parameters given in the preceding paragraph we find that $\nu_p^{-1} \ll 10^{-6}$ sec if $\tau_r(0) = (\alpha N_0^0)^{-1} = 2 \times 10^{-6}$ sec. We note that this criterion is necessary but not sufficient. It becomes more stringent when the ratio p_1/p_n is reduced. It follows from this estimate that the fast-trapping approximation can be used for compensated GaAs with a large safety margin. We also note that the qualitative conclusion of increase in the domain velocity in the presence of mobile holes applies also to the opposite limiting case when $\nu_p \to 0$ (this will be shown in Sec. 4).

4. SLOW TRAPPING OF HOLES

In this case the contribution of the charge localized at the centers can be ignored. It follows from Eq. (3) that

$$\rho_p = e(p - p_1) = \frac{\varepsilon p_1 \mu_p}{4\pi D_p} \int_{E_1}^{E} \frac{dE'(E' - E_1)}{\rho_n^{(0)}(E')} \times \exp\left[\frac{\varepsilon}{4\pi D_p} \int_{E'}^{E} \frac{dE''(\mu_p E'' - u)}{\rho_n^{(0)}(E'')}\right]. \quad (31)$$

Substituting Eq. (31) into Eq. (12a), we obtain integral conditions which determine the domain velocity and the correction to the maximum field in a domain in the case when there is no hole trapping. The expressions which are obtained in this way represent, in principle, the solution of the problem but they are far too cumbersome for practical applications. Therefore, we shall consider the case of weak diffusion of electrons and holes, which is closest to the experimental situation. The diffusion of holes can be ignored if the argument of the exponential function is large. Later, when we determine the domain velocity, we shall give the relevant criterion in its explicit form. If we ignore the diffusion, the hole charge is

$$\rho_p = e(p - p_1) = \frac{e\mu_p(E - E_1)}{u - \mu_p E} p_1. \quad (32)$$

Substituting this expression into Eq. (13), including the diffusion of electrons, and retaining only the terms which are lowest in n, we obtain

$$1 + \frac{v_n(E_1)}{u}\left[\frac{n_1}{N_0^0} + g\tau_r(0)\right] = F(u), \quad (33)$$

where

$$F(u) = \frac{4\pi}{\varepsilon} e p_1 \mu_p \tau_r(0)(\mu_p E_1 - u) \int_{E_1}^{E_m} dE \rho_n^{(0)}(E)(u - \mu_p E)^{-2} \times \left\{\int_{E_1}^{E_m} dE \rho_n^{(0)}(E)\right\}^{-1}.$$

Figure 2 shows the qualitative dependence F(u). The left-hand side of Eq. (33) is a hyperbola. It follows from the nature of the dependence F(u) that there is always one root $u < 0$ and, if the hole density is sufficiently high, there may be two roots $u > 0$. However, we shall not consider the positive roots because we must have $u < 0$ in order to ensure that $[\rho_n^{(0)}]^2$ in Eq. (8) is positive for high-field domain. As mentioned earlier, the

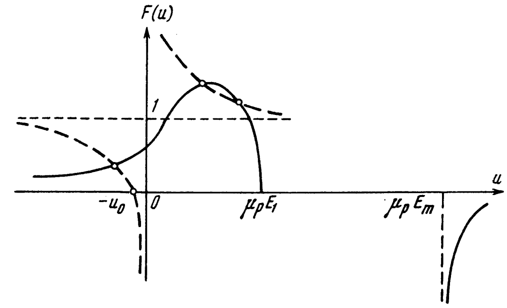

FIG. 2. Graphical determination of the domain velocity u. The continuous curves represent the dependence F(u), the dashed curves represent the two branches of the hyperbola corresponding to the left-hand side of Eq. (33), and $-u_0$ is the domain velocity in the absence of holes when F(u) = 0.

roots $u > 0$ apply only to low-field domains (Fig. 1). It is evident from Fig. 2 that holes accelerate the motion of a domain. The expression for u can be found explicitly from Eq. (33) in three limiting cases which, taken together, cover the full range of possible values of u: $|u| \ll \mu_p E_1$, $\mu_p E_1 \ll |u| \ll \mu_p E_m$, and $|u| \gg \mu_p E_m$. We shall give the formulas for u only for the two extreme cases. In the $|u| \ll \mu_p E_1$ case, which is probably closest to the experimental situation, we obtain

$$u = -v_n(E_1)\left[\frac{n_1}{N_0^0} + g\tau_r(0)\right]^{-1} [1 - F(0)]^{-1}. \quad (34)$$

Since in this case $F(0) < 1$, it follows from Eq. (34) that the holes accelerate the motion of a domain. Equation (34) remains valid up to hole densities such that $1 - F(0)$ becomes so small that $|u|$ becomes comparable with $\mu_p E_1$.

The opposite limiting case $|u| \gg \mu_p E_m$ is interesting because the domain velocity

$$u = -\frac{4\pi e}{\varepsilon} \mu_p p_1 \tau_r(0) v_n(E_1) \equiv -v_n(E_1)\frac{\tau_r(0)}{\tau_{mp}} \quad (35)$$

is identical with Eq. (17), which gives the domain velocity in the case of fast trapping of holes. It follows that the domain velocity is independent of the trapping kinetics provided the hole density is sufficiently high (this is also true in the absence of holes).

We shall now consider the criterion of validity of our theory in the case of slow hole trapping. To be specific, we shall restrict our discussion to the case when $|u| \ll \mu_p E_m$. In this case the conditions of slow trapping, weak displacement current, small hole charge, and weak diffusion of holes lead to the following inequalities:

$$\nu_p \tau_r(0) \sqrt{\left|\frac{u}{u_0}\right|} \ll \sqrt{\frac{8\pi e \mu_p^2 E_v}{\varepsilon \alpha(0) \mu_n E_1}}, \quad (36a)$$

$$\left|\frac{u}{u_0}\right| \ll \frac{2\pi e \mu_n E_1}{\varepsilon \alpha(0) E_v}, \quad (36b)$$

$$\left|\frac{u}{u_0}\right| \ll \frac{\varepsilon \alpha(0) E_v}{2\pi e \mu_n E_1}\left(\frac{N_0^0}{p_1}\right)^2, \quad (36c)$$

$$\left|\frac{u}{u_0}\right| \gg \frac{8\pi T^2 (N_0^0)^2 \alpha(0)}{\varepsilon E_v^3 E_1 e \mu_n}. \quad (36d)$$

Here, $T = eD_p/\mu_p$ is the lattice temperature.

The inequality (36a) is the reverse of the inequality (20a) (see Sec. 3). The quantity on the right-hand side of the inequality (36b) is large ($\sim 2.5 \times 10^4$ for GaAs, as derived from the parameters given in Sec. 3). Therefore, this criterion is not "stringent." Since, under experimental conditions, the ratio N_0^0/p_1 is very large (it may be much larger than 10^3), the criterion (36c) is also not "stringent." At $T \sim 300°K$ the left-hand side of the inequality (36d) represents 10^{-7} for the numerical values of the parameters given in Sec. 3, i.e., once again the inequality is satisfied by a large margin. Thus, the most "stringent" is the criterion (36a). It is this criterion that determines which of the approximations (the approximation of slow or fast hole trapping) corresponds to the experimental situation.

5. CONCLUSIONS

It is demonstrated in Secs. 3 and 4 that mobile holes increase the velocity of recombination domains in the case of fast hole trapping and in the absence of such trapping. It is interesting to compare this conclusion with the results given in [11], which show that holes may increase considerably the velocity of Gunn domains and may also give rise to Gunn domains traveling rapidly in the opposite direction (from the anode to the cathode).[1)]

We note also that the results derived in the present paper apply also to the Gunn effect in compensated semiconductors. In fact, it follows from Eq. (18) that the sufficient condition for the appearance of a domain is the presence of a falling region in the field dependence of the electron current density $j_n(E)$. Under the Gunn effect conditions such a falling region may appear as a result of the dependence of the drift velocity on the field, $v_n(E)$, even if the electron trapping is independent of the field. This situation is a special case of the problem considered in the present paper and all the results derived here apply to this case. We are grateful to R. F. Kazarinov and R. A. Suris for drawing our attention to this point. We are also grateful to A. F. Volkov for a detailed discussion of the method used in the solution of the initial system of equations.

[1)]We have considered only the case of weak diffusion electrons because this case corresponds to the experimental situation.[5,7] It is interesting to point out that in the opposite case of strong diffusion of electrons, which can hardly be realized for reasons discussed in detail in[7], there are also solutions corresponding to domains traveling from the cathode to the anode if the hole density is high, corresponding to the limit when $|u| \gg \mu_p E_m$.

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