Calculation of the dependence of the space charge field on physical parameters for photorefractive semiconductor multiple quantum wells

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ABSTRACT. We solved the material equations for photorefractive gratings in semiconductor multiple quantum wells (MQW), in the steady state, including the effect of an applied electric field parallel to the layer planes. We calculated the dependence of the space charge field on the relevant physical parameters. Finally, we offer some optimization guidelines.

RESUMEN. Resolvimos las ecuaciones del material para enrejados fotorrefractivos en pozos cuánticos múltiples semiconductores, en el estado estacionario, incluyendo la presencia de un campo eléctrico aplicado paralelamente a las capas del material. Calculamos la dependencia del campo de carga espacial en los parámetros físicos relevantes. Finalmente, hacemos algunas sugerencias para la optimización de estos sistemas fotorrefractivos.

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The photo refractive effect has many potential applications to photonics, [1–3]. Most work has been performed on electro optic oxides (*e.g.*, $LiNbO_3$) and to a lesser extent on bulk semiconductors [4]. Recently, some experiments were carried out on semi insulating semiconductor multiple quantum wells (MQW) [5–11]. They seem very promising because of their high expected (second order) electro optic coefficients and short response times ($\sim \mu$s).

In this paper the material equations are solved for the steady state (taking into account an applied electric field parallel to the layer planes), following the approach given in Ref. [12] for a bulk semiconductor and without recoursing to the simplifications involved in other previous approaches [7,13]. In this way, a general expression for the space charge field is obtained. From this, we exhibit the dependence of the space charge field on the relevant physical parameters, *i.e.*, applied field, grating spacing, trap density and carrier mobilities. Finally, we suggest some general guidelines for optimization of the system.

The geometrical arrangement is taken as follows: the layer planes of the MQW are perpendicular to the Z axis and the light interference pattern is

$$I = I_0[1 + m\cos(kx)]\exp(-\alpha z), \tag{1}$$

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along the x-axis. The modulation depth is m, and $k = 2\pi\Lambda$, Λ being the fringe spacing. Light attenuation is taken into account through the absorption coefficient α. The external electric field is also applied along x.

Following previous works [7,13], we simulate the structure of the MQW by a strongly anisotropic homogeneous semiconductor with much higher parallel than perpendicular mobilities. In this way, we neglect the perpendicular motion of the carriers. On the other hand, the parallel transport involves both electrons and holes. In a photorefractive experiment, photons with energy above the band gap of the wells generate electrons and holes, whose relaxation to the discrete levels in the wells is much faster than the recombination and transport processes. In order to simplify the analysis only one electron and one hole level will be considered. Deep trap concentrations, N^+ for electrons and $(N - N^+)$ for holes are introduced to simulate the semi insulating character of the structure.

We have, then, the following material rate equations:

$$\frac{\partial n_\mathrm{e}}{\partial t} = bI - \gamma n_\mathrm{e} N^+ + \frac{1}{e}\frac{\partial j_\mathrm{e}}{\partial x}, \tag{2}$$

$$\frac{\partial n_\mathrm{h}}{\partial t} = bI - \gamma n_\mathrm{h}(N - N^+) - \frac{1}{e}\frac{\partial j_\mathrm{h}}{\partial x}, \tag{3}$$

$$\frac{\partial N^+}{\partial t} = \gamma n_\mathrm{h}[(N - N^+) - n_\mathrm{e} N^+], \tag{4}$$

$$j_\mathrm{e} = e\mu_\mathrm{e} n_\mathrm{e}(E_\mathrm{a} + E_1) + k_\mathrm{B} T \mu_\mathrm{e}\frac{\partial n_\mathrm{e}}{\partial x}, \tag{5}$$

$$j_\mathrm{h} = e\mu_\mathrm{h} n_\mathrm{h}(E_\mathrm{a} + E_D) - k_\mathrm{B} T \mu_\mathrm{h}\frac{\partial n}{\partial x}, \tag{6}$$

$$\frac{\partial E}{\partial x} = \frac{e}{\epsilon}[N^+ + n_\mathrm{h} - n_\mathrm{e} - N_\mathrm{A}^-], \tag{7}$$

where N is the total concentration of traps, N^+ the concentration of electron acceptors at any instant, and n_e and n_h are the electron and hole concentrations respectively. N_A^- is the initial concentration of acceptors (which we arbitrarily take as $N/2$). The electron and hole currents are represented by j_e and j_h respectively. The applied electric field is E_a, and E_1 the space charge field. The average dielectric constant for the MQW is ϵ, and γ refers to an appropriate trapping coefficient (which we are assuming as equal for electrons and holes); the électron-hole photogeneration is b. The temperature is T and k_B is the Boltzmann's constant. The initial condition ($t = 0$) for the traps is $N^+(0) = N_\mathrm{A}^- = N/2$.

Under steady-state conditions,

$$\frac{\partial n_\mathrm{e}}{\partial t} = \frac{\partial n_\mathrm{h}}{\partial t} = \frac{\partial N^+}{\partial t} = 0. \tag{8}$$

For the solutions of Eqs. (2), (3), (4), (5), (6) y (7), in the stationary state [Eqs. (8)], can be written as:

$$n_\mathrm{e} = n_{\mathrm{e}\,0} + n_{\mathrm{e}\,1}\exp(ikx), \tag{9}$$

$$n_{\mathrm{h}} = n_{\mathrm{h}\,0} + n_{\mathrm{h}\,1} \exp(ikx), \tag{10}$$

$$N^+ = N_0^+ + N_1^+ \exp(ikx), \tag{11}$$

$$j_{\mathrm{e}} = j_{\mathrm{e}\,0} + j_{\mathrm{e}\,1} \exp(ikx), \tag{12}$$

$$j_{\mathrm{h}} = j_{\mathrm{h}\,0} + j_{\mathrm{h}\,1} \exp(ikx), \tag{13}$$

$$E = E_{\mathrm{a}} + E_1 \exp(ikx), \tag{14}$$

where the corresponding average quantities are given by $n_{\mathrm{e}\,0}$, $n_{\mathrm{h}\,0}$, N_0^+, $j_{\mathrm{e}\,0}$, $j_{\mathrm{h}\,0}$, and E_{a}, and the factors of the exponentials may have a real and an imaginary part. In this way it is clear that the solutions may present arbitrary phase shifts with regard to the intensity pattern. The space charge field, after some manipulation, results

$$E_1 = 2m \, \frac{A - iB}{C + iD}, \tag{15}$$

where

$$A = E_{\mathrm{D}}(E_{\mathrm{Mh}} - E_{\mathrm{Me}}), \qquad B = E_{\mathrm{a}}(E_{\mathrm{Mh}} + E_{\mathrm{Me}}),$$

$$C = \frac{E_{\mathrm{a}}}{E_{\mathrm{q}}}(E_{\mathrm{Mh}} - E_{\mathrm{Me}}), \tag{16}$$

$$D = \left[E_{\mathrm{D}}^2 + E_{\mathrm{a}}^2 + E_{\mathrm{D}}(E_{\mathrm{Mh}} + E_{\mathrm{Me}}) + 2E_{\mathrm{q}}(E_{\mathrm{Mh}} + E_{\mathrm{Me}} + E_{\mathrm{D}})\right] / E_{\mathrm{q}} \tag{17}$$

and

$$\begin{aligned} E_{\mathrm{Me}} &= \frac{\gamma N}{4\mu_{\mathrm{e}} k}; \qquad E_{\mathrm{Mh}} = \frac{\gamma N}{4\mu_{\mathrm{h}} k}, \\ E_{\mathrm{q}} &= \frac{eN}{4k\epsilon}; \qquad E_{\mathrm{D}} = \frac{k_{\mathrm{B}} T}{e}\, k. \end{aligned} \tag{18}$$

Equation (15) is a general solution for the space charge field, which corresponds to the one given by Mainguet *et al.* [12]. It is straightforward to show that if $k \to 0$, *i. e.*, when diffusion is negligible, $E_1 = mE_{\mathrm{a}}$.

If the value of E_{q} is very large compared with the other characteristic fields, one obtains that

$$E_1 = -\frac{m\left[E_{\mathrm{a}}(E_{\mathrm{Mh}} + E_{\mathrm{Me}}) + iE_{\mathrm{D}}(E_{\mathrm{Mh}} - E_{\mathrm{Me}})\right]}{E_{\mathrm{Me}} + E_{\mathrm{Mh}} + E_{\mathrm{D}}}, \tag{19}$$

which is the expression given in Ref. [7], when the recombination times are the same for electrons and holes. Since the condition $E_{\mathrm{q}} \to \infty$ is well achieved in practice when $k \to 0$, Eq. (19) is expected to be adequate for large grating spacings and will certainly fail for

TABLE I. Parameters used in this work for a GaAs-$Al_{0.3}Ga_{0.7}$ AS MQW.

$\mu_e = 5000$ cm^2/V s	Electro optic coefficient $s = 2.0 \times 10^{-12}$ cm^2/V^2
$\mu_h = 300$ cm^2/V s	Writing wavelength = 630 nm
Average refractive index, $n_r = 3.5$	Reading wavelength = 825 nm
Carrier life time, $\tau = 0.2$ ns	Reading incidence angle = 10°
MQW thikness $L = 1.0$ μm	Modulation coefficient: $m \approx 1.0$

small Λ, where E_q may become comparable to E_a and E_D. Consequently, it will be not either valid for high enough applied fields.

On the other hand, the space charge field in Ref. [13] was obtained after neglecting the recombination, γN_D, versus the transport, Dk^2 and μkE, terms *in the material equations.* Under these conditions Eq. (15) reduces to

$$E_1 = M\left(\frac{1}{\mu_h} + \frac{1}{\mu_e}\right) + iQ\left(\frac{1}{\mu_h} - \frac{1}{\mu_e}\right), \tag{20}$$

where

$$M = \frac{meNE_a}{(4\tau\epsilon)F(E_a^2 + E_d^2)}; \qquad Q = \frac{meNE_D}{(4\tau\epsilon)F(E_a^2 + E_D^2)}$$

and

$$F = -\frac{k^2 + \epsilon ekNE_D}{E_a^2 + E_D^2}, \qquad \tau = \frac{2}{\gamma N}.$$

Note that the corresponding equation in Ref. [13] was erroneous. Moreover, in that reference the appearance of a perpendicular (to the MQW planes) space charge field is predicted in the steady state, prediction which is also erroneous.

The approximation involved in Eq. (20) will not appropriate for $k \to 0$, *i.e.*, for large Λ. However, for small Λ the validity of this equation is assured whatever the applied field.

In summary, the simplifying approximations used in Refs. [7] and [13] are complementary and valid in the $k \to 0$ and $k \to \infty$ ranges respectively.

In order to determine the role of the various physical parameters and compare to experimental data, our results will be applied to an GaAs/GaAlAs MQW, as used in Refs. [1–9]. In this section we will consider the space-charge fields that are directly obtained from the material equation. Although the measured quantities are the diffraction efficiencies, the space-charge field is sufficiently representative to discuss the role of the physical parameters. The values of all material and geometrical parameters used in the simulation are summarized in Table I.

Figure 1 shows the dependence of the space charge field amplitude on applied electric field for a grating spacing $\Lambda = 2.4$ μm. A rapidly increasing E_1 with applied field up to a saturation value followed by a slower decrease is predicted. This behaviour is in good agreement with experiment (the decreasing part of the curve has not been experimentally observed, although physically it is expected). The dependence derived from the approximate approach of Ref. [7] has been also included in the figure. The expression given in

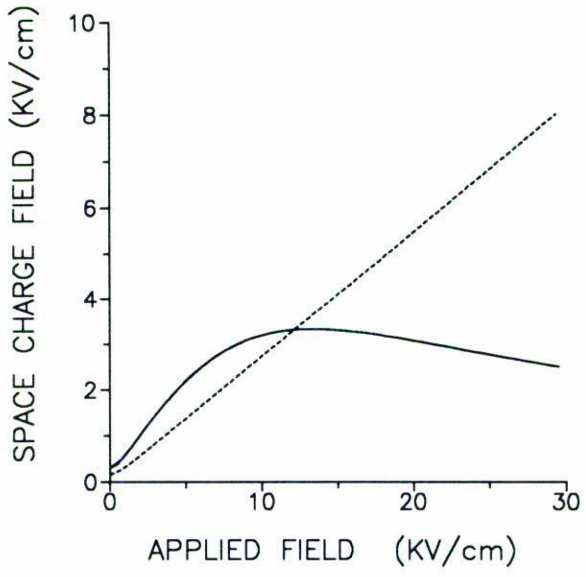

FIGURE 1. Dependence of the space charge field amplitude on the applied field with experimental parameters as given in Table I (with $\Lambda = 2.4$ μm, $N = 10^{17}$ cm^{-3}). Present work and Ref. [13]: are coincident and given by —; Ref [7]: - -.

Ref. [13] coincides with our present work. On the other hand, the calculations developed in Ref. [7] predict a linear dependence of E_1 with E_a, which is not supported by experiment.

The dependence of the space-charge field amplitude on the grating spacing is plotted in Fig. 2 for an applied field of 5 kV/cm. The amplitude increases with Λ and reaches a steady value at $\Lambda \geq 20$ μm. This behaviour is in accordance with experiment [7] and is also well accounted by the approach used in the same reference. On the other hand, the expression derived in Ref. [13] yields a dependence that coincides with the present model only for $\Lambda \leq 3$ μm.

Figure 3 shows the dependence of the space-charge field amplitude on the trap concentration. The amplitude increases with concentration from 10^{16} cm^{-3} and reaches saturation for 10^{19} cm^{-3}. Unfortunately, no experimental data are available.

The influence of the hole mobility on the space charge field derived from Eq. (15) is illustrated in Fig. 4. In this figure physical parameters are as given in Table I and the electron mobility is kept fixed at a value of $\mu_e = 5000$ cm^2/V s; $\Lambda = 2.4$ μm, $E_a =$ 5 KV/cm. The maximum possible value for the space charge field corresponds to $\mu_h \to 0$ and is

$$E_1 = \frac{2m(E_D - iE_a)}{E_a + i(E_D + 2E_q}.$$

It becomes, then, independent of the electron mobility. The same behaviour represented by Fig. 4 is obtained by keeping μ_h constant and changing μ_e.

Finally, one may ask about the parameters of the material that optimize the space-charge field in an MQW. It can be seen, form Figs. 2 and 3 that we can obtain the trap

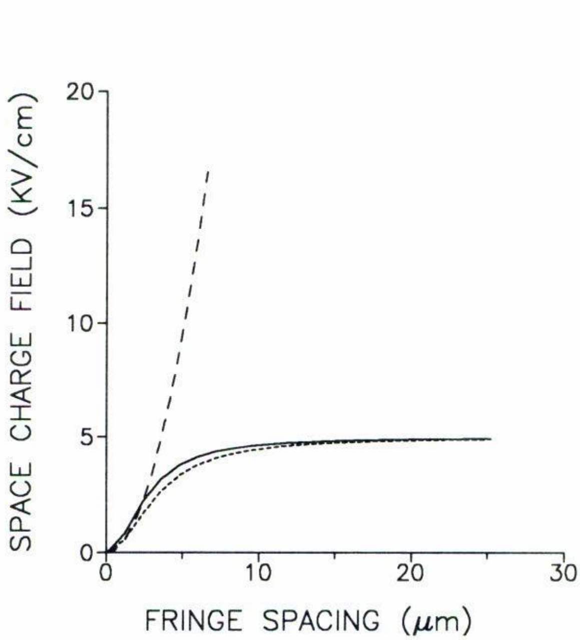

FIGURE 2. Dependence of the space charge field amplitude on the grating spacing (with E_a = 5.0 KV/cm, $N = 10^{17}$ cm^{-3}). Present work: —; Ref. [13]: - - - ; Ref. [7]: – – –. Experimental parameters are as given in Table I.

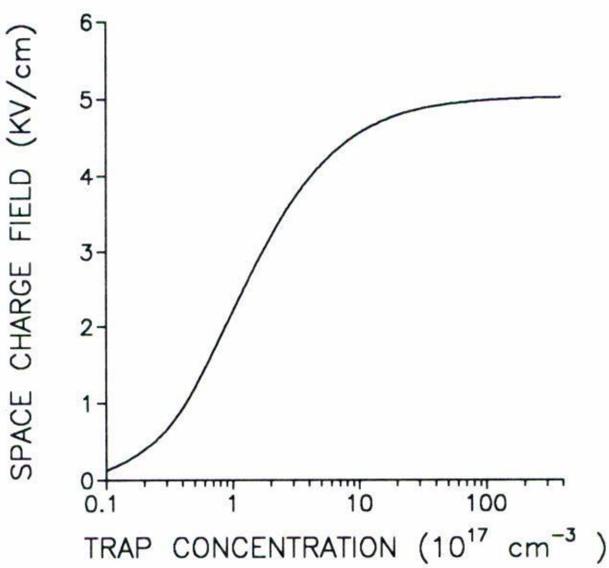

FIGURE 3. Dependence of the amplitude of the space charge field on trap concentration (E_a = 5.0 KV/cm, $\Lambda = 2.4$ μm). Experimental parameters as in Table I.

concentration ($N \sim 5 \times 10^{19}$ cm^{-3}) and grating spacings ($\Lambda \sim 12$ μm) that maximize the amplitude. However, one may also play with the carrier mobilities to enhance the photorefractive response, as illustrated in Fig. 4. It is clear that E_1 increases rapidly on decreasing μ_h and μ_e and reaches the maximum value $E_1 = mE_a$ for either $\mu_h = 0$ or

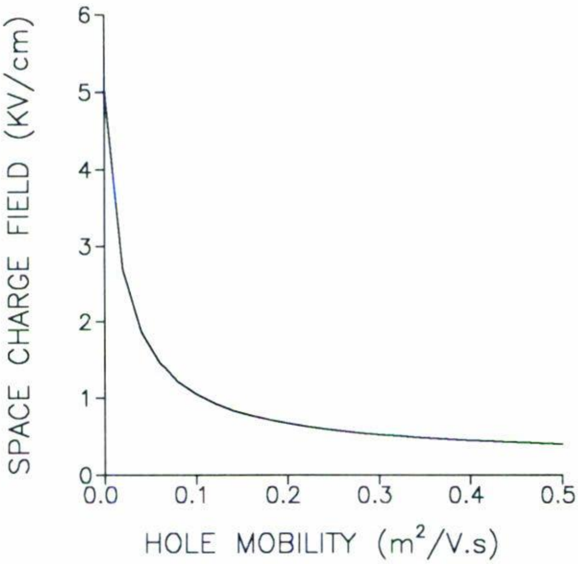

FIGURE 4. Influence of hole mobility on the amplitude of the space charge field ($E_a = 5.0$ KV/cm, $N = 10^{17}$ cm^{-3}, $\Lambda = 2.4$ μm). Experimental parameters as in Table I.

$\mu_e = 0$. This favors low mobility materials, and this may imply a longer response time. However, we could have the situation where one of the carriers has zero mobility and the other one has a high mobility, in this case, the response time would not be very high and still we would have the maximum value for E_1.

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