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Submitted on 24 Feb 2012

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Continuous-wave two-beam coupling in InP:Fe and GaAs: evidence for thermal hole–electron competition in InP:Fe

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Received May 4, 1990; accepted July 24, 1990

We show that even if there is no direct hole–electron competition in InP:Fe the gain is lower than expected. We attribute this reduction of the gain to a thermally induced hole–electron competition that involves the excited state of Fe²⁺ (*T₂*). We present a new model for the photorefractive effect in InP:Fe, which we use to interpret our beam-coupling results. Some material parameters of the InP:Fe sample and particularly of the excited state are deduced. The same energy-transfer measurements conducted in GaAs give us the ratio of hole and electron photoionization cross sections.

INTRODUCTION

In a large number of semi-insulating materials, such as sillenites, ferroelectrics, and III-V semiconductors,¹ the photorefractive effect has now been identified and studied. In general, it can be well described by a model with a single active center with one or two types of charge carrier (holes or electrons). However, in semi-insulators, for example BaTiO₃ and Bi₁₂SiO₃₀, discrepancies between theory and experimental results lead to the inclusion of secondary centers or shallow traps in models in order to increase the agreement with experiment and to be able to explain some peculiarities.²⁻⁶ Semiconductors, in particular InP, are extremely pure compared with other materials. Thus secondary centers are not important, but, as will be shown, the Fe²⁺ excited state of iron-doped InP plays an important role in the photorefractive effect. Its introduction into the model leads to a reduction of the photorefractive gain.

We conducted cw energy transfer experiments by two-wave mixing in InP:Fe and GaAs:EL₂ crystals. For these experiments we used a diode-pumped cw Nd:YAG laser (emitting at \( \lambda = 1.06 \mu m \)). The grating wave number \( k \) was directed along the (001) axis of the crystal, and the two beams were linearly polarized in the (110) direction. The results in the iron-doped InP crystal are incompatible with those predicted by the current theoretical beam-coupling model and the known parameters for our crystal. Being aware of the importance of the excited state (*T₂*) of Fe³⁺ in other experiments, such as nanosecond induced absorption,⁷ we have introduced this excited state (called Fe³⁺⁺ below) into the current band-transport model. The result is a new type of hole–electron competition. Thermal emission into the conduction band empties all electrons that are excited into the Fe³⁺⁺ level. The effect can be called thermally induced hole–electron competition. As a consequence, we obtain a new expression for the space-charge field and the photorefractive gain. Good agreement is found when the experimental results and the gain deduced from the new expression are compared, and the determination of the concentration of Fe³⁺ is in accord with the one determined by electron paramagnetic resonance measurements. Finally, we present beam-coupling results for a sample of GaAs:EL₂ and deduce the photoionization cross section of holes and the concentrations of EL₂ and EL₂⁺ of the crystal.

INFLUENCE OF Fe²⁺⁺ ON THE PHOTOREFRACTIVE EFFECT

The current model for the photorefractive effect in semiconductors takes into consideration a single active center that is coupled with both conduction and valence bands.⁸⁻⁹ The resultant hole–electron competition induces a reduction of the photorefractive gain compared with that which would be obtained with a single type of carrier. We conducted two-wave mixing experiments on an InP:Fe sample grown at the Centre National d'Études des Télécommunications (CNET), Lannion, for which the electron contribution should be negligible. In a sample from the same boule, electron paramagnetic resonance and secondary ion mass spectroscopy measurements gave an Fe³⁺ density of \([\text{Fe}^3^+] = 8 \times 10^{16} \text{ cm}^{-3}\) and a total iron density of \([\text{Fe}] = 7 \times 10^{16} \text{ cm}^{-3}\). With the accuracy of these measurements we can estimate the upper limit of Fe³⁺ density to be \([\text{Fe}^{3^+}] \leq 10^{16} \text{ cm}^{-3}\). A similar Fe³⁺ concentration was obtained in our sample in a cross measurement.¹¹ The photoionization cross sections for holes (\(S_h\)) and electrons (\(S_e\)) are \(S_h = 5 \times 10^{-17} \text{ cm}^2\) and \(S_e \leq S_p\).¹² If we now split the total absorption into an electron (\(\alpha_e\)) and a hole (\(\alpha_p\)) contribution, we obtain \(\alpha_e = S_e[\text{Fe}^{3^+}] \leftrightarrow \alpha_p = S_p[\text{Fe}^{2^+}]\). This implies that the hole–electron competition is negligible. The photorefractive gain in our sample should be as high as that calculated for a single type of carrier. To our surprise, the measured photorefractive gain is much smaller than expected (Fig. 1, curves A and B).

Photoluminescence,¹³ deep-level optical spectroscopy, and deep-level transient spectroscopy¹⁴,¹⁵ have shown that Fe²⁺ exists in two states, the \(^2E\) ground and the \(^2T_2\) excited states. The latter is located 0.35 eV above the \(^2E\)
EXPRESSION OF THE SPACE-CHARGE FIELD

To establish the expression of the photorefractive gain, we extended Kukhtarev's model, considering both photogeneration and thermal emission of electrons and holes from Fe$^{2+}$, Fe$^{3+}$, and Fe$^{4+}$. In the following $N_T$ represents the total iron density, $N$ corresponds to [Fe$^{2+}$], $N^*$ to [Fe$^{4+}$], and $N_T - N - N^*$ to [Fe$^{3+}$]. The electron and hole current densities are $j_n$ and $j_p$, and the free hole and electron densities are $p$ and $n$. $E$ is the electric field inside the crystal. The material equations are

$$\frac{\partial N}{\partial t} = \left( \beta_n + S_nI \right) \left( N_T - N - N^* \right) - \gamma_n n N$$
$$+ (\beta_n^* + S_n^* I) N^* - \gamma_n^* n N - (\beta_p + S_p I) N + \gamma_p n(N_T - N - N^*) - (\beta_p^* + S_p^* I) N + \gamma_p^* n N,$$

the current density equations,

$$j_n = e n u_E + \mu_n k_BT \nabla n,$$
$$j_p = e p u_E - \mu_p k_BT \nabla p;$$

div the continuity equations,

$$\frac{\partial n}{\partial t} = \text{div}(j_n / e) + (\beta_n + S_n I) (N_T - N - N^*) - \gamma_n n N$$
$$+ (\beta_n^* + S_n^* I) N^* - \gamma_n^* n N$$
$$- (\beta_p + S_p I) N - \gamma_p p(N_T - N - N^*)$$
$$+ (\beta_p^* + S_p^* I) N - \gamma_p^* p N^*;$$

and the Poisson equation

$$\text{div } E = \left(-\varepsilon / \mu_n \right) (N_T - N - N_D + N_A + n - p).$$

$I$ is a spatially modulated illumination (photon current in sec$^{-1}$ cm$^{-2}$), $I(z) = I_0 \left[1 + \text{Re} \left(\exp(ikz)\right)\right]$, $\varepsilon$, $\mu_n$, and $\mu_p$ are the absolute values of electron and hole charges and mobilities; $\varepsilon$ is the static dielectric constant of the material ($\varepsilon = \varepsilon_0 \varepsilon_r$ with $10\varepsilon_0 = 12.7$), and $N_D$ and $N_A$ are the density of compensative donors and acceptors, respectively. In these equations $S$ represents the photoionization cross sections, $\gamma$ the recombination coefficients, and $\beta$ the thermal emission rates. The indices $n, p, \text{ and } *$ stand for electron, hole, and Fe$^{4+}$, respectively.

Considering small modulations of the illumination pattern $m \ll 1$, we perform the usual linearization of the previous equations, keeping only the zeroth-order term and the spatially modulated first-order term, expressed as

$$X(t) = X_0 + \text{Re} \left[X_1(t) \exp(ikz)\right].$$

A general analytical solution can be found, for quasi-cw illumination. The dark conductivity is due mainly to electrons. The thermal emission rate is $10^{-10}$ sec$^{-1}$ at ambient temperature (300 K). Since thermal emission rates depend exponentially on the energy difference between the levels and the conduction band, $\beta_n^* = 10^7$ sec$^{-1}$ is 6 orders of magnitude larger than $\beta_n$. This is an approximate value, since it was calculated with the same parameters as $\beta_n$ except level energy. The rate $\beta_p$ is com-

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**Fig. 1.** Curve A, theoretical gain expected from a Fe$^{2+}$/Fe$^{3+}$ level coupled with both conduction and valence bands with $\xi = 1$ ($\alpha_n \ll \alpha_p$) and $k_0 = 500$ $\mu$m$^{-2}$ ($\{\text{Fe}^{2+}\} = 10^{-16}$ cm$^{-3} \ll \{\text{Fe}^{3+}\}$). Curve B, experimental gain. Curve C, theoretical gain with contribution of the Fe$^{2+}$ level considered.

**Fig. 2.** Energy diagrams for InP: Fe at room temperature.
puted from \( p = [\text{Fe}^{3+}] \beta_p \tau_p \) with \( p < 10^7 \text{ cm}^{-3} \) (electrons are dominant in dark current) and the recombination time of \( \text{Fe}^{3+} \) \( \tau_p = 120 \text{ nsec} \) giving \( \beta_p = 10^{-4} \text{ sec}^{-1} \ll \beta_n \). For an illumination of several tens of milliwatts, the dark current in the conduction band is smaller than or approximately equal to the electron photocurrent; thus \( \beta_n \ll \beta_p \). Assuming equal recombination coefficients \( (\gamma_p = \gamma_n) \) for holes on \( \text{Fe}^{3+} \) and \( \text{Fe}^{3+*} \), one has \( \beta_n \gg \gamma_p \beta_p = (0.1^2 \text{ sec}^{-1} \times I_0 \times h \nu = 100 \text{ mW cm}^{-2} \). This means that \( \text{Fe}^{3+*} \) is changed into \( \text{Fe}^{3+} \) primarily by thermal excitation of electrons and not by hole recombination. For low irradiance, the population of the \( \text{Fe}^{3+*} \) level is always extremely small, \( N_0^* < N_0, N_T - N_0 \). We now make the usual simplifications for low irradiance:

\[
n_0, p_0 \ll N_0, N_T - N_0, \quad n_1, p_1 \ll N_1.
\]

Moreover, the times considered in quasi-cw illumination are much longer than the lifetimes of \( \text{Fe}^{3+*} \) and both carriers; so we have

\[
\frac{\partial n_1}{\partial t} = \frac{\partial p_1}{\partial t} = \frac{\partial N_1^*}{\partial t} = 0.
\]

The resolution of the equations yields a first-order differential equation that governs the spatially modulated part of the field \( E_1 \):

\[
E_1 = \text{Im} \left( \frac{k_B T}{e} \right) \frac{\partial N_1^*}{\partial t}
\]

\[
\times \frac{k(k^2 + V^2)(\alpha_p - \alpha_n) + k[(\alpha_p + \alpha_n^*)\kappa_p^2 - (\alpha_n + \alpha_p^*)\kappa_p^2 + iV[(\alpha_p + \alpha_n^*)\kappa_p^2 + (\alpha_n + \alpha_p^*)\kappa_p^2]}{[(\alpha_n + \alpha_p^*)\kappa_p^2 + (\alpha_p + \alpha_n^*)\kappa_p^2] + k^2(\alpha_n + \alpha_p + 2\alpha_p^*)} + \frac{k^2(k^2 + V^2)/\kappa_p^2}{(\alpha_n + \alpha_p + \alpha_p^*) + iV(\alpha_n + \alpha_p - \alpha_p^*)}.
\]

(2)

This is the complex expression of the space-charge field in the presence of an external field. For small grating spacings (i.e., large grating wave number \( k \)) we can neglect the influence of the diffusion lengths \( (\kappa_n, \kappa_p \ll \lambda_p) \). Then the expression for the space-charge field becomes

\[
E_1 = \text{Im} \left( \frac{k_B T}{e} \right) \frac{\partial N_1^*}{\partial t}
\]

\[
\frac{\partial N_1^*}{\partial t} = \frac{k^2(k^2 + V^2)}{\kappa_p^2}[(\alpha_n + \alpha_p + 2\alpha_p^*) + \frac{k^2(k^2 + V^2)/\kappa_p^2}{(\alpha_n + \alpha_p + \alpha_p^*) + iV(\alpha_n + \alpha_p - \alpha_p^*)}]
\]

(3)

The temperature-dependent resonance of the photorefractive gain in the presence of an external field that was observed and described by Picoli et al. \( 31 \) also appears in this expression. For \( \alpha_n - \alpha_p = 0 \), the space-charge field becomes purely imaginary and increases proportionally to \((k^2 + V^2)\) and thus with the external field. The condition corresponds to \((\beta_n + \beta_p) [\text{Fe}^{3+*}] = S_p [\text{Fe}^{3+}]/I_0 \) or, with \( \beta_n \gg S_p/I_0 \), to \((\beta_n + \beta_p) [\text{Fe}^{3+*}] = S_p [\text{Fe}^{3+*}] \). This is the expression found in Ref. 21, with the only difference being that here \( S_p \) is not the total hole photoionization cross section \((S_p + S_p^* \) but is only the part responsible for the ionization of holes with the final level \( \text{Fe}^{3+*} \). The condition for resonance is slightly different from that predicted by Picoli et al., but the behavior of the resonance with respect to the illumination and the temperature is still the same.

Without an applied field, the steady-state space-charge field \( E_1 \) is always purely imaginary and can be written as \( E_1 = \text{Im} E_0 \). This 90° phase-shifted space-charge field creates an energy transfer by the electro-optic effect.
The gain is
\[ \Gamma = 2\pi \frac{n^3 r_{41} k_B T}{\lambda \cos \theta} E_{ac}, \]  
(4)
where \( n \) is the refractive index, \( r_{41} \) the electro-optic coefficient, and \( \theta \) the half-angle between the two beams inside the crystal.

From Eqs. (2) and (4) we derive
\[ \Gamma = \frac{-2\pi n^3 r_{41} k_B T}{\lambda \cos \theta} \left( \frac{k_B T}{e} \right) \left[ \frac{\left( \alpha_n - \alpha_p \right) k^2}{\alpha_T + \alpha_p} + \left( \frac{\alpha_n + \alpha_p^* \kappa_n^2 - \left( \alpha_p + \alpha_p^* \right) \kappa_p^2}{\left( \alpha_T + \alpha_p^* \right) k^2} \right) \right] \]
\[ + \frac{\left( \alpha_n + \alpha_p^* \right) \kappa_p^2}{\left( \alpha_T + \alpha_p^* \right)} \left( \frac{k^2}{k_0^2} \right) \left( \frac{\alpha_T}{\alpha_T + \alpha_p^*} \right) \]

\[ + \frac{\left( \alpha_n + \alpha_p^* \right) \kappa_p^2 + \left( \alpha_p + \alpha_p^* \right) \kappa_n^2}{\left( \alpha_T + \alpha_p^* \right)} \right] \]  
(5)

We took \( A_n = 1 \). This approximation is justified because the measured gain does not increase with increasing intensity of the illumination, or, in other words, because the gain is saturated with respect to intensity. The symbol \( \alpha_T \) denotes the total absorption of the sample; \( \alpha_T = \alpha_n + \alpha_p + \alpha_p^* \).

**BEAM COUPLING IN InP**

We measured the photorefractive beam coupling gain \( \Gamma \) as a function of the grating spacing. The grating spacing was varied from 0.7 to 3 \( \mu \)m. Within this range the grating wave number \( k \) is always larger than or approximately equal to the inverse of the electron or hole diffusion lengths, \( k \approx \kappa_e, \kappa_p \). For the spacings where \( k^2 > \kappa_e^2, \kappa_p^2 \), Eq. (5) can be simplified to

\[ \left| \Gamma \right| = \left| A \right| \frac{\xi_0 k}{1 + \left( k^2/k_0^2 \right)}, \]

with
\[ A = 2\pi \frac{n^3 r_{41}}{\lambda \cos \theta} \left( \frac{k_B T}{e} \right), \]
\[ \xi_0 = \frac{\alpha_n - \alpha_p}{\alpha_T + \alpha_p^*}, \]
\[ k_0^2 = k_0^2 \left( \frac{\alpha_T + \alpha_p^*}{\alpha_T} \right). \]

By plotting our experimental results in the form \( Ak/\Gamma \) versus \( k^2 \), we obtain a straight line for the large values of \( k^2 \) (Fig. 3). \( A \) is a known quantity, calculated with the values of \( n, r_{41}, k_B T/\xi_0 \), and \( \cos \theta \). The intercept at the origin and the slope of the straight line give \( 1/\xi_0 \) and \( 1/k_0^2 \xi_0 \), respectively.

For small values of \( k \), the previous approximation is no longer valid. Indeed, for these \( k \) values the curve departs from the straight line. In this case Eq. (5) cannot be simplified. We have fitted our results with the following function for all grating spacings:

\[ \left| \Gamma \right| = \left| A \right| \frac{\xi_0 k^2 + b - c}{k^2 + \left( k^4/k_0^2 \right) + b + c}, \]

where \( b = \frac{\alpha_n + \alpha_p^*}{\alpha_T + \alpha_p^*} \kappa_p^2 \), \( c = \frac{\alpha_p + \alpha_p^*}{\alpha_T + \alpha_p^*} \kappa_n^2 \), and \( \left| A \right|, \xi_0 \), and \( k_0^2 \xi_0 \) as defined above. By iteration, one finds the parameters giving the best fit, as shown in Fig. 1, curves B and C:

\[ \xi_0 = -0.424 \pm 0.03, \]
\[ k_0^2 = 260 \pm 50 \mu \text{m}^{-2}, \]
\[ b \leq 0.05 \mu \text{m}^{-2}, \]
\[ c = 1.4 \pm 0.5 \mu \text{m}^{-2}. \]

The sign of \( \xi_0 \) was determined by an additional experiment, as described in Refs. 22 and 23. The data can be perfectly fitted with three parameters, since \( b \) can be set to zero without a visible effect. By including \( b \) in the fitting process, we get only an upper limit for its value.

We note that the values we found here for \( k_0^2 \xi_0 \) and \( \xi_0 \) are close to those determined by Valley et al. in their beam-coupling experiments on another InP:Fe crystal.4

With the above set of parameters and the value of the total absorption \( \alpha_T = 1.95 \pm 0.04 \text{ cm}^{-1} \) that we measured separately, we can now determine \( \alpha_p, \alpha_p^*, \kappa_e, \kappa_p \), and \( \kappa_p^2 \). Absorption \( \alpha_n \) has been neglected, since in our crystal we have \( \alpha_n \ll \alpha_p, \alpha_p^* \), as previously discussed. We obtain

\[ \alpha_p = 1.16 \pm 0.05 \text{ cm}^{-1}, \]
\[ \alpha_p^* = 0.79 \pm 0.05 \text{ cm}^{-1}, \]
\[ k_e^2 = 185 \pm 40 \text{ \mu m}^{-2}, \]
\[ \kappa_e^2 = 2 \pm 1.5 \text{ \mu m}^{-2}, \]
\[ \kappa_p^2 < 0.2 \text{ \mu m}^{-2}. \]

The values of \( \alpha_p \) and \( \alpha_p^* \) can be expressed as percentages of the total hole absorption \( \alpha_p^{tot} = \alpha_p + \alpha_p^* \):

\[ \frac{\alpha_p}{\alpha_p^{tot}} = \frac{S_p}{S_p^{tot}} = (60 + 3)\%, \]
\[ \frac{\alpha_p^{*}}{\alpha_p^{tot}} = \frac{S_p^{*}}{S_p^{tot}} = (40 + 3)\%. \]

\( S_p^{tot} \) corresponds to the total photoionization cross section \( (S_p^{tot} = S_p + S_p^{*}) \). This parameter was measured by...
deep-level optical spectroscopy as $S_{p}^{\text{el}} = 5 \times 10^{-17} \text{ cm}^2$.12 With this value we calculate the Fe$^{3+}$ concentration and obtain $[\text{Fe}^{3+}] = 4 \times 10^{15} \text{ cm}^{-3}$. This value is slightly lower than the value given by CNET but is in perfect accord with a study on the induced nanosecond absorption done on this same crystal.7

From $k_0^2$ we calculate the effective trap density

$$N_{\text{eff}} = [\text{Fe}^{3+}] [\text{Fe}^{2+}] / ([\text{Fe}^{3+}] + [\text{Fe}^{2+}]),$$

which is equal to $[\text{Fe}^{3+}] = (3.2 \pm 0.5) \times 10^{15} \text{ cm}^{-3}$.

The results for $\kappa_\alpha^2$ and $\kappa_\alpha^2$ give only estimates of the diffusion lengths. However, their values are in good accordance with those calculated from values of the mobilities found in the literature8 and the recombination times for electrons and holes on iron in InP.20

**BEAM COUPLING IN GaAs**

We performed the same beam-coupling experiment as above in an undoped GaAs: EL$_2$ sample. The experimental result can be well explained by a model with one deep level and with electrons and holes as charge carriers. The theoretical expression for the gain is deduced from Eq. (5), with $\alpha_p^*$ = 0 (no excited state in GaAs):

$$\Gamma = -2\pi \frac{n^2 r_41}{k_B T} \left( \frac{k_B T}{e} \right) \left( \frac{\kappa_\alpha^2 \kappa_\alpha^2}{\kappa_\alpha^2 + \kappa_\alpha^2} \right) \left( \frac{k_B T}{k_0^2} \right)^2 \left( \frac{\alpha_\alpha^2 + \alpha_p^2}{\alpha_\alpha^2 + \alpha_p^2} \right).$$

We use the same technique as that used for InP to analyze our experimental results. For GaAs the experimental curve $\Lambda(k)/\Gamma = f (k^2)$ (Fig. 4) is a straight line down to 10 $\mu$m$^{-2}$. The small departure at even lower $k$ values does not permit the determination of $\kappa_\alpha^2$ and $\kappa_\alpha^2$. From the parameters of the straight line, we obtain $\xi_0 = 0.74 \pm 0.05$ and $k_0^2 = 91 \pm 10 \mu$m$^{-2}$. The measured absorption of the crystal at $\lambda = 1.06 \mu$m is $\alpha = 0.95 \pm 0.05 \text{ cm}^{-1}$. We consider, as is generally accepted, that electrons are the dominant carriers for the photorefractive effect in GaAs: EL$_2$. Therefore $\xi_0$ is positive. Then we deduce hole and electron absorptions $\alpha_p$ and $\alpha_\alpha$, and

$$\text{Fig. 4. Measured beam-coupling gain } \Gamma (+) \text{ plotted in the form } \Lambda(k)/\Gamma \text{ as a function of } k^2 \text{ for GaAs with a fitted straight line. } \Lambda = 8.34 \times 10^{-2} \text{ for } \Gamma \text{ in inverse centimeters and } k \text{ in inverse micrometers, } n_0 = 3.48 \text{, and } r_41 = 1.43 \text{ pm V}^{-1}.$$

$$\begin{align*}
\text{Fig. 5. Variation of } S_p, [\text{EL}_2], [\text{EL}_f] \text{ as a function of } S_n. \\
2 \times 10^{-16} & \text{ and } [\text{EL}_f] \text{ as a function of } S_n. \\
2 \times 10^{-16} & \text{ and } [\text{EL}_f] \text{ as a function of } S_n.
\end{align*}$$

the effective trap density from $k_0^2 = k_0^2$ (with $\varepsilon = \varepsilon_0\varepsilon_R$ and $\varepsilon_R = 12.9$) (Ref. 25):

$$\begin{align*}
\alpha_p &= S_p[\text{EL}_2] = 0.83 \pm 0.05 \text{ cm}^{-1}, \\
\alpha_\alpha &= S_p[\text{EL}_f] = 0.12 \pm 0.01 \text{ cm}^{-1}, \\
N_{\text{eff}} &= \frac{[\text{EL}_2]^2/[\text{EL}_2] + [\text{EL}_f] \times (1.6 \pm 0.2) \times 10^{15} \text{ cm}^{-3}.}
\end{align*}$$

We have three relations among the four parameters $S_n$, $S_p$, [EL$_2$], and [EL$_f$], and we can plot three of them as a function of $S_n$ (Fig. 5). As soon as one of the four parameters is fixed, all four are known. The plot shows the weak dependence of $S_p$ and [EL$_f$] on the value of $S_n$; so we can consider that this method gives a good order of magnitude for $S_p$ and [EL$_f$]. Taking the well-accepted value $S_n = 1 \times 10^{-16} \text{ cm}^2$ from Ref. 26, we obtain the following set of parameters: $S_p = 6 \times 10^{-17} \text{ cm}^2$, [EL$_2$] = $8 \times 10^{-15} \text{ cm}^2$, and [EL$_f$] = $2 \times 10^{-16} \text{ cm}^2$.

The same experiments were reported in Ref. 27 for different samples of one ingot. The concentration of [EL$_2$] and [EL$_f$] and their ratio varied for the different samples, leading to different values of $\xi_0$ (i.e., different strengths of hole–electron competition). The above analysis can be applied to the two samples that show hole–electron competition (seed center and seed side). Taking $r_41 = 1.43 \text{ pm V}^{-1}$ and $S_n = 1 \times 10^{-16} \text{ cm}^2$, we can deduce that for these two samples values of $S_p$ are close to the one found for our sample: $S_p = 5.5 \times 10^{-17} \text{ cm}^2$ for seed center and $S_p = 5.75 \times 10^{-17} \text{ cm}^2$ for seed side. Moreover, the ratio $S_p/S_n = 0.6$ that was determined for our crystal is similar to the one found by Valley et al.26 with their picosecond technique ($S_p/S_n = 0.76$).

**CONCLUSION**

This study confirms the importance of the excited state of Fe$^{3+}$ for the photorefractive effect. The excited state induces a drastic limitation of the photorefractive gain through a thermal hole–electron competition. This limitation will disappear when the photon energy is no longer sufficient to raise electrons from the valence band to the
Fe²⁺⁺ level; i.e., $h\nu < 1.05$ eV. For these wavelengths the model without the excited state will correctly describe the photorefractive effect. Another possibility for suppressing this hole–electron competition is a lowered temperature. If the inverse of the thermal emission rate $[P_n = KT^{-2}\exp(-E/k_B T) \text{ (Ref. 19)}]$ is larger than the recombination time of holes on Fe²⁺⁺ the Fe²⁺⁺ level will no longer be emptied by thermal emission of electrons in the conduction band but by recombination of holes from the valence band. Then Fe²⁺⁺ will play exactly the same role as Fe³⁺, and the thermally induced hole–electron competition will disappear. The transition from one behavior to the other should occur near 170 K. A temperature-dependent study of the photorefractive effect would provide more information.

The study of undoped GaAs permitted us to determine by a cw photorefractive experiment the photoionization cross section of holes, which is not well known. A comparison with another experiment of the same type for other GaAs crystals confirms our findings. We find a ratio $S_p/S_n = 0.6$, which is close to the value found by a picosecond pump–probe technique.

ACKNOWLEDGMENT

We warmly thank the Direction des Recherches, Etudes et Techniques for its support.

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