Ultrafast relaxation of hot minority carriers in *p*-GaAs

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The dynamics of hot minority carriers in *p*-GaAs is calculated for doping concentrations in the range of 1.5×10^{17} cm^{-3} to 1.5×10^{18} cm^{-3}. It is shown that the electron-hole interaction increases the rate of dissipation of the excess energy of the minority carriers in the early stages of the process. However, this channel for energy dissipation becomes weaker as the cooling of the minority carriers proceeds, an effect more noticeable in the case of high doping levels. When the electron-hole interaction is disregarded, the dissipation rate is always smaller for low doping concentrations.

Considerable insight into the scattering mechanisms determining the physical properties of intrinsic semiconductors is obtained with the study of the ultrafast relaxation of hot carriers.[1–3] Technical advancements in this field were so successful that nowadays it is possible to investigate relaxation processes in photoexcited carriers in a time scale of the order of 30 fs or smaller.[4,5] The situation is not as favorable in the case of the experimental investigation of high field transport transients in intrinsic semiconductors of direct gap. Few experiments are available[4,6] in which use is made of a time resolution that impairs the complete determination of phenomena like velocity overshoot[7,8] and ultrafast structured mobility.[9,10]

Less attention was given to the study of dynamics and high field transport of carriers in doped semiconductors, both from the experimental and theoretical points of view, in spite of their importance for the design of high-speed bipolar and heterojunction bipolar transistors.[11] For example, only recently the steady-state behavior of minority carriers in *p*-GaAs submitted to high electric fields was reported:[12] these authors show that the electron-hole (e-h) interaction must be taken into account to obtain a better description of the stationary state properties when the doping concentration varies from 1.5×10^{17} to 1.5×10^{18} cm^{-3}.

Using the results of Furuta *et al.*[12] to obtain the momentum and energy relaxation times, $\tau_p(\epsilon)$ and $\tau_\epsilon(\epsilon)$, respectively, Alencar *et al.*[13] calculated the transient response of minority carriers in *p*-GaAs submitted to high electric fields, to show that the velocity overshoot is less pronounced for high doping concentration, and that the e-h interaction reduces the overshoot effect.

While the confirmation of the results of Alencar *et al.*[13] depend on experiments that seems to be of difficult realization (as in the case of intrinsic semiconductors), theoretical calculations of the ultrafast relaxation of hot minority carriers may be easily confirmed in experiments involving ultrafast laser spectroscopy.

To our knowledge studies of the dissipation process of the excess energy of minority carriers in *p*-GaAs is presented here for the first time. We consider the cases of doping concentrations of 1.5×10^{17} and 1.5×10^{18} cm^{-3}. We expect that this may stimulate experimental efforts to prove the role of the e-h interaction in the process of relaxation of the excess energy of photoexcited minority carriers in *p*-GaAs.

The dynamical equation for the energy ϵ of the minority carrier in *p*-GaAs in the relaxation time approximation is

$$\frac{d\epsilon}{dt}=\frac{\epsilon-\epsilon_0}{\tau_\epsilon(\epsilon)}, \tag{1}$$

where $\epsilon_0(=3k_bT_0/2)$ is the minority carrier energy when in thermal equilibrium with the bath at temperature T_0. Equation (1) can be solved once the energy relaxation time $\tau_\epsilon(\epsilon)$ is given. Analytical expressions for $\tau_\epsilon(\epsilon)$ can be obtained by means of Boltzmann and quantum transport equations.[1,14] Instead we obtain $\tau_\epsilon(\epsilon)$ from the steady-state relations between the minority carrier energy and the applied electric field E as described in Ref. 12. This method is frequently used to calculate the transient behavior of hot carriers in semiconductors,[15–17] and was recently improved to take into account the inertia of intervalley transitions.[18]

Using the experimental results of Furuta *et al.*[12] for the steady state, we obtained a relaxation time which we call $\tau^{\rm exp}_{\epsilon_{\rm ph,eh}}(\epsilon)$, while resorting to Monte Carlo calculations, with and without the inclusion of the electron-hole (e-h) interaction,[12] we obtained $\tau^{\rm mc}_{\epsilon_{\rm ph,eh}}(\epsilon)$ and $\tau^{\rm mc}_{\epsilon_{\rm ph}}(\epsilon)$, respectively, for the relaxation time. Using these three types of approximated relaxation times, we find the corresponding values for the minority carrier energy ϵ, which we call $\epsilon^{\rm exp}_{\rm ph,eh}(t)$, $\epsilon^{\rm mc}_{\rm ph}(t)$, and $\epsilon^{\rm mc}_{\rm ph,eh}(t)$, respectively.

Choosing an initial temperature of 733 K for the photoexcited minority carrier in *p*-GaAs, and a bath temperature of 300 K, we calculate the time evolution of the minority carrier energy. Figures 1 and 2 show the evolution of the minority carrier energies $\epsilon^{\rm mc}_{\rm ph,eh}(t)$ and $\epsilon^{\rm exp}_{\rm ph,eh}(t)$, respectively, for the case of photoexcited *p*-GaAs with doping concentrations of 1.5×10^{17} cm^{-3} and 1.5×10^{18} cm^{-3}.

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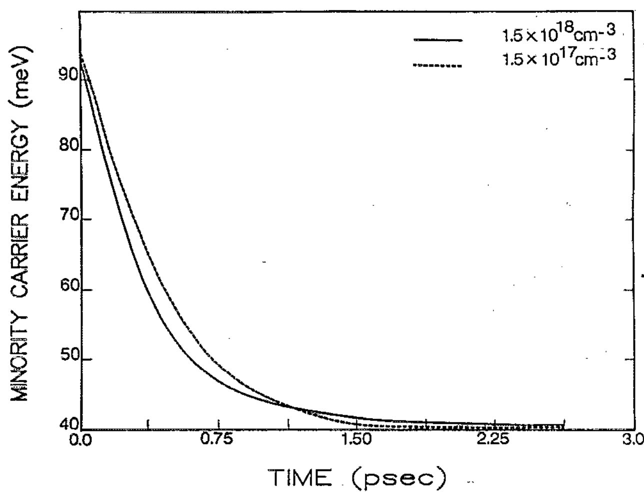

FIG. 1. The time evolution of the minority carrier energy $\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)$, for the doping concentration of 1.5×10^{17} cm^{-3} (dotted line) and 1.5×10^{18} cm^{-3} (solid line).

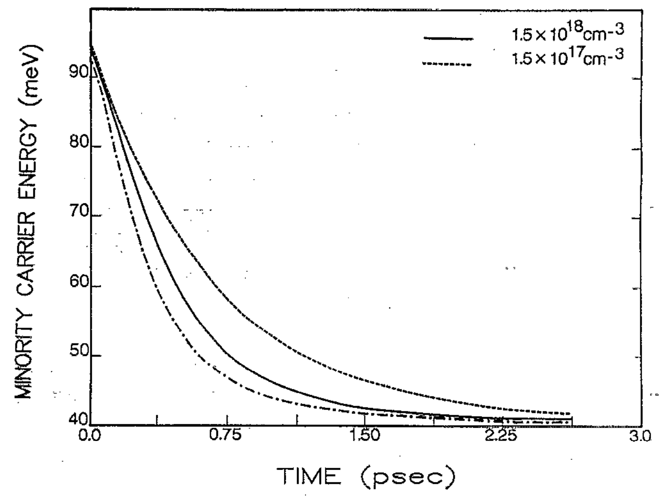

FIG. 3. The time evolution of the minority carrier energy $\epsilon_{\mathrm{ph}}^{\mathrm{mc}}(t)$, for the doping concentration of 1.5×10^{17} cm^{-3} (dotted line) and 1.5×10^{18} cm^{-3} (solid line). For the sake of comparison, the curve for $\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)$, for the doping concentration of 1.5×10^{18} cm^{-3}, is also shown in this figure (chain dotted line).

It can be seen that the relaxation of the excess energy of the minority carriers is initially always faster in the case of high doping concentration. As the time evolution of the dissipation process proceeds, the energy relaxation rate $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ $[d\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)/dt]$ at $t>1.0$ ps ($t>1.4$ ps) becomes higher in the case of a doping concentration of 1.5×10^{17} cm^{-3} than that of a doping concentration of 1.5×10^{18} cm^{-3}. This does not occur for $d\epsilon_{\mathrm{ph}}^{\mathrm{mc}}(t)/dt$, as inspection of Fig. 3 shows.

These results can be understood by the fact that it is possible to write, in the range of validity of Mathiessen's rule,[19] that

$$\frac{1}{\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{mc}}(\epsilon)}=\frac{1}{\tau_{\epsilon_{\mathrm{ph}}}^{\mathrm{mc}}(\epsilon)}+\frac{1}{\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{mc}}(\epsilon)}, \tag{2}$$

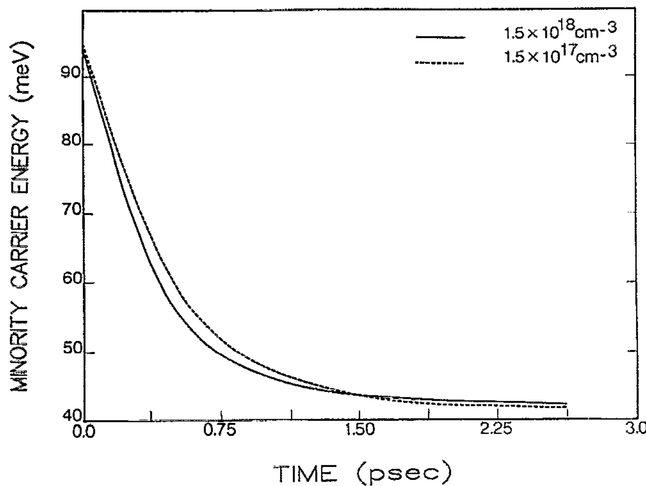

FIG. 2. The time evolution of the minority carrier energy $\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)$, for the doping concentration of 1.5×10^{17} cm^{-3} (dotted line) and 1.5×10^{18} cm^{-3} (solid line).

$$\frac{1}{\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{exp}}(\epsilon)}=\frac{1}{\tau_{\epsilon_{\mathrm{ph}}}^{\mathrm{exp}}(\epsilon)}+\frac{1}{\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{exp}}(\epsilon)}, \tag{3}$$

where $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{mc}}(\epsilon)[\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{exp}}(\epsilon)]$ is the contribution to $\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{mc}}(\epsilon)$ $[\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{exp}}(\epsilon)]$ from the e-h interaction, while $\tau_{\epsilon_{\mathrm{ph}}}^{\mathrm{mc}}(\epsilon)[\tau_{\epsilon_{\mathrm{ph}}}^{\mathrm{exp}}(\epsilon)]$ is the contribution from the carrier scattering with LO phonons.

The values of $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{mc}}(\epsilon)$ and $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{exp}}(\epsilon)$ decrease both with the departure from the equilibrium state of the carrier system and the increase of the doping concentration. Because their initial contributions to $\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{mc}}(\epsilon)$ and $\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{exp}}(\epsilon)$ are smaller in the case of high doping concentration, the energy relaxation rates $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ and $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)/dt$ are initially higher for the doping concentration of 1.5×10^{18} cm^{-3} than that of 1.5×10^{17} cm^{-3}— see Figs. 1 and 2, respectively.

With increasing dissipation of the excess energy, both $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{mc}}(\epsilon)$ and $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{exp}}(\epsilon)$ increase more rapidly in the case of high doping concentration, and their contributions to $\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{mc}}(\epsilon)$ and $\tau_{\epsilon_{\mathrm{ph,eh}}}^{\mathrm{exp}}(\epsilon)$ become higher. The increase of these contributions is higher for the doping concentration of 1.5×10^{18} cm^{-3}, and consequently the energy relaxation rates $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ and $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)/dt$ become higher for the lowest doping concentration. In the present case, this follows after $t\sim1.0$ ps ($t\sim1.4$ ps) for the energy relaxation rate $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ $[d\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)/dt]$.

Because both $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{mc}}(\epsilon)$ and $\tau_{\epsilon_{\mathrm{eh}}}^{\mathrm{exp}}(\epsilon)$ strongly increase during the final stages of the dissipation process, the assymptotic behavior of $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ and $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)/dt$ will be the same for all doping concentrations. This is verified on account of the fact that the difference between the energies $\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)$ and $\epsilon_{\mathrm{ph,eh}}^{\mathrm{exp}}(t)$ of the minority carriers, calculated for the doping concentrations of 1.5×10^{17} cm^{-3} and 1.5×10^{18} cm^{-3}, always decrease after $t\sim1.0$ ps and $t\sim1.4$ ps, respectively.

This conclusion is compatible with the absence of a crossover of the curves calculated for $d\epsilon_{\epsilon_{\mathrm{ph}}}^{\mathrm{mc}}(t)/dt$ with the doping concentrations of 1.5×10^{17} cm^{-3} and 1.5×10^{18} cm^{-3}, as shown by Fig. 3, where we can also see that the relaxation rate $d\epsilon_{\mathrm{ph}}^{\mathrm{mc}}(t)/dt$ increases with the doping concentration. Finally, it is worth mentioning that for a given doping concentration, $d\epsilon_{\mathrm{ph}}^{\mathrm{mc}}(t)/dt$ is always smaller than $d\epsilon_{\mathrm{ph,eh}}^{\mathrm{mc}}(t)/dt$ and $d\epsilon_{\mathrm{ph,eh}}^{\exp}(t)/dt$, thus highlighting the fact that the e-h interaction is an important channel for the dissipation of the excess energy of minority carriers in p-GaAs.

In conclusion, we have presented a theoretical description of the relaxation process of hot minority carriers in p-GaAs, with doping concentrations of 1.5×10^{17} cm^{-3} and 1.5×10^{18} cm^{-3}. It was shown that the e-h interaction increases the dissipation energy rates, accelerating the carriers cooling at the early stages of the process. However, this channel of energy dissipation becomes weaker as the time evolution of the minority carriers cooling proceeds. These results have a similarity with that obtained by Alencar *et al.*[13] in a study of the high-field transport transient of minority carriers in p-GaAs, where it is shown that the behavior of the momentum relaxation time $\tau_p(\epsilon)$ which is similar to that of the energy relaxation time $\tau_\epsilon(\epsilon)$ described here, determine a velocity overshoot or its absence as a function of the applied electric field.

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