

High-field transport transient of minority carriers in *p*-GaAs

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The time evolution of the minority electron velocity and temperature in *p*-GaAs towards the steady state is calculated for high-electric fields and doping concentrations of 1.5×10^{17} and $1.5 \times 10^{18} \text{ cm}^{-3}$. It is shown that the velocity overshoot is less pronounced for high doping concentration. The electron-hole interaction reduces the overshoot effect, which indicates its role in the high-field transport transient of minority carriers in *p*-GaAs.

The study of minority-carrier transport in doped semiconductors has considerable importance to the design of high-speed bipolar and heterojunction bipolar transistors.¹ Several experimental and theoretical investigations were performed, most of these concentrating on the steady-state²⁻⁴ and transient⁵ transport properties of minority carriers in low-electric fields. It was shown, for example, that electron-hole collisions make the holes in the *n*-type materials less mobile than in the *p*-type materials.² More recently, high-field transport studies of the steady-state regime of minority electrons in *p*-GaAs were also performed.⁶⁻⁹ Reduction of the steady-state drift velocity for the high-doping concentration, and thermally nonequilibrium states between electrons and holes, were observed.⁷ However, to the knowledge of the present authors, there is no calculation of the transient minority-carrier behavior in *p*-GaAs.

Presented in this letter, for the first time, is the temporal evolution of the drift velocity and temperature of minority electrons in *p*-GaAs towards the steady state for doping concentrations of 1.5×10^{17} and $1.5 \times 10^{18} \text{ cm}^{-3}$, and electric field intensities up to 10 kV/cm. The theoretical calculations were performed with and without the electron-hole interaction. One is able to see the influence of this interaction on the transient regime of the transport parameters.

The dynamical equations utilized are two coupled differential equations for the energy and drift velocity of the minority electron, derived from the Boltzmann equation in the approximation of momentum and energy relaxation times, τ_p and τ_ϵ , respectively.^{10,11}

The well known and frequently utilized basic equations are of the type:¹²⁻¹⁴

$$\frac{dv}{dt} = \frac{qE}{m} - \frac{v}{\tau_p(\epsilon)} \quad (1)$$

$$\frac{d\epsilon}{dt} = qvE - \frac{\epsilon - \epsilon_0}{\tau_\epsilon(\epsilon)} \quad (2)$$

where v is the minority electron velocity, $\epsilon (= 3k_bT/2)$ is the average minority electron energy, T is the minority electron temperature, k_b is the Boltzmann constant, ϵ_0 is the thermal energy of the minority electron at the lattice temperature $T_1 = 300 \text{ K}$, q and m are, respectively, the

charge and effective mass of the minority electron, and finally, E is the applied electric field.

The system of equations was solved numerically using the steady-state relations between the minority electron velocity and energy with the applied electric field, $v_s(E_s)$ and $\epsilon_s(E_s)$, for the calculation of $\tau_p(\epsilon)$ and $\tau_\epsilon(\epsilon)$. The steady-state data utilized were those published recently by Furuta *et al.*⁷ for *p*-GaAs with doping concentrations of 1.5×10^{17} and $1.5 \times 10^{18} \text{ cm}^{-3}$.

While the Monte Carlo approach to transient situations is very time consuming, the method of solution of Eqs. (1) and (2) that was used requires short computation

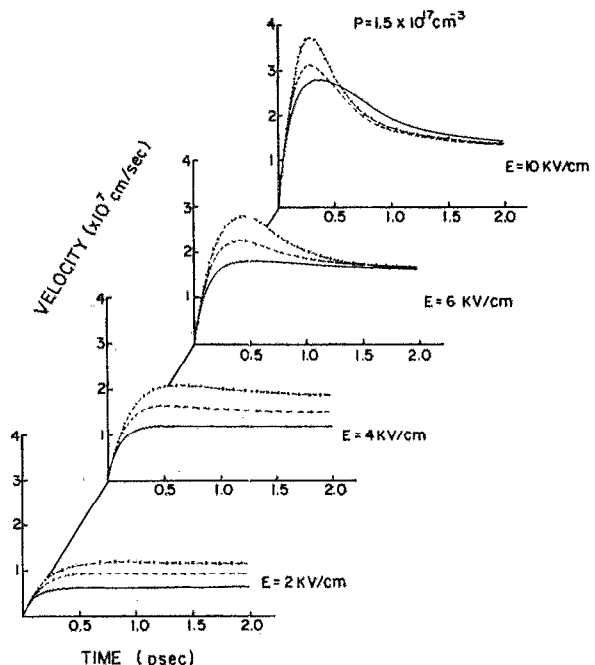


FIG. 1. Time evolution towards the steady state of the minority electron velocity in *p*-GaAs, with doping concentration of $1.5 \times 10^{17} \text{ cm}^{-3}$. (a) solid lines (—): experimental steady-state data were utilized for the calculation of the relaxation times; (b) chain dotted lines (- · - · -): Monte Carlo steady-state data, obtained only with the LO-phonon scattering, were utilized for the calculation of the relaxation times; (c) dotted lines (- - -): Monte Carlo steady-state data, obtained with LO-phonon and electron-hole scattering, were utilized for the calculation of the relaxation times (see Ref. 7).

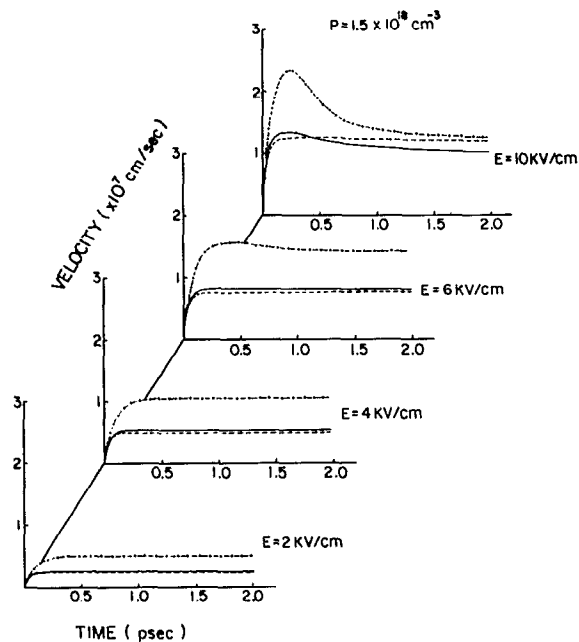


FIG. 2. Time evolution towards the steady state of the minority electron velocity in *p*-GaAs, with doping concentration of $1.5 \times 10^{18} \text{ cm}^{-3}$. The meanings of the lines (solid, chain dotted, and dotted) are the same as in Fig. 1.

time. It enables one to perform systematic studies and is helpful for device improvement. The method was used previously in the determination of the transient behavior of hot carriers in GaAs,¹⁰ and in the modeling of a submicrometer gate field-effect transistor including effects of nonsteady-state dynamics.¹¹ Later Gorfinkel and Shofman improved the method to describe the electron heating dynamics in many-valley semiconductors.¹²

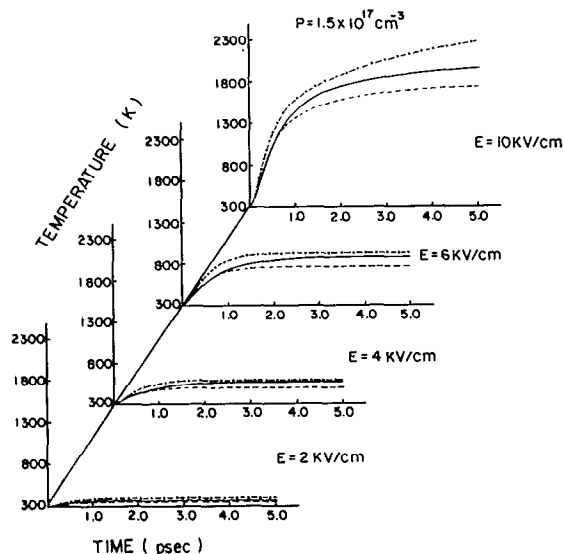


FIG. 3. Time evolution towards the steady state of the minority electron temperature in *p*-GaAs, with doping concentration of $1.5 \times 10^{17} \text{ cm}^{-3}$. The meanings of the lines (solid, chain dotted, and dotted) are the same as in Fig. 1.

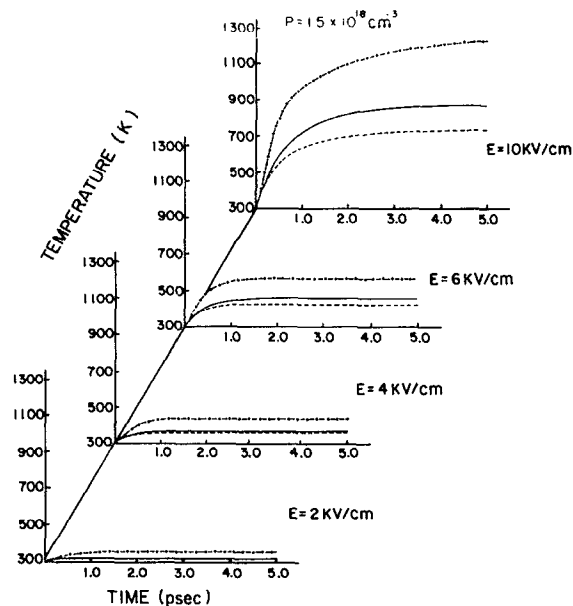


FIG. 4. Time evolution towards the steady state of the minority electron temperature in *p*-GaAs, with doping concentration of $1.5 \times 10^{18} \text{ cm}^{-3}$. The meanings of the lines (solid, chain dotted, and dotted) are the same as in Fig. 1.

The results for the time evolution of the minority electron velocity and temperature in *p*-GaAs are shown in Figs. 1 and 3 (2 and 4), respectively, when the doping concentration is $1.5 \times 10^{17} \text{ cm}^{-3}$ ($1.5 \times 10^{18} \text{ cm}^{-3}$). In both cases, the applied electric field has the values 2, 4, 6, and 10 kV/cm. In these figures, graphics drawn with solid lines were obtained with the utilization of the experimental steady-state measurements of Furuta *et al.*⁷ for the calculation of the momentum and energy relaxation times; graphics drawn with chain dotted lines were obtained with the utilization of the steady-state Monte Carlo results of Furuta *et al.*⁷ (including energy loss by electron-optical phonon interaction only) for the calculation of both relaxation times. Finally, graphics drawn with dotted lines were obtained with the utilization of the steady-state Monte Carlo results of Furuta *et al.*⁷ (with one more channel of energy loss, the electron-hole interaction) again for τ_p and τ_e calculations.

By inspecting Figs. 1 and 2 one can see that the minority electron velocity overshoot for high-electric fields is less pronounced in the case of high-doping concentration. Consequently, the lowest electric field intensity that produces an overshoot is that applied to the small doping concentration (about 5 kV/cm when $p = 1.5 \times 10^{17} \text{ cm}^{-3}$, in our case). On the other hand, the electron-hole interaction reduces the overshoot effect, eliminating it in the case of high-doping concentration.

The temporal evolution of the minority electron velocity obtained here has the same general behavior for both doping concentrations. However, while the time necessary for the minority electron velocity to arrive at the steady state increases with the electric field intensity, its smallest value ever occurs when $p = 1.5 \times 10^{18} \text{ cm}^{-3}$. The velocity results with the inclusion of the electron-hole interaction

are closest to those obtained with the use of the experimental steady-state data of Furuta *et al.*⁷ for the calculation of τ_p and τ_e . This means that the electron-hole Coulomb interaction plays a relevant role in the description of high-field transport transient of minority carriers in *p*-GaAs.

The curves for the time evolution of the minority electron temperature as a function of different applied electric fields are shown in Figs. 3 and 4. They enable one to see that the minority electron energy ($\epsilon = 3k_bT/2$) arrives faster at the steady state when the energy losses by both electron-optical phonon and electron-hole interaction are considered (dotted line). Finally, it is worth mentioning that the time necessary for the minority electron temperature to arrive at the steady state also increases with the electric field intensity, being always smaller for the high-doping concentration.

In summary, the first theoretical results of high-field transport transient of minority electrons in *p*-GaAs with two different doping concentrations, 1.5×10^{17} and $1.5 \times 10^{18} \text{ cm}^{-3}$, were presented. It was shown that the time evolution of the transport parameters depends on the energy transferred from the electrons to the hole gas by the electron-hole interaction. A minority electron velocity overshoot is predicted for high-electric fields, a result susceptible to experimental confirmation.

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