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ELECTRIC FIELD DEPENDENCE OF LONGITUDINAL ELECTRON DIFFUSIVITY IN GaAs

ЗАВИСИМОСТЬ КОЭФФИЦИЕНТА ПРОДОЛЬНОЙ ЭЛЕКТРОННОЙ ДИФФУЗНОСТИ В GaAs ОТ ЭЛЕКТРИЧЕСКОГО ПОЛЯ.

Ľ. HRIVNÁK*, Bratislava

Ruch and Kino [1] measured the electron drift velocity and the longitudinal diffusion coefficient in semi-insulating GaAs. Many papers appeared which tried to explain theoretically the observed electric field dependences of these quantities in GaAs, especially by the Monte Carlo method [2—6]. However, this numerical method is rather cumbersome for the analysis of various devices based on GaAs when it is necessary to estimate the high field effects.

Thim [7] introduced a simple empirical formula for the electron drift velocity in GaAs:

$$v_d(E)=\frac{\mu_n E+v_{sat}(E/E_0)^4}{1+(E/E_0)^4}, \tag{1}$$

where μ_n is the low field electron mobility, v_{sat} is the saturation velocity, and E_0 is a constant, the value of which is close to the value of the electric field strength corresponding to the maximum of the drift velocity. This formula was used also by other authors [8—10]. The v_d versus the E dependence computed according to the formula (1) with $\mu_n=0.75\ \mathrm{m^2/V\,s}$, $E_0=4\times10^5\ \mathrm{V/m}$, $v_{sat}=10^5\ \mathrm{m/s}$ is shown in Fig. 1. The full curve corresponds to the measurements by Ruch and Kino (see Fig. 5 in [1]).

In this short note we want to point out that the longitudinal electron diffusion coefficient can be coupled with electron drift velocity by a simple relation with only one empirical parameter which is the energy relaxation time. We start from a rough generalization [11] of the Einstein relation

$$D_n(E)=\frac{2}{3}\,\frac{v_d(E)\langle\varepsilon\rangle}{eE} \tag{2}$$

in which we insert for the mean energy of electrons in the presence of the electric field [11]

$$\langle\varepsilon\rangle=\frac{3}{2}\,k_BT+ev_d(E)E\tau_\varepsilon\,, \tag{3}$$

where T is the lattice temperature and τ_ε is the energy relaxation time. We get

$$D_n(E)=\frac{k_BTv_d(E)}{eE}\left[1+\frac{2\tau_\varepsilon e}{3k_BT}\,v_d(E)E\right]. \tag{4}$$

This simple formula is in very good agreement with the experimental results of Ruch and Kino if we

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* Institute of Electrical Engineering CEPR Slov. Acad. Sci., CS-842 39 BRATISLAVA.

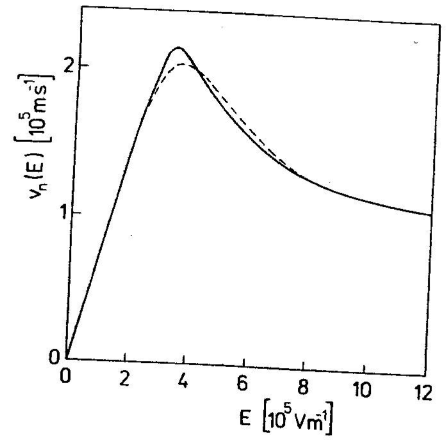


Fig. 1. Electron drift velocity in GaAs as a function of electric field strength at 300 K. The full curve corresponds to the experimental results of Ruch and Kino (see Fig. 5 in [1]). The dashed curve is computed by the use of the formula (1) with $\mu_n = 0.75$ m^2/Vs, $v_{sat} = 1\times10^5$ m/s, and $E_0 = 4\times10^5$ V/m.

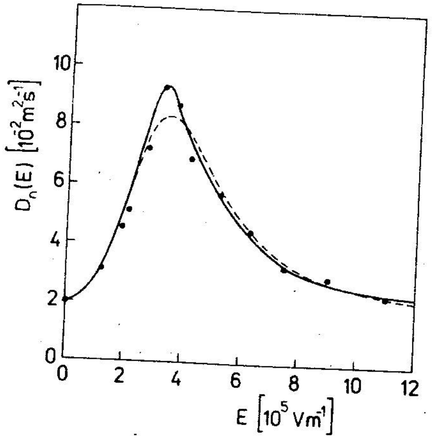


Fig. 2. Longitudinal diffusion coefficient of electrons in GaAs as a function of electric field strength at 300 K. The curves are computed by the use of the formula (4) with $\tau_\epsilon = 2.5\times10^{-12}$ s, and the values of v_d(E) corresponding to the full curve in Fig. 1 (full curve), and to the dashed curve in Fig. 1 (dashed curve). Dots indicate the experimental results of Ruch and Kino (see Fig. 7 in [1]).

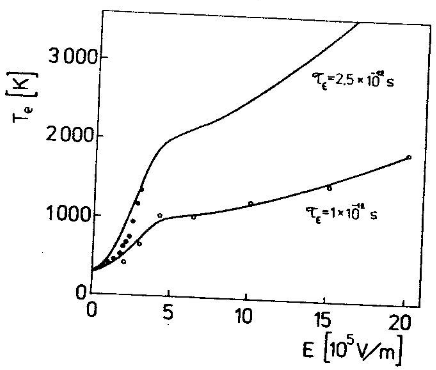
insert the measured values of $v_d(E)$ by these authors and $\tau_\epsilon = 2.5\times10^{-12}$ s (the full curve in Fig. 2). The dashed curve in Fig. 2 is computed by the use of formula (4) with $v_d(E)$ given by the Thim formula (dashed curve in Fig. 1) and the same value of τ_ϵ. Both computed curves in Fig. 2 are in better agreement with the measured values (marked by dots) than any other published computed longitudinal electron diffusion coefficient as a function of the electric field strength. (For comparison see Fig. 25 in a review paper by Jacobini and Reggiani [11] or the recent paper by Požela and Reklaitis [6]). Moreover, the value of τ_ϵ which we have used is the same as found by Glover [12] at low electric fields. However, according to measurements of Glover, τ_ϵ in his GaAs samples with a resistivity in the range of 2—5 Ω cm increases with an increasing electric field strength in the range of 1.5×10^5—3×10^5 V/m. To explain the experimental results of Ruch and Kino gained on semi-insulating GaAs we need not consider the electric field dependence of the energy relaxation time.

In accordance with the relation (3) we can introduce the electron temperature $T_e = 2\langle\epsilon\rangle/3k_B$ by the relation

$$T_e = T\left[1 + \frac{2e\tau_\epsilon}{3k_BT}\, v_d(E)E\right]. \tag{6}$$

By the use of the relation (1) with $E_0 = 4\times10^5$ V/m, $\mu = 0.75$ m^2/Vs, $v_{sat} = 1\times10^5$ m/s, $\tau_\epsilon = 1\times10^{-12}$ s and $\tau_\epsilon = 2.5\times10^{-12}$ s, respectively, we get for $T = 300$ K the T_e versus E dependences which are plotted in Fig. 3. The circles are taken from Fig. 11 of the paper by Maloney and Frey [13] who calculated electron temperature T_e during the Monte Carlo runs for steady-state velocity. Thus we can fit the theoretical results of these authors by the relation (6) with the electric field independent energy relaxation time $\tau_\epsilon \simeq 1\times10^{-12}$ s. The dots in Fig. 3 correspond to measured electron temperature by

Fig. 3. Electron temperature in GaAs as a function of electric field strength at 300 K. The curves are computed according to the formula (6) with parameters given in the text. The circles are calculated by Maloney and Frey. The dots are Glower's experimental data.



Glower (the data have been read from Fig. 7 of paper [12] taking $E_{TH} = 3.3\times10^5$ V/m in accordance with the Fig. 3 of the same paper). As can be seen the experimental data of Glower are between the curves corresponding to the relation (6) with the above given values of parameters. We remark that some parameters which enter the above formulas (e.g. μ and τ_ϵ) depend on the scattering mechanism of electrons and need not have the same values in various samples of GaAs. Therefore, comparing the experimental results of various authors we cannot expect to get a quantitative agreement with the same values of parameters which we have used to explain the experimental results of Ruch and Kino.

The relation (4) can be approximated by the Einstein relation

$$D_n = \frac{k_BT\mu_n}{e} \tag{6}$$

when

$$v_d(E) = \mu_n E \tag{7}$$

and

$$E^2 \ll \frac{3k_BT}{2e\tau_\epsilon\mu_n}. \tag{8}$$

In GaAs at room temperature these conditions are fulfilled if $E < 5\times10^4$ V/m.

In the case of such high electric fields that the electron drift velocity is close to its saturated value and

$$E \gg \frac{3k_BT}{2\tau_\epsilon e v_{sat}} \tag{9}$$

($E \gg 10^5$ V/m at 300 K) the electron diffusion coefficient is again independent of the electric field strength and can be expressed as

$$D_{sat} = \frac{2}{3}\,\tau_\epsilon v_{sat}^2. \tag{10}$$

We have shown that in GaAs the formula (4) is in remarkable agreement with the experimental results of Ruch and Kino and thus it can be used for the estimation of the various consequences to which the electric field dependence of the longitudinal electron diffusion coefficient can lead in some electronic devices based on this semiconductor.

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