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P.A. Maksym, P.A. Maksym

Institutions: University of Warwick, University of Leicester

Published on: 01 Oct 1981 - Web Science

Topics: Electron density, Electron, Photoexcitation, Scattering and Electron scattering

JOURNAL DE PHYSIQUE
Colloque C7, supplément au n°10, Tome 42, octobre 1981 *page* C7-143

THE EFFECT OF ELECTRON-ELECTRON SCATTERING ON HOT PHOTOEXCITED ELECTRONS IN GaAs

P.A.Maksym*

Department of Physics, University of Warwick, Coventry, CV4 7AL, England

Résumé - L'effet de la diffusion électron-électron sur les électrons chauds et photoexcités dans GaAs est étudié par un calcul numérique de la fonction de la distribution électronique. Les calculs s'appliquent aux conditions de photoexcitation continue et monochromatique et tiennent compte des effets suivants : injection des électrons dans la bande de conduction (l'énergie d'injection est supposée être inférieure à l'énergie du phonon L.O.), collisions entre électrons de spin anti-parallèle, collisions entre électrons de spin parallèle, collisions entre électrons et phonons (via les interactions piézoélectrique et de déformation potentielle) et recombinaison. Il est démontré que divers écarts du quasi-équilibre ont lieu si la densité des électrons est suffisamment basse ($\leqslant 10^{12} cm^{-3}$) ou suffisamment élevée ($\geqslant 10^{18} cm^{-3}$).

Abstract - The effect of electron-electron scattering on hot photoexcited electrons in GaAs is studied by performing numerical calculations of the electron distribution function. The calculations apply to conditions of continuous monochromatic photoexcitation and take account of the following effects: injection of electrons into the conduction band (the injection energy is taken to be less than the L.O. phonon energy), collisions between electrons of unlike spin, collisions between electrons of like spin, electron-phonon collisions (via the piezoelectric and deformation potential interactions) and recombination. It is shown that various departures from quasi-equilibrium occur if the electron density is sufficiently low ($\leqslant 10^{12}$ cm^{-3}) or sufficiently high ($\geqslant 10^{18}$ cm^{-3}).

1. Introduction - The form of the energy distribution function (d.f.) for non-equilibrium electrons in semiconductors depends on the effect of electron-electron (e.e.) scattering. If e.e. collisions dominate over electron-phonon (e.p.) collisions the d.f. can have a quasi-equilibrium form (Maxwell-Boltzmann or Fermi-Dirac). However, if e.e. collisions are less important the d.f. may have a grossly non-equilibrium form. For photoexcited electrons, such departures from quasi-equilibrium can be especially pronounced if the lattice temperature is in the liquid helium range because the background of thermally excited carriers is then too small to have a significant effect on the d.f. The present work is concerned with the d.f. for photoexcited electrons in GaAs under these conditions. The purpose of the work is to estimate the range of electron densities in which departures from quasi-equilibrium are likely to occur and to study the form of the corresponding non-equilibrium energy distributions. This is done by using a one band, Boltzmann

* present address: Department of Physics, University of Leicester, University Road, Leicester, LE1 7RH, England

This work was completed at the University of Leicester.

equation model to compute the electron density dependence of the d.f. A novel aspect of the work is that the e.e. collision integrals are evaluated exactly. This enables both collisions between electrons of unlike spin and collisions between electrons of like spin to be fully taken into account. The details of the model are summarized in section 2 and some pertinent features of the e.e. scattering rates are explained in section 3. Following this, the computed d.f. are given in section 4: it is shown that departures from quasi-equilibrium may occur if the electron density is sufficiently low ($\ll 10^{12}$ cm^{-3}) or sufficiently high ($\gg 10^{18}$ cm^{-3}). Finally, the conclusions following from this work are summarized in section 5.

2. The Model - The electron distribution is assumed to be spatially uniform and non-degenerate. In addition the d.f. is taken to be isotropic in $\underline{k}$ space because impurity scattering is expected to randomize the electron momentum distribution. Thence the d.f. obeys the Boltzmann transport equation in the form:

$$G(k) + \int f(k') \, S(\underline{k}' \rightarrow \underline{k}) d\underline{k}' - f(k) \int S(\underline{k} \rightarrow \underline{k}') d\underline{k}' - Rf(k) = 0 \qquad (1)$$

Here G(k), the generation rate, is the rate at which the electrons are injected into the band (no thermally excited electrons are present). It is assumed that the generation rate is monoenergetic:

$$G(k) = \frac{Q}{\rho(\epsilon_i)} \, \delta(\epsilon - \epsilon_i) \qquad (2)$$

where ϵ_i is the injection energy, Q is the total rate at which the electrons are injected and ρ is the density of states. The assumption of monoenergetic injection allows us to study only the overall features of the departures from quasi-equilibrium: in reality monochromatic photoexcitation of GaAs involves non-monoenergetic injection but the injection spectrum could well be dominated by injection from the heavy hole band. The kernel $S(\underline{k} \rightarrow \underline{k}')$ is the transition rate for inelastic scattering from $\underline{k}$ to $\underline{k}'$. We take account of e.e. scattering and e.p. scattering (by acoustic phonons only because ϵ_i is taken to be below the L.O. phonon threshold energy). The main features of e.e. scattering are summarized in section 3. The model for e.p. scattering is as previously used by Maksym (1980): piezoelectric scattering (T.P.) by phonons of transverse polarization and piezoelectric scattering (L.P.) and deformation potential scattering (D.P.) by phonons of longitudinal polarization are taken into account. Screening of the e.e. and piezoelectric interactions is estimated by using the Debye approximation. The recombination rate, R, is taken to be 10^7 s^{-1} (which is consistent with experimental results due to Ulbrich (1973)). The d.f. are computed by using an iterative technique to solve the Boltzmann equation. It is thought that the non-Maxwellian d.f. are accurate to $< 10\%$ and that the electron temperatures are accurate to $< 20\%$. Greater accuracy would require substantially more computer time. A more detailed account of the model has been submitted for publication elsewhere (Maksym, 1981).

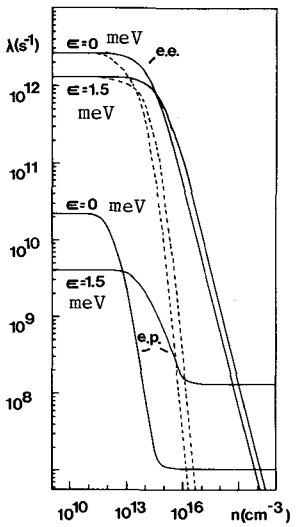

Fig.1

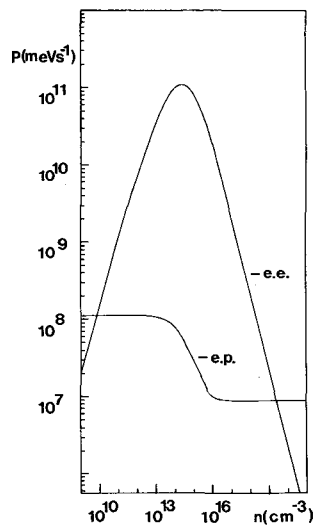

Fig.2

Figs. 1 and 2: The n dependence of the scattering and energy exchange rates for a 5 K Maxwellian distribution of electrons in GaAs at 1 K. Fig. 1 shows λ_{ee} and λ_{ep}. The upper 4 curves show λ_{ee} for unlike spin collisions (solid lines) and like spin collisions (broken lines). The lower 2 curves show λ_{ep}. The electron energies are as shown above. Fig. 2 shows P_{ee} (unlike spin collisions) and P_{ep}.

3. Electron-electron scattering - The e.e. scattering rates we use are as given by Landsberg (1960; see also Hearn, 1979). These rates are derived by time dependent perturbation theory: the electrons are taken to be in Bloch states (unity overlap) and they are assumed to interact via the screened Coulomb interaction. Thus the e.e. contribution to the kernel S is:

$$S_{ee}(\underline{k}' \to \underline{k}) = \left[\frac{1}{8\pi^3}\right]^2 \frac{2\pi}{\hbar} \iint \left[M^2(\underline{k} - \underline{k}'') + M^2(\underline{k}' - \underline{k}) + \left\{ M(\underline{k} - \underline{k}'') - M(\underline{k}' - \underline{k}) \right\}^2 \right] f(k'') \times$$

$$\delta(\epsilon(\underline{k}' + \underline{k}'' - \underline{k}) + \epsilon(\underline{k}) - \epsilon(\underline{k}') - \epsilon(\underline{k}'')) \, d\underline{k}''$$

where $M(\underline{q}) = e^2/(\mu^2 + q^2)\varepsilon\varepsilon_0$, μ is the inverse screening length and ε is the dielectric constant.

Using the above rate in the Boltzmann equation results in a 5 dimensional integral for the scattering rates, however, this integral can be simplified because f is isotropic. We do the angular parts of the $\underline{k}''$ and $\underline{k}'$ integrations analytically (see Maksym, 1981) leading to a two dimensional integral over k' and k''. The numerical evaluation of this integral is sufficiently rapid to enable computation of the d.f.

The e.e. scattering rates depend strongly on the electron density because both the d.f. and the inverse screening length depend on the electron density. There are two types of e.e. collision, namely collisions between electrons of unlike spin (corresponding to the terms $M^2(\underline{k} - \underline{k}'') + M^2(\underline{k}' - \underline{k})$ in equation 2) and collisions between electrons of like spin (corresponding to the term

$\{M(\underline{k} - \underline{k}'') + M(\underline{k}' - \underline{k})\}^2$ in equation 2). The rates of these collisions have a different density dependence. This effect is illustrated in Fig. 1, which shows the density dependence of the scattering out rates λ_{ee} ($\lambda_{ee} = \int S_{ee}(\underline{k} \rightarrow \underline{k}')d\underline{k}'$) for electrons having a Maxwellian distribution (T_e = 5 K). For comparison, the acoustic phonon scattering out rates, λ_{ep}, for GaAs with a lattice temperature of 1K are also shown. It can be seen that λ_{ee} is independent of n for small n and then decreases with n for large n. The decrease with n is caused by the effect of screening, however, the rate of collisions between electrons of like spin decreases more rapidly than the rate of collisions between electrons of unlike spin ($\sim n^{-3}$ compared with $\sim n^{-1}$). Because of this effect we ignore collisions between electrons of like spin when computing d.f. corresponding to an electron density $\geq 10^{15}$ cm^{-3}.

Collisions between electrons of unlike spin can be characterized by an energy exchange rate, P_{ee} (Hearn, 1965) which is the mean rate at which an electron exchanges energy with the other electrons in the distribution. This quantity also has a strong density dependence, as shown in Fig. 2: the figure shows P_{ee} as a function of n for an electron in a 5K Maxwellian distribution. For comparison the mean rate, P_{ep}, at which an electron, in a 5K Maxwellian distribution, loses energy to the lattice is also shown. It can be seen that P_{ee} is small at both large and small n. This density dependence reflects the effect of screening: for small n the screening is small so the electrons undergo frequent but small angle collisions; whereas for large n the collisions are infrequent but large angle collisions are relatively important.

Electron-electron scattering can affect the energy distribution only if the e.e. collisions involve a sufficiently large energy exchange and if they are sufficiently frequent. Comparing the e.e. and e.p. rates shown in Figs. 1 and 2 we see that these conditions are not simultaneously satisfied either if n is sufficiently small or sufficiently large. Departures from quasi-equilibrium can then occur, as explained in the next section.

4. Distribution Functions - The d.f. corresponding to monoenergetic injection have the form (Maksym 1980a, 1981):

$$f(k) = \bar{f}(k) + \frac{Q}{\rho(\epsilon_i)} \frac{1}{\lambda(k_i) + R} \delta(\epsilon - \epsilon_i)$$

where the singular part of the d.f. is characteristic of those electrons which are injected and remain in the band without undergoing inelastic scattering and the non-singular part, $\bar{f}$, is characteristic of the inelastically scattered electrons. Our computed d.f. are shown in Figs 3-6 as plots of $\bar{f}$ against ϵ. The fractions of electrons contributing to $\bar{f}$ (denoted as α) are given in the captions to the figures. All the d.f. are appropriate to electrons injected at 1.46 meV (see arrow in figures) into the conduction band of GaAs having a lattice temperature of 1 K. The computed d.f. fall into three classes: they are non-Maxwellian if the electron

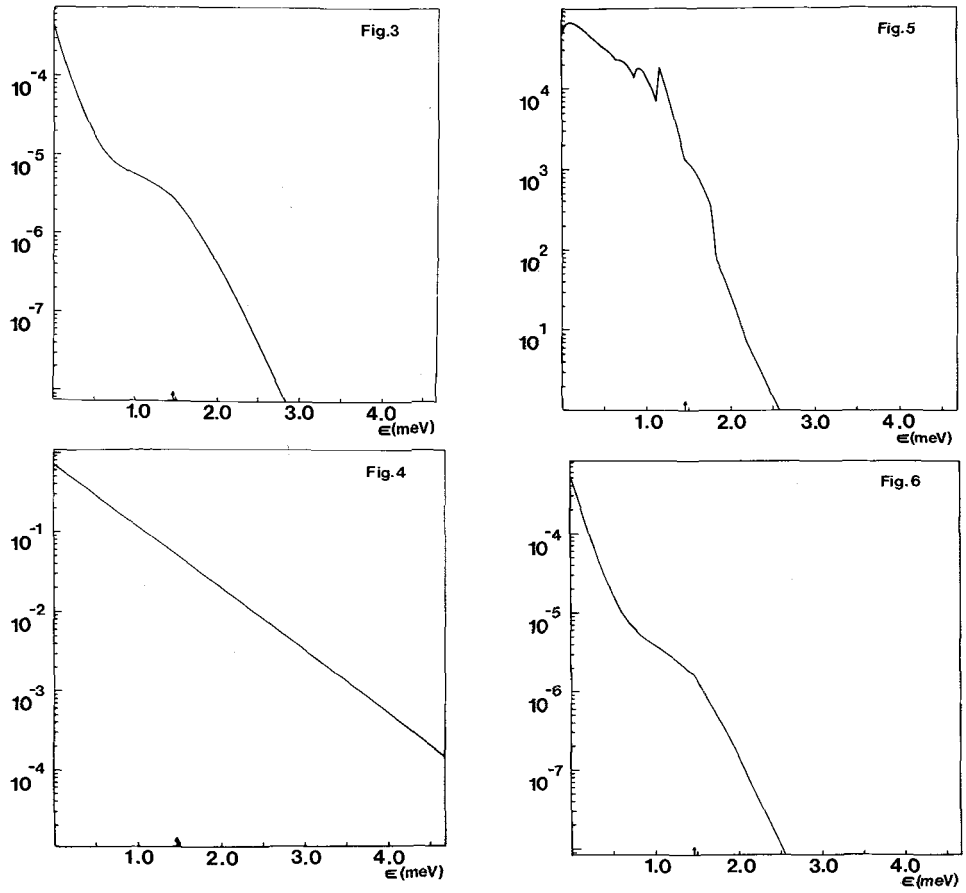

Fig.3: A non-Maxwellian d.f. low density; n = 10^{11} cm^{-3}; $\alpha > 99.99\%$
Fig.4: A Maxwellian d.f.; intermediate density; n = 10^{15} cm^{-3}; $\alpha = 99.99\%$
Fig.5: A non-Maxwellian d.f.; n = 10^{20} cm^{-3}; $\alpha = 92.91\%$
Fig.6: A non-Maxwellian d.f. low density, as Fig.3, but like spin collisions ignored

density is sufficiently low (10^{11} n $\leqslant$ 10^{12} cm^{-3}) or sufficiently high ($10^{18} \leqslant n \leqslant 10^{20}$ cm^{-3}) but are Maxwellian in the intermediate density range ($10^{13} \leqslant n \leqslant 10^{17}$ cm^{-3}). One d.f. from each class is shown in figs 3-5.

The d.f. in the low density range (Fig. 3) are established primarily by T.P. and L.P. scattering. As a result of these processes the injected electrons undergo a cascade of acoustic phonon emissions and then thermalize at the band minimum. These effects cause $\bar{f}$ to have a shoulder and some fine structure at $\epsilon \sim \epsilon_i$ (see Maksym 1980, 1981). Electron-electron scattering rounds the shoulder, smears out the fine structure and heats the electrons contributing to the tail of the d.f. leading to $\bar{f}$ as shown in Fig. 3. (For the d.f. shown in Fig. 3 the tail temperature is $\sim$ 2 K compared with the lattice temperature of 1 K). Note that collisions between electrons of like spin are particularly effective at rounding the shoulder

(compare Figs. 3 and 6; collisions between electrons of like spin have not been taken into account in computing Fig. 6). The result that the d.f. are non-Maxwellian if $n < 10^{12}$ cm^{-3} is consistent with experiments due to Ulbrich (1976). In the high density range (Fig. 4) the d.f. are Maxwellian but the electron temperature depends on the electron density. This is because the rate at which the electrons lose energy to the lattice depends on the electron density via the screening of the piezoelectric interaction. In the high density range (Fig. 5) the d.f. are non-Maxwellian because the e.e. interaction is highly screened. The piezoelectric interaction is also highly screened so the high density d.f. are established primarily as a result of D.P. scattering. This results if $\bar{f}$ having a turnover at the band minimum and some pronounced fine structure at $\epsilon \sim \epsilon_i$ (see Maksym 1981). It is unlikely that the particular non-Maxwellian d.f. shown in Fig. 5 could be observed in practice because the electron distribution is likely to be degenerate at the high densities involved. However, our results lead to the suggestion that photoexcited electrons in GaAs may have a non-Fermi-Dirac d.f. in the electron density is sufficiently high. There is some evidence that this effect occurs (Leheney and co-workers 1979; Shah 1978).

5. Conclusion - Numerical calculations of the distribution function for photo-excited electrons in GaAs with a lattice temperature of 1 K, have been used to show that various departures from quasi-equilibrium can occur if the electron density is sufficiently low ($\ll 10^{12}$ cm^{-3}) or sufficiently high ($\gg 10^{18}$ cm^{-3}). Otherwise the electrons have a Maxwellian distribution with a temperature which depends on the electron density. These results are consistent with the available experimental data.

Acknowledgements - I would like to thank Drs. J.R. Barker and C.J. Hearn for many useful and fruitful discussions and I am grateful for SRC financial support.

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