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ANALYSIS OF HOT ELECTRON TRANSPORT USING EXPERIMENTALLY OBTAINED DISTRIBUTION FUNCTIONS

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Analysis of hot electron-hole recombination spectra in GaAs has yielded important information about the electron distribution function. The non-Maxwellian distribution function was measured at high fields over a wide range of electron energies up to 3 $\hbar\omega_{LO}$, much higher energies than have been previously observed. The experimental results indicate that LO phonon scattering and inter-carrier scattering have a significant effect on the electron distributions.

I. Introduction

The introduction of optical spectroscopy for studing hot carrier phenomena in semiconductors has allowed microscopic analysis of non-linear transport problems [1,2]. The new access has given a deep insight into electron and hole distribution functions (D.F.) and scattering processes which were not determined by the conventional measurement of average velocity or sample conductivity[3,4].

This paper is concerned with hot electron D.F. determined from the recombination spectra of GaAs, to which an electric field is applied. The D.F. at high electric fields are compared with that determined by the Monte Carlo simulation. Here we will pay close attention to the scattering processes which should be faithfully reflected on the shape of the D.F. Reasonable comparisons between the experimental D.F. and the theoretical results will give considerable information about electron-electron, (e,e), scattering which is still of central importance for quantitative description of electrical transport in considerably doped semiconductor devices. Furthermore, at high electric fields, the coupling constant of inter-valley scattering which have been assumed in many previous theories will be discussed with the electron fraction in the central valley.

II. Hot Electron-Hole Recombination Spectra

Band-to-band recombination spectra have been used to determine the hot electron D.F. The analysis used in this paper is substantially the same as the previous works [5]. In the present analysis, the non-parabolicity of the conduction band was taken into account to analyze the recombination spectra over a wide range of photon energies. Electric field-dependent photoluminescence was excited in a p-type GaAs (N_A-N_D=3 x 10^{15} cm^{-3}) immersed in liquid nitrogen by a He-Cd laser light with the output power of 50 mW at 4416 Å. A thin epitaxial wafer less than 1 μm was photo-etched to form a bridge-shaped sample with a small cross section area (200 x 200 μm^2) on which laser light was focused. The D.C. pulse voltage with a duration of 5μsec was also applied to the active region of the sample. Since the scattering times for (e,e) and electron-phonon interactions are shorter than the recombination lifetime due to the band-to-band transition [6], it is reasonable to consider that thermalization of photo-excited carriers is established under the external electric field and the equilibrium carrier distribution should be reflected in the recombination spectra.

In Fig.(1) the emission spectra of hot electron-hole recombination are depicted for typical electric fields. Current-voltage characteristics of the sample have been simultaneously measured to observe any instabilities, which cause inhomogeous field distribution. Even at higher electric fields than the threshold of Gunn effect, no current instability has been observed. The decrease in total emission intensity with increasing electric field is attributed to the change of the electron density. The electron sweep-out from the active region is important, because some electrons can pass through the active region between ohmic contacts before they recombine with holes. This effect causes a significant reduction of the emission intensity as the drift velocity increases. At fields above the threshold, on the other hand, valley transfer of hot electrons is predominant process for decreasing the intensity which can serve information of intervalley phonon scatterings.

III. Hot Electron Distribution Function and Scattering Process

Figure (2) shows the D.F. derived from the spectra, some of which are shown in Fig.(1). Electron D.F., or occupation probability, has been determined for electron energies up to more than $3\hbar\omega_{LO}$ (36.74 meV) from the conduction band edge. The experimental results at low electric fields are shown by a full line in Fig.(3) (at 600 V/cm) and Fig.(4) (at 1.3 kV/cm). It should be noted in a set of the experimental data that the shape of the D.F. is modulated significantly due to the scattering process at each electric field. The LO phonon kink was clearly observed in the D.F. at 0.6-2.8 kV/cm, whereas this became insignificant at higher electric fields. It is obvious that the D.F. can not be approximated with a straight line, that is, the Maxwellian D.F.

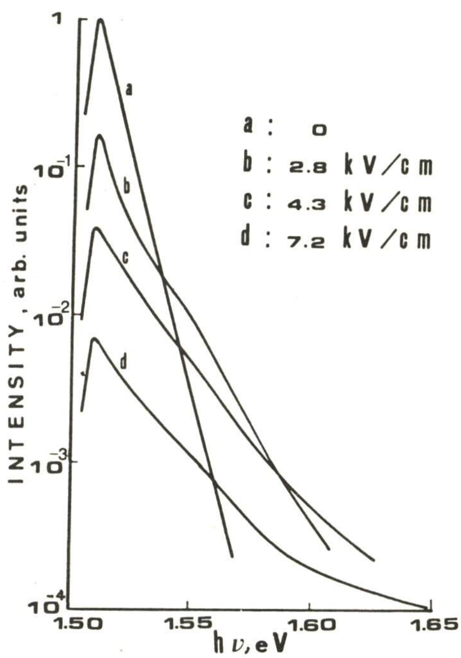

Fig.(1) Photoluminescence spectra at 77 K with and without electric field

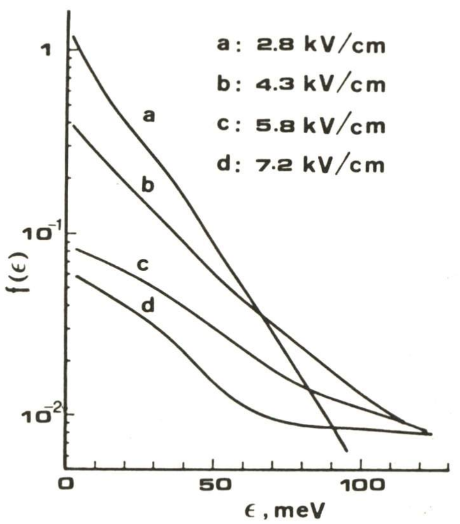

Fig.(2) Experimentally determined electron distribution functions

Here we compare the experimental results with D.F. derived from Monte Carlo calculations. In Fig.(5) the theoretical D.F. are shown for the same electric fields as in the experiments. The resemblance between the sets of curves in Fig.(2) and (5) is strong, although there is some difference in a fine structure. Electron-electron scattering which may be important was taken into account by using the same method as in the previous paper [7]. At the electric fields, 0.6 and 1.3 kV/cm, the effects of (e,e) scattering is clearly seen in Fig.(3) and (4). We have to recall the experimental condition and consider how many electrons and holes were there in the active region. For the photon energy of 2.81 eV in the present experiment, most of incident photons must be absorbed within 0.1μm. Self-absorption of the recombination radiation is also important. Therefore, the electrons which recombine with holes near the surface are mainly responsible for the experimental D.F. In order to estimate the carrier density near the surface, photoconductivity has been measured in thin layers processed by a slow etching technique. The apparent carrier density near the surface was expected to be the order of 10^{16} cm^{-3} under the photo-excitation. It seems reasonable to assume slightly higher electron and hole concentrations, $n=p=5 \times 10^{16}$ cm^{-3}, than the original impurity concentration of the sample. The interaction between electron and heavy hole was considered, while the effect

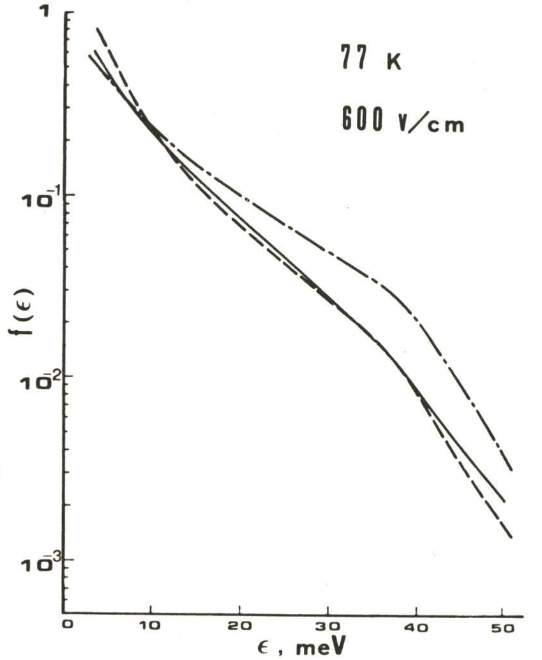

Fig.(3) Comparison between the experiment(full line) and the theory[dashed line : with (e,e) scattering, dash-dotted line : without (e,e) scattering]

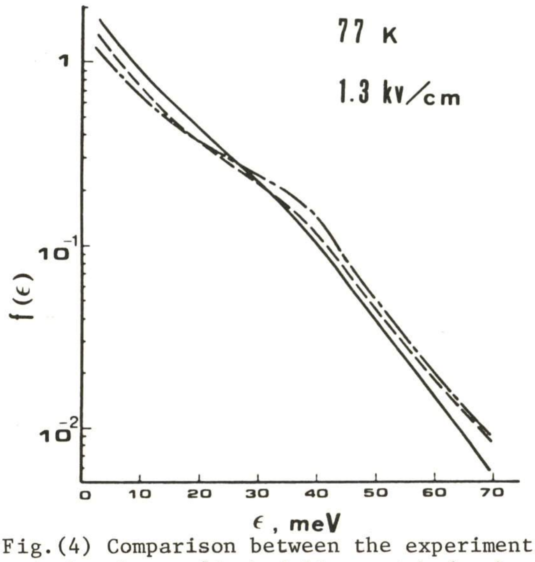

Fig.(4) Comparison between the experiment and the theory [dashed line : with (e,e) scattering, dash-dotted line : without (e,e) scattering]

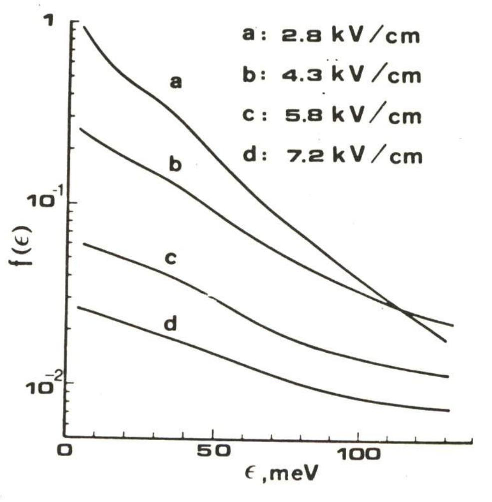

Fig.(5) Theoretical D.F.

of light hole was neglected. Because the density of light hole is considerably lower than that of heavy hole. The scattering rate for this process was calculated by using the same formula as for ionized impurity scattering, since the heavy hole mass is much larger than the electron mass in GaAs. At 600 V/cm, as seen in Fig.(3), (e,e) scattering is effective and gives a good agreement with the experiment. At 1.3 kV/cm, however, the only small shift of the D.F. was given by (e,e) scattering as seen in Fig.(4). The important features of the results are :

(i) Electron-electron scattering modulates the shape of the D.F. to be close to a smooth line, and the LO phonon kink becomes indetectable. This supports the common understanding that after predominant inter-carrier scatterings the D.F. can be reasonably approximated by the Maxwellian D.F.

(ii) The effect of (e,e) scattering is of less importance at high electric fields. This is the same as for ionized impurity scattering.

The electron density was estimated by the integration of the experimental D.F. multiplied by the density of states. Although the experimental D.F. was cut off at 120 meV from the conduction band edge, relative changes of the electron density which is responsible for the recombination radiation can be depicted as a function of the electric field. Figure (6a) shows the experimental results which are normalized by the density at 2.8 kV/cm. For comparison with the experiment, a fraction of electrons in Γ valley calculated by the simulation is shown in Fig.(6b). Two curves are for different coupling constants of inter-valley scattering between Γ and L valleys. Theoretical curves have resemblance to the experimental results. Although the coupling constant,or intervalley deformation potential, can not be determined from the present data, more careful measurements and analysis on the extensive tail of the D.F. will make a conclusion about this important parameter.

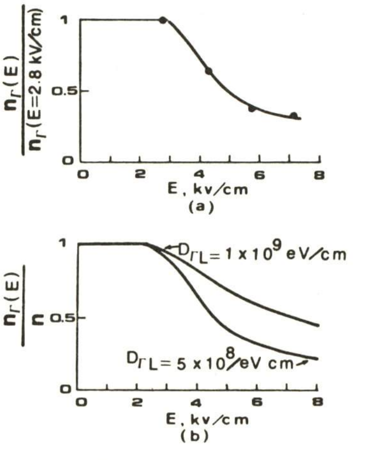

Fig.(6a) Experimentally derived electron density as a function of the field. (6b) Theory : Fraction of electrons in the Γ valley

To summarize, the present experiments have shown the hot electron D.F. over a wide range of electron energies at 0.6 - 7.2 kV/cm. The D.F. determined from the experiments were carefully compared with the theoretical D.F. We have devoted discussions to the important effects of LO phonon, electron-electron and intervalley scatterings on the shape of the D.F. These microscopic analysis using the experimentally obtained D.F. will help to further elucidate transport problems in semiconductors.

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