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NON MAXWELLIAN ELECTRON DISTRIBUTION FUNCTION IN GaAs

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Résumé : La distribution des électrons chauds est étudiée dans l'AsGa de type n d'une qualité très pure. Les électrons sont stimulés par des champs électriques continus dans des champs magnétiques. L'émission cyclotron, qui en résulte, est analysée par des détecteurs photoconducteurs d'une résolution de 0.25 cm⁻¹. En configuration E//B les températures des électrons, distribués entre des niveaux de Landau, s'élévent extrêmement jusqu'à 180 K. La distribution des électrons devrait dévier considérablement d'une loi maxwellienne. La bande d'électrons diffère d'une parabole plus que prédit théoriquement.

Abstract: Hot electron distribution functions in a magnetic field are investigated in high purity n-type GaAs. The electrons are excited by d.c. electric fields and the resulting Cyclotron emission is analysed with narrowband photoconductive detectors with a resolution of 0.25cm⁻¹. Extremely high interband electron temperatures up to 180K are observed in the E//B configuration indicating strong deviations from a Maxwellian type distribution function. The nonparabolicity of the conduction band is found to be considerably stronger than theoretically predicted.

1. Introduction:
The electron system in a semiconductor at very low temperatures is no longer in thermal equilibrium with the lattice when a moderate electric field (some V/cm) is applied. In this case the electron distribution is described in terms of a temperature $T_e$ higher than the lattice temperature /1,2/. This hot electron concept has been treated in various ways with special emphasis on n-type InSb. One approach involving electric field (E) modulated cyclotron resonance, was pursued by the group of Otsuka /3,4,5/. The electric field dependent far infrared transmission was used to determine hot electron distribution functions in a quantizing magnetic field (B). The intensity and lineshape of the cyclotron resonance lines was analysed. Two types of electron temperatures (inter- and intrasubband) were found necessary to describe the observed data. Deviations from a Maxwellian type distribution were found in the manner pedicted by Yamada and Kurosawa (YK) /6/ and Kotera /7/ with stronger deviations for the E//B, than for the EiB case. However the observed $T_e$ values
(T_e(max) \approx 50K) are considerably lower than the calculated (T_e(calculated) \approx 100-200K) ones.

A second approach to the hot electron problem uses the analysis of cyclotron emission spectra /8-10/. This technique, which has previously also been applied to InSb yields information on the distribution of electrons in higher Landau levels. Müller et al /9/ have performed detailed experimental studies for the case E \perp B and found the electron heating to depend on the free carrier concentration of the sample. Partl et al /10/ could show that this effect is due to the role of electron-electron scattering in combination with optical phonon emission. They included electron-electron scattering and Landau level broadening into the theory of YK /7/ and improved significantly the agreement between experimental and theoretical T_e values. The deviation of the distribution function from a Maxwellian type is found to be small due to the randomizing effect of the electron-electron scattering in n-type InSb.

The present work is an extension of the emission technique to n-type GaAs. GaAs is available in considerably higher purity than InSb. In the absence of significant electron-electron scattering strong deviation from Maxwellian type distributions are expected. In this paper we will show for the first time that electron temperatures between 100K and 200K can be achieved in high purity GaAs in agreement with the predictions of YK /7/.

II. Experimental results

Investigations of electrically excited recombination radiation between Landau levels were carried out in the magnetic field range between 3.0 and 8.0 T at liquid helium temperatures. The experimental system used has been described in detail previously /9/. It consists of two superconducting magnets positioned in a distance of 26cm. One holds the emitter sample the other the photoconductive detector. A high purity
extrinsic n-type GaAs detector is used to detect and analyse the radiation. The narrowband response (linewidth 0.25 cm\(^{-1}\)) of the 1s-2p \((m=+1)\) transition is used for spectral analysis between 40 and 100 cm\(^{-1}\); the broadband response due to the 1s-continuum transitions at B=0 for measurements of the integral intensity.

Two different GaAs samples are investigated: sample R137 with a free carrier concentration of \(n_0=2.10^{13} \text{cm}^{-3}\) and a total ionized impurity concentration \(N_I=8.10^{13} \text{cm}^{-3}\) and sample L83 with \(n_0=1,2.10^{14} \text{cm}^{-3}\) and \(N_I=2.10^{14} \text{cm}^{-3}\).

Emission spectra as a function of the emitter magnetic field are shown in Fig.1 for two electric fields in the \(E//B\) configuration. The detector is set with a constant magnetic field to a certain frequency. Resonant peaks occur in the spectra when the emission line coincides with the detector line. As the emitter is tuned, higher energies appear on the low magnetic field side, lower at the high field side. The spectra for the lower emission frequency consists of up to 4 lines, for the higher of two lines.

From the increase in intensity of the additional lines with increasing electric fields we conclude, that these lines are due to transitions between higher Landau levels. In the spectra for the lower magnetic field the intensity due to emission from the \(N=2\) Landau level is dominant. The separation of the emission spectrum in several individual lines reveals a strong effect of nonparabolicity. To demonstrate the effect of nonparabolicity we have plotted in Fig.2 the energy of higher Landau level transitions with respect to the lowest transition \((N=1 \text{ to } N=0)\), which is simply the apparent splitting from the first line in cm\(^{-1}\). The deviation from a parabolic behaviour amounts up to 5\% for the \(N=3 \text{ to } N=2\) transition. The full curves in Fig.2 show calculated energy differences between Landau levels using the formula given by Stillmann et al. \(^{12}\).

The calculated splittings are significantly smaller, however the tendency is

![Fig. 2: Energy differences (cm\(^{-1}\)) of Landau transitions 2-1 and 3-2 in respect to 1-0. The full curves are theoretical plots according to \(^{12}\). Different symbols represent data from different samples.](image-url)
well described. At present we do not have an explanation for the observed nonparabolicity.

III. Analysis and discussions
The emitted radiation is due to transitions between different Landau levels. Since the spin splitting in GaAs is very small \cite{12} the observed lines correspond to transitions from electrons with increasing quantum number: line 1 from $N=1$, line 2 from $N=2$ and so on. The observed emission line intensities reflect directly the population in the initial Landau levels. The apparent strong nonparabolicity of the conduction band of GaAs provides the basis for our data analysis: Since each emission line appears at a different energy (or magnetic field in the spectra) we can determine the originating Landau level of the electrons and the distribution function in a wide energy range. However, the density of states peaks at the Landau level edges so that we track predominantly the population at the bottom of each level.

Electron temperatures can be defined in two ways: one is the intersubband temperature defined by the relative population of Landau subbands. This temperature is determined from the ratio of the individual intensity peaks. The other is the intrasubband temperature defined through the distribution within each subband. Our present analysis is restricted to the calculation of intersubband temperatures. Information on intraband temperatures could be obtained from a linewidth analysis of the individual lines \cite{5}. This is not possible from our experiments since the separation between the lines is comparable to their width.

The emission intensity from Landau level $N$ is given by $I_N = C \cdot N \cdot n_N$ where $C$ is a constant (if $B, E$ are constant) and $n_N$ is the population of the level $N$ \cite{3}. The interband electron temperature $T_{N, N-1}$ is defined through the relation: $n_N = n_{N-1} \exp(-\hbar \omega_c / k_B T_{N, N-1})$ where $\omega_c$ is the cyclotron frequency and $n_{N-1}$ the population in the $(N-1)$ level. Combining the two relations we obtain for

$$T_{N, N-1} = \frac{1}{k_B} \hbar \omega_c / \ln \left( \frac{N}{N-1} \frac{I_{N-1}}{I_N} \right).$$

Interband temperatures $T_{2,1}$ for sample $R137$ as derived from emission spectra at several magnetic fields are shown in Fig.3 as a function of the applied electric field for the $E//B$ configuration.

There are two ranges of emission frequencies which show the same behaviour: For frequencies between 40 and 65 cm$^{-1}$ (corresponding to magnetic fields between 3.5 and 5 T) the electron heating is independent of magnetic field. Extremely high temperatures between 75K and 180K
are obtained. For frequencies between 70 cm$^{-1}$ and 85 cm$^{-1}$ the heating is reduced, but again nearly independent of magnetic field.

In the picture of the YK theory /6/ for the E//B configuration the electron heating is governed by an interplay of energy gain in the electric field and cooling due to optical phonon emission. The magnetic field only influences the scattering rate for E//B which could reduce the energy gain. However this effect seems not to be significant in GaAs, since the heating is nearly independent of B. The enhanced electron cooling above a certain magnetic field suggests the existence of a resonant cooling effect. It is interesting to note, that this enhanced cooling coincides with the N=4 Landau level passing through the optical phonon energy.

Interband temperatures $T_{2,1}$ for the E\perp B configuration are shown in Fig. 4 for sample R137 and L83. The temperatures are lower than for the E//B case for all frequencies. No difference in the heating is observed when the sample concentration is increased from $2.0 \times 10^{13}$ cm$^{-3}$ to $1.4 \times 10^{14}$ cm$^{-3}$ indicating no significant influence of the electron-electron-scattering in contrast to the results in InSb /4/. A systematic decrease in heating with increasing magnetic field is observed. The observed behaviour might be due to an
enhancement of an acoustic phonon emission with increasing magnetic field. To obtain a rough picture of the distribution function, the knowledge of $T_{1,0}$ is necessary. $T_{1,0}$ can be derived from the electric and magnetic field dependence of the integral intensity according to the approach of Müller et al. We have used this technique to determine $T_{1,0}$ in the frequency range between $50\text{cm}^{-1}$ and $70\text{cm}^{-1}$ using a GaAs detector at zero magnetic field. The interband temperatures $T_{1,0}$ obtained are considerably lower than the temperatures between higher levels.

A plot of the distribution function for a electric field of $150\text{ V/cm}$ and two different magnetic fields is shown in Fig.5 for the $E//B$ configuration. Our data yield only information about interlevel temperatures, so that we can only draw straight lines between the levels. In the figure $T_{3,2}$ values obtained are also included. The resulting distribution functions are extremely non Maxwellian and reveal clearly the run away effect in the longitudinal configuration. The drop on the high energy side is due to optical phonon emission. In the $E\perp B$ case the form of the distribution functions is similar however the deviations from a Maxwellian type are smaller.

Further experiments to determine in the intra Landau level temperatures from a linewidth analysis are in progress.

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