RECOMBINATION RADIATION FROM LANDAU STATES IN IMPACT IONIZED GaAs∗

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Recombination radiation from Landau states in impact ionized high-purity GaAs has been observed. The narrow band (~ 3 cm⁻¹) emission has been magnetically tuned from 80–120 cm⁻¹, and used to observe rotational transitions in water vapor.

WE HAVE studied the far-infrared recombination radiation from excited states in impact-ionized, high-purity GaAs at high magnetic fields (60 kG < B < 100 kG). For voltages just above breakdown, the spectra are dominated by emission from a single level. Analysis of the magnetic field dependence of this radiation shows it to be decay between adjacent Landau levels. Tuna-

bility of the radiation from 80 to 120 cm⁻¹ has been observed and the 'resolution' of the source has been estimated from water vapor absorption measurements.

In contrast, luminescence from similar samples previously observed by Melngailis et al.1 at zero magnetic field, and by Stillman et al.2 at low magnetic fields, was dominated by the 2P → 1S hydrogenic donor transition which peaks at about 35.5 cm⁻¹. Zeeman splitting of the 2P → 1S radiative decay was observed at 7.5 kG.

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The 350μ thick, 5 x 5 mm epitaxially grown GaAs sample used in our experiment had a donor concentration of ND = 5.6 x 10¹⁴ cm⁻³, an acceptor concentration of NA = 1.4 x 10¹⁴ cm⁻³, and a mobility at 77 K of μ = 105,000 cm²/V sec. Ohmic contacts were attached along two sides and the sample was mounted inside a one-half inch brass light pipe, with the large surface of the sample perpendicular to the magnetic field. The sample was immersed in liquid helium at 4.2 K and positioned in the bore of a 100 kG superconducting magnet. Voltage pulses just sufficient to produce impact ionization were applied to the sample and the luminescence thereby generated was guided by a tapered light pipe into a grating monochromator, purged with dry nitrogen gas. The radiation at the output of the monochromator was detected with a germanium bolometer operating at 1.8 K. The bolometer signal was fed into either a lock-in amplifier or boxcar integrator, depending on the duty cycle of the pulses. The best signal-to-noise ratio was obtained with lock-in detection at a repetition rate of 100 Hz and a 30 per cent duty cycle.

The spectral dependence of the recombination radiation on magnetic field is shown in Fig. 1, along with cyclotron resonance absorption measurements previously made on similar samples using H₂O laser
FIG. 1. A plot of the magnetic field dependence of the observed recombination radiation in GaAs. Also shown for comparison are 4.2 K cyclotron resonance absorption measurements at 84.3 and 127.5 cm⁻¹. The straight line between these two points indicates the magnetic field dependence of \( n = 0 \rightarrow n = 1 \) cyclotron resonance absorption.

lines at 84.3 and 127.5 cm⁻¹. The coincidence of the recombination radiation spectra with the cyclotron resonance absorption measurements and the linear dependence of radiation energy on magnetic field support our claim that decay between Landau levels is the principal source of the observed luminescence. Although previous low field results confirm large oscillator strengths of the \( 2P \pm 1 \rightarrow 1S \) impurity transitions in GaAs, at high magnetic fields dominance of Landau radiation is anticipated. The oscillator strength for the \( \Delta n = 1 \) Landau level transition is essentially unity. Moreover, comparison of the density of states strongly favor this transition. The density of states for the \( n \)th Landau level (including both spin states) is

\[
\frac{dN(n; E_H)}{V} = \frac{2}{(2\pi)^3} \frac{eb \left( 2m^* \right)^{1/2}}{\hbar^2} \frac{dE_H}{(E_H)^{1/2}}
\]

where \( E_H \) is the electron energy parallel to the magnetic field,

\[
E_H = \frac{\hbar^2 k_H^2}{2m^*}
\]

When the effects of scattering are taken into account, the singularity in the density of states for \( E_H = 0 \) is removed. For the purpose of estimating the number of levels per unit volume, however, it is sufficient to integrate equation (1) over allowed values of \( E_H \). We can then write the number of states per Landau level per unit volume as

\[
\frac{N(n, \Delta E_H)}{V} = \frac{4\sqrt{2} \left( m^* \right)^{3/2}}{(2\pi)^2 \hbar^3} E_{CR} (\Delta E_H)^{1/2},
\]

where

\[
E_{CR} = \frac{\hbar e B}{m^* c}
\]

and \( \Delta E_H \) is the upper limit of the electron energy parallel to the magnetic field. If we take \( E_{CR} = 10 \text{ meV} \) (corresponding to cyclotron resonance at 59 kG in GaAs) and \( \Delta E_H = 0.01 E_{CR} \), we find that \( N/V \approx 10^{16} / \text{cm}^3 \) for Landau states in GaAs, more than an order of magnitude greater than the density of impurity levels in our sample.

Recently other studies of the recombination radiation spectra from impact ionized donors have been made by Gornik and Kobayashi in InSb samples as a function of magnetic field. Gornik, using the tunability of an InSb photodetector (in a magnetic field), has concluded that radiation due to impurity transitions is dominant for fields below 10 kG. At fields between 10 and 15 kG, Kobayashi, employing the narrow-band detectivity of a Ge/Sb photodetector, has identified emission resulting principally from Landau states. A more positive determination of the states contributing to the luminescence in InSb requires more detailed spectral analysis. However, these results are generally consistent with this and the previous work in GaAs.

The total radiated power from the GaAs sample is estimated from detector responsivity, light pipe losses and lock-in signal to be about \( 5 \times 10^{-9} \text{ W} \). The maximum output power is insensitive to magnetic field at the optimum applied voltage. The breakdown voltage, however, increases monotonically with magnetic field, from 4V/cm at zero field to 40V/cm at 100 kG. Because we were limited by the low signal-to-noise ratio, the entrance and exit slits of the monochromator were set at maximum opening, giving a resolution of about 5 cm⁻¹. To investigate the line width of our radiation further, we constructed a 'spectrometer' using a water cell to examine the water vapor absorption of our radiation. Our setup is as shown in Fig. 2.

The water cell consisted of a section of brass light pipe 8ft. long and one-half in. in diameter. The two ends were vacuum sealed with polyethylene windows.
The cell was first evacuated and then water vapor was bled into the cell through a needle valve from a flask of water. The pressure in the cell was maintained at about 10 torr at room temperature (298 K).

We tuned our radiation with the magnetic field from 60 to 71 kG. The insert of Fig. 2 is a plot of the transmitted intensity through the water cell vs magnetic field, showing two strong absorptions centered at 63.3 and 66.5 kG. These two lines correspond to energies of 88 and 93 cm\(^{-1}\) and can be identified as the \(3_{03} \rightarrow 4_{14}\) and \(1_{10} \rightarrow 2_{21}\) rotational water vapor transitions observed by Hall and Dowling. The fact that these two lines are resolved indicates that the width of our luminescence is \(\leq 3\) cm\(^{-1}\).

A more accurate determination of the emission linewidth, using a 0.5 cm\(^{-1}\) resolution Michelson interferometer, is now in progress. The linewidths and intensity of radiation from samples with various doping levels will be measured to determine their dependence on impurity concentration.

REFERENCES

Wir konnten die Rekombinationsstrahlung von Landau niveaus im stossioni-
sierten GaAs großer Reinheit beobachten. Die schmalbändige Strahlung
(\( \sim 3 \text{ cm}^{-1} \)) konnte magnetisch zwischen 80 und 120 cm\(^{-1}\) eingestellt werden, um Rotationsübergänge vom Wasser dampf zu beobachten.