Far-infrared emission from magnetically quantized two-dimensional electron gases in $GaAs/Al_xGa_{1-x}As$ heterojunctions

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(Received 20 September 1993; revised manuscript received 17 December 1993)

An investigation has been made of the far-infrared cyclotron emission from electrically heated, magnetically quantized two-dimensional electron gases using a technique employing a broad-band detector. Spectral resolution is obtained by using the substrate as a Fabry-Pérot étalon. The experiments indicate that the system is well adapted for measuring the electron temperature as a function of magnetic field. Further spectroscopic information is obtained by including a low-pass filter. The system has been used to investigate the emission spectrum and its intensity in fields up to 3 T and currents up to 1 mA (current density of 5 mA/mm). The measurements demonstrate that 20–30 % of the emission occurs at frequencies less than ω_c.

INTRODUCTION

In recent years, two-dimensional electron gases (2DEG's) have been extensively studied by far-infrared (FIR) transmission and reflection spectroscopy in both zero and quantizing magnetic fields.[1–3] Somewhat less attention has been given to investigating the FIR radiation emitted when the temperature of the 2DEG is raised above that of the lattice by passing a current from source to drain. However work has been carried out both in zero field[4–7] and in quantizing magnetic fields[8–12] where it has been shown that the emission occurs predominantly at the cyclotron frequency as expected. The measurements in quantizing fields were all made using narrow-band GaAs photodetectors although for other measurements, broad-band detectors have been used combined with fixed frequency[13] or tunable[7,14] narrow-band filters.

The dissipation in magnetically quantized 2DEG's is intrinsically inhomogeneous with different behavior in the current entry and exit regions near the contacts than in the rest of the sample. There may also be detectable differences between the dissipation at the edges and that in the rest of the 2DEG. As a result the electron temperatures might vary with position and this should be reflected in the FIR emission. So the emission spectrum, and its variation with electron current, magnetic field, position, and sample geometry, are expected to be quite complex but should provide detailed information on the nature of the dissipation.

The main purpose of the present experiments has been to develop a technique capable of determining absolute values of FIR intensity for a range of magnetic fields and so cyclotron frequencies. A broad-band detector is used and spectroscopic information is obtained by using the substrate as a Fabry-Pérot étalon. Interference effects arising from reflections from the surfaces are a familiar and usually unwanted feature of FIR spectroscopy[1,15,16] and the present work may be the first in which they have been used intentionally. Additional spectroscopic information is acquired by inserting a low-pass filter between the source and detector. Absolute measurements of intensity are valuable in that they provide direct information on the electron temperature T_e. The FIR intensity has been used to obtain T_e values of 2DEG's for both GaAs (Refs. 4 and 5) and Si (Ref. 6) in zero field but not previously in magnetic fields. In the latter case T_e values have usually been obtained from the amplitudes of the Shubnikov–de Haas oscillations in magnetoresistance; however this method may only be applicable at low fields, where the energy variation in density of states is small ($\mu B \lesssim 1$ where μ is the mobility and B is the magnetic field), and at low temperatures $T_e \lesssim 20$ K. The FIR technique is not restricted in this way so it should be possible to use it to determine T_e values in strongly quantized systems and at appreciably higher temperatures than is possible with other techniques.

The paper also describes and analyzes measurements of the total FIR intensity from several GaAs heterostructures as a function of current up to 1000 μA and magnetic field up to 3 T. A conference report on some of the results has recently been presented.[17]

EXPERIMENTAL ARRANGEMENT

The arrangement is shown in Fig. 1. The sample is bonded with GE7031 varnish to a copper post whose further end is in contact with liquid helium. The post is fitted with a heater and thermometer so that, if required, measurements can be made with the sample temperature raised above that of the helium bath. The sample and detector are located 1–2 mm from the two ends of an evacuated 18 cm copper light pipe of inner diameter 5 mm, allowing the detector to be in an essentially field-free region while magnetic fields from a 0–7 T superconducting solenoid are applied normal to the sample.

The FIR detector is a thin InSb crystal operated as a hot-electron device. It has a nominal cross section of 5×5 mm^2 and is mounted on a 5° quartz wedge. Its op-

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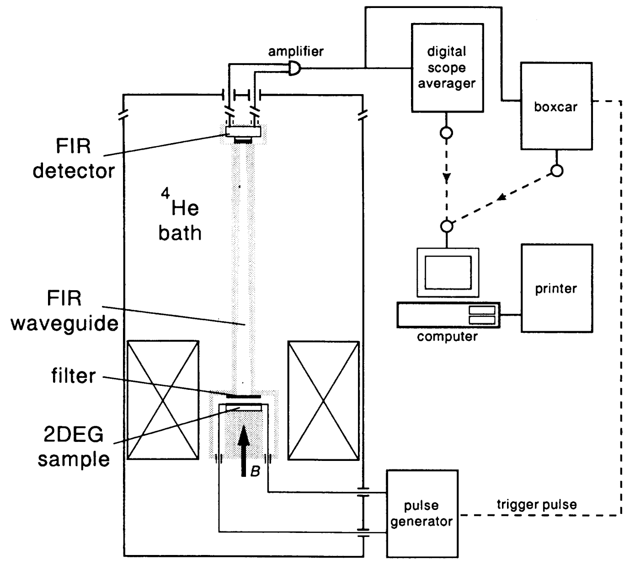

FIG. 1. The experimental arrangement.

tical response is constant for $\nu < 15\ \mathrm{cm}^{-1}$ but for $\nu \geq 15\ \mathrm{cm}^{-1}$ it falls as $\exp[(\nu - 15)/15.4]$ with ν in cm^{-1}; its integral sensitivity is $5.0\ \mathrm{kV\,W}^{-1}$. The detector output is amplified and stored using either a digital oscilloscope or a boxcar integrator. A low-pass filter can be placed in the light path above the sample and the filter used in the present work has a sharp cutoff in transmission at $15\ \mathrm{cm}^{-1}$, falling as $T_\nu \simeq \{1 + \exp[(\nu - 15)/0.5]\}^{-1}$ for $\nu > 15\ \mathrm{cm}^{-1}$. The filter, detector, and amplifier system was supplied and calibrated by QMC Instruments, Queen Mary and Westfield College, London University. Measurements of the optical efficiency of the light pipe for various incident angles made using a FIR laser showed that its efficiency falls from ~ 1 (axial incidence) down to ~ 0.5.

Spectroscopic information is obtained by using the substrate as a Fabry-Pérot étalon. Part of the FIR emission from the 2DEG travels towards the back surface of the substrate furthest from the 2DEG where it is reflected up towards the detector and interferes with the other component of the emission. The reflectivity is increased by polishing both the back surface and the top of the copper post to which it is bonded.

The 2DEG's are heated by current pulses of duration 10–120 μs and the repetition rate is always kept below 1 kHz. Under these conditions the rise in substrate temperature at the maximum power level is estimated to be less than 1 K. To eliminate pickup alternate pulses of opposite sign are used. A series resistor is used to maintain approximately constant pulse current during the field sweeps. Some higher current experiments were made at constant voltage in both zero and quantizing magnetic fields.

Experiments were carried out on several single GaAs/(Al,Ga)As heterojunction devices processed from three wafers with the following sheet densities n (in $10^{15}\ \mathrm{m}^{-2}$) and transport mobilities μ_0 (in $\mathrm{m^2\,V^{-1}s^{-1}}$): NU276, $n = 2.3$, $\mu_0 = 22$; NU444, $n = 3.4$, $\mu_0 = 144$; NU711, $n = 2.9$, $\mu_0 = 80$. The results shown here are for three devices typical of those for each wafer. The first two devices (from NU276 and NU444) are standard eight-contact Hall bars with channel dimensions $2.5 \times 0.2\ \mathrm{mm}^2$ and the third (from NU711) has the shape of a cross in which each leg has dimensions $4.0 \times 0.2\ \mathrm{mm}^2$ and a contact at its extremity. The contact resistances were all less than 50 Ω so should contribute negligibly to the FIR emission.

THEORY

The detector signal can be written

$$P_C^D = \int_0^\infty E(\omega) I(\omega) D(\omega)\, d\omega, \tag{1}$$

where $E(\omega)$, $I(\omega)d\omega$, and $D(\omega)$ are respectively the emissivity of the 2DEG, the intensity emitted in the range ω to $\omega + d\omega$ by a blackbody at temperature T_e of area equal to the 2DEG, and the detector sensitivity. The expression makes the usual assumption that electron-electron relaxation is sufficiently fast compared with electron-phonon relaxation for the heated electron system to be in internal thermal equilibrium. It also assumes that there is no net emission from the substrate and metal contacts, which seems reasonable since their emissivities and temperatures relative to the detector are both very much less than that of the 2DEG. The emissivity of the substrate is evidently very small since it is transparent at these frequencies and the metal films are estimated to have emissivities smaller than that of the 2DEG by ~ 10. The detector sensitivity was measured by the manufacturer and $D(\omega)$ in Eq. (1) neglects any reduction in transmission efficiency of the light pipe from radiation at oblique incidence.

From electromagnetic theory, the emissivity $E(\omega)$ in the direction normal to the plane of a 2DEG of conductivity $\sigma(\omega)$ at the surface of a transparent medium of thickness d and relative permittivity ϵ is given by

$$E(\omega) = \frac{4\mathrm{Re}[\sigma(\omega)/\epsilon_0 c]}{|\, 1 - \imath\sqrt{\epsilon}\cot\delta + \sigma(\omega)/\epsilon_0 c\,|^2}, \tag{2}$$

where $\delta = 2\pi d/\lambda$, ϵ_0 is the vacuum dielectric constant, and λ is the wavelength inside the medium. This expression assumes perfect reflection at the back surface with a phase change of π but neglects reflection at the upper surface. $E(\omega)$ oscillates with magnetic field B normal to the 2DEG with a period of oscillation

$$\Delta B = \frac{\pi m^* c}{ed\sqrt{\epsilon}} \tag{3}$$

and has minima at $\delta = \jmath\pi$, where $\jmath$ is an integer (m^* is the electron effective mass and c is the velocity of light *in vacuo*).

The conductivity $\sigma(\omega)$ is strongly modified by a magnetic field and we assume the classical Drude expression[15]

$$\sigma(\omega) = \frac{(ne^2\tau/m^*)(1 + \imath\omega\tau)}{(1 + \imath\omega\tau)^2 + \omega_C^2\tau^2}, \tag{4}$$

where the cyclotron frequency $\omega_C = eB/m^*$ and τ is the electron relaxation time for momentum relaxation. In zero magnetic field $\tau = \tau_0$ can be obtained from $\sigma = ne^2\tau_0/m^*$. However, in magnetic fields, the relaxation time τ_C obtained from the cyclotron resonance linewidth differs appreciably from τ_0 because of screening and other effects such as the different role of small-angle scattering in zero and quantizing magnetic fields.[2,3]

The emission from the 2DEG is not confined to the normal but since the critical angle for transmission from the substrate is $\sim 16°$, Eq. (2) above should provide a reasonable description for the emissivity of the total ra-

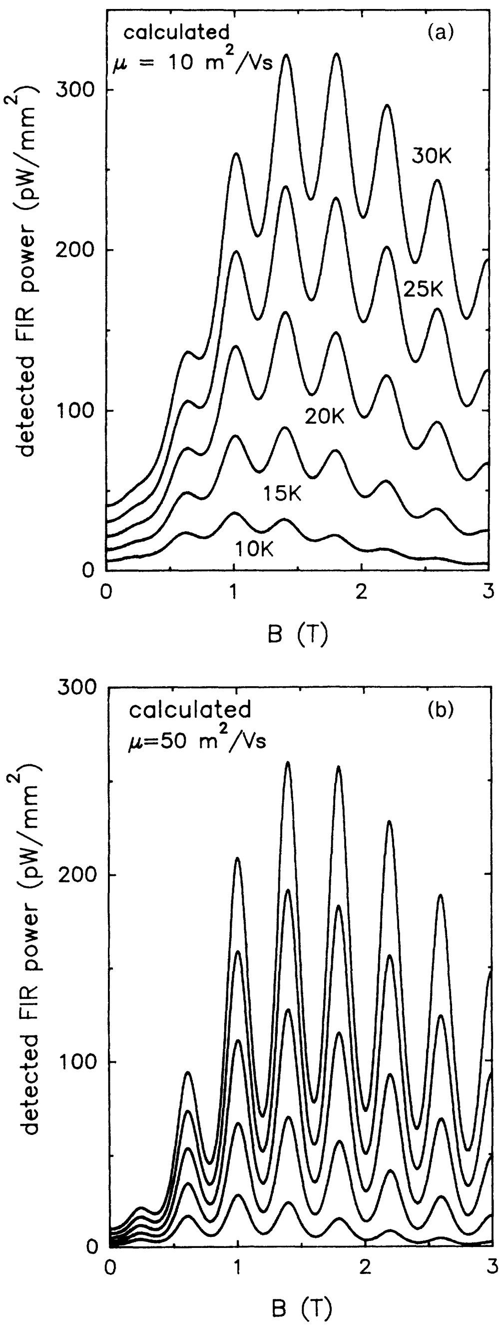

FIG. 2. Calculated values of the detected FIR emission from a heated GaAs 2DEG at various values of electron temperature as a function of magnetic field for two samples of substrate thickness 250 μm and mobility (a) 10 $m^2\,V^{-1}\,s^{-1}$ and (b) 50 $m^2\,V^{-1}\,s^{-1}$; the values of T_e are the same as in (a). The lattice temperature was assumed to be 4.2 K. The calculations are based on the Drude model as described in the text.

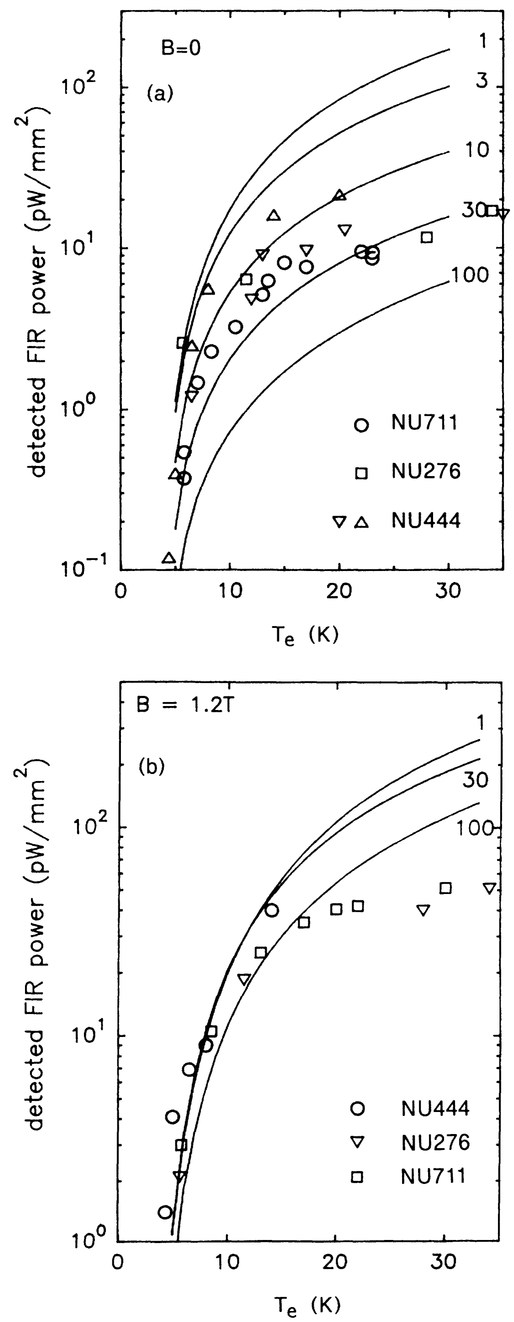

FIG. 3. Values of the detected FIR power from a heated GaAs 2DEG as a function of electron temperature for a lattice temperature of 4.2 K. The mobilities in $m^2\,V^{-1}\,s^{-1}$ for which the curves are calculated are shown to the right of the figures and the points are experimental data using T_e values from Ref. 17. Results are shown for (a) $B = 0$ T; (b) $B = 1.2$ T.

diation. Figure 2 shows examples of the detector signal as a function of magnetic field calculated using Eqs. (2) and (4) for $d = 250$ μm, $\epsilon = 13$ (GaAs), various values of T_e, and two values of 2DEG mobility $\mu = e\tau/m^*$. The oscillations become more pronounced with increasing mobility, since their cyclotron linewidths (half width at half maximum, HWHM) decrease as $\Delta\omega = 1/\tau$. They are superimposed on an average signal which rises steadily with increasing field to a maximum between 1 and 2 T and then falls. The initial rise with field coincides with the replacement of the free carrier Drude emission by emission at the cyclotron frequency, and the signal continues to rise because the product $E(\omega)I(\omega)$ increases as the peak in $\sigma(\omega)$ moves towards the maximum of $I(\omega)$ at $\omega = 2.8k_BT_e/\hbar$. For $T_e \sim 15$ K this occurs at a frequency ~ 30 cm^{-1} equal to the cyclotron frequency in a magnetic field of 2 T. The fall in signal is due to the fall in $I(\omega)$ and the decreasing sensitivity of the detector for frequencies greater than 15 cm^{-1}. The field at which the maximum of the signal occurs increases with T_e because of the shift to higher frequencies that occurs in the blackbody spectrum. The fall in zero-field signal with increasing mobility is due to the decrease in emissivity $E(\omega) \propto \mathrm{Re}[\sigma(\omega)] = \sigma_0/(1+\omega^2\tau^2)$ and its increase with T_e is shown by the curves for five different mobilities given in Fig. 3. The increase is stronger, $P \propto (T_e^4 - T_l^4)$, at the lower temperatures and so emission frequencies where the emissivity and detector sensitivities are both approximately independent of frequency (T_l is the lattice temperature). At higher temperatures, the blackbody spectrum extends to frequencies at which the emissivity and detector sensitivity fall appreciably below their low-frequency values and the temperature dependence of P drops to approximately $P \propto (T_e - T_l)$.

The increase in signal with T_e in a fixed magnetic field is also illustrated in Fig. 3, which shows curves for three values of mobility calculated for $B = 1.2$ T corresponding to a cyclotron frequency just above the detector cutoff frequency. At this field the signal is close to an oscillation minimum and to obtain an average value we take $P_D^C = \frac{1}{4}[P_D^C(1.0) + P_D^C(1.4)] + \frac{1}{2}[P_D^C(1.2)]$ where the P_D^C values are for the magnetic fields (in T) shown in parentheses; $B = 1.0$ T and $B = 1.4$ T are the magnetic fields at adjacent maxima. A useful feature for thermometry is that the total intensity emitted in the cyclotron line is nearly independent of μ: the peak value of $\sigma(\omega) \propto \sigma_0/2 \propto \tau$ and the linewidth $\propto 1/\tau$ so that the area under the line is approximately constant. This behavior contrasts with that in zero field where the intensity is strongly dependent on mobility, as seen in Fig. 3.

RESULTS AND DISCUSSION

We first present data relating to the spectrum and source of the FIR. Examples of the detected power as a function of magnetic field for various sample currents are given for NU276 and NU711 in Fig. 4 for a lattice temperature of 4.2 K; these two samples show, respectively, the smallest and largest oscillation amplitudes, relative to the average background. No evidence for parallel conduction could be detected in measurements of Shubnikov–de Haas oscillations on these samples, but to establish that all the FIR was indeed from the 2DEG (evidence for emission from both 2DEG and bulk GaAs has been reported in work by Gornik *et al.*[8]), measure-

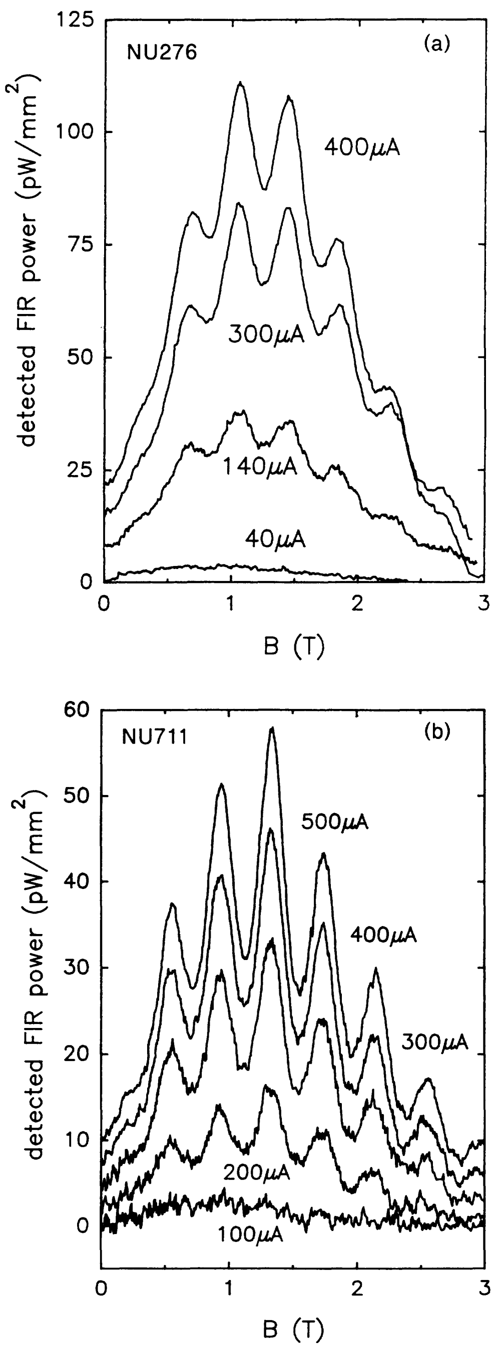

FIG. 4. Detected FIR emission from electrically heated 2DEG's for various source-drain currents as a function of magnetic field applied normal to the 2D plane: (a) NU276 and (b) NU711. The substrate temperature was 4.2 K.

ments were also made on NU711 with the field applied at $\theta = 40°$ to the 2DEG normal. Figure 5 shows the two sets of data plotted against $B\cos\theta$. Their similarity indicates that the FIR emission is due to the 2DEG. (The small difference in shape of the two curves might be caused by the tilted sample being further from the light guide.) The periods of the oscillations for the three samples are in very good agreement with the periods calculated assuming a narrow emission line at ω_C. A further check was made by reducing the substrate thickness of all of the samples by $\approx 25\%$. The periods changed by the expected amounts.

The overall form of the curves in Fig. 4 is very similar to that of the calculated curves in Fig. 2 although, as in transmission experiments, appreciably lower mobility values μ_C than μ_0 are needed to achieve this: NU276, $\mu_C = 7$, NU444, $\mu_C = 10$, and NU711, $\mu_C = 15$ $\mathrm{m^2\,V^{-1}\,s^{-1}}$.

The effect of inserting a low-pass filter in the light path is demonstrated in Fig. 6 which show data for the three devices with and without the filter, which cuts off at 15 $\mathrm{cm^{-1}}$. The FIR signal drops rapidly when $B > 1$ T, $\nu_C > 15\ \mathrm{cm^{-1}}$ (the drop is less steep for NU276 in line with its greater cyclotron width) and does not drop to zero when $\nu_C > 15\ \mathrm{cm^{-1}}$ but falls to between 0.2 and 0.3 of its value just below the cutoff, showing that part of the emission occurs at $\nu > \nu_C$. There is however no significant emission at $\nu > \nu_C$ since the filter has little effect on the intensity when $\nu_C < 15\ \mathrm{cm^{-1}}$. The decrease in signal with magnetic field above the cutoff suggests

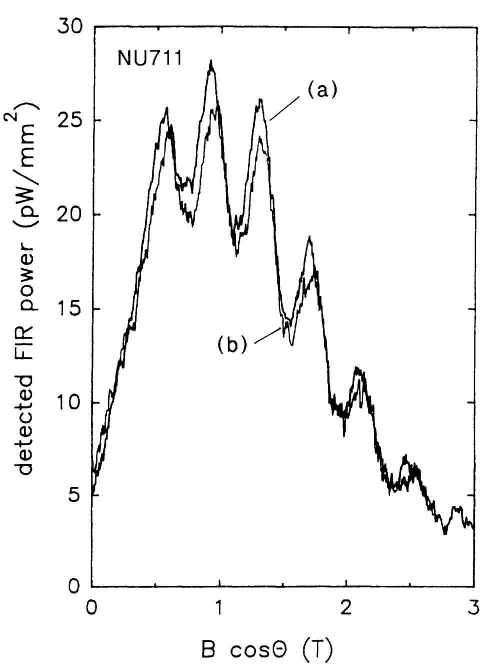

FIG. 5. Detected FIR emission from NU711 for a current of 500 μA as a function of the normal component of magnetic field $B\cos\theta$ for two directions of magnetic field (curve a, $\theta = 0^0$ and curve b, 40^0).

either that the intensity of this low-frequency emission falls with magnetic field or that its frequency increases so that a steadily increasing fraction is cut off by the filter. A possible explanation for this latter case is that part of the cyclotron energy is being emitted as a phonon: an equivalent process in absorption was suggested[18] for a 3D system and seen experimentally for optical phonons.[19,20] The former case could arise if the low-frequency emission were associated with low-frequency magnetoplasmon modes of wavelength comparable to the width of the 2DEG.

The intensity in zero field varied strongly from run to run in contrast with the intensity in magnetic fields which was essentially reproducible except at the lowest fields. The irreproducibility in zero-field is illustrated by the three curves for the NU444 device shown in Fig. 7. The curves are at somewhat different currents so the variation is demonstrated through the ratio of the zero-field signal to that at 1.4 T, which has values from 1.8 to 4.3. It appears likely that the variation in intensity from run to run that occur in zero field is due to change in the detail of the inhomogeneity. Current flow and so power dissipation occur predominantly in the high-mobility regions. However the outer areas of the low-mobility regions will also be heated by thermal conduction in the electron system over distances comparable to the diffusion length $L_D = (\frac{1}{2}v_F^2\tau_{e\text{-}i}\tau_{e\text{-ph}})^{1/2}$, where v_F is the Fermi velocity and $\tau_{e\text{-}i}$ and $\tau_{e\text{-ph}}$ are the relaxation times for impurity and phonon scattering respectively. This has a value $L_D \simeq 10\ \mu$m for NU444 assuming $\tau_{\mathrm{ph}} \sim 0.1$ ns. Since the emissivity increases as the mobility falls these areas could contribute significantly to the total FIR signal by an amount which depends on the detail of the inhomogeneity. The decrease in irreproducibility with increasing magnetic field is consistent with the rapidly decreasing diffusion length $L_D(B) = L_D(0)[1 + (\omega_C\tau)^2]^{-1/2}$. Indirect support for an additional contribution to the FIR emission in zero field comes from the intensity values which are appreciably higher than those calculated using the Drude model and taking T_e values obtained by Shubnikov–de Haas measurements.[21] These effects may only be significant in relatively high-mobility samples however and were not observed in the work of Hirakawa *et al.*[7] for two lower-mobility samples ($\mu_0 = 3.7$ and 11 $\mathrm{m^2\,V^{-1}\,s^{-1}}$) for which the emissivity of the conducting regions is higher and diffusion lengths are lower.

We now discuss the use of the FIR technique for determining electron temperatures in magnetic fields, which was the main purpose of this work. The system appears to be very reproducible and has been shown to be linear to within experimental error. So, in principle, it should be capable, after calibration, of providing quite accurate values of T_e. At present, however, there are uncertainties in the absolute intensity, and also determination of T_e relies on a theoretical expression for the emissivity. As a test of the method, though, we compare the T_e deduced from the FIR intensity, when $B = 1.2$ T with that obtained from Shubnikov–de Haas oscillations measured in the middle of the sample. Figure 3 shows plots of FIR power at the detector per $\mathrm{mm^2}$ of emitting surface as a function of T_e for three values of mobility calculated using the theoretical expression for the emissivity given in Sec. III. To compare these with experimental values, we use T_e values for the same power density I^2R_{xx}/A (A is the 2DEG area of the Hall bar) obtained from Shubnikov–de Haas measurements on low-mobility samples whose substrate temperature was kept at 4.2 K.[21] (The magnitudes of the Shubnikov–de Haas oscillations on the present devices for $B < 1$ T are consistent with these T_e values but are for values of $\mu_C B$ greater than the range for which the technique is strictly applicable.) The hot-electron measurements of Ref. 21 were made as a function of power dissipation I^2R_{xx} with the lattice temperature at 4.2 K as in the present work. The agreement between the theory and the experimental points shown in Fig. 3 seems reasonable up to $\sim$ 15 K but the experimental values fall below the calculated curves at higher temperatures. It should be possible to calibrate the electron temperatures by measuring the FIR intensity emitted when the tem-

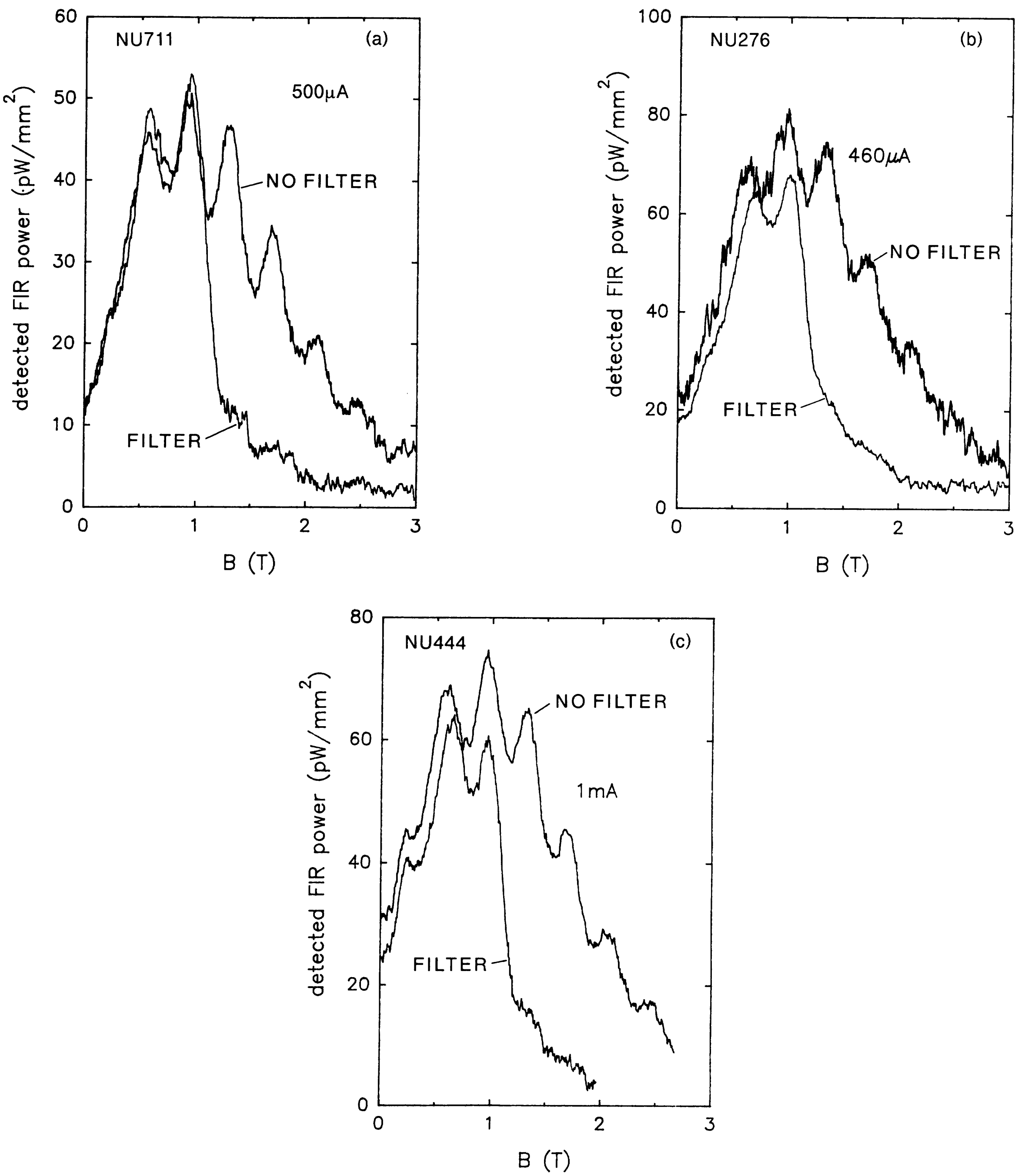

FIG. 6. FIR emission detected from three 2DEG samples with and without a low-pass filter. (a) NU711, $I = 500$ μA; (b) NU276, $I = 460$ μA; and (c) NU411, $I = 1000$ μA.

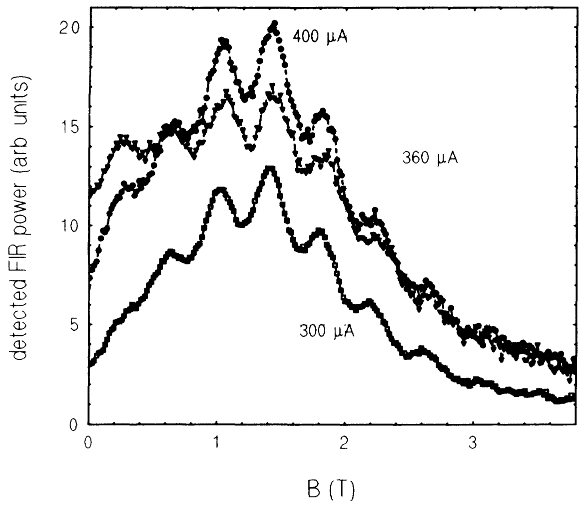

FIG. 7. Examples of the detected FIR emission from NU444 measured in three different experiments; the sample had been warmed to room temperature in between. For all but the lowest magnetic fields, the signals interpolated to 350 μA are the same to within experimental error while at low fields they varied by up to a factor 2.4.

perature of the whole device is raised above that of the helium bath by means of a heater. Samples with transparent (high-resistivity) gates will be needed so that the part of the emission due to the 2DEG can be determined by switching the 2DEG in and out as has been done for Si in zero magnetic field.[6]

Finally we note that the similarity of the data in Fig. 3 for the three samples suggests that their electron temperatures are similar for the same power input, implying that the phonon emission rate is approximately independent of mobility for this mobility range. The energy levels are strongly quantized at 1.2 T ($8 < \mu_C B < 18$) so the independence of phonon emission rate of mobility suggests that it takes place largely by inter-Landau-level rather than intra-Landau-level transitions, for which the rate should vary with linewidth.

CONCLUSION

Measurements of the FIR intensity from a 2DEG as a function of heating current in fields up to 3 T indicate that the intensity of the cyclotron emission should provide a valuable technique for measuring electron temperatures in magnetically quantized 2DEG's. The values obtained using a theoretical expression for the emissivity based on the Drude model are consistent, at least at lower powers, with Shubnikov–de Haas measurements made at the center of the 2DEG. This might be because most of the FIR is emitted from the bulk of the sample rather than the current entry and exit points; further work is needed to confirm this.

The intensity of the FIR emission in zero field varies from run to run, suggesting that it is influenced by extrinsic effects. Measurements made using a low-pass filter demonstrate that, at $B = 1$ T, 20–30 % of the FIR intensity occurs at $\omega \le \omega_C$ but at present we have no other information on its spectral composition.

ACKNOWLEDGMENTS

We gratefully acknowledge help with the experiments by Dr. A. V. Akimov, Dr. J. M. Chamberlain, Dr. T. Cheng, Dr. M. Henini, B. Hill, Dr. J. J. Harris, Dr. A. F. Jezierski, J. Middleton, and Dr. B. Sujak-Cyrul. We are also grateful for stimulating discussions with Professor R. Suris and theoretical colleagues from the Ioffe Physical Technical Institute, St. Petersburg and for financial support from the Science and Engineering Research Council, the Royal Society, and the European Commission.

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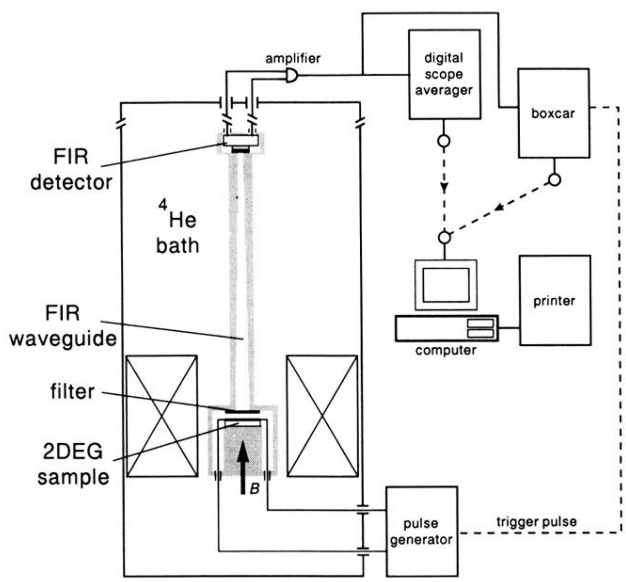

FIG. 1. The experimental arrangement.