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PHONON EMISSION, ABSORPTION AND REFLECTION FROM A TWO-DIMENSIONAL ELECTRON GAS

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1. INTRODUCTION

The strong coupling that exists in a solid between the electrons and the phonons suggests the value of using phonons to study electronic properties. The approach is particularly well adapted to low dimensional structures such as two-dimensional electron gases (2DEGs) since the electrons are confined to small regions by potential barriers and, at low temperatures, the phonons emitted by a hot 2DEG can travel across the substrate without being scattered. Hence information on their angular and frequency distribution can be deduced using detectors on the surface and, in recent years, a number of experiments of this type have been carried out on phonon emission from 2DEGs in Si and GaAs. There have also been related experiments on phonon absorption and reflection using beams of phonons incident onto a 2DEG and the two types of experiment are shown schematically in figures 1 and 2. In these lectures only a selection of this work can be given and a number of pioneering experiments have had to be omitted that would be included in a complete review.

2. PHONON EMISSION

When a 2DEG at low temperatures is heated by a current I, the power dissipated I^2R_{SD} (R_{SD}- source-drain resistance) is mainly radiated as phonons with only a very small fraction emitted as far infra-red. For moderate power inputs , $kT_e \ll \hbar\omega_{LO}$,(T_e-electron temperature ,ω_{LO} - optical phonon frequency) the phonons are largely acoustic but at higher powers, optical phonon emission becomes increasingly important. The efficiency of the total energy transfer to phonons in zero or quantizing magnetic fields can in fact be studied by making electrical or optical measurements rather than phonon measurements since it involves measuring T_e as a function of power input. T_e can conveniently be obtained from $R_{SD}(T_e)$ at low temperatures, T_e, $T_L \lesssim 10K$,since the phonon scattering is so weak that R_{SD} can be considered to be independent of T_L, the lattice temperature. The technique used [1] is to measure R_{SD} as a function of power input for say T_L~1K and then to vary T_L and calibrate R_{SD} against a standard thermometer. In the calibration experiment a low current is used so that T_e~T_L . Magnetic fields are sometimes used to increase the sensitivity [2] using the amplitude of the Shubnikov-de Haas oscillations in R_{SD} as a thermometric property. This increase in sensitivity may introduce some uncertainty however since the heat transfer coefficient is unlikely to be completely independent of magnetic field . The phonon scattering increases rapidly with T_L and above about 10K it no longer seems safe to assume that R_{SD} only depends on T_e and the intensity of the far infra-red emission has been used to determine T_e[3].

Studies of this type, of the total phonon emission rate from a 2DEG, and, in some cases, how it varies with sheet density n_s provide valuable quantitative information. To obtain more detailed information however we need to study the angular, frequency and polarization distribution of the phonons and also in some cases the locations of the sources of the emission and to do this a number of techniques have been used in recent years .

These depend on the fact already noted, that at low temperatures and modest frequencies ($\lesssim$1000GHz), the mean free paths of the acoustic phonons emitted are much greater than the thickness of the substrate so that the phonons travel in straight lines to the opposite face of the substrate . So the angular distribution from a small area source can be deduced from the spatial variation of the intensity on this face -a 'phonograph'- and the polarization distribution can be deduced by using time-of-flight techniques to separate the faster longitudinal modes from the slower transverse modes. The resolution of both of these measurements can be improved by using thick substrates, ~5mm ,rather than the usual 0.5mm. Since the phonon intensity is often closely confined to a cone around the normal to the 2DEG, the intensity phonograph can also be used with a thin substrate to determine the location of intense sources of phonon emission such as occur in the Quantum Hall regime.

2.1 Zero Magnetic Fields

Several theoretical treatments of the phonon emission have now been given eg (4) and references therein, and these suggest that the angular dependence of the phonons should be of particular interest. For $kT_e \ll E_F$, an electronic transition results in a maximum loss of electron wavevector $k_{||}$ in the plane of the 2DEG which is approximately equal to the diameter of the Fermi circle and this leads to an in-plane component of the phonon wavevector, $q_{||} < 2k_F$. There is of course no change in $k_\perp$ since we are considering transitions within a particular electric sub band. This does not, however, imply that $q_\perp$ 0 since the electrons are localised within a length $\sim a_o$ and the Uncertainty Principle only restricts $q_\perp$ to $< a_0^{-1}$. So the angular distribution is determined by the relative sizes of $2k_F$, a_o^{-1} and, of course, $q \sim 4kT_e/\hbar v_s$ where v_s is the sound velocity of the mode. For $2k_F < a_o^{-1}$, which is often the case, we can visualise the distribution approximately as a cone of semi-angle $\sin^{-1}(2k_F/q)$ which can be opened up or closed by varying the sheet density n_s and so k_F as shown in Figure 3 . As n_s is incresed still further, electrons start to occupy the first excited sub-band E_1 and since the Fermi diameter $2k_F^1$ of these electrons is quite small, the phonons they emit come out in a small-angle cone as shown in the figure .The theory also predicts that the total emission should increase quite rapidly with T_e (for simplicity we assume $T_e \gg T_L$) and with a temperature dependence which again depends rather critically on the relative sizes of $2k_F$, a_o and $4kT_e/\hbar v_s$.

A number of experimental studies of the angular dependence of the emission have now been made . In the first of these [5], the 2DEG in a Si MOSFET was pulse-heated and superconducting tunnel junction detectors were placed at several points on the opposite surface to study the emission at different angles to the normal. Two types of junction were used. The first, Al, acts effectively as a bolometer since it is sensitive to a wide range of phonon frequencies, 100-800GHz, while the second, Pb, has only a narrow detection window from 650-800GHz. Fig 4 shows the dependence of the TA phonon signal with n_s at three angles θ to the normal for the Pb detector. Now theory predicts that the cut-off in the emission from a 2DEG that occurs when $q_{||} > 2k_F$ should be preceded by a strong peak at $q_{||} = 2k_F$. So as n_s is varied, the signal detected at a frequency ν_d (~650-800GHz) and at angle θ to the normal should reach a peak when $n_s = \pi(\nu_d \sin\theta / v_s)^2$ so that

n_s(peak) should increase with θ as $\sin^2\theta$. This increase is clearly seen in fig 4 and the peak positions are in reasonable agreement with the theoretical predictions shown by the broken curves. The authors suggest that the second peak at $\theta=23°$ is due to occupation of an upper sub-band. It is also of note that it was possible to observe a change in the angular distribution with direction of electron drift velocity presumably as a result of phonon drag.

Further pulse measurements showing the concentration of the emission in the forward direction have been made using discrete semiconducting CdS film bolometers [6] and by an imaging system which uses a large area (6x4 mm^2) superconducting tunnel junction as detector[7]. The energy gap of the superconductor can be reduced by illumination from a focussed laser beam so by biassing the junction appropriately , tunnel current can be made to flow principally through the illuminated spot. The current is reduced when a pulse of phonons is incident so the technique can be used to measure the local phonon intensity .The spot can be raster-scanned across the junction area to build-up an image or phonograph . The technique is very sensitive and of high resolution (~3μm) but cannot, of course, be used in magnetic fields and the interest in doing this led to a proposal based on CdS [8]which has recently been built [9] and used in fields up to 7T [10]. The image is formed by a 3x3mm^2 array of 100μm strips of evaporated CdS film whose resistance is measured using Cu strips as electrodes, Fig 5. CdS is a semi-insulator at low temperatures because the donor electrons are trapped by deep levels but when illuminated briefly by a 100μm diameter laser beam, electrons are excited to and remain in shallow donor states producing a 100μm wide conducting path between two Cu strips whose resistance is very sensitive to small increases in temperature caused by an incident phonon pulse. When the phonon intensity on this sensitized area has been measured, the area is desensitized by putting a large voltage between the Cu strips which heats the CdS film allowing the electrons to return to deep levels. The laser beam can then be raster-scanned as in the previous technique .A phonon image produced in this way from a 2DEG in a (100) Si MOSFET is shown in fig 6 . The phonon cone is seen as a circle at the centre of the image. Outside the circle the intensity falls away but in certain directions - those lying in (100) and (110) planes - it is increased by 'phonon focussing'. This is caused by the elastic anistropy of Si which concentrates the acoustic energy into beams.

These imaging techniques have been used to provide detailed information on the angular distribution of the emitted phonons for power inputs down to ~20μWmm^{-2} and to get to lower levels (~0.2μWmm^{-2}) a CW technique shown in fig 7 has been used[11]. The phonon intensity in the direction normal to the 2DEG is inferred from the temperature rise it produces at a point on the surface opposite the 2DEG. This is shown in fig 8 for a 2DEG in Si[11] as a function of gate voltage and so sheet density, n_s, for constant input power (the power is computer controlled to compensate for resistance changes). The fall in forward intensity as n_s and so the cone angle increases is clearly seen (B→C) as is the increase (C→D) for $n_s > n_s^c \approx 4.9\times10^{16} m^{-2}$ (Vg~180V) caused by the increase in forward intensity arising from the occupation of an excited sub-band which was discussed earlier . The value of n_s^c gives a value for the excitation energy $E_{ex}-E_F=n_s^c D(E)=31meV$. It is interesting that the forward intensity from this excited band remains constant and does not fall as n_s increases as we should expect . This suggests that k_F and so E_F must remain approximately fixed relative to E_{ex} and this is consistent with theoretical arguments[12] and is also supported by Shubnikov-de Haas measurements which showed no change in period for $n_s > n_s^c$.

The fall in forward intensity at low n_s (B→A) is also of interest and is thought to be due to the decreasing efficiency of TA mode emission due to the decreasing number of available phonon modes. There is also a decrease in the number of LA modes but this is less severe because of their larger sound velocity. So there should be a gradual switch in emission from TA to LA phonons. This leads to a decrease in forward intensity both because LA modes can be emitted at large angles and because the [100] forward direction is not a focussing direction for LA modes while it is for TA.

2.2 Quantizing Magnetic Fields

In a strong magnetic field B, where $\mu B > 1$ (μ is the electron mobility) phonon emission can occur either by electronic transitions from excited Landau levels, (inter-Landau level transitions), or by transitions within a level,(intra-Landau level transitions). Since the first process results in emission at the cyclotron frequency, ω_c, and its harmonics, we refer to the phonons emitted as cyclotron phonons and note that they are evidently of higher frequency than the intra-Landau level phonons whose frequency $< 2\Gamma_N$ where Γ_N is the line width. Theoretical analysis has been given of both cyclotron phonon emission[13] and of intra-Landau level emission[14]. Evidently the proportion of cyclotron phonons should be very sensitive to the position of the Fermi level being greatest when this lies in the middle of a gap. It should also depend on the electron temperature and on the index of the highest filled Landau level.

An interesting complication in many experimental situations is that a significant fraction of the phonon emission does not occur from the bulk of the 2DEG sample but from two diagonally opposite corners where the current enters and leaves. The reason for this can be seen in Fig 9 which shows the equipotential lines in a Hall bar, in the Quantum Hall regime (E_F mid-gap, $kT_e \ll \hbar\omega_c$). In the bulk of the 2DEG, the equipotentials are very nearly parallel to the sides of the bar because $\rho_{xx} \ll R_H$ so that the voltage drop along the bar is very much less than the Hall voltage V_H across it. However, since the 3D contacts are assumed to be good conductors and to have negligible Hall voltages, the nearby electric field in the 2DEG must be perpendicular to the contacts requiring the equipotentials to be parallel to them as shown. (An analytical description of the form of the equipotentials has been given[15].) The net result is a potential drop of V_H between the two contacts and dissipation $IV_H = I^2 R_H$ shared between the two diagonally opposite corners where the potential drop occurs and experimental evidence for this was obtained by observing the FIR cyclotron emission from the sample[16]. Two of the corners were shaded and the emission from the rest of the sample was seen to fall when the field direction was reversed so that corners where the potential drops occur moved into the shaded regions. It is, of course, also a feature of this description that the current should enter and leave the Hall bar at these two corners and evidence for this was obtained using contacts split into 5 separate regions[17]. In these corners the current has to pass between equipotentials resulting in dissipation, $\underline{E}.\underline{J} = 0$, while in the bulk of the sample where $\rho_{xx} \sim 0$, $\underline{E}.\underline{J} = 0$ and the current flows along the equipotential lines. We note, incidentally, that in this idealised model we have assumed the current to flow through the bulk of the sample and not along the edges.

I have discussed this situation in some detail, because of the interest in learning more about it through the phonon emission from the corners. The first experiment on this was carried out on a 2x3mm^2 Si MOSFET (0.5mm substrate) using the arrangement shown in fig 10 . Thermometer contacts of area 0.25mm^2 were attached opposite one of the corners and opposite the middle of the Hall bar. The power input I^2R_{SD} was again kept constant by computer control while the gate voltage was swept and Fig 11 shows the temperatures opposite (a) the middle, T_M, and (b) the corner of the 2DEG, T_c [18]. When $B=+6T$ and E_F is in a gap, as indicated by the minimum in R_{SD}, the middle cools and the corner under the contact warms up (T_c out of phase with T_M) demonstrating the movement of dissipation from the middle to the corner. When the field was reversed ($B=-6T$), the average value of T_c fell consistent with the dissipation moving to the other two corners. It then cooled still further when E_F was in the gap in phase with T_M as expected. The most interesting result of this experiment, however, was the effect of reversing the current so exchanging the positions of the current entry and exit points. No change in T_c could be detected to 1/300 , the experimental limit, suggesting that the dissipation was shared equally between the current entry and exit points as would be expected in the simple model described earlier. This is not an obvious result however and, indeed, the only microscopic analysis published so far suggested that the dissipation should be greatest at the corner where the electrons enter[19].

The experiments have since been repeated over a range of currents from 50 to 1500μA and show no evidence of assymmetry[20] but it has not, so far, been possible to extend them below I_c with any precision ($I_c \sim 15\mu A$ at 6T). Experiments providing further confirmation of the intense emission from hot spots have also been carried out using the CdS imaging technique[21] and also by an ingenious technique[22] which uses superfluid helium film to image the surface temperature and was originally developed to study phonon focussing[23]. The thickness of the film increases with temperature because of fountain pressure and can be displayed by shining a laser onto the surface .

Despite this work there remains a great deal more to be learnt about the dissipation processes in the hot spots and whether these are the same as those that occur in the bulk of the 2DEG when $I>I_c$. It seems likely that in both cases part of the emission occurs as cyclotron phonons although the emission process for these is expected to become very slow at high fields because of the difficulty of conserving both in-plane and out of plane momentum q_{11} and q_1 (13,24). The electrons are localised to $\sim l_B$,the magnetic length ,$(\hbar/eB)^{½}$, so that $q_{11} \leq l_B^{-1} \alpha B^{½}$ and since $q \alpha B$,the phonon emission is restricted to an increasingly narrow cone of phonons perpendicular to the 2DEG as B increases and becomes slower and slower when $q_{\perp} \sim q$ exceeds a_o^{-1}. In this situation the electron temperature seems likely to rise to values where optical phonon emission becomes possible, $kT_e \sim \hbar\omega_{LO}$.

Evidence for optical phonon emission has been obtained from a 1.5x1 mm^2 2DEG in GaAs for power inputs of 50mW [25] . A CdS bolometer on the opposite face of the 5mm substrate was used as a detector and was gated for a time after the input pulse equal to the time taken by TA phonons to travel ballistically across the sample . The detector signal is shown in Fig12 as a function of magnetic field and it is seen that there are resonant increases at fields corresponding to $n\omega_c = \omega_{LO}$. When this condition is satisfied , inter-Landau level transitions of energy $\hbar\omega_c$ are able resonantly to excite optical phonons of energy $\hbar\omega_{LO}$ which can then decay rapidly down to ballistic TA phonons . The size of the increase indicates how much more efficient the optical phonon process is at the higher fields compared with cyclotron phonon emission . Evidence for resonant excitation of optical phonons from a 2DEG has of course been seen before through resonant changes in electrical resisitivity , the magneto-phonon effect[26] , but this is the first time it has been seen directly in phonon emission.

3 PHONON SCATTERING

Phonon absorption can take place as a result of electronic transitions by the reverse process to that already described with similar constraints to $q_{||}$ and $q_\perp$ and this should then normally be followed by either stimulated or spontaneous emission of one or more phonons . Stimulated emission could be induced by phonons from the incoming beam so that the emitted phonon would either occur in the direction of the incoming beam or in the direction of specular reflection from the plane of the 2DEG while spontaneous emission should lead to an angular distribution of phonons broadly similar to that from a hot 2DEG. In general these effects will be modified by the thermalising effects of electron-electron scattering although these seem likely to be less effective when the phonon absorption energy $\hbar\omega >> kT_e$.

It is also interesting to consider a macroscopic description in which specular reflection of sound is the result of a change in acoustic impedance ρv_s . To see why the velocity of sound inside the 2DEG should be different from that in the surrounding Si we recall that the wave equation relates the response of a system $\rho\ddot{u}$ to a driving force which, outside the 2DEG, is caused by the strain together with the elastic modulus of the lattice . However, inside the 2DEG , there is an additional force arising from the deformation potential and this leads to a change in v_s and so in acoustic impedance .

The first experiment to demonstrate phonon scattering by a 2DEG used the arrangement shown in fig 13 [27]. 90ns pulses of phonons were generated by shining a laser pulse onto a constantan film on the suface of the Si and were detected using a superconducting Al bolometer placed at the angle for specular reflection. The gate and so n_s were pulse-modulated to determine the signal associated with the 2DEG and it was found that the specular reflection from the Si-SiO_2 interface was reduced by up to about 2% when the 2DEG was created. It was later shown that this is too large an effect to attribute to absorption but could be explained by destructive interference between the reflection from the Si-SiO_2 interface and that from the 2DEG[28]. Further information has been obtained from recent studies on a Si 2DEG in which the bolometer was replaced by an Al superconducting tunnel junction which only detected phonons of frequency above 70GHz[29] . Interestingly ,the reflected signal now <u>increases</u> with sheet density n_s by up to 6% suggesting that the amount of specular reflection from the Si-SiO_2 interface is rather weak above 70GHz so there is little or no destructive interference . This suggests that the earlier results are due to the higher degree of specular reflection expected from the Si-SiO_2 interface at lower frequencies although, since it seems a little surprising that these contribute so strongly to the total signal, the interface in that sample may also have been somewhat more specular at higher frequencies . A decrease with n_s was also seen for a gated GaAs 2DEG[29] . The highly polished GaAs surface was coated with SiO so it seems reasonable to expect strong specular reflection to occur at the GaAs/SiO interface .

A number of studies have also been made of the field dependence of the phonon transmission of 2DEGs in both Si and GaAs using a CdS bolometer and an arrangement similar to that in fig 2 though with normal incidence . Fig 14 shows transmission data for GaAs[30]. The phonon spectrum of the incident pulse is cut-off at around 1000 GHz as a result of isotope scattering in the substrate . So since the cyclotron frequency ν_c= 470B GHz T^{-1}, there are no phonons in the beam capable of inducing inter-Landau level transitions when B $\gtrsim$2T, and the transmission loss must be due to intra-Landau level transitions. This leads to the signal minima observed when E_F lies within a Landau level. However when B$\lesssim$1T inter-Landau level transitions become possible and the resulting loss in transmission due to these processes should be greatest when E_F lies in a Landau gap . So this is the explanation for the change in phase apparent in Fig 14 at around 1.6T .

Similar results have been seen in Si MOSFETS[6] and measurements as a function of the sheet density n_s allowed the magnitude of the loss to be measured. AT B=0 this was ~6% for n_s ~ 5 x $10^{16}m^{-2}$ and since this is similar in magnitude to the amount of specular reflection[29] it seems reasonable to assume that the transmission loss is largely due to reflection, suggesting a 40% difference in the velocity of sound in the 2DEG from that in Si. The loss falls with magnetic fields presumably because the 2DEG becomes transparent for phonons in the beam with frequencies between ν_c and 2Γ (the Landau level width).

Although most of the absorbed energy is rapidly re-emitted, the electron energy /temperature is raised during the duration of the incident pulse and in Si this gives rise to an increase in resistance R_{SD}. The first experiment to show this was on a GaAs/(AlGa)As heterostructure[31] at 0.2K ($\hbar\omega_c$ >> kT_e) and the absorption due to intra-Landau level transitions with ν <2Γ ~ 20GHz was studied as a function of Landau level index. The experiment was carried out by holding the heater power constant and varying the low frequency intensity by passing the pulse through ^{4}He which down-converts a certain proportion of the phonons to < 20GHz . The proportion decreases with increasing pressure in line with the fall in absorption signal seen in fig 15 which also shows that the absorption increases with Landau level index N.

Results showing absorption at higher frequencies in a Si MOSFET are shown in fig 16 as a function of n_s for B = 7T[32]. At the lower phonon powers, the rise in electron temperature is greatest when E_F lies within a

Landau level implying that intra Landau level transitions are largely responsible. However, at the higher powers, additional peaks occur when E_F is mid-gap suggesting that strong absorption is also occurring at the cyclotron frequency and this was confirmed at lower fields by showing that the rise in T_e was proportional to the intensity at ν_c. (This was increased by increasing the power to the heater). So this system provides a frequency-selective phonon detector. The band-width is large in Si, ~ 300GHz, because of the modest mobility but band-widths of a few GHz should be possible with GaAs/(AlGa)As heterostructures.

Field dependent phonon scattering from a 2DEG has also been seen in the thermal conductivity below 1K of a 50μm GaAs wafer with multilayer heterostructures on one face. The surface scattering is largely specular and so sensitive to diffuse scattering (from absorption and re-emission) that is greatest when E_F lies in a Landau level[33,34].

We also note two other very interesting experiments in which the angular dependence of the electron phonon interaction has been imaged by moving the source of phonons - a focussed laser beam. In the first of these [35], the signal measured is the electric field along the 2DEG resulting from the absorbed in-plane momentum -phonon drag - and in the second it is the resistance change produced by the temperature rise due to the absorbed energy [36].

Scattering measurements have also been made at much lower frequencies and Fig 17 shows the transmission loss in a GaAs 2DEG for longitudinal ultrasonics at 9.36GHz[37]. The transmitted signal was detected with a CdS bolometer. The ultrasound modulates m* and so $\hbar\omega_c$ and the attenuation at normal incidence and the background at oblique incidence, may be the result of relaxation effects. Oscillations in the attenuation for B > 1T are attributed to Joule heat loss due to piezo-electric fields and the signal minimum at 0.36T to the first observation in 2D of magnetoacoustic geometric resonance. The ultrasound produces modulation in the 2DEG plane, with wavefront separation $\lambda_{11} = \lambda/\sin\theta = 0.70\ \mu m$. Geometric resonances should occur when $n\lambda_{11} \sim$ the electron orbit diameter, $2\hbar k_F/Be \sim 0.55\mu m$ so lower field resonances (n=2,3...) may be observable at higher mobilities. These effects may be compared with magnetoresistance oscillations seen recently using static periodic modulation[38].

Shubnikov-de Haas effects can also be seen using surface acoustic waves (SAW)[17,39] and provided the first observations of ultrasonic interaction with a 2DEG[39]. The SAW are generated in a range from 70 -600MHz using interdigital transducers and examples of data are given in fig 18[37].

4. CONCLUSION

Phonon studies of two-dimensional electron gases are evidently capable of providing a great deal of information that is not possible to obtain in other ways. The studies are still relatively recent and there is much more to be done on these 2DEG systems as well as on other types of low-dimensional structure which should also be sensitive to this type of measurement.

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Figure Captions

1 Phonon Emission . The 2DEG is heated electrically ($P=I^2R_{SD}$) and the angular frequency of the phonons emitted is measured from detectors on the opposite face of the substrate.

2 Phonon Scattering . The phonons incident on the 2DEG are generated by a heater or by an ultrasonic transducer.

3 The effect of increasing sheet density ,n_s , on the angular distribution of the emitted phonons .(a) shows the increase in E_F and so k_F which leads eventually to the occupation of an excited sub-band and (b) shows the increasing cone angle of the phonon distribution and the appearance of a second cone when the excited sub-band is reached..

4 Phonon emisssion in the frequency range 650-800GHz at 3 different angles to the normal to the 2DEG (solid lines) . The measurements were made at constant electric field so that the power decreases with increasing n_s. The broken lines show theoretical results [5]

5 Phonon imaging system based on an extended CdS bolometer. [8,9]

6 An image of the phonons emitted from a (100) Si MOSFET.[10]

7 The experimental arrangement used to investigate changes in the angular distribution of the phonon emission by measuring the temperature at points on the opposite substrate surface [11]

8 The change in temperature (phonon intensity) directly opposite the 2DEG in a Si MOSFET as a function of gate voltage and so n_s [11].

9 Equipotentials in the Quantum Hall regime for bulk current flow.

10 Experimental arrangement for observing the phonon emission from 'hot spots' in the Quantum Hall regime[18]. M,C and R are thermometer contacts . The Si device ,mounted in a vacuum is connected to a He bath by a Cu link.

11 The temperatures T_M and T_c opposite the middle and one corner of a 2DEG in a Si MOSFET for $P=I^2R_{SD}=350\mu W$ (a) B=+6T (b) B=-6T [18]. The minima in R_{SD} indicate when E_F is in the gap between two Landau levels (Quantum Hall regime)

12 Magneto-phonon resonances in the phonon emission from a 2DEG in GaAs[25]

13 Experimental arrangement used to study phonon scattering from a 2DEG in Si[27]. The cut in the substrate prevents direct transmission between generator and bolometer.

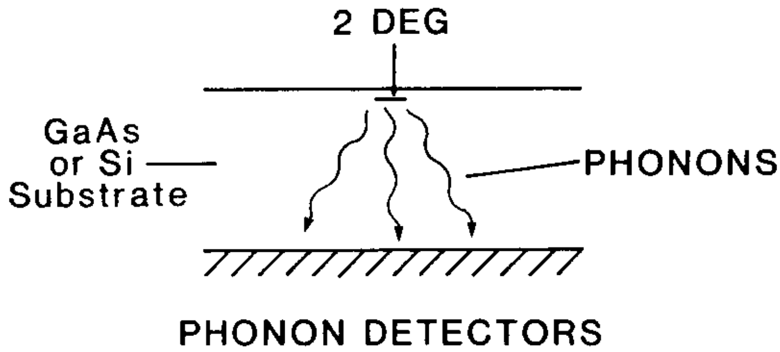
14 The transmission of LA phonons through a 2DEG in GaAs[30].

15 Energy absorbed by a 2DEG in GaAs [31]. A proportion of the phonons from a heater are down-converted to <20 GHz by passing through liquid ^4He and the proportion increases with hydrostatic pressure . The 3 curves show the absorption when E_F lies in the N= 0,1, and 2 Landau levels

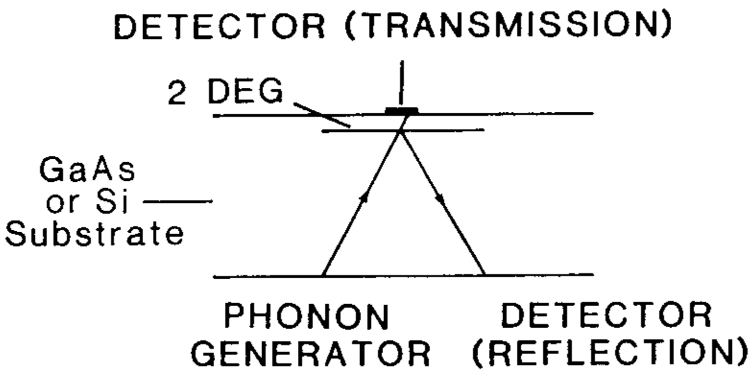
16 Phonon absorption by a 2DEG in Si[32]. When the dominant phonon frequency from the heater is less than ν_c ($P=0.5Wmm^{-2}$) the resonant absorption is due to intra Landau-level transitions while at higher frequencies ($P=5Wmm^{-2}$) maxima due to cylotron phonon absorption are also present.

17 Ultrasonic transmission by a 2DEG in GaAs (a) experimental arrangement (b) results [37]

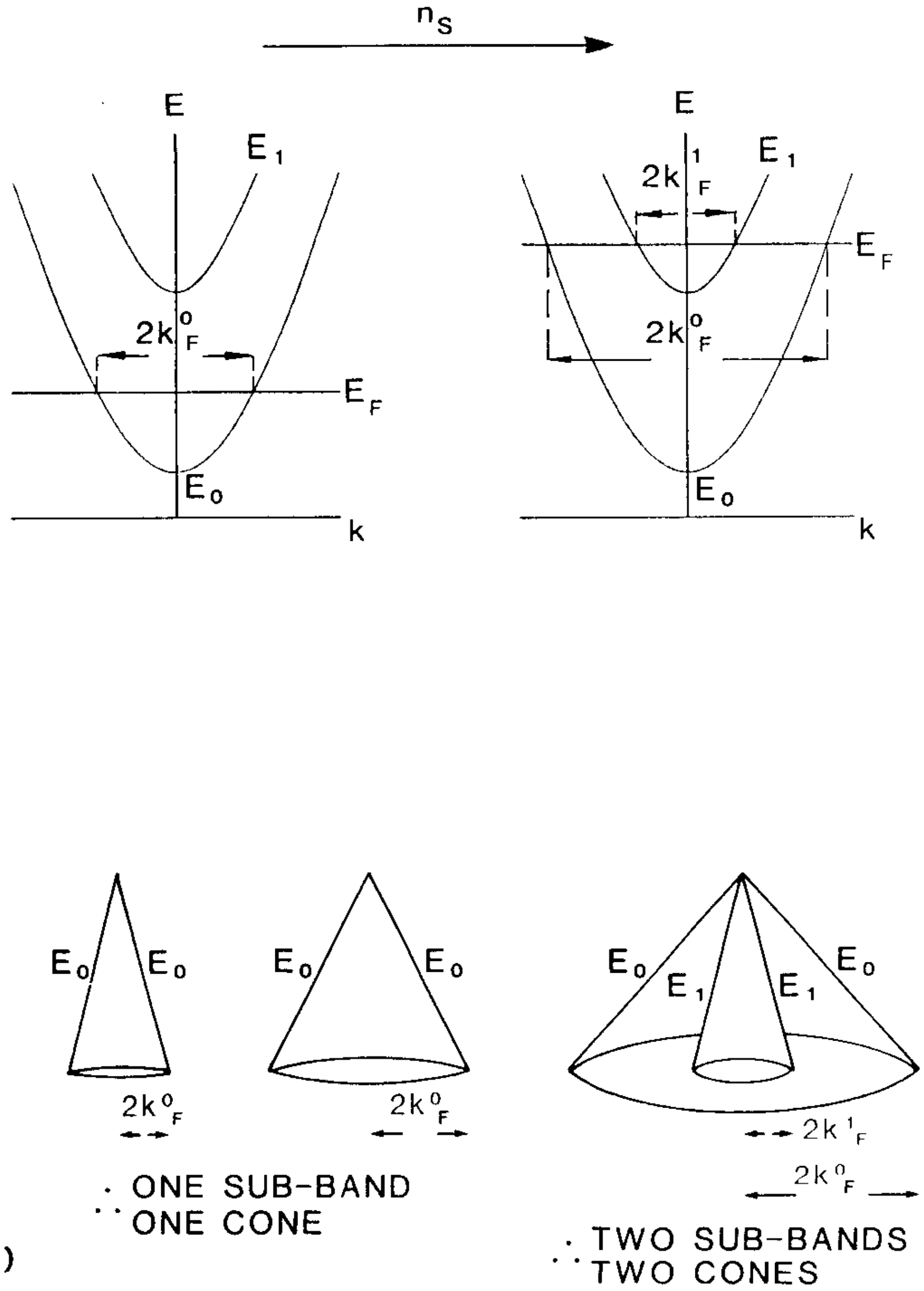
18 Attenuation of surface acoustic waves by a 2DEG in GaAs [37]



2 DEG
GaAs
or Si
Substrate
PHONONS
PHONON DETECTORS

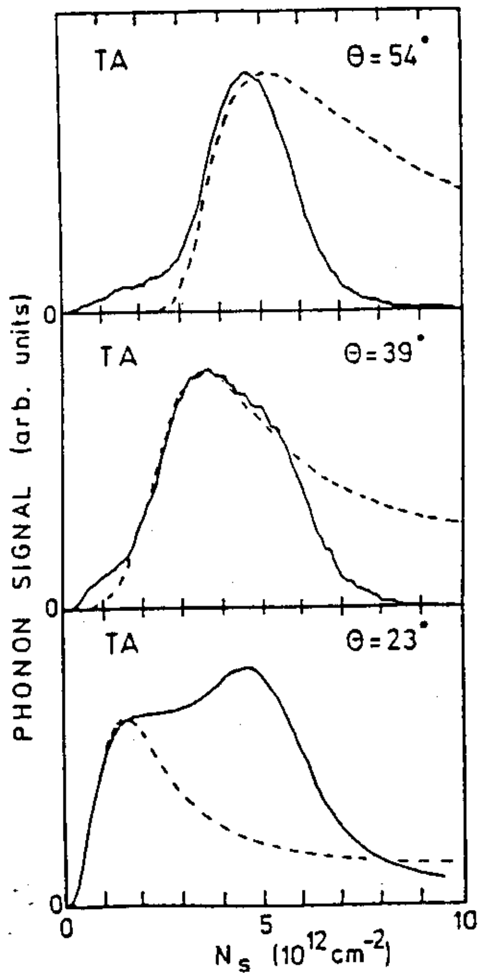


DETECTOR (TRANSMISSION)
2 DEG
GaAs
or Si
Substrate
PHONON
GENERATOR
DETECTOR
(REFLECTION)

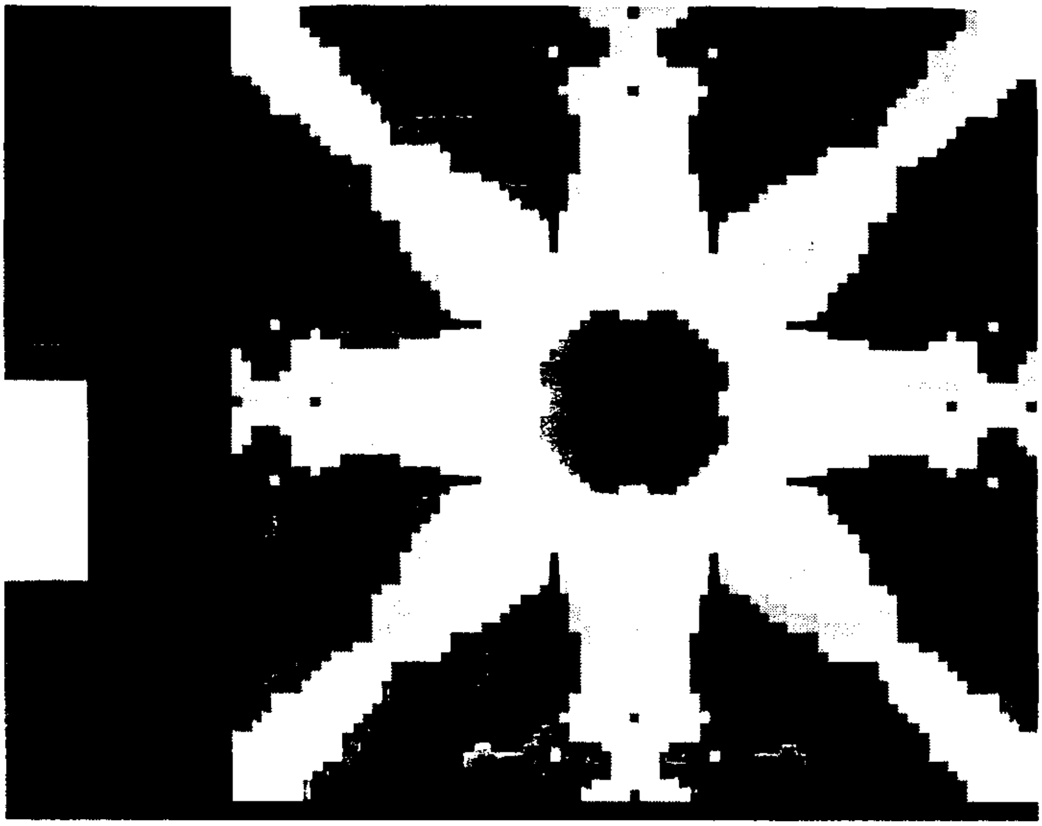


n_S
E
E_1
2k^0_F
E_F
E_0
k
E
2k^1_F
E_1
E_F
2k^0_F
E_0
k
E_0
E_0
E_0
E_0
E_0
E_1
E_1
E_0
2k^0_F
2k^0_F
2k^1_F
2k^0_F
∴ ONE SUB-BAND
∴ ONE CONE
∴ TWO SUB-BANDS
∴ TWO CONES

)



TA
Θ = 54°
TA
Θ = 39°
TA
Θ = 23°
PHONON SIGNAL (arb. units)
0
0
0
0
5
10
N_s (10^12 cm^-2)



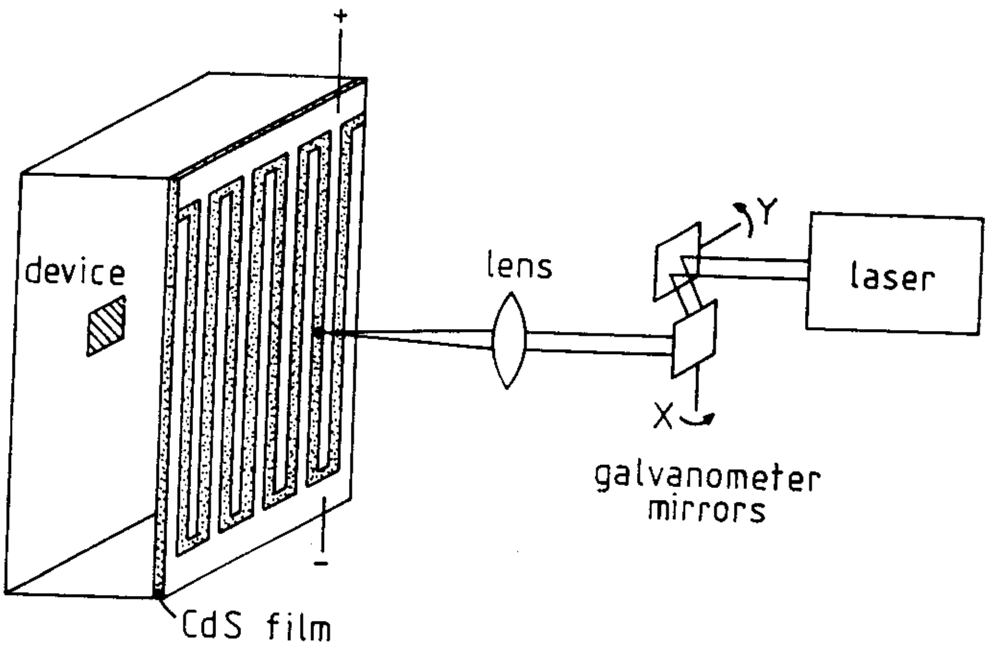
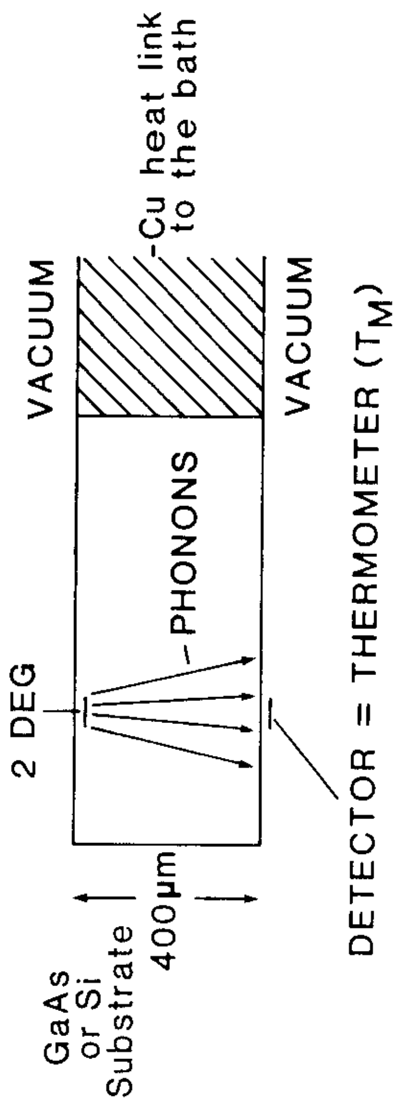
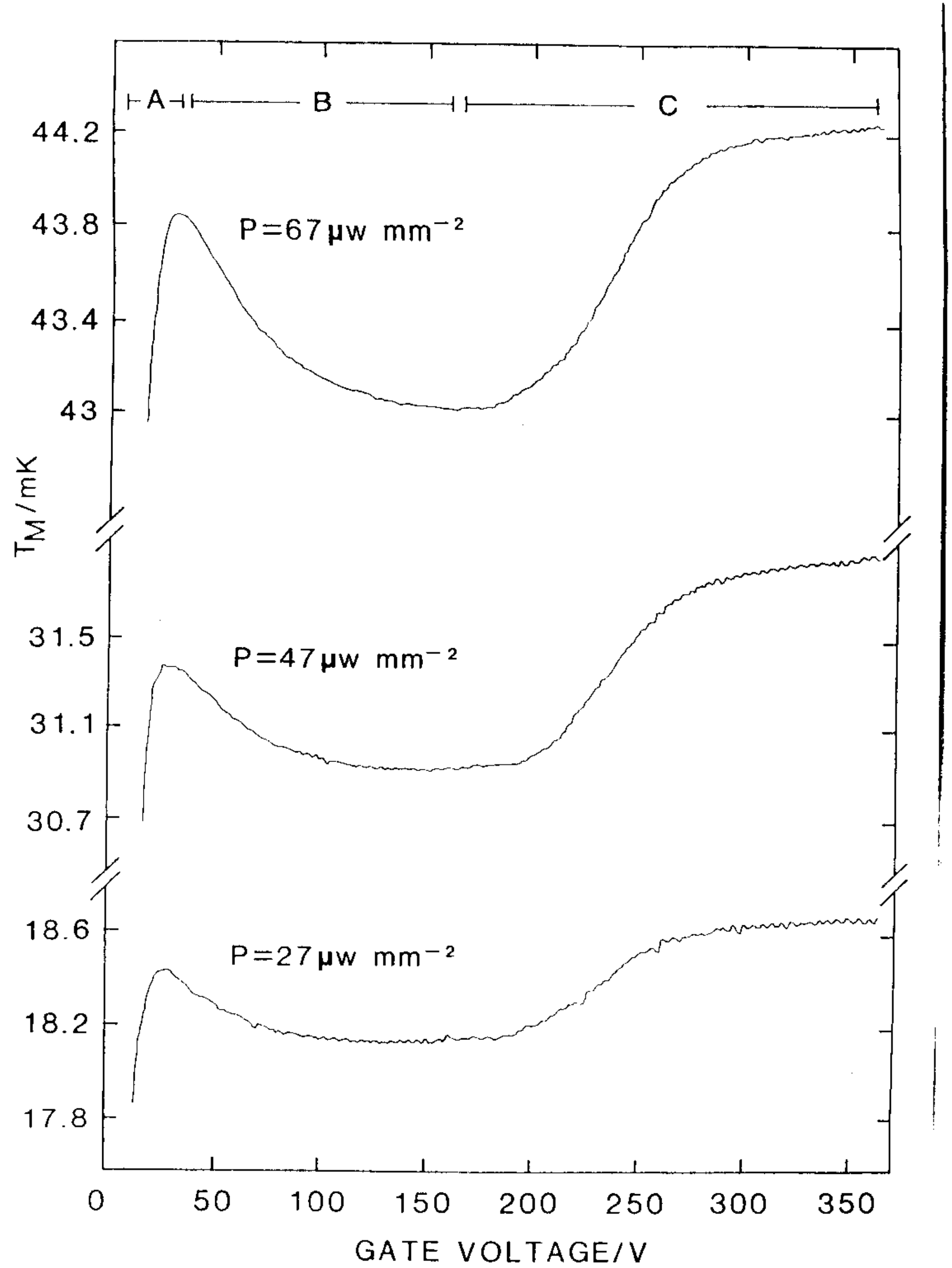


Fig 5


VACUUM
VACUUM
-Cu heat link to the bath
PHONONS
2 DEG
DETECTOR = THERMOMETER (T_M)
400μm
GaAs or Si Substrate


A
B
C
P=67μw mm⁻²
P=47μw mm⁻²
P=27μw mm⁻²
T_M/mK
44.2
43.8
43.4
43
31.5
31.1
30.7
18.6
18.2
17.8
0
50
100
150
200
250
300
350
GATE VOLTAGE/V

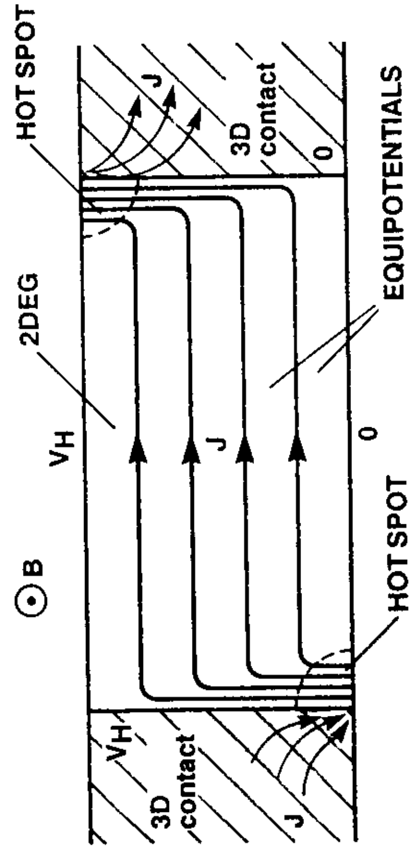

HOT SPOT
J
3D
contact
0
EQUIPOTENTIALS
2DEG
V_H
J
0
B
HOT SPOT
V_H
3D
contact
J

Fig 9

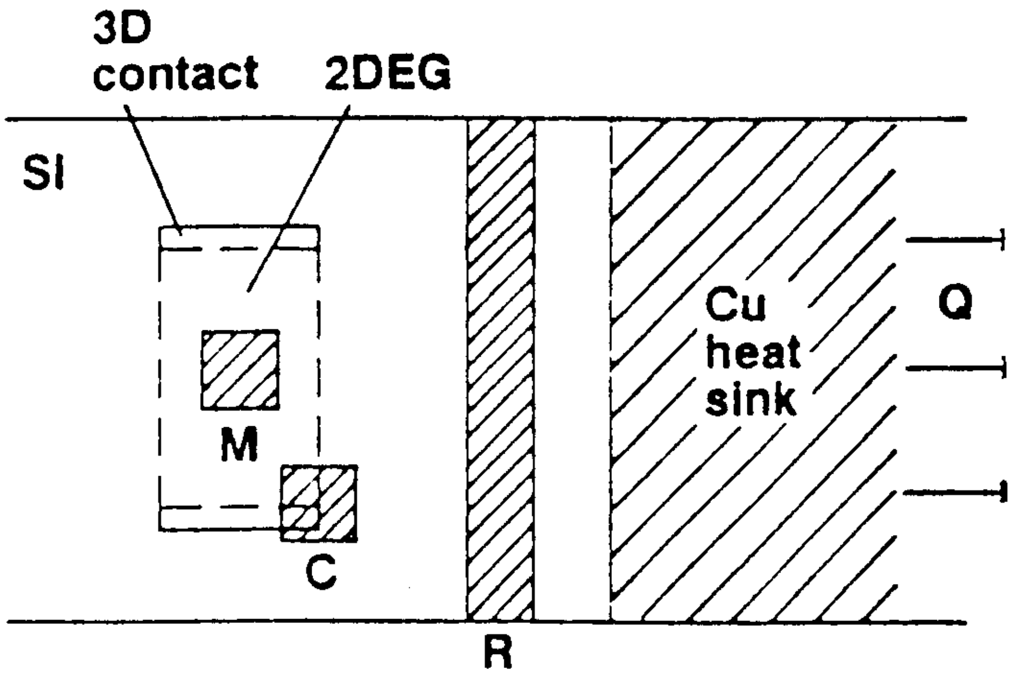
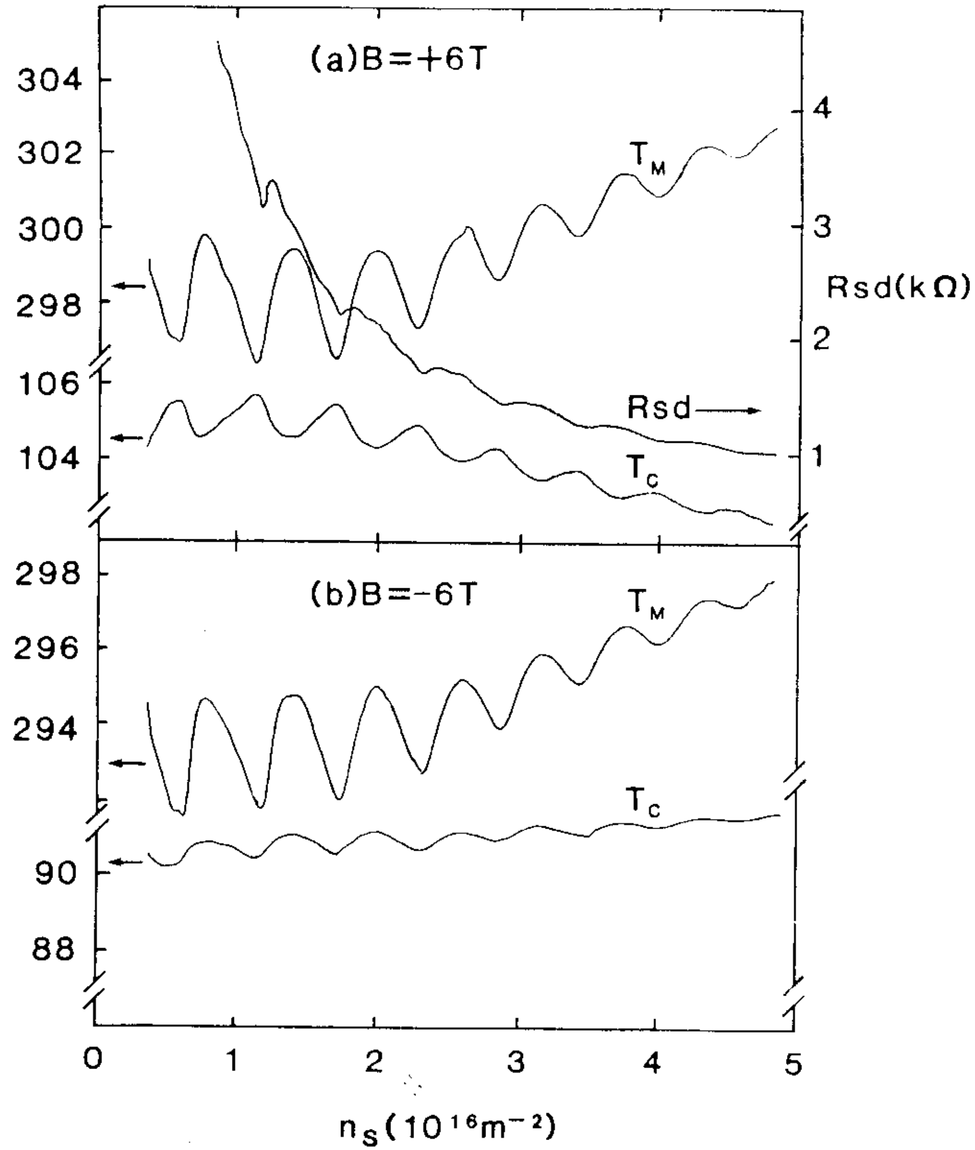

3D
contact
2DEG
SI
M
C
R
Cu
heat
sink
Q

Fig 10


(a)B=+6T
(b)B=−6T
T_M
T_c
Rsd
Rsd(kΩ)
$n_s(10^{16}m^{-2})$
304
302
300
298
106
104
296
294
90
88
0
1
2
3
4
5

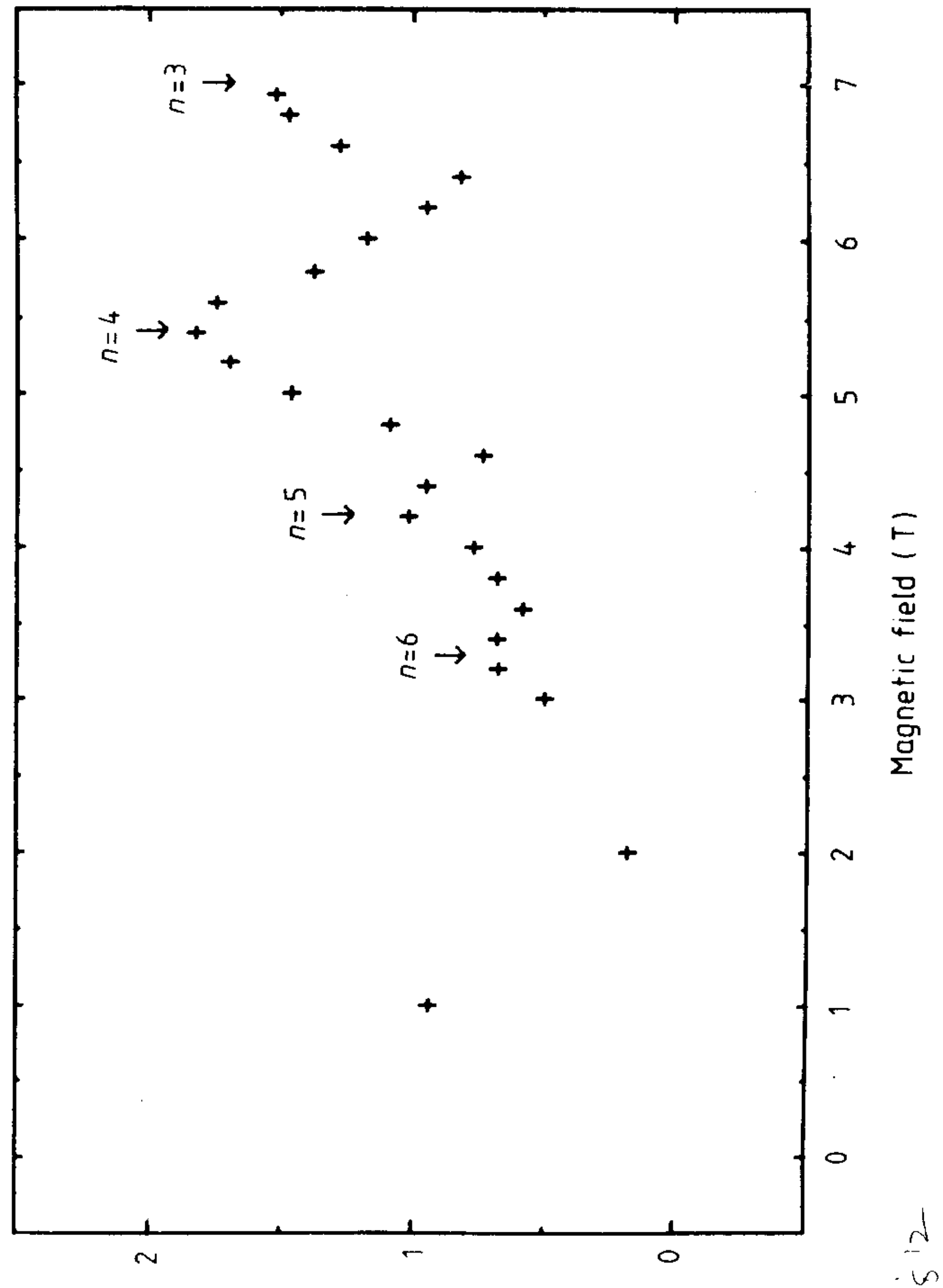
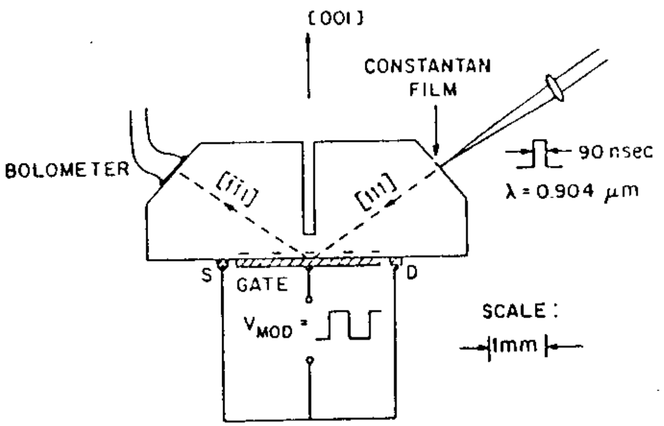

n=3
n=4
n=5
n=6
Magnetic field (T)
0
1
2
3
4
5
6
7

Fig 12


[001]
CONSTANTAN
FILM
BOLOMETER
[1̄11]
[111]
90 nsec
λ = 0.904 μm
S
GATE
D
V_MOD =
SCALE:
1mm

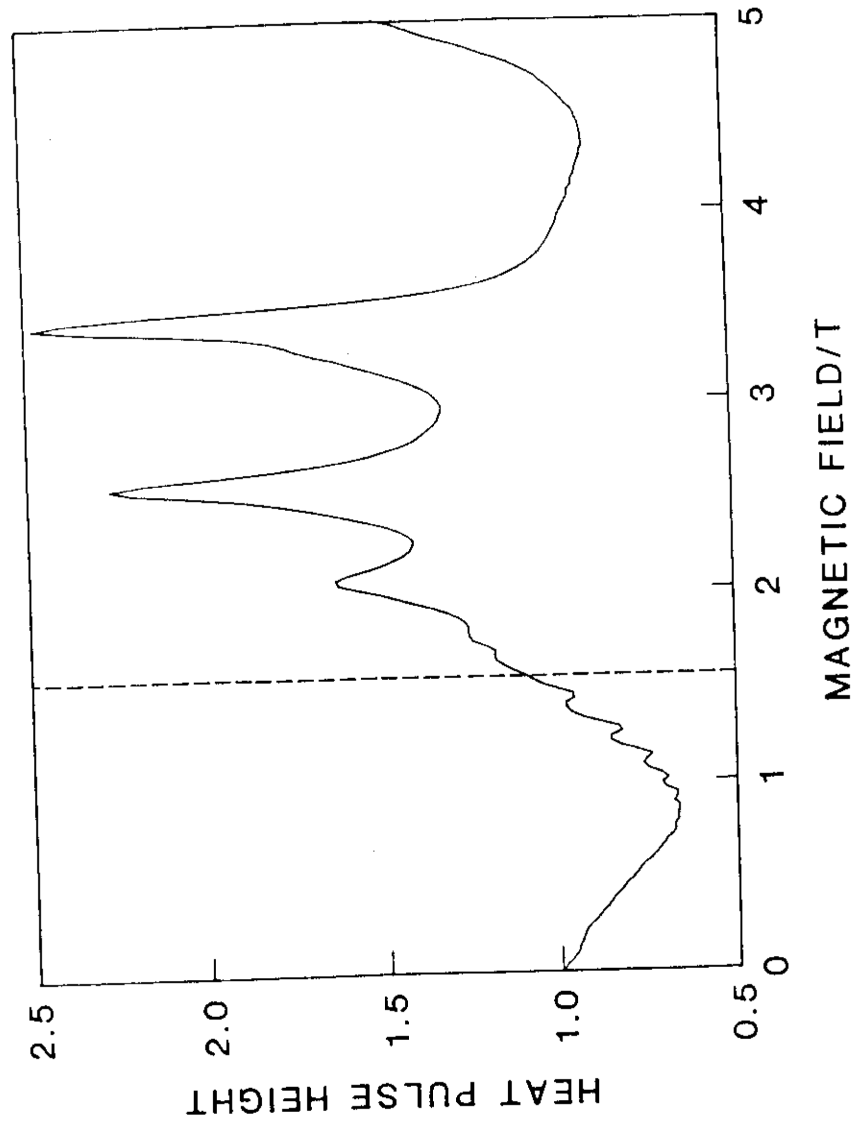
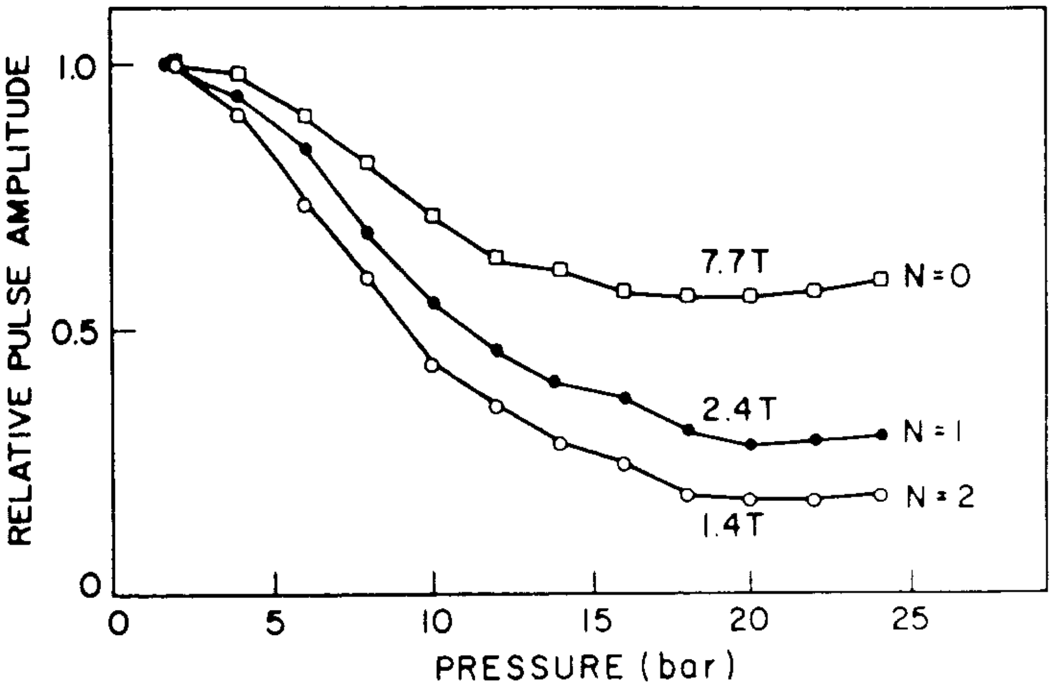

HEAT PULSE HEIGHT
2.5
2.0
1.5
1.0
0.5
0
1
2
3
4
5
MAGNETIC FIELD/T

Fig 13


RELATIVE PULSE AMPLITUDE
1.0
0.5
0
0
5
10
15
20
25
PRESSURE (bar)
7.7T
N=0
2.4T
N=1
1.4T
N=2

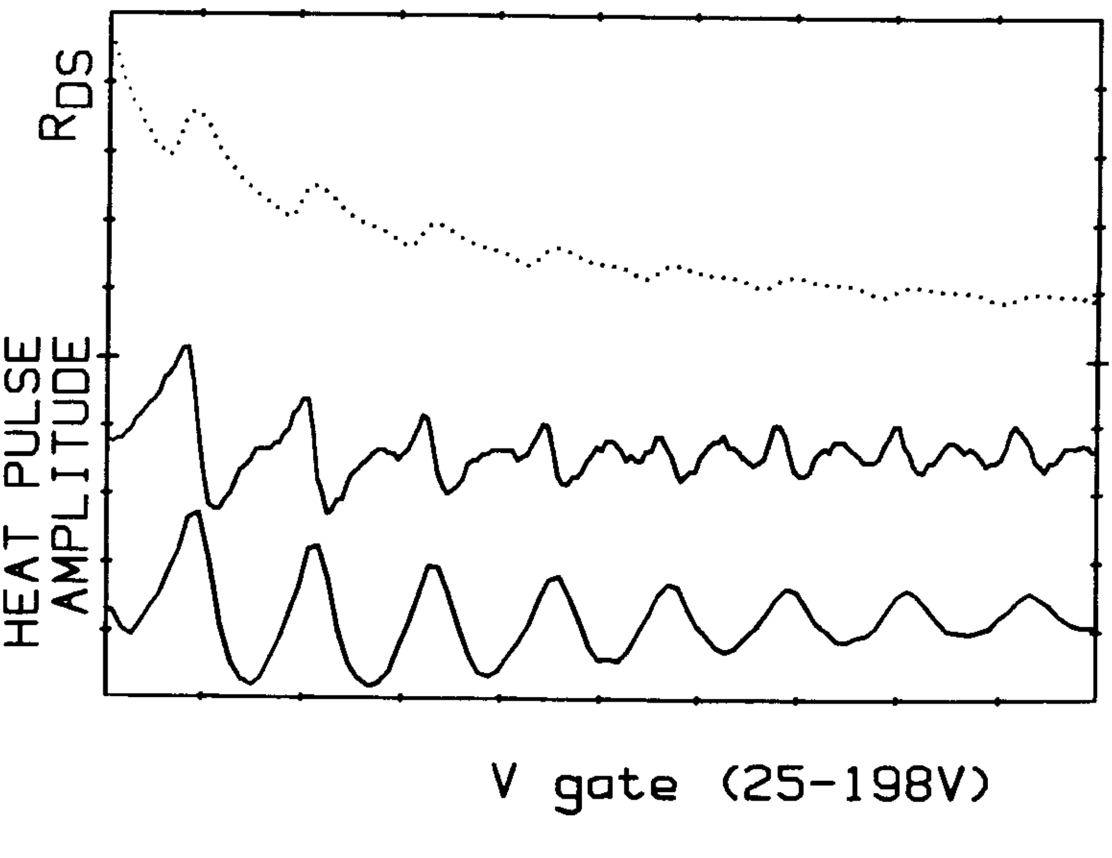

R DS
HEAT PULSE AMPLITUDE
V gate (25-198V)

Fig 6

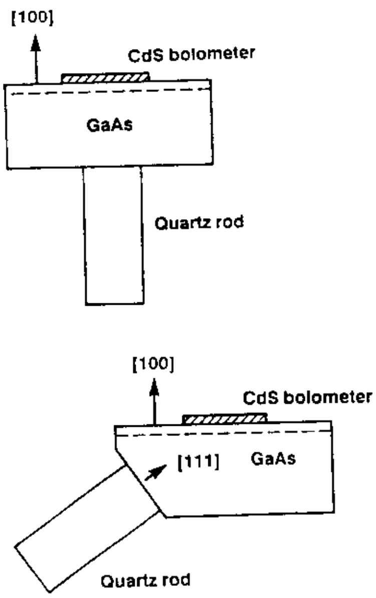
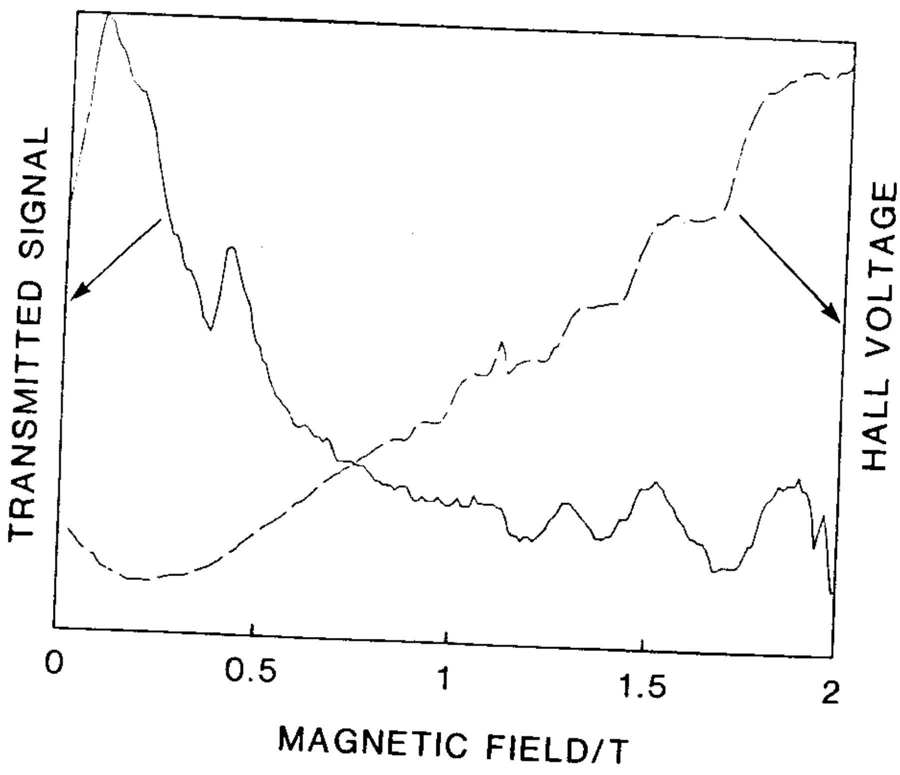

[100]
CdS bolometer
GaAs
Quartz rod
[100]
CdS bolometer
[111]
GaAs
Quartz rod

Fig 17 (a)


TRANSMITTED SIGNAL
HALL VOLTAGE
0
0.5
1
1.5
2
MAGNETIC FIELD/T

17 (b)

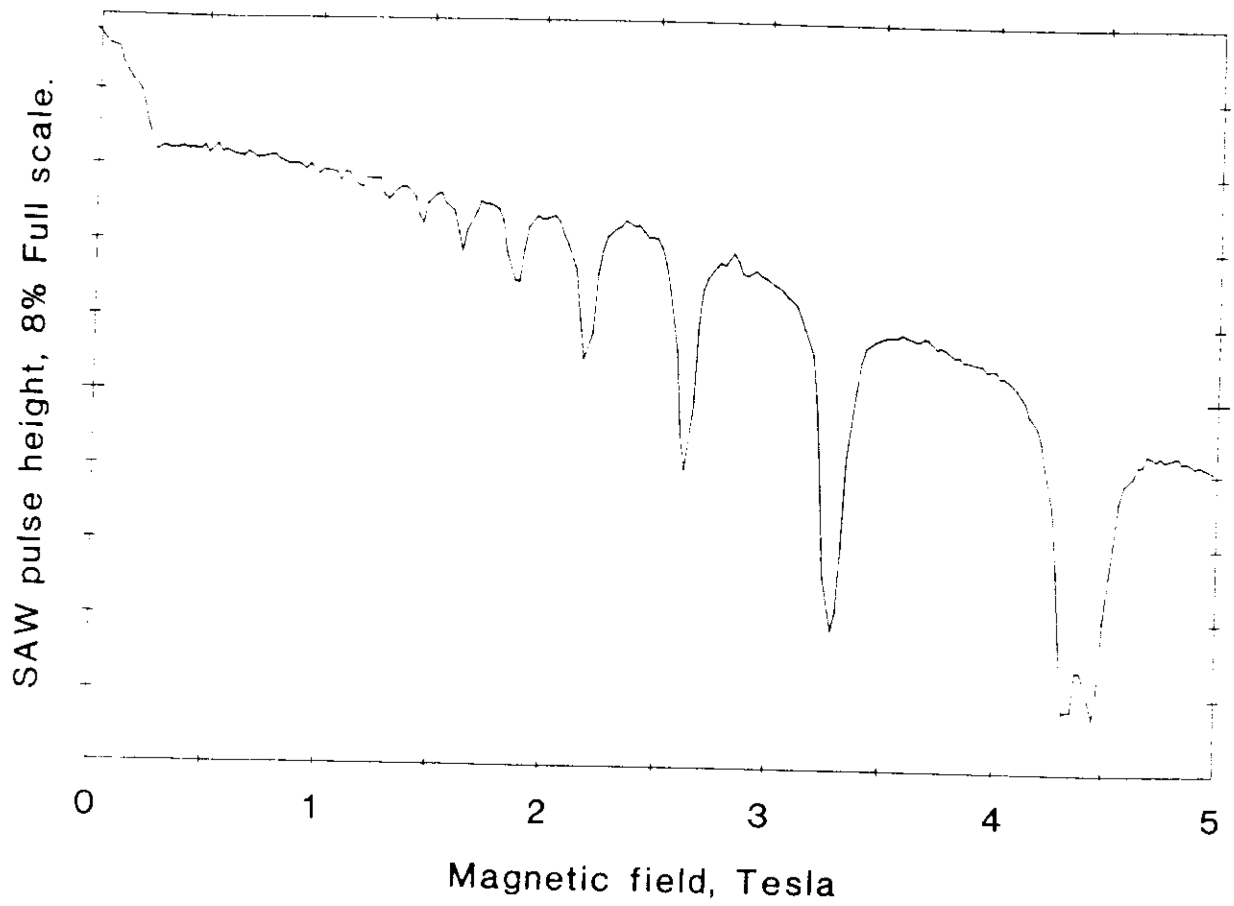


Fig 5