The imaging of nonequilibrium acoustic phonons in semiconductors is now being applied to many problems of scientific and technological interest.

Studying Low-Dimensional Structures by Phonon Imaging

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It is remarkable feature of Nature that heat pulses consisting of nonequilibrium acoustic phonons having frequencies of 100-1000 GHz can propagate ballistically for distances of up to a few millimetres in high-quality dielectric crystals at liquid helium temperatures. In a typical experiment (Fig.1), the phonons are generated by means of a small heat pulse which is usually a few tens of nanoseconds in duration, *i.e.,* less than the time taken for the phonons to traverse the crystal at the speed of sound. This allows the longitudinal and two transverse phonon modes to be resolved owing to their different speeds.

The speed of acoustic phonons in crystals is in the range 2-10 mm/s. It depends on mode (the longitudinal mode being the fastest), on the material and on the direction of propagation of the heat pulse. The dependence of speed on propagation direction, *i.e.,* the acoustic anisotropy of the crystal, gives rise to a phenomenon known as *phonon focusing* [2]. The effect of phonon focusing is the generation of an anisotropic energy flux from an initially isotropic distribution of phonon wavevector directions. Despite its name, the effect should not be confused with the focusing of light by a lens where the energy propagation direction is normal to the wavefronts, which are curved by the lens. In fact, phonon focusing arises because, in an elastically anisotropic medium, the energy propagation (or group velocity) direction of phonons is not generally the same as their wavevector direction.

In order to observe phonon focusing one needs either a movable phonon source or a spatially sensitive phonon detector. The first approach is typified by a laser-based imaging system [4]. A pulsed laser beam is focused onto a metal film deposited on the surface of the crystal in which the beam is thermalized, thereby producing nonequilibrium phonons. The laser beam is moved across the film by means of a pair of galvanometer *x-y* mirrors, thus changing the position of the phonon source relative to a fixed bolometer on the opposite surface of the crystal. The mirrors are controlled by a microcomputer which also records the detected signal, and so by raster scanning the laser a map or phonon image can be recorded. In another arrangement, which is similar in principle but capable of higher spatial resolution, the sample is mounted in a low-temperature scanning electron microscope and the heating is produced by a focused electron beam [5]. Such systems are capable of generating images that are so good as to be practically indistinguishable from theoretical simulations.

In cases where it is undesirable or impractical to move the phonon source, a spatially sensitive detector is required. A number of such detectors have been demonstrated and they are usually based on: (a) the fountain effect in ^{2}He [6]; (b) phonon-induced fluorescence [7]; (c) large-area superconducting tunnel junctions [8]; (d) optically activated semiconducting bolometers. The last approach will be considered later in this article, but in general interested readers should consult the references for details.

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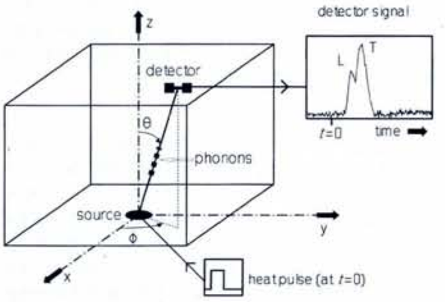

Fig. 1 - Schematic illustration of a heat-pulse experiment. Phonons are generated by means of a small heat pulse applied to the surface of the sample. They transverse the sample and are detected using a thin-film bolometer.

Calculating Phonon Focusing Patterns

The propagation of phonons of frequency much less than the Debye frequency can be analyzed mathematically by considering the crystal to behave as an elastic continuum and applying a three-dimensional generalisation of Hooke's law:

$$\sigma_{ij} = \sum_{kl} C_{ijkl} e_{kl}$$

where σ_{ij} is the stress tensor, e_{kl} is the strain tensor and C_{ijkl} is the (fourth rank) elastic tensor of the crystal. Each of the subscripts refer to the Cartesian axes of the system *(x,y,z)*. The equation of motion of a volume element of a crystal is given by

$$\rho \ddot{u}_i = \frac{\partial \epsilon_{ij}}{\partial r_j} = \sum_{jkl} C_{ijkl} \frac{\partial^2 u_k}{\partial r_j \partial r_l}$$

where ρ is the density of the crystal and u the displacement. This equation has wave solutions of the form $\mathbf{u} = \bar{\xi} \exp\text{-}i(\mathbf{q}.r - \omega t)$, where $\mathbf{q}$ is the phonon wavevector, ω the angular frequency and $\bar{\xi}$ a polarization vector. In general there are three solutions with eigenvectors $\bar{\xi}$ and related eigenvalues $\omega(\mathbf{q})$ corresponding to each of the phonon modes. A conventional $\omega(\mathbf{q})$ versus $\mathbf{q}$ dispersion curve is inadequate for depicting the results of these three-dimensional calculations. The physically most transparent way for doing this uses the so-called slowness surface which is the constant-frequency surface in $\mathbf{q}$-space. Fig. 2 shows schematically a two-dimensional cut through the centre of a slowness surface of a single acoustic mode in an arbitrary anisotropic crystal (in the case of a hypothetical isotropic elastic medium, the slowness surface is spherical and such a cut would be circular in shape). In this diagram, the length of any wavevector from the origin to the surfaces is given by $q = \omega/c$ where c is the speed, hence the name *slowness surface.* Since linear dispersion is implicit in the assumption of an elastic continuum, the phase velocity $\omega(\mathbf{q})/\mathbf{q}$ depends only on the wavevector direction. This is the case in most real materials at phonon frequencies below about 1 THz.

It can be shown that the group velocity $\mathbf{v} = \partial\omega/\partial\mathbf{q}$ is the normal to the slowness surface which is also the direction of energy propagation in the crystal. It is clear from Fig. 2 that the energy flow directions corresponding to a number of different wavevector directions are the same, and so for a non-spherical slowness surface a source of phonons having an isotropic distribution of wavevector directions will give rise to an enhancement of the phonon energy flux in certain directions. Numerical solutions of the equations of motion and calculation of the phonon group velocities are best suited to a digital computer [3]. Simulations of the phonon focusing effects can be made using Monte-Carlo techniques: "phonons" with a random distribution of wavevector directions are "generated" and the corresponding group velocity components calculated; the resulting phonon flux is mapped onto a planar surface opposite the source point. An example of a phonon focusing pattern for all modes in GaAs is shown in Fig. 3 (note the non-linear intensity scale which is used because the centre of the pattern is so intense that on linear scale the other features would not be visible).

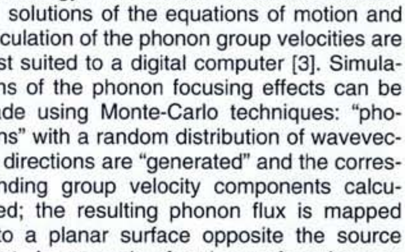

Fig. 2 - The propagation in three dimensions of phonons in an elastically anisotropic crystal is best described in terms of a slowness surface. The figure illustrates a two-dimensional cut through the centre of a slowness surface for a single acoustic mode in an arbitrary anisotropic crystal. The group velocity directions corresponding to a number of different phonon wavevector directions are indicated with arrows.

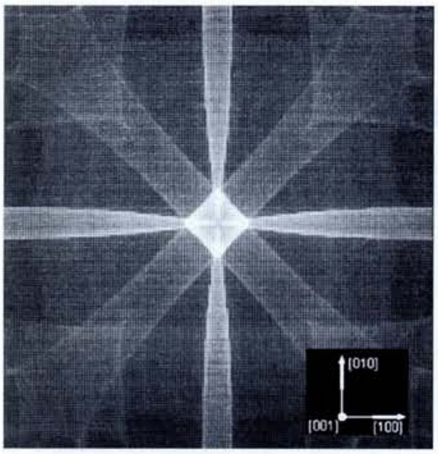

Fig. 3 - Calculated phonon focussing pattern for (100) GaAs. It gives the phonon flux on the front surface of a sample (of "dimensions" $2 \times 2 \times 1$ units^3) generated by a "source" located on the back surface at a position located directly opposite the centre of the pattern. The bright features running vertically and horizontally are due to fast transverse modes and the diagonal features are due to slow transverse modes. Longitudinal modes have a near-spherical slowness surface and do not focus strongly.

Imaging Two-Dimensional Structures

Apart from demonstrating ballistic phonon focusing in a range of materials, phonon imaging techniques are able to give a wealth of other information regarding phonon propagation in crystals. The technique has been used to study phonon scattering by imperfections, reflection at boundaries and interfaces, and the propagation of dispersive phonons [9]. At Nottingham, we are particularly interested in the interaction of phonons with two-dimensional electron and hole gases (2DEGs and 2DHGs) in semiconductors [10] and phonon imaging has proved to be an invaluable tool.

Interest in phonon interactions with 2-D carriers arises because:
- phonon scattering has a considerable affect on the performance of practical devices based on high mobility materials;
- phonon emission is the dominant process of energy relaxation by hot carriers;
- phonons can be used as an effective spectroscopic probe of the electronic states in low-dimensional systems.

Intuitively, it might be expected that the interaction of 2-D carriers with 3-D lattice modes would show some striking anisotropies. This is indeed the case, as can readily be seen by considering energy and momentum conservation in the carrier-phonon processes. The Fermi surface of 2-D electrons in (100) silicon and gallium arsenide devices is a circle in k-space having a diameter $2k_F$ where k_F is the Fermi wavevector. In order that momentum can be conserved when a phonon is emitted or absorbed, the component of phonon wavevector parallel to the plane of the 2DEG, $q_{||}$, cannot exceed $2k_F$ (assuming the carrier temperature T is not too high — in other words $k_B T < E_F$ where k_B is Boltzmann's constant and E_F is the Fermi energy). There is therefore a maximum angle to the 2DEG normal at which a phonon of wavevector $q > q_{||}$ can be emitted or absorbed, given by $\sin(\theta_{max}) = 2k_F/q$. The magnitude of q is determined by energy conservation such that $\varepsilon_q = \hbar q/c$. In addition to this there are other anisotropies which are attributable to the finite thickness of the 2-D layer, namely the angular dependence of the deformation potential, piezoelectric couplings, and of course the phonon focusing effects discussed above. In the case of phonon emission by a 2DEG, the phonon flux is enhanced in a direction normal to the plane of the 2DEG at the expense of emission at larger angles.

Interesting changes in the phonon interactions occur if a quantizing magnetic field is applied to the 2DEG. Under these conditions the electron energy spectrum breaks up into a series of discrete Landau sub-bands, separated by the cyclotron energy, and phonon emission and absorption are possible [11].

Experimental Results

A scanned phonon detector must be fabricated on the face of the substrate opposite the fixed device in order to image phonon emission from a 2DEG device. An optically activated semiconductor detector based on cadmium sulphide (CdS) has been found most suitable for our experiments at Nottingham. For this application, the other types of spatially sensitive detector listed above have certain disadvantages. In particular, (a) does not give quantitative data suitable for comparison with theory; (b) lacks sufficient sensitivity for low-energy phonons; and (c) will not work in a strong magnetic field.

The CdS imaging bolometer developed at Nottingham is shown in Fig. 4 while Fig. 5 shows an image of the phonon emission by a 2DEG in a silicon metal-oxide-semiconductor field-effect transistor (Si MOSFET). The focusing effects are clearly dominant in this image. However, the phonon flux at the centre *(i.e.,* directly opposite the device) is further enhanced in agreement with theoretical predictions. The phonon focusing effects may be seen as a disadvantage to these experiments because they distort the angular dependence information. However, there are a number of ways in which the original directional dependence of the phonon emission may be extracted from the images.

Spectroscopy

The focusing has been used to advantage in some experiments. The extremes of the "bright" region at the centre of the pattern in Fig. 3 subtend an angle of about 12° at the point source. This region is like a "searchlight beam" of phonons. If the wafer is thin the spreading of the beam is small so the beam can be used to spectroscopically probe localized areas of an extended 2DEG. In the experiments we have carried out at Nottingham [12] the phonons were generated on one side of a 0.3 mm GaAs wafer by thermalising a laser in a metal film; they were detec-

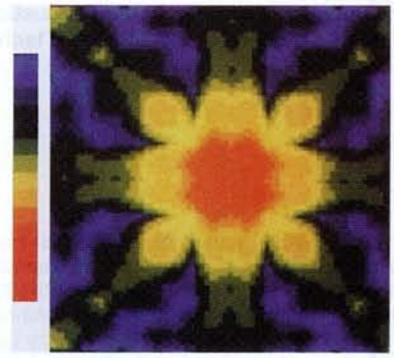

Fig. 5 - A CdS imaging system image of phonon emission from the two-dimensional electron gas in a 1×1 mm^2 silicon metal-oxide field-effect transistor in a 5 mm thick Si wafer with a (100) crystal orientation. The probe beam covered an area of 10×10 mm^2. The phonon flux in the central region is enhanced, in agreement with theoretical predictions.

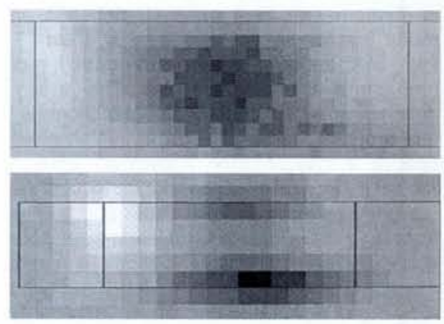

Fig. 6 - Photoconductivity images of a GaAs 2DEG in a quantizing magnetic field (the device is outlined in black). a, upper) The Fermi level is coincident with a Landau level. b, lower) The Fermi level is between two Landau levels. The increase in conductance (white) seen when phonons are incident near the contacts is due to thermally activated conduction in the disordered contact regions.

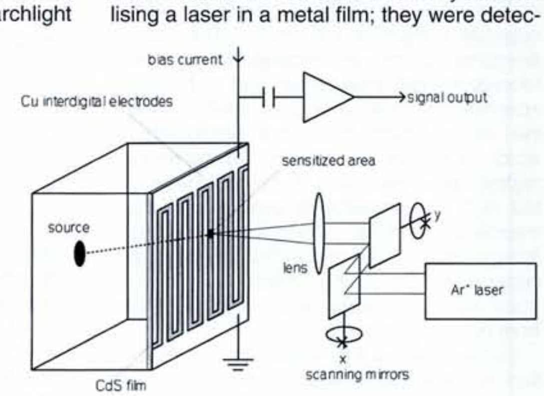

Fig. 4 - A CdS scanning bolometer imaging system. A thin (0.5 μm) film of CdS is deposited on the (polished) surface of a GaAs wafer by thermal evaporation. Large-area copper interdigital electrodes with fingers about 100 μm wide and about 100 μm apart are then fabricated on top of the CdS. When cooled to liquid helium temperatures, the CdS becomes semi-insulating and is insensitive to acoustic phonons. However, illuminating the CdS between the fingers with band-gap radiation from a focused argon laser produces persistent photoconductivity at a point. The conductivity has a strong positive temperature coefficient and so, with a constant bias current flowing, phonons incident on the illuminated point produce a voltage signal which is amplified and detected. The film can be desensitised by electrical heating and another point illuminated to build up an image of the phonon flux from the source on the opposite side of the crystal. The performance of the CdS detector is not influenced by strong magnetic fields of up to at least 12 T.

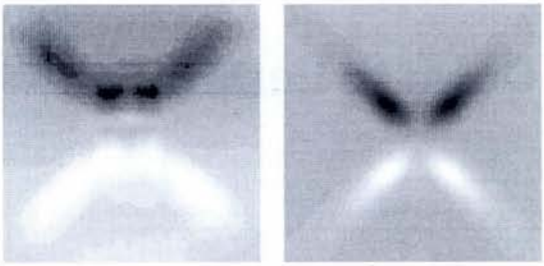

Fig. 7 - a, left) Phonon drag image of a 2-D hole gas in a GaAs/(AlGa) As heterojunction. The device is located opposite the mid-point of the image and is oriented vertically. The scan area is 4 x 4 mm^2 and the wafer thickness is 2 mm.
b, right) Theoretical simulation of the drag pattern for the fast transverse mode showing that the 2-D hole-phonon interaction is highly anisotropic. The image includes the anisotropy of the hole-phonon interaction but excludes the source and detector size effects which tend to smear out the experimental image.

ted by the change in conductance of a 3 x 1 mm^2 heterojunction device fabricated on the opposite side of the wafer. By scanning the laser, a map of the photoconductivity of the device with a resolution of about 100 μm can be obtained. The frequency spectrum of the phonons is approximately Planckian and the peak is determined by the source temperature T_s such that $\omega_{max} \approx 3k_B T_s/\hbar$, so spectroscopic information may be obtained by changing the source temperature.

Fig. 6a shows an image of the response of a magnetically quantized 2DEG with the Fermi energy co-incident with a Landau subband. A decrease in conductance (increase of resistance), which appears dark on the image, is due to phonon scattering of carriers within the partially filled Landau level. If, on the other hand, the Fermi energy is in the gap between levels, then the response is restricted to the edges of the device (Fig. 6b): intralevel phonon scattering is no longer possible because the Landau levels below E_F are completely filled and the ones above are empty. Furthermore, the phonons are not sufficiently energetic to cause inter-level scattering in the bulk. However, at the sample edges where the Landau levels bend closer together, energy and momentum conserving transitions are possible because the electron wavefunction must vanish outside the sample.

Imaging Phonon Drag

Additional information regarding the angular dependence of the 2-D carrier-phonon interaction can be obtained by imaging the phonon drag of cold carriers [13]. Nonequilibrium phonons are generated by thermalizing a laser beam in a metal film as described earlier. The phonons traverse the substrate and fall upon the device: momentum is transferred from the phonons to the carriers during collisions (the so-called phonon-drag effect), and the components of momentum parallel to a line joining the electrical contacts give rise to a small current which may be detected. Fig. 7a shows an experimental image of the phonon drag of a (100) 2-D hole gas in a GaAs/(AlGa)As heterojunction. Note that the polarity of the signal changes depending on the direction of propagation of the phonons relative to the device contacts, which are oriented vertically. The fast transverse mode focusing structure is very evident in this structure. However, the pattern is modified by the anisotropy of the hole-phonon interaction. In principle, the focusing structure can be deconvoluted from this image to give the angular dependence of the hole-phonon interaction. Alternatively, theoretical calculations of the angular dependence corresponding to the experimental conditions can be used as the original q-vector distribution in a Monte-Carlo focusing calculation to produce the image of Fig. 7b showing that the 2-D hole-phonon interaction is highly anisotropic. The image also gives information about the precise nature of the hole-phonon coupling.

Outlook

Interest in the properties of low-dimensional structures, particularly the behaviour of 2DEGs and 2DHGs in the extreme quantum limit and of one- and zero-dimensional electronic systems, is likely to continue in the near future. Phonon imaging will also have a part to play in investigating these systems. Lateral confinement in quantum wires and dots will modify significantly the angular dependence of the electron-phonon interaction by relaxing the in-plane momentum conservation restrictions. Phonon spectroscopic measurements on 2DEGs in the fractional quantum Hall effect (FQHE) regime have also been carried out recently. The accepted explanation of the effect requires the existence of an energy gap near a minimum in the energy dispersion curve for excitations from the two-dimensional quantum liquid ground state (the excitations near the minimum are known as magnetorotons). A direct determination by phonon spectroscopy gives an energy gap that is close to the predicted value [14]. By using imaging techniques it will be possible to probe other regions of the curve for excitations in the FQHE regime, and to investigate the rôle of edge states.

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