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FAR INFRARED EMISSION FROM 2D ELECTRONS AT THE GaAs-$Al_xGa_{1-x}As$ INTERFACE

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We report the first observation of far infrared emission resulting from radiative decay of inter-subband and cyclotron excitations of the two-dimensional electrons in GaAs/$Al_xGa_{1-x}As$ hetero-structures.

It is well known that quasi-two-dimensional (2D) carriers can exist at the semiconductor-semiconductor interface of GaAs/$Al_xGa_{1-x}As$ heterojunctions and heterojunction superlattices[1-4]. Recently, the use of selective doping, which places the donor or acceptor impurities inside the $Al_xGa_{1-x}As$ to achieve spatial separation of the free carriers from their ionized impurities, has made it possible to grow heavily doped heterostructures with high carrier mobilities[3]. As a result, there is considerable current interest in the electronic properties of these 2D carriers and several new experiments, including cyclotron resonance[2] and ineleastic light scattering[5,6],has already been reported. Here we report the investigation of the narrow band emission in the far infrared (FIR) from this 2D electronic system. Similar experiments were previously carried out with Si-inversion layers[7].

The emission results from radiative decay of the electronic excitations, created by heating up the 2D electron distribution with an electric field applied along the layers. In the presence of a quantizing magnetic field, B, cyclotron emission resulting from transitions between Landau levels is dominant. In fact, cyclotron emission from the bulk as well as the 2D electrons was observed in a single interface sample of GaAs/$Al_xGa_{1-x}As$ heterojunction, where the bulk GaAs is n-type. It is well known that the cyclotron frequency, ω_c, of a 2D electron is determined only by the component of B perpendicular to the electron layer, while that in the bulk by B. Therefore by tilting B, we were able to resolve the two emission lines and to determine the cyclotron mass, m*, of the 2D electrons in terms of the well known bulk mass, $m_o^* = 0.665\, m_o$ in the same sample. We obtained $m^* = (1.068 \pm 0.03)\, m_o^*$. In the absence of B, an emission line at $\sim$18meV was observed in a superlattice sample in the direction parallel to the GaAs/$Al_xGa_{1-x}As$ interface. We assigned this line to the inter-subband electronic excitations, shifted by plasma screening.

The GaAs/$Al_xGa_{1-x}As$ heterostructures were grown by molecular-beam epitaxy (MBE) on Cr-doped, semi-insulating GaAs substrate[8]. The single interface heterojunction consists of a 3μm thick, unintentionally doped n-type GaAs layer ($n \approx 10^{16}/cm^3$) and 2 μm thick n-type $Al_xGa_{1-x}As$ doped with Si to a concentration of $\sim 3 \times 10^{17}/cm^3$. The modulation doped

superlattice consists of 120 layers of 400 Å thick undoped GaAs, seperated by 390 Å thick Si doped n-typed $Al_xGa_{1-x}As$. The mole fraction of Al in either sample is x=0.26 and the conduction band discontinuity at the interface is E_c= 280meV.
The samples were approximately 3mmx4mm platelets with ohmic contacts made by alloying In metal in H_2 atmosphere at 400°C. The electronic excitation is created by applying voltage pulses to the contacts. The radiation was detected and analysed by using narrow band detectors, which are high purity extrinsic n-type GaAs and InSb single crystals[9]. Extrinsic GaAs forms a narrow band ($2cm^{-1}$halfwidth) photoconductive detector with a detection window at 4.40meV. It has an 10^5V/W sensitivity. When the emission is not tunable the cyclotron absorption in n-type InSb is used to detect the radiation and analyse it by tuning the cyclotron absorption window of InSb with B[9].

A. Cyclotron Emission

Fig.1 shows data taken from a $GaAs/Al_xGa_{1-x}As$ heterojunction and a modulation doped multilayer at 4.2K with a GaAs detector. The detector response is plotted as a function of B, which is applied at an angle Θ from the normal to the $GaAs/Al_xGa_{1-x}As$ interface. The background is due to broadband radiation, which, because of the magnetoresistance of the sample, decreases with increasing B.
The narrow band emission due to transitions between Landau levels is tunable with B and, therefore, appears as peak in the spectra. The peak position is the B field, at which the cyclotron energy, $\hbar\omega_c$, is 4.40meV, which is the detection window of the GaAs detector. The cyclotron frequency is given by $\omega_c = eB/m_o{}^*c$ for bulk electrons but by $\omega_c = eB\cos\Theta/m^*c$ for 2D electrons. We have observed cyclotron emission by 2D electrons in both the single interface and the multilayer sample and the expected cosΘ dependence on the direction of B is obeyed. In the data shown for the single interface (Fig.1) two peaks appear. One peak which moves to higher B as Θ increases, is from 2D electrons. The other peak, which does not change with Θ, is from bulk electrons. For the multilayer sample (Fig.1) only emission by 2D electrons exist since no bulk peak is observed. Obviously m* can be measured directly in terms of $m_o{}^*$ the observed bulk effective mass through $m^* = (B_2\cos\Theta/B_1)m_o{}^*$, where B_1 and B_2 are the position of the bulk and 2D cyclotron peaks, respectively. Our results for the single interface sample, yield $m^* = (1.068 \pm 0.03)m_o{}^*$. For the 2D electron gas in the multilayer sample $m^* = (1.10 \pm 0.05)m_o{}^*$ is found. Störmer et al.[2] reported a cyclotron resonance experiment, where FIR absorption was measured. They observed a mass enhancement in the 2D electrons and attributed

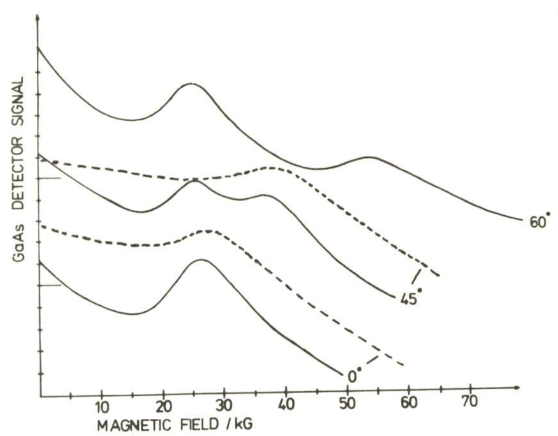

Fig.1 Cyclotron emission data from $GaAs/Al_xGa_{1-x}As$(x=0.26) at 4.2K; full curves: heterojunction, dashed curves: multilayer. The detector is high purity GaAs with a detection window at 4.40meV. Θ is the angle between B and the normal to the junction interface

it to the nonparabolicity of the GaAs conduction band. The enhancement was 10% in the surface channel with $n=1.2\times10^{12}cm^{-2}$. Our results give further evidence for this explanation. We observed as expected a smaller mass increase for samples with lower channel concentrations ($n=8.7\times10^{11}cm^{-2}$ for the single interface and $n=7.3\times10^{11}cm^{-2}$ for the multilayer).
An rough analysis of the emission linewidth gives values of $\Delta\omega \approx 16cm^{-1}$ ($\pm3cm^{-1}$) for the bulk emission. From this values we can determine the total bulk doping to $N_I \approx 2.5\times10^{16}cm^{-3}$ if we use the experimentally determined relation $\Delta\omega \propto \sqrt{N_I}$ [10] with $\Delta\omega = 1cm^{-1}$ for $N_I = 1\times10^{14}cm^{-3}$. This value is in good agreement with the expected doping level from technological considerations. However the linewidth of the 2D electron gas is found to be somewhat narrower $\Delta\omega \approx 13cm^{-1}$ ($\pm3cm^{-1}$) for the single interface sample while considerably broader ($\Delta\omega \approx 25cm^{-1}$ ($\pm5cm^{-1}$) for the multilayer sample. If we assume ionized impurity scattering to be predominantly responsible for the linewidth the narrower linewidth for the 2D electrons in the single interface sample indicates screening of impurities by the higher concentration of electrons in the channel compared to the bulk. For the multilayer either a higher doping level of the GaAs layer or selfabsorption broadening has to be assumed to explain the data.

B. Subband Emission

The radiation resulting from electronic transitions between the 2D subbands is expected to propagate along the interface with polarization perpendicular to it. Therefore, the two surfaces of the sample were coated with Al to allow the radiation, propagating along, the interface, to emit from the ends of the sample. The frequency is not tunable consequently a tunable InSb detector was empoyed. Fig.2 shows the response of a n-InSb detector as a function of the tuning magnetic field, as the GaAs/Al_xGa_{1-x}As multilayer sample was pulsed with an electric field E= 15V/cm, 25V/cm and 50V/cm. The response, in all three cases, shows a broad band peaked at $B \approx 17kG$ with a weak, but discernible, peak at $B \approx 23kG$ superposed on it. The amplitude as well as the peak position of the broad background are extremely sensitive to the DC bias applied to the InSb detector. The weak peak, however, if it is not masked by the broad background, always appears at $B \approx 23kG$. Consequently, we identify the weak peak as a narrow band emission at ~ 18meV which is the cyclotron energy of InSb at 23kG. The broad background is due to the change in the detector sensitivity to broad band radiation with increasing B. This identification was confirmed by checking the detector response with another InSb crystal as a FIR source. It is well known that the InSb emitter, in the presence of B, is a convenient narrow band source at its cyclotron frequency and a broad band source at B=0[9].
The origin of this narrow band

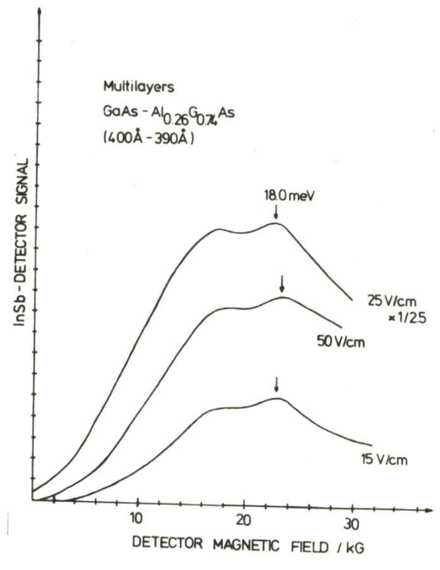

Fig.2 Emission signal from a GaAs/Al_xGa_{1-x}As multilayer: The radiation is emitted parallel to the interface and detected with a magnetically tunable InSb detector. The pulsed electric fields applied are indicated

emission can be either impurity states in the $Al_xGa_{1-x}As$ for example, or intersubband excitations of the 2D electrons. However, similar structure has not been observed in the single interface sample, which is expected to have only one quantum level in the surface potential well. This fact suggest that we assign it to the intersubband excitation of the 2D electrons. Emission from intersubband excitations was previously observed in Si inversion layers[7]. It is known, that the excitation energy is not simply the subband splitting, obtained from self-consistent Hartree calculation. Contributions from exchange and correlation effects[11], plasma screening effects[12], and the exciton-like effect[13] are important. In case of GaAs[14], the many-body effects are negligible, and the intersubband excitation energy may be written as $\hbar\omega_r = (E_{01}{}^2 + E_p{}^2)^{1/2}$, where E_{01} is the subband splitting between the 0 and 1 levels and E_p is the energy of the plasma oscillation, polarized perpendicular to the electron layer[15]. For our sample, a Hartree calculation gives $E_{01} = 4$meV[16] and the plasma energy is $E_p = 16$meV. The inter-subband excitation is expected at 16.5meV, sufficiently close to the observed peak to support our assignment.

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