Direct observation of magnetophonon resonances in Landau-level lifetimes of a semiconductor heterostructure

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Landau-level lifetimes are determined from saturation cyclotron resonance measurements on an InAs/GaSb double heterojunction using a picosecond far-infrared free-electron laser. Strong nonparabolicity of the conduction band truncates the equidistant Landau-level ladder, and saturation is achieved at all wavelengths. The Landau-level lifetimes show minima at $N\hbar\omega_c=\hbar\omega_{\mathrm{LO}}$, a direct observation of the magnetophonon effect. Observed picosecond lifetimes are due to LO-phonon emission which dominates electron-electron scattering at the magnetophonon resonance condition. [S0163-1829(96)01924-8]

We report a quantitative measurement of resonant electron cooling by LO-phonon emission in a semiconductor heterostructure in magnetic fields. Saturated cyclotron resonance (CR) shows that resonant cooling times can be as short as 0.85 ps in an InAs/GaSb heterojunction. Resonant optic-phonon absorption has long been known to be responsible for the magnetophonon effect, which generates oscillatory structures in a variety of transport properties such as magnetoresistance[1] at the resonance condition

$$N\hbar\omega_c=\hbar\omega_{\mathrm{LO}}, \tag{1}$$

where $\hbar\omega_c=\hbar eB/m^*$ is the cyclotron energy, and N is an integer. A direct measurement of the associated resonant *momentum* relaxation was reported by Barnes *et al.*,[2] who found that magnetophonon resonances (MPR's) could be observed in the linewidth of cyclotron resonance. In this work large changes in the electron *energy* relaxation rate are observed directly, and this is attributed to oscillatory phonon emission at the resonance condition of Eq. (1). This phenomenon has been inferred previously from measurements of the hot electron magnetophonon effect in bulk[3] and two-dimensional (2D) (Refs. 4 and 5) systems, and oscillations in phonon emission have been observed,[6] but it has not been possible to measure directly the electron decay times. Previous works on saturated CR have observed relatively long scattering times for photon energies well below the optic-phonon energies, considerably longer than the relaxation times found in the present study.[7] By contrast interband optical excitation to energies well above the LO phonon finds lifetimes on the order of 1–10 ps.[8,9] Finally, direct measurements of the intersubband relaxation by Raman measurements give subpicosecond values comparable to the minimum values reported here.[10]

The basic principle of a saturation CR measurement is to study the bleaching of the CR absorption due to high-intensity excitation between the absorbing levels. Since the conventional picture of the electron Landau levels is of a continuous series of levels, this process can only occur if the ladder of available states is truncated. The mechanism used to achieve truncation is band nonparabolicity, which means that the effective mass of the electrons increases with electron energy. In order to achieve sufficient nonparabolicity, we use a structure based on the narrow-gap material InAs, which has a far larger nonparabolicity than GaAs (which has been used in previous studies), due to its much smaller band gap (0.42 eV).

The sample studied is an InAs/GaSb double heterojunction, grown by metal-organic vapor-phase epitaxy on a GaAs undoped substrate.[11] A thick GaSb buffer layer (~ 1 μm) is grown on top of the substrate to accommodate strain, then a thin-layer semiconducting InAs/GaSb superlattice followed by the 400-Å InAs layer, and finished with a 200-Å GaSb capping layer. The carrier density at helium temperatures has been determined by transport measurements to be 6.0×10^{11} cm^{-2}, with a mobility of 40 000 $\mathrm{cm}^2/\mathrm{V\,s}$. Transport measurements and self-consistent calculations indicate that one electron and one heavy-hole state are occupied. The substrate of the sample was wedged to avoid interference effects; however, the substrate prevented us from measuring in the GaAs reststrahlen band (31–37 meV).

The sample was mounted in the Faraday configuration (light and magnetic field normally incident to the sample) in a superconducting magnet. The laser was directed to the sample via a light pipe and focused on the surface with a cone, with calibrated attenuators used to vary the laser intensity. The transmission was measured by a thinned Allen-Bradley resistor mounted behind the sample in the cryostat,

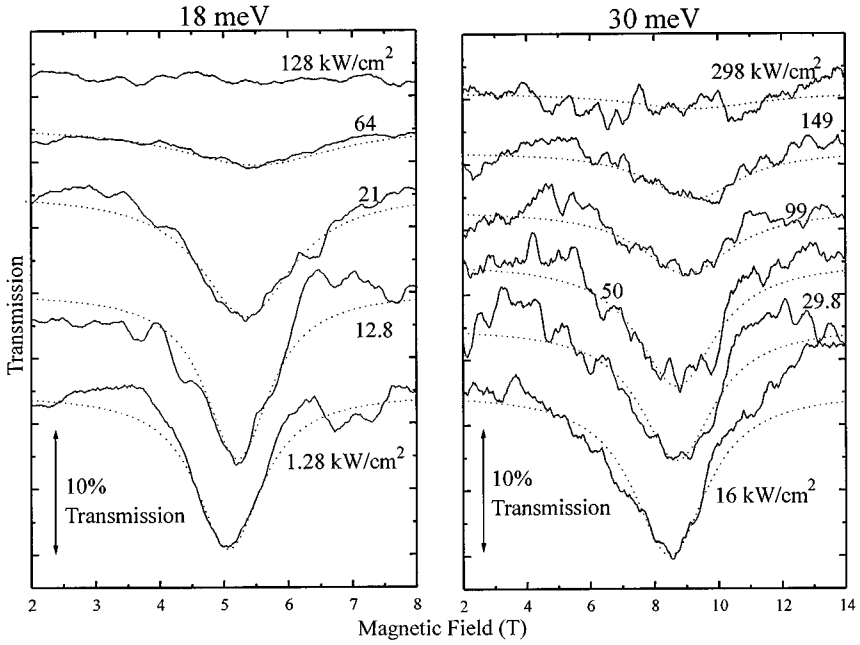

FIG. 1. The CR transmission spectra at 18 and 30 meV, at several indicated power densities. The dashed lines are Lorentzian fits.

with a second resistor mounted in front of the sample in the light pipe as a reference. The sample and detectors were cooled to 2 K. The measurements were performed using the far infrared picosecond free electron laser FELIX at Rijnhuizen.[12] FELIX delivers ''macropulses'' of typically 4-μs duration at a 5-Hz frequency. Each macropulse consists of a train of micropulses 8–15 ps long in our experiment, separated by 1 ns. Photon energies between 12 and 42 meV were used, with peak power levels in the micropulse of up to 400 kW/cm^2.

A typical series of resonances is shown in Fig. 1 as a function of power at energies of 18 and 30 meV. The LO-phonon energy of InAs is also 30 meV, so here resonant polaron coupling would be expected to split the resonance into two branches. However, it is known that the high carrier density used here causes a strong suppression of resonant polaron coupling due to the effects of level occupancy, and no splitting is observed. As the intensity of the laser increases, the intensity of the absorption process decreases, and the linewidth of the resonances increases. Care is taken to distinguish heating from saturation effects[13] by using the total integrated area of the resonance, since in the case of heating the area does not decrease with intensity, while the peak absorption still falls. The resonances were fitted with Lorentzian line shapes. In Fig. 2 the area of the absorption resonances is plotted as a function of intensity for several wavelengths. The total area decreases in all cases, but the saturation behavior is clearly quite strongly dependent on the photon wavelength. One example of the calculated intensity-dependent absorption is plotted for the 30-meV data. The saturation intensity (defined as the intensity at which the integrated absorption area falls to half its low-intensity limit) is plotted as a function of photon energy in Fig. 3. This shows two clear peaks at energies of 15 and 30 meV.

Extraction of the Landau-level lifetimes from the saturation data requires detailed modeling of the absorption process, and depends on both the lifetimes and details of the nonparabolic ladder of Landau levels. The nonparabolicity of the effective mass is described in terms of the transition energy $\hbar\omega_c$ as[14]

$$m^*(n,\hbar\omega)=m_0^*\{1+[2.6(n+1)\hbar\omega_c+E_{\rm conf}]/E_G\}, \quad (2)$$

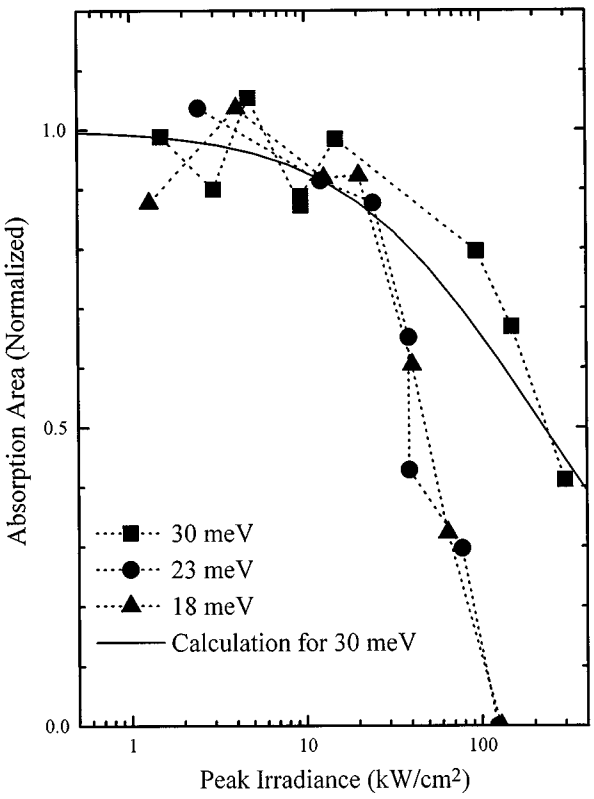

FIG. 2. Integrated areas of the Lorentzian fits of the CR transmission spectra (normalized vs the low-intensity area), for a selection of energies. The solid line is the calculated absorption area at 30 meV, assuming a lifetime a 0.85 ps.

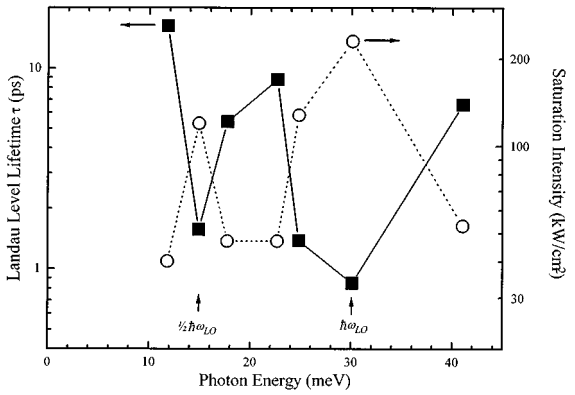

FIG. 3. Saturation intensities (○) and Landau-level lifetimes (■) as a function of energy. The magnetophonon resonance conditions are indicated by arrows. Note that the lifetimes at 41, 23, and 12 meV are lower limits; see text.

where m_0^* is the band-edge effective mass ($m_0^*=0.023m_0$ in InAs), E_G is the band gap, $E_{\rm conf}$ is the subband energy, and n is the index of the initial Landau state of the transition. We find a value of $E_{\rm conf}=47$ meV best fits the observed low-intensity resonances, in good agreement with self-consistent calculations. Using the relation $\tau_{\rm cr}=m^*/(e\Delta B)$, our resonance linewidths (half-width at half-maximum, HWHM) of $\Delta B\approx 0.6$ T indicate a momentum relaxation time of $\tau_{\rm cr}\approx 0.3$ ps, consistent with the mobility.

The higher carrier density does not allow for a simple analysis of the lifetimes. We are well below the quantum limit, and so have to take account of several fully or partially occupied Landau levels. For each level n, a rate equation accounting for stimulated emission, stimulated absorption, and nonradiative emission is written as

$$\frac{df_n}{dt}=\Phi[A_{n-1}-A_n]+[f_{n+1}(1-f_n)/\tau_{n+1}] -[f_n(1-f_{n-1})/\tau_n], \quad (3)$$

where A_n is the absorption between levels n and $n+1$, $\Phi=I/(2N\hbar\omega)$ is the photon flux per electron inside the sample, N is the total carrier density, f_n is the filling factor, and τ_n is the interlevel nonradiative relaxation lifetime. Using linearly polarized light renders only half of the incident radiative CR active, therefore the photon flux has been divided by 2. Due to the complex nature of the relaxation process which may involve broadening- and field-dependent electron-electron scattering and LO-phonon emission between nonadjacent levels, we adopt the simplifying assumption of a single phenomenological lifetime $\tau_n=\tau$ for all n. The absorption A_n is calculated in the Drude approximation, accounting for reflection at the surface and the filling-factor-dependent conductivity of each level (see Refs. 7 and 15). The Landau-level ladder is truncated by the decrease in the conductivity in the tail of the Drude function as the transition energy between adjacent levels decreases with increasing n. At the saturation intensity, we find only three levels significantly populated at 41 meV, while as many as ten or more levels are populated at lower photon energies.

The coupled rate equations of Eq. (3) describing the time evolution of the level populations are solved numerically, where the total absorption is integrated across a single micropulse. The nonradiative relaxation lifetime τ is an input to the model, and so is fitted to reproduce the experimentally observed saturation intensity Φ_s. In all cases the relevant lifetimes are considerably shorter than the laser repetition rate of 1 ns, justifying the single-micropulse model.

Using the above analysis the Landau-level lifetime τ is determined as a function of photon energy, as shown in Fig. 3. For photon energies of 41, 23, and 12 meV, low saturation intensities were found. Since the rate equation model is not as sensitive to long lifetimes (i.e., when negligible nonradiative emission occurs during the light pulse), we give the lower of the fitted value and the micropulse full width as a lower bound of the lifetime. The lifetimes show clearly defined minima at the magnetophonon resonance condition. The absolute accuracy is relatively poor, due to systematic uncertainties in both the experimental parameters such as radiation intensity, which depends on the exact amount of focusing achieved in the cone arrangement above the sample, and the assumptions used in the calculation. The absolute lifetimes are estimated to be accurate to within a factor of 3. The relative accuracy is considerably better, of order $\pm 20\%$ for lifetimes shorter than the micropulse, since all measurements are made with a fixed experimental setup, and use the same assumptions in the calculation. Since LO-phonon emission is a monoenergetic process, a detailed model would require nonradiative transitions with $\Delta n=2$ for the $N=2$ resonance of Eq. (1). A lifetime was calculated with this assumption at $2\omega_c=\omega_{\rm LO}$, which although 75% longer than the $\omega_c=\omega_{\rm LO}$ lifetime, is still considerably shorter than lifetimes at nearby energies. The values for the lifetimes are of the order of a picosecond, much shorter than all previous measurements of inter-Landau-level relaxation in other heterostructures. This difference is attributed to the importance of electron–LO-phonon scattering, which is the origin of the oscillations in lifetime. Extrapolating the data of Maran *et al.*[7] to our higher density of 6×10^{11} cm^{-2} gives an electron-electron-scattering lifetime of ~ 10 ps. It is therefore likely that relaxation at non-MPR conditions occurs mostly via this longer-lifetime mechanism, and so in this system the magnetic field allows tuning between two different relaxation regimes: LO phonons at the MPR condition, and electron-electron scattering at other fields.

It is known that *intersubband* relaxation in quantum wells is strongly dependent on the subband separation, and that once this exceeds the LO-phonon energy, lifetimes of order picoseconds or less have been observed by interband optical methods.[8,9] Theoretical models of 2D intersubband relaxation have shown enhanced cooling at the equivalent of the MPR condition,[16] where the subband separation energy equals the LO-phonon energy. This mechanism has been proposed to give rise to an electrophonon effect in calculations of carrier scattering rates using the momentum conservation approximation.[17,18] Pevzner, Gurevich, and Iafrate[19] predict a similar phenomenon in 1D systems as well. Experimentally, Shank *et al.*[8] found cooling lifetimes $\tau<1$ ps for excited energy states in GaAs/Al_xGa_{1-x}As multiple-quantum-wells using time-resolved absorption, when direct excitation was made above the LO-phonon energy with ex-

cited carrier densities similar to those here. Experimental and theoretical studies of LO-phonon-assisted cooling rates in III-V bulk materials likewise find lifetimes between 0.1 and 0.7 ps depending on carrier concentration.[20,21]

Warmenbol *et al.*[22] calculate the energy relaxation rates of hot electrons in applied magnetic fields in GaAs/$Al_xGa_{1-x}As$ heterojunctions, but for lower carrier densities (3.4×10^{11} cm^{-2}), finding relaxation rates which correspond to lifetimes of tens of picoseconds. Their ladder is nonterminated, so that thermal distribution promotes electrons to high energies. Nonetheless, they predict LO-phonon-emission-induced oscillations in the relaxation rate, which for our broadening results in a lifetime peak-to-valley ratio of 3–4, consistent with our observations. In practice a detailed comparison with theory is also likely to require a treatment of the energy input mechanism. There are likely to be significant differences between the present case, where carriers flow upwards in energy before relaxing via phonon emission, and conventional hot-electron photoluminescence experiments in which carriers are injected at high energies and cascade downwards. In addition, the complicated scattering and relaxation process at non-MPR conditions will need to be considered.

This experiment differs markedly from all previous two-dimensional electron gas CR saturation studies, which have been performed in GaAs/$Al_xGa_{1-x}As$ systems. Previous studies relied on the polaron effect to truncate the ladder of available Landau states, hence saturation was possible only for energies below the LO phonons, and used carrier densities less than 4×10^{11} cm^{-2}. The InAs/GaSb system, with its large band nonparabolicity, saturates even when high carrier densities suppress the polaron effect. Application of a magnetic field then allows tuning between LO-phonon-assisted energy relaxation and electron-electron scattering.

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