Influence of Collective Effects on the Linewidth of Intersubband Resonance

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We have measured the intersubband resonances of an InAs/AlSb quantum well with two occupied subbands from cryogenic temperatures to well above room temperature. The higher energy mode is very robust with increasing temperature; the lower energy mode, however, broadens above 200 K. We explain the results in terms of Landau damping and argue generally that the collective nature of the intersubband resonance is crucial for an understanding of the scattering mechanisms that determine the intersubband resonance linewidth. [S0031-9007(98)05471-4]

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Intersubband resonance (ISR) is a fundamental excitation of a low-dimensional semiconductor system. In a single-particle picture, the resonance corresponds to the transition between two quantized states. However, ISR is not a single-particle process [1,2]. Instead, ISR is a collective phenomenon better described as a plasmon, or charge-density excitation. The most obvious consequence of the collective effects is a shift of the ISR away from the energy separating the single-particle states. This shift tends to be only a small proportion of the resonance energy as the direct electron-electron interaction (depolarization field) and the exchange-correlation interaction (exciton effects) cause blueshifts and redshifts, respectively, and tend to cancel [3,4].

Recently, the collective effects have been dramatically revealed by studying systems with a broad single-particle density of states. Nevertheless, for large densities the ISR is a single, narrow line. For instance, in a system with a highly nonparabolic energy dispersion, the single-particle transition energy is a strong function of wave vector k, being smaller at the Fermi wave vector k_f than at $k = 0$. The single-particle spectrum is then broad, yet the ISR is a sharp peak [5–7]. The collective effects condense all the available oscillator strength into a single mode. A similar effect also occurs in weakly coupled quantum wells which have a broad and complicated single-particle spectrum yet a narrow ISR can be observed [8,9]. In the nonlinear regime where ISR is excited with a very intense source, optical pumping of carriers induces a redshift as the collective effects weaken [10].

These experiments show very convincingly that ISR is indeed a collective phenomenon. It has been argued that in the best samples the resonance is homogeneously broadened [11,12], in which case one can pose the question: What are the scattering mechanisms which destroy the coherence of the plasma oscillation? Surprisingly perhaps, a microscopic theory to answer this question does not seem to exist. In fact, the ISR linewidth is usually described with the single-particle scattering rates [11,12], ignoring the collective nature of the resonance. Calculations of the ISR width at low temperature in Si/SiO_2 from charged ion scattering [13] suggest that this approach is likely to be misleading. Generally, it appears to be unclear how the prevalent single-particle picture of electron scattering, particularly with phonons [14], must be modified in order to predict the ISR linewidth when collective effects are taken into account. Pragmatically, experiments suggest that the low temperature lifetime is limited by elastic, momentum nonconserving scattering off extrinsic defects such as interface roughness [12] or ionized impurities [15]. Furthermore, the ISR scattering time seems to have no obvious correlation with the transport mobility [12], and has a weak temperature dependence, both for Si [16] and GaAs [17] systems. In fact, at room temperature linewidths comparable to those at low temperature have been reported [17].

The purpose of this paper is to show how collective effects are crucial to an understanding of the ISR linewidth. The picture which emerges is that the ISR linewidth is determined by processes which can couple the zero wave vector ($q = 0$) ISR plasmon to $q > 0$ single-particle transitions. This approach can account, at least qualitatively, for the experimental facts listed above. The ISR linewidth is of particular relevance for ISR-based detectors [18] and, notably, emitters in the form of the quantum cascade laser [19].

Our experiment utilizes the highly nonparabolic band structure of the narrow gap semiconductor InAs. The effective mass increases with energy so that the single-particle intersubband energies decrease strongly with increasing in-plane momentum k. We studied samples from a heterostructure with two occupied subbands. The heterostructure consists of twelve 180 Å InAs quantum wells, each embedded in AlSb barriers, δ doped 50 Å away from the interfaces. The wells are separated by 100 Å. We observed a beating in the low-temperature Shubnikov–de Haas oscillations, allowing us to determine the densities of the first and second subbands as $n_1 = 1.89 \times 10^{12}$ and $n_2 = 0.74 \times 10^{12}$ cm^{-2}. We have calculated the in-plane dispersion of our quantum well using four band $\mathbf{k} \cdot \mathbf{p}$ theory [6]. As the confinement effects are very large in this system (very high potential barriers), we have neglected the static many-electron effects, i.e., the Hartree and exchange-correlation terms. The results are shown in Fig. 1. We adjust the Fermi energy E_f to reproduce the experimental $n_1 + n_2$ and then calculate the corresponding n_1 and n_2. We find n_1 (n_2) = 1.95 (0.68) $\times 10^{12}$ cm^{-2}, in excellent agreement with the magnetotransport.

We excited the ISR's by shining light onto a beveled edge of the sample, as shown in the inset in Fig. 2(a). We deposited silver on the surface to force the polarization to lie along the growth direction. The resonance was highly saturated with a complete covering of Ag. In order to minimize this problem, we measured samples with only a 0.2 mm wide stripe of Ag (1000 Å thick). Spectroscopy in the mid infrared was carried out with a Fourier transform spectrometer, and we used a sample with 70 Å well width to provide a reference spectrum.

The transmission spectrum of the 180 Å well width sample at low temperature is shown in the bottommost curve of Fig. 2(a). There are two resonances: the weaker, lower energy ISR is 1−2 and the stronger, higher energy ISR is 2−3, labeling the quantum well states as 1, 2, 3, etc. The ISR's are close to Lorentzians in shape, implying that the broadening is predominantly homogeneous. In a single-particle picture, the resonance intensities at low temperature should scale as $(n_1 - n_2)z_{12}^2$ for 1−2 and $n_2 z_{23}^2$ for 2−3, where z_{12} and z_{23} are the z-dipole matrix elements. Figure 1 makes this point clear. All the electrons in the second subband ($0 < k < k_f^2$) can be excited into the third subband, but only those electrons in the first subband with $k_f^2 < k < k_f^1$ can contribute to 1−2, the others at lower k being blocked by the Pauli exclusion principle. We calculate $z_{12} = 36.5$ and $z_{23} = 39.5$ Å, implying that for our sample the 1−2:2−3 intensities should scale as 1.3:1. This is clearly not the case. The explanation is that the collective effects couple the two resonances, resulting in a transfer of oscillator strength from the 1−2 ISR to the 2−3 ISR. The ISR's correspond to oscillations of the charge density along the growth direction but they cannot oscillate independently owing to the Coulomb coupling. One has then a (1−2)-like mode where the two charge oscillations are predominantly out of phase, and a (2−3)-like mode where the oscillations are predominantly in phase. The in-phase mode couples strongly to the oscillating light field and so takes oscillator strength from the out-of-phase mode which couples weakly to the light field. According to this interpretation, the coupling should become even stronger at higher density leading to an even more marked transfer of oscillator strength from 1−2 to 2−3. This is exactly what we observe: at a density of 6×10^{12} cm^{-2}, for instance, the 2−3 mode takes virtually all the oscillator strength such that we can no longer observe the 1−2 mode.

Shown also in Fig. 2 is the behavior on increasing the temperature, from 10 up to 577 K. The two modes exhibit completely different temperature dependencies. The upper mode is remarkably robust with increasing temperature, broadening only slightly even at very high

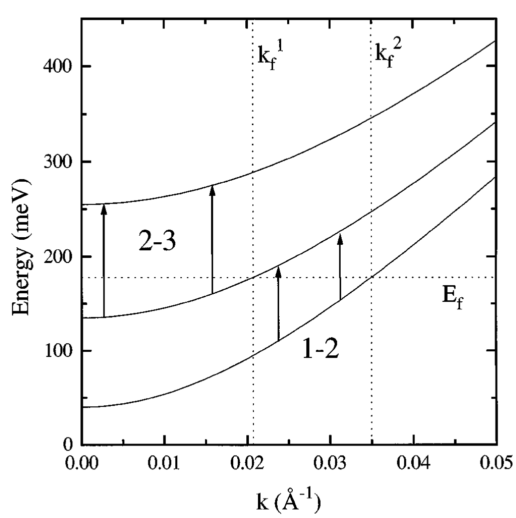

FIG. 1. The in-plane dispersion of the subbands in a 180 Å InAs/AlSb quantum well calculated with four band **k · p** theory. Static many-electron effects have been neglected. The low temperature Fermi energy E_f and corresponding Fermi wave vectors k_f^1 and k_f^2 are shown as dotted lines. The energy zero corresponds to the bottom of the InAs well.

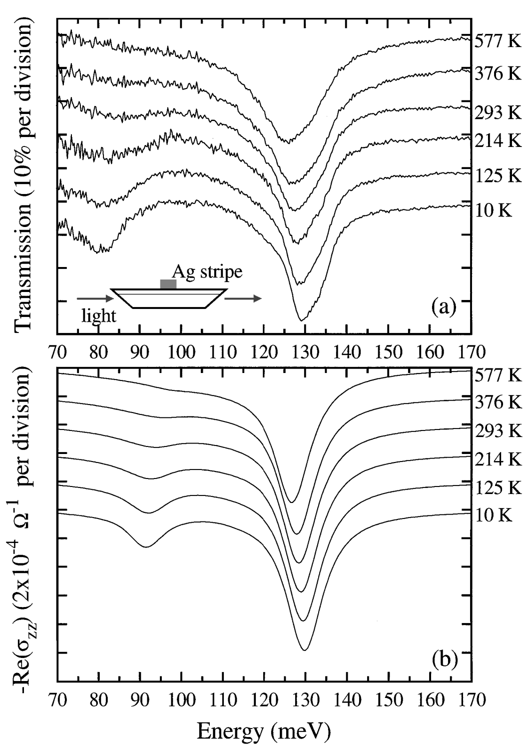

FIG. 2. (a) Experimental transmission spectra of the intersubband resonances of a 180 Å InAs/AlSb quantum well. The spectra are offset from 1 for the various temperatures. (b) Calculations of the real part of the dynamic conductivity, σ_{zz}, at zero wave vector in the self-consistent field approximation. The curves are offset from 0 for clarity.

temperature. Conversely, the lower mode broadens above 200 K, such that it becomes a low-energy tail of the upper mode at the highest temperatures.

The 1−2 ISR is up shifted from the background single-particle energies by the depolarization field. At low temperature one can deduce from the band structure of Fig. 1 that the energy of the 1−2 ISR lies above the 1−2 single-particle energies yet below the 2−3 single-particle energies. On increasing the temperature, electrons are thermally excited up the bands. This means that the 2−3 single-particle transitions now spread to higher k and hence to lower energy. Similarly, the 1−2 single-particle spectrum also becomes broader. The net effect is that the 1−2 collective mode becomes degenerate with an increasingly large background single-particle density of states. We suggest that this degeneracy forces the collective mode to decay into single-particle transitions, an effect (Landau damping) known from metal physics to be very effective at scattering plasmons [20].

In order to quantify this argument, we have performed calculations in the self-consistent field approximation. We have extended the formalism of Ando [2] to incorporate elevated temperatures, a nonparabolic band structure, and multiply occupied subbands. At the carrier densities here, the dominant collective interaction is the direct one, so we have neglected the exciton term. As single-particle states we take the results of the band structure calculation shown in Fig. 1. The severest assumption of the model is that each single-particle state has a broadening, Γ, which is state and temperature independent. We calculate the real part of the out-of-plane dynamic conductivity, $\Re(\sigma_{zz}(E))$, at $q = 0$ which is linearly related to the absorption; $-\Re(\sigma_{zz}(E))$ can be compared with the transmission data.

Figure 2(b) shows the results of the calculations with $\Gamma = 11$ meV chosen to reproduce the experimental, low temperature 2−3 width. At 10 K it can be seen that the calculation reproduces the relative intensities of the 1−2 and 2−3 modes. The energy of the 2−3 mode is accurately modeled, but the 1−2 energy is overestimated by ~10 meV, possibly owing to the omission of exchange-correlation effects. On increasing the temperature the 1−2 resonance broadens, exactly as in the experiment. The Landau damping argument is supported by Fig. 3. Plotted is $\Re(\sigma_{zz}(E))$ without collective effects; the dotted lines mark the energies of the low temperature 1−2 and 2−3 collective modes. At the 1−2 energy, the background single-particle density of states increases drastically with increasing temperature, enhancing the decay of the plasmon into single-particle transitions. The calculations show that the coupling to the 2−3 single-particle transitions, not to the 1−2 single-particle transitions, damps the 1−2 collective mode.

It is particularly striking in Fig. 2(a) that the 2−3 mode has a linewidth which is very weakly temperature dependent. At 577 K the linewidth is only ~1.7 times larger than at 10 K. The calculations of Fig. 2(b) give a temperature-independent width largely because there is no increase in the background density of states at this energy (Fig. 3), in contrast to the behavior at the 1−2 energy. However, the calculations do not include coupling to phonons. We argue that the weak temperature dependence cannot be accounted for with a single-particle description of electron-phonon coupling. At low temperature, the lifetime of an electron in the second subband is limited to about 1 pS [11,14] by LO phonon emission. This would give a contribution to the ISR linewidth of a few meV, which is not incompatible with the experimental results. However, on increasing the temperature, the LO-phonon emission rate should increase as $1 + n_{\rm ph}$, where $n_{\rm ph}$ is the LO-phonon occupation. This should at least double the linewidth in the measured temperature range. Furthermore, absorption of LO phonons should also contribute to the linewidth (at ~600 K, $n_{\rm LO} \sim 1$) leading to a much stronger temperature dependence than seen experimentally. It would appear then that phonon scattering is unimportant. The reason for the weak ISR-phonon coupling is that the ISR is collective. A phonon has to scatter the ISR plasmon along its dispersion relation, severely restricting the number of phonons which can participate.

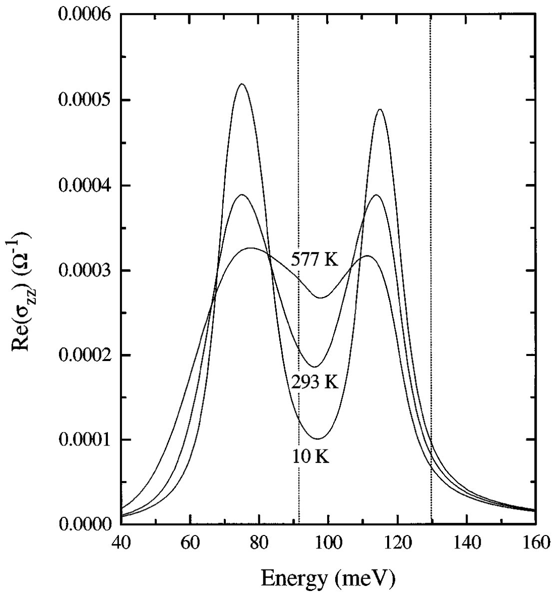

FIG. 3. The calculated real part of the dynamic conductivity, σ_{zz}, without collective effects at three different temperatures. The curves correspond to the density of single-particle transitions with $q = 0$ which form the single-particle background density of states for the calculations in Fig. 2(b). The two dotted lines show the calculated energies of the 1−2 and 2−3 collective modes at low temperature.

We find then that the 1−2 mode is Landau damped by thermally excited single-particle transitions, and that the 2−3 mode is neither damped in this way nor scattered by phonons. The ISR width is a strong function of well width (not shown here). These results imply that the 2−3

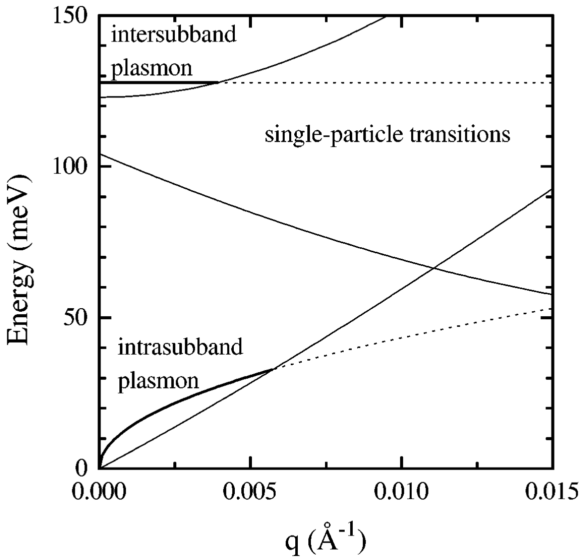

FIG. 4. The energy-wave vector dispersion for the intersubband and intrasubband plasmons and for the single-particle transitions for a 150 Å InAs/AlSb quantum well with one occupied subband and carrier density 10^{12} cm^{-2}. The dotted lines show the parts of the dispersions where Landau damping occurs.

width for the present sample is determined by scattering off well-width fluctuations, even at high temperature. It now becomes clear why such short-range fluctuations are the predominant scatterers of the ISR plasmon. They allow elastic scattering processes taking the $q = 0$ plasmon to $q \sim \pi/L$, where L is the characteristic length of the fluctuations. If this q is large enough, the plasmon moves into a part of its dispersion where Landau damping occurs. It is also no surprise that the ISR linewidth has little to do with the transport mobility as the processes involved are completely different.

We illustrate the Landau damping in Fig. 4 by plotting dispersion curves for a system of general interest, a single quantum well with one occupied subband. As a representative case we have taken a 150 Å InAs/AlSb quantum well with $n_1 = 10^{12}$ cm^{-2}. Shown in Fig. 4 are the almost dispersionless intersubband plasmon, the intrasubband plasmon with its characteristic $\sqrt{q}$ dependence, and the bands of single-particle excitations. For high enough q both the intrasubband and intersubband modes become degenerate with single-particle excitations and are Landau damped. In this particular case, $q \sim 0.004$ Å^{-1} is required for the ISR to enter the Landau-damped regime, corresponding to a length fluctuation of $\sim$800 Å, i.e., quite short range. Confirmation that Landau damping is a strong scattering mechanism in two-dimensional semiconductor systems comes from Raman studies of the charge-density excitation of an electron gas in GaAs [21,22]. At high enough q, the mode broadens as it enters the region of single-particle transitions in the $E - q$ plane.

For ISR-based applications, the present results are very encouraging. High operating temperatures and band nonparabolicity have caused considerable concern. The present results, however, show that a sharp ISR can be expected in the conditions which typically prevail in an ISR-based photodetector or laser.

To conclude, we have shown how the linewidth of ISR in semiconductor quantum wells is strongly influenced by the collective nature of ISR. A single-particle picture of the scattering mechanisms cannot account for our experimental results. We hope that this work will stimulate work on a detailed microscopic theory of ISR.

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