Observation of intersubband transitions to motionally bound states

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We report the observation of resonant transitions to motionally bound subbands in an *n*-type InAs accumulation layer. The far-infrared transitions are observed in the pinning regime of Shubnikov–de Haas oscillations, which is a signature of motionally bound subbands, and at surface-electron densities that are in good agreement with a recent theoretical prediction.

I. INTRODUCTION

In quantum wells with mass-mismatched barriers as well as in inversion or accumulation layers on narrow-gap semiconductors, subbands can exhibit novel dispersion properties for motion transverse to the confinement direction. Accumulation layers on *n*-type InAs provide an ideal system in which to study such effects because, in this system, the binding potential depends on transverse motion through the band nonparabolicity. The continuous spatial variation of the effective mass away from the semiconductor surface, caused by the nonparabolicity, is a limiting case of a mass-mismatched quantum well. Using a simple square-well model, Doezema and Drew[1] showed that the "motional binding" due to the mass variation could account for the observed pinning of Shubnikov–de Haas (SdH) oscillations at total carrier density N_s values below those expected by conventional extrapolation. More realistic self-consistent potentials[2,3] give good quantitative agreement with existing SdH data.

For each subband a range of N_s corresponds to motional binding. Under these conditions carriers can only be bound to the surface for transverse wave vectors k_t larger than a critical value k_c. Figure 1 shows schematically the energy structure of an accumulation layer when the first excited state is motionally bound; i.e., the subband with index $j=1$ exists for $k_t > k_c$. Until now, the existence of such motionally bound states was deduced from the observed pinning of the frequency of SdH oscillations near subband occupation thresholds. Recent calculations[2,3] predict the pinning regimes, i.e., the conditions of motional binding, to exist over N_s ranges even larger than observed by the SdH experiments. In this paper we report the observation of intersubband transitions to motionally bound states over the predicted N_s range, constituting direct evidence indeed for their existence.

The situation we wish to study is illustrated in Fig. 1. The location of the critical k_t value k_c determines three cases of interest. First, when k_c lies above point A, transitions from occupied states are not possible. Second, k_c will move through point A to point B with increasing electron density N_s. In this regime the strength of intersubband resonance increases from zero (at $T=0$) to full strength with increasing N_s. Finally, as k_c decreases through point B to point C (at which point the subband is fully bound), the intersubband resonance remains at full strength, taking only final-state availability into account. It is in this N_s range that SdH oscillations corresponding to the motionally bound subband can first appear, and until the subband is fully bound, their oscillation frequency depends nonlinearly on N_s.[1–3] To search for intersubband transitions to motionally bound states, therefore, it is clear that one must look in the N_s regime below the onset of linearity in the SdH oscillation frequency.

II. EXPERIMENT AND ANALYSIS

The samples we use are typically $1\times1\times0.1$ cm^3 bulk, crystalline InAs slabs with (100) orientation. The bulk concentration $n=2.0\times10^{17}$ cm^{-3}, determined from the bulk SdH effect at 4 K, is chosen to correspond to existing experimental and theoretical results. The sample surface is polished in a methanol-bromine solution and then

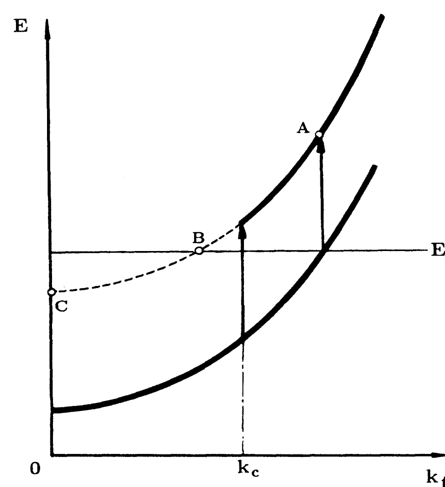

FIG. 1. Schematic dispersion curves for intersubband transitions to a motionally bound subband. The upper subband exists only for $k_t > k_c$, as indicated by the solid line. The dashed line indicates possible subband dispersion as the binding potential increases. Allowed transitions occur for k_t values from k_c (or point B if $k_c < k_B$) to k_A, the k_t value for point A.

capped with a SiO_2 layer of thickness ~1000 Å and a semitransparent NiCr gate. An optically pumped far-infrared laser is used to provide radiation for wavelengths longer than about 40 μm. A CO_2 pump laser itself is used for the 9–11-μm range. The radiation is guided to the sample to reflect at about 45° incidence and then detected with a He-cooled, Ga-doped Ge bolometer. The gate voltage V_g is modulated so that the detected signal is proportional to dR/dV_g, the reflectance derivative. The measured device capacitance is used to convert the gate voltage to the total electron concentration N_s.

Reflectance-derivative spectra at five wavelengths are shown in Fig. 2. The resonance structure in the 10.6-μm trace was previously reported by Reisinger and Koch.[4] It was identified as a depolarization-shifted transition from the ground-state subband to the first-excited subband (0-1)*. The unshifted transition (0-1) was found to lie at an approximately 15% higher N_s value.[15] These Reisinger-Koch identifications are indicated in Fig. 2 on the 10.6-μm trace. At the longer wavelengths seen in the figure, one observes a pair of resonances resolved here on the strong background signal, which was noted by Reisinger and Koch in the 30–50-μm range.[4] We attribute these resonances to the (0-1)* and (1-2)* transitions. The (0-1)* transition observed in the 46.7-μm, 57.0-μm, and 70.5-μm traces occurs at N_s values where the frequency of SdH oscillations is "pinned" to the Fermi circle area,[3] i.e., the N_s regime of motional binding where the critical wave vector lies between B and C of Fig. 1. SdH oscillations are observed[6] and pinned over this whole range. The range where the (1-2)* transition is observed in Fig. 2 corresponds to a similar (B to C in Fig. 1) range for subband 2. However, SdH oscillations for subband 2 are not observed below $N_s = 2.5 \times 10^{12}$ cm^{-2}.[3,6] Thus we observe intersubband resonance well below this onset of SdH oscillations for the excited subband as one expects in the motional binding picture for accumulation layers on degenerate semiconductors. (Although, of course, oscillations should in principle be observable over the whole B to C range.)

The conclusion that we are observing transitions to motionally bound subbands is strengthened by comparison with a theoretical prediction. In Fig. 3 we show results of a self-consistent calculation by Zhang, Slinkman, and Doezema[3] which took into account the motional binding. The figure shows the wavelength λ_{ij} corresponding to the subband spacing $E_j - E_i$ for allowed transitions. In the 9–11-μm range, the observed[4] 0-1 transition is in good agreement with self-consistent calculations.[3,7] The depolarization shift in this wavelength range is observed and predicted[7] as about 15%, but at the longer wavelengths of Fig. 3, it is predicted[7] to be less than 5%. Several factors, discussed in Ref. 7, contribute to this reduction: reduced oscillator strengths at low N_s, increased wave-function extent at low N_s, and an increased dielectric function below the optical-phonon frequencies of InAs.

Assuming that the depolarization shifts are nearly negligible, it is clear from Fig. 3 that the agreement between the theoretical prediction and our data is quite good. (Without motional binding there would be no theory prediction below the N_s values labeled C.) The absence of an observed 0-1 transition at 96.5 μm in Fig. 2 occurs, according to the calculation, because the critical

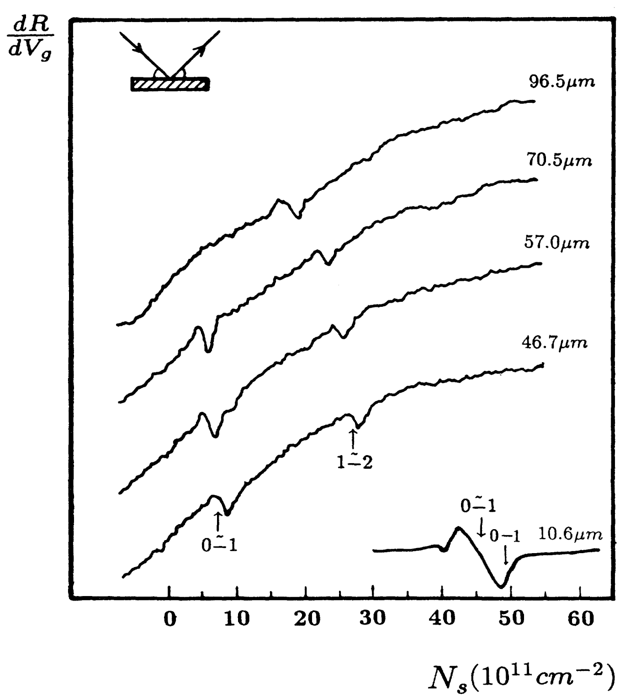

FIG. 2. Differential reflectivity at several far-infrared wavelengths. Unpolarized radiation is incident at approximately 45° as indicated at the top of the figure.

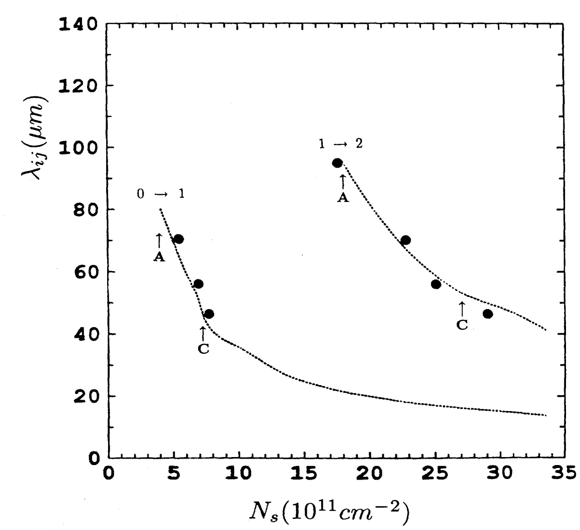

FIG. 3. Comparison of observed intersubband resonance positions to the results of a calculation by Zhang, Slinkman, and Doezema (Ref. 3). Far-infrared wavelength is plotted against the electron density at which resonance occurs. Labeled points correspond to the conditions of Fig. 1.

wave vector k_c for subband $j=1$ lies above point A of Fig. 1.

III. CONCLUSIONS

The data presented here are beautifully consistent with our basic picture of motional binding. The resonances which are ascribed to transitions to motionally bound subbands occur in an N_s regime where SdH oscillations are observed to be pinned. We have used the data of Radantsev *et al.*[6] (at $n=1.8\times10^{17}$ cm^{-3}) to identify this pinning regime for our 2×10^{17} cm^{-3} (i.e., essentially the same n) sample; but similar data of Reisinger, Schaber, and Doezema[8] at $n=1\times10^{17}$ cm^{-3} point to the same pinning regime, whose N_s location is observed[8] to be only weakly dependent on n. The theoretical prediction of transitions to motionally bound states to which we have compared our data has the bulk density n as its only free parameter. This calculation, planned to be published elsewhere,[3] yields excellent agreement to SdH data within and without motional binding regimes and, furthermore, predicts observed intersubband spacings outside the motional binding regimes as does a calculation by Reisinger.[7] In summary, theory and experiments all require identification of the resonances presented here as transitions to motionally bound states.

Several interesting problems remain. The A-B regime of Fig. 1 occurs over a very narrow N_s range, according to calculation,[3] but is worth further attention. The behavior of the resonances in this regime is expected to reflect how abrupt the k_c cutoff is. We hope to pursue this question using Fourier-transform spectroscopy to sweep frequency as N_s is tuned through the A-B range. The behavior of motionally bound states in magnetic fields is also of interest for future work.

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