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Electronic properties and far infrared spectroscopy of InAs/AlSb quantum wells

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The electronic and magneto-optical properties of the interesting system InAs/AlSb are investigated at low temperatures and in high magnetic fields. The system yields very deep quantum wells with type II staggered bandstructure and can have very high electron concentrations with high mobilities. Far-infrared spectroscopy reveals very pronounced oscillations in the linewidth of the cyclotron resonance absorption line. In the regions of the reststrahlenbands of the system we observe strong interaction of the cyclotron resonance with optical phonons. The number of electrons in this system can be tuned via persistent photoeffect which unexpectedly can lead to both an increase as well as a decrease of the carrier density depending on the wavelength of the illuminating light.

The combination of InAs and AlSb in heterostructures [1] is a potentially very interesting system. It offers several features that might lead to superior performance in semiconductor devices. The deep quantum wells (1.3 eV) are filled with very high electron concentrations ($N_s \leq 3 \times 10^{12}$ cm^{-2}) and exhibit high mobilities ($\mu \leq 400000$ cm^2/V s) [2]. Also, the small effective mass in InAs ($0.023 m_0$ at $k = 0$) and the resulting large quantization energies make this system promising for opto-electronic applications.

Here, we would like to report the first characterization of this new system using far-infrared (FIR) spectroscopy. Experiments are performed at low temperatures ($T \leq 2$ K) and in high magnetic fields ($B \leq 15$ T) using a rapid-scan Fourier transform-spectrometer. Experimentally, we investigate the relative change in transmission at a fixed magnetic field with respect to the one at $B = 0$. The samples under investigation consist of typically 15 nm wide InAs quantum wells with AlSb barriers. They are grown on GaAs substrates by molecular beam epitaxy (MBE) using a relatively complex buffer layer system employing layers of GaSb and AlSb [3] to minimize dislocations caused by the rather large lattice mismatch of the species involved. Even though misfit dislocations cannot be fully eliminated, comparably high electron mobilities can be obtained. In the samples reported here, neither the AlSb-barriers nor the InAs-quantum wells were intentionally doped by conventional doping techniques. Free electrons in the well seem to result from "antisite" doping, i.e. As atoms occupying Al sites [2].

In fig. 1 we depict a set of cyclotron resonance traces at magnetic fields between $B = 2$ T and $B = 8.5$ T. Adjacent traces were recorded at magnetic fields differing by $\Delta B = 0.1$ T. Typical linewidths at full width half maximum (FWHM) are 20 cm^{-1}, typical absorption depths are 30 to 40%. A line shape analysis including saturation effects thus yields mobilities of the order of 150000 cm^2/V s and carrier densities of 8×10^{11} cm^{-2}. The cyclotron resonance spectra in fig. 1

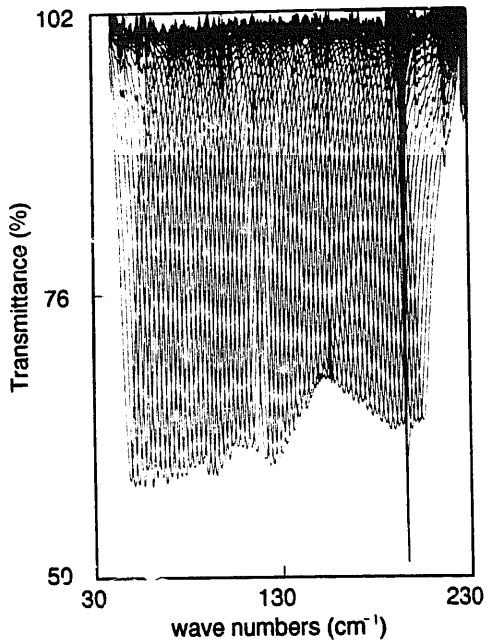

Fig. 1. Cyclotron resonance measurements between 2 and 8.5 T with $\Delta B = 0.1$ T. Oscillations of the absorption depth can be explained in terms of filling factor-related screening. The very sharp structure around 195 cm^{-1} is an artefact of the FIR spectrometer (velocity peak).

exhibit very pronounced oscillations in both absorption depth as well as in linewidth similar to those reported earlier on the InAs/GaSb system [4]. The amplitude of these oscillations decreases with decreasing magnetic field. This behaviour has been interpreted in terms of filling factor-related screening effects. Comparison with magnetotransport measurements on the same sample shows coincidence of the most pronounced absorption minimum around 155 cm^{-1} with the integer filling factor $\nu = N_S/N_L = 6$, where $N_L = eB/h$ denotes the degeneracy of a Landau level at the magnetic field B. At integer filling factors the localization of the carriers leads to a reduced self-consistent screening of scattering centers and potential fluctuations as has originally been suggested by Das Sarma [5]. At low magnetic fields the Landau levels overlap thereby reducing the modulation of screening behaviour. The overall envelope of the CR spectra thus reflects the Shubnikov–de Haas oscillations of the magnetoconductivity σ_{xx} where minima of the CR amplitude (i.e. transmittance maxima) coincide with minima in σ_{xx}.

At higher magnetic fields ($B > 8.5$ T) we observe additional modifications of the CR lineshape, which are of different origin, namely the interaction with optical phonons. This, too, has been observed previously in the InAs/GaSb-system [6]. Specifically, deviations in the CR lineshape are visible at the frequencies of the TO- and LO-phonons of the polar layers embedded in our system. Fig. 2 shows additional structure at 220 cm^{-1} corresponding to the frequency of the InAs TO-phonon (218.5 cm^{-1}), at 230 cm^{-1}, ($TO_{GaSb} = 230.5$ cm^{-1}), at 240 cm^{-1} ($LO_{GaSb} = 240.0$ cm^{-1}) and at 244 cm^{-1} ($LO_{InAs} = 242.5$ cm^{-1}). Since these layers (except GaAs) are thin, no real reststrahlen bands are formed between these frequencies. Similar to the results of ref. [6] we believe that most of the structure in the CR lineshape is of purely macroscopic dielectric origin and can be explained by a multilayer transmission model. The explanation is strongly supported by the fact that GaSb is only present in both the cap and the buffer layers which are remote from the quantum well so that no electronic interaction is to be expected. Only the

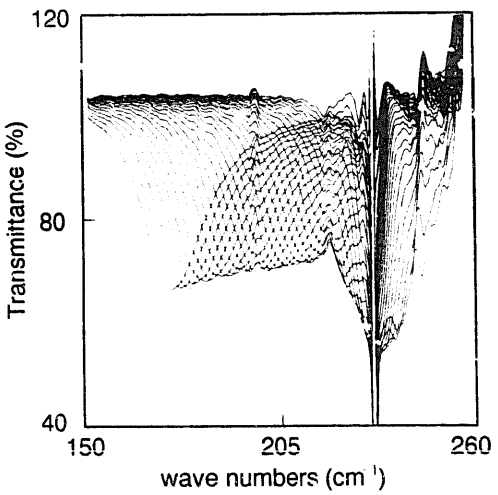

Fig. 2. Cyclotron resonance measurements between 8 and 11 T. Coupling to optical phonons leads to distortions of the CR lineshape due to the divergence of the dielectric function at the phonon energies. This is most pronounced in the present figure around the energy of the GaSb TO phonon (230.5 cm^{-1}).

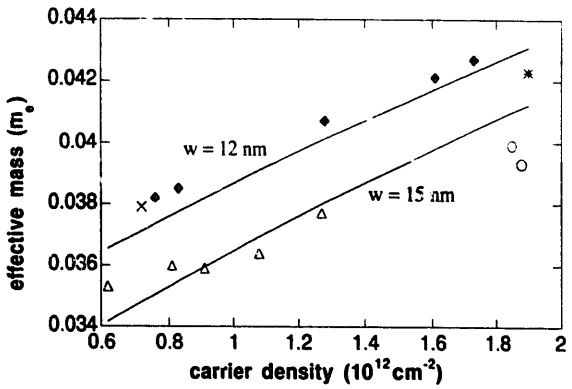

Fig. 3. Effective mass vs. carrier density of several quantum wells. Solid lines represent calculations taking into account nonparabolicity. The symbols represent experimental data as obtained from CR measurements. Different open symbols represent different samples of well width $w = 15$ nm, filled symbols depict the results for various 12 nm wide wells.

splitting of the CR in the vicinity of the LO_{InAs}-frequency (242.5 cm^{-1}) strongly depends on the carrier density. This may arise from the fact that, by tuning the carrier density, we also tune the Landau level filling factor associated with the magnetic field corresponding to a given CR position. Resonant polaron effects [7] are predicted to strongly depend on the actual screening and thus would crucially depend on the position of the Fermi energy with respect to the Landau levels. A detailed study of resonant LO-polaron effects therefore requires a fine tunability of the carriers density, e.g. by field effect, which is not available to us, to date.

Due to the small band gap of InAs (0.4 eV), the quantum well system exhibits strong nonparabolicity. From the CR positions we extracted the effective mass in the quantum well for the different samples investigated. Since we can change the carrier density within certain limits by persistent photoeffects (see below), we are able to study the dependence of the mass m^* on the Fermi energy. This is depicted in fig. 3, where we plot m^* versus N_s for various samples of different quantum well widths together with results of a simple calculation. Here, we assume the quantum well to be infinitely deep, implicating subband energies of $E_n = E_1 n^2$ $(n = 1, 2, \ldots)$. We include only one occupied subband and then calculate the energy dependence of the effective mass according to the Kane-model [8], given by

$$m^*(E) = m^*(0)\left(1 + \frac{2(F_1 + E_F)}{E_{gap}}\right).$$

Qualitatively the theoretical results and the experimental values are in good agreement. Judging the quantitative accuracy one should keep in mind that the determination of the electron density by means of CR-lineshape analysis is usually accurate only within 5 to 10%. Considering these limitations the simple analytical model has proven to be a very good approach to describe the nonparabolicity in the InAs/AlSb-quantum well.

To vary the carrier density in the quantum well we used the persistent photoeffect by illuminating the samples with light emitting diodes (LED). A consequential increase of the carrier density which remains persistent at low temperatures is common in various heterostructures and bulk semiconductors and is usually attributed to the photoionization of donors, namely DX-centers [9]. Initial transport measurements [3] revealed that in the InAs/AlSb-system, in contrast, the carrier density can be reduced persistently by illumination. Such a persistive decrease is unusual. On GaAlAs/AlGaAs-heterostructures experiments have shown a decrease only under continuous illumination with comparable high energy densities [10]. Moreover, our experiments show that in the InAs/AlSb-system both positive and negative persistent photoeffects coexist where the sign of the change of the carrier density depends on the wavelength used for illumination.

Fig. 4 shows three CR-traces at a fixed magnetic field of $B = 8$ T at $T = 2$ K. The trace recorded after cooling down the sample in the dark is marked as "initial". After illuminating the sample with a green LED ($E \approx 2$ eV) the CR drastically loses oscillator strength which indicates a decrease in carrier density. As expected for a nonparabolic system the CR-position given by $\omega_C = eB/m^*$ also shifts to a higher frequency. However, when the sample is illuminated with an IR-LED ($E \approx 1.2$ eV), the CR-absorption depth increases and its position shifts to a lower frequency in accordance with an increase of the

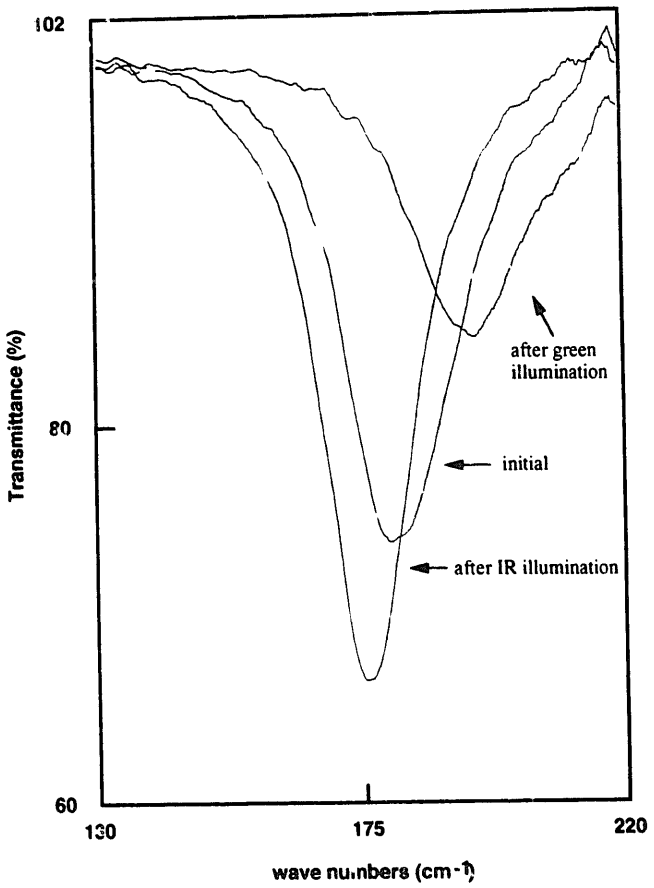

Fig. 4. Three CR-traces at $B = 8$ T were recorded after cool down (initial) and after illumination with a green and an IR-LED. Carrier densities increase or decrease depending on the wavelength of the illuminating light, causing a change in absorption depth and position.

carrier density. Both effects are reversible so that by illuminating the sample with green and infrared light subsequently, the carrier density can be "switched" between two values. This switching behaviour is also detectable in transport measurements at temperatures up to $T = 77$ K. Presently, we are investigating the time scale of the mechanisms involved which could be interesting in the context of optical signal processing.

Experiments are being prepared to study the photoeffects in detail, especially to determine the threshold photon energy at which the effect changes sign. Presently, we propose the following approach to understand the mechanism. At photon energies smaller than the AlSb band gap ($E_g = 1.4$ eV), we assume that donors in the AlSb can be ionized. Some of the photoelectrons are expected to migrate into the quantum well causing an increase of the carrier density. If the photon energy is larger than the AlSb bandgap electron–hole pairs are generated. Due to the staggered (type II) band lineup at the AlSb/InAs-interface most of the holes move towards the quantum well while only some of the created electrons fill the well. Due to the overlap of the wave functions the holes recombine with electrons in the well, causing a net decrease of the electron density.

In summary, we have reported on the electronic and magneto-optic properties of the promising material combination InAs/AlSb yielding very deep quantum wells with high carrier densities and high mobilities. Analysis of cyclotron resonance absorption reveals large quantum oscillations both in intensity as well as in lineshape. These oscillations are explained in terms of a filling factor-related screening behaviour of the electron system. We observe interaction between the CR and optical phonons in the system. A simple analytic calculation including nonparabolicity explains quantitatively rather well the observed strong density-dependence of the effective mass in the InAs-quantum well. The system exhibits both negative and positive persistent photoeffects. These effects lead to a multistable switching behaviour of the conductivity of the samples.

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