Far-Infrared-Study of Shallow Etched Quantum Wires on High Mobility GaAs/AlGaAs Heterostructures

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The far infrared response of arrays of periodic quantum wires has been investigated by cyclotron resonance transmission and photoconductivity (PC) measurements. The wire structures have been prepared by laser holography and ultra fine wet chemical shallow mesa etching of modulation doped $Al_xGa_{1-x}As$/GaAs heterostructures. Due to narrow geometrical dimensions (300 nm) quantum confinement arises and leads to the formation of one dimensional electronic subbands with a typical energy separation of 1-3 meV. The far infrared transmission spectra of the quantum wire structures show one strong resonance, which can be described by a harmonic oscillator model, assuming that the confining potential is of parabolic shape. Depending on the intensity of bandgap illumination a well pronounced transition from a one-dimensional electronic system behavior to a modulated 1D system and finally to a pure 2 dimensional system can be achieved. The photoconductivity can be measured by applying contacts to the sample. The photoconductive signal is observed over a wide range of magnetic fields. The position of the PC-peak can be assigned to the plasmon-shifted cyclotron resonance. In addition in specially grown samples, which contain a low density ($4 \times 10^{10}\mathrm{cm}^{-2}$) and high mobility channel, an extremely sharp line with a line width of 0.15 cm^{-1} is observed.

I. Introduction

The characterization of nanostructures is a topic of vital interest, since the dimensions of commercially available semiconductor devices are now in a range, where quantum size effects become evident. In this paper, two methods are presented to characterize low-dimensional structures. Far infrared transmission and photoconductivity measurements are used to determine the low-dimensional properties, e.g. the subband energies.[1]

Much insight into the electronic properties of low-dimensional electron systems is gained from investigations of their FIR excitations. They have demonstrated that in etched[2] as well as field-effect[3] induced low-dimensional electron systems the bare confinement V_{ext} is of parabolic shape in a very good approximation. Taking the generalized Kohn theorem[4] into account, the FIR conductivity exhibits a single dimensional resonance at a frequency that corresponds to the characteristic frequency of the bare potential. The meaning of "bare potential" here is, the potential is induced by all external charges contributing to the confinement as e.g. charges on a gate pattern, in surface states or image charges on the semiconductor interfaces, but not the electrons that occupy the quantum wire. Experiments[5] as well as model calculations demonstrate that the electron systems usually are smaller than the lithographic defined patterns on the surface due to lateral depletion widths of the order of some 10 nm.

Therefore, once the wires in a superlattice are defined, they can be regarded as decoupled in a very good approximation since wide barriers separate them. In the present paper, FIR transmission and photoconductivity measurements are used to investigate the lD subband spacings of low dimensional structures fabricated on GaAs-AlGaAs heterostructures.

II. Sample characterization and experimental setup

The samples, which are typically used for all the presented experiments, consist of an unintentionally p-doped GaAs layer grown on a semiinsulating substrate ($N_A < 10^{14}$ cm^{-3}), followed by an undoped spacer (d = 240 Å), and doped Al$_x$Ga$_{1-x}$As (d = 360 Å), $N_D = 2.8 \cdot 10^{18}$ cm^{-3}, $x = 0.29$). The additional GaAs cap layer is highly n-doped (d = 100 Å, $N_D = 5.7 \cdot 10^{18}$ cm^{-3}).

Then, laser holographic gratings having a period of typically between 475 nm and 630 nm, were fabricated on the samples. The geometrical dimensions of the structured sample are 3 × 3 mm^2. The photoresist patterns are transferred step by step into the GaAs by wet chemical etching (H_2O: H_2O_2: NaOH=1: 300: 500) down into the modulation doping area. This results in a periodic potential with a modulation up to 10 meV [5]. In these samples, the transverse conductivity vanished and separated wires with several 1D subbands occupied are expected (quasi 1- dimensional electron gas). The etching times vary from 10 s to 50 s. Thus, the subband spacing is expected to increase with increasing etching time. By bandgap illumination with a red LED the filling of the wires could be tuned. In the region of shallow etching, the electronic system could be changed from electrically isolated wires to a density modulated system and back to an almost perfect two dimensional system with increasing duration of illumination. The mobility of the unstructured samples was $n = 1.5 \cdot 10^6$ cm^2/Vs and the electron density was $4.0 \cdot 10^{11}$ cm^{-2} at T = 4.2 K. A schematic view of the samples is shown in the inset of Fig. 1.

The experimental setup is the standard configuration of a commercial FIR gas laser, connected via a light pipe to a cryostat with two high field magnets. In the center of the upper one the sample and in the lower one the FIR-detectors for the transmission measurements were located. The FIR laser was optically pumped by a $C0_2$ laser, the wavelength range was between 70 μm and 742 μm. For the detection of the chopped FIR radiation narrowband InSb and high purity GaAs layers were used. The photoconductivity has been measured along the wires, therefore two Indium contacts were alloyed into the wire array.and a current of typically some 50 nA was passed along the wires. Together with the chopper signal, the voltage drop at the contacts, or in case of transmission measurements, at the detector was used for low noise lock-in-technique. All measurements were performed at 4.2 K.

III. FIR characterization by transmission and photoconductivity measurements

In figure 1 the experimental FIR spectra of a one layered shallow etched (15 s etched) quantum wire structure measured at a fixed laser wavelength of 163.6 μm in transmission geometry with different band gap illumination times are shown. The resonance position of the non illuminated quantum wire structure is shifted to lower magnetic fields, i.e. it is shifted to higher resonance energies, with respect to the strong illuminated sample, which appears at the position of the unperturbed cyclotron resonance.

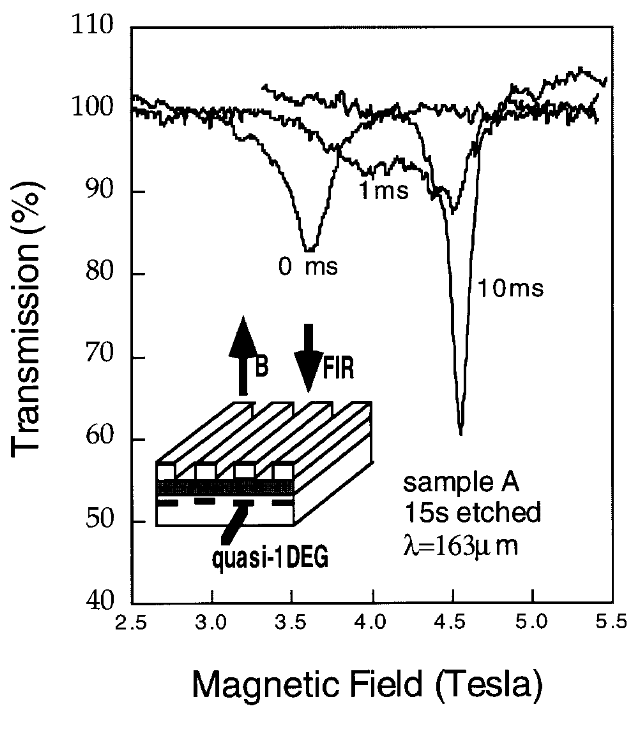

Figure 1. Transmission of a 630nm period quantum wire sample for different durations of the above bandgap illumination measured with the FIR-laser. A transition from the localized to the extended magnetoplasmon and finally the unperturbed 2D CR is observed. The inset shows the geometry of the sample.

The spectrum of the short illuminated sample shows a resonance peak at the CR position and at a position shifted towards higher energies. In case of electrically separated wires, the FIR excitation should measure the confined plasmon mode[6]:

$$\omega_p^2 = \frac{e^2}{2\epsilon\epsilon_0 m^*} n_{2D} (j+\alpha) \frac{\pi}{w} \quad , \quad j = 1,3,5 \qquad (1)$$

with the effective two dimensional carrier density in the wires n_{2D} the effective mass of the carriers m^* and the electrical wire width w and α, which denotes a correction for the phase shift occurring due to the reflection of the electrons at the wire walls. In a density modulated system, one expects to find two resonances[7], the unperturbated CR and an extended plasmon, which is a better description, when coupling between the electrons in the different parallel wires becomes important. Then ω_p is dominated by the grating period a[8]:

$$\omega_p^2 = \frac{e^2}{2\epsilon\epsilon_0 m^*} n_{2D} \frac{2\pi}{a} \qquad (2)$$

By increasing the illumination, the potential modulation disappears at all, and one finds the pure two dimensional behavior of the system (Fig. 2b). By subsequently etching the sample, the resonance position shifts to higher energies, and is not affected anymore by above bandgap illumination. (Fig. 2a). Due to surface charge depletion effects, the effective electron concentration decreases rapidly and therefore the amplitude of the resonance also decreases.

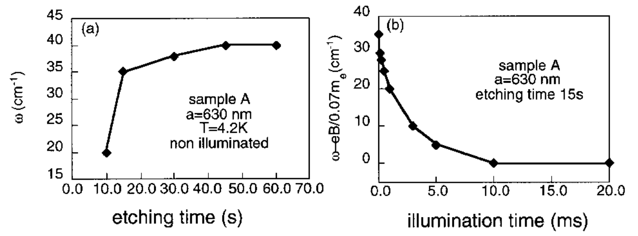

Figure 2. 2. (a)Energy shift of the magnetoplasmon versus the etching time of the quantum wire structure for the non illuminated sample. (b) Energy shift of the magnetoplasmon with respect to the cyclotron resonance-energy of a 2D system with a CR-mass of 0.07 m_0 versus the above bandgap illumination time.

In Fig. 3 a FIR photoconductivity spectrum is shown taken at a laser wavelength of 163 μm. Comparing the transmission data with the data obtained from the photoconductivity measurements performed on the same sample (Fig. 3), one clearly sees, that the resonances appear at the position of the confined plasmon. The plasmon energy is easily determined from a plot like Fig. 4.

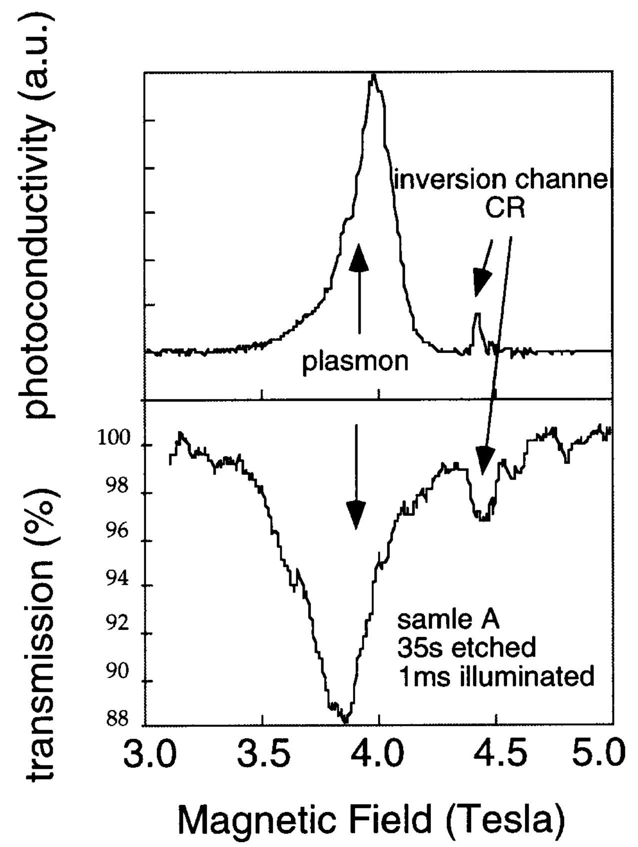

Figure 3. Typical spectra obtained with the FIR-laser in photoconductivity and transmission measurement.

In addition, there is a small, but very sharp resonance (FWHM = 0.15 cm^{-1}, an effective mass of 0.067 m_0 and an effective 2D electron density of $4 \cdot 10^{10}$ cm^{-2}) near the position of the unperturbed 2D CR. It can also be seen in non-structured samples and its position is not affected by the etching process of the wires. So we expect the origin of this resonance to be due to an inversion channel deep in the sample, as well known from similar grown samples[9].

The spectrum taken with the FIR laser is in good agreement with the bolometric model of the PC [10], [11], where the PC grows both with the absolute resistance of the system and its temperature dependence. The evaluation of the resonance energies for PC and transmission measurements of the sample with a = 630 nm and an etching time of 35s are given in a double squared plot (Fig. 4.) With good agreement between the different methods, the plasmon resonance follows the quadratic dispersion

$$\omega^2 = \omega_p^2 + \omega_c^2 \qquad (3)$$

which is obtained for the collective excitation of the electrons in an magnetic field coupling quadratically to the cyclotron resonance $\omega_c = eB/m^*$.

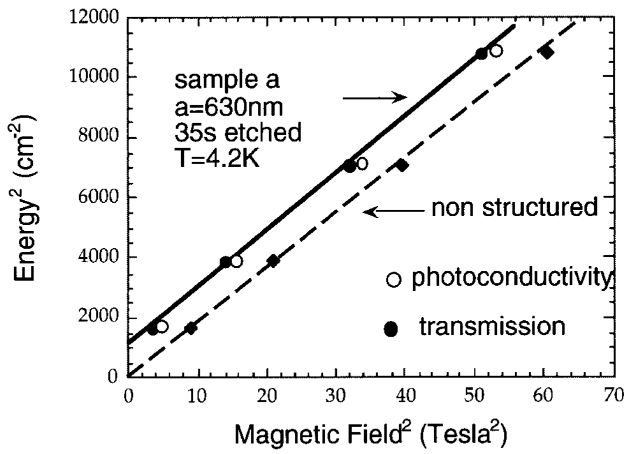

Figure 4. Squared energy of the evaluated resonance position (transmission and photoconductivity results) versus squared magnetic field for different laser lines. The dotted line corresponds to the unperturbed 2D CR with a mass of $m^* = 0.07m_0$.

Assuming a harmonic oscillator model for the confining potential

$$V_{ext} = \frac{1}{2} m^* \omega_0^2 \chi^2 \tag{4}$$

the same relation for the dispersion of the 1D resonance energy as eq.(3) can be obtained. For the non illuminated sample A (35 s etched) we derive a subband spacing $\omega_0 = 3$ meV and an electrical width $w = 380$ nm (dark) and $w = 510$ nm (illuminated), calculated from eq. 1 with $\epsilon = 12.9$.

Differences in the resonance position between transmission and PC values are attributed to changes in the population of the wires, which may have different causes: heating of the electron system by the high FIR intensity as well as heating and charging of the wires by the current.

IV. Conclusion

Two different FIR spectroscopy techniques on quantum wires have been presented. It is shown, that via above band gap illumination the electronic properties of the shallow etched wire structured sample could be changed from quasi 1D to a density modulated 2D system and finally to a pure 2D system. The PC is strongly correlated to the position of the localized plasmon in FIR transmission. Recent PC measurements [11] were successfully performed on a tiny sample of $80 \times 200 \mu m^2$ with 130 wires. The big advantage of the PC measurements is, that there is no need for large structured area as in transmission experiments. In our samples we see also a very sharp resonance, which may origin from an inversion layer deep in the sample.

Acknowledgement

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