PHYSICAL REVIEW B VOLUME 37, NUMBER 11 15 APRIL 1988-I

One-dimensional subbands of narrow electron channels in gated $Al_xGa_{1-x}As/GaAs$ heterojunctions

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(Received 17 December 1987)

Lateral quantization of the electronic motion in $Al_xGa_{1-x}As/GaAs$ heterojunctions with a microstructured gate electrode is investigated with static magnetotransport and infrared spectroscopy. In these structures a negative gate bias causes a transition from two-dimensional to quasi-one-dimensional electronic behavior. Spacings of one-dimensional subbands as well as one-dimensional electron densities are derived from quantum oscillations of the magnetoresistance and compared with intersubband resonance energies and electron densities extracted from infrared spectra.

In narrow inversion channels on semiconductors with widths in the 100-nm range, lateral quantization of the electronic motion into one-dimensional (1D) subbands has recently been established in several experiments.[1–6] In single narrow inversion channels at the $Al_xGa_{1-x}As/GaAs$ interface of heterojunctions Berggren and coworkers[2,3] as well as van Houten *et al.*[4] observed magnetic-field-induced depopulation of 1D subbands via quantum oscillations of the magnetoresistance. Spectroscopic studies of intersubband resonance transitions between adjacent 1D subbands have recently been reported for laterally periodic multichannel devices on GaAs and InSb (Ref. 5) as well as on Si (Ref. 6). Here we study quantum oscillations of the static magnetoresistance and, simultaneously, 1D intersubband resonances at infrared frequencies on $Al_xGa_{1-x}As/GaAs$ heterojunctions in which a periodically modulated gate electrode is used to create many parallel narrow inversion channels. Using multichannel devices we average out conductance fluctuations that often dominate quantum transport in short, single-channel devices.[4,7] Approximating the self-consistent lateral confining potential[8,9] by a parabolic potential we extract from the quantum oscillations the number of occupied 1D subbands, the separation $\hbar\Omega$ of adjacent subbands, and the one-dimensional carrier density N_{1D} in the inversion channels. These are compared to resonance position and oscillator strength of the simultaneously observed infrared excitations. Such a comparison allows us to quantitatively determine the effect of many-body interactions on the intersubband resonance and to critically test the accuracy with which one-dimensional densities can be extracted from different experiments.

As in previous work,[5,6] the samples are modulation-doped $Al_xGa_{1-x}As/GaAs$ heterojunctions covered with a holographically defined insulator grating and a front gate evaporated on top. The active sample area is defined by a mesa and has diffused source-drain contacts at both ends such that a dc source-drain current can be passed parallel to the grating lines. Application of a negative gate bias V_g results in formation of narrow inversion channels below a certain threshold voltage V_d at which the channel areas between the insulator stripes are fully depleted. Since the gate is 2.5 mm wide about 7000 such channels are measured in parallel.

At liquid-helium temperatures we measure the two-terminal source-drain resistance R at constant current of typically 1 μA in a magnetic field B applied perpendicularly to the sample surface. To enhance quantum oscillations of the channel resistance we modulate the gate voltage at low frequency and measure dR/dV_g with lock-in detection. This modulation technique also minimizes magnetic-field-dependent signals from the ungated contact regions.

In the following we discuss results obtained on a representative sample where the distance between the electron system confined at the $Al_xGa_{1-x}As/GaAs$ interface and the gate varies periodically between 51 nm and about 170 nm with period $a = 400$ nm. From the Shubnikov–de Haas (SdH) oscillations of the magnetoresistance at $V_g = 0$ V we derive a homogeneous 2D electron density $N_s = 6\times10^{11}$ cm^{-2}. From capacitance-voltage traces as well as from the infrared spectra[5] we determine the threshold voltage $V_d = -0.5$ V below which we have isolated inversion channels. Quantum oscillations in dR/dV_g vs B traces at gate voltages V_g above and below this threshold are displayed in Fig. 1. At low magnetic fields ($B < 0.5$ T) we observe a gate-voltage-dependent structure that may be attributed to geometry and interference effects (see, e.g., Ref. 10). Here, however, the features of interest are the quantum oscillations that become visible at magnetic fields above 0.5 T.

In the fan diagram in Fig. 2 we plot a suitably chosen running index $(n+\phi)$ $(n = 1,2,3,\ldots)$ of the maxima of the quantum oscillations in dR/dV_g vs their position in $1/B$. At sufficiently high magnetic fields we obtain a nearly linear behavior in $1/B$ as is expected for Landau levels in a two-dimensional (2D) electron system.[11] In Fig. 2 we have adjusted the phase ϕ so that the data extrapolate to $n = 0$ for $1/B = 0$. Since we observe no spin-splitting we assume a twofold spin degeneracy. The deviation of the

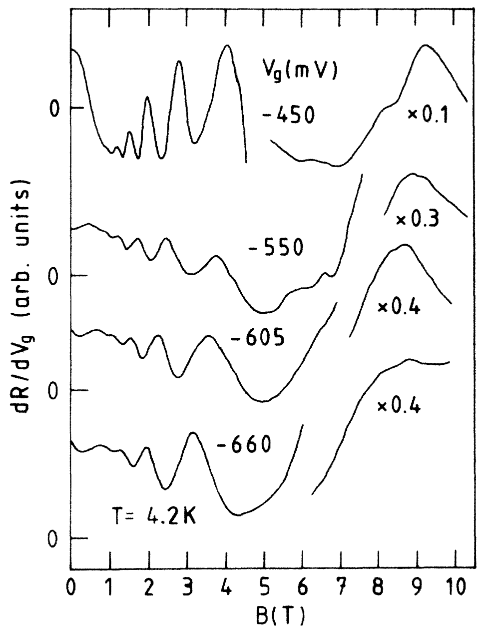

FIG. 1. Gate voltage derivative of the source-drain resistance dR/dV_g vs magnetic field B for an $Al_xGa_{1-x}As/GaAs$ heterojunction with a laterally periodic gate structure of period $a=400$ nm.

observed quantum oscillations from linear 2D behavior at lower magnetic fields reflects the quantization of the electronic motion by the lateral confining potential.[2-4] At $B=0$ the lateral confinement creates a finite number of occupied 1D subbands. With increasing B their energetical spacing as well as their density of states increases and they become successively depopulated. Quantum oscillations arise whenever the Fermi energy drops below the bottom of the nth 1D subband. At very high magnetic fields where the Landau energy $\hbar\omega_c$ is much larger than the subband spacing $\hbar\Omega$ the quantum oscillations in the confined system become indistinguishable from SdH oscillations in a 2D electron system. In lack of self-consistent calculations[8,9] for our structures we approximate the effect of lateral confinement by a harmonic oscillator potential $V(x)=\frac{1}{2}m^*\Omega^2x^2$, where x denotes the direction in the sample plane perpendicular to the grating. In a magnetic field perpendicular to the sample plane the 1D subband spacing becomes $\hbar\omega=\hbar(\Omega^2+\omega_c^2)^{1/2}$ with $\omega_c=eB/m^*$.[3,12] The 1D subband density of states is easily derived as

$$D(E)=\frac{2}{\pi\hbar}\left(\frac{m^*}{2}\right)^{1/2}\frac{\omega}{\Omega}\sum_{E>E_n}(E-E_n)^{-1/2}, \quad (1)$$

where $E_n=\hbar\omega(n+\frac{1}{2})$. We now adjust the 1D electron density N_{1D} and the $B=0$ subband spacing $\hbar\Omega$ to best fit the observed quantum oscillations. The calculated $1/B$ values where the Fermi energy crosses the bottom of the nth subband are also entered in Fig. 2. The results for $\hbar\Omega$ and N_{1D} vs V_g will be discussed together with the results determined from the infrared spectra.

To study the infrared excitations we measure the transmission of infrared radiation through the gate region with a Fourier transform spectrometer at different magnetic fields and for light polarization parallel and perpendicular to the grating stripes. As discussed in Refs. 5 and 6 we observe at $B=0$ 2D-like plasmons of frequency ω_p at gate voltages $V_g \geq V_d$ and 1D intersubband resonances of frequency Ω^* at $V_g < V_d$. Their resonance energy is plotted in Fig. 3 versus gate voltage. As observed previously[5] the resonances change their character at about $V_g=V_d=-500$ mV. In Fig. 3 we have also entered the 1D subband spacing $\hbar\Omega$ derived from the quantum oscillations of the magnetoresistance. The difference between the intersubband resonance energy $\hbar\Omega^*$ and the subband

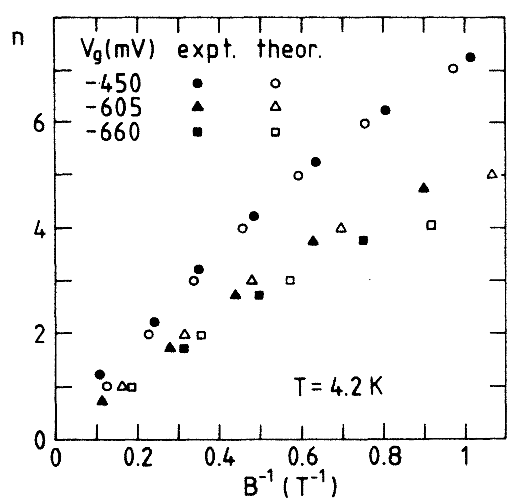

FIG. 2. Quantum index n of the maxima in dR/dV_g from Fig. 1 vs reciprocal magnetic field (filled symbols). The open symbols represent fit values of a parabolic confinement model. Since we measure the derivative dR/dV_g the field values of the experimental maxima are expected to be phase shifted with respect to the calculated ones.

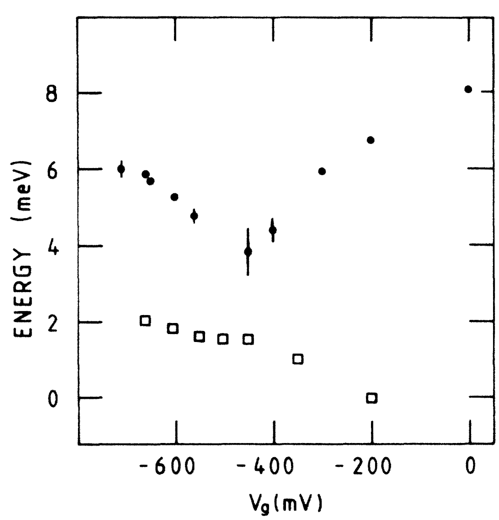

FIG. 3. Resonance energies of the infrared excitations (filled circles) at magnetic field $B=0$ vs gate voltage V_g. Also entered is the spacing of adjacent 1D subbands (open squares) as determined from the quantum oscillations of the magnetoresistance.

spacing $\hbar\Omega$ will be discussed below. Here we wish to point out that we observe deviations from linear behavior in the $1/B$ fan chart in Fig. 2 already at $V_g \geq V_d$ and thus derive a finite $\hbar\Omega$ at, e.g., $V_g = -350$ mV, whereas linear behavior is seen at all $V_g \geq -200$ mV. Apparently lateral quantization becomes visible in magnetotransport already at voltages $V_g \geq V_d$ where the lateral density modulation does not yet result in isolated electron channels.

The infrared spectra also provide information about the average areal densities $\bar{N}_s$. For the region $V_d \leq V_g \leq 0$ V we can use the plasmon frequency $\omega_p^2 = \bar{N}_s e^2(\pi/a)/(\bar{\epsilon}\epsilon_0 m^*)$ to obtain $\bar{N}_s$. The effective dielectric constant $\bar{\epsilon} = 14.4$ we determine at $V_g = 0$ V by using the electron density extracted from SdH experiments and the measured plasmon frequency. Another measure for $\bar{N}_s$ is provided by the oscillator strength of the observed resonances. At sufficiently high magnetic fields ($B \simeq 11$ T) we use the classical cyclotron resonance formula[13] to fit cyclotron resonances at $V_g > V_d$ as well as cyclotron-shifted 1D intersubband resonances at $V_g < V_d$. For parallel polarization we obtain values for $\bar{N}_s$ that are in good agreement with the values derived from the plasmon frequency ω_p at $V_g > V_d$. At $V_g < V_d$ they agree well with the values extracted from the quantum oscillations of the dc magnetoresistance using $\bar{N}_s = N_{1D}/a$. For perpendicular polarization we find that the oscillator strength is significantly enhanced in comparison to the parallel polarization data even if we adjust for the anisotropy of the gate conductance.[13] This enhancement is particularly strong at $V_g \leq V_d$ where it typically reaches a factor of 1.6. Such enhancement of the oscillator strength in the presence of a grating coupler has previously been observed in cyclotron resonance experiments on 2D systems[14] and is not yet understood quantitatively. Because of this enhancement we cannot extract reliable values for $\bar{N}_s$ from the resonance strength in perpendicular polarization, even at $B = 0$.[5,15]

The shift of the intersubband resonance $\hbar\Omega^*$ to energies significantly above the subband spacing $\hbar\Omega$ we attribute to many-body effects as in 2D systems.[11,16] We assume that depolarization effects are dominant and thus have $\hbar\Omega^* = \hbar(\Omega^2 + \omega_d^2)^{1/2}$ with depolarization frequency ω_d. In lack of a better model we use the classical expression $\omega_d^2 = 2e^2 N_{1D}/(\bar{\epsilon}\epsilon_0 m^* W^2)$ for a quantitative estimate with the same $\bar{\epsilon}$ that is derived from the plasmon resonance at $V_g = 0$ V.[15] As a value for the channel width W we may choose the potential width at the Fermi energy $W = [8E_F/(m^*\Omega^2)]^{1/2}$, where the Fermi energy and the subband spacing are determined from the magnetoresistance oscillations. Here we note that this definition is somewhat arbitrary. When several subbands are occupied we also might derive an effective channel width $W^* = N_{1D}/N_{2D}$ with $N_{2D} = m^* E_F/(\pi\hbar^2)$. We then get values W^*, that are a factor of about 0.7 lower than W.

TABLE I. Parameters obtained from the quantum oscillations of the magnetoresistance at representative gate voltages V_g. These are, respectively, the Fermi energy E_F, the subband spacing $\hbar\Omega$, the 1D electron density N_{1D}, the channel width W, and the estimated depolarization energy $\hbar\omega_d$.

V_g (mV)	E_F (meV)	$\hbar\Omega$ (meV)	N_{1D} (10^6 cm^{-1})	W (nm)	$\hbar\omega_d$ (meV)
−500	14.5	1.5	6.7	240	5.7
−550	14.1	1.6	6.1	220	5.9
−660	11.7	2.0	3.7	160	6.3

In Table I we summarize data determined from the quantum oscillations of the magnetoresistance and the thus predicted depolarization energies. Within the accuracy of our simple model the depolarization shift may account for the observed difference between the subband spacing $\hbar\Omega$ and the intersubband resonance $\hbar\Omega^*$. Note, however, that both the subband spacings and the estimated depolarization energies are less affected by the gate voltage than the observed intersubband transition energies $\hbar\Omega^*$.

A direct comparison between subband spacings determined from quantum oscillations of the magnetoresistance and 1D intersubband resonance transitions studied on the same samples helps us to achieve a more quantitative understanding of 1D subband quantization in $Al_xGa_{1-x}As/GaAs$ heterojunctions. In the structures studied here 1D subband spacings are more directly determined from magnetoresistance oscillations and 1D intersubband resonances are strongly shifted from subband spacings by many-body effects. Surprisingly, we find that the simple models that we use to describe confinement as well as many-body effects can rather quantitatively describe our experimental observations. Nevertheless, self-consistent models for confinement and quantum-mechanical calculations of many-body effects on 1D intersubband resonances including both depolarization and excitonic effects[11,16] are highly desirable. Related experiments on laterally microstructured metal-oxide-semiconductor devices on InSb (Refs. 5 and 17) show that in other sample configurations depolarization effects on the 1D intersubband resonance can be more effectively screened and thus be significantly smaller than observed here.

We gratefully acknowledge financial support by the Stiftung Volkswagenwerk.

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