PHYSICAL REVIEW B VOLUME 37, NUMBER 8 15 MARCH 1988-I

Subband spacings of quasi-one-dimensional inversion channels on InSb

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(Received 18 December 1987)

In metal-oxide-semiconductor structures on InSb we measure the static and the far-infrared conductivity of an array of narrow inversion channels that exhibit quantization into one-dimensional (1D) subbands. From oscillations in the static magnetoresistivity we determine the single-particle 1D subband spacings. These energies are compared with intersubband energies of transitions between the 1D subbands obtained by far-infrared Fourier spectroscopy. We find that depolarization and exciton shifts account for about 20% of the intersubband energies at an electron density $n_l = 3\times10^6$ cm^{-1}.

The two-dimensional (2D) electron gas[1] of layered semiconductor structures becomes quantized into 1D subbands when their laterally confining dimensions are narrow enough. This has been inferred from oscillatory structure in the conductance of multichannel metal-oxide-semiconductor (MOS) devices on silicon[2] as well as from magnetoconductance oscillations in single channels[3] of GaAs/$Ga_{1-x}Al_xAs$ field-effect transistors. Recently, 1D subband quantization was demonstrated by direct observation of transitions between the subbands applying far-infrared (FIR) spectroscopy to periodic arrays of submicron inversion channels.[4] Such microstructures of macroscopic area are prerequisite for spectroscopic experiments and are also advantageous to detect 1D quantization in transport studies since universal conductance fluctuations, which tend to obscure conductance oscillations of the subband quantization,[5] are averaged out in multiwire systems.

Here we study the quasistatic conductivity ($\nu \approx 10$ Hz) and the FIR transmittance ($\bar{\nu} = 50$–200 cm^{-1}) in multiwire inversion channels on InSb at liquid-helium temperatures. In our device, which is depicted in the inset of Fig. 1, NiCr stripes are evaporated onto InSb to form Schottky barriers in which the Fermi energy is pinned in the band gap.[4] The grating of period $a = 250$ nm and width $w \simeq 100$ nm between two successive NiCr stripes has an area $A = 2\times3$ mm^2 sufficiently large to enable FIR Fourier spectroscopy. The inset depicts the geometry of the sample. Between NiCr stripes that act as Schottky barriers, 1D electron inversion channels (perpendicular lines) are induced via a gate oxide and a homogeneous NiCr gate film which cover the whole grid area and parts of the Sn contacts (hatched areas), but are not shown.

Free electrons are induced into the narrow channels between the stripes by the gate voltage V_g. Via four diffused Sn contacts, the quasistatic resistance R and its derivative dR/dV_g are measured in the direction parallel and perpendicular to the stripes. A threshold voltage V_t is determined from the onset of the conductivity along the channels and we use the voltage difference $\Delta V_g = V_g - V_t$ as a measure for the density of mobile electrons in the channels. There is virtually no quasistatic conductivity perpendicular to the channels in the whole range of gate voltages studied.

In narrow inversion channels, oscillations in the magnetoresistance arise from the depopulation of subbands[3] in increasing magnetic fields B. The spin-split subband energies E can be given analytically[6] if the laterally confining potential is represented by a harmonic oscillator of eigenfrequency ω_0:

$$E = E_i + \hbar\omega(n+\tfrac{1}{2}) + \frac{\hbar^2 k_y^2}{2m^*}\left(\frac{\omega_0}{\omega}\right)^2 \pm \tfrac{1}{2} g^* \mu_B B . \quad (1)$$

In this equation, we have the hybrid frequency $\omega = (\omega_0^2 + \omega_c^2)^{1/2}$ with cyclotron frequency $\omega_c = eB/m^*$. The motion of electrons in x and z directions is quantized into equally spaced 1D subbands $n = 0,1,\ldots$ and into 2D subbands $i = 0,1,\ldots$ of the corresponding homogeneous 2D electron gas, respectively. The electrons are only free to move along the channels in the y direction with dispersion that depends on the ratio ω_0/ω. In the calculations we take the effective mass $m^* = 0.014 m_e$ and Landé factor $g^* = -51$ at the conduction-band edge and only consider the ground 2D subband $i = 0$. From the density of states[3] of the spin-split levels $E_{i,n} = E(k_y = 0)$

$$D(E) = \left(\frac{\omega}{\omega_0}\right)\left(\frac{m^*}{2\pi^2\hbar^2}\right)^{1/2} \sum_{E \geq E_n} (E - E_n)^{-1/2} , \quad (2)$$

the Fermi energy E_F can be calculated, provided the 1D electron density n_l per channel length and the subband spacing $\hbar\omega_0$ are known.

Figure 1 depicts the calculated subband energies ($k_y = 0$) and Fermi energy versus magnetic field strength for channel density $n_l = 2.2\times10^6$ cm^{-1} and quantization energy $\hbar\omega_0 = 11.5$ meV. The Fermi energy exhibits maxima when it crosses the subband energies and it is pinned to the ground level 0^+ in the quantum limit of strong magnetic fields. When the Fermi energy passes through a subband edge, there is a discontinuity in the density of states and in the intersubband scattering. This causes the oscillatory structure in the magnetoresistivity.[7]

We note that the Fermi energy crosses a finite number of levels in the whole range of magnetic fields and, hence, only a finite number of oscillations is observable. In contrast to this, the Fermi energy in a 2D system crosses an

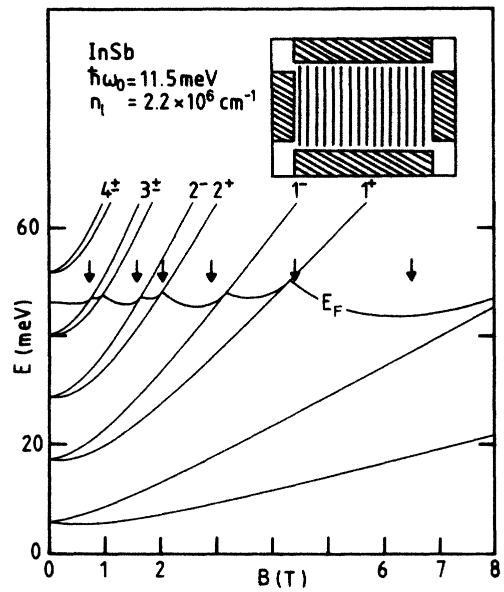

FIG. 1. One-dimensional (1D) subband levels $n^{\pm}$ and Fermi energy E_F vs magnetic field strength in the harmonic well approximation. The arrows mark experimental values for gate voltage $\Delta V_g = 29$ V that are described by a quantization energy $\hbar\omega_0 = 11.5$ meV and an electron density $n_l = 2.2\times 10^6$ cm^{-1}.

infinite number of Landau levels when the magnetic field increases from zero and the number of observable oscillations depends on electron mobility ($\mu B > 1$).

Experimental traces of derivatives dR/dV_g taken at various voltages ΔV_g and constant current 1 μA are shown in Fig. 2 where we also assign subband indices $n^{\pm}$ to the maxima. There is some weaker structure in the traces that is not due to 1D subband quantization. At very weak magnetic fields there is a maximum whose position $B \sim 0.1$ T does not significantly shift with gate voltage and whose amplitude becomes less pronounced at higher gate voltages. We think that this structure is related to quantum interference causing negative magnetoresistance in weak magnetic fields.[8] The shoulders at magnetic fields $B \simeq 4$–5 T at voltages $\Delta V_g = 10$–16 V are due to Shubnikov–de Haas oscillations arising from the 2D regions[9] between the grating and the contact areas. An additional oscillation occurs for voltages $\Delta V_g \gtrsim 40$ V at magnetic fields $B \approx 5$ T and is attributed to an oscillation of the $i = 1$ subband.

The maxima for voltage $\Delta V_g = 29$ V are indicated by arrows in Fig. 1 as an example. Except for the 0^- level, their positions agree fairly well with the cusps of the Fermi energy for the chosen values of electron density n_l and quantization energy $\hbar\omega_0$. According to previous studies[7] on low-dimensional systems, maxima in the magnetoresistance $R(B)$ reflect maxima of the Fermi energy. Hence, we rather should take the zeros on the right-hand sides of the oscillation maxima dR/dV_g in Fig. 1. However, these zeros are difficult to identify in the traces. Since we found by numerical simulation that choosing maxima instead of zeros affects the values n_l and $\hbar\omega_0$ at most by 10%, we adhere to the maxima. Because of this choice, the position of the 0^- maximum lies below its calculated position. In

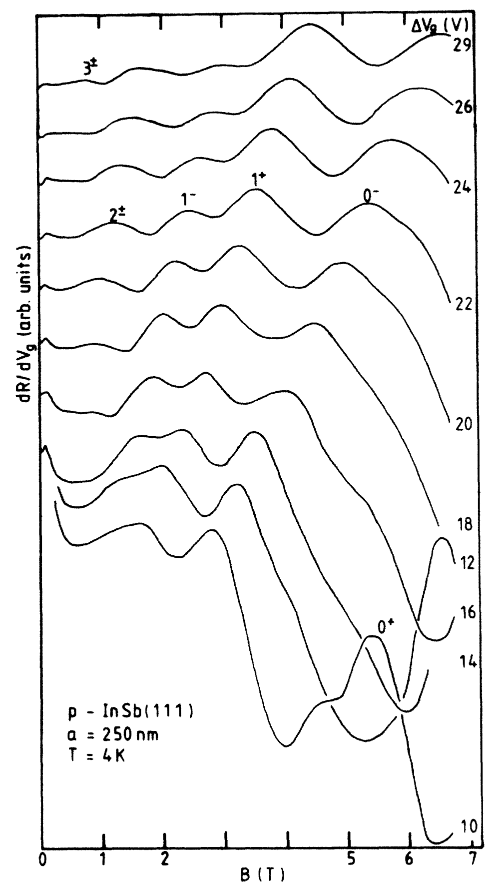

FIG. 2. Derivatives of the magnetoresistance along the inversion channels at various gate voltages ΔV_g above threshold. The oscillation maxima are marked by their subband indices.

fact, the positions of levels $0^{\pm}$ are not decisive for the evaluation of parameters n_l and ω_0, since 1D quantization most strongly influences oscillations in low magnetic fields ($\omega_c < \omega_0$).

Normalized FIR transmittances of the same sample are reproduced in the inset of Fig. 3 for light polarization perpendicular to the channels. The line shapes, but not their amplitudes, are well described by the formula

$$T(V_g)/T(V_t) \approx 1 - \frac{2}{1+\sqrt{\epsilon}}\,\frac{\sigma_0/Y_0}{1+(\omega-\omega_0^2/\omega)^2\tau^2}\,, \tag{3}$$

which is adopted from its counterpart[10] for homogeneous 2D electron systems. In Eq. (3), we use the classical conductivity of electrons $\sigma(\omega) = \sigma_0/[1+(\omega-\omega_0^2/\omega)^2\tau^2]$ with relaxation time τ in a parabolic well, the wave admittance of vacuum $Y_0 = (\epsilon_0/\mu_0)^{1/2} = (377\ \Omega)^{-1}$, the dielectric constant ϵ of the semiconductor, and an effective static conductivity $\sigma_0 = e\bar{n}_s\mu$. The areal density $\bar{n}_s$ denotes an average over the whole grating area and may be calculated from the relation $\bar{n}_s = n_l/a$. The sheet resistivities of the homogeneous NiCr gate film and of the metal stripes are neglected for the perpendicular light polarization.

For gate voltage $\Delta V_g = 30$ V, we deduce a mobility $\mu = 16000$ cm^{+2}V^{-1}s^{-1} and a value $\bar{n}_s = 1.7\times 10^{11}$ cm^{-2}. This density is almost a factor of 2 larger than the one $n_l/a = 0.9\times 10^{11}$ cm^{-2} obtained from the transport

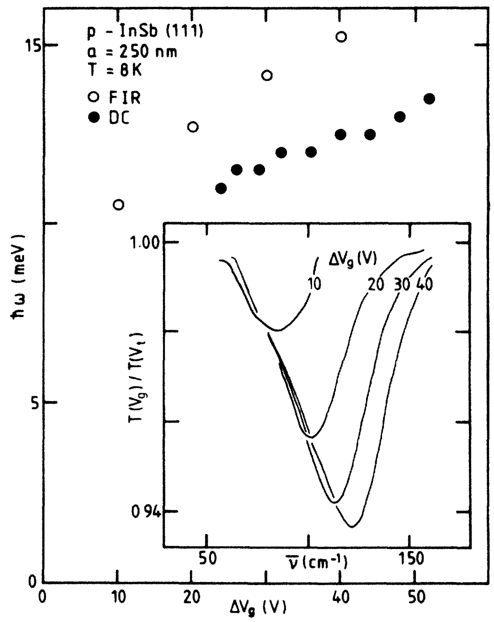

FIG. 3. One-dimensional (1D) subband spacings determined from magnetoresistance oscillations (closed circles) vs gate voltage ΔV_g above threshold. For comparison, intersubband energies read from the Fourier spectra of the inset are included (open circles).

measurements. Only part of this discrepancy can be explained by the population of the $i=1$ subband which contributes to the FIR signal. To give an idea, at higher electron densities this subband contains about 30% of the totally induced electrons in a homogeneous 2D gas on InSb.[9] Presumably, the action of the metallic grating on the light wave, which is not covered by Eq. (3), is responsible for the enhanced amplitudes.

In Fig. 3, intersubband energies (open circles) are compared with subband spacings (closed circles) deduced from the magnetoresistance oscillations. The experimental error of the intersubband energies, which are directly read from the Fourier spectra, is approximately 0.3 meV. The reliability of the subband spacings determined from the above model is about 1 meV. The model, however, does not account for band nonparabolicity[9] whose influence we estimated with an energy dependent mass in Eqs. (1) and (2). Whereas the subband spacings at low gate voltages $\Delta V_g \lesssim 25$ V are not affected significantly, somewhat decreased ($\lesssim 3$ meV) energies are obtained at a higher voltage $\Delta V_g = 52$ V.

The FIR energies exceed the subband spacings and increase more pronounced with gate voltage, i.e., increasing electron density ($n_l/\Delta V_g \approx 0.075\times10^6$ V^{-1}cm^{-1}). Qualitatively, this can be explained by the depolarization shift $\omega_d^2 = \omega^2 - \omega_0^2$ which is generally observed for optical resonances of confined electron systems.[11] In case of wire grid structures,[12] the depolarization frequency

$$\omega_d = \left[\frac{2e^2 n_l}{\bar{\epsilon}\epsilon_0 m^* w^2}\right]^{1/2} \tag{4}$$

must be calculated with an effective dielectric constant $\bar{\epsilon}$ which accounts for the discontinuity of the dielectric constant at the oxide-semiconductor interface and for screening of the metallic stripes and the homogeneous gate film. This is very difficult to calculate, but an estimate may be deduced from the present experiments. For gate voltage $\Delta V_g = 40$ V (see Fig. 3), we observe a shift $\hbar\omega_d = 8.7$ meV and we have a channel width $w \simeq 100$ nm and an electron density $n_l = 3\times10^6$ cm^{-1}. These values require a constant $\bar{\epsilon} \simeq 74$ in Eq. (4) which is much larger than the dielectric constant of InSb ($\epsilon = 17.7$) and SiO_2 ($\epsilon = 3.8$) and indicates, that screening due to the metallic stripes is very important to describe the present microstructures. In addition, a quantitative description of the measured subband energies should also take into account the exciton shift, which was found to partly compensate the depolarization shift in 2D systems.[1]

In conclusion, transport measurements in narrow inversion channels on InSb demonstrate 1D subband quantization with subband spacings $\hbar\omega_0 \simeq 10$ meV. Depolarization shifts of optical resonances are effectively suppressed in our structure due to screening in its metallic stripes. In 1D multiwire channels of $GaAs/Ga_{1-x}Al_xAs$ heterojunctions, where similar experiments were carried out,[13] many-body effects influence intersubband energies more pronounced than observed here.

We thank J. P. Kotthaus for valuable discussions and acknowledge financial support of the Stiftung Volkswagenwerk.

[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[2]A. C. Warren, D. A. Antoniadis, and H. I. Smith, Phys. Rev. Lett. **56**, 1858 (1986).

[3]K. F. Berggren, T. J. Thornton, D. J. Newson, and M. Pepper, Phys. Rev. Lett. **57**, 1769 (1986).

[4]W. Hansen, M. Horst, J. P. Kotthaus, U. Merkt, Ch. Sikorski, and K. Ploog, Phys. Rev. Lett. **58**, 2586 (1987).

[5]S. B. Kaplan and A. Hartstein, Phys. Rev. Lett. **56**, 2403 (1986).

[6]D. Childers and P. Pincus, Phys. Rev. **177**, 1036 (1969).

[7]K. F. Berggren and D. J. Newson, Semicond. Sci. Technol. **1**, 327 (1986).

[8]T. J. Thornton, M. Pepper, H. Ahmed, D. Andrews, and G. J. Davies, Phys. Rev. Lett. **56**, 1198 (1986). From Eq. (2) of this reference, we estimate a phase coherence length $\simeq 0.1$ μm for lower densities $n_l \lesssim 1\times10^6$ cm^{-1} at temperature $T=4$ K.

[9]U. Merkt, M. Horst, T. Evelbauer, and J. P. Kotthaus, Phys. Rev. B **34**, 7234 (1986).

[10]G. Abstreiter, J. P. Kotthaus, J. F. Koch, and G. Dorda, Phys. Rev. B **14**, 2480 (1976).

[11]S. J. Allen, Jr., H. L. Störmer, and J. C. M. Hwang, Phys. Rev. B **28**, 4875 (1983).

[12]W. Hansen, J. P. Kotthaus, A. Chaplik, and K. Ploog, in *High Magnetic Fields in Semiconductor Physics,* edited by G. Landwehr, Springer Series in Solid State Sciences, Vol. 71 (Springer, Berlin, 1987), p. 266.

[13]F. Brinkop, W. Hansen, J. P. Kotthaus, and K. Ploog (to be published).