Intersubband Resonance in Quasi One-Dimensional Inversion Channels

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With infrared spectroscopy we study the electronic excitations in laterally periodic GaAs-AlGaAs heterojunctions and metal-oxide-semiconductor devices on InSb in which narrow inversion channels are created and controlled by field effect. Quantization into quasi one-dimensional subbands is demonstrated by direct observation of resonance transitions between those subbands.

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High-resolution lithography now makes possible the fabrication of semiconductor structures in which confinement of the electronic motion in two directions gives rise to quasi one-dimensional (1D) electronic properties. Conductivity studies on metal-oxide-semiconductor (MOS) structures on Si with a very narrow inversion channel have demonstrated large conductance fluctuations associated with electronic transport along a single wire.[1-3] Quantization into 1D subbands has been inferred from the observation of oscillatory conductance structure[4] in multiwire MOS structures on Si as well as from magnetoconductance oscillations on narrow-channel GaAs-AlGaAs heterojunction field-effect transistors.[5] Wave functions and subband energies[6-8] as well as elementary excitations[9] in such 1D inversion channels have recently been calculated.

Here we report on direct far-infrared spectroscopy of electronic excitations in 1D multiwire structures in which many parallel ($\sim 10^4$) and extremely narrow inversion channels of widths $W < 200$ nm are created and controlled by field effect. Our samples are laterally microstructured field-effect devices fabricated on GaAs-AlGaAs heterojunctions or prepared as InSb MOS structures by holographic lithography.[10] In the GaAs device pictured in Fig. 1(a), a transparent gate electrode is periodically displaced by a 120-nm-thick insulator grating of period $a \leq 500$ nm for the surface of a heterojunction. This consists of a GaAs epitaxial layer grown on the GaAs substrate, a 6-nm-thick undoped $Al_xGa_{1-x}As$ spacer ($x = 0.33$), a 40-nm-thick Si-doped $Al_xGa_{1-x}As$ layer, and a 5-nm-thick GaAs cover layer. At gate voltage $V_g = 0$ and $T = 4.2$ K, there is a 2D electron inversion layer with homogeneous areal density $N_{s0} = 6\times10^{11}$ cm^{-2} and mobility $\mu = 80000$ cm^2 V^{-1} s^{-1} at the GaAs-AlGaAs interface. A negative gate voltage applied between gate and inversion layer predominantly depletes those stripes under the gate which are not covered by the insulator grating. Below a threshold voltage V_d these stripes are fully depleted and isolated inversion channels are created. In the MOS structure on InSb shown in Fig. 1(b), we use a semitransparent NiCr grating which is directly evaporated onto the p-type InSb substrate as Schottky contact. This grating is covered by a 400-nm-thick SiO_2 oxide and a homogeneous NiCr gate. Application of a sufficiently high positive gate voltage V_g with respect to the InSb substrate causes formation of narrow inversion channels between the stripes of the Schottky grating, where the gate field causes conduction-band bending. In both structures, we study the gate-voltage–induced change of transmission of normally incident infrared radiation $\Delta T/T = [T(V_g) - T(V_r)]/T(V_r)$, where V_r is a reference voltage. Our experiments are performed at low temperatures with a Fourier-transform spectrometer and infrared lasers.

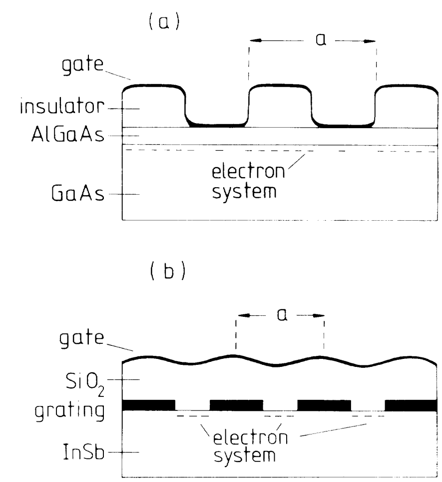

FIG. 1. Schematic cross section of laterally microstructured field-effect devices prepared on (a) GaAs-AlGaAs heterojunctions and on (b) p-type InSb substrates. The respective location of the narrow electron inversion channels is indicated. Actual samples consist of typically 10^4 channels.

The characteristic changes of the infrared excitations that occur with the transition from 2D to 1D electronic behavior are best discussed for the GaAs heterojunction, where this transition can be observed directly. Spectra measured on a sample with $a = 500$ nm at fixed magnetic field B for different gate voltages are shown in Fig. 2. The reference voltage is chosen to be sufficiently negative ($V_r = -1$ V), so that the GaAs-AlGaAs interface is almost depleted of mobile carriers. At voltages between $V_g = 0$ and $V_g = V_d = -0.5$ V, we observe two distinct types of resonances of a 2D electron system, namely, cyclotron resonance at frequency $\omega_c = eB/m^*$ and magnetoplasmon resonance at frequency ω_{mp}. The magnetoplasmons are excited at wave vector $q = 2\pi/a$ by the spatially modulated infrared field and are only observed with light polarized perpendicular to the grating ($E \perp$ polarization). In Fig. 2, the magnetoplasmon for $V_g = 0$ is split into two modes because of nonlocal interaction with the cyclotron resonance harmonic $2\omega_c$ as reported previously.[11] Above the threshold voltage ($V_g > V_d$), the frequency of the cyclotron resonance remains essentially unaffected by V_g, but the frequency of the magnetoplasmon ω_{mp} is shifted to lower frequencies, reflecting the decrease in the average areal density $\bar{N}_s$ of inversion electrons.[12]

At voltages $V_g \le V_d$, the electron system at the GaAs-AlGaAs interface consists of isolated inversion channels as we deduce from capacitance-voltage curves as well as from dc conductivity studies. The transition from a 2D inversion layer with modulated density to many isolated inversion channels is accompanied by a pronounced change of the excitation spectrum. Below the threshold ($V_g \le V_d$), we observe neither cyclotron resonance nor magnetoplasmons, but a single strong resonance with frequency $\omega_{\text{res}} > \omega_c$ and the following characteristic features. The frequency ω_{res} increases with decreasing gate voltage V_g, i.e., decreasing density $\bar{N}_s$. As observed previously in ungated heterojunctions with periodically etched channels of submicrometer width and fixed electron density,[13] we find the following dependence on magnetic field strength. The resonance follows the relation $\omega_{\text{res}}^2 = \omega_c^2 + \omega_0^2$, where ω_0 is the observed resonance frequency at $B = 0$. At $B = 0$ the resonance is only excited with $E \perp$ polarization. At sufficiently high magnetic fields ($\omega_c > \omega_0$), the resonance can be excited in both polarizations with approximately equal oscillator strength. These properties show that the resonance becomes cyclotron-resonance-like in high magnetic fields and is excited by the spatially unmodulated ($q = 0$) infrared field. Thus, this resonance is not a magnetoplasmon but rather a cyclotron-shifted $q = 0$ resonance. In fact, plasmons propagating with arbitrary wave vectors perpendicular to the grating no longer exist once the inversion channels are electrically insulated from each other and cannot exchange charge.

In the following, we wish to demonstrate that the excitations observed at voltages $V_g \le V_d$ are transitions between 1D subbands in the narrow inversion channels. In Fig. 3, we plot the squared resonance frequencies ω_0^2 versus gate voltage. Above threshold ($V_g > V_d$), i.e., in the 2D regime, this is the squared plasmon frequency $\omega_p^2 = \bar{N}_s e^2 q / 2\bar{\epsilon}\epsilon_0 m^*$ at wave vector $q = 2\pi/a$ (see Refs. 11 and 12). At voltage $V_g = 0$, where the inversion layer is not density modulated, the observed plasma frequency

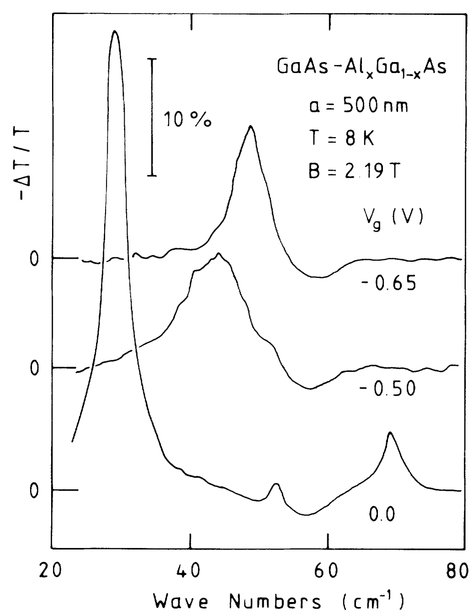

FIG. 2. Infrared spectra of inversion electrons in a laterally microstructured GaAs heterojunction at fixed magnetic field B. The gate voltage V_g is applied between the gate and the inversion channel.

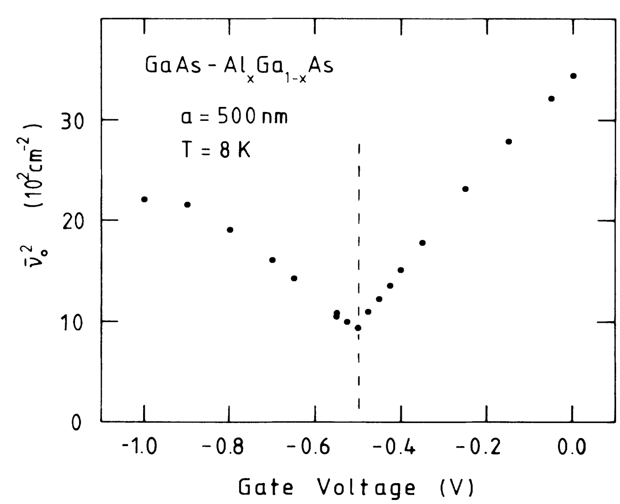

FIG. 3. Gate-voltage dependence of the squared resonance frequency $\bar{\nu}_0 = \omega_0/2\pi c$ in the absence of a magnetic field. The dashed line indicates the threshold voltage V_d, below which the inversion channels are isolated.

is well described by the above equation, if we use parameters $m^* = 0.07m_0$, $\bar{N}_s = N_{s0} = 6\times10^{11}$ cm^{-2}, which is the value of the unmodulated electron density derived from Shubnikov-de Haas oscillations, and an effective dielectric constant $\bar{\epsilon} = 13.6$ which corrects for screening of the metal gate.[11] Above threshold ($V_g > V_d$), the squared frequency ω_p^2 decreases proportionally to the gate voltage V_g. This implies that $\bar{N}_s$ decreases linearly with gate voltage V_g and it becomes $\bar{N}_s = 1.8\times10^{11}$ cm^{-2} at threshold ($V_g - V_d$). From the gate-voltage dependence of the cyclotron-resonance oscillator strengths, we extrapolate approximately the same value. We can use this value to estimate the effective width W of the isolated inversion channels. Below threshold ($V_g \le V_d$), we denote the areal density in the inversion channel as N_c and have $\bar{N}_s = (W/a)N_c$. From the capacitance, we estimate the density $N_c \simeq 0.9N_{s0}$ at threshold and thus obtain $W \simeq 160$ nm. Note that this width is somewhat smaller than the geometrical width of the insulator stripes (250 nm). Below threshold ($V_g \le V_d$), the density $\bar{N}_s$ decreases further with decreasing V_g. Using classical cyclotron resonance to fit the high-magnetic-field spectra, we find $\bar{N}_s$ to decrease with gate voltage V_g and to become $\bar{N}_s = 0$ at $V_g \simeq -1.1$ V.

We now want to estimate the relevant quantization energies in the inversion channels. We know from self-consistent calculations of the 1D subband energies[6,8] that the separation of adjacent subbands changes little with subband index. This implies that the effective lateral confining potential can well be approximated by a harmonic-oscillator potential. Thus we can write the subband separation as $\hbar\Omega = (\hbar/W)(8E_F/m^*)^{1/2}$, where W is the width of the potential at the Fermi energy E_F, which is measured with respect to the bottom of the potential well. At sufficiently high channel densities N_c, several 1D subbands are occupied and we can use the 2D density of states to estimate the relation between density N_c and Fermi energy and find $\hbar\Omega \approx (\hbar^2/m^*W) \times (8\pi N_c)^{1/2}$. For an inversion channel in GaAs of width $W = 100$ nm and density $N_c = 5\times10^{11}$ cm^{-2}, we estimate $\hbar\Omega \approx 4$ meV and occupation of five subbands. This subband spacing is very close to the energy $\hbar\omega_0$ observed below threshold ($V_g < V_d$) as shown in Fig. 3. Below the threshold, the strengths of the $B = 0$ resonances also can be well described by a harmonic oscillator[13] if we use values for N_c that agree within 30% with those derived from cyclotron resonance at high magnetic fields. From the width of the resonance at $V_g = -0.65$ V we may extract a phenomenological scattering time $\tau = 1.4\times10^{-12}$ s, which is roughly a factor of 2 smaller than the one derived from the mobility at $V_g = 0$. Polarization dependence, oscillator strengths, and resonance positions demonstrate that the observed resonances are in fact intersubband resonances between 1D subbands.

A final proof of subband quantization is provided by the observed dependence of energy $\hbar\omega_0$ on gate voltage V_g. Only 1D quantization can explain a finite resonance frequency as the density $\bar{N}_s$ approaches zero. This is observed in the GaAs and in the InSb samples. In Fig. 4 we show spectra measured on MOS structures on InSb as depicted in Fig. 1(b) with an even smaller period $a = 250$ nm. For these structures, which are similar to the ones used in Ref. 4, we know from the anisotropy of the gate-voltage–induced microwave reflection that the inversion channels are isolated from each other at all gate voltages. The resonances shown in Fig. 4 exhibit essentially the same dependence on magnetic field and polarization as the resonances for the GaAs-AlGaAs structures below threshold ($V_g \le V_d$). If we use classical cyclotron resonance to fit the high-magnetic-field resonances, we find the average density $\bar{N}_s$ to increase in proportion to $\Delta V_g = V_g - V_t$, where V_t denotes the onset of inversion and we have $\bar{N}_s/\Delta V_g \simeq 3.6\times10^9$ cm^{-2} V^{-1}. We extrapolate a finite resonance energy $\hbar\omega_0 \simeq 5.2$ meV for vanishing density N_s. The effective channel width is estimated as the geometrical distance $W \simeq 80$ nm between the Schottky grating stripes. Using this value, we estimate at $\Delta V_g = 50$ V a channel density $N_c \simeq 6\times10^{11}$ cm^{-2}, which is about the same as in the GaAs-AlGaAs sample at threshold ($V_g = V_d$). Because of the smaller width W and the smaller effective mass $m^* = 0.014m_0$ of InSb, one might have expected an essentially higher subband spacing for the InSb structures than for the GaAs structures. However, occupation of several 2D subbands occurs and keeps the Fermi energy relatively low.[14] Also, the effective potential modulation may be quite

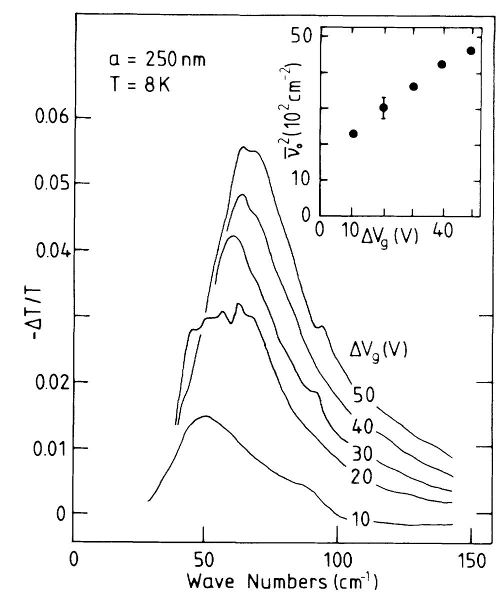

FIG. 4. Spectra of quasi one-dimensional subband resonances in narrow electron inversion channels on p-type InSb. Inset: squared resonance frequencies vs gate voltage ΔV_g above inversion onset.

shallow. The strength of the $B=0$ resonance is again well described by a harmonic oscillator with essentially the same parameters that are needed to fit the high-field resonances with classical cyclotron resonance.

It is well known that the 2D intersubband resonance energy is shifted from the subband separation by depolarization and excitonlike effects which partially compensate each other.[15] We expect similar shifts in 1D subband spectroscopy, but cannot estimate them reliably without an appropriate many-body theory. An upper bound on depolarization effects can be put classically[13] and yields $\omega_d^2 = 2N_c e^2/(\bar{\epsilon}\epsilon_0 m^* W)$. Such a classical equation describes the infrared excitations in inversion layer systems with lateral dimensions $W > 1$ μm, where quantization is not yet important.[16] In our experiments, however, quantization is demonstrated to be dominant and a classical description is expected to grossly overestimate depolarization effects as it does in the 2D case.[15] It should be expected, however, that the transition from a classical depolarization resonance to a 1D depolarization-shifted intersubband resonance as observed here is hardly noticeable as quantization slowly becomes important. The main difference is that a classical depolarization resonance will always approach zero energy as the density approaches zero. Thus our experimental spectra can be unambiguously interpreted as intersubband resonances in 1D inversion channels.

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