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Dimensional excitations in narrow electron inversion channels on Si

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Electronic excitations in periodic arrays of isolated electron inversion channels on Si are studied in the far-infrared frequency domain at liquid-helium temperatures. A versatile dual-gate device allows one to tune the width of the channels W, their electron density, and the depth of the lateral confining potential nearly independently via field effect. In sufficiently wide channels ($W=1.5$ μm) up to four-dimensional resonances with wave vectors $k_n=n\pi/W$ and odd n characteristic for a single-electron channel are observed and well described by a classical theory. With W decreasing below 100 nm we study the transition from classical to quantum confinement.

In recent years there have been considerable efforts to understand the energy spectrum and the electronic excitations in electron inversion channels on semiconductors confined to narrow wires or dots.[1-7] By now the realization of electron inversion channels with width $W \simeq 100$ nm on Si and III-V compounds such as GaAs and InSb is well established. Electronic excitations in such channels are commonly studied with far-infrared (FIR) spectroscopy on periodic arrays covering areas much larger than the FIR wavelength.[1,4-6] In the narrowest channels the discrete excitations are well described by transitions between one-dimensional (1D) subbands more or less shifted by collective phenomena.[4,5,8] At present we still lack understanding how this quantum confinement merges into the classically confined regime[9] and how the excitation spectrum depends on the shape of the confining potential and the coupling between channels. Here we employ a special metal-oxide-silicon (MOS) device to study the electronic excitations in arrays of narrow, isolated electron inversion channels with widths W voltage tunable from 1.5 μm to below 100 nm. Advantageously we can control the potential shape and the areal electron density N_s in the channel nearly independently. In wide classically confined channels we observe a series of dimensional resonances which with decreasing channel width W are found to collapse into a single resonance that finally becomes the 1D intersubband resonance. For the classical regime we observe the excitation spectrum to critically depend on the shape of the potential walls confining the electrons.

Figure 1 depicts schematically our dual gate MOS device fabricated on p-Si (100) with resistivity 20 Ω cm. The top gate is a semitransparent NiCr layer of sheet resistance $R_g \simeq 0.5$–1 k$\Omega/\square$, whereas the structured bottom gate sandwiched between a thermal and a plasma-enhanced chemical-vapor deposition (PECVD) SiO_2 layer is a grating consisting of thin tungsten stripes. It has a period $a=2$ μm and an opening $t=500\pm50$ nm. The two gates can be biased independently via voltages V_{gt} and V_{gb} applied between the substrate and the top and bottom gate, respectively. Periodic arrays of isolated electron inversion channels can be induced at the SiO_2-Si interface either with V_{gt} or V_{gb} defining N_s.[2] The other voltage is then used to provide isolation between adjacent channels and to define the potential height at the edge of the channel. At low temperatures we charge the inversion channel to density N_s in the presence of band-gap radiation via the substrate contact. In the dark we can then also vary the depletion potential at fixed linear density $N_L=N_sW$ by further raising the gate voltage via a substrate bias voltage V_{SB} and thus effectively decrease W. Our samples with gate areas 3×3 mm^2 have peak mobilities of 5000 cm^2/V s at liquid-helium temperature at areal densities around $N_s \simeq 1.5\times10^{12}$ cm^{-2}. We investigate the high-frequency response at temperature 2 K with FIR Fourier spectroscopy in transmission.[10] The radiation is incident parallel to the sample normal and polarized perpendicularly to the grating stripes. We measure the relative change in transmission $-\Delta T/T=[T(0)-T(N_s)]/T(0)$, with N_s depending on the gate potential $\Delta V_g=V_g-V_t$ above threshold voltage V_t. With Shubnikov–de Haas (SdH) experiments we find even for the narrowest channels without substrate bias $N_s=\epsilon_{ox}\Delta V_g/(ed_{ox})$ as for the equivalent homogeneous case.

Figure 2(a) shows the excitation spectrum for electron channels located at the SiO_2-Si interface underneath the

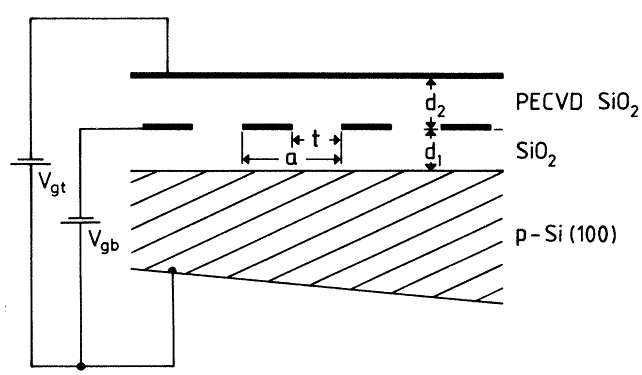

FIG. 1. Schematic cross section of a dual-gate metal-oxide-silicon device. The top gate is continuous, whereas the bottom gate is a stripe grating of periodicity $a=2$ μm and opening $t=500\pm50$ nm sandwiched between a thermal ($d_1=50$ nm) and a PECVD ($d_2=130\pm10$ nm) SiO_2 layer.

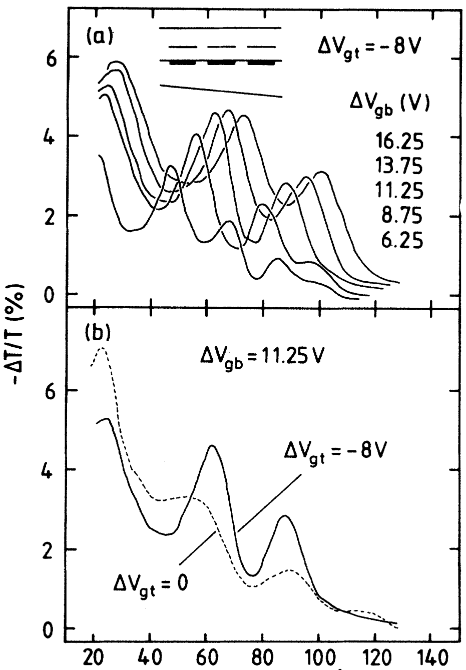

FIG. 2. Relative change of FIR transmission $-\Delta T/T$ of a periodic array of electron channels with $W \simeq 1.5$ μm located below the bottom gate as indicated in the inset. Here the depletion charge is $N_{\text{depl}} = 0.9 \times 10^{11}$ cm^{-2}. In (a) N_s is varied via ΔV_{gb} at fixed $\Delta V_{gt} = -8$ V, whereas in (b) we vary the confining potential via ΔV_{gt} at fixed ΔV_{gb}.

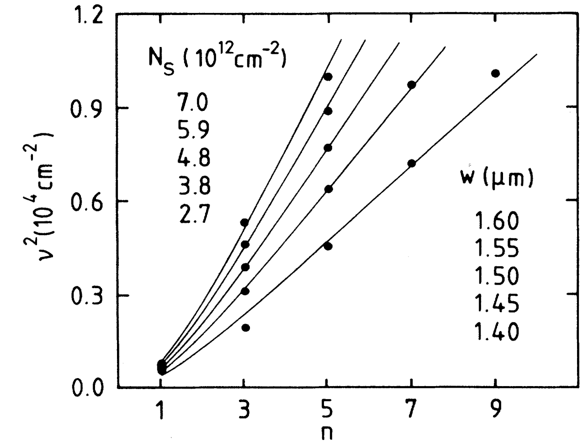

FIG. 3. Squared resonance frequencies of dimensional excitations as shown in Fig. 2(a) vs mode index n. The solid lines are calculated with Eq. (1) varying the discrete mode index $n = 1,2,3,\ldots$ continuously only to increase visibility. The channel width W is adjusted for a best fit as indicated for each N_s.

bottom gate at various N_s. Here $\Delta V_{gt} = -8$ V results in a depth of the lateral confining potential exceeding the band gap of Si. In Fig. 2(a) we find a series of well-defined resonances that we identify as dimensional resonances of an isolated inversion channel never observed previously but long predicted by theory.[9] The excitation of these resonances can be understood as follows: The incident radiation polarizes the channel. The resulting charge distribution in conjugation with the external FIR field lead to a self-consistent field with Fourier components $k_n = n\pi/W$ ($n = 1,2,\ldots$) that can couple to collective modes of standing-wave type. Classically, we expect that only modes are excited which yield an antisymmetric charge distribution at the opposing channel boundaries, i.e., modes with odd n. In Fig. 3 we display the squared-resonance frequencies of data as in Fig. 2(a) versus index n. The solid lines represent a simple dispersion law

$$\omega^2 = \frac{N_s e^2}{m^* \bar{\epsilon}} \frac{n}{W}, \tag{1}$$

with effective mass $m^* = 0.19 m_e$ and effective constant $\bar{\epsilon}$ as discussed in detail below. The excellent agreement between experiment and theory demonstrates unambiguously that we observe dimensional resonances with odd $n = 1,3,5,7,9$.

For $n = 1$, Eq. (1) yields the same result as found by Allen *et al.* and differs by a factor $\pi/2$ from the result of Ref. 9. For $\bar{\epsilon}$ we have used $\bar{\epsilon} = [(a-t)\bar{\epsilon}_1 + t\bar{\epsilon}_2]/a$ with $\bar{\epsilon}_i = [\epsilon_{\text{Si}} + \epsilon_{\text{ox}} \coth(k_n d_i)]/2$ which we consider an appropriate approximation for our complex sample geometry. As the only fit parameter we retain W and obtain values in good agreement with the geometrical width of the bottom gate, slightly increasing with increasing N_s. We think this N_s dependence reflects fringing field effects. Note that with a simplified $\bar{\epsilon} = \bar{\epsilon}_1$, we obtain values W typically 0.1 μm smaller than the ones given in Fig. 3, indicating that the choice of $\bar{\epsilon}$ is not very critical. From comparison between experiment and the single-channel theory we also deduce, that the mutual coupling between channels is small. In Fig. 2(a) we have chosen $\Delta V_{gt} = -8$ V sufficiently negative that there is slight hole accumulation between the electron channels. Possibly, these holes screen interaction between the electron channels. Generally, we find good agreement between the experiment and the dispersion law Eq. (1) only if we create a deep confining potential with steep edges as well as relatively large N_s. The influence of the edge on the electronic excitations is illustrated in Fig. 2(b). Increasing ΔV_{gt} to $\Delta V_{gt} = 0$, where there are no free carries between the electron channels, results in a decrease of oscillator strength of the higher-order modes ($n > 1$) as well as a deviation from Eq. (1). Similarly, we find less agreement between Eq. (1) and the experiment at low N_s as visible for $N_s = 2.7 \times 10^{12}$ cm^{-2} in Fig. 3. From the above we conclude that square-well confinement is essential for observing higher-order ($n > 1$) dimensional resonances as predicted by Eq. (1).

Finally, we would like to discuss the transition from classical to quantum confinement. A reduction of the channel width by about a factor of 3 is readily achieved in our device by inducing the electrons via ΔV_{gt} at the SiO_2-Si interface underneath the bottom gate openings. The dimensional excitations observed in this configuration are displayed in Fig. 4 for various N_s and two depletion charges N_{depl}. By permanently exposing the sample to band-gap radiation we induce quasiaccumulation (N_{depl}

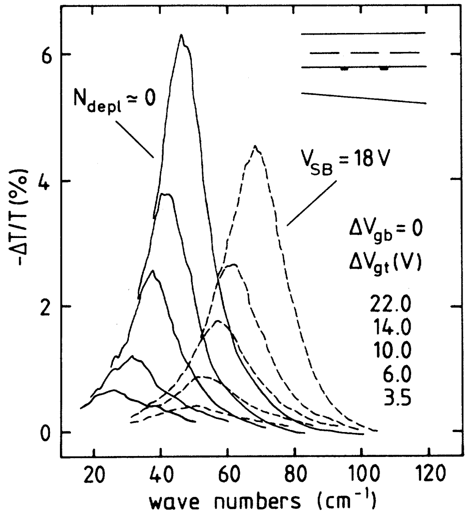

FIG. 4. Relative change of FIR transmission $-\Delta T/T$ for periodic arrays of narrow electron channels at different ΔV_{gt} or equivalent different N_L and $N_{depl} \simeq 0$ (solid lines) and $N_{depl} = 3.8 \times 10^{11}$ cm^{-2} (dashed lines). The inset shows the location of the channels with respect to the bottom gate.

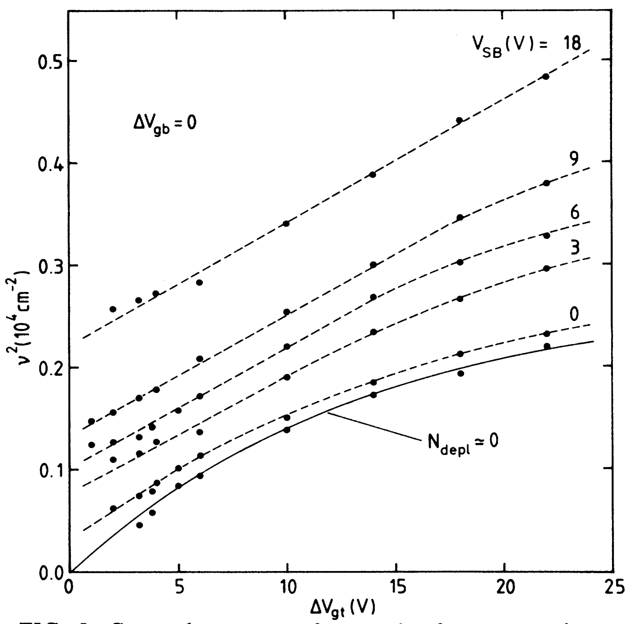

FIG. 5. Squared resonance frequencies for narrow electron channels on Si at different substrate bias voltages vs gate voltage ΔV_{gt} which is proportional to the linear electron density N_L. The solid line is calculated with Eq. (1) as discussed in the text. The dashed lines are guides to the eye.

$\simeq 0$) and observe a dimensional resonance as represented by the solid traces. The lateral confining potential under this condition is rather shallow. After charging the channels at V_{gt} we increase the gate potential at the top gate in the dark by a substrate bias voltage $V_{SB} = 18$ V. We thus create a large depletion potential equivalent to $N_{depl} = 3.8 \times 10^{11}$ cm^{-2} for the homogeneous case[11] and obtain the dashed traces in Fig. 4. Note that the application of substrate bias does not noticeably change the oscillating strength and hence N_L. In both cases we only observe a single-dimensional resonance. The disappearance of higher-order resonances we believe to result from a softening of the confining potential as the spread of the confining edge approaches the channel width. As in previous studies[4] we find that the application of a magnetic field B normal to the sample surface increases all observed resonance frequencies according to $\omega^2(B) = \omega^2(B=0) + \omega_c^2$ with $\omega_c = eB/m^*$ the cyclotron frequency.

In Fig. 5 we display the dependence of the squared resonance frequency versus gate voltage ΔV_{gt} for various depletion conditions. The quasiaccumulation data ($N_{depl} \simeq 0$) are well described by the lowest ($n=1$) classical dimensional resonance as shown by the solid line. This is calculated with Eq. (1) assuming $\bar{\epsilon} = (\bar{\epsilon}_1 + \bar{\epsilon}_2)/2$ and using a width W increasing linearly with $N_L = N_s W$ from 0.38 to 0.56 μm between $\Delta V_{gt} = 0$ and $\Delta V_{gt} = 30$ V, respectively. We note that for $N_{depl} \simeq 0$ the resonance frequency extrapolates to zero for vanishing N_L as expected for classical confinement. For finite depletion charge densities and in the limit of vanishing N_L we find a finite resonance energy continuously increasing with increasing V_{SB}. As in similar studies on InSb (Ref. 12) we take this behavior as convincing proof of quantum confinement. At finite N_L the dimensional resonances become 1D intersubband resonances increased in energy by a collective shift.[4,5,8] At intermediate N_L and without knowledge of the channel width W we cannot separate collective effects from 1D subband energies. Qualitatively, we expect W to decrease with decreasing N_L and increasing V_{SB}. At the largest densities N_L in Fig. 5 we find from SdH experiments that $N_s = N_L/W$ and thus W changes by a factor of 1.5 between $V_{SB} = 0$ and $V_{SB} = 18$ V. Since the slope of ν^2 vs N_L, which classically should be proportional to W^{-2}, changes by about 2.3, we conclude that collective effects dominate at the largest N_L. For N_L approaching zero we obtain 1D subband spacings exceeding 5 meV at $V_{SB} = 18$ V, continuously tunable with V_{SB}. Using a parabolic potential approximation this value corresponds to a channel width of only 20 nm, much smaller than the bottom gate openings.

In conclusion, using a versatile dual-gate device on Si we have realized a system in which narrow electron inversion channels can be tuned via field effect from classical to quantum behavior. In the classical limit and for sufficiently deep square-well confinement we observe well-defined series of standing-wave-type resonances as predicted by classical theory. With increasing confinement these collapse into a single-dimensional resonance which finally becomes a 1D intersubband resonance. Our results show that the transition from collective to single-particle-like behavior that occurs with increased confinement needs further theoretical attention. Particularly, it would be desirable to understand how the oscillator strength of the observed resonances is successively transferred into the lowest mode with increased confinement.

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