Lifting of the Spin Degeneracy of Hole Subbands in a Surface Electric Field on Silicon

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In hole space-charge layers on silicon we observe lifting of the quasispin degeneracy by the surface electric field in the absence of an external magnetic field. This lifting is detected in a splitting of intersubband resonance transitions and increases with increasing surface carrier density, reflecting an increase with quasimomentum. We have performed calculations of the subband excitation spectrum which confirm the experimentally observed quasispin splitting.

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An outstanding feature of the band structure in systems without inversion symmetry is that the degeneracy of the quasispin states is inherently, i.e., without external magnetic field, lifted for quasimomentum $\vec{k}_{\parallel} \neq 0$. This is a consequence of the effect of an asymmetric potential on the spin-orbit interaction. In the bulk of zinc-blende-type compounds asymmetry effects are extremely small[1] and have only been observed by applying stress to enhance the inversion asymmetry.[2] Inversion asymmetry also exists in quasi-two-dimensional (2D) space-charge layers. There it is induced by a surface electric field in a metal-oxide-semiconductor (MOS) structure or in heterostructure interfaces. In these systems, mobile carriers are confined in a very narrow potential well which causes a 2D energy spectrum consisting of a set of "subbands" with energy dispersion $E_i(\vec{k}_{\parallel},\sigma)$ [$i=1,2,3,\ldots$; $\vec{k}_{\parallel}=(k_x,k_y)$ is the quasimomentum parallel to the interface].[3]

It was pointed out in calculations of Bangert and co-workers[4,5] and Ohkawa and Uemura[6] that the asymmetry of this potential splits the energy eigenvalues of different spin states σ for $\vec{k}_{\parallel} \neq 0$. Experimental evidence for the lifting of the spin degeneracy in high-mobility space-charge layers of GaAs heterostructures has been reported recently by Störmer *et al.*[7] and Stein, Klitzing, and Weimann.[8] However, these experiments are performed in high magnetic fields—which cause spin splitting by themselves—and are extrapolated to $B=0$. We have directly observed spin splitting without the presence of a magnetic field in hole space-charge layers of Si using intersubband spectroscopy.

In intersubband spectroscopy, resonant transitions between different subbands of the 2D system are studied (see, e.g., Ref. 3; for hole-intersubband spectroscopy, e.g., Refs. 9–12). Important for our investigations is the parallel excitation, which means that the electric field vector of the exciting radiation is polarized parallel to the 2D space-charge layer. For details of the experimental technique we refer to Batke and Heitmann.[13]

The samples are high-mobility (intraband scattering time $\tau=4\times10^{-13}$ s) *n*-type Si(110) MOS capacitors. The inverted *p* channel is isolated from the substrate by a depletion layer ($N_{\rm depl}=1.6\times10^{11}$ cm^{-2}) which causes a finite depletion field. Experimental spectra, measured with Fourier-transform spectroscopy, are shown in Figs. 1 and 2(a). $\Delta T/T=[T(V_g)-T(V_t)]/T(V_t)$ is the relative change of transmission for radiation transmitted normally through the MOS sample with semitransparent gate. $T(V_g)$ and $T(V_t)$ are the transmission at gate voltage V_g and conductivity-threshold voltage V_t, respectively. $-\Delta T/T$ is proportional to the real part of the dynamic 2D conductivity σ. The spectra contain a Drude-type intrasubband absorption background and resonant intersubband transitions. The intersubband structure in Fig. 1 consists of three close, but well-resolved resonances. The three transitions cannot be resolved in low-mobility samples[12] and can hardly be extracted if the depletion field is lowered by band-gap-radiation–induced carriers (quasiaccumulation). All resonances shift with increasing N_s to higher energies, corresponding to larger subband separations in the steeper potential well.

In Fig. 2(a) we compare spectra for polarization of the electric field vector parallel to [001] and [$\bar{1}$10], respectively. The difference in the Drude background reflects the anisotropy of the (110) surface. Figure 2(a) also indicates a strong anisotropy for the excitation strengths of intersubband reso-

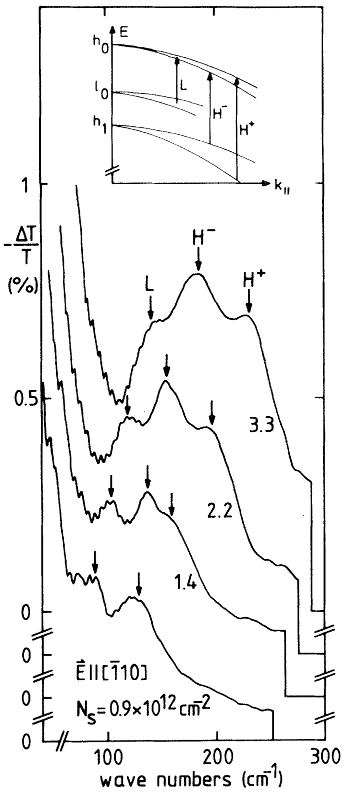

FIG. 1. Experimental spectra of parallel-excited intersubband resonances in hole space-charge layers of Si(110) for different charge densities N_s.

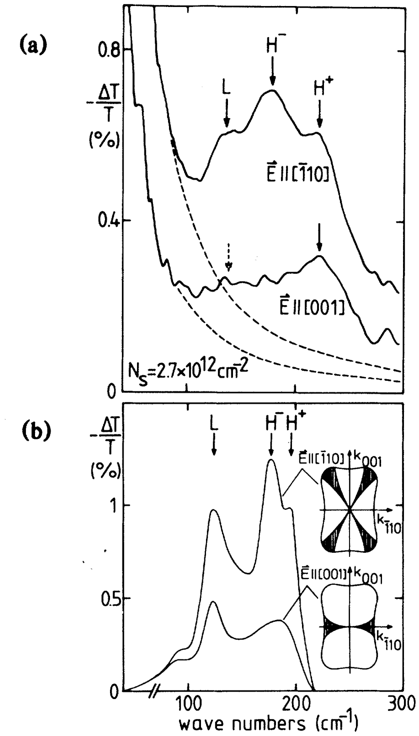

FIG. 2. (a) Experimental spectra for polarization of $\vec{E}$ parallel to $[\bar{1}10]$ and [001]. Dashed lines indicate the extrapolated Drude background. The dashed arrow marks a weak resonant contribution which can be extracted by subtracting the Drude background and which is observed for all densities N_s. (b) Calculated intersubband transitions $-\Delta T/T$ (without Drude background) in absolute units. The inset shows schematically the Fermi contours in the 2D $\vec{k}_{\parallel}$ space. Shaded areas indicate the regime of $\vec{k}_{\parallel}$ values which contribute dominantly to the excitation of intersubband transitions.

nances. This anisotropy is different for different transitions. The transition labeled H^-, which is dominant for polarization parallel to $[\bar{1}10]$, is not observed for polarization parallel to [001], whereas transitions labeled L and H^+ are excited, with different strengths, for both polarizations. In the following we will show that the three resonances reflect the spin splitting of the hole-subband system.

A very surprising observation in Figs. 1 and 2(a) is that such sharp structures are observed in a hole-subband system. Previously one has expected that the nonparabolicity and the nonparallelism of the hole subbands[4-6] would smear out transition energies over a wide energy range. In fact, so far the profile of experimental hole-intersubband resonances has been interpreted mostly to be governed by this nonparallelism.[9-12] Here, as far as a half-width ΔE can be extracted from the separated transitions in Fig. 1, ΔE coincides with $2\hbar/\tau$, where τ is the intraband scattering time deduced from the Drude background. We explain the surprising sharpness of the structures by matrix-element effects: For small values of $\vec{k}_{\parallel}$ the constant energy contours of the valence bands are rather symmetric. The situation is similar to electrons on Si(100), where intersubband transitions are strictly forbidden for parallel excitation. With increasing $\vec{k}_{\parallel}$ the energy contours of the holes become warped, the symmetry is lowered, and transitions are less forbidden. This implies that the dominant contributions to the intersubband resonance are transitions at $\vec{k}_{\parallel}$ values close to the 2D Fermi vector, eventually, only from a certain segment of the Fermi contour. If this regime of $\vec{k}_{\parallel}$ values is small enough, the nonparallelism of the bands will not affect the intersubband resonance linewidth and transitions between different quasispin states of different bands can be resolved.

To support our interpretation of the experimental results we have calculated the 2D hole-subband states self-consistently based on Luttinger's 6×6 $\vec{k}\cdot\vec{p}$ Hamiltonian and with use of the Hartree approximation (for details see Refs. 4, 5, and 14). In addition, we have calculated the absolute intersubband contribution to $-\Delta T/T$ via the matrix elements of the velocity operator, taking into account the $\vec{k}_{\parallel}$ dependence of the final- and initial-subband states $|f,k\rangle$ and $|i,k\rangle$ as well as that of the velocity operator $v(\vec{k}_{\parallel})$. We label the ground hole subband h_0. The first and second excited subbands are l_0 and h_1, respectively [see inset of Fig. 1(a)]. h (heavy) and l (light) denote the dominant character of the subband wave functions. For transitions from the ground subband h_0 to the l_0 and h_1 subband we find that parallel excitation is strictly forbidden at $\vec{k}_{\parallel}=0$, but becomes allowed for $\vec{k}_{\parallel}\neq 0$, and increases roughly in proportion with the square of $\vec{k}_{\parallel}$. Therefore, in accordance with our qualitative explanation, only transitions at $\vec{k}_{\parallel}$ values close to the 2D Fermi vector are effective for the intersubband excitation. Areas of the 2D $\vec{k}_{\parallel}$ space, where transitions contribute dominantly to the intersubband resonance, are indicated in the inset of Fig. 2(b). The transition matrix elements for $\vec{k}_{\parallel}$ values outside these areas are much smaller or zero.

Theoretical intersubband transition spectra in absolute units for the parameters of the experiment of Fig. 2(a) are shown in Fig. 2(b). Calculations are performed without any fitting parameter with use of the volume band-structure parameters (e.g., Ref. 14). Resonant structures labeled H^- and H^+ are transitions from the lower quasispin state of the h_0 band to the upper spin branch of the h_1 subband, and from the upper spin branch of the h_0 band to the lower spin branch of the h_1 subband, respectively (see inset of Fig. 1). The peak labeled L includes transitions from the h_0 subband to both quasispin states of the l_0 subband. To compare the theoretical transition probability with the experiment one has to subtract the Drude background in the experimental spectra. The differences in the absolute values for theoretical and experimental resonance energies and absolute excitation strengths are surprisingly small if one takes into account that important contributions to the intersubband resonance are not included in our calculations of this complex system, e.g., many-body corrections and final-state interactions.[4,5] Also, τ is assumed to be infinite in the theoretical evaluation, which explains differences in line shape and the fact that the low-energy structures are not resolved in experiment. The integrated intensity of the intersubband resonances agrees surprisingly well (within 10%) with the theoretical value.

The calculations confirm the main features of the experimental spectra, and also the strong anisotropy

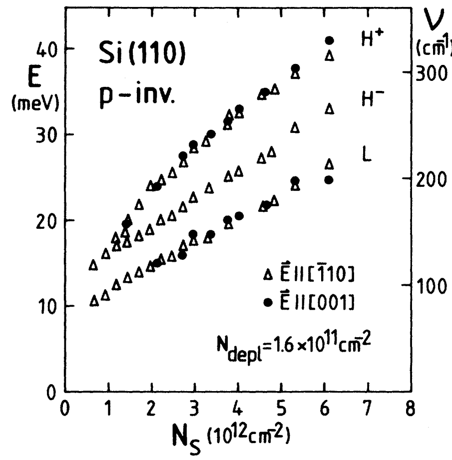

FIG. 3. Experimental intersubband resonance positions vs charge density N_s.

(different for different transitions) for polarization parallel to [$\bar{1}$10] and [001]. This comparison with theory thus unambiguously identifies the experimentally observed peaks H^+ and H^- as transitions between spin-split bands.

The experimental resonance positions for different charge densities are plotted in Fig. 3. As is discussed above, the sharpness of the resonances implies that the resonance positions represent the subband separation at the largest quasimomentum $\vec{k}_{\parallel}$ occupied at the charge density N_s. Thus with decreasing N_s resonance energies for decreasing $\vec{k}_{\parallel}$ are measured. Both resonances H^+ and H^- approach the same resonance energy of about 12 meV for $N_s \to 0$. This demonstrates that the spin splitting goes to zero with $\vec{k}_{\parallel}\to 0$. The extrapolated experimental resonance energies for $N_s \to 0$ of the L and H transitions agree very well with our calculated values of 7.6 and 11 meV, respectively. It is important that our experiments are performed at a finite depletion potential. For accumulation conditions (i.e., $N_{\rm depl}\approx 0$) the separation between all subbands will go to zero for $N_s \to 0$.

In conclusion, we have demonstrated that there is an inherent splitting of quasispin states for hole space-charge layers of Si. This splitting is caused by the spin-orbit interaction in an asymmetric surface electric potential and increases with increasing $\vec{k}_{\parallel}$. The spin splitting is considerable, e.g., at $N_s = 3\times 10^{12}$ cm^{-2}, which corresponds to a k value of about 3×10^6 cm^{-1}, it is 6 meV. Our results also show the importance of the $\vec{k}_{\parallel}$ dependence of transition matrix elements in the interpretation of intersubband resonance spectra in nonparabolic nonparallel subband systems.

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