Resonant Interaction of Plasmons and Intersubband Resonances in a Two-Dimensional Electron System

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Intersubband resonances and collective intraband plasmon resonances are the elementary dynamic excitations of a two-dimensional electronic system. By applying uniaxial stress to a Si(100) metal-oxide-semiconductor system we can tune and energetically match the two resonances. In the crossing regime we find a resonant interaction of the two excitations leading to an enhancement of the intersubband resonance amplitude and a splitting of the dispersion.

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In metal-oxide-semiconductor (MOS) or in heterostructure systems, electrons can be confined in narrow potential wells.[1] The energy spectrum of these quasi two-dimensional (2D) electron systems consists of discrete subbands $E_i(\mathbf{k}_\parallel)$, $i=0,1,2,\ldots$, arising from the free motion of the electrons parallel to the interface and the quantized energy levels for the motion perpendicular to the interface. Two characteristic resonances govern the dynamic properties of the system: (a) intersubband resonances,[1,2] the resonant transitions between the subbands in the 2D system which correspond to oscillations of the carriers perpendicular to the interface (z direction), and (b) 2D intraband plasmons,[1,3-5] the resonantly excited collective oscillations of the system in the 2D plane (x-y plane). In experiments reported so far, the two resonance energies are widely separated and no interaction of the excitations has been observed.[6] Here we have used uniaxial stress to tune the resonance frequencies of both the intersubband resonance and the plasmon resonance in 2D electron space-charge layers of Si(100). For certain values of the applied stress p, charge density N_s, and plasmon wave vector q, we can match the resonance energies of the excitations. In this regime of energetic level crossing we find a resonant interaction of the two excitations resulting in an enhancement of the intersubband resonance amplitude and a splitting of the dispersion.

For Si(100) two nonequivalent subband systems exist, resulting from the projection of the six energy ellipsoids of the conduction-band minimum of bulk Si onto the (100) surface.[1] Without stress and at low temperatures T and charge densities N_s the lowest subband E_0 of a system E_i with twofold valley degeneracy ($g_v=2$) is occupied. A second subband system E_i' (denoted by primes) with $g_v'=4$ can be occupied at large N_s, by an increase in temperature, or by application of uniaxial stress. The effect of uniaxial stress on the subband structure of Si has been investigated both theoretically and experimentally (for example, see the works of Takada and Ando,[7] Vintner,[8] Das Sarma *et al.*,[9] Stallhofer, Kotthaus, and Abstreiter,[10] Englert, Tsui, and Logan,[11] Kunze,[12] and Oelting, Heitmann, and Kotthaus[13]). For our experiments it is important that stress in the [001] direction lowers the energy E_i' of two of the originally fourfold degenerate valleys with respect to E_i. At a certain value p_0 of the applied stress the primed subband system becomes occupied. We will show that for this special case, in which both subband systems are simultaneously occupied, a strong stress dependence of the subband separations exists because of the self-consistent arrangement of the electron wave functions. In particular, the $0' \rightarrow 1'$ separation increases with increasing stress.

The 2D plasmon frequency ω_p is given by[3,4]

$$\omega_p^2 = e^2 N_s q/(2\bar{\epsilon} m_p), \tag{1}$$

where $\bar{\epsilon}$ is an effective dielectric function.[4] The plasmon mass m_p can be written for the experiments here, with q and the uniaxial stress p both parallel to the [001] direction, as

$$m_p^{-1} = (N_{s0}/m_{p0} + N_{s0}'/m_{p0}')/N_s. \tag{2}$$

Here N_{s0}/N_s and N_{s0}'/N_s are the relative occupations of the two subband systems. The plasmon mass m_{p0}' for the [001] direction in the primed system is $0.92 m_0$ and hence larger than the mass in the unprimed system ($m_{p0}=0.19 m_0$). Thus an occupation of E_0' leads to an increase of the plasmon mass and a decrease of the plasmon frequency at fixed N_s.[11,13]

The experiments are performed on Si MOS capacitors of size 5×6 mm^2 with resistivity 20 $\Omega\cdot$cm and oxide thickness 50 nm. A well-defined uniaxial stress can be applied to the samples at low temperatures ($T \simeq 12$ K) with a standard stress apparatus used in optical experiments.[13] Quasi electron-accumulation conditions are established in the p-type samples by continuous illumination with band-gap radiation. The excitation of plasmons is observed in the transmission of normally incident far-infrared (FIR) radiation. The gate consists of periodic stripes of alternating high and low conductivity with a periodicity $a = 514$ nm. This grating couples the FIR radiation to plasmons of wave vector $q_n = n2\pi/a$, $n=1,2\ldots$,[5,14] q is in the [001] direction. The same grating coupler also induces in the near field components e_z of the exciting FIR electric field. Via these e_z components intersubband resonances can be excited.[14,15]

Experimental spectra measured at a fixed laser energy $\hbar\omega = 17.6$ meV, fixed stress p, and varying charge density N_s are shown in Fig. 1. The structures at low densities arise from a rapid variation of the mobility at low N_s. The pronounced resonance at $N_s \approx 7\times10^{12}$ cm^{-2} for $p=0$ is the plasmon resonance at $q=2\pi/a$. With increasing stress the plasmon resonance shifts to higher N_s. This is expected from formula (1) because of the increase of the plasmon mass if the primed subband system becomes occupied. (In an energy-sweep experiment at fixed N_s this is equivalent to a decrease of the plasmon resonance energy.) For a certain regime of stress p, shown in small increments of p in Fig. 1, we observe a second resonance which shifts with increasing stress to lower N_s (corresponding to a shift to higher energies in a frequency sweep at fixed N_s). We will show in the following that this resonance is a $0'\to1'$ intersubband resonance. In the crossing regime the two resonances show all the characteristics of a resonant interaction, first a resonant enhancement of the intersubband resonance amplitude and second a splitting of the dispersion.

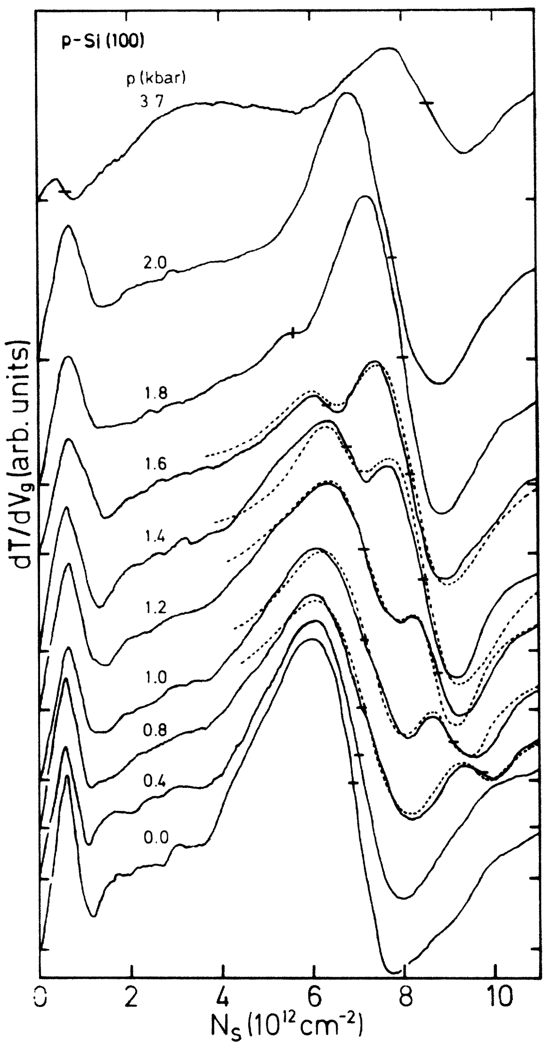

FIG. 1. Experimental spectra of dT/dV_g, the derivative of the transmission with respect to the gate voltage, vs charge density N_s for different values of the uniaxial stress $p \parallel [001]$ at temperature $T \simeq 12$ K and laser energy $\hbar\omega = 17.58$ meV. The spectra shown are for sample A, except for the trace at $p=3.7$ kbar, a stress value which has only been reached on a second similar sample B. Plasmon resonances of wave vector $q=1.22\times10^5$ cm^{-1} are observed at $N_s > 4\times10^{12}$ cm^{-2}. They shift with increasing p to higher N_s. For $p=0.4$ to 1.8 kbar a $0'\to1'$ intersubband resonance shifts with increasing p to lower N_s. In the crossing regime a resonant interaction of both resonances is observed. Dotted lines are fits to the spectra assuming superposition of two Lorentzian resonances.

The dispersion of the two resonances is shown in Fig. 2. To extract the exact positions $N_{s1}(p)$ and $N_{s2}(p)$ of the two resonances we approximate the spectrum by the superposition of two Lorentzian lines $S=S_1+S_2$ with

$$S_i \sim A_i(N_s)[N_{si}^2(p) - N_s^2 + \Gamma_i^2]^{-2}, \quad i=1,2, \tag{3}$$

where Γ_1 and Γ_2 are phenomenological damping constants. $N_{s1}(p)$ and $N_{s2}(p)$ are then determined from

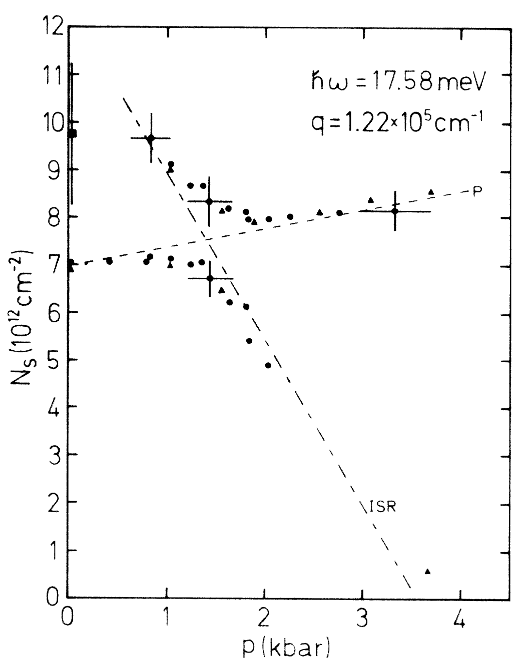

FIG. 2. Experimental resonance positions extracted from fits to the spectra as in Fig. 1. The interaction of the plasmon excitation (P) and the intersubband resonance (ISR) leads to a resonant splitting of the dispersion. Sample A is marked by circles, sample B by triangles. The $0'\to1'$ subband separation for $N_{\text{depl}}=0$ extracted from Ref. 12 is denoted by squares.

fits of the derivative dS/dN_s to the experimental spectra, as is shown in Fig. 1.

Whereas the identification of the 2D plasmon resonance is clear, we want to show why we identify the second resonance with the $0' \rightarrow 1'$ intersubband resonance. This is not immediately obvious, since our experiments study for the first time intersubband resonance excitation in systems with uniaxial stress. If we extrapolate the experimental intersubband resonance position to $p=0$ we find a density of $N_{\rm ISR}(0) \approx 12\times10^{12}$ cm^{-2} for the laser energy of 17.6 meV used here. This agrees with the $0' \rightarrow 1'$ subband spacing of 16 ± 2 meV at $N_s = 8.5\times10^{12}$ cm^{-2} found for accumulation in tunneling spectroscopy.[12] The intersubband resonance energy differs from the subband spacing because of depolarization and exciton effects. However, for the high densities used here, the net effect of the two is small.[1] Without stress $0' \rightarrow 1'$ intersubband resonances have been observed for $N_s > 7 \times 10^{12}$ cm^{-2} and inversion conditions ($N_{\rm depl} > 10^{11}$ cm^{-2}).[15] Within the accuracy ($\approx \pm 20\%$) of extrapolating of these data to accumulation ($N_{\rm depl}=0$) they also confirm that the intersubband resonance observed here is the $0' \rightarrow 1'$ resonance.

To discuss the p dependence of the $0' \rightarrow 1'$ resonance we recall that with increasing stress $p \parallel [001]$ two of the four $0'$ subbands are lowered in energy and become occupied. This has a strong influence on all other subband energies in the system and their relative positions. The wave functions of the $0'$ subband extend deeply into the Si as a result of the small m_z' mass amd strongly influence the potential at large distances z from the interface and thus the wave functions and energies of the higher subbands. Thus with increasing stress the $0' \rightarrow 1'$ subband separation increases. This behavior has been directly observed in tunneling spectroscopy for inversion conditions[12] and is caused by the same mechanism that explains the shift of the intersubband resonances to lower N_s with temperature-induced E_0' occupation.[16,17]

Note that this dependence on stress is a special feature for the case that two different types of subbands are occupied. On the very same samples we observe for smaller laser energies $0'$-$1'$ resonances at lower $N_s < 5\times10^{11}$ cm^{-2} and $p \geqslant 2$ kbar.[13] Here we find that for sufficiently high p the intersubband resonance energy does not depend significantly on p. The reason is that at these low densities nearly all electrons are in the E_0' subband, as is known from stress phase diagrams.[7,8] Thus here, stress only changes the energy of the whole subband ladder, but not the separation within a system. Thus the possibility to tune the $0' \rightarrow 1'$ resonance through the plasmon resonance in the experiments here arises from the complex self-consistent arrangement of subbands in a multivalley system.

We will discuss next the amplitudes of the resonances. Outside the regime of the plasmon resonance the amplitude of the $0' \rightarrow 1'$ resonance is, at the given grating coupler efficiency, too low to be observed due to the relatively low occupation N_s' at $N_s > 6\times10^{12}$ cm^{-2}. 2D plasmons have—in contrast to volume plasmons in a bulk plasma and similar to surface plasmons on a semi-infinite plasma—transverse field components e_z. Both the $e_x(\omega,q)$ and the $e_z(\omega,q)$ components show a resonant enhanced amplitude. The enhanced e_z component causes an enhanced excitation of the intersubband resonance, since the field strength is induced directly in the vicinity of the 2D system. This process makes it possible to observe the $0' \rightarrow 1'$ resonance. From the fits in Fig. 1 we find that the amplitude $A_{\rm ISR}$ of the intersubbandlike mode is resonantly enhanced, approximately in proportion to the amplitude of the plasmonlike mode. Plasmon-enhanced excitation processes are well known for surface plasmon excitations at the boundaries of semi-infinite plasma,[18] e.g., plason-enhanced light scattering, giant-Raman effect, etc. In our experiments such resonant enhancement is demonstrated for the first time to be caused by the 2D plasmon resonance.

The trace at high $p=3.7$ kbar in Fig. 1 shows an additional resonance at low $N_s \approx 0.6\times10^{12}$ cm^{-2}. We identify this resonance as the $0' \rightarrow 1'$ subband transition at high stress (see also Fig. 2). Here we have the situation discussed above, that nearly all carriers are in the primed subband system. The relative occupation N_s'/N_s is high and the $0' \rightarrow 1'$ resonance can be clearly resolved from the Drude background without the plasmon enhancement effect. The $0' \rightarrow 1'$ resonances at smaller p extrapolate excellently to this data point. This resonance position also agrees with data found for temperature-induced $0'$ occupation.[16,17]

Finally we wish to discuss the strength of the plasmon–intersubband resonance interaction that governs the amount of the splitting. From Fig. 2 we deduce a splitting on the N_s scale of $\Delta N_s \approx 1.6\times10^{12}$ cm^{-2}, which corresponds to $\Delta\omega_p = 1.9$ meV on the energy scale if we use the plasmon dispersion (1). The nonresonant influence of virtual intersubband excitations on the plasmon dispersion has been calculated by Das Sarma.[19] If we use the same formalism for a resonant interaction, then the splitting of the resonance is in a two-subband (a and b) approximation:

$$\Delta\omega \approx \omega_p (2N_s^2 E_{ab} V_{aaab}^2 q/m\omega_p^4)^{1/2}. \qquad (4)$$

The splitting thus depends on the Coulomb matrix element V_{aaab} reflecting the combined intersubband and intrasubband excitation. The wave functions and thus the Coulomb matrix elements for our experimental conditions, a stress-induced occupation of E_0 and E_0' subbands, are not known. To estimate the interaction strength we use values for the Coulomb matrix elements given for the E_0 and the E_1 subbands by Nakamura, Ezawa, and Watanabe.[20] With these values we find $\Delta\omega \approx 2.8$ meV. Thus from theory one estimates an interaction strength comparable to that found in the experiment.

In conclusion, we have studied the resonant interaction of intersubband resonances and collective plasmon resonances in a 2D electronic system by tuning their energies via uniaxial stress. In the crossing regime a resonant enhancement of the intersubband resonance amplitude and a splitting of the dispersion are found. The resonant interaction that is investigated here allows an accurate determination of plasmon-intersubband resonant coupling. Such coupling also influences the plasmon dispersion via nonresonant processes, an effect that is particularly important in superlattice structures.[19] Resonant enhancement phenomena via two-dimensional plasmons may possibly also be utilized to study other modes at interfaces.

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