7 Tunneling–Coupled Systems

7.1 Introduction

The plasmon spectrum of spatially separated two–component plasmas without tunneling has been studied for quite some time (see, e.g., [1]). For finite Coulomb coupling between the layers, the intrasubband charge–density excitation spectrum consists of two modes: The optical plasmon (OP) where both layers oscillate in phase parallel to the layers (see Fig. 7.1a), and, the acoustic plasmon (AP) where the carriers in both layers oscillate out of phase (see Fig. 7.1b). At long wavelengths, the energy of the OP is proportional to $\sqrt{q}$ and the energy of the AP goes linear in q, where q is the wave vector parallel to the layers. It was shown [1] that at large spatial separation of the two layers, the AP can move outside of the continua of possible intraband single–particle transitions. The first experimental observation of coupled–layer plasmons by inelastic light scattering was reported by Fasol et al. [2] on GaAs-AlGaAs samples containing five layers in parallel. In Coulomb–coupled double quantum wells, the observation of AP and OP was reported by Kainth et al. [3].

During the past decade there has been a growing interest in *tunneling-coupled* bilayer systems. In those systems, the interplay between many–particle Coulomb interaction and tunneling coupling – which, in the first place, is a single–particle effect – can be nicely studied. The additional degree of freedom, which comes into play in these systems due to the tunneling coupling, is commonly known as the so called pseudo spin. For bilayers with a perfectly symmetric potential in growth direction, the ground state is determined by the tunneling–split symmetric and antisymmetric single–particle states. New phenomena are expected due to intra– and interlayer Coulomb interactions. In the past decade, quite a number of experimental [4, 5, 6, 7, 8, 9, 10, 11] and theoretical [12, 13, 14, 15, 16, 17, 18, 19, 20] papers appeared, concerned with tunneling–coupled systems. Most inelastic light scattering experiments so far have been performed in symmetric tunneling–coupled bilayer systems [6, 7]. For this specific case, theory predicts two excitations, an *optical* intraband plasmon, which evolves from the OP of a purely Coulomb–coupled system, and an intersubband plasmon (ISP) [17, 18], which is qualitatively new, when compared to the situation without tunneling. As in the case of a single layer, the intraband plasmon is an ex-

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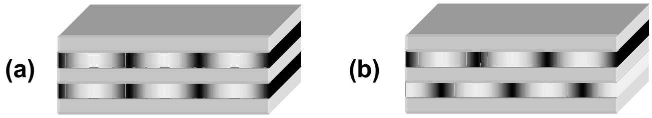

Fig. 7.1. Schematic snapshot picture of the electron–density distributions for (**a**) the optical plasmon (OP), and, (**b**) the acoustic plasmon (AP) of a Coulomb–coupled double–layer system. High electron density is indicated by a dark color

citation where, macroscopically, the total electron density in both layers is oscillating within the plane. The ISP, on the other hand, consists of transitions of electrons between the tunneling–split subbands, i.e., it is a density oscillation *between* the two layers. These excitations have been studied, e.g., in [6, 7], where in [6] it was reported that for occupation of both tunneling–split subbands, the exchange–interaction contributions from both subbands approximately cancel, and the intersubband SDE therefore has the same energy as the intersubband SPE. In this chapter we will concentrate on the spectrum of CDE's in tunneling–coupled systems to study the interplay between direct Coulomb and tunneling coupling. It can be shown that the energy of the AP is close to zero in the case of strong tunneling [20]. As soon as the potential deviates from perfect symmetry, however, the excitation spectrum becomes more subtle. In particular, the excitation energy of the AP increases again so that it should be observable in experiment.

In this chapter recent experiments on strongly coupled double quantum wells will be discussed. In those experiments, the theoretically predicted [20] plasmon spectrum could be observed, employing samples with external gates, which allow one to tune the symmetry of the double quantum–well potential in growth direction [11]. The chapter is finalized by a section, where first experiments on strongly tunneling–coupled quantum wires will be presented.

7.2 Charge–Density Excitation Spectrum in Tunneling–Coupled Double Quantum Wells

Figure 7.2 shows schematic pictures of the potentials and wavefunctions of double quantum wells in growth direction. In Fig. 7.2a, a symmetric potential is shown. The wavefunction in this case is perfectly symmetric or antisymmetric for the tunneling–split state with lower or higher energy, respectively. For a symmetric potential, the tunneling gap, Δ_{SAS}, is minimal. If the potential becomes nonsymmetric (Fig. 7.2b), the tunneling gap is larger than for the symmetric case, i.e., $\Delta > \Delta_{\mathrm{SAS}}$, and the wavefunctions have no longer a defined symmetry. With increasing tilt of the potential, the wavefunctions of