

# 6 Quantum Wires: Interacting Quantum Liquids

## 6.1 Introduction

In 1989, the first inelastic light scattering experiments on electronic excitations in quantum wires were reported [1, 2]. Since then, a number of experimental papers appeared about, e.g., many-particle interactions and selection rules in those systems [3, 4, 5, 6, 7, 8, 9] and investigations with applied external magnetic field [10, 11, 12]. All these experiments were performed on lithographically-defined GaAs-AlGaAs structures. Consequently, the lateral sizes of these structures were on the order of 100 nm, or at least not much below [8, 9]. Unlike for the case of quantum dots, there is no well-established method of self-organized growth of modulation-doped quantum wires. During the past few years, Carbon nanotubes have evolved as new and alternative quantum-wire structures. So far, the main focus in the investigation of those very promising quantum structures by optical experiments has been on phonon excitations [13]. Phonon Raman spectroscopy has greatly helped in unveiling the topological structure of Carbon nanotubes [13]. An interesting further method to produce very narrow wires with atomic-layer precision is the so called cleaved-etched overgrowth (CEO) [14]. However, with CEO it is difficult to grow very large arrays of wires, which would be necessary to get enough signal strength in inelastic light scattering experiments. Hence, there are so far no reports of inelastic light scattering experiments on CEO wires, though these might be promising structures for high-sensitivity experiments. As mentioned, most of the existing experimental reports are on lithographically-defined GaAs-AlGaAs quantum wires with rather mesoscopic widths. Hence, in those experimental structures, typically several Q1D subbands are occupied with electrons. In this chapter we will discuss both, experiments and calculations on such samples. The main focus will be on the microscopic origin of confined plasmons and interesting internal interaction effects in a magnetic field. These experimental results are described well within the RPA, i.e., a Fermi-liquid theory, as we will see later.

Much *theoretical* research on Q1D electron systems has been triggered by the fact that in the so called Tomonaga-Luttinger model [15] one is able to treat the Coulomb interaction in a *strictly* one-dimensional system exactly. This model relies on the approximations that the one-dimensional subband dispersion is linearized in the vicinity of the Fermi wave vector, and backscat-

tering events are neglected. For this case, the so called bosonization technique allows one to treat the Coulomb interaction exactly. An important result of this theory is that in a Luttinger liquid, all elementary electronic excitations are *intrinsically* collective [16], i.e., electrons are no defined quasiparticles. This is a very important difference to the Fermi-liquid theory. Hence, in a Luttinger liquid, there are no SPE's, and one should expect collective SDE's and CDE's as the only electronic excitations. There has, however, been some debate, whether or not a Luttinger liquid can be realized in a real quantum wire sample [17, 18]. One would assume that a Q1D quantum wire has to be at least in the quantum limit, i.e., only one subband is occupied by electrons, in order to be close to a Luttinger liquid. There is only one report in literature – of F. Perez et al. [8, 9] – where the authors report about the realization of very narrow GaAs–AlGaAs quantum wires, which are supposed to be in the quantum limit. However, experimentally it seems to be difficult to decide if either the Fermi liquid, or the Luttinger liquid theory is better suited to describe the experimental observations [9]. The dilemma here is that the Q1D plasmon wave-vector dispersion, which can be measured by inelastic light scattering, is in both theories exactly the same [17]. In Sect. 6.4 we will discuss experiments on very narrow, lithographically-defined structures, which are close to the quantum limit. However, the experimental proof of a Luttinger liquid still remains a challenge.

## 6.2 Electronic Elementary Excitations in Quantum Wires

### 6.2.1 Ground State and Excitations

Similar to quantum dots, in deep-etched quantum wires, the lateral confining potential is determined by the homogeneously distributed ionized remote donors in the AlGaAs barrier, and negatively-charged surface states, as sketched in Fig. 6.1. By analytical calculations one can show that this lateral potential, which acts on a test electron within the structure (*bare* potential), is for the case of dots [19] in  $x$  and  $y$  direction, and, in wires, for the direction perpendicular to the wires (in the following  $y$  direction) in good approximation parabolic. Of course, the presence of other electrons in the one-dimensional channel screens the interaction of the test electron with the remotely localized charges, and the effective potential will deviate from a parabolic shape. A positive effect of the negative surface charges, however, is that due to Coulomb repulsion the *electronic* width,  $a$ , of the Q1D electron system is smaller than the geometrical width  $w$  (see Fig. 6.1). The length  $(w - a)/2$  is called depletion length. Its value depends on the structure of the sample and may also depend on experimental conditions, as the illumination strength. For optical experiments, the depletion length is typically a few tens of nanometers [8].