Admittance and Noise Detection in Mesoscopic Systems via GHz Impedance Matching

Thesis (Dissertationen, Habilitationen)

ID 4135112
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Year 2017
Title Admittance and Noise Detection in Mesoscopic Systems via GHz Impedance Matching
Type of Thesis Dissertation;
Start of thesis 01.03.2013
End of thesis 31.03.2017
Name of University University of Basel
Name of Faculty Philosophisch-Naturwissenschaftliche Fakultät;
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Fast measurement of small currents and even smaller fluctuations in devices with large impedance is not trivial. Standard low frequency lock-in measurements suffer from stray capacitance of the order of nF reducing the bandwidth to merely kHz and a time resolution of ms. One approach of increasing the bandwidth is to connect the high-impedance device next to a low input impedance amplifier, though, the signal is decreased by the ratio of the impedances of the device and the amplifier, easily a factor of a thousand. Therefore, long averaging times are required to detect the small signal. Moreover, 1/f noise still affects the measurements. The issues of small bandwidth, impedance mismatch and 1/f noise can be simultaneously addressed using resonant LC circuits. The success of this impedance transformer lies in replacing the slow operation of applying voltages and measuring currents by applying fast radio frequency signals and measuring the reflectance. LC circuits remain appealing because of a rather simple assembly. Nonetheless, the challenge to reproducibly achieve the resonance frequencies in gigahertz (GHz) range while matching to high impedance still remains due to the large parallel stray capacitance of the measurement setup. Resonance frequency in GHz range is desirable for two reasons. Firstly, measurements are faster and 1/f noise smaller. Yet more importantly, one can profit from the wide range of measurement techniques developed in the context of circuit quantum electrodynamics, such as FPGA based hardware and quantum limited Josephson parametric amplifiers.
In this thesis, a matching circuit namely stub tuner based on coplanar transmission lines is designed, fabricated and integrated with mesoscopic devices. Owing to the simple design, we could predict the frequency response of a stub tuner in terms of the standard circuit model (Chapter 3). We initiated certain necessary fabrication adaptations to achieve integration of niobium circuits with devices. In particular, a reliable stamping of carbon nanotubes from the growth substrate to the target substrate was accomplished, improving both the device quality and yield (Chapter 4). RF reflectometry is employed to perform admittance measurements on CNT quantum dots. We could reliably deduce all circuit and device properties using the resonance response. The measurement bandwidth is shown to be in MHz range which is three orders of magnitude larger than that for DC measurements. In particular, using the phase response of the circuit, double-dot qubit energy and dephasing rate are studied (Chapter 5). We could even get rid of conventional contacts that could degrade the device properties, and still extract quantum capacitance and dissipation in graphene p-n junctions. The residual doping is shown to affect not only the mean free path but also the Fermi velocity. We further see that at small doping, electron-electron interactions could modify the Fermi velocity and that the dispersion relation could deviate from

linearity (Chapter 6).
In the second half of the scientific results, real strength of stub tuner is tested in transmission measurements. The large bandwidth and signal to noise ratio is utilized to measure extremely clean noise power densities at high speed and draw comparisons with the corresponding average current. Clear changes in the shot noise spectrum are seen when a transport channel is added or removed from the bias window of the quantum dot. We especially observe noise enhancement outside the Coulomb diamonds due to blocking states (Chapter 7). Finally, we investigate noise properties of quantum dots when leads are superconducting. Distinct charge transfers due to multiple Andreev reflections are visible in the shot noise. The main finding, however, was the thermal noise at zero bias. We observed its periodic suppression and emergence across the quantum dot resonance. In another device, shot noise due to the Kondo effect is found to be enhanced in the superconducting state when the Kondo temperature exceeds the value of the superconducting gap (Chapter 8). Simple design and reliable calibration of the GHz matching circuit in both reflectance and transmission pave a way for fast and non-invasive measurements of mesoscopic conductors.