"Coherent and ballistic transport in InGaAs and Bi mesoscopic devices"

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ABSTRACT

In 'clean' confined conductors (the so-called mesoscopic systems), the electronic phase and momentum can be preserved over very long distances compared to the system dimensions. This gives rise to peculiar transport properties, bearing signatures of electron interferences, ballistic electron trajectories, electron-electron interactions, regular-chaotic electron dynamics and (in some cases) spin-orbit coupling. Examples of such effects are the Universal Conductance Fluctuations (UCFs) and the Weak Localization observed in the low-temperature magnetoconductance of many confined electronic systems. Of central importance, the electronic phase coherence time and the spin-orbit coupling time determine the amplitude of these quantum effects. In the first part of this thesis, we use UCFs to extract these characteristic timescales in open ballistic quantum dots (QDs) fabricated from InGaAs heterostructures. We observe an intrinsic saturation of the coherence time at low temperature in the InGaAs QDs. The origin of this phenomenon has been intensely debated during the last decade. Based on our observations and previous experimental data in QDs, we propose an explanation: the dwell time becomes the limiting factor for electron interferences in QDs at low temperature. Then, we report on magnetoconductance measurements in a bismuth ballistic nano-cavity. The cavity is found to be zero-dimensional for phase coherent processes at low temperature. We evidence an anomalous reduction of the phase coherence time in the cavity with respect to data obtained in thin Bi films, while the spin-...

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Hackens, Benoît. Coherent and ballistic transport in InGaAs and Bi mesoscopic devices. Prom. : Bayot, Vincent http://hdl.handle.net/2078.1/5174

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Chapter 6

Conclusions and perspectives

*Time brings truth to light*

Aristotle

The most significant contribution of this thesis concerns the temperature dependence of the electron phase coherence time $\tau_\phi$ in confined systems. We have observed a low-temperature saturation of $\tau_\phi$ in each of our InGaAs open quantum dots, over a wide range of temperature. We could rule out any 'extrinsic' origin, related to the substrate material or the measurement system. We found that it is the dwell time that limits the measured phase coherence time, i.e. $\tau_\phi^{sat} = \tau_d$ (where $\tau_\phi^{sat}$ is the saturated coherence time and $\tau_d$ is the dwell time). Electron interferences can only occur during the average time spent by electrons inside the quantum dot. The observed saturation is therefore directly related to the measurement method.

As a consequence, our work questions the experimental evidences for the existence of a low temperature intrinsic saturation of $\tau_\phi$ in confined systems. The conclusion of our work implies that the saturation of the 'true', or intrinsic, coherence time has not been observed yet in any experiment on quantum dots, since we are able to explain all experimental reports of saturation of the coherence time in these systems, and the only available experiment on samples with a virtually infinite dwell time (i.e. closed dots) did not reveal any saturation of the intrinsic $\tau_\phi$.

Furthermore, it might be necessary to reconsider previous experimental reports of saturation of the coherence time in many other confined systems, such as quantum wires. Indeed, a dwell time can also be defined in such systems, but has never been taken into account in the extraction of $\tau_\phi$, as
far as we know. Therefore, our conclusions for quantum dots are likely to lead to a similar study in quantum wires (in particular short wires, with a small dwell time), for which many report of low temperature saturation of $\tau_\phi$ have been published.

Our work also clears up the way for theoretical works. Previous experimental reports on quantum dots put constraints on a possible theory of the real saturation of $\tau_\phi$. As we could attribute previous observations in quantum dots to an intrinsic, but sample-specific origin, part of these constraints is lifted. Even though we do not bring the proof for the existence or nonexistence of an intrinsic saturation of $\tau_\phi$, our findings help to discriminate between experiments reporting a 'real' or 'artificial' - sample specific - saturation.

In addition, we provide new $\tau_\phi$ vs $T$ data for open quantum dots, in unexplored ranges of mean energy level spacings, number of modes, and materials parameters. In the temperature-dependent regime, we found that, in one sample, $\tau_\phi$ vs $T$ follows quantitatively the theoretical prediction for decoherence by electron-electron interactions in two-dimensional disordered systems. In the other samples, discrepancies were observed, that we attribute to the population of the second subband in the quantum well. However, theoretical work is needed to confirm the latter hypothesis.

In chapter 4, we study phase coherence and spin-orbit coupling in Bi films and in a single-crystal Bi cavity. We show that the cavity is quasi-ballistic and zero-dimensional for phase coherent processes. Our work therefore provides the first insight into the transport properties of this type of Bi systems. $\tau_\phi$ in films is significantly larger than in the cavity, while the spin-orbit scattering time $\tau_{so}$ is similar in both systems. The reason for this difference remains to be investigated. A large unexplained discrepancy is also found between our $\tau_\phi$ data and the prediction of the 2D Nyquist theory, although the temperature dependence ($\tau_\phi \propto T^{-1}$) is consistent with this model in the films and the dot.

Beside the questions over the origin of these discrepancies, our work on Bi samples raises a large number of interesting perspectives. In particular, we believe that the technique developed to obtain films with large crystallites can be further improved. Another substrate material could be used instead of SiO$_2$, with a lattice parameter closer to that of bismuth. This could be combined with a slower deposition process at higher temperature, and a thermal treatment to align the crystallites along the same direction in the plane of the film (which would suppress the uncertainty over the crystal orientation in the cavity). This would allow to produce monocrystalline devices on thinner films, e.g. in the vicinity of the semimetal-semiconductor
transition. The influence of the lateral size of the cavity on the weak anti-localization effect is another interesting problem to study. As explained in chapter 1, weak anti-localization can be suppressed in GaAs quantum dots with a lateral size smaller than $L_{st}$. One can naturally wonder if a similar suppression would occur in the same conditions in a Bi sample. In view of the $L_{st}$ values that we found, ballistic bismuth cavities with dimensions smaller than $L_{st}$ are possible to fabricate using the process that we developed. Such a small cavity, with a small electron dwell time would also allow to test our explanation of the saturation of $\tau_\phi$.

In the last part of the thesis, we discuss the nonlinear transverse voltage-longitudinal current characteristics of ballistic cross junctions. We show that the conductances measured between the channels of the junctions are crucial to the understanding of the nonlinear behaviour. Reversals of the slope of the transverse voltage are observed in some cases, coinciding with a decrease of the longitudinal conductance. Furthermore, the sign and the amplitude of the nonlinear transverse voltage can be tuned by changing the conductances (or the width) of the branches in the junction. Theories based on an energy-dependent Landauer-Büttiker formalism or on energy-dependent collimation effects can not fully explain these observations. We suggest that Monte Carlo (MC) methods are better suited to study the behavior of our structures. MC simulations of our cross structures have recently been undertaken in the group of Profs. Javier Mateos and Tomas Gonzalez in Salamanca University. We hope that the result of these simulations will help to explain our data.