UNIVERSITÉ CATHOLIQUE DE LOUVAIN
Faculté des Sciences Appliquées
CERMIN
Unités PCPM & DICE

Coherent and ballistic transport in InGaAs and Bi mesoscopic devices

Dissertation présentée en vue de l'obtention du grade de
Docteur en Sciences Appliquées
par
Benoit HACKENS

Promoteur:
Prof. Vincent BAYOT

Janvier 2005

Université Catholique de Louvain
Faculté des Sciences Appliquées
CERMIN
Unités PCPM & DICE

Coherent and ballistic transport in InGaAs and Bi mesoscopic devices

Dissertation présentée en vue de l'obtention du grade de
Docteur en Sciences Appliquées
par
Benoit HACKENS

Membres du jury:

Prof. Vincent Bayot, promoteur
Prof. Patrick Bertrand, président
Dr. Sylvain Bollaert
Prof. Isabelle Huynen
Prof. Jean-Paul Issi
Prof. Rodolfo Jalabert
Prof. Luc Piraux

Janvier 2005

In memory of my father

Acknowledgements

Je voudrais remercier ici, par ordre (à peu près) chronologique, tous ceux qui ont participé à créer l'environnement et les conditions idéales dont j'ai pu bénéficier pour mener à bien ce projet de thèse. Le premier d'entre eux est bien sûr mon promoteur de thèse, Vincent Bayot, qui m'a fait entrer de plein pied dans le monde étrange des gaz d'électrons bidimensionnels et de la physique mésoscopique. Je le remercie tout particulièrement pour les idées nouvelles qu'il a pu insufler aux moments-clés de ce travail, tout en me laissant la liberté nécessaire pour acquérir une autonomie en tant que chercheur, ainsi que pour son 'pragmatisme' d'expérimentateur, qui a permis de simplifier et de résoudre beaucoup de problèmes.

Lorsque j'ai entamé mon travail de thèse proprement dit, le noyau dur de l'équipe était composé de Cédric et de Sorin (en plus de Vincent). Je suis reconnaissant envers Sorin, qui m'a fait mieux comprendre ce qu'est la rigueur scientifique, dans le bon sens du terme, et la 'bonne' façon de rédiger un article. Avec Cédric, j'ai fait mes premiers pas dans l'art subtil de la nanolithographie en chambres propres et des mesures à basses températures. Ses compétences en informatique ont également rendu les périodes de mesure bien plus faciles et m'ont permis d'économiser un temps précieux. Sébastien est arrivé peu après moi dans l'équipe; il a été d'une aide inestimable par son 'endurance' en périodes de mesures (surtout pour les nombreux transferts d'hélium. . .), et par son ingéniosité technique. Deux mémorants, François et Loïk, ont également contribué à ce travail lors de leur passage dans notre groupe: grâce à eux, j'ai pu réaborder avec un regard neuf certaines questions.

Le chapitre sur la cavité en bismuth n'aurait pas vu le jour sans le travail préalable qu'avait réalisé Jean-Paul Minet, lui-même habilement conseillé par Jean-Paul Issi, sur les films de bismuth, et sur les dépôts à haute température dans l'évaporateur. Tous deux méritent amplement mes remerciements. Jos Heremans m'a également été d'un grand secours pour l'analyse des données, ainsi que Piet Brouwer, de Cornell, et Caio Lewenkopf, de Rio de Janeiro, qui ont toujours répondu de manière très claire à mes interrogations par email sur les méandres de la 'Random Matrix Theory'.

Durant mes trois dernières années de thèse, j'ai eu la chance de collaborer au projet européen NANOTERA, concernant les propriétés des dispositifs balistiques à haute fréquence (ce sujet n'est pas abordé ici, bien qu'il ait occupé une bonne part de mon temps). Grâce au travail de Lukasz, Rashmi, Sarah, Hervé et à la supervision attentive et efficace d'Isabelle Huynen à l'UCL, ce projet commence à porter ses fruits de manière concrète, et un certain nombre de nouveaux résultats seront bientôt publiés. Les discussions avec l'équipe de l'IEMN, composée de Jean-Sébastien, Sylvain, Yannick et Alain Cappy ainsi que leurs conseils m'ont également été très utiles au niveau de la fabrication des échantillons. Je les remercie bien sûr également pour avoir mis à notre disposition les substrats InGaAs, sur lesquels ont été fabriqués la plupart des dispositifs présentés ici. Les simulations de l'équipe de Salamanca, composée de Beatriz, Tomas et Javier, ont permis de reconsidrer certains résultats, et vont probablement très prochainement aider à solutionner les questions non-résolues présentées dans le dernier chapitre. Accessoirement, je remercie Tomas et Javier pour la mémorable découverte de la très belle ville de Salamanca. Une autre collaboration fructueuse, initiée récemment avec Colleen Marlow et Richard Taylor, de l'université d'Oregon, vise à étudier la dimension fractale des fluctuations de conductance dans mes différents échantillons InGaAs, et débouchera bientôt sur une publication.

Comme dans toute thèse expérimentale, le savoir-faire et la disponibilté des techniciens a joué un grand rôle. Je suis plein de gratitude pour André, dont l'expérience et l'ouverture (surtout en cas de problèmes) ont permis de résoudre un tas de petites contrariétés, ainsi que pour David, Christian, Miloud, Pascal, Boghdan, et les autres techniciens du DICE, et pour Luc et Guy au PCPM. Ce travail doit aussi beaucoup à tous les utilisateurs du SEM au DICE, qui ont permis d'améliorer les techniques de lithographie électronique, et en particulier à Sébastien (une fois de plus) et Alex.

Un ingrédient non-négligeable, qui a participé de manière 'inquantifiable' à la réussite de cette thèse, est l'ambiance extraordinaire, détendue et cosmopolite, de collaboration et d'entraide, qui règne entre tous les membres du PCPM. Il est difficile d'attribuer cette alchimie, qui se perpétue depuis de longues années, à l'une ou l'autre personne en particulier. J'adresse donc un merci collectif à tous les professeurs, secrétaires, permanents, chercheurs, informaticiens, ... qui sont passés par le PCPM durant toutes ces années.

Dans l'ordre chronologique, ce texte est la dernière étape de mon cheminement en tant que thésard. Je remercie tous les membres de mon jury, Vincent Bayot, Luc Piraux, Isabelle Huynen, Jean-Paul Issi, Patrick Bertrand, et en particulier les membres extérieurs Sylvain Bollaert et Rodolfo Jalabert, pour le temps qu'ils ont consacré à le lire et à le critiquer.

Finalement, je dois aussi beaucoup à ceux qui ont toujours été là: Delphine, dont la patience a été mise à rude épreuve lors de mes visites nocturnes au labo et les préparations de conférences, ma mère, dont la contribution énorme est bien sûr incalculable, et mon père, qui, bien que nous ayant quittés trop tôt - avant le début de cette thèse - m'a probablement inconsciemment mis sur cette voie.

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, *i.e.* tiny electron islands connected to electron reservoirs through two narrow apertures). Our samples are fabricated from InGaAs heterostructures hosting a two-dimensional electron gas. We observe an intrinsic saturation of the coherence time at low temperature. 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 to the phenomenon: the dwell time becomes the limiting factor for electron interference effects 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 a strong reduction of the phase coherence time in the cavity with respect to data obtained in thin Bi films, while the spin-orbit coupling time is similar in both systems.

Finally, we examine the current-voltage characteristics of asymmetric InGaAs nano-junctions in the nonlinear regime. We observe a new tunable rectification effect, whose amplitude and sign are governed by the conductances of the junctions' channels. We show that the effect is ballistic and exhibits new features with respect to predictions of available models.

Preface

Donc le temps n'est pas un mouvement,
mais ce par quoi le mouvement a un nombre

Aristotle (4th century BC)

To begin, I would like to pay a tribute to the electrons. It is truly fascinating to note how such small and apparently simple particles could generate such a wealth of new physics during the last century, and will probably continue to do so for the decades to come. This is even more surprising knowing that an equation, established by Schrödinger in the 20's, fully describes the evolution of electron wavefunctions in time and space.

As an example, the effort of many solid state physicists have recently focused on very simple systems : two-dimensional electron layers. These layers can be made (almost) disorder-free, so that many complications seem to be removed. Even twenty year of relentless efforts were not sufficient to solve all the issues related to electron dynamics in such an ideal system, particularly when a large magnetic field is applied, *i.e.* in the regime of the Quantum Hall Effect, integer and fractional.

This thesis is dedicated to the study of systems with an even smaller number of electrons, fabricated from similar thin electron layers. Based on the above considerations, we were confident, at the beginning of our work, that the subject of electron dynamics in these so-called low-dimensional systems would be far from exhausted when time would come to write this text.

Research in this domain has been partly driven by the interesting technological perspectives offered by these systems. On one side, the general trend of the electronics industry towards the fabrication of chips with smaller and smaller elementary components naturally leads to wonder what is the smallest size below which these components no longer work in a classical, or usual, way. On the other side, some of the effects discovered in low-dimensional systems, instead of being viewed as 'parasitic', could also raise possibilities in terms of new devices with different working principles. As an example, large efforts have been directed towards the field of spintronics, whose goal is to create logic functions by taking advantage of the spin degree of freedom of the electron. Obviously, this requires to understand and control the mechanisms which perturb the electron spin. Other proposals rely on the wave nature of electrons. Similarly, the basic requirement for the practical realization of such proposals is to maintain electron phase coherence for a sufficiently long time, so that phase decoherence mechanisms need to be investigated.

The work presented here is still far upstream from the realization of logical functions based on the electron phase coherence. Nevertheless, we have tried to address a limited number of unsolved fundamental questions regarding transport properties of low-dimensional systems where electron dynamics is ballistic and/or phase coherent. As explained in chapter 1, which sets the scene, several effects related to the wave nature of electrons can be used to estimate quantitatively the electron phase coherence in ballistic systems. After a brief phenomenological introduction to these effects, we present the theories relating them to the time scale τ_ϕ over which electron phase coherence is preserved in our samples. Experimental reports on the temperature dependence of τ_ϕ in different low-dimensional systems raised contradictions with existing theories describing the loss of phase coherence. In particular, τ_ϕ saturates at low temperature in many systems, a phenomenon for which there is no widely accepted explanation. At the end of chapter 1, we give a brief review of the proposed origins of this saturation. In general, in this chapter, we often refer to the relevant reference works for each effect, and we adopt a 'pedagogical' approach, aimed at understanding the content of chapters 3-4. Note that, as the subject of chapter 5 is somewhat different, a specific introduction to this part is given at the beginning of the chapter.

Chapter 2 is the technical part of the thesis. We first present some relevant properties of the materials constituting our samples, *i.e.* InGaAs heterostructures and bismuth. Then, we explain the details of the process that we developed to produce confined systems (quantum dots) from these substrates. Technology in this field has quickly evolved, but hard work in cleanrooms is still necessary to fabricate devices with features of less than 100 nm in size. The time scale for the fabrication of a single working device is therefore far from negligible, compared to the average duration of a PhD thesis. At the end of chapter 2, the setup for low-temperature magnetoconductance measurements is briefly presented. Again, the portion of the thesis dedicated to the measurement technique is not proportional to the time and efforts needed to adjust and improve the measurement setup and parameters.

Then, we report on our experimental results, and we get to the heart of the matter. The data presentation starts in chapter 3, with low-temperature measurements of τ_ϕ in InGaAs open quantum dots. The core of this chapter is the search for the origin of the saturation of τ_ϕ at low temperature. We find a solution to this problem by gathering our data with previous results obtained on quantum dots fabricated from other substrates. Some other issues are also addressed. The 'high' temperature behaviour of τ_ϕ (*i.e.* in the temperature range where τ_ϕ varies) is different from one sample to another. We investigate on the fundamental reasons of these differences, and compare our results to predictions of theoretical models and experimental data on GaAs quantum dots. Finally, we find signatures of ballistic transport in one of our samples, in the form of slow fluctuations of the magnetoconductance, visible up to relatively high temperatures. We provide an analysis of these fluctuations based on theories used for ballistic focusing effects.

Chapter 4 concerns the transport properties of confined samples fabricated from bismuth. The analysis is more complex here, because both the phase and the spin of the electrons come into play, and many assumptions have to be made due to the peculiar properties of bismuth. Nothing had been done before on zero-dimensional bismuth systems. We hope that our work fills part of this gap, and points out some interesting new problems. In particular, we evidence an anomalous reduction of τ_ϕ in a bismuth cavity with respect to two-dimensional films. The results of this chapter have also a direct connection with chapter 3, as they help to elucidate the question of the saturation of τ_ϕ.

Finally, in chapter 5, we discuss the nonlinear current-voltage characteristics of ballistic InGaAs cross-junctions. The precise mechanisms underlying these nonlinear effects are still debated, as explained in the introductory section of this chapter. The geometry of our devices was inspired by a recent theoretical proposal. The results of this chapter are weighted against the predictions of this theoretical work, and to a very recent experimental results based on the same proposal. We show that our results complement existing data, and that our samples show a significantly new tunable behaviour, unexpected on the basis of previous works. Note that the effects that we report, and in particular the tunability of the nonlinear current-voltage characteristics, may lead to useful applications at high frequency, owing to the reduced transit times associated with ballistic transport.

Contents

Symbols and abbreviations

2DEG	two-dimensional electron gas
A	area
$\mathbf{A}$	magnetic vector potential
a	lattice constant
A_p	amplitude of a focusing peak
AAS	Al'tshuler-Aronov-Spivak
AB	Aharonov-Bohm
ac	alternating current
AFM	atomic force microscope
B	magnetic field (induction)
B_c	correlation magnetic field
$C(\Delta B)$	magnetic field correlation function
D	diffusion constant
d	etching depth
D_{e}	dose
E	energy
E_F	Fermi energy
E_g	band gap
e	absolute value of electron's charge
e-ph	electron-phonon
ee	electron-electron
EBL	electron beam lithography
f	frequency
f_c	cut-off frequency
$f(E)$	Fermi function
G	conductance
$G_{\square}$	conductance per square
h	Planck constant
$\hbar$	$h/2\pi$
H_0	characteristic magnetic field corresponding to τ_0

H_{so}	characteristic magnetic field corresponding to τ_{so}
H_{ϕ}	characteristic magnetic field corresponding to τ_{ϕ}
I	electric current
$i_i(E)$	electric current per unit energy
k_B or k	Boltzmann constant
$\mathbf{k}$	wavevector
$\mathbf{k}_F$	Fermi wavevector
L_0	scattering length
l_e	elastic scattering length
L_e	trajectory length
l_i	inelastic scattering length
L_s	spacer layer thickness
L_f	'focusing' mean free path
l_{μ}	mean free path
L_{ϕ}	phase coherence length
L_{so}	spin-orbit coupling length
m	effective mass tensor
m^*	electron's effective mass
m_0	electron's mass in vacuum
m_i	components of the effective mass tensor
m_{cb}	bulk Bi trigonal cyclotron effective mass
m_{cF}	bulk Bi trigonal cyclotron effective mass at the Fermi level
MBE	molecular beam epitaxy
MIBK	Methylisobutyl-ketone
M	number of modes in each of the two QPCs of a QD
N	total number of modes in an open quantum dot
n_a	density of states
N_i	number of modes in lead i
n_s	areal electron density
n	volume electron density
N_{δ}	density of impurities in the delta-doping layer
N_{ϕ}	number of modes in a 'fictitious' voltage probe
PMMA	Polymethyl-methacrylate
QD	quantum dot
QPC	quantum point contact
R	electrical resistance
$\mathfrak{R}$	total reflection coefficient
r_c	cyclotron radius
R_{Hall}	Hall coefficient
r_{ij}	reflection matrix

$\mathcal{R}_i$	reflection coefficient for lead i
R_{xx}	longitudinal resistance
R_{xy}	transverse resistance
RMT	Random Matrix Theory
RTA	rapid thermal annealing
S	scattering matrix
S_G	power spectrum
SC	semiclassical
SEM	scanning electron microscope
SdH	Shubnikov-de Haas
SO	Spin-Orbit
T	temperature
$\mathcal{T}$	total transmission coefficient
T_{el}	temperature of the electronic system
t_{ij}	transmission matrix
$\mathcal{T}_{ij}$	transmission coefficient from lead i to lead j
T_{onset}	temperature corresponding to the onset of the saturation of τ_ϕ
T_r	rotation operator
t	time
TLS	two-level systems
UCFs	Universal Conductance Fluctuations
V	electric potential difference
v	particle velocity
V_{ij}	electric poetential difference between i and j
v_F	Fermi velocity
V_H	Hall voltage
$var(G)$	variance of the conductance fluctuations
vs	versus
W	width
WAL	Weak Anti-Localization
WL	Weak Localization
α_{cl}	inverse area
γ	escape rate from a cavity
Γ	energy-level broadening
Γ_i	transmission probability in lead i
Γ_ϕ or γ_ϕ	decoherence rate ($= 1/\tau_\phi$)
Δ	mean energy level spacing
Δ_0	overlap between the valence and conduction bands
ΔE_c	conduction band offset
δG	weak localization amplitude

λ	Lyapunov exponent
λ_F or l_F	Fermi wavelength
μ	carrier mobility
μ_i	chemical potential in reservoir i
τ	escape time or scattering time
τ_0	elastic scattering time
τ_d	dwell time
τ_E	Ehrenfest time
τ_e	elastic scattering time
τ_{ee}	inelastic electron-electron scattering time
τ_{erg}	ergodic time
τ_i	inelastic scattering time
τ_N	Nyquist scattering time
τ_s	spin-spin scattering time
τ_{so}	spin-orbit scattering time
τ_ϕ	coherence time
$\tau_{\phi,e-ph}$	electron-phonon dephasing time
τ_ϕ^{sat}	'saturated' coherence time
Φ	magnetic flux
ϕ_0	magnetic flux quantum
ϕ_i	wavefunction
Ψ	digamma function

List of Figures

List of Tables