



Can-Ming Hu (Autor)  
**Interplay of spins, charges and photons in low-dimensional systems**

Can-Ming Hu

---

**Interplay of spins, charges and photons  
in low-dimensional systems**

---

Habilitation



 Cuvillier Verlag Göttingen

<https://cuvillier.de/de/shop/publications/2670>

Copyright:  
Cuvillier Verlag, Inhaberin Annette Jentsch-Cuvillier, Nonnenstieg 8, 37075 Göttingen,  
Germany  
Telefon: +49 (0)551 54724-0, E-Mail: [info@cuvillier.de](mailto:info@cuvillier.de), Website: <https://cuvillier.de>

To the memory of my father,  
and with gratitude to my academic friends



# General Introduction

This *Habilitationsschrift* is based on 20 selected papers published/submitted after I joined the University of Hamburg on September 2, 1999, which include 2 invited ones, 16 others published in Physical Review Letters, Europhysics Letters, Physical Review B, Applied Physics Letters, and 2 preprints. Three papers on spintronics are based on experiments performed before I joined the Universität Hamburg. Writing the work provides me a chance to look back over my past five and a half year's academic life in Hamburg, where I have enjoyed and appreciated the hospitality of my colleagues in the Institut für Angewandte Physik of Universität Hamburg.

The Habilitationsschrift begins with this general introduction followed by a list of papers on three seemingly different topics: spintronics, photoconductivity, and the bilayer two-dimensional electron system. The work covers three different materials, namely semiconductors, ferromagnetic metals, and their hybrid samples. They are experimentally investigated by three different techniques: magneto- and spin-dependent transport, far-infrared transmission spectroscopy, as well as microwave and infrared photoconductivity spectroscopy. Cross thinking of different systems *vs* various techniques has been a convenient source of developing new ideas for performing experiments. At the heart of the topics which I have been absorbed over the years is the interplay between spins, charges, and photons in low-dimensional electron systems.

The Habilitationsschrift is organized in five chapters:

- spin-orbit coupling,
- spin-charge conversion in transport,
- spin-charge mixing in spectroscopy,
- electron-electron interaction,
- electron-phonon interaction.

We start with a chapter on spin-orbit coupling, followed by a chapter studying spin injection in transport experiments. The three other chapters investigate the interplay and coupling between spin-, charge-, and lattice-

dynamics. An introduction has been written for each chapter, to give a brief historical context of the subject, to explain how our work fits into the general evolution of the research field, and to point out connections between different chapters. Writing the Habilitationsschrift provides me a distant but consistent view to the papers selected. Some critical thoughts are given in the brief outlook at the end of each chapter. The Habilitationsschrift ends with a chapter of general outlook describing briefly a blueprint and a vision of the future. With my collaborators, we are on the way in those directions.

In the legend of the ancient Chinese intellectual society, friendships are said to be established by exchanging papers (以文会友). My past five years of academic life in Hamburg started with a hard time by losing my father, — my first mentor, who ignited my interests in science with books hardly available in a time when life itself was hard to make. It comes up with the endless joy that many of my mentors, colleagues and students became my friends during these years. A French philosopher once said "*all the past are future in preparation*", I realized that the main experimental techniques I set up in Hamburg together with my young collaborators, namely, microwave and infrared photoconductivity on low-dimensional electron systems, which inherently combines the transport with spectroscopy, is mainly based on the knowledge I learnt from my mentors, namely, photo-thermal-ionization spectroscopy from Professor Shuechu Shen, far-infrared transmission spectroscopy from Professor Edwin Batke and Professor Detlef Heitmann, spin- and magneto-transport from Professor Junsaku Nitta, Professor Hideaki Takayanagi and Professor Gottfried Landwehr. Equally fortunate for me is that I have the privilege to collaborate with many talented colleagues and young students in China, Japan, and especially in Germany.

In this sense, I dedicate my Habilitationsschrift to my father and to my academic friends. I was thinking whether I should also dedicate it to my two lovely sons David and Peter, both born in Hamburg. However, it becomes clear that they are now more interested in their own toys than in mein, and it is a big question whether any paper printed here would remain worth reading after they grow up. It is a great challenge to write a paper which I would feel confident that David and Peter would proudly read decades later, — perhaps I should take this as the best motivation for my research in future.

# Contents

<b>List of Selected Publications</b>	<b>1</b>
<b>1 Spin-orbit coupling</b>	<b>5</b>
1.1 Introduction: the <i>spin</i> , from atoms to crystals . . . . .	5
1.2 Beating pattern in Shubnikov–de Haas oscillations . . . . .	9
1.2.1 Energy dispersion with spin-orbit coupling . . . . .	9
1.2.2 Measuring the spin-orbit coupling (1): via charge density	12
— P6 . . . . .	14
— P5 . . . . .	19
1.3 Weak anti-localization . . . . .	24
1.3.1 Time constants for quantum transport . . . . .	24
1.3.2 Measuring the spin-orbit coupling (2): via interference	25
— P19 . . . . .	27
1.4 Spin-flip excitation (combined resonance) . . . . .	34
1.4.1 Selection rules for spin and charge excitations . . . . .	34
1.4.2 Photoconductivity vs transmission I: higher sensitivity	35
1.4.3 Measuring the spin-orbit coupling (3): via spectroscopy	36
— P9 . . . . .	37
1.5 Outlook . . . . .	42
<b>2 Spin-charge conversion in transport</b>	<b>43</b>
2.1 Introduction: Johnson-Silsbee experiment . . . . .	43
2.2 Spin injection via spin-charge conversion . . . . .	45
2.2.1 The diffusive picture . . . . .	45
2.2.2 The ballistic picture . . . . .	48
— P2 . . . . .	49
— P3 . . . . .	54
2.2.3 Experiments on hybrid devices: . . . . .	68
— P4 . . . . .	69
— P1 . . . . .	74
2.3 The bolometric spin effect . . . . .	80

2.3.1	Photoconductivity vs transmission II: spin effect . . . .	80
—	P10 . . . . .	81
2.4	Outlook . . . . .	89
<b>3</b>	<b>Spin-charge mixing in spectroscopy</b>	<b>90</b>
3.1	Introduction: has Maxwell anything to do with spintronics ? .	90
3.2	Magnetostatics and magnetodynamics . . . . .	92
3.2.1	FMR and FMAR: the spin dynamics . . . . .	92
3.2.2	Spin and charge dissipation in ferromagnets . . . . .	93
3.2.3	Photoconductivity vs transmission III: bridging static and dynamic responses . . . . .	94
—	P20 . . . . .	96
3.3	Outlook . . . . .	102
<b>4</b>	<b>Electron-electron interaction</b>	<b>103</b>
4.1	Introduction: are there single-particle resonances? . . . . .	103
4.2	Magnetoplasmon in the QHE regime . . . . .	104
4.2.1	CR and magnetoplasmon: the charge dynamics . . . .	104
4.2.2	Photoconductivity <i>vs</i> transmission IV: spatial effect . .	106
—	P8 . . . . .	108
4.3	Plasmon in the tunnelling-coupled bilayer system . . . . .	113
4.3.1	The pseudo spin picture . . . . .	113
—	P18 . . . . .	114
—	P17 . . . . .	118
4.3.2	Intra- and intersubband plasmons . . . . .	123
—	P16 . . . . .	124
—	P14 . . . . .	129
—	P15 . . . . .	134
4.4	Outlook . . . . .	139
<b>5</b>	<b>Electron-phonon interaction</b>	<b>140</b>
5.1	Introduction: the same question asked in every 20 years . . . .	140
5.2	Charge excitations within the Reststrahlen band . . . . .	141
5.2.1	TO and LO phonons: the lattice dynamics . . . . .	141
5.2.2	Photoconductivity <i>vs</i> transmission V: looking into the Reststrahlen band . . . . .	143
5.2.3	Electron-phonon mixing around TO . . . . .	143
—	P11 . . . . .	144
5.2.4	Electron-phonon interaction near LO . . . . .	151
—	P13 . . . . .	152
—	P12 . . . . .	158

5.3 Outlook . . . . .	163
<b>6 General outlook: where are we going?</b>	<b>165</b>
6.1 Go down to the nano world . . . . .	165
6.2 Mix up in the hybrid world . . . . .	165
6.3 Power up into the coherent world . . . . .	166
<b>References</b>	<b>168</b>
<b>Acknowledgements</b>	<b>176</b>



