Millikelvin Confocal Microscopy of Electrostatic Exciton Traps and Filter-Function Description of Noisy Quantum Dynamics

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Colophon
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The source code of this thesis is available at: `https://github.com/thangleiter/phd_thesis`.

Tobias Hangleiter
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Summary

Quantum technology promises to be a paradigm shift in the precision, speed, and breadth of application of technology. Recent advances in the fields of quantum computing, quantum networks, and quantum sensing have been rapid, but large-scale utilization is still out of reach. This is largely due to the fragility of the individual quantum systems that this technology seeks to control and manipulate. While small demonstrators have by now shown these novel machines to work in principle, the task in the coming years will be to make them reproducible at scale. Leveraging the advanced semiconductor fabrication technology of today's classical computers, spin qubits in semiconductors such as Si/SiGe or GaAs/AlGaAs are hoped to meet this challenge. In this thesis, I present contributions in four different areas towards this overarching goal. I present an open-source software tool for Fourier-transform noise spectroscopy, improvements and characterization of a Millikelvin confocal microscope, optical measurements of electrostatic exciton traps, and a general filter-function formalism for the description of noisy quantum dynamics. I review the theory of noise spectroscopy based on Welch's method of overlapping periodograms and lay out the design of the hardware-agnostic, open-source `python_spectrometer` software package that facilitates interactive noise spectroscopy in everyday use. In a didactic fashion, I explore the features and capabilities of the tool and guide the reader through its operation. I then characterize a confocal microscope incorporated in a cryogen-free dilution refrigerator, applying the aforementioned noise spectroscopy tool to evaluate the displacement noise power spectral density of the system. I develop an optical technique based on a knife-edge reflectance contrast to measure the displacement noise reaching a shot-noise floor of $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$. Using this technique, I determine a displacement noise RMS of $100\,\mathrm{nm}$. I measure the electron temperature of a GaAs/AlGaAs quantum dot in the microscope, finding $76\,\mathrm{mK}$, and demonstrate at hand of a second-order correlation measurement of a self-assembled quantum dot the setup's optical capabilities. In the experimental part of this thesis, I first provide an introduction to photoluminescence and the quantum-confined Stark effect in semiconductor quantum wells, appealing to simple analytical theory to develop an intuition for the relevant effects. I then describe the `mjolnir` measurement framework developed to conduct optical measurements of electrostatic exciton traps in semiconductor membranes, and present extensive measurements in search of signatures of single-photon emitters. Finally, I develop a comprehensive theoretical formalism for describing and analyzing the noisy quantum dynamics of quantum systems based on filter functions. I combine the Magnus and cumulant expansions to derive a quantum-operations formulation of the dynamics under arbitrary classical noise that can be expressed in terms of filter functions capturing the susceptibility of a quantum system in response to noise at a given frequency. I present the `filter_functions` software package that implements the formalism and demonstrate its efficacy using several examples.

Zusammenfassung

Quantentechnologie verspricht einen Paradigmenwechsel in Bezug auf Präzision, Geschwindigkeit und Anwendungsvielfalt von Technologie. Die jüngsten Fortschritte in Quantencomputing, Quantennetzwerken und Quantensensorik waren rasant, doch eine großflächige Nutzung ist noch nicht in Sicht. Dies liegt hauptsächlich an der Fragilität der einzelnen Quantensysteme, die diese Technologie zu steuern versucht. Während kleine Demonstratoren gezeigt haben, dass diese Maschinen im Prinzip funktionieren, besteht die Aufgabe darin, sie in großem Maßstab reproduzierbar zu machen. Unter Nutzung fortgeschrittener Halbleiterfertigungstechnologie heutiger klassischer Computer soll diese Herausforderung mit Spin-Qubits in Halbleitern wie Si/SiGe oder GaAs/AlGaAs bewältigt werden. In dieser Arbeit stelle ich Beiträge in vier Bereichen in Richtung dieses Ziels vor. Ich präsentiere ein Open-Source-Softwaretool für die Fourier-Transform-Rauschspektroskopie, Verbesserungen eines Millikelvin-Konfokalmikroskops, optische Messungen elektrostatischer Exzitonenfallen und einen allgemeinen Filterfunktionsformalismus zur Beschreibung rauschbehafteter Quantendynamik. Ich gebe einen Überblick über die Theorie der Rauschspektroskopie auf der Grundlage von Welchs Methode und stelle das Design des hardwareunabhängigen Open-Source-Pakets `python_spectrometer` vor, das interaktive Rauschspektroskopie im täglichen Gebrauch erleichtert. Auf didaktische Weise untersuche ich die Funktionen des Tools und führe den Leser durch dessen Bedienung. Anschließend charakterisiere ich ein konfokales Mikroskop, das in einen kryogenfreien Mischungskryostaten integriert ist, und wende das oben genannte Tool an, um die spektrale Leistungsdichte des Positionsrauschens zu messen. Ich entwickle eine Technik auf der Grundlage eines Messerkanten-Reflexionskontrasts, um das Positionsrauschen zu messen, das einen Schrotrauschuntergrund von $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ erreicht. Mit dieser Technik bestimme ich ein Positionsrauschen (RMS) von $100\,\mathrm{nm}$. Ich messe die Elektronentemperatur eines GaAs/AlGaAs-Quantenpunkts im Mikroskop und erhalte einen Wert von $76\,\mathrm{mK}$. Anhand einer Korrelationsmessung zweiter Ordnung eines selbstorganisierten Quantenpunkts demonstriere ich die optischen Fähigkeiten des Aufbaus. Im experimentellen Teil gebe ich zunächst eine Einführung in Photolumineszenz und den quantenbegrenzten Stark-Effekt in Halbleiter-Quantentöpfen und stütze mich dabei auf einfache analytische Theorie. Anschließend beschreibe ich den `mjolnir`-Messrahmen für optische Messungen von elektrostatischen Exzitonfallen in Halbleitermembranen und präsentiere umfangreiche Messungen auf der Suche nach Signaturen von Einzelphotonenemittern. Schließlich entwickle ich einen theoretischen Formalismus zur Beschreibung der verrauschten Quantendynamik von Quantensystemen auf der Grundlage von Filterfunktionen. Ich kombiniere Magnus- und Kumulanten-Entwicklungen zur Ableitung einer Quantenoperationsformulierung der Dynamik unter klassischem Rauschen, ausgedrückt durch Filterfunktionen.

Acknowledgements

It's been a journey. In a way, this endeavor started nine years ago, when I took up a HiWi job for a few months before the start of my Bachelor's project. Hendrik, it is a testament to you, the group you've built, and to the research you pursue that I have kept coming back for my Master's and finally for my PhD projects despite external factors in my life pulling me away from Aachen. Thank you for the opportunity, and for giving me the freedom, to grow, learn, and explore. Quantum technology is a hugely interdisciplinary field of research, and your vision of the grand scheme of things as well as your appreciation of not only the experimental physics but also the theory, software, and engineering that come along with it made this group an immensely rewarding place to be.

Having been part of the group for so long, there are many people that I am grateful to have shared my time with at the institute. Simon, who ad-hoc introduced me to the Bloch sphere when I stumbled into his office looking for a Bachelor's thesis, and whose curiosity and eagerness to learn about just about anything are inspiring. Who could have ever imagined that the world of Glam Metal is so big and yet so small?[*] Pascal, who supervised both my Bachelor's and Master's projects, and whose influence on both the group and my own personal growth cannot be overstated. Julian, for sticking to theory amidst so many experimentalists and teaching them lessons in diplomacy. René, with whom I shared the central office for the longest time, and who was my partner in solitude manning the office during the Covid years. Alex, who took his place – literally speaking – and continues to teach everyone sour lessons in roasting. Sebastian, who labored and toiled away in the clean room, and who I shared pains and successes with on the lone isle of optics land—it's been a joy collaborating with you! Thomas, whose work ethic enabled him to do Sebastian's and my job simultaneously, and whose shoulders most of my work stands on.

I have appreciated discussions in the optics team, in particular with Beata Kardynał, who was always available to share insight into the field of semiconductor optics that was new to me, and Maxim, who is wise beyond his years. Thank you also to the mechanical workshop, Frank and Helmut in particular, who always find a solution to whichever problem you come to them with. I am grateful to all my proof readers – Paul, Max, Alex, Sebastian, Evelyn, Maxim, and Dominik – that have had to cope with my complex thesis repository layout and knack for convoluted sentences.

Pursuing a PhD is more than just a job, and so I am also thankful to the people who have made it possible to reach this point or whose paths have touched mine during the course of my time here. Constanze and Ulrich, who took me in and gave me a roof over my head 13 years ago when I came to Aachen with a backpack and a duffle bag, surprised at the fact I had not found a place to live yet despite having looked for all but a few weeks

[*] This was before they were famous.

before the start of the semester. The anonymous gentleman walking his dogs in Melaten every morning who was a regular friendly face during the lockdown weeks and beyond. "Einen erfolgreichen Tag und bleiben Sie gesund!" Stefan Schael, for being a demanding but understanding neighbor.

Crucially, and emphatically unironically, my parents, who have placed me in the privileged position of being able to pursue my studies – both of them! – without financial worries or lofty expectations looming over my head. Papa, without your enduring and patient help and support I would have never made it this far.

It is perhaps fitting that as this chapter of my life closes, another, one that also started nine years ago, merely changes shape. Idske, you have been with me through all the highs and lows, you have helped me make decisions, lifted my spirits, shared my joy, made me laugh—in short, you have made my life the life it is, and I will not imagine it any other way anymore. I cannot wait to start the next part of that chapter with you.

Tobias Hangleiter
Aachen, September 2025

Preface

The present thesis consists of four parts. Each part is a largely self-contained accounting of one aspect of my work during the last years. Unfortunately, not everything always goes according to plan, and so there is not the *one* overarching theme that connects all parts. Yet it is in the nature of physics that there are always points of contact and connections.

One of these is *noise*, which I have dealt with extensively from various different points of view. In Part I, I present a software package to facilitate noise spectroscopy as an everyday tool in physics labs. The experiments that we conduct as condensed-matter physicists suffer from many kinds of noise, and this tool is intended to help analyze it. That is, given the *system*, what is the noise and how can we quantify it? In Part II, I then analyze, characterize, and improve upon a experimental setup designed to perform confocal optical spectroscopy of semiconductor nanostructures at Millikelvin temperatures. There, the topic of noise enters as an undesired but unavoidable external influence, and I apply the tools developed in Part I to characterize and mitigate the noise in order to improve the experimental capabilities of the setup. That is, given the *noise in the current state of the system*, how can we modify the system in order to ameliorate it? In Part IV, I develop a theoretical formalism to describe noise and its influence on the coherent evolution of single quantum systems. Also there, of course, the aim is to reduce the influence of noise, but in quite a different way. There, I deal with modeling the noise and the way it interacts with the intended dynamics of a controlled quantum system so as to understand and come up with ways of avoiding perturbations induced by the noise. That is, given the *noise*, how can we predict how the system reacts to it, and how might we be able to control the system in a way that is robust to noise?

Another recurring theme of the present thesis is *research software*. As physicists, much of our work – be it experimental or theoretical – relies on computers doing some aspect of it for us. Developing, and sharing, this software has thus become an integral part of physics research, and in the present thesis I contribute to the open-source research software ecosystem. In Part I, I introduce the `python_spectrometer` software package already mentioned above, which implements hardware-agnostic data acquisition, processing, and visualization for Fourier-transform noise spectroscopy. In Part III, I present optical measurements of electrostatic exciton traps in the Millikelvin confocal microscope discussed in Part II. These measurements are facilitated by the `mjolnir` measurement framework, which abstracts the complex hardware stack required to perform the measurements, allowing for minimal coding overhead going from the concept of a measurement to its execution. In Part IV, I introduce the `filter_functions` software package, which implements the formalism developed in the same part, enabling easy adoption of the techniques for the computation of noisy quantum processes.

The present thesis has been typeset with LuaLaTeX and is optimized for digital reading. The document source code is available on Github. Throughout the document, I make liberal use of cross-references and acronyms, the latter of which link to and are defined in the Glossary on page 11. As such, I recommend a PDF viewer that can preview the targets of internal hyperlinks for reading the present thesis in order to avoid having to jump back and forth within the document.

The various figures included in this document are either generated by LaTeX/TikZ or by a Python script included in the source repository in the `img/py` directory. Figure captions contain a hyperlink to the list of figure source files and parameters on page 13 whose entries point to the source file that generates the figure. For figures that contain experimental data, the entry in the list of figure source files and parameters on page 13 furthermore typically contains values of external parameters that were fixed during the measurement. In the spirit of open data, all data discussed in the present thesis are included in the `data` directory at the top level of the source repository.

Finally, I frequently employ an asinh-scale for data that spans several orders of magnitude. This scaling is asymptotically equivalent to a symmetric logarithmic scale for large $|x|$, $\operatorname{asinh}(\pm x) \sim \pm \log|x|$, but avoids the divergence close to zero, instead being linear, $\operatorname{asinh}(x) \sim x$. The crossover from linear to logarithmic behavior is governed by a parameter x_0 such that $x \to x_0 \operatorname{asinh}(x/x_0)$ and that can be freely chosen, thus influencing the representation of the data. The particular value of x_0 (corresponding to the `linear_width` parameter in `matplotlib`) in a given figure can be looked up in the script file that generates it.

Tobias Hangleiter
Aachen, September 2025

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A Flexible Python Tool For Fourier-Transform Noise Spectroscopy

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Part IV

A Filter-Function Formalism For Unital Quantum Operations

Appendix

Glossary

R

RMS root mean square. iii, v

Figure source files and parameters

Declaration of Authorship

I, Tobias Hangleiter, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I do solemnly swear that:

1. This work was done wholly or mainly while in candidature for the doctoral degree at this faculty and university;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others or myself, this is always clearly attributed;
4. Where I have quoted from the work of others or myself, the source is always given. This thesis is entirely my own work, with the exception of such quotations;
5. I have acknowledged all major sources of assistance;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published before as:

[1] Pascal Cerfontaine, Tobias Hangleiter, and Hendrik Bluhm. "Filter Functions for Quantum Processes under Correlated Noise." In: *Physical Review Letters* 127.17 (Oct. 18, 2021), p. 170403. DOI: 10.1103/PhysRevLett.127.170403.

[2] Thomas Descamps, Feng Liu, Tobias Hangleiter, Sebastian Kindel, Beata E. Kardynał, and Hendrik Bluhm. "Millikelvin Confocal Microscope with Free-Space Access and High-Frequency Electrical Control." In: *Review of Scientific Instruments* 95.8 (Aug. 9, 2024), p. 083706. DOI: 10.1063/5.0200889.

[3] Tobias Hangleiter, Pascal Cerfontaine, and Hendrik Bluhm. "Filter-Function Formalism and Software Package to Compute Quantum Processes of Gate Sequences for Classical Non-Markovian Noise." In: *Physical Review Research* 3.4 (Oct. 18, 2021), p. 043047. DOI: 10.1103/PhysRevResearch.3.043047.

Aachen, September 18, 2025.