PHYS-464

Solid state systems for quantum information

Scarlino Pasquale

Cursus	Sem.	Type
Ing.-phys	MA2, MA4	Opt.
Minor in Quantum Science and Engineering	E	Opt.
Physicien	MA2, MA4	Opt.
Quantum Science and Engineering	MA2, MA4	Opt.

Language of teaching	English
Credits	4
Session	Summer
Semester	Spring
Exam	Oral
Workload	120h
Weeks	14
Hours	**4 weekly**
Lecture	2 weekly
Exercises	2 weekly
Number of positions	

Summary

This course will give an overview of the experimental state of the art of quantum technology for Quantum Information Processing (QIP). We will explore some of the most promising approaches for realizing quantum hardware and critically assess each approach's strengths and weaknesses.

Content

We will provide a systematic introduction to experimental realizations of quantum information processing with solid-state systems, with a particular focus on the Superconducting Circuit Quantum Electrodynamics platform. We will explore the fundamentals of qubits, quantum gates, and measurements.
We will also introduce spin qubits defined by electrons and holes confined in a semiconductor environment. We will explain how we can isolate single electrons or holes in semiconducting islands called quantum dots and control them to perform quantum gates.
In addition, we will provide a thorough introduction to other physical implementations pursued in current research for realizing more robust solid-state qubits. We will also analyze hybrid devices implemented combining spin and mechanical degrees of freedom with superconducting technology on the same quantum device.

1. Introduction to Quantum Information Processing

• DiVincenzo criteria and universal quantum computers. Quantum gates, circuit representation. Example of algorithms.

2. Superconducting quantum hardware for quantum computing and QIP

• Understanding the physical concepts underlying superconducting qubits experiments: superconductivity and Josephson effect. Superconducting Quantum Interference Device. Quantization of electrical circuits.

3. Josephson junctions-based circuits.

• Cooper-pair box and Quantronium. Flux and Phase qubit. The transmon (limit) and its use as a quantum bit. Frequency tunability with SQUIDs. Fluxonium.

4. Measurement and Control of Superconducting qubits.

• Interfacing qubits and photons: circuit quantum electrodynamics (cQED). Design and fabrication of superconducting circuits and Experimental Setup for cQED experiments. Dispersive limit and readout of superconducting qubits. Characterizing qubit coherence.

5. Realizations of algorithms and protocols.

• Multiqubit devices: qubit/qubit interaction and entangling gates. Quantum Error Correction

6. Survey of other Physical Implementations for QIP: Electronic and nuclear spins in semiconductor quantum dots.

• Define Quantum Dots and Spin Qubits (Loss-Di Vincenzo, Singlet-Triplet, Exchange only,...) in GaAs, Si and Ge. Spin to Charge conversion readout. Electron spin manipulation. Two Spin qubits gates. Scaling up spin qubits.

7. Survey of other Physical Implementations for QIP: **Majorana fermions and Superconducting Protected qubits.**

8. Circuit Quantum Electrodynamics with Hybrid Systems.

• Coherent coupling of Superconducting systems to: Charge and Spin system in QDs, small ensembles of spins, mechanical systems. Electrically tunable Transmon (Gatemon).

Keywords

Quantum technology, quantum electrodynamics, quantum computing, quantum simulation, quantum optics, quantum measurement, quantum devices

Learning Prerequisites

Required courses

All students with a general interest in quantum information science, quantum optics, and quantum engineering are welcome to this course.
Basic knowledge of quantum physics and quantum systems concepts, e.g., from courses such as Quantum Physics I and II, or courses on topics such as atomic physics, solid-state physics, is a plus but not a strict requirement for successful participation in this course.

Recommended courses

Quantum Physics I, Quantum Physics II, Quantum Information and Quantum Computing

Important concepts to start the course

Superconductivity. Two-level system and harmonic oscillator in quantum mechanics.

Learning Outcomes

By the end of the course, the student must be able to:

• Develop a basic understanding of the different elements necessary to build superconducting and semiconducting quantum circuits.

• Analyze and understand the scientific literature about the state-of-the-art of solid state quantum technology for quantum information.

• Establish conceptual insight into the operation, opportunities, and challenges of various qubit implementations.

• Work out / Determine the requirements of quantum hardware for quantum computing and quantum information technology.

• Compare various qubit implementations in different solid-state quantum platform.

Teaching methods

Ex-cathaedra, exercise classes. Mini-conference with student presentations.
In this course, lectures are combined with homework assignments as well as presentations of recent research papers.

Expected student activities

Weekly problem sheet solving, paper reading and presentation.

Assessment methods

Oral examination

Resources

Bibliography

Reviews and research papers to be studied at home, material presented during lectures.

For a review of the basics of Quantum Information and Computing:

• Quantum computation and quantum information / Michael A. Nielsen & Isaac L. Chuang. Reprinted. Cambridge: Cambridge University Press; 2001

For a review of superconducting quantum technology and circuit Quantum Electrodynamics:

• Girvin, S. M. (2011), Circuit QED: superconducting qubits coupled to microwave photons. Quantum machines: measurement and control of engineered quantum systems, 113, 2.

• P. Krantz, et al., A quantum engineer's guide to superconducting qubits, *Applied Physics Reviews* **6**, 021318 (2019); https://doi.org/10.1063/1.5089550

• Mahdi Naghiloo, Introduction to Experimental Quantum Measurement with Superconducting Qubits, *arXiv:1904.09291*

• A. Blais, A. L. Grimsmo, S.M. Girvin, and A. Wallraff, Circuit quantum electrodynamics, *Rev. Mod. Phys.* **93**, 025005 (2021).

For a review of semiconductor Spin Qubits:

• W. G. van der Wiel, S. De Franceschi, J. M. Elzerman, T. Fujisawa, S. Tarucha, and L. P. Kouwenhoven, Electron transport through double quantum dots, *Rev. Mod. Phys.* **75**, 1 (2002).

• R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen, Spins in few-electron quantum dots, *Rev. Mod. Phys.* **79**, 1217 (2007).

Ressources en bibliothèque

• Mahdi Naghiloo, Introduction to Experimental Quantum Measurement with Superconducting Qubits
• A.M. Zagoskin, Quantum engineering: theory and design of quantum coherent structures
• Girvin, S. M. (2011), Circuit QED: superconducting qubits coupled to microwave photons
• W. G. van der Wiel, S. De Franceschi, J. M. Elzerman, T. Fujisawa, S. Tarucha, and L. P. Kouwenhoven, Electron transport through double quantum dots
• R. Hanson, L. P. Kouwenhoven, J. R. Petta, S. Tarucha, and L. M. K. Vandersypen, Spins in few-electron quantum dots
• A. Blais, A. L. Grimsmo, S.M. Girvin, and A. Wallraff, Circuit quantum electrodynamics
• Quantum computation and quantum information / Michael A. Nielsen & Isaac L. Chuang
• P. Krantz, et al., A quantum engineer's guide to superconducting qubits

Moodle Link

• https://go.epfl.ch/PHYS-464