Publishable Summary for 17FUN04 SEQUOIA

Single-electron quantum optics for quantum-enhanced measurements

Overview

This project will develop new metrological tools to enable the characterisation of the quantum state of electrons in semiconductor quantum devices and quantum enhanced sensing based on the technique of *single-electron quantum optics*. This approach uses the control, transfer, manipulation and measurement of on-demand single-electron wave packets. This project will develop a solid-state on-demand single-electron interferometer for the time-resolved direct on chip measurement of local electric and magnetic fields, as used to manipulate quantum states in electronic quantum devices. Furthermore, it will develop tools for the characterisation of the electron quantum state.

Need

The first quantum revolution resulted in ground-breaking technologies such as the transistor and the laser. A second quantum revolution is expected to bring transformative advances to key areas of science, industry and technology. Consequently, the European Commission announced a quantum technology flagship effort to foster the role of European industry and research in the area. This new quantum technology will generate the need for fundamentally new measurement capabilities as seen in the past for every technological revolution. Quantum technology will also allow us to exploit quantum effects for enhanced sensing or for the metrology of single particles.

For applications like quantum computation and simulation it is important to develop *scalable* quantum technology. Semiconductor quantum devices promise good potential for complex integrated quantum circuitry. A prerequisite to utilise the electron quantum state as a resource is the ability *to characterise its properties*. Control of quantum states requires exact knowledge of local magnetic and electric fields, best to be gained by *in-situ time-resolved sensing*.

These requirements for a metrology of electron quantum states and for in-situ fast quantum sensors can be addressed by harnessing the properties of on-demand electron wave packets. By analogy with the use of photons in quantum optics, the transmission and manipulation of such wave packets allows the realisation of '*electron quantum optics*' and could be used for sensitive quantum-enhanced measurements.

To underpin these important technological developments this project will provide a metrology toolbox for sourcing and detection (objective 1), testing and validation (objective 2), and for the quantum state tomography (objective 4) of single-electron wave packets. Furthermore, on-chip quantum sensing will be enabled using single-electron wave packet interferometry (objective 3). This project will thus deliver a solid metrological foundation for future scalable solid-state quantum device applications and it will foster and hasten the development of semiconductor-based quantum information technology.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Objectives

The goal of the project is to develop new measurement techniques to support the development of semiconductor quantum technology. These techniques themselves will be based on the use of a new field of quantum techniques, namely on-demand single-electron quantum optics, where the quantum properties of moving electrons within a semiconductor device are examined and utilised. The specific objectives addressed to realise and to make use of these new measurement capabilities are:

1. **To produce semiconductor device components for on-demand single-electron quantum optics-based sensing and state tomography**, including quantum dot based high-energy on-demand synchronised single-electron sources for time-resolved interferometry, single-charge detectors for electron quantum optics, and correlation measurement techniques and devices for quantum state metrology.
2. **To develop the metrological tools for the verification of single-electron sources required for the assessment and optimisation of the emitted electron wave packet states**, including the characterisation of the dynamic electron state within the source quantum dot and the indistinguishability test of the travelling single-electron wave packet.
3. **To develop an experimental technique for on-demand single-electron wave packet interferometry for the sensing of local magnetic and electric fields with high time resolution** (~ 1 ns or below) and high spatial resolution (~ 1 µm).
4. **To develop concepts and theoretical tools for a full quantum state tomography to enable the realisation of quantum enhanced measurements using electron wave packets.**
5. **To foster the application of single-electron wave packet devices for quantum metrology and the European metrology capabilities for quantum technology**.

Progress beyond the state of the art

New device components: For present electron quantum optics devices only the average current and noise of many repeated electron transmissions are measured. Within this project, the consortium will develop readout on a single-electron basis. This will result in a major step forward in measurement sensitivity and it will also allow us to read out more complex information. To also detect electrons with the smallest possible energy, *levitons*, completely new techniques will be explored.

New metrological tools for single-electron sources: Though very promising for on-chip time-resolved sensing, electron wave packets sourced at higher energies have yet to be characterised in any detail. This project will provide the necessary measurement techniques for time-energy distribution, indistinguishability, and wave packet dynamics. This will be used to optimise the sourced electron wave packets for electron quantum optics applications.

Techniques for on-demand single-electron wave packet interferometry: Interferometry of single on-demand electrons has not yet been demonstrated. Within this project, techniques for the realisation of an on-demand single-electron interferometer with <1 ns time resolution at ~ 1 µm size will be developed. Applied as local magnetometer this will exceed the time resolution of e.g. nano-SQUID sensors by at least an order of magnitude.

Quantum state tomography and quantum enhanced sensing: A full quantum state tomography of the emitted single-electron wave packet, a prerequisite for the application of single-electron quantum optics devices in quantum technology, does not yet exist. Within this project a quantum tomography protocol will be developed and optimised with respect to the technical advances achieved during the project.

Potential and practicability of single-electron quantum optics for quantum metrology: Presently insufficient experimental data is available to determine the limits and the advantages of the different single-electron quantum optics techniques. Within this project the different techniques will be scrutinised with respect to their application in metrology.

Results

Device components for on-demand single-electron quantum optics-based sensing and state tomography:

Indispensable components of every quantum optics realisation are the waveguides which are used to transfer single-electron wave packets between all the other components. Especially for electrons with excess energy, inelastic scattering has to be suppressed. Especially for high energy electrons phonon emission is an important relaxation mechanism. This is addressed in the project both by a theoretical study, published in [1], which offers guidance for optimisations, and by experimental studies. Experimentally, the energy relaxation was examined as a function of emission energy for different energy ranges, path geometries, electrode designs and settings. A comparative study has been performed on the electron relaxation mechanisms due to electron-electron interactions and optical phonon emission in GaAs systems using a variety of wafer material provided by different partners. The scattering rates were found to be strongly material-dependent. For high energy electron wave packets survival probabilities larger than 97% could be demonstrated for path length of several microns. This is sufficiently large for integration into more complex devices [4,7].

Another important component is the detector for the outcome of single-electron experiments. Aside improving more conventional current correlation measurements, innovative techniques for the detection of the fate of every single electron have been developed. A first demonstration of single-electron wave packet capture and detection has reached a fidelity of 99.9 %, opening a new route for the realisation of single-electron quantum optics [7].

Metrological tools for the assessment and optimisation of electron wave packet states:

The characterisation and preparation of single-electron wave packets with controlled properties is a key step towards complex metrological applications of single-electron quantum optics. For both high-energy (~ 100 meV) and low-energy (< 1 meV) electrons a tomographic measurement technique for the energy-time distributions has been developed. It was used to measure the dependence of the distribution of ejection conditions and to establish a connection between the dynamic change of energy in the emitting quantum dot to the phase space distribution of the electron. A model for single-electron emission from dynamic quantum dots was successfully validated using these measurements [4]. This tomographic scheme allowed partners to set up ejection conditions for the two high-energy single-electron wave packet sources used in a Hong-Ou-Mandel geometry.

The initial state preparation in the dynamic quantum dot used for high energy electron preparation was also examined; a model has been developed and validated by experimental data. The role of relaxation for the outcome of initialisation has been clarified [2].

Tomographic techniques were also employed to characterise the state, including the energy and time distribution, of electron wave-packets excited at low energy. For the third type of electron wave packets examined in the project, excited by Lorentzian voltage pulses, the temporal width has been characterised. For all types of wave-packets temporal widths sufficiently small for the targeted time resolution (< 1 ns) have been observed [3].

The characteristics of the quantum Hall breakdown were studied on Hall bars made of graphene grown by CVD on SiC [5] and of h-BN encapsulated graphene by measurement of the temperature and current dependence of the dissipation. A small ac current was injected to test the detection sensitivity in the breakdown regime triggered by a main dc current. The frequency dependence of the noise characteristics has been determined. This method will be extended to detect a single leviton excitation.

A quantum Hall valley beam splitter in a pn-junction in graphene has been demonstrated as an important step towards a tomography of single Leviton excitations in graphene. The beam splitter transmission could be tuned from zero to near unity. The beam splitter is realized and controlled by tuning the mixing point of edge channels at the corner of a pn junction by a electrostatic side gate.

Techniques for on-demand single-electron wave packet interferometry:

The transmission of single electrons through a Fabry-Perot cavity was studied as prerequisite for single-electron wave packet interferometry. We observed a modulation of the transmission with a contrast close to 20% when either the magnetic field or the area of the cavity (controlled by a plunger gate) were varied. The variation of the current with the plunger gate voltage was exploited to sample a time-dependent electric field generated by applying a time dependent voltage to the plunger gate. By varying the delay between the emission of single electron pulses and the time-dependent voltage, the local potential of the Fabry-Perot cavity was sampled as a function of time. The sampling time resolution is around 100ps (close to the limit imposed by the width of single electron pulses) and the space resolution is of a few microns (corresponding to the typical size of the cavity).

Quantum state tomography and quantum enhanced sensing:

A protocol for quantum tomography of single-electron wave packets by dynamical scattering has been developed based on a fully quantum-mechanical model. This protocol has been applied to the experimental data for the measurement of energy-time distribution of high-energy electrons. It was also used to measure the quantumness of the wave-packets in this initial test. This is also an important characteristic for the application in interferometry. The developed methods will be used in further optimisation of the wave packet source towards emission of states with higher purity and for the characterisation of the quantum state properties [4]. The effect of experimental RF bandwidth on the fidelity of tomography results was investigated.

The theoretical study of quantum scattering of single-electron wave-packets by dynamical barriers, that underpins the new tomography protocol, has also established a theoretical framework to determine quantum limits on resolution of single-electron signal-sampling techniques [6].

Two-electron interactions in the Hong-Ou-Mandel geometry have been investigated for high-energy electrons. A signature considered to be due to long-range Coulomb interaction has been observed. The data from noise measurements are being analysed for the confirmation of indistinguishability of the two electrons.

A control of the overlap of split wave packets in the Mach-Zehnder geometry has been achieved for high-energy electrons by tuning their drift velocity in the split paths independently. A new batch of devices with a small enclosed path area is being fabricated for the demonstration of interference. Decoherence effect in high-energy Mach-Zehnder interferometry was studied and strategies for improving the visibility of interference have been proposed [8].

A quantum tomography protocol for low-energy electrons (< 1 meV) has also been developed. It is based on the realisation and analysis of two-electron collision experiments in the Hong-Ou-Mandel geometry. It is used to characterise the temporal and energy distributions of low-energy single electron wave packets. It also provides information of the purity of the emitted state and can thus be used to characterise precisely by how much they deviate from pure electron states. In particular, it establishes the crucial role of thermal fluctuations in reducing the purity of low-energy single electron states [3].

Impact

The impact objective is for the project to foster the application of single-electron wave packet devices for quantum metrology and the European metrology capabilities for quantum technology. This will be achieved through training workshops for partners, stakeholders and collaborators, as well as publications, presentations, and liaison with relevant industries and standards bodies.

A number of high-level scientists from national metrology institutes, industries basic research labs, public research institutes and universities, all active in the field of quantum technology, have been informed about the goals of our project and have joined the projects stakeholder board. A contact to the Quantum Community Network, which is part of the Flagship on Quantum Technologies governance structure, has be established, having one of its members in our stakeholder group.

Impact on industrial and other user communities

The early uptake of the project’s results will be in a R&D environment of industry and in basic academic research labs. The implementation of local time resolved sensing of electric and magnetic control fields is expected to be integrated into devices serving quantum technology development and evaluation, allowing to directly measure these fields at relevant time scales. This can speed up the development and implementation of scalable semiconductor technology for quantum computation and simulation. Similarly, an adoption of quantum tomography techniques is expected as diagnostic tools to evaluate the performance and outcome of quantum state control and manipulation in dedicated technology test applications.

Two partners had discussions with scientists at the basic research laboratory of NTT, a stakeholder of the project, on the implementation of single electron quantum optics techniques in silicon based single electron devices manufactured and examined at NTT.

SEQUOIA Project partners have engaged with industrial suppliers of RF components used to carry the microwave signals that control and readout qubits in prototype quantum computers. Our new measurement capabilities can be used to test and validate elements in the RF signal chain, particularly those at low temperature. Tests of cryogenic multi-terminal RF interconnects are planned with a key supplier of RF components into healthcare, defence, aerospace and academic research. A noise measurement system developed during for SEQUOIA device readout schemes is to be used for device tests for a company in the Quantum Technology sector. In this way novel test methods developed within SEQUOIA can be made available to equipment manufacturers to speed up the development of effective, scalable control infrastructure and devices for quantum systems.

Impact on the metrology and scientific communities

The project will advance the research in all areas of electron quantum optics and introduce new technologies like single-electron detection and new concepts for quantum state tomography into this field. Furthermore, it will deepen the understanding of the QHE breakdown in high-mobility encapsulated graphene. Also, the new experimental tools for on-chip time resolved sensing and advanced single wave packet detection and characterisation enabled by the project will advance basic academic research on quantum physics in solid state systems, providing new experimental capabilities. By involving the top-level academic experts in on-demand single-electron quantum optics this project will create further impact by establishing state of the art knowledge and experimental techniques in the metrological community, enabling it to face future challenges generated by a rapidly developing quantum technology.

Five stakeholder institution and one other university, represented by ten scientists, participated in a workshop on single electron quantum optics for quantum-enhanced measurements held at the midterm meeting of the project. Among these one NMI and one academic institution have started to work experimentally on the implementation of single-electron quantum optics for metrology. Several academic stakeholders have taken up research questions that have arisen from the project and are now contributing to the development of metrological tools based on single-electron quantum optics. Thus, the project has started to inspire a thriving community for the development of this new field of metrology.

Exchange of ideas on the theory of quantum advantage and the practical single-electron technologies between members of the consortium and the Centre for Quantum Computing at University of Latvia has led to a new scientific collaboration (with prof. Andris Ambains) in novel interdisciplinary direction. A major result, accepted for publication in Nature Communications, introduces the technique of benchmarking by error accumulation from the field of quantum computing to the quantum electrical metrology. The newly proposed random benchmark for single-electron circuits puts a rigorous mathematical foundation on error estimation in direct realisations of the quantum ampere.

First contact with end-user communities and demonstrations of new techniques are often initiated via interactions within NMIs from users in areas outside electrical metrology (e.g. mass metrology, environmental monitoring). To encourage these interdisciplinary interactions, one partner held two internal workshops. The first to give a picture of state-of-the-art metrology research, including results from SEQUOIA. The second, a foresighting exercise, provided an opportunity to see how such emerging technology may meet long term societal challenges. Follow up discussions, e.g. in several metrology areas (e.g. communications beyond 5G) are planned.

Impact on relevant standards

Due to the early stage of quantum technology, i.e. first demonstrations in academic lab environments, no standards exist yet for quantum information processing or for other electronic quantum bit-based devices. However, the expected future commercialisation of such technology will generate the need for standardisation for relevant properties of quantum states or quantum devices and procedures for measurement or verification of these properties. The metrology bodies will only be able to input into standards and guide the process of standardisation, if they are building up the necessary expertise and capabilities in time. This project will generate these needed capabilities and experience within the participating NMIs and it will spread knowledge into the wider metrological community to set the basis for future standardisation processes.

First results of the project have been presented at the TC-EM DC QM subcommittee meeting, which is the relevant subcommittee of the European metrology community, organised in EURAMET, for all questions regarding electrical quantum metrology.

Longer-term economic, social and environmental impacts

The present research and development of scalable quantum solid state technology as a key technology for wide spread future applications and high-tech products is highly beneficial for the advancement of the European information technology industry. This project provides underpinning metrology for this rapidly evolving field thereby impacting future IT technology, European IT industry, and hence future employment in this sector.

List of publications

1. C. Emary, L. A. Clark, M. Kataoka, and N. Johnson, *Energy relaxation in hot electron quantum optics via acoustic and optical phonon emission*, Phys. Rev. B **99**, 045306 (2019). DOI:10.1103/PhysRevB.99.045306, click here for open access full text
2. T. Wenz, J. Klochan, F. Hohls, T. Gerster, V. Kashcheyevs, H. W. Schumacher. *Quantum dot state initialization by control of tunneling rates*. Phys. Rev. B **99,** 201409(R) (2019). DOI:10.1103/physrevb.99.201409
3. R. Bisognin, A. Marguerite, B. Roussel, M. Kumar, C. Cabart, C. Chapdelaine, A. Mohammad-Djafari, J.-M. Berroir, E. Bocquillon, B. Plaçais, A. Cavanna, U. Gennser, Y. Jin, P. Degiovanni and G. Fève *Quantum tomography of electrical currents,* Nature Communications **10**, 3379 (2019). DOI:10.1038/s41467-019-11369-5
4. J. D. Fletcher, N. Johnson, E. Locane, P. See, J. P. Griffiths, I. Farrer, D. A. Ritchie, P. W. Brouwer, V. Kashcheyevs and M. Kataokam, *Continuous-variable tomography of solitary electrons,* Nature Communications ***10***, 5298 (2019). DOI:10.1038/s41467-019-13222-1
5. W. Poirier, S. Djordjevic, F. Schopfer, O. Thévenot, *The ampere and the electrical units in the quantum era*, C. R. Phys., 20, 92 (2019). DOI:10.1016/j.crhy.2019.02.003
6. E. Locane, P. W. Brouwer, V. Kashcheyevs, *Time-energy filtering of single electrons in ballistic waveguides*, New J. Phys. **21**, 093042 (2019). DOI:10.1088/1367-2630/ab3fbb
7. L. Freise, T. Gerster, D. Reifert, T. Weimann, K. Pierz, F. Hohls, N. Ubbelohde. *Trapping and Counting Ballistic Nonequilibrium Electrons.* Phys. Rev. Lett **124**, 127701 (2020). DOI:10.1103/PhysRevLett.124.127701
8. L. A. Clark, M. Kataoka, and C. Emary, *Mitigating decoherence in hot electron interferometry*, New J. Phys. **22**, 103031 (2020). DOI: 10.1088/1367-2630/abb9e5

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 May 2018, 42 months</td></tr>
<tr><td colspan="3">Coordinator: Dr. Frank Hohls*, Physikalisch-Technische Bundesanstalt (PTB)*
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Project website address: https://www.ptb.de/empir2018/sequoia/project/</td></tr>
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