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 characterization of the electrons 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 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.

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 realize 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

Semiconductor device components for on-demand single-electron quantum optics based sensing and state tomography

The project will develop optimised and new components for the implementation of a single-electron wave packet based metrology in a wide range of electron excitation energies (10 µeV – 100 meV) and in two material systems (in the conventional semiconductor gallium-arsenide and in the promising new material graphene). Existing source-designs and control schemes for on-demand single-electron wave packets will be improved for application in sensing and state tomography. Device components for single-wave packet detection at different energy ranges will be developed. Different device components will be integrated into single-electron wave packet quantum circuits for sensing and tomography.

Metrological tools for the verification of single-electron sources required for the assessment and optimisation of the emitted electron wave packet states

The project will develop single-shot detection methods for single-electron wave packets. This will transform electron quantum optics: Instead of the present average outcome of many repetitions, the result of every single electron will be recorded. This is especially difficult for minimal excitations (called *levitons*) in graphene, for which a radically new concept of avalanche based detection by quantum-Hall-effect breakdown will be examined, also resulting in a better understanding of this breakdown in graphene.

New measurement techniques for the characterisation of the time and energy distribution of the wave packets will be developed. These will also be used to optimise the sourced wave packets for sensing and quantum tomography applications.

Another single-electron property is the indistinguishability of electrons, which for the first time will also be characterised for single-electron wave packets with excess energies above 10 meV, which are relevant for the realization of robust single-electron interferometry.

Experimental technique for on-demand single-electron wave packet interferometry for the sensing of local magnetic and electric fields with high time resolution

The project will demonstrate the two-path interference of single electrons generated on demand within a semiconductor device. This allows to access the single-electron wave packet coherence, firstly to characterise it, and secondly to utilise it for time resolved sensing, using the sensitivity of the interference to phase shifts by magnetic or electric fields. Using very short single-electron wave packets, this promises a time resolution well below 1 ns while still benefitting from the sensitivity of interference.

Concepts and theoretical tools for a full quantum state tomography to enable the realisation of quantum enhanced measurements using electron wave packets

The project will advance the modelling of wave packet dynamics, addressing source initialisation and emission, provide theoretical tools for the optimised preparation of high energy single-electron wave packets and advance the modelling of decoherence and relaxation.

Notably the project will enable quantum state tomography for single-electron wave packets at finite energies by developing concepts, models and analysis tools. Finally, the project will research the yet unexplored potential of single-electron wave packet based *quantum enhanced sensing*, adapting the concept of the standard quantum limit to single electron metrology and examining the advantages of non-classical states.

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.

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.

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.

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.

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.

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<tr><td colspan="2">Project start date and duration:</td><td>01 May 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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<tr><td>Internal Funded Partners:
1 PTB, Germany
2 LNE, France
3 NPL, United Kingdom</td><td>External Funded Partners:
4 CNRS, France
5 CEA, France
6 LatU, Latvia</td><td>Unfunded Partners:</td></tr>
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