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Single-electron quantum optics for quantum-enhanced measurements

Overview

This project developed new measurement techniques to support the development of semiconductor quantum technology. These techniques were based on the use of quantum techniques, namely on-demand single-electron quantum optics, where the quantum properties of moving electrons within a semiconductor device are examined and used. The new metrological tools developed by the project have enabled the characterisation of (i) the quantum state of electrons in semiconductor quantum devices and (ii) quantum enhanced sensing based on the technique of single-electron quantum optics. The project's approach used the control, transfer, manipulation and measurement of on-demand single-electron wave packets. The project has also developed a solid-state on-demand single-electron interferometer for the time-resolved direct on chip measurement of local fields, as used to manipulate e.g. quantum states in electronic quantum devices. Furthermore, the project developed tools for the characterisation of the on-demand single-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 launched a quantum technology flagship in 2018 to foster the role of European industry and research in this area.

New quantum technologies will allow the exploitation of quantum effects for enhanced sensing or for the metrology of single particles; however, such new technologies will also need new measurement capabilities. For applications like quantum computation and simulation, scalable quantum technology needs to be developed. Semiconductor quantum devices have demonstrated the potential for complex integrated quantum circuitry. However, a prerequisite for using the electron quantum state as a resource is the ability to characterise its properties. In addition, the control of quantum states needs exact knowledge of local magnetic and electric fields, via in-situ time-resolved sensing.

These needs for the metrology of electron quantum states and for in-situ fast quantum sensors were 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 on-demand electron wave packets has allowed the realisation of 'electron quantum optics' which can be used for sensitive quantum-enhanced measurements.

To support these important technological developments in semiconductor quantum technology, the project has also produced a metrology toolbox for (i) the sourcing and detection (Objective 1), (ii) testing and validation (Objective 2), and (iii) quantum state tomography (Objective 4) of single-electron wave packets. Furthermore, on-chip quantum sensing was developed using single-electron wave packet interferometry (Objective 3). Therefore, this project has delivered the much needed, metrological foundation for future scalable solid-state quantum device applications and has enabled the development of semiconductor-based quantum information technology.

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Objectives

The goal of this project was to develop new measurement techniques to support the development of semiconductor quantum technology. These techniques were 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 used. The specific objectives for the project were:

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 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 semiconductor device components: for on-demand single-electron quantum optics-based sensing and state tomography: Prior to the start of this project only the average current and noise of repeated electron transmissions had been measured for electron quantum optics devices. This project has gone beyond this by developing readout on a single-electron basis. This has resulted in a major step forward in measurement sensitivity and has also allowed the read out of more complex information. Further to this, the project developed completely new techniques towards the detection of electrons with the smallest possible energy, i.e. levitons.

New metrological tools for the verification of single-electron sources required for the assessment and optimisation of the emitted electron wave packet states: Prior to the start of this project electron wave packets sourced at higher energies had yet to be characterised in any detail. This project has gone beyond the state of the art by developing the necessary measurement techniques for time-energy distribution, indistinguishability, and wave packet dynamics. These techniques have then been used to examine the dependence of the sourced electron wave packets on emission parameters for electron quantum optics applications.

Experimental techniques for on-demand single-electron wave packet interferometry for the sensing of local magnetic and electric fields with high time resolution: Prior to the start of this project interferometry of single on-demand electrons had not been demonstrated. This project has gone beyond this by developing techniques for the realisation of an on-demand single-electron interferometer with 0.1 ns time resolution at < 1 µm size. In addition, the techniques were demonstrated for local measurement of electric fields. Further to this, single-electron interferometry in a new type of interferometer based on a p-n junction in graphene was successfully used as detector of magnons emitted at the edge of a quantum Hall ferromagnet.

Tools for full quantum state tomography to enable the realisation of quantum enhanced quantum enhanced measurements using electron wave packets: This project has gone beyond the state of the art by developing and optimising a quantum tomography protocol for the full quantum state tomography of emitted single-electron wave packets. The full quantum state tomography of emitted single-electron wave packets can now be used for the application of single-electron quantum optics devices in quantum technology.

Results

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:

Waveguides are vital components for on-demand single-electron quantum optics realisations as they are used to transfer single-electron wave packets between all other components. This is especially true for (i) electrons with excess energy, where inelastic scattering must be suppressed., and (ii) for high energy electrons (~ 100 meV) where phonon emission is an important relaxation mechanism.

The project successfully performed a theoretical study, published in [1], which offers guidance for the optimisation of energy relaxation in hot electron quantum optics via acoustic and optical phonon emission. The project also performed experimental studies to examine, the energy relaxation as a function of emission energy for different energy ranges (10 – 200 meV), path geometries and lengths (1 to 15 µm), electrode designs (e.g. without and with top gate) and settings (including stocastic and on-demand sources). In addition, a comparative study was performed on the electron relaxation mechanisms due to electron-electron interactions and optical phonon emission in Gallium Arsenide (GaAs) semi-conductor systems using a variety of wafer materials (13 wafers from 3 different molecular beam epitaxy systems) provided by project partners. In the comparative study the scattering rates were found to be strongly dependent on the wafer material. For high energy electron wave packets survival probabilities larger than 97 % were demonstrated for a path length of several microns, which is sufficiently large for integration into more complex semiconductor devices [4,7].

Another important component for on-demand single-electron quantum optics is the detector for the outcome of single-electron experiments. As well as improving conventional correlation measurements, innovative techniques for the detection of the fate of every single electron were developed by the project. The project's first ever demonstration of single-electron wave packet capture and detection for ballistic high energy electrons in semiconductors reached a fidelity of 99.9 %, thus providing a new route for the realisation of single-electron quantum optics [7].

The project has also successfully demonstrated the use of a quantum Hall valley beam splitter in a p-n junction in graphene which is an important step towards the tomography of single Leviton excitations in graphene. The beam splitter transmission could be tuned from zero to near unity and was controlled by tuning the mixing point of edge channels at the corner of a p-n junction by an electrostatic side gate [9].

2. To develop the metrological tools for the verification of single-electron sources required for the assessment and optimisation of 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:

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. The project has successfully developed a tomographic measurement technique for the energy-time distributions for both high-energy (~ 100 meV) and low-energy (< 1 meV) electrons. The project's new tomographic measurement technique was used (i) to measure the dependence of the distribution of ejection conditions and (ii) 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 also successfully validated [4].

The project's tomographic measurement technique has also been used by partners to set up ejection conditions for the two high-energy single-electron wave packet sources used in a Hong-Ou-Mandel (HOM) geometry. The project investigated two-electron interactions in the HOM geometry, for high-energy electrons. The results of the investigation showed that the behaviour in the high energy HOM systems is different to the low energy ones, due to the difference in screening of the coulomb interaction. This subject has been investigated further and addressed by theoretical work on the collision of two interacting electrons on a mesoscopic beamsplitter [arXiv:2201.13439].

The project has also examined the initial state preparation in the source dynamic quantum dot used for high energy electron preparation. To do this this the project developed a model for the loading of electrons into the quantum dot which was then validated by experimental data. The role of relaxation for the outcome of initialisation was clarified [2] by the project and was found to be crucial.

The project's newly developed tomographic techniques were also used to characterise the state, including the energy and time distribution, of electron wave-packets excited at low energy. In addition to high-energy and low-energy electron wave packets, a third type of electron wave packets were also examined in the project, these were electron wave packets excited by Lorentzian voltage pulses. The temporal width of this third type of electron wave packets was characterised, and for all three wave-packets sufficiently small temporal widths (< 1 ns) were observed [3].

The characteristics of the Quantum Hall Effect (QHE) breakdown were studied by the project, on (i) graphene grown by Chemical Vapour Deposition (CVD) on Silicon carbide (SiC) [5] and (ii) Hexagonal Boron Nitride (h- BN) encapsulated graphene. This was done through the measurement of the temperature and current dependence of the dissipation. The project demonstrated the effect of a graphite gate close to the graphene layer on the QHE breakdown properties. A small AC current was injected to test the detection sensitivity in the QHE breakdown due to DC current and the frequency dependence of the noise characteristics were determined. The signal-to-noise still needs to be increased for single Leviton detection, nonetheless the project's results on the QHE breakdown mechanism are significant and highly relevant for the application of graphene in resistance metrology.

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).:

The transmission of single electrons through a Fabry-Perot cavity was studied as prerequisite for single-electron wave packet interferometry. The project observed a modulation of the transmission of single-electrons with a contrast close to 20 % when varying the magnetic field and more than 50 % when varying the gate voltage at a plunger gate at one side of the cavity. The project also used the variation of the current with the plunger gate voltage in order to sample the time-dependent electric field generated by a time dependent voltage locally at 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 was around 0.1 ns (close to the limit imposed by the width of single electron pulses) and the space resolution was < 1 µm corresponding to the width of the gate finger. The project also found that time dependent magnetic field sensing is possible analogous with a spatial resolution corresponding to the typical size of the cavity (2 µm for the smallest cavity).

A Mach-Zehnder type interferometer of much smaller size was developed based on the quantum Hall valley beam splitter (developed in Objective 1) in a p-n-junction in graphene with an active area of 0.15 μm^2. A strong current modulation with visibility of nearly 1 as function of applied magnetic field and side gate voltage was demonstrated by the project and can be used for the basis for future wave-packet based time dependent sensing of magnetic fields with sub-micron resolution [9]. Further to this the project demonstrated graphene based interferometric sensing: the interferometric signal in the p-n-junction device was very sensitive to a phase shift and to decoherence due to excitations generated in the quantum Hall system, whose edges are used to form the wave guides of the interferometer. For a quantum Hall ferromagnet, at a filling factor $\nu = 1$ with full valley and spin polarisation of the electrons, the low energy excitations carry a magnetic moment and are called magnons. The effect of these magnons on the single-particle wave packets traversing the p-n junction interferometer were successfully demonstrated by the project and used to extract information on the magnon emission process [14].

4. To develop concepts and theoretical tools for full quantum state tomography to enable the realisation of quantum enhanced measurements using electron wave packets:

A protocol was developed for the quantum tomography of single-electron wave packets using dynamic scattering and based on a fully quantum-mechanical model. This protocol was applied to the experimental data (from Objective 2) for the measurement of the energy-time distribution of high-energy electrons. The protocol was also used to measure the quantumness of the wave-packets in this initial test; as this is an important characteristic for the application in interferometry.

Further to this, the developed protocol for the quantum tomography of single-electron wave packets was used (i) for the optimisation of the wave packet source for emission of states with higher purity and (ii) for the characterisation of the quantum state properties [4]. The effect of experimental RF bandwidth on the fidelity of tomography results was also investigated and found to not be a limiting factor.

The project theoretically studied quantum scattering of single-electron wave-packets by dynamical barriers and used the results to optimise the new tomography protocol. The results of the theoretical study were also used to establish a theoretical framework to determine quantum limits on resolution of single-electron signal-sampling techniques [6].

The project developed a method for the control of the overlap of split wave packets in the Mach-Zehnder geometry (from Objective 3) for high-energy electrons. It did this by tuning their drift velocity in the split paths independently. Decoherence effects in high-energy Mach-Zehnder interferometry were also studied and strategies for improving the visibility of interference determined [8]. In addition, analytical and numeric modelling of Mach- Zehnder interferometry with realistic energy-time distributions of high-energy single-electron wave packets were used to examine the effect of asymmetric arm length. The results of this revealed additional design criteria (e.g. carefully tailored asymmetry) which are needed for optimised interferometer visibility [13].

A quantum tomography protocol for low-energy electrons (< 1 meV) has been developed by the project. It was based on the analysis of two-electron collision experiments in the HOM geometry from Objective 2. The quantum tomography protocol for low-energy electrons was used to characterise the temporal and energy distributions of low-energy single electron wave packets. The protocol 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]. The tomography protocol for low-energy electrons was further refined by the project, by the introduction of a signal-processing algorithm based on orthogonal elementary single-particle states, the electronic atoms of signals [11]. This project output is an important step towards the signal processing of quantum electrical currents.

Impact

The project has fostered the application of single-electron wave packet devices for quantum metrology and the European metrology capabilities for quantum technology through (i) training workshops for partners, stakeholders and collaborators, (ii) publications, (iii) conference presentations, and (iv) liaisons with relevant industries and standards bodies. In particular contact with the Quantum Community Network, which is part of the Flagship on Quantum Technologies governance structure, was established and one of its members, become a member in our project’s Stakeholder Committee.

Impact on industrial and other user communities

The early uptake of the project’s results by industry has already occurred and is expected to continue. Examples include:

- Two stakeholder institutions (KRISS (the Korean NMI) and the Korea Advanced Institute of Science and Technology (KAIST) have started to implement single electron quantum optics experiments from Objectives 1 & 2 following discussions with the consortium.
- Partners PTB and NPL have had discussions with scientists at the basic research laboratory of stakeholder Nippon Telegraph and Telephone Corporation (NTT in Japan), on the implementation of single electron quantum optics techniques from Objectives 1 & 2 in silicon based single electron devices manufactured at NTT.
- Partner NPL engaged with an industrial supplier of RF components used to carry the microwave signals that control and readout qubits in prototype quantum computers. The project’s new measurement capabilities on hot electron quantum optics in Objective 1 could be used to test and validate elements in the RF signal chain, particularly those at low temperature. Tests of cryogenic multi-terminal RF interconnects have been conducted with Intelliconnect, who are a leading manufacturer of RF connectors, adaptors and cable assemblies.

More generally, the uptake of the project’s local time resolved sensing of electric and magnetic control fields (Objectives 2 & 3) into devices used for quantum technology development and evaluation, should allow the direct measurement of these fields at relevant time scales and support the development of scalable semiconductor technology for quantum computation and simulation. Similarly, the adoption of the project’s quantum tomography techniques (Objective 4) is expected as a diagnostic tools to support the evaluate the performance of quantum state control and manipulation in dedicated technology test applications. Further to this, the project’s demonstration of magnon detection (Objective 3) and examination by single-particle interferometry has shown the prospect of quantum sensing of a wider range of signals.

Impact on the metrology and scientific communities

The project has disseminated its outputs to the metrology and scientific communities via 14 open access publications in journals such as Physical Review X, Physical Review Letters, Nature Communications and Nature Physics, as well as 34 posters/presentations at conferences.

The project's results have advanced research in electron quantum optics and introduced new technologies like single-electron detection (Objective 1 & 2) and new concepts for quantum state tomography (Objective 4). The project has also advanced the understanding of the QHE breakdown in high-mobility encapsulated graphene (Objective 2). Furthermore, the project's new experimental tools for on-chip time resolved sensing and advanced single wave packet detection and characterisation (Objectives 2 & 3) will advance academic research on quantum physics in solid state systems. The project's research on the optimisation of high-energy single-electron pumps (Objective 1 & 2) will also be used in further improvements of single-electron quantised current pumps for the realisation of the quantum ampere in the new SI [10]. The understanding of the electron back-tunnelling and emission processes examined in [2,4,7] is directly related with the accuracy of single-electron sourcing. A very recent result of the project published as preprint [arXiv: 2112.10713] on new schemes for operating high-energy single-electron sources could also allow easier operating conditions for single-electron pumping for quantum current generations. This work will be furthered in the electrical quantum metrology activities at partner PTB. A further improvement for quantised current sourcing is the use of fast time dependent beam-splitters as used in Objective 2 [4] for a filtering of erroneously sourced electrons. This work will be furthered in the electrical quantum metrology activities at partner NPL.

The project's liaisons with the quantum technology community have resulted in participation in a technology roadmap paper on quantum nanotechnologies, in which partners contributed a section on applications of high energy single-electron sources for metrology [10].

The project engaged with a stakeholder (University of Waterloo) from the quantum technology community who had special device fabrication knowledge. This collaboration resulted in the validation of dopant-free single-electron technology for use in quantum metrology [12] and offers a new path towards jitter-free single-electron wave-packet based quantum optics devices with improved performance.

The project's results on dissipation mechanisms in high mobility h-BN graphene in the QHE regime and the study of gating effects (Objectives 2) have provided a first step towards implementing van der Waals graphene heterostructures for quantum Hall resistance standard application at low magnetic fields. These results are also relevant for the implementation of devices equipped with a gate involving the quantum anomalous Hall effect at zero field. Follow on work is already planned at partner LNE.

To encourage uptake and dissemination to a wide range of stakeholders in the metrology and scientific communities the project held two internal workshops. The first was a workshop on single electron quantum optics for quantum enhanced measurements in October 2019, which gave an overview of the state-of-the-art metrology research, including results from the project. The second workshop on Quantum Electrical Metrology, was a foresighting exercise, and provided an opportunity to see how such emerging technology may meet long term societal challenges and end-users needs. Finally, a 2-day final online project workshop with more than 100 participants was organised by the consortium in October 2021. This workshop had participants from 14 countries, representing key stakeholders, the metrology community and the quantum science research community. The workshop was on Single-Electron Quantum Optics for Metrology and was preceded by introductory tutorials, followed by presentations from the consortium and renown researchers from the field of quantum technologies.

Impact on relevant standards

Due to the early stage of quantum technology, no standards currently exist yet for quantum information processing or for other electronic quantum bit-based devices. However, the commercialisation of such technology will require standardisation for relevant properties of quantum states or quantum devices and procedures for measurement or verification. This project has contributed important knowledge to standardisation bodies in the areas of electrical quantum metrology in order to foster the production of future standards. Project partners of the project have participated in and presented the results of the project to EURAMET Technical Committee Electricity and Magnetism (TC-EM) Sub-committee (SC) DC and Quantum Metrology, IEC TC 113 Nanotechnology for electrotechnical products and systems WG3 Performance assessment, DKE K 141 Nanotechnology and BIPM and CIPM's Consultative Committee for Electricity and Magnetism (CCEM).

Longer-term economic, social and environmental impacts

This project has developed new measurement techniques to support the development of semiconductor quantum technology in Europe. The project's new techniques were based on the use of on-demand single-electron quantum optics and have enabled the characterisation of (i) the quantum state of electrons in semiconductor quantum devices and (ii) quantum enhanced sensing based on the technique of single-electron quantum optics. The project's outputs have provided underpinning metrology for the rapidly evolving field of quantum technologies, thereby supporting future IT technology, the European IT industry, and hence future employment in this sector. In the longer-term, the research and development of scalable quantum solid state technology will be a key technology for future applications and high-tech products is highly beneficial for the advancement of the European information technology industry.

List of publications

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9. M. Jo, P. Brasseur, A. Assouline, G. Fleury, H.-S. Sim, K. Watanabe, T. Taniguchi, W. Dumnernpanich, P. Roche, D. C. Glattli, N. Kumada, F. D. Parmentier, and P. Roulleau, *Quantum Hall Valley Splitters and a Tunable Mach-Zehnder Interferometer in Graphene.* Phys. Rev. Lett. **126**, 146803 (2021). DOI:10.1103/PhysRevLett.126.146803
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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 May 2018, 42 months	
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