Title: Detection and characterisation of quantum phase slip for development of nanoscale quantum circuits

Abstract

It has been predicted that Quantum phase slip (QPS) will give rise to electrical quantum phenomena in ultra-narrow superconducting nanowires, which are dual to the Josephson effects. Recent experimental data suggest that QPS is just at the border of unambiguous demonstration. Detection of quantised current steps under a microwave drive, analogous to Shapiro voltage steps, would simultaneously demonstrate QPS and the prototype of a new quantum current standard. New metrological techniques are needed for electrical characterisation of nanowires that exhibit QPS. These will aid the development of QPS devices such as electrometers, microwave detectors, parametric amplifiers and qubits, with potential impact similar to SQUIDs.

Conformity with the Work Programme

This Call for JRPs conforms to the EMRP Outline 2008, section on “Grand Challenges” related to Health, New Technologies & Fundamental Metrology on pages 9 and 25.

Keywords

Nanofabrication, nanowire, superconductivity, quantum phase slip, electrical metrology, kinetic inductance, kinetic capacitance, qubits, sensors.

Background to the Metrological Challenges

Nanotechnology is a major driving force for economic growth in the EU. As elements reach the nanoscale, their behaviour becomes governed by quantum effects. There is a need to develop metrological tools to characterise and optimise these effects in order to (a) utilise the effects for the development of novel nanoscale devices, (b) understand the ultimate limits that the effects post on the device characteristics.

New nanofabrication techniques will be needed to create reproducible ultra-narrow superconducting nanowires and associated circuit elements. The dimensions required are challenging, and are pushing the limits of what is currently possible. Miniaturisation of electrical components will require a transition from the use of geometrical parameters such as capacitance and inductance to their kinetic (non-linear) counterparts, in order to keep their values at a practical level. New superconducting materials like NbxSi1-x, whose properties vary according to Nb content, are required to enable the design of kinetic inductors and capacitors with a wide range of values.

A few years ago, important results showing Coulomb blockade in superconducting nanowires embedded in a high-ohmic environment were obtained in academia, but no new results have been reported since. A JRP from the 2008-2011 EMRP programme has recently yielded similar results (T1 J1.3 REUNIAM). These observations are prerequisites of unambiguous demonstration of QPS. Even more recently, a charge-transistor effect has been demonstrated in a double QPS circuit with capacitive gate and on-chip Cr resistors. The interpretation of this result in terms of interference of coherent QPS events (an effect dual to quantum interference in an overdamped DC-SQUID) is currently being verified.

The state of the art in the fabrication of superconducting nanowires using Al and Ti resides in academia. NMIs have also made progress recently, particularly in the improved adhesion of Ti to the substrate. The state of the art in NbSi nanowire technology resides both at NMIs and in academia. An NMI has pioneered technology of fabrication of highly resistive thin-film Cr-O resistors.

The resolution of the commercial e-beam lithography systems owned by NMIs and academic institutes limits the widths of the nanowires that can be achieved. To create narrower nanowires (to enable the use of materials with a wider range of characteristics), new fabrication techniques are needed. The current nanowire widths that can be achieved are as follows: NMIs: 15-20 nm, academic institutes: ~ 5 nm. For comparison, some of the most recently released computer processors (January 2011) have a feature size of 32 nm.

Scientific and Technological Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the JRP-Protocol.

The JRP shall focus on the development of new techniques for electrical characterization of nanowires that exhibit Quantum Phase Slip (QPS) in order to enable metrological applications of such devices.

The specific objectives are

1. Development and characterisation of materials and nanostuctures to provide an unambiguous, reproducible detection of QPS, including
   - superconducting thin films with designed parameters
   - development of nanofabrication techniques capable of producing superconducting nanowires with sufficiently small cross sectional area to enable the detection of QPS.
2. Development of metrological techniques for the characterisation of nanoscale devices exhibiting QPS including the measurement of inductive energies, damping strength and electron temperature, as well as the analysis of the role of possible intrinsic dissipation and possible immunity to background charge noise, both in the DC and microwave regime.
3. Development and characterisation of devices based on QPS technology and the novel materials associated with it. For example:
   - thin film high-ohmic resistors of compact design, capacitors with low-loss dielectric and inductors, which are capable of providing the electrical parameters required to enable detection and utilisation of QPS;
   - nonlinear resonators allowing parametric conversion and bifurcation-based detecting of weak signals, sensitive and fast dispersive electrometers, superconducting qubits without Josephson tunnel junctions and prototype quantum current standards.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research, the involvement of the appropriate user community such as industry, and standardisation and regulatory bodies, is strongly recommended.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. The proposed JRP should clearly explain any relationship with existing results delivered from previous EMRP JRPs and demonstrate how it extends any relevant outputs from such JRPs.

The total eligible cost of any proposal received for this SRT is expected to be around the 2.7 M€ guideline for proposals in this call.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community. This may be through the inclusion of unfunded JRP partners or collaborators, or by including links to industrial/policy advisory committees, standards committees or other bodies. Evidence of support from the “end user” community (eg letters of support) is encouraged.

You should detail other impacts of your proposed JRP as detailed in the document “Guide 4: Writing a Joint Research Project”

You should detail how your JRP results are going to:

- feed into the development of urgent documentary standards through appropriate standards bodies
- transfer knowledge to the nanotechnology sector.

- transfer knowledge to the metrology community and other potential users, eg: superconductivity detector/sensor technology.

You should also detail how your approach to realising the objectives will further the aim of the EMRP to develop a coherent approach at the European level in the field of metrology. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of Member States and countries associated with the Seventh Framework Programme whose metrology programmes are at an early stage of development to be increased
- outside researchers & research organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.