Final Publishable JRP Summary for NEW08 MetNEMS
Metrology with/for NEMS

Overview

Micro electromechanical systems (MEMS) are well-established in consumer products such as electronic displays, inkjet printers, car airbags and engine control systems, however there is increasing demand for more complexity, speed and performance combined with smaller size. Nano-Electro- Mechanical Systems (NEMS) is an emerging technology that can provide a potential solutions to a range of technological barriers for sectors including ICT, physical sensors and biological sensor applications.

This project addressed the need for traceable measurement by developing novel high-frequency, high-performance NEMS devices, which were tested and validated using new specifically developed methods. Using the new measurement techniques it was possible to optimise fabrication techniques and new materials for NEMS devices. Arrays of NEMS devices were also tested. Dynamic cooling methods for measurements beyond the limit of thermal noise were also investigated, as well as the integration of NEMS with Superconductivity Quantum Interference Devices (SQUIDs).

Need for the project

The trend towards ultra-miniaturisation in electronic components and circuits is mirrored by a similar trend in sensors and in the scale of measurement requirements. These trends pose extreme challenges and NEMS are an important part of the solution. Unlike electrical circuits, which are approaching some hard limits in size and frequency, NEMS devices have yet to be exploited at their limits of size or performance. They have the potential to offer measurement and sensor capabilities which exceed conventional electronic approaches for many applications.

If the metrology community does not anticipate and meet industries' metrological needs technological growth in Europe will be significantly limited. In the short term this project will yield highly innovative metrology with wide ranging applications. In the longer term major new security, biotechnology, IT and QIP (Quantum Information Processing) applications are expected, as well as enhanced quantum metrology. NEMS resonators and actuators will address several leading scientific challenges including 'nanotechnology, ultra-low-loss new materials, and metrology of single entities, leading in turn to future traceable measurement requirements in the bio, security, telecoms and sensing areas.

If Europe is to remain competitive in innovative industries with the USA and Asia it is crucial to address the challenges of measurement at the nanoscale. The project is very challenging; no single organisation can provide all the required capabilities at the leading edge, so collaboration with leading research academics and industrials is essential.

NEMS devices can detect single photons and single molecules; and general force, displacement, mass and voltage sensing at the nanoscale. However, there was no metrological framework for the robust assessment of NEMS prior to the start of this project. In order to exploit NEMS devices the limits of their performance needs to be measured and determined. Then new and improved NEMS devices can then be designed and fabricated using existing (aluminium nitride and silicon) and new materials, such as graphene and magnesium diboride (MgB_2). Testing and validating the performance of the NEMS devices will also require new measurement methods.

Nanoscale devices, fabricated on silicon (Si) chips, will increasingly demand nanoscale on–chip measurement standards such as voltage and temperature. At the nanoscale, the definition of local temperature becomes unclear and understanding temperature is important as it is crucial to performance. In addition, the coupling between microwave and NEMS devices leads to the phenomenon of dynamic cooling, which needs to be investigated in order to achieve measurements 'beyond the classical' limits of thermal noise. SQUIDs are

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measurement devices that are very sensitive and used at low temperatures. New designs for the integration of SQUID-NEMS combinations need to be developed to enable the operation of NEMS resonators at very low temperatures close to the thermal equilibrium quantum limit (i.e. mK-temperatures).

Scientific and technical objectives

The main objective of this project was to develop the measurement capabilities in NMIs project partners to meet the needs of NEMS developers. Improved measurement methods and traceability are crucial to validate device modelling and to understand their operational behaviour.

The project aimed to identify the most suitable materials and fabrication techniques for NEMS devices (objectives 1 and 2), and develop methods to test the performance and cooling methods (objectives 3 and 4) and test arrays and combinations of NEMS (objective 5). The project had the following objectives:

1. To optimise novel materials for high performance NEMS
2. To develop innovative near-field microwave resonator excitation and readout techniques
3. To develop NEMS sensors, references and detector arrays for traceable electromagnetic metrology and precision instrumentation
4. To develop dynamic cooling methods to enable measurement 'beyond classical' thermal limits.
5. To fabricate and optimise cryogenic SQUID-NEMS combinations, enabling the operation of NEMS resonators at close to thermal equilibrium quantum limits (mK-temperatures).

Results

1. To optimise novel materials for high performance NEMS

The selection and optimisation of materials is vital for optimising performance with the resulting application potential of NEMS structures. Several materials, including graphene and MgB_2, were investigated for NEMS use at either room temperature or cryogenic temperatures. Graphene was tested for NEMS use at room temperature. The project demonstrated, using methods from objective 2, that graphene has extremely desirable properties for the performance of NEMS resonators, such as high strength and low mass density. A non-contact method for the measurement of graphene resistance was also developed [9, 21].

Researchers at Imperial College and NPL investigated the use of graphene and Si materials for NEMS by developing chemical vapour deposition growth onto silicon nitride and silicon dioxide [22, 34]. The performance of these Si and graphene NEMS was tested and was found that Si NEMS were good for low frequency applications, whereas graphene NEMS were better for high frequency applications where higher sensitivity is required.

For NEMS resonators operating at cryogenic temperatures (below −150°C), INRIM fabricated a prototype cryogenic resonator based on superconducting MgB_2 nanowires. Superconductivity is the property of zero electrical resistance below their critical temperature. Thus, the advantage of using a superconducting NEMS resonator is that the applied excitation is proportional to the oscillation/readout which means that it can then be maximised to produce high performance NEMS. The advantage of using MgB_2 is that its critical temperature at which it becomes a superconductor is approximately 40 K higher than traditional superconductors and therefore less cooling is required.

2. To develop innovative near-field microwave resonator excitation and readout techniques

The main technological objective of this work was to identify a method to determine the exact trajectory of motion of the moving element of a MEMS/NEMS oscillator.

Two methods were developed for NEMS resonator excitation and readout, which were able to simultaneously excite and detect the oscillation (i.e. the motion of the moving element) from a mechanical NEMS resonator. One of the systems was developed by NPL, who produced a novel system based on near-field microwave excitation and readout which was capable of detecting the oscillations/displacements from a range of extremely small NEMS resonators; ranging in size from hundreds of microns to submicron lengths [3], [18].

The second system was an optical method for NEMs readout and excitation based on stroboscopic scanning white light interferometry (SSWLI). The SSWLI system was used for the measurement of both moving samples and hidden NEMS structures, which are an important issue for the nano-electrical industry in terms of understanding nanostructure motion due to thermal effects so as to avoid electrical shorts. The SSWLI system was modified and used to create calibration methods and transfer standards necessary for the first ever characterisation of vertical movement of NEMs.

A comparison between the SSWLI system (of UH and MIKES) and the near-field microwave system (of NPL) showed that vertical movement of a NEMS resonator at 10.7 kHz could be reliably measured using both. In addition, the NEMS resonator was stable enough to be used as a transfer standard for the comparison of measurements between the project partners and to provide calibration of NEMS structures.

The objective was achieved by developing and correlating two methods for NEMs readout and excitation which were able to determine the trajectory of motion of the moving element of a NEMS oscillator. These methods were then used to validate the performance of the NEMS devices in the other objectives.

3. To develop NEMS sensors, references and detector arrays for traceable electromagnetic metrology and precision instrumentation

This objective aimed to develop architectures for integration/readout of NEMS sensors, references and arrays. NEMS sensors can be used as ultra-sensitive mass detectors, potentially important for single-molecule mass spectrometers. However, such sensors require both ultra-low mass resonators and ultra-sensitive read-out mechanisms. NPL and researchers at Imperial College (developed NEMS sensors that could meet these performance requirements using single layer graphene mechanical drum resonator arrays (from objective 1) coupled to NPL's near-field microwave excitation and readout method (from objective 2). The performance achieved so far with the NEMS sensors has been very positive and has allowed the project to predict that attogram mass sensitivity is achievable.

MIKES built a test set-up for the electrical properties of MEMS using the MEMS/NEMS materials from objective 1. Using this a MEMS-based detector for voltage and a MEMS voltage reference were developed.

For use at cryogenic temperatures, INRIM designed, fabricated and characterised (NEMS) nano-Transition Edge Sensor (TES) photon detectors using their superconducting MgB_2 NEMS (from objective 1). These nano-TES photon detectors can be used as an absolute calibration technique for photon number and to measure quantum efficiency.

PTB developed different types of novel nanoSQUID gradiometers and current sensors with nanoscale hafnium- titanium SNS (superconductor-normal metal-superconductor) junctions, as well as a new niobium thin film process to enhance the quality of SQUID current sensors. For the readout of NEMS sensors, PTB developed novel nanoSQUID current sensors that operated with modified SQUID electronics from project partner MAG, a leading supplier of high performance SQUID electronics. MAG and PTB now have the experience to commercialise of these new nanoSQUID sensors, which is currently in progress.

4. To develop dynamic cooling methods to enable measurement 'beyond classical' thermal limits.

Dynamic cooling is a key technological innovation that allows measurements at the nanoscale, or 'beyond the classical' thermal limits (i.e. the limits of thermal noise), and can be achieved through the coupling of microwave and mechanical NEMS resonators. NPL developed their own microwave based dynamic cooling technique using the near-field microwave methods (from objective 2) coupled with the high performance graphene NEMS resonators (from objective 1). NPL's microwave based dynamic cooling technique demonstrated measurements 'beyond the classical' limits of thermal noise for force and mass. NPL's microwave based dynamic cooling technique also showed significant temperature reductions (i.e. dynamic cooling) at room temperature.

In addition, Imperial College and NPL modelled the microwave based dynamic cooling technique, specifically the effect of coupling strength between the near-field microwave resonator and the mechanical high performance NEMS resonator. From this, they found that the electric field around the sharpened tip of the NEMS resonator could be enhanced by several orders of magnitude, and this enhancement allowed NPL to demonstrate that coupling between the near-field region of an open-ended microwave NEMS resonator and a conducting mechanical cantilever can be used for both excitation and detection of the motion of the cantilever 'beyond classical' thermal limits.

Dynamic cooling from 300 K to 60 K was also demonstrated for NEMS by the project using detuned microwave excitation [18].

5. To fabricate and optimise cryogenic SQUID-NEMS combinations, enabling the operation of NEMS resonators at close to thermal equilibrium quantum limits (mK-temperatures).

NEMS sensors combined with SQUIDs were developed to enable the operation of NEMS resonators at temperatures close to thermal equilibrium quantum limits. As part of this the cryogenic temperature NEMS from objective 1 and the SQUIDs from objective 3 were integrated and tested.

The SQUID-NEMS combinations were designed and fabricated using different techniques by different NMIs. The performance of the SQUID-NEMS combinations was then characterised using low temperature (4.2 K to 35 K) measurement capabilities developed at NPL, PTB, INRIM and researchers at Royal Holloway. Royal Holloway also developed a SQUID-based measurement setup for investigating the properties of NEMS resonators using high stress silicon nitride beams at ultra-low temperatures.

Finally, PTB established a new method using electron-beam lithography and chemical-mechanical polishing to fabricate novel nanoSQUID gradiometers with nanoscale HfTi (hafnium titanium) SNS (superconductor-normal metal-superconductor sandwich) junctions. These nanoSQUID HfTi SNS devices were then coupled to NEMS using NPL's established Focussed Ion Beam technique, and are the first ever example of nanoscale HfTi SQUIDs-NEMS combination.

Actual and Potential Impact

Dissemination of results

The project results were presented and shared with a broad range of scientific stakeholders and industrial end-users. A total of 35 papers were published in high impact journals and 92 presentations were made at international and national conferences such as the International Symposium on Precision Engineering Measurements and Instrumentation (ISPEMI), the International Superconductive Electronics Conference (ISEC), the Micromechanics and Microsystems Europe Conference (MME) and the IEEE International Conference on Nanotechnology.

The project hosted five successful end-user workshops, one sponsored by Oxford Instruments plc (a UK based manufacturing and research company). The final workshop was attended by a number of companies, particularly SMEs such as TDK-Lambda GmbH (a German based manufacturer of power supply units and converters for industrial and medical applications) and Entropy GmbH (a German based manufacturer of systems for ultra-low temperature measurements).

Input to standards

At least seven separate inputs to standardisation bodies have been made during the project, including EURAMET TC-L Technical Committee for Length, the IEC TC90 committee on Superconductivity - WG 14 Superconducting electronic devices, CIPM/CCEM Consultative Committee for Electricity and Magnetism and the EURAMET TC-EM Technical Committee for Electricity and Magnetism. The results from the project were presented, as well as input to a draft regulation on the generic specification for sensors and detectors for IEC TC90 WG14 superconducting electronic devices.

Early impact

The project addressed the development of sensors based on NEMS to provide traceable nanoscale metrology for the characterisation of materials, and other novel sensors at the micro/nano scales necessary for wider applications. An improved understanding of graphene mechanical resonators was achieved and novel excitation and readout methods for these promising nano-sensors were developed. A non-contacting method for the measurement of graphene sheet resistance was also developed and has attracted much industrial attention for measuring the electrical properties of other 2D materials as well as graphene. Semimetrics Ltd, a UK based SME that provides solutions for semiconductor measurement problems, is keen to develop and commercialise the non-contact method.

The novel nanoSQUID current sensors were developed by PTB and operated with modified SQUID electronics from project partner, MAG (Magnicon), a German supplier of high performance SQUID electronics. The low-noise nanoSQUID sensors/arrays and customised SQUID systems developed in this project are also being commercialised.

Potential future impact

The enhanced sensor capabilities emerging from the project will have a positive impact on the development and deployment of NEMS-based sensors in areas such as security surveillance (through smaller and more sensitive sensors and detectors) and biosensors in the medical sector. NEMS sensors can also be used as ultra-sensitive mass detectors and NPL is already collaborating on a proposal to use NEMS biosensors to distinguish between the mass of different types of cancerous cells.

In the longer term the outputs of the MetNEMS project will provide improved ultra-sensitive, traceable measurements and traceable metrology for mass, force and displacement, temperature, single photon and single molecule measurement at the nanoscale, as well as the potential for on-chip ultra-stable miniaturised voltage references. The results of the MetNEMS project will support the development of metrology beyond the 'conventional classical limits' and will help address the implications of quantum measurement in nanoscale metrology.

List of publications

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