Name of Quantum Technology

Quantum Sensors

What is the potential vision for this area?

In the next 5 years…

- Fast telecoms wavelengths detectors with high fidelity
- Nano- scale, biologically compatible temperature sensors
- Single molecule MRI
- Q Sensor arrays?
- Gravity sensors for oil, gas, minerals and defence
- Miniature optical clocks
- High efficiency devices, exploiting correlation effects e.g. in quantum materials
- Single local "atom" sensors to image/probe (e.g. magnetic/electro field for storage
- Non invasion detection of local & transient phenomena is materials
- Electromagnetic field sensors with higher performance than classical sensors (sensitivity re solution, field of view, speed, tini resolution
- Integrate graphene multi layers with old atoms to achieve hybrid quantum systems that overcome and present limitations on size and power consumption
- Implanted sensors improving health
- Miniaturised sensors for deployment in the field
- Improved magnetic sensing – heart, brain imaging (real time)

- Industry view ! Where is the market for a quantum sensor based product - How do we make money out of the science?
- High sensitivity, portable gravimeter Improved sensitivity for oil prospecting and security
- Demonstration of quantum imaging through turbulence at a range ~ 1 km

In the longer term…

- Remote sensing by EPR entanglement (Quantum II)
- Quantum chips for accelerometry, gyroscopes, gravimetry, magnetometry, timekeeping
- Transformative biomedical imaging
- Will my company invest real money in quantum technology? - Not yet
- We'll maintain a watching brief
- Energy harvesting by quantum sensors
- Future relativistic quantum technologies
- Imaging through walls
- Inertial sensors for precision navigation
- Determine: structure/properties/ interactions of soft/solid state matter in real time with high spatial and energy resolution at ambient conditions
- Chip - sized quantum sensors
  - gravity
  - Magnetic field
  - Clock
  - Inertia etc
- Easy mapping of the gravitational field, effective use for geological prospection, civil engineering (mapping of the underworld) and archaeology
- Enabling internet-of-things?!

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What prevents this vision from being realised?

Research challenges to overcome...

- Going from lab experiments to useful sensors portable, robust etc.)
- Quantum codes - Space time systems
- New signal processing algorithms
- Prototyping
- Engineering of Quantum Sensors
- Full understanding of many body effects
- Minimizing and controlling fluctuations
- Decoherence of the environment
- Miniaturization and integration error correction
- Error compensation control sequences
- Material uniformity
- Intelligent gravity inversion
- Sensitivity sealing methods (e.g. large momentum beam splitter)
- Noise modelling
- Development of novel sensor schemes with noise immunity
- Heterogeneous integration to build complete quantum sensor systems
- Fast and reliable “classical” readout
- Interface between quantum and classical input/output
- Making miniature gravimeters with high sensitivity
- Lack of understanding (for quantum materials)
- Single atom XXXX – chip based
- Fast image recovery for real time video (Q Imaging)
- Scale up of technology to size for applications

Scientific / technological barriers...

- Reproducible positioning and properties of sensors (Nano-scale quantum systems)
- Communication of Q sensing ideas to non-quantum people
- Integrated lasers – photonic circuits
- ASICS for laser control
- Small, passive ultra-high vacuum chambers
- Packaging and interfacing
- Software for automatic operation
- Miniaturisation of bulky (and power hungry) technology
- Embed industry in academic departments
- Will a quantum sensor offer something a conventional sensor cannot offer? – If it can’t it’s doomed
- Ultrastable laser systems with sub- Hz line width
- Small optical isolations for visible and near IR wavelength
- Vibration control
- Internal platforms in small scale
- Quantum models
- Groups not working together: researchers should collaborate by theme not institutional alliance
- Material compatibility
- Fabrication process compatibility
- Constructible atom sources
- Integration of quantum sensors in silicon-based technology
- Difficult to scale up
- Can anyone design and manufacture something that the rest of the world wants to buy? market pull – technology push
- Ability to control and manipulate on atomic scale structure / properties of “Quantum” Materials
- Who, outside university laboratories will be able to manufacture quantum devices?

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What can the UK do to deliver this vision?

What we currently know... Silicon is really good

- Sensing via single quantum systems
- Sensors beyond SQL using e.g. squeezing / entanglement/discord?
- Niche to wide-interest applications
- require survival of quantum-ness in ambient /messy / noisy systems
- Integration of solid state quantum sensors in conventional silicon electronics
- Atoms, light and matter can all form the basis of sensors; each with different advantages
- Relativistic effects can also be exploited tom improve quantum sensing devices arXiv:1307.7082
- Some quantum sensors realised in the lab are already better than their classical counterparts (e.g. gravity measurements by atom interferometry)
- Atom interferometry
- Quantum effects can be exploited for sensing / energy harvesting
- Enhanced light-matter interactions in Nanostructures metal/ semiconductor materials

What we need to know...

Device design

- How will a quantum device talk to the real (classical) world
- Integration with existing technology – eg silicon
- How does an iPhone tilt sensor work?
- How to miniaturise chip-based quantum sensors? – e.g. 1) near-surface atom trapping, (2) Small UHV systems , (3) integrated optical traps on a chip
- Use quantum field theory which properly incorporates quantum theory and relativity to measure gravitational field strengths acceleration etc. – arXiv1307.7082
- Goal orientation surface passivation techniques – diamond, silicon, functional oxides
- Understand the market (could be in closer reach than the other 4 themes)
- Draw on the expertise of the UK semiconductor community to produce the next generation atom Chips for portable clocks and quantum sensors etc. Current atom chips are similar to electronic devices before the advent of the transistor
- Some needs are identified (gravity, inertial, magnetic sensing), by know industry (oil & gas etc) but better knowledge / understanding of industrial needs is required
- Robust (error-resistant) protocols – how to fabricate without roughness / defects / materials problems
- How can we make quantum-ness survive in noisy/messy/ambient systems
- Is a single platform sufficient or do we need hybrid systems and interfaces
- Hybrid devices – gas-phase/ solid state
- Chip-based device
- Quantum classical
- Get better understanding / control of the priorities of quantum materials
- Real world noise sources and their compensation

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What can the UK do to deliver this vision?

What should the UK do differently?

- Facilties from technology open for researchers (Silicon/ III-V/Supercond)
- open up the present "cartel" to other universities doing research on quantum phenomena and quantum device
- Seek international advice rather than the UK only
- Ensure that there is independent expert input to decisions, themes and priorities chosen by RCUK
- Define sensors more broadly than just those based on entanglement and superposition
- Cross disciplinary funding
- Encourage collaboration between atoms, light and Matter communities
- Take care to avoid conflicts of interest on panels: it seems to me that these are occurring in the QT arena e.g. patients shared by assessors and the assessed .
- Are we prepared to fund this area properly? How does our budget compare with the budget of other countries?
- Multidisciplinary research teams
- Coherent funding from basic demo (EPSRC)– development (TSB) – exploration
- Clarify whether interferometers actually fit under this category (presumably they should?)
- Influence future calls from TSB and H2020 to fund specific QT challenges (similar to DARPA)
- Identify grand challenge questions in broader science community relevant for sensing
- Invest in novel sensing concepts & materials
- Provide more direct sources of grant-based PhD studentship on a competitive basis – not just through CDTs, which only favour very large groups
- Technology development requires funding to allow systems demonstrators →exploitation
- Increase basic funding levels – basic research should not be funded based on expected applications – the interesting ones are the unexpected ones!
- Do not narrow funding on only a few hand picked approaches / solutions
- Dedicated workshops with experts across the disciplines
- Complex systems simulation
- Coordinate UK efforts with European and global programmes and funding – emphasize international co-operations (→ UK leadership in EU training + research grants) over competition
- Facilitate internationally co-funded cross-border joint projects
- Include Quantum well infrared photo detectors and avalanche photodiodes
- UK needs an identifiable network/programme for quantum technologies to facilitate collaboration with industry and research organisations
- Put emphasis on practical proof-of-concept demonstrations.
- Structure to support research →applications →product development
- Encourage training in both experimental and theoretical aspects simultaneously