Quantum materials

Quantum mechanics describes how atoms bind and electrons interact at a fundamental level.

Naively speaking, all materials are quantum because all matter, in the end, must be explained by quantum mechanics.

For example, our body is largely made up of water.

In water, chemical reactions bind hydrogen and oxygen atoms together. Although this can be explained by quantum mechanics, we usually don't think about water in these terms, and a high-school-level chemistry description does the job.

This is, because we can often approximate the quantum behaviour in materials by a classical description.

It turns out that a classical description is in fact suitable for most of the phenomena that we experience in the macroscopic world around us.

Sometimes, however, to fully understand the behaviour of certain materials, it is necessary to keep quantum in view: there is no classical explanation to help our understanding.

A feature of the broad category of Quantum Materials is that their behaviour is generally rooted in the quantum world.

And while behaviours observed in quantum materials cover a wide spectrum, there are some common features that recur.

For example, many quantum materials derive their properties from reduced dimensionality. Electrons trapped in 2, 1, or 0 dimensions have different characteristics than electrons in 3D.

Emergence is another recurring theme across quantum materials. Phenomena emerge due to the collective behaviour of original constituents.

In superconductor materials, the interaction between electrons, mediated by vibrations of the crystal lattice, creates the so-called Cooper pairs.

Differently from individual electrons, Cooper pairs can share the same quantum state. Superconductivity emerges from the concerted state of pairs that propagates without electrical resistance through the crystal. Certainly, you need quantum mechanics to understand this!

The first quantum revolution, with the development of quantum mechanics, provided a microscopic understanding of nature. It had a tremendous impact in our life.

Once you understand the periodic table and electronic wave functions, you understand semiconductors and how transistors are built and work. We now carry around billions of transistors in our pockets to perform complex tasks.

It is clear that we need the concept of the photon to understand the laser.

We are currently in the midst of a second quantum revolution, in which quantum matter is engineered to develop disruptive technologies beyond the reach of classical understanding.

Quantum computing is the man on the moon goal of such second quantum revolution. By working in a fundamentally different way, quantum computers have the promise of solving complex problems that classical computers cannot handle.

Quantum materials provide the environment where qubits, the elemental unit of quantum information processing, are defined and live.

Therefore, quantum materials are at the basis of a quantum computer.

To have a working quantum computer you need to couple together many qubits, while maintaining their long coherence time. These requirements are often conflicting.

Qubits that are hard to couple together have long coherence times, because they tend to be isolated. On the other hand, systems that are easy to couple together tend to lose coherence quickly, because they can be perturbed easily by the environment.

In all cases, the precision of the qubit materials is crucial to solve these two challenging requirements. And when we say "precision", we mean precision in terms of: materials uniformity, chemical composition, and electrical properties

Ultimately, to make the phenomenally large number of qubits necessary to build a quantum computer, we would like to use the same manufacturing techniques of the microelectronic industry.

Chemical vapour deposition, or CVD, is an industrial process that uses high purity gases to make high quality materials, with desired physical and electronic properties.

For example, by depositing layers of silicon and silicon-germanium, we can tune the lattice parameter of silicon to be larger than usual and match that one of silicon germanium.

As a result, the electronic properties of such hetero-structure, which is made of different materials, make it possible to form a 2D electron gas at the interface between silicon and silicon-germanium. Qubits can then be made by isolating with electric fields one electron spin at that interface.

If you want to isolate one single electron spin and make it a qubit, you need to know the properties of the host material very well.

Once we make our crystal into a silicon heterostructure, we usually break it, and have a close look at it from the side with a high-resolution electron microscope.

We call this microscope a transmission electron microscope, or TEM.

Its working principle is based on electronic diffraction, another quantum effect, of an electron beam passing through a thin piece of material. The spatial resolution is so high that we are able to see atomic arrangements in the lattice.

In addition, a TEM is capable of distinguishing different elements from each other by their atomic weight.

Therefore, it is a useful tool to analyze materials composition. Light elements appear darker than heavy elements. This allows us to check precisely to what extent, the material we made matches our expectations.

For example, you see here the perfect atomic arrangement of silicon and germanium atoms at the critical interface between silicon and silicon-germanium. The lattice spacing is exactly the same at both sides of the sharp interface, indicating that the CVD process successfully strained silicon to match the underlying silicon-germanium.

The fact that we are able to make crystals with such precision and very little imperfections, is a key asset to then make good qubits.

Once we know how the material we made looks like, we usually study its electronic properties, by modifying them with external parameters.

Temperature, electric fields, and magnetic fields are the few knobs that we turn in our labs to probe quantum materials.

These studies provide useful feedback to make the material a better environment for the qubits.

Take, for example, the Si heterostructure mentioned earlier.

If we cool it to the very low temperatures at which qubits usually operate, say below one degree above absolute zero, it would be insulating.

However, we can make the material conducting by imposing a vertical electric field.

The electric field forms a metallic channel at the interface between silicon and silicon-germanium, which is then populated by electrons. The higher the electric field, the more the electrons in the channel.

By studying how the electrical resistance of such channel responds to a magnetic field, we are able to measure the number of electrons in the channel and their mobility.

The mobility tells us how fast electrons can travel in such channel, and is an indication of the disorder in the system. The higher the mobility, the lower the disorder, and there will be a better chance of fabricating many qubits with similar properties.

Materials homogeneity is one requirement to scale up the number of qubits into a quantum computer. Think of the billions of transistors in your laptop, if they were all behaving differently, there would be no chance of having them to work for you.

And while we are currently optimizing quantum materials to build a quantum computer, ultimately, the hope is that when such a machine will exist, one of the first uses will be to efficiently simulate quantum systems, fulfilling the vision put forward by Richard Feynmann more than 30 years ago.

In turn, this will help us understand and build even more complex quantum materials with extraordinary properties that today we cannot even predict.