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What are some exciting practical applications of nanotechnology and how are they transforming everyday life?

After about 20 years of nanoscience research, nanotechnology has led to both expected and unexpected benefits to society. Nanotechnology has revolutionized many technology and industry sectors, for example information technology, medicine, and energy. Nanotechnology allows the tailoring of materials at extremely small scales to achieve specific properties. Materials can be stronger, lighter, more durable, and better conductors. Nanotechnology has led to the development of flexible electronics, which are integrated into a variety of applications. Achievements of nanotechnology have contributed to the development of computers and mobile phones. Nanotechnology has enabled new medical tools, knowledge, and therapies and is greatly enhancing alternative energy approaches like solar panel films. In addition, nanotechnology can help to detect and clean up environmental contaminants, such as low-cost detection and treatment of impurities in water.

What developments do you foresee in the field of nanotechnology over the next decade?

There are many new possibilities. For example, the testing of novel ideas and protocols for future devices governed by the principles of quantum mechanics. Technologies based on the laws of quantum mechanics will lead to a wave of new technologies. The first quantum revolution, concerning the understanding and application of physical laws, resulted in ground-breaking technologies, such as transistors, solid-state lighting and lasers, as well as the GPS. Governments and companies, such as Google, Microsoft, Intel, Toshiba, and IBM are investing substantially to support a second quantum revolution. This will make use of the ability to exploit quantum effects for new quantum technologies with far-reaching applications, including secure communication networks, sensitive sensors for biomedical imaging, and fundamentally new paradigms of computation.

The focus of quantum technologies will be on atomic quantum clocks, quantum sensors, a secure intercity quantum link, quantum simulators, a global quantum-safe communication network, and universal quantum computers. I have worked in the field of molecular quantum magnets, which is a new field of research that will contribute to the second quantum revolution. It has made considerable progress in the last ten years, showing that molecular spins provide an excellent area to test novel ideas and protocols.

How did you become interested in nanomagnets and their use in quantum spintronics?

As a doctoral student at the low-temperature laboratory in Grenoble, we developed a nano-SQUID, a pioneering instrument to measure extremely small magnetic fields by studying magnetic properties of individual nanostructures. All of these results were important for data storage applications in order to understand the stability of stored data and how to read and write them efficiently. Moreover, our group and others revealed that molecules can exhibit a significant zero-field magnetization with an orientation that is stable over long periods of time as in ordinary magnets. These single-molecule magnets (SMM) show the classical properties of magnets, but also exhibit quantum characteristics that are important for the development of quantum computers. We found that molecular magnets behave according to the laws of quantum mechanics. For example, we discovered quantum phase interference, spin-parity dependent tunneling, and spin-spin cross relaxation. Based on our findings, we were able to build electronic circuits with single molecules in which the electric current can be controlled by the magnetization of the molecule.

Please describe your current research on the realization of an operational quantum computer.

We aim to contribute to one of today’s most ambitious technological goals: the realization of an operational quantum computer, or more generally, the development of devices working on the principles of quantum mechanics. The basic building block of such devices is a quantum bit (or qubit), which must be fully controllable and measurable, and thus requires a connection to the macroscopic world. In our approach, we interconnected the qubit electrically, which allows for a large variety of complex and scalable architectures. We were able to fabricate, characterize, and study the first molecular devices (molecular spin-transistors, spin-valves, spin filters) in order to read and manipulate the spin states and to carry out basic quantum operations. For instance, we have built a novel spin-valve device in which a non-magnetic molecular quantum dot, consisting of a single-wall carbon nanotube contacted with nonmagnetic electrodes, is laterally coupled via supramolecular interactions to a molecular magnet. The localized magnetic moment of the SMM leads to a magnetic field-dependent modulation of the conductance in the nanotube with magneto-resistance ratios of up to 300%. Recently, we managed to manipulate and read-out the spin-states of single molecules to perform basic quantum operations, e.g., implementation of Grover's quantum algorithm. We are now planning to develop reliable, fast, and scalable optical methods for the read-out of both electron and nuclear spin-states, allowing us to perform basic quantum information processing protocols.

How has the transition from being the research director at the Institut Néel in Grenoble to becoming an Alexander von Humboldt Professor at the Karlsruhe Institute of Technology in 2016 contributed to your research?

The Alexander von Humboldt Foundation honors leading researchers who worked abroad during the first part of their career. In my case, I conducted cutting-edge, long-term research at the Néel Institute, CNRS, in Grenoble. I forged links which will remain during the second part of my career at the Karlsruhe Institute of Technology (KIT). In fact, the Polygone campus in Grenoble (CNRS, CEA) and the KIT are currently two of the biggest European centers in the field of condensed-matter physics and nanophysics. The research conducted in these two advanced technological centers follows a long tradition of development from fundamental research to industrial applications, with an emphasis on cutting-edge techniques. Numerous collaborations and the training of young scientists have been successfully pursued between the two centers over the years. I will help to enhance scientific ties to France, since numerous scientists at KIT have shown an interest in developing regular exchanges with Grenoble. In 2018, we will most likely launch a CNRS collaborative body called Laboratoire International Associé (LIA), which will support scientific collaborations between both institutions for an initial duration of four years. On the German side, we are currently applying for financial support to develop and sustain this bilateral collaboration.

A close collaboration with partners in Grenoble will allow us to integrate extremely small and quick molecular quantum processors into the highly advanced microelectronic chip technology. The challenge mainly lies in connecting these new switch elements based on magnetizable molecules with the so-called CMOS technology that is based on semiconductor components. If we are successful, molecular nanomagnets coupled to semiconductor transistors might be used in future quantum computers.