Executive Summary

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Introduction

Doping semiconductors has the purpose of tailoring their electrical properties. To this end, only the charge-related properties of dopant atoms (binding potential, Bohr radius, …) are of interest. However, the charge carriers bound to dopants also have spin, which can be used as the basis for radically different computing paradigms in the context of spintronics or spin-based quantum computing. I will discuss two aspects of spins in dopants:

(1) The progress on harnessing spins for quantum computing;

(2) The possible implications of single-spin detection on the microscopic understanding of the behavior of dopant atoms in classical transistors, and how this may help the design of future semiconductor devices.

The progress of selected topics over the past five years including your results

More than 10 years ago, the spin of the electron or the nucleus on single dopant in silicon has been identified as an excellent system to encode and manipulate quantum information [B.E. Kane, *Nature* **393**, 133 (1998)]. In addition, it was expected that the technological progress in the conventional semiconductor industry would help harnessing single dopants. In the last 5 years, it has become increasingly clear that the opposite can be true as well, i.e. the research devoted to controlling single dopants for quantum information can have an impact on classical electronics [M. Pierre et al., *Nature Nanotechnology* **5**, 133 (2009)].

The recent progress in controlling single-dopant spins has been particularly exciting. The essential elements for success can be summarized as:

- Accurate positioning of single dopants;
- New ideas for the electrical detection of spins, by coupling them to transistor-like nanostructures;
- Exquisite control of the local electric and magnetic fields.

The first point has been developed extensively and will be discussed by other participants.

The measurement of a single dopant spin has long been seen as the tallest hurdle, because no known method of magnetic measurement is sensitive enough to detect directly such a small magnetic moment. The breakthrough occurred 2 years ago, when my group proposed an architecture which exploits a metal-oxide-semiconductor single-electron transistor (SET), tunnel-coupled to nearby P donors. The SET is essentially a modified MOSFET, which makes the architecture very interesting for integration with conventional control electronics. We have now demonstrated fast (~10 μs), high-fidelity (>90%) single-shot readout of the electron spin of a single implanted P donor in silicon [A. Morello et al., *Nature* **467**, 687 (2010)]. The spin has exceptional properties as a carrier of quantum information, with a measured excited state lifetime up to 6 seconds.

The readout method is rather general, and can be extended to STM-fabricated devices or electrostatically induced quantum dots. Most importantly, it may even work for single dopants strongly coupled to the channel of a small FET. A similar idea has indeed been applied to the detection of spin resonance of a charge trap [M. Xiao et al., *Nature* **430**, 435 (2004)].

Very recently we have made progress on the control of the spin state of the dopant, by using resonant microwave excitation, delivered to the dopant by a nanofabricated transmission line. This work completes the demonstration of a functional spin qubit in silicon. Future developments will focus on the controlled coupling of two spins to perform quantum logic operations, and the transport of spin information across the chip.

Potential application opportunities, if possible (What is the potential impact on ITRS?)

Spin resonance experiments have long been known to provide precious information on the environment of the dopant [see e.g. H. Huebl et al., *Phys. Rev. Lett.* **97,** 166402 (2006)]. With the miniaturization of transistors comes the opportunity to detect single dopants or traps in their channel, thereby acquiring truly local information on e.g. electric fields, strain, etc… As an example, measuring the spin resonance of a P donor yields the electro-nuclear hyperfine coupling, which is a function of the local electric field and strain. The single dopant therefore becomes an accurate field and strain sensor, and could be used as a diagnostic tool for the design and development of scaled-down transistors.

The difficult challenges and potential solutions for the next 10 – 15 years

For dopant-based quantum computing, the greatest challenges will be in the controlled coupling of two dopant spins, and the coherent transport of quantum information. The level of control and accuracy required by these operations goes well beyond what has been necessary to succeed in detecting a single spin. Exquisite process control, interface quality and ultra-small (possibly <10 nm) lithography will become essential. For a fully-functional, scaled-up quantum computer, the availability of high-quality isotopically purified silicon wafers will also be important.

Experts and expertise with references

- *Single-dopant spin readout and control*

Dr. Andrea Morello & Prof. Andrew Dzurak

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- *Electrically detected donor spin resonance*

Prof. Martin Brandt

Walter-Schottky Institut, Technical University of Munich, Am Coulombwall 3, D-85748 Garching, Germany.

- *Modeling of single spins as local sensors*

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