2nd Deterministic Doping Workshop
November 12, 2010, UC Berkeley

Executive Summary

Title: Deterministic doping by single ion implantation

Name(s): Thomas Schenkel

Affiliation(s): Lawrence Berkeley National Laboratory

Introduction

Dopant fluctuations in scaled transistors lead to increased variability e. g. of threshold voltages. On the positive side, new device functionalities based on manipulation of single dopant atoms are emerging, e. g. for electron and nuclear spins of donors in silicon. Single ion implantation, i. e. the implantation of exactly counted numbers of dopant atoms into precise locations is a technique that enables the study of dopant fluctuation effects on transport properties of scaled transistors and it enables the testing of quantum coherent device concepts based e. g. on the manipulation of coupled donor spin states (e. g. following Kane, Nature 1998).

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

Several groups have now demonstrated single ion implantation (e. g. Shinada, Jamieson, Schenkel) using detection of secondary electrons or electrical detection of ion impacts in devices (diodes or FETs). Single ion implantation is becoming an important tool that enables systematic studies of single atom devices, i. e. devices where functionality is based on the presence of a single, deliberately placed dopant atom. In parallel, several groups have made great advances in the study of single atom transport effects in scaled silicon devices (e. g. Shinada, Ono, Sanquer, Rogge, Morello, and others). There was a very nice workshop back in Spring in Leiden on the subject (http://www.lorentzcenter.nl/lc/web/2010/390/extra.php3?wsid=390). STM based P atom device formation has also made great progress (Simmons).

Beyond silicon, studies of single color centers in diamond have really exploded in the last 5 years (Wrachtrup, Awschalom, Lukin, Hammer, Prawer, and many others). Here, the direct optical access at room temperature to single electron spin control with close to 1 ms lifetimes allowed great advances in control of quantum states, including demonstration of basic quantum logic with a few qubits and transfer of quantum information form electrons to photons. However, while single color centers can easily be found (post selection) the yield of their deterministic fabrication is very low, typically <<50% and active research also in my group aims at improving this and achieving truly deterministic single color center formation with high spatial resolution.

Here, as well as for deterministic doping of silicon devices, the integration of ion beams with scanning probes for alignment and placement of single ions into regions of interest which we developed in my group is a key enabling tool.

Many challenges remain: e. g. the reliable detection and placement of single atoms with <10 nm resolution, at sufficiently low implant energy so that range straggling is also <10 nm. The development of device processing steps that yields high quality devices (e. g. mobility and interface quality) while keeping dopant diffusion minimal. Very good progress has been made in all areas (see also references from my group below), but many challenges remain.

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

That dopant fluctuation effects will eventually lead to increased device performance variability was already pointed out in the early ‘70ies e. g. by Kelly. Getting rid of the dopants in the channel is one way out, but this still leaves the issue of in-diffusion form the Source – Drain contacts. Maybe ultrathin chemical doping profiles will minimize this effect and offer, together with fully depleted SOI channels a solution (well, several other problems will also have to be solved, like gate work function control and control of SOI thickness variations, etc.).

At this point I can not see how deterministic doping via single ion implantation could be scalable to be economic at production levels (but I am for sure no expert in manufacturing or tool design).

I think that understanding transport in scaled devices where transport is strongly affected by the discreet distribution of dopants, as well as true single atom devices (i. e. exactly one dopant atom placed into the device) can benefit the ITRS greatly because these basic studies can lay the foundation for wide spread use of transport studies as a metrology tool (room temperature and low temperature transport, including with magnetic fields and in some cases microwaves).

Further, and potentially very high impact are the real prospects that new device concepts can be discovered based on the manipulation of single atoms in scaled devices (in silicon and beyond). These would be post-CMOS devices for logic and memory and e. g. the manipulation of single spin states is one promising example.

Needless to say, this research requires funding and any support in identifying or helping to develop funding sources would greatly increase the rate of progress.

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

Some points:

-mass fabrication of deterministically doped devices is a key challenge

-also, dopant fluctuations is just one source of variation (which can be addressed e. g. with undoped channels in planar, fully depleted SOI devices), other sources of device variability have to controlled in parallel to benefit from control of the dopant numbers.

-even with undoped channels, in diffusion of dopants form the source / drain regions into scaled channels leads also to threshold voltage variability increases, so more abrupt S/D junctions are needed, with requirements that might be even more stringent then for ULS because now dopants at concentrations below 5E18 cm^-3 also contribute to transport variations.

-understanding not just longitudinal but also lateral dopant diffusion is important to track this effect and improved 2D dopant profiling methods are important

-I think that room temperature as well as low temperature magneto-transport studies (possibly including microwave excitation to access single dopant spin states) can become an important metrology tool for tracking dopant fluctuation effects. As we understand single dopant transport effects better we can use these measurement techniques to characterize fab runs by probing small ensembles of devices. These studies are currently pursued for basic research and studies towards quantum computing or for novel device concept ideas with e. g. single donor spin control. With deepening understanding these techniques can lay the foundation of possibly very useful process characterization tools were they can complement traditional transport methods and metrology tools.

-device concepts that take full advantage of single atom control are likely to emerge in the next ten years, and these should / might offer paths for post-CMOS scaling. Likely to succeed themes seem advanced quantum – classical hybrid integration schemes, hetero-integration of silicon with other materials (e. g. carbon allotropes), and magneto-electrical integration (including few and single spin devices).

Experts and expertise with references

Here a series of articles from my group from the last five years that are related to aspects of deterministic doping and single atom device development:

1. D. M. Toyli, C. D. Weis, G. D. Fuchs, T. Schenkel, and D. D. Awschalom, “Chip-scale nanofabrication of single spins and spin arrays in diamond”, submitted, NanoLetters, June 2010
2. C. C. Lo, A. Persaud, S. Dhuey, D. Olynick, F. Borondics, M. C. Martin, Hans. A. Bechtel, J. Bokor, and T. Schenkel, “Device fabrication and transport measurements of FinFets built with 28-SOI wafers towards donor qubits in silicon”, Semicond. Sci. Technol. 24, 105022 (2009)
3. T. Schenkel, C. C. Lo, C. D. Weis, A. Schuh, A. Persaud, and J. Bokor, “Critical issues in the formation of quantum computer test structures by ion implantation”, Nucl. Instr. Meth. B 267, 2563 (2009)
4. C. D. Weis, A. Schuh, A. Batra, A. Persaud, I. W. Rangelow, J. Bokor, C. C. Lo, S. Cabrini, D. Olynick, S. Duhey, and T. Schenkel, “Mapping of ion beam induced current changes in FinFETs”, Nucl. Instr. Meth. B 267, 1222 (2009)
5. C. D. Weis, A. Schuh, A. Batra, A. Persaud, I. W. Rangelow, J. Bokor, C. C. Lo, S. Cabrini, E. Sideras-Haddad, G. D. Fuchs, R. Hanson, D. D. Awschalom, and T. Schenkel, “Single-atom doping for quantum device development in diamond and silicon”, J. Vac. Sci. Techn. B 26, 2596 (2008)
6. M. Sarovar, K. C. Young, T. Schenkel, K. B. Whaley, “Quantum non-demolition measurements of single donor spins in semiconductors”, Phys. Rev. B 78, 245302 (2008)
7. J. J. L. Morton, A. M. Tyryshkin, R. M. Brown, S. Shankar, B. W. Lovett, A. Ardavan, T. Schenkel, E. E. Haller, J. W. Ager, S. A. Lyon, “Solid state quantum memory using the ^{31}P nuclear spin”, Nature 455, 1085 (2008)
8. C. C. Lo, J. Bokor, T. Schenkel, J. He, A. M. Tyryshkin, and S.A. Lyon, ”Spin-Dependent Scattering off Neutral Antimony Donors in ^{28}Si Field-Effect Transistors”, Appl. Phys. Lett. 91, 242106 (2007)
9. A. Batra, C. D. Weis, J. Reijonen, A. Persaud, S. Cabrini, C. C. Lo, J. Bokor and T. Schenkel, “Detection of low energy single ion impacts in micron scale transistors at room temperature”, Appl. Phys. Lett. 91, 193502 (2007)
10. A. Persaud, K. Ivanova, Y. Sarov, Tzv. Ivanov, B. E. Volland, I. W. Rangelow, N. Nikolov, T. Schenkel, V. Djakov, D. W. K. Jenkins, J. Meijer, T. Vogel, “Micromachined piezoresistive proximal probe with integrated bimorph actuator for aligned single ion implantation”, J. Vac. Sci. Technol. B 24, 3148 (2006)

11. T. Schenkel, A. M. Tyryshkin, R. deSousa, K. B. Whaley, J. Bokor, J. A. Liddle, A. Persaud, J. Shangkuan, I. Chakarov, and S. A. Lyon, “Electrical activation and spin coherence of ultra low dose antimony implants in silicon”, Appl. Phys. Lett. 88, 112101 (2006)
12. T. Schenkel, J. A. Liddle, J. Bokor, A. Persaud, S. J. Park, J. Shangkuan, C. C. Lo, S. Kwon, S. A. Lyon, A. M. Tyryshkin, I. W. Rangelow, Y. Sarov, D. H. Schneider, J. Ager, and R. de Sousa, “Strategies for integration of donor electron spin qubits”, Microelectr. Engin. 83, 1814 (2006)