# From single-atom spectroscopy to lifetime enhanced triplet transport in MOSFETs

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## 1. Introduction

Dopants play a vital role in the functionality of semiconductor devices. Scaling down dimensions to the nanoscale regime will give undesirable device-to-device variations. This is due to randomness of the dopant distribution that becomes important at these length scales. Dopants in such devices have the ability to bind a few charges. We explore single dopants as basic components for new device technology.

## **2.** General Instructions

Recently, we have shown that it is possible to electrically access a single As donor close to a Si/SiO2 interface by means of an electric gate in a nanoscale MOSFET (Fig. 1) [1,2]. The advantage of this system over, for example, a conventional single electron device is that the ionic donor potential is very robust and can (in principle) be reproduced perfectly. Crucial to enable the implementation of functionality using the charge and/or spin degree of freedom in this system is to understand the quantum mechanical electronic states. Here we investigate several aspects of single dopants in nanostructures using transport spectroscopy and discuss the implementation of new device technology.

We investigate the donor states using transport spectroscopy at low temperature, i.e. < 10 Kelvin. Using these techniques we extract the one-electron (D0) excited state energies (Fig. 2). Combining these data with a full-scale tight-binding model [3], we infer the depth of the donor below the interface as well as the local electric field (Fig. 3 and Table 1). In addition, we determine the chemical species of the donor by the characteristic excited state spectrum. The one-electron state of this system is largely understood and extensively investigated in the abovementioned references [1,2,4].

The rich structure of the stability diagrams we measure has been shown to allow for the implementations of binary and ternary logic [5]. In this scheme the internal electronic structure of the donor-interface system is used as a look-up table to generate the output for a given input. Besides this, the potentially long spin coherence times in Si, makes this system a promising candidate for future implementation of quantum spintronics schemes [6].

From the point of view of new device technology the two-electron state (D-) is even more interesting than the one-electron state (D0). Electron-electron interactions that play a major role in the structures we study can be used to

read, write and store information [6]. At the same time interactions greatly complicate the modeling of the problem. In contrast to a donor in bulk, we observe bound two-electron excited states. This is due to the enhanced binding energies of the donor states due to the presence of the nearby interface. We not only determine the two-electron excited state energies, but also find a lower bound for the spin triplet (excited) state (Fig. 4). Furthermore, we study the Kondo effect in this system as an additional tool to get a better understanding of the role of spin.

# 3. Conclusions

We have shown that single donors are promising candidates for a range of conceptually new device implementations due to their intrinsically robust electronic structure. The first steps towards the understanding of the electronic structure opened up opportunities for new device technology.

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### References

- 1. H. Sellier *et al.*, Transport spectroscopy of a single dopant in a gated silicon nanowire. Phys. Rev. Lett. **97**, 206805, (2006)
- 2. G.P. Lansbergen *et al.*, Gate-induced quantum-confinement transition of a single dopant atom in a silicon FinFET, Nat. Phys. **4**, 656-661, (2008)
- G. Klimeck *et al.*, Atomistic Simulation of Realistically Sized Nanodevices Using NEMO 3-D Part I: Models and Benchmarks, IEEE TED 54, 2079-2089, (2007)
- 4. G.P. Lansbergen *et al.*, Transport-based dopant mapping in advanced FinFETs, IEEE IEDM, p. 713-716, 2008.
- 5. M. Klein *et al.*, Reconfigurable logic devices on a single dopant atom operation up to a full adder by using electrical spectroscopy, ChemPhysChem. **10**, 162-173, (2008)
- 6. B. E. Kane, A silicon-based nuclear spin quantum computer, Nature **393**, 133-137, (1998)



Figure 1: The nanoscale MOSFET we investigate (a) and the band profile. Charge spectroscopy at low bias reveals the positions of the charge states (b).



Figure 2: The conductance stability diagram reveals the positions of the one-electron excited states. Excited states, indicated by the dashed lines, appear symmetrically in bias voltage as peaks in the conductance. The corresponding bias voltage in mV at the Coulomb diamond edges can directly be converted in energy in meV.



Figure 3: Tight binding simulations result in an one-electron excited state spectrum as a function of the local electric field F (a) as well as the corresponding charge distributions (b), (c) and (d) of the donor-interface system.

Sample	E <sub>x1</sub> (meV)	E <sub>x2</sub> (meV)	E <sub>x3</sub> (meV)	F (MV/m)	d (nm)
10G16	2	23	23	37.3	3.3
11G14	4.5	13.5	25	31.6	3.5
13G14	3.5	15	28	35.4	3.2
HSJ18	4.5	15.5	25.5	26.1	4.1
GLG14	1.5	10	25	23.1	5.2
GLJ17	7.5	15	22.5	21.9	4.9

Table 1: The three lowest one-electron excited states are experimentally determined and fitted to a tight binding model. From this we determine the values for the local electric field and the donor depth listed in the right two columns.



Figure 4: Here two parts of the current stability diagram of a sample are shown. The one-electron  $(D^0)$  excited state spectrum (a) shows an asymmetry in the steps with respect to the bias position. This is due to the asymmetry in the tunnel barriers on both sides of the central region. The two-electron  $(D^0)$  spectrum (b) however shows a step (indicated as p1) that is not present in the one-electron spectrum. This step appears due to the importance of spin selection rules in the two-electron states. Knowing the tunnel rates we find a lower limit for the lifetime of the triplet excited state of ~48 ns.