Advanced Simulation of a Donor Spin Qubit Device

Fahd A Mohiyaddin[1,2], Rajib Rahman[3], Rachpon Kalra[1,2], Gerhard Klimeck[4], Lloyd C L Hollenberg[1,5], Jarryd J Pla[1,2]
Andrew S Dzurak[1,2] & Andrea Morello[1,2]

[1]Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology, Australia
[2]School of Electrical Engineering & Telecommunications, University of New South Wales, Sydney NSW 2052 Australia
[3]Advanced Device Technologies, Sandia National Laboratories, Albuquerque, NM 87185, USA
[4]Network for Computational Nanotechnology, Purdue University, West Lafayette, IN 47907, USA
[5]School of Physics, University of Melbourne, Melbourne Victoria 3010 Australia

Introduction and Experiment

Donor spins in silicon are strong candidates for solid state quantum bits due to long spin coherence and relaxation times. The single-shot spin readout [1,2] and coherent spin control required for qubit operations have been recently demonstrated in a Si-MOS nanostructure. Here we discuss a suite of simulation techniques and results to understand the physics of single donor qubits in a realistic spin qubit device.

Figure 1(a) : CMOS-compatible device for spin readout and control. The device consists of implanted phosphorous donors [3] tunnel-coupled to an SET Island, and a microwave transmission line (ML) to achieve spin control of the electron and nucleus [2].

1(a)

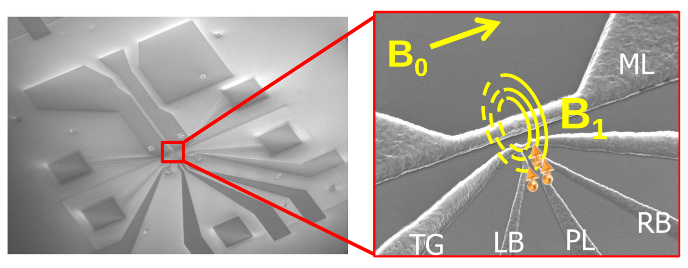


Figure 1(b) : The energy levels of the system during the spin readout phase. The Zeeman splitting between spin up/down states result in spin dependant tunneling of the donor electron to the SET. The current due to tunneling is an indication of the initial spin state of the donor electron.

1(b)

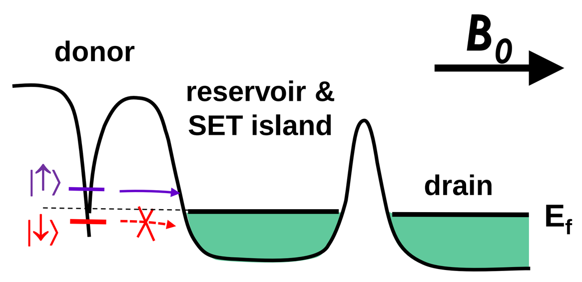
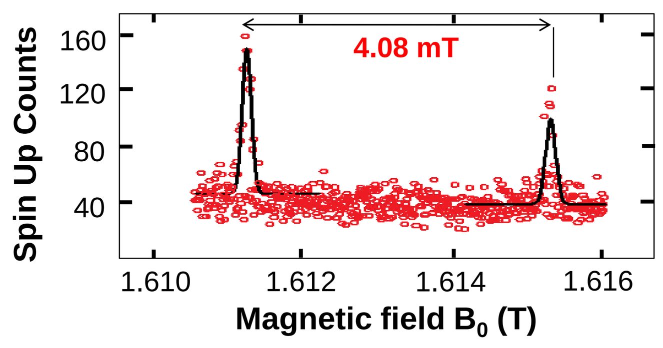


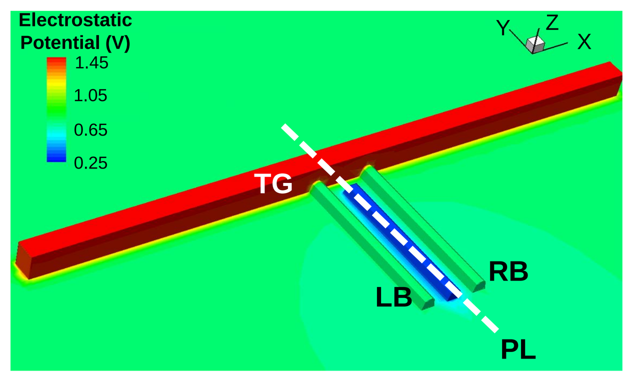
Figure 1(c) : B_0 is varied and several projective measurements were made on the final spin of the electron. Two resonant peaks split by the hyperfine interaction of 4.08 mT were observed. The hyperfine is Stark shifted from the bulk value due to strong electric fields in the nanostructure.

1(c)



Simulation of Spin Readout

2(a)



2(b)

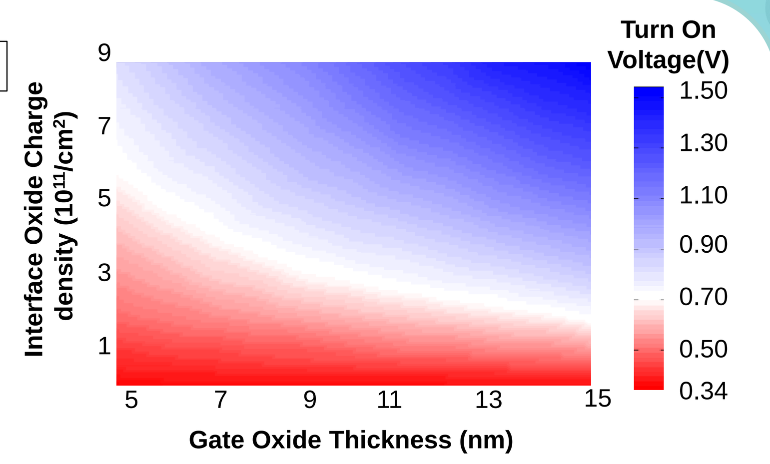


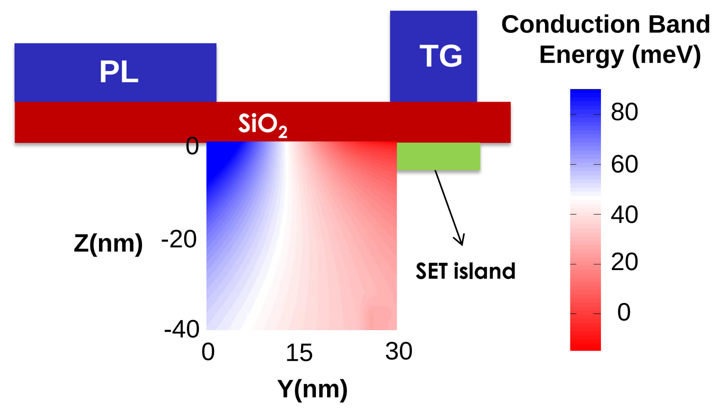
Figure 2(a): TCAD model (in the absence of donor) of the nanostructure with experimental gate voltages and dimensions.

Figure 2(b) : Calibration of threshold voltage of the model with experiment, by addition of interface (Si/SiO_2) charges.

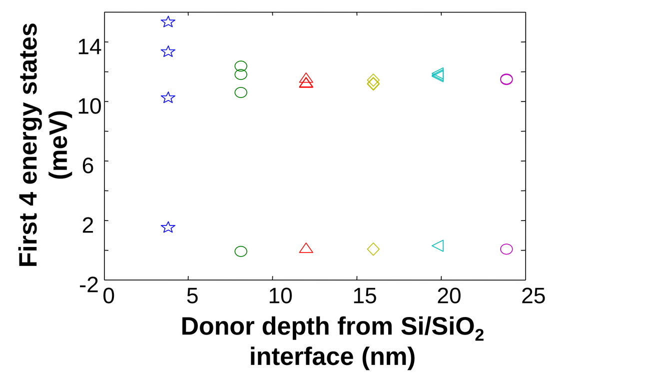
Figure 2(c) : Conduction band profile in the nanostructure to obtain the locus of donor locations compatible with electron spin readout.

Figure 2(d) : NEMO 3D donor energy states on placing donors in the lattice, where TCAD conduction band is 45.6 meV above the Fermi level.

2(c)

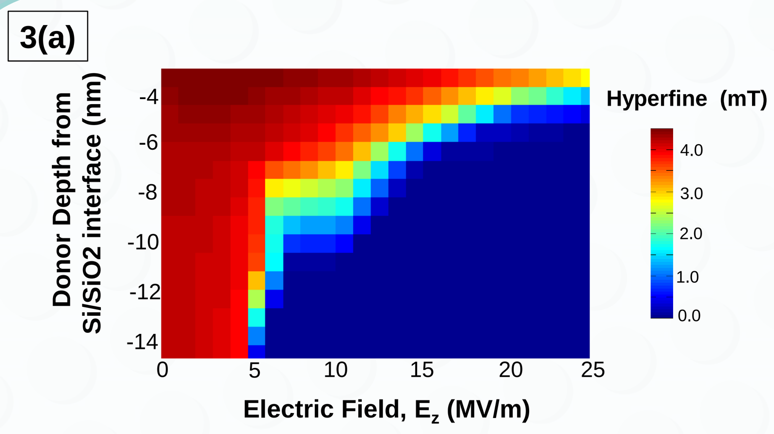


2(d)



Stark shift of the Hyperfine

3(a)



3(b)

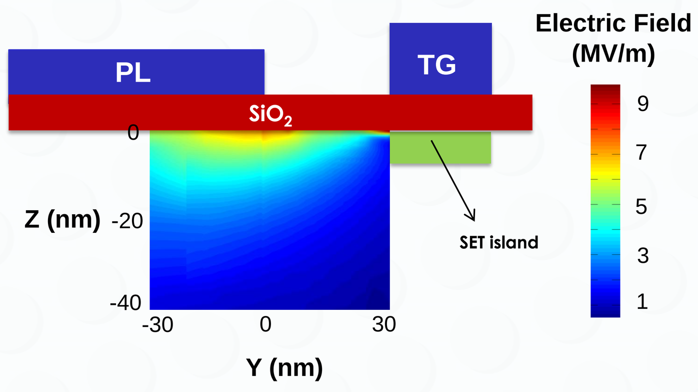


Figure 3 (a): NEMO 3D calculation of the hyperfine interaction [4] between the donor (^{31}P) electron and nucleus, as a function of electric field and depth from SiO_2 interface.

3(c)

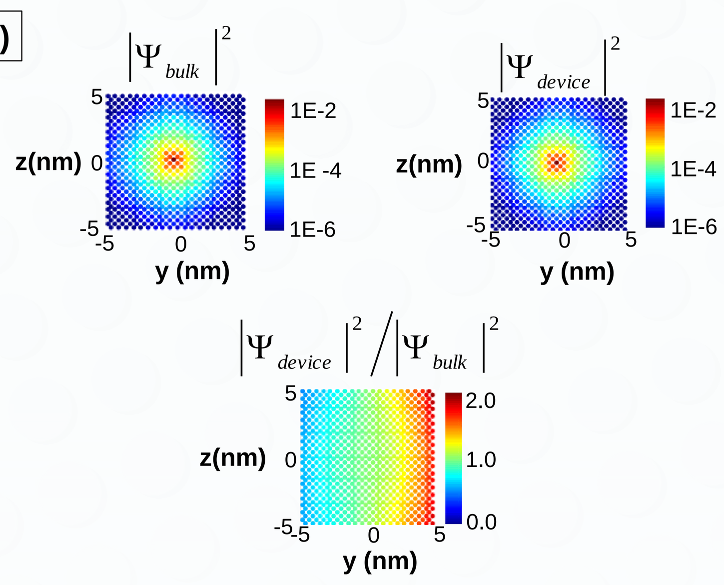


Figure 3(b) : TCAD model of electric fields in the device which Stark shift the hyperfine from the bulk value (4.2 mT).

Figure 3(c): The wave functions for the donor in bulk and for a donor in the device. The ratio of the two wave functions is used to model the wave function distortion in the nanostructure.

3(d)

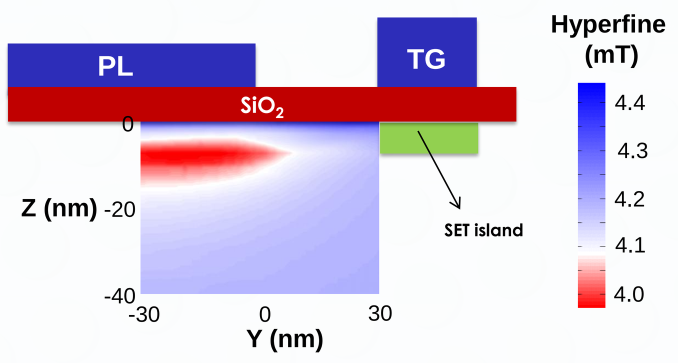


Figure 3(d) : Calculation of the hyperfine splitting based on NEMO (Fig. 3(a)) and TCAD (Fig 3(b)).

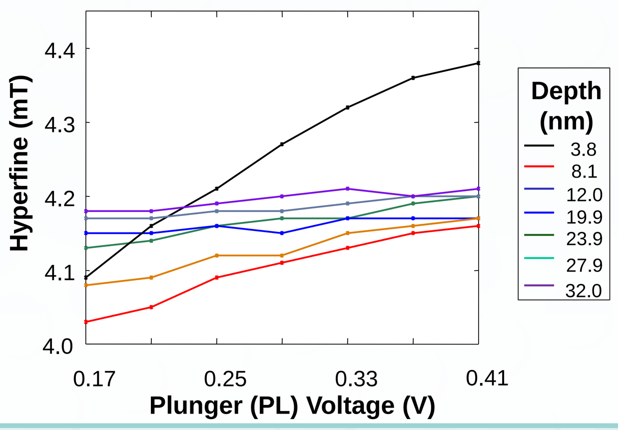
Figure 3(e): Tunability of the hyperfine with Plunger Gate Voltage (V_{PL}) for donors at locations obtained from Fig 2(c). The tunability for donors far away from the SiO_2 interface is limited by:

(i) Bulk Hyperfine of 4.2 mT

(ii) Increased vertical distance from gates

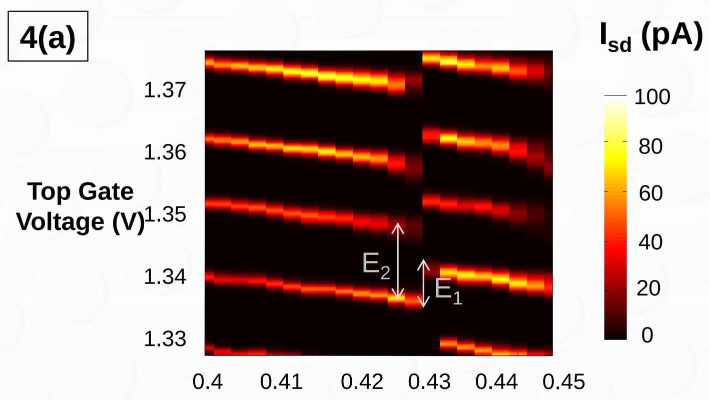
(iii) Quick ionisation with Electric Field

3(e)



Charge Transfer Signal

4(a)



$$\frac{E_1}{E_2} = \frac{\Delta q}{e} = \frac{C_{donor-SET}}{\sum C_{donor}}$$

4(b)

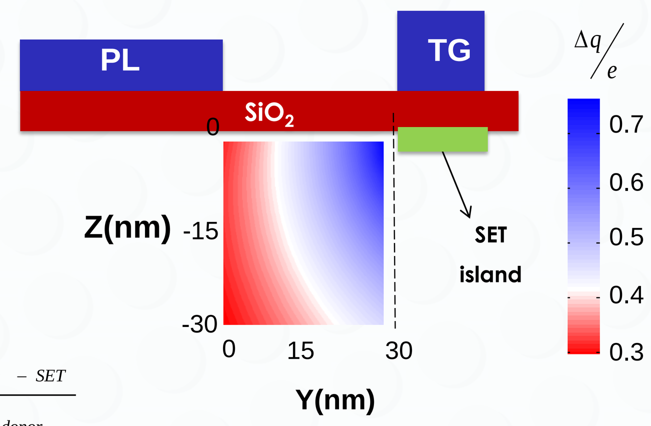
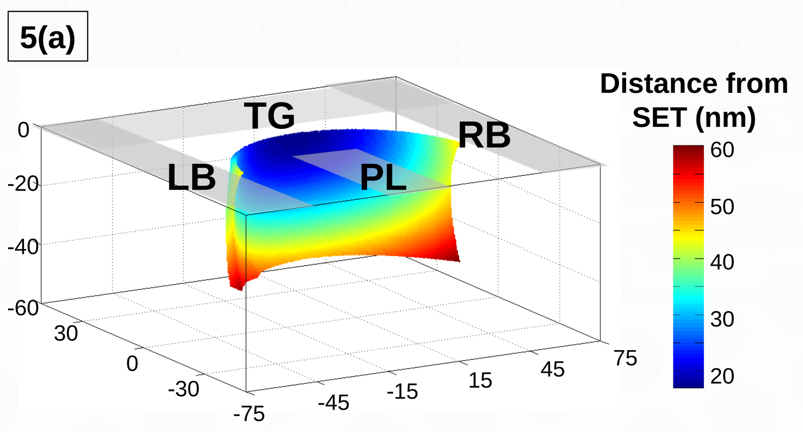


Figure 4(a) : The charge stability diagram, with transitions resulting from electron tunneling between donor and SET.

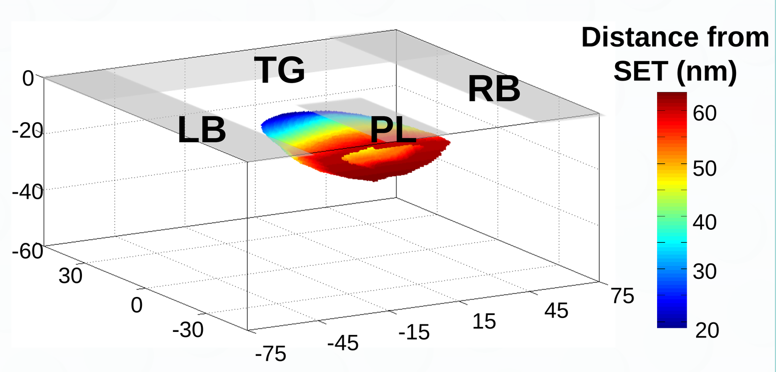
Figure 4(b) : The charge transfer signal calculated from mutual capacitances in the device by boundary element technique.

Location of Donors

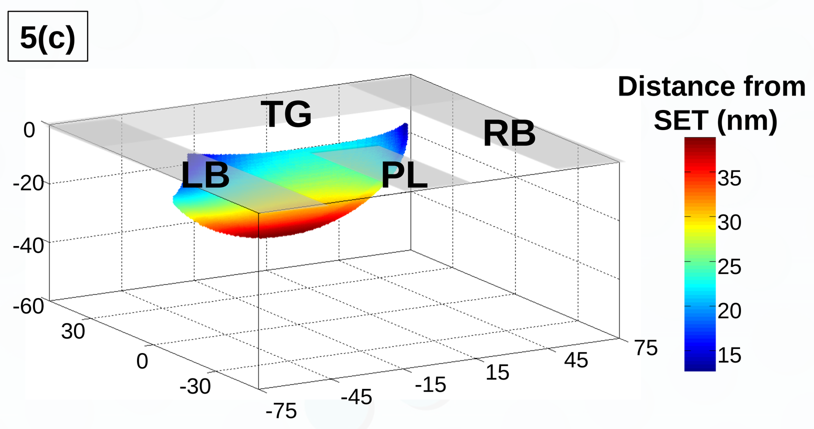
5(a)



5(b)



5(c)



5(d)

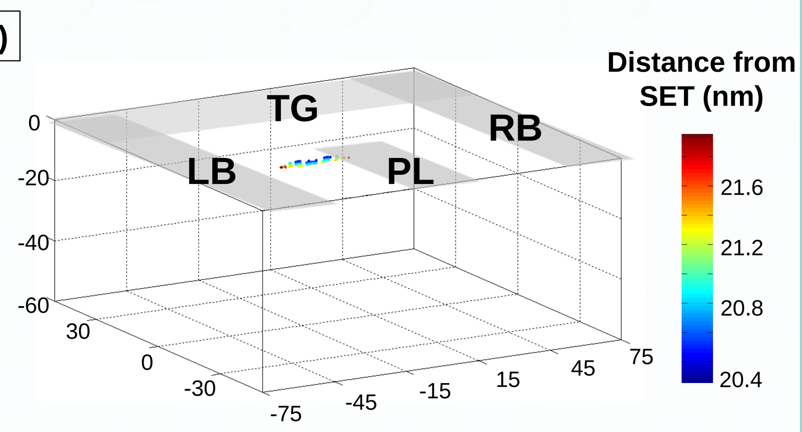


Figure 5 : 3D map of donor locations obtained by matching experimental

(a) Spin readout criterion (b) Stark shift of hyperfine

(c) Charge Transfer Signal (d) Intersection of (a), (b) and (c)

Summary and Future Work

- Developed TCAD, NEMO 3D and FASTCAP models to match experimental results of spin readout/control device.
- Obtained a locus of donor locations compatible with ion implantation, based on simulating experimental results.
- Future work will concentrate on the device-specific modelling of
  - (i) Triangulation of mutual capacitances
  - (ii) Anisotropy of the hyperfine interaction
  - (iii) Tunnel Rate between donor electron and SET Island
  - (iv) Multi-donor qubit devices

References

[1] A. Morello et al., Nature 467, 687 (2010).

[2] A. Morello et al., Phys. Rev. B 80, 081307(R) (2009).

[3] D.N. Jamieson, et. al., Appl. Phys. Lett. 86, 202101 (2005).

[4] R. Rahman et al., Phys. Rev. Lett. 99, 036403 (2007) .

Acknowledgements

We acknowledge support from the Australian Research Council, the Australian Government, the US National Security Agency and the US Army Research Office under contract number W911NF-08-1-0527. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

UNSW THE UNIVERSITY OF NEW SOUTH WALES SYDNEY · CANBERRA · AUSTRALIA

Australian Government
Australian Research Council