Abstract #2218, 224th ECS Meeting, © 2013 The Electrochemical Society

Single Electron and Single Atom CMOS perspectives

Xavier Jehl (1), Marc Sanquer (1), M. Vinet (2) and Romain Wacquez (2)
(1) CEA-DSM-INAC and (2) CEA-LETI-MINATEC
CEA-Grenoble, 17 rue des martyrs 38054 Grenoble, France

Downward scaling of nanowire FDSOI field-effect transistors has opened a new era where i) electrons in the channel can be counted one-by-one thanks to the Coulomb blockade effect [1] and ii) transport spectroscopy through one [2] or two [3] shallow donors (phosphorus, arsenic) immersed in a small silicon crystal is achievable [4].

We have fabricated a MOS-SET (MOS-Single electron transistor) by a proper underlapped source-drain architecture where the access resistances to source and drain are comparable to the quantum of resistance (about 26kΩ) [1]. By down scaling the MOS-SET to the limit where the diameter of the channel (~10nm) is comparable to the Fermi wave length of carriers we obtained an artificial atom in silicon [5]. Coupled MOS-SETs can be obtained by the same technique [6] and moreover a modulation from a MOS-SET to a MOS-FET can be achieved by tuning the substrate bias [7]. This makes the MOS-SET a versatile single electron device fully compatible with the CMOS technology. This device offers opportunities for very low-power applications, electrometry and single electron transfer such as electron pumps for instance.

The MOS-SET –also in its artificial atom version- relies on the potential defined by top-down lithographic techniques. It is also possible to follow a bottom-up line of fabrication starting from the microscopic confinement potential provided by real shallow donors in silicon. This potential is very steep close to the donor's atom core and less sensitive to mesoscopic details and therefore to process variability sources.

We have fabricated a single atom transistor (SAT) using the same platform used for the MOS-SET but with a proper overlapped source-drain architecture [2]. In this device it is difficult to obtain the excitation spectrum for the shallow arsenic donor and to test in particular if the energy separation between the ground and the first excited states of the donor is as large as expected for an isolated donor in a bulk silicon crystal. This energy separation is a marker for the stiffness of the confinement potential as well as an essential feature to manipulate non degenerate isolated quantum state for quantum bit purposes.

To perform this spectroscopy we fabricated a coupled atom transistor (CAT) where two Phosphorus donors are coupled in series in the channel and individually controlled by two separate gates [3]. Using the first donor ground state as an efficient energy filter to measure the spectrum of the second donor it is possible to measure that the energy separation between the ground and first excited state –known as the valley-orbit splitting – is about 10 meV in agreement with theoretical simulations which include the actual geometry of the sample and screening effects. The large valley-orbit splitting is barely diminished as compared to its value for a phosphorus atom in bulk silicon (13.7meV). This means that the wave function for electrons near the core potential of the P atom is not dramatically affected by the mesoscopic environment of the trigate MOSFET, an essential result for building electronic functionalities based on shallow donors in silicon ("solotronics") [4].

To test the potentialities of our CAT we performed Landau-Zener–Stückelberg interferometry, which consists in continuously sweeping one level with respect to the other in the GHz frequency range [8]. This allows to estimate a charge relaxation time T2=0.3ns ± 0.1 ns, a value comparable to other semiconductor charge qubits and much larger than the estimated operation time for manipulating a single electron on the two donors. Therefore a way is open to manipulate coherently at very high frequency an electron between two shallow donors.

We also realized the first electron pump based on these donors in series [9]. While quantized pumping is achieved in the low frequency adiabatic regime, we observe remarkable features at higher frequencies when the charge transfer is limited by the different tunnelling rates. The transitions between quantum states are modelled involving Landau-Zener transitions, allowing reproducing in detail the characteristic signatures observed in the non-adiabatic regime [9].

References

[1] M. Hofheinz, X. Jehl , M. Sanquer , G. Molas, M. Vinet and S. Deleonibus , Applied Physics Letters **89**, 143504 (2006).

[2] M. Pierre *et al.* Nature Nano. **5**, 133 (2010); R. Wacquez *et al.*, VLSI symp. 2010, pp. 193-194.

[3] B. Roche, E. Dupont-Ferrier, B. Voisin, M. Cobian, X. Jehl, R. Wacquez, M. Vinet, Y.-M. Niquet and M. Sanquer, Phys. Rev. Lett. **108**, 206812 (2012).

[4] F. Zwanenburg *et al.*, accepted for publication in Rev. Mod. Phys., arxiv:1206.5202.

[5] Enrico Prati, Michielis Marco De, Matteo Belli, Simone Cocco, Marco Fanciulli, Dharmraj Kotekar-Patil, Matthias Ruoff, Dieter Kern, David Wharam, Arjan Verduijn, Giuseppe Tettamanzi, Sven Rogge, Benoit Roche, Romain Wacquez, Xavier Jehl, Maud Vinet and Marc Sanquer, Nanotechnology **23**,215204 (2012)

[6] M. Pierre, B. Roche, R. Wacquez, X. Jehl, M. Sanquer, and M. Vinet, J. of Applied Phys. **109**, 084346 (2011)

[7] B. Roche, B. Voisin, X. Jehl, R. Wacquez, M. Sanquer, M. Vinet, V. Deshpande, B. Previtali, Applied Physics Letters **100**, 032107 (2012)

[8] E. Dupont-Ferrier, B. Roche, B. Voisin, X. Jehl, R. Wacquez, M. Vinet, M. Sanquer and S. DeFranceschi, Phys. Rev. Lett., **110**, 136802 (2013).

[9] B. Roche, R.-P. Riwar, B. Voisin, E. Dupont-Ferrier, R. Wacquez, M. Vinet, M. Sanquer, J.Splettstoesser and X. Jehl, Nature Communications **4**, 1581 (2013).