Exponentially Adiabatic Switching in Quantum-dot Bits

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Active power dissipation is a crucial problem for nanoelectronics. Techniques currently employed to lower the power dissipation in CMOS processors include multicore architectures, dark silicon (turning off areas of the chip), and lowering clocking frequency. Clock frequencies have not increased much in the last decade for this reason. A more radical proposal is to alter the clocking waveforms and indeed the circuit architecture so that quasi-adiabatic switching can be achieved [1]. This can further lower the dissipated energy and may offer the next practical step in dissipation reduction. Adiabatic CMOS power reduction is *linear* in the switching time. Here we investigate a potential longer term approach to digital computation, quantum-dot cellular automata (QCA) [2]. We consider a ramped switching potential which flips the bit state of a quantum double dot. By solving the time-dependent Schrödinger equation, the excess energy deposited in the system during switching can be calculated. This energy must eventually be dissipated as heat. We show that this energy decreases *exponentially* with the switching time and demonstrate how an adiabaticity parameter can characterize the switching. We further examine the basic logical operations of a clocked three-dot QCA cell that functions as a latch [3]. Single molecule mixed-valence systems have been synthesized which target this functionality. [4] We calculate the excess energy of a WRITE operation, and both an ERASE and an ERASE WITH COPY. The results illustrate the effect of the Landauer principle connecting physical dissipation with logical reversibility.

[1] Athas, W.C., Svensson, L.J., Koller, J.G., Tzartzanis, N., Chou, E.Y.-C.: Low-power digital systems based on adiabatic-switching principles. IEEE Trans. VLSI Syst. 2 (4), 398−407 (1994).
[2] Lent, C.S.; Tougaw, P.D. A device architecture for computing with quantum dots. Proc. IEEE 85, 541–557 (1997).
[3] Orlov, A.O.; Kummamuru, R.; Ramasubramaniam, R.; Lent, C.S.; Bernstein, G.H.; Snider, G.L. A two-stage shift register for clocked quantum-dot cellular automata, J. Nanosci. Nanotechnol. 2, 351–355 (2002).
[4] Christie, J.A.; Forrest, R.P.; Corcelli, S.A.; Wasio, N.A.; Quardokus, R.C.; Brown, R.; Kandel, S.A.; Lu, Y.; Lent, C.S.; Henderson, K.W. Synthesis of a Neutral Mixed-Valence Diferrocenyl Carborane for MolecularQuantum-Dot Cellular Automata Applications. Angew. Chem. 127, , 15668–15671 (2015).

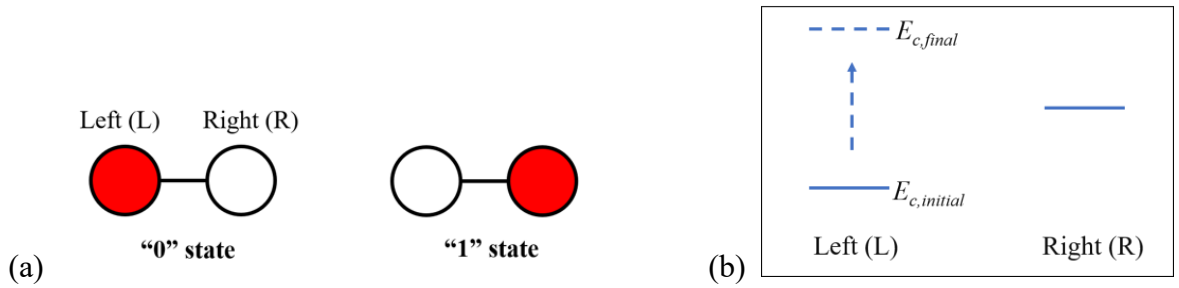

Figure 1. Switching a bit represented by a single charge in two quantum dots. (a) A charge on the left dot represents a binary 1 and a charge on the right represents a binary 0. The two dots are coupled by a Hamiltonian tunneling matrix element γ. (b) Switching can be accomplished by raising the potential energy of the left dot by an amount ΔE_c, *from* $E_{c,initial}$ *to* $E_{c,final}$ *over a switching time T.*

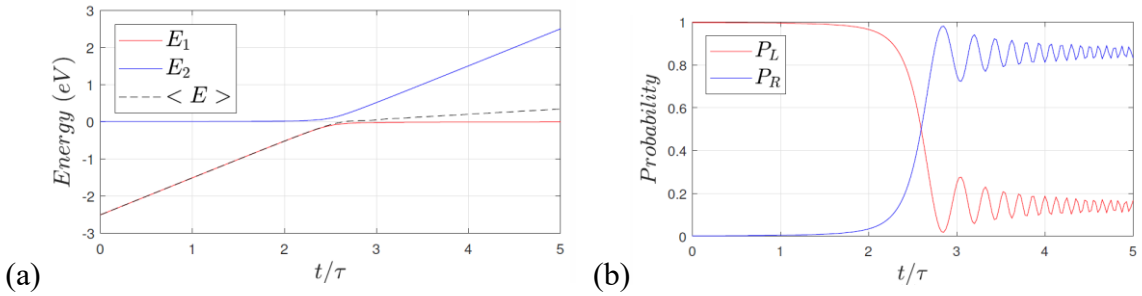

Figure 2. Rapid switching of a two-dot system. The results shown are from a numerical solution of the time-dependent Schrodinger equation as the potential of the left dot is smoothly increased over time. The characteristic time is given by $\tau \equiv \pi\hbar / \gamma$. *Here γ = 0.1 eV and* $E_L = E_c$ *is increased from -2.5 to +2.5 eV over a switching time of T = 5 τ. The right dot on-site potential is held constant. (**a**) The instantaneous energy eigenstates $E_1(t)$ and $E_2(t)$, showing the expected avoided level crossing. After the cross-over, the energy expectation value* $\langle E \rangle$ *is higher than $E_1(t)$. The difference between the two, E_{excess}, represents the energy deposited in the system during the switching event. (**b**) Probabilities are shown for the left and right dot occupancy. At time t = 2.5 τ, the charge transfers from the left dot to the right dot. Because the switching is very rapid however, ringing is evident.*

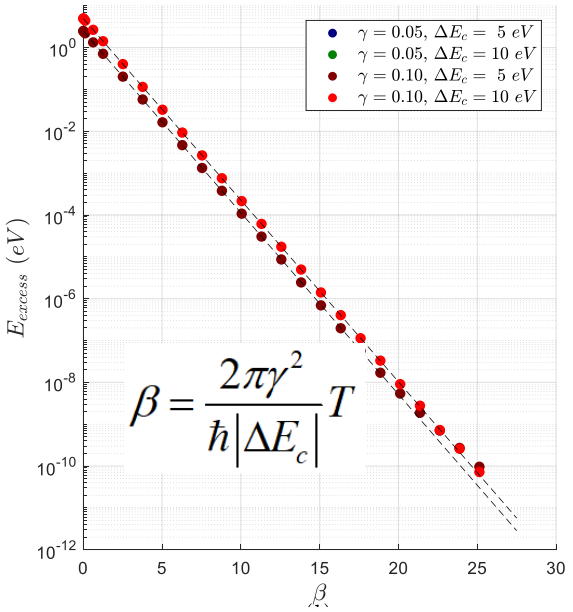

Figure 3. Exponential decrease in the excess energy deposited in the system due to switching. The adiabatic parameter β can be viewed as a scaled switching time which depends on the slope of the switching potential and the tunneling energy γ. As the switching time is increased the amount of excess energy decreases exponentially.