Nanotechnology Highlights 2003

NIRT: Architectures and Devices for Quantum-dot Cellular Automata (0210153)

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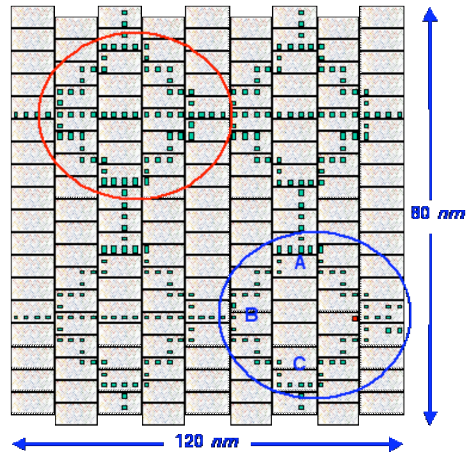
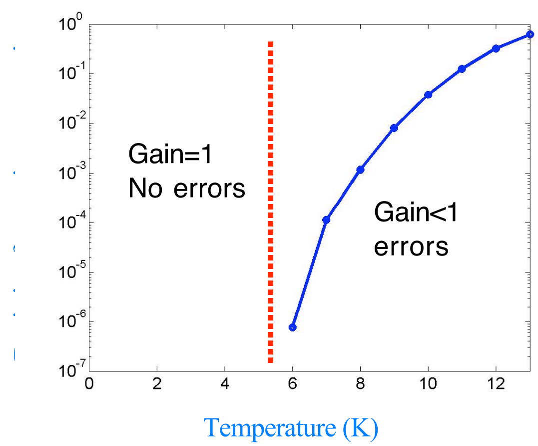
Quantum dot Cellular Automata (QCA) uses coulombic interactions between electrons in quantum dots to represent and transfer binary information within a QCA circuit. This project focuses on questions that arise from attempting to architect and then implement potentially real systems from them, with a focus on regular structures such as might be found in FPGA (Field Programmable Gate Arrays). For 2003 significant advances occurred at three levels: circuit, power gain, and design process.



Each Green dot is a single QCA cell. The blue circle denotes a programmable logic block. The red circle demonstrates a routing block (again programmable).

At the circuit level, an FPGA needs two replicable units, a circuit that can perform some logic function, and one that can perform routing functions between logic blocks. Both need to be programmable. The latter is by far the more complex and area consuming. In CMOS, the existence of a "pass transistor" allows for such programmable interconnect relatively easily. QCA has no direct equivalent, so different combinations of new "device types" (3 dot cells) and circuits were used to derive a complete, but unoptimized QCA FPGA cell, that when implemented with molecules, fits comfortably within the area of just the gate of a *single* modern transistor.

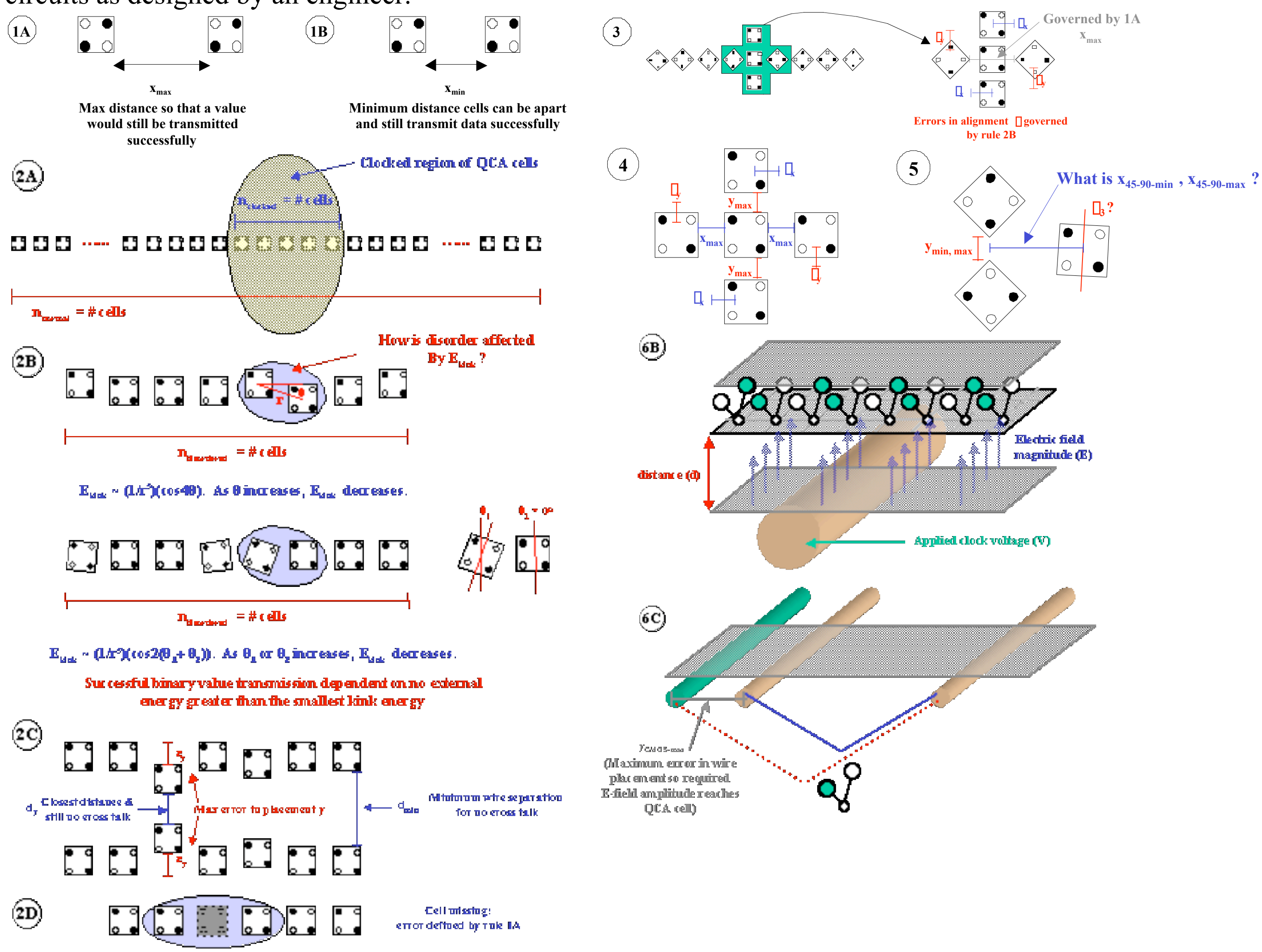
Next, power gain is a crucial requirement of any successful nanoelectronic or molecular electronic technology. Without power gain, energy lost to unavoidable dissipative processes is not replaced in the signal path. As a result signal strength degrades over multiple stages and noise-produced errors can overwhelm the signal information. Power gain is lacking in many molecular electronics approaches (e.g. crossbar switches). We have demonstrated theoretically and experimentally that QCA devices do indeed exhibit power gain. Power lost to dissipation is replaced by energy from the clock. We have recently measured a power gain of 3 in metal-dot QCA circuits at low temperatures. In an effort to understand the role of power gain in noise immunity and the temperature dependence of power gain, we have performed time-dependent simulations of semi-infinite QCA shift registers. We find that there exists a critical temperature above which power gain falls below unity and



Deviation from unity power gain in a metal-dot QCA shift register as a function of temperature. For temperatures higher than a critical value, here about 5K, the power gain of the shift register drops below 1. This results in the generation of thermal errors. Below the critical temperature, the power gain is precisely 1, and transmission over arbitrarily long distances is possible with no errors. The demonstration that power gain exists in QCA devices, and provides immunity from thermal errors is crucial to the development of this promising alternative to transistors for molecular nanoelectronics . For molecular devices, the critical temperature is much above room temperature.

thermal errors accumulate. Remarkably, below this critical temperature, thermal errors do not degrade signals even for infinitely long lines. This helps account for the experimental observation of data integrity preserved in shift registers much longer than would be expected by simple thermodynamic estimates which ignore the effect of the restoration of signal by energy flowing in from the clocking circuit at each stage. Importantly for molecular QCA, clocking can be implemented without making electrical contact to molecules individually.

Finally, the ability to accurately specify, describe, and verify designs that are more than a handful of devices is crucial, especially as the parameters of the underlying technology advance. In CMOS, the Mead-Conway concept of "design rules" that abstracted the physics to a point where engineers could deal with designs, and (more importantly) computer-aided design tools could analyze and verify designs. We now have a basic set of such design rules that permit such CAD packages to be developed for real QCA technologies, in a technology independent fashion. These rules are based on potential failure points in the fab process, and how they are reflected in circuits as designed by an engineer.



Kummamuru RK, Timler J, Toth G, Lent CS, Ramasubramaniam R, Orlov AO, Bernstein GH, Snider GL, Power gain in a quantum-dot cellular automata latch, Appl. Phys. Lett. 81 (7): 1332-1334 (2002).

A.O. Orlov, I.Amlani, R. K. Kummamuru, R. Ramasubramaniam, C. S. Lent, Gary H. Bernstein, and Gregory L. Snider, Clocked quantum-dot cellular automata shift register, Surface Science 532-535, p. 1193-1198 (2003).