PERSPECTIVES: NANOTECHNOLOGY

Computation Without Current

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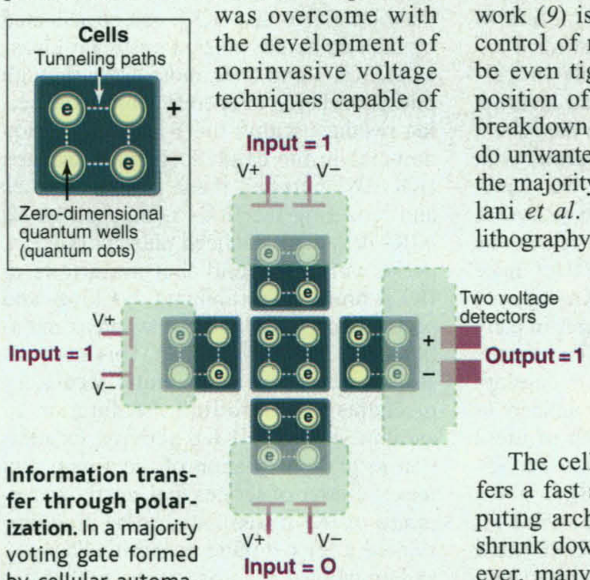
In today's computers, most information is transferred from one place to another with the use of electric currents, that is, the transfer of charge. In 1994, Tougaw and Lent (*1*) proposed an alternative technique for transferring information that involves the propagation of a polarization state from one cell-like structure to the next. They proposed that each cell should contain four zero-dimensional quantum wells (quantum dots) (*2*), one at each corner, and that these quantum wells should be coupled by tunnel barriers. Quantum dots are small semiconductor or metal islands with a diameter small enough to make their charging energy greater than $k_B T$ (where k_B is the Boltzmann constant and T is the operating temperature) and trap individual charge carriers. When two electrons are added to the cell, Coulomb repulsion ensures that they reside in opposite corners, creating two possible degenerate polarization states. If such cells, called cellular automata, are placed in a line and the first cell is polarized with an external electric field, it polarizes the second, which in turn polarizes the third, and so on. In this way, information can be transferred along a line of cells as a polarization reversal, without a current. By assigning one polarization state as the "1" state and the other as the "0" state, binary signals can be processed.

If this idea would only result in a metal wire being replaced by a line of millions of polarizable cells, then it would remain a theoretical technology. However, by branching lines and combining lines of cells, various logic functions can be performed, and this may prove advantageous compared with current technology. On page 289 of this issue, Amlani *et al.* (*3*) demonstrate a majority voting gate using a cell structure consisting of small metal islands connected by tunnel barriers. The output on one side of the cell depends on the polarization states presented as inputs on the other three sides (see the figure). However, before you throw away your computer to buy the latest cellular automata–run processor, you should be aware that the current device only works at 0.1 K (or –272.9°C). Smaller cells should allow an increase in the temperature of operation.

Many technical difficulties had to be overcome to perform logic functions with cellular automata. It was clear that data input could be achieved by placing metal electrodes near the start of the chain of cells to create an electric field that polarizes the first cell, but measuring the polarization of the last cell after computation proved harder to achieve. The problem was overcome with the development of noninvasive voltage techniques capable of measuring single electron movements (*4*). Recently, voltage detectors with the required resolution have been demonstrated that operate at hundreds of megahertz (*5*).



Information transfer through polarization. In a majority voting gate formed by cellular automata, two input values of "1" and one input value of "0" results in an overall output of "1." Larger assemblies of cells could perform more complicated logic computations.

So cells can be driven and the resulting output can be read quickly. But how quickly can the cells be switched? Answering this question requires a detailed understanding of the energy loss processes in each dot. Tougaw and Lent (*6*) have calculated that no useful switching can be achieved without some energy loss process. However, when they introduced absorbing boundary conditions to simulate energy losses, they found that switching could be recovered. Wang *et al.* (*7*) have shown that switching can only occur if the driver is switched such that the polarization changes much more slowly than the inelastic scattering time. For dots separated by 35 nm and fabricated in a GaAs/GaAlAs heterostructure material, the switching time can be as fast as 200 ps.

If this technology is to be implemented, the manufacturability and robustness to fabrication tolerances of the cellular automata concept must be assessed (*8*). Theoretical work by Governale *et al.* (*9*) has shown that in the case of a GaAs/GaAlAs heterostructure cell with dot diameters of 90 nm and a center-to-center separation between the dots of 110 nm, the ease with which one cell polarizes the next is hypersensitive to any disorder in the cell dot diameter or in the intercell separation. For example, if the diameter of one dot is varied by just one part in 10,000 (or 0.009 nm), the cell will remain stuck in one polarization state. The prediction in this work (*9*) is that for smaller systems, the control of manufacturing tolerances must be even tighter. A 0.05-nm shift in the position of one of the dots also causes a breakdown in the operation of the cell, as do unwanted charges close to the cell. For the majority voting gate discussed by Amlani *et al.* (*3*), these unwanted errors in lithography or doping are offset by applying different voltages to electrodes placed in the four corners of each cell. This is feasible for small numbers of cells, but it would not be an option for a large processor with millions of cells.

The cellular automata technology offers a fast switching and low-power computing architecture that in theory can be shrunk down to the molecular scale. However, many problems are associated with manufacturing large numbers of cells with subatomic resolution and control over the position of every stray charge. It may be that the architecture could be implemented with self-assembled molecules, although there are no candidates as yet and there are questions as to whether molecular assemblies would give enough control over cell positioning. Perhaps the architecture could be implemented by replacing the electrically polarized cell with some other polarization field. One possibility may be to use the magnetic interaction between single-domain magnetic particles that has been demonstrated recently (*10*).

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References and Notes

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