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Mesoscopic Devices: Will They Supersede Transistors in ULSI?

by

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Si MOSFETs can clearly be scaled to 100 nm channel length, and somewhat below. Although the design and fabrication of dense CMOS circuits utilizing such devices represent formidable challenges, it nevertheless appears to be a straightforward development of existing and evolutionary technologies. If, in addition, 0.1 μm CMOS is cooled below ~ 100K, improvements in device and interconnect performance can result in several orders-of-magnitude increase in circuit functionality with respect to state-of-the-art 0.5 μm technology.

The existing types of quantum-effect devices, such as resonant tunneling transistors (both planar and grown-layer types), electron interference devices, and single-electron transistors cannot approach the speed/density and power-delay-product figures-of-merit of cooled 0.1 μm CMOS. On the other hand, 0.1 μm CMOS, in its principle of operation, does not approach physical limits. (A circuit based on a single electron signifying a bit would, presumably, be at that limit!) So, we are confronted with the following dilemma: whereas existing lithography technology permits the fabrication of devices with minimum features of the order of 20 nm (and x-ray nanolithography makes even manufacturing at this scale feasible with only evolutionary improvements) we do not have any clear concept for quantum-effect-based systems that could compete with cooled CMOS.

The problem probably lies in the human mind's tendency to think in terms of analogies. A resonant-tunneling transistor or a single-electron transistor is asked to replace a conventional transistor in a conventional circuit topology and system architecture. But it cannot do this because it lacks fanout capability, clearly defined threshold, or exhibits some other flaws. A device based on electron wave guiding and interference is asked to duplicate the performance of a microwave or an optical device; but it cannot do so because thermal, impurity, or electron-electron scattering prevents the analogy from being operative. (Electrons in the solid state loose phase coherence rather quickly, whereas photons do not.)

We believe that as long as computation or memory systems are configured with three wires running to every switch, mesoscopic devices cannot possibly compete with CMOS. The potential of mesoscopic devices resides in the unique aspects of their structures: quantum effects get stronger as dimensions are reduced; quantum effects (e.g. charge, energy levels, etc.) are naturally discrete; near neighbors can communicate either via tunneling or electrostatics; etc.

We submit that a new paradigm is needed if mesoscopic devices are ever to supersede the transistor in ULSI. A quantum-effect computation system must be based on the positive and robust features of quantum behavior and not be threatened because "conventional behavior" is not obtained. Perhaps, one of the flaws in our existing paradigms for computation and memory circuits is the demand for absolute determinism (i.e., our computation systems are completely deterministic in the same sense that Newtonian mechanics is). When we consider quantum-effect-based computation we carry over the assumption that complete determinism is essential. Perhaps we must "match the task to the worker". Perhaps we have to better understand the fundamental interdeterminacy inherent in quantum phenomena and harness this knowledge for novel computation systems. Perhaps such systems will provide only "fuzzy" logic. Perhaps that would be quite acceptable.