Interconnects for Nanoelectronics

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ABSTRACT — **In the nanoelectronics era with ever smaller devices and higher densities, there will be challenges of signal transmission and information communications via interconnects. We examine the interconnect issues for both charge-based and spin-based information systems. For charge-based systems, since there are substantial among of activities in optical interconnect, this paper will focus other concepts and approaches. Self-assembled molecular wires, carbon nanotubes/nanowires and virus engineered metallic wires can be used for interconnects of nanodevices. The use of new nano-architectures such as cellular automata, which uses mostly nearest neighbors, will make the use of self-assembled interconnects even more attractive. These techniques may be applied readily to molecular devices. Spin-based devices offer a new opportunity for low power, high functional throughput applications. We will analyze the use of spin waves for information transmission bus or referred to as spin wave bus. By introducing these novel circuits built on the spin-based devices and spin wave interconnect, we anticipate enhanced logic functionality. The challenges and issues are discussed.**

Index Terms — **Nanotechnology, molecular electronics, semiconductor devices, spintronics.**

I. INTRODUCTION

There is an impetus for the development of advanced interconnect technology for new information and signal processing in line with scaled CMOS and beyond (ITRS 2004) in order to provide high information/signal processing rate and be scaleable to the nanometer range. The development of novel nano-scale ordered materials and structures, together with processes for monolithic, heterogeneous integration with CMOS, may pave the way to revolutionary new types of electronic circuitry with capabilities far beyond conventional one. In the nano-systems, neighbor interactions may be done naturally through quantum mechanical interactions such as tunneling, exchange interaction or other quantum mechanical wave interactions. Molecular wires and resonant tunneling diodes are among the most likely nano-device candidates for providing such interconnection. While RTD traditionally offers the high operational frequency advantage, molecular wires implementation allows for unprecedented scaling down to eventually single electron operation and for the latter, it afford potential low cost alternative in nano-manufacturing using self-assembly .

Long wiring in the nano-systems will impose additional constraints for the performance due to the increased complication as the result of high integration density and small size of individual devices. In addition to the use wireless and optical interconnects, a possible solution may, for example, come from the use of spin wave bus, where the interaction between the nano-devices is accomplished in a wireless manner without the transport of charged carriers (electrons), via the spin waves. In this paper we present an overview of possible approaches to nanoscale interconnect design and associated to them functional nano-architectures.

II. WIRING THE MOLECULES

Molecular wires [1] are considered to be a candidate for nanoscale interconnects – they are smaller than a few nanometers in length, they can be self-assembled onto an underlying structure, and they have the potential to operate at the single-molecule level [2]. These systems have been studied extensively in molecular electronic junction devices [3], and they serve as the bottom-up component of heterogeneously integrated devices. To date, a lot of fundamental work has been performed on molecular wires composed of a class of compounds called oligo (phenylene enthynylenes) (OPEs) [4] that contain delocalized electronic states. There structures are derived from conducting polymers, such as the well-known poly (*p*-phenylene) and polyacetylene, but, once reduced to their component parts, the potential modes of charge transport differ [1]. The ideal situation is on-resonance coherent electron motion where the rate of electron transfer follows the Landauer formula in the conduction process, and more importantly, electron tunneling occurs in the absence of dissipative effects. A derived interconnect would be expected to have similar properties to a resonant tunneling diode. Nonresonant conditions are also possible, as is incoherent electron transfer, a situation that may display inelastic processes as the electron motions are coupled to the internal vibrations of the molecular wire.

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Of the range of molecular wires considered to date, from OPEs to other classes, a wide variety of conductance and switching properties have been observed. The assignment of the observed phenomena, including negative differential resistance [4] and device switching [5], are only now becoming scrutinized and verified to be derived solely from the intrinsic properties of the molecules. Outstanding issues include the nature of the molecule-electrode interface and its influence on the transport properties of interconnects based on molecular wires as well as changes to the structure of the molecular wire and to its orientation during conduction [4] and switching. Fundamental studies establishing how molecular electronic components change [5] their properties when they are moved out of the solution phase [6] and into the solid-state are also being pursued. These avenues of research and testing are establishing the basis for wiring up molecules to serve as the potential self-assembling scaled interconnects for nanoelectronics applications.

III. TUNNELING

Another approach to the interconnect problem is to avoid the use of the conducting channels but utilize the quantum tunneling effects. The use of tunneling is particularly beneficial for computational architectures of homogenous arrays of nanostructures. Among the examples are cellular arrays and nano FPGA. In Fig. 1, we schematically show an example semiconductor tunneling structure, where the interconnection between the elementary units - quantum dots is accomplished via tunneling. The structure may be built on a conductive substrate as shown in the bottom of the figure. The core of the structure consists of the six layers of two different semiconductor materials with quantum dots embedded in between. One of these two materials, depicted by the lighter shade, has a large band gap (quantum barrier), while the other one, depicted in the darker shade, has a small band gap (quantum well). The dark square wells on the top of the structure depict metallic contacts isolated between each other by silicon oxide. Without the loss of generality, silicon and germanium are used for illustration. In this case, the layered structure may consist of Si substrate, a $Si_{1-x}Ge_x$, Si layer, Ge self-assembled quantum dots, another Si layer, $Si_{1-x}Ge_x$ layer, and finally a Si layer grown in a sequence from the bottom to the top.

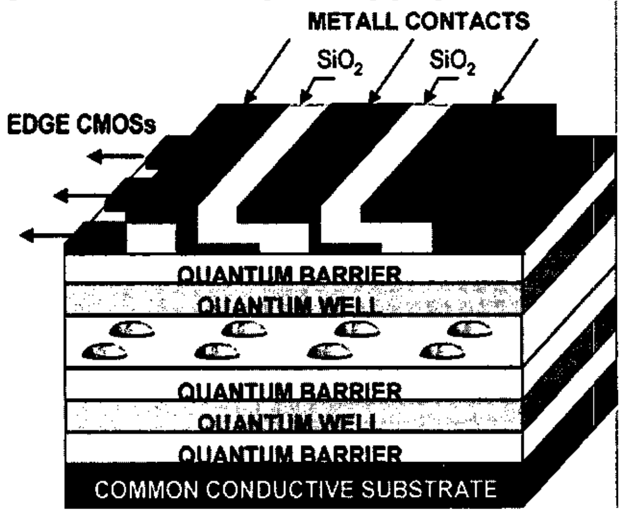

Fig.1 A possible material structure, where all interconnects are accomplished without metallic wires but via tunneling.

The sequence of the large-small-large band gap semiconductor structure forms a resonant tunneling diode. An elementary logic cell in this scheme consists of two RTDs connected in series (from the top metallic contact to the common conducting substrate) and a quantum dot between them. The coupling of one cell to its neighbors is achieved by the dot-to-dot tunneling when they are sufficiently close to each other. Only the nearest neighboring dots are assumed to be affected by the center dot because tunneling probability exponentially decreases with the inter-dot distance.

Due to the dot-to-dot tunneling, the potentials of the nearest quantum dotes become associative i.e. the particular charge state of the center dot is the function of the charge states of its neighbors. By proper bias adjustment, it is possible to manipulate these collective charge states, making some of them stable at one applied voltage and unstable at others. The use of tunneling for interconnection also results in the enhanced logic functionality due to the non-monotonic tunneling characteristics. The examples of logic functionality for image processing are described in Ref. [7].

IV. SPIN WAVE BUS

For long-range interconnection, it is possible to use waves, such as spin and other quantum waves, for interconnection. In Fig.2, spin waves are shown as a prototype logic device as well as an interconnect bus, or referred to as Spin Wave Bus. The core of the structure consists of a ferromagnetic film grown on a semi-insulating substrate. The film is polarized along with the X axis (as shown in Fig. 2(a)). There are three conducting loops (asymmetric coplanar strip (ACPS) transmission lines) on the top of an insulating layer, which isolates it from the underlying ferromagnetic layer and are used for spin wave excitation and detection. The structure resembles the one used for the time-resolved measurements of propagating spin waves described in Ref.[8]. The thickness of the ferromagnetic layer can be as thin as tens of nanometers, and the thickness of the insulating layer can be scaled similarly to that of scaled CMOS (nanometers). A voltage pulse applied to the ACPS line produces a magnetic field perpendicular to the polarization of the ferromagnetic film, and, thus, generates a spin wave (spin wave packet). Upon excitation, the spin wave propagates through the ferromagnetic film. As it reaches the nearest ACPS line, the phase of the spin wave can be detected by the inductive voltage measurements. When two spin waves are excited from two ACPS lines, the output ACPS line detects the inductive voltage produced by the superposition of two waves. Depending on the relative phase of the spin waves, the amplitude of the inductive voltage may be enhanced (two waves are in phase) or decreased (two waves are out of phase) in comparison to the inductive voltage produced by a single spin wave. Potentially, the proposed approach may resolve the interconnect problem, as there are no conducting wires for long-range interconnections, but all interactions are accomplished in a wireless manner via magnetic field. The shortcoming of the use of spin wave bus is the low propagating velocity but the advantage lies in its effective generation and detection. The energy dissipation in the creation, transmission and detection should be benchmarked with wired interconnects.

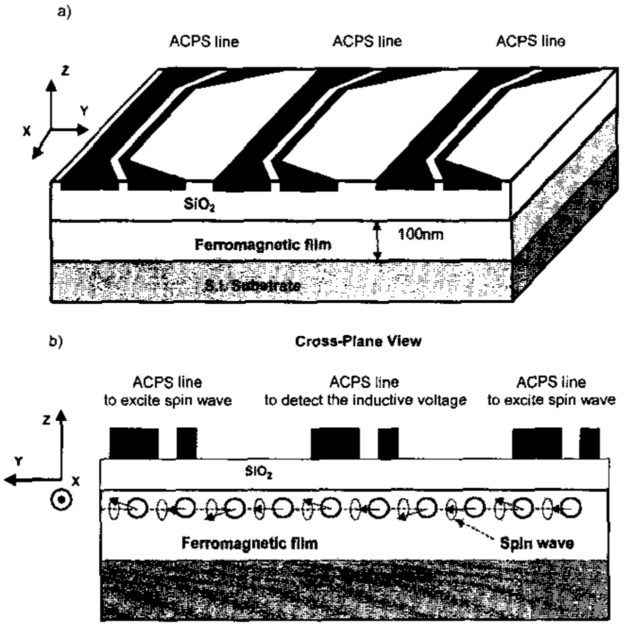

Fig.2 (a) A prototype logic device with Spin wave Bus. There are three conducting loops (ACPS lines) on the top of a ferromagnetic layer. Each of the loops can be used for spin wave excitation by current pulse and detection by the inductive voltage measurement. (b) The cross-plane view of the proposed device. Spin waves propagate along with Y axis.

V. SUMMARY

We have described several approaches to the nanoscale interconnect problem. Molecular wires together with metallic particles are considered as among one of the candidates because of their scalability down to the few nanometer diameter size and potential low cost for nano-manufacturing based on self-assembly. The use of tunneling structures demonstrates another possibility of resolving the interconnect problem by constructing a homogenous Cellular Automata like structures, where all local interconnections are achieved via the tunneling between the nearest nano-devices. For long-range wiring, a novel type of information channel – spin wave bus is used as an example to the use of wave functions. The interconnections between the nano-devices can be accomplished in a wireless manner via the waves. Potentially, the spin wave bus may be an effective tool for spin-based devices interconnection. Ultimately, the use of coherent quantum waves in the case of quantum information systems will totally eliminate a lot of interconnect problems, taking advantage of entanglement and substantial reduced numbers of devices (qubits) needed in the systems. For the latter, we will not discuss it further due to limited space.

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