Plenary Lecture

The Circuit Paradigm in Nanoelectronics – Field-Coupled and Hybrid Nanoelectronic Circuits

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1 Introduction

In electronics, modeling, simulation and design of a system are based on the “circuit paradigm.” Equivalent circuit models of devices and their interfaces are developed, and the models of systems are composed of the equivalent circuits of their building blocks. The circuit paradigm assumes that the designer is able to build a system-architecture from blocks in such a way that the equivalent circuits of the building blocks do not depend on the neighboring blocks. Physical charge and energy always conserve, thus properly constructed device and circuit models obey Kirchhoff’s Laws.

The circuit paradigm was successfully extended to electromagnetic systems, microwave circuits and integrated optics as well. During the last century, it has been the bridge between device physics and physical level system design.

Today metal wired interconnections of nanoelectronic devices are being explored. Each device is equipped with metal contacts which serve as equal-potential “heat baths” and the contacts are connected with “wires.” Circuits composed of resonant tunneling diodes (RTD) and single electron transistors (SET) are the best known examples. Metal contacted quantum dots are being studied, even metal-molecule-metal junctions with only a single molecule embedded in the junction have been demonstrated, and studies on molecular transistors published. The case studies presented in this paper show the efforts and call the attention on the difficulties of metal wiring in nanoelectronics. Metal wired nanoelectronic circuits suffer from a basic limitation. Nanodevices and wires are different in nature.

The internal dynamics of nanodevices is governed by the laws of quantum physics, wires are considered to be “classical.” Laws of physics are not scale-invariant, and there exists a significant change in the laws as we shrink the scale from micro to nano. If each device is metal-contacted, the circuit contains as many quantum-to-classical behavior converters as the number of nanodevice contacts, and the performance of a nanocircuit deteriorates as the number of devices grows. On the other hand, real nanoscale wires, the so called nanowires, are not any more “classical,” because electron transport becomes “ballistic,” and the conceptual advantages of the circuit paradigm are lost.

In this paper an alternative approach will be reviewed. Nanodevices can be connected not only with (i) wires, but they can be coupled with electromagnetic fields between neighboring devices as well, with (ii) Coulomb forces between charges, with (iii) magnetic forces between magnets, and also with (iv) electromagnetic radiation between “nano-antennas.” We are referring to circuits coupled according to (ii), (iii) and (iv) as “field-coupled nanoelectronic circuits.”

Recently circuits have been proposed and demonstrated composed of filed-coupled nano-scale devices and sub-circuits embedded in microelectronic environment. To interface the two worlds of different scales, special, so called “hybrid,” devices are needed. Nanoelectronic devices embedded in microelectronic systems will be referred as “hybrid nanoelectronic circuits.”

In this paper we review the application of the circuit paradigm to field-coupled nanoelectronic and hybrid micro-nano circuits.

2 A Note on the Frontiers of CMOS Technology

Today, the mainstream is still the development of silicon CMOS. We are witnessing a transition from micro-CMOS to nano-CMOS, and the exponential increase in transistor count predicted by Gordon Moore in 1964, continues. An assessment of the requirements and technological challenges that will have to be addressed to maintain the current rate of exponential miniaturization is published each year in an annual update of the International Technology Roadmap for Semiconductors (ITRS), also known as “The Roadmap” [1]. ITRS extends for 15 years, but there are no guarantees that the problems confronting Si technology will be solved over this period.

Recently, the National Academy of Engineering (NAE) published a Report on the “Fundamental Limits of Nanotechnology” in the book Frontiers of Engineering [2]. The conclusion is that at the current pace industry will reach the end of conventional CMOS scaling down before the end of 2016, perhaps as early as 2010.

The emerging non-CMOS nanoelectronic circuits will not be competitors of the mainstream CMOS in the areas of microprocessors, memories or even digital ASICs. Certainly, not before 2010’s. However, significant enhancements of microelectronics with embedded nanoelectronic circuits, and a host of new applications are emerging already in the coming years. Thus the study and exploration of the potential and also the limits of non-CMOS research devices are important [1, 3]

3 Nanoelectronic Circuits Composed of Coulomb-coupled Nanodevices

The circuit paradigm has been successfully applied to integrated nanoelectronic circuits composed of nanodevices coupled to each other by electrostatic Coulomb-forces, under the condition that the devices are far enough apart from each other thus the overlap between their quantum-wave functions can be ignored. Relatively weak forces govern the interactions between devices thus their effects can be described using perturbation theory. In the unperturbed system there are no interactions between the devices, and the state functions are simple products of single-device state functions. The perturbation consists of the electrostatic interaction between the devices and that of the external electromagnetic forces.

The internal electronic dynamics of the devices is described by quantum Markovian master equations of finite-state systems [4]. It has been shown that integrated circuit dynamics can be described by a set of mixed quantum-classical state-equations forming a set of coupled non-linear differential equations. The conservation of charge and energy enables us to introduce formal “charges” and “voltages” obeying Kirchhoff’s equations, thus the equivalent circuit of an integrated system can be composed of circuit models of the devices, and standard simulation and design techniques of electronic circuits can be applied.

In principle, nanoelectronic systems built from quantum-devices do have equivalent circuit models if quantum dynamics is restricted to the internal behavior of the devices, but the coupling between them can be considered to be classical. The state equations of these systems are mixed quantum-classical sets of nonlinear differential equations.

4 Nanoelectronic Circuits Composed of Magnetic-field-coupled Single-Domain Nanomagnets

The magnetization dynamics of ferromagnetic materials can be described by the micromagnetic equations describing the time evolution of the magnetization vector field under the influence of an external magnetic field. If the magnetic particle is sufficiently small (i.e. smaller than few times 100 nm), then its magnetization behavior can be approximated by the single-domain Landau-Lifshitz Equation, which describes a damped precession of the magnetization. This precession drives the magnetostatic energy toward a local energy minimum.

A magnet can exchange energy with externally applied fields, with neighboring single-domain nanomagnets, and it also dissipates energy. Circuit model of a single-domain nanomagnet has been constructed [5] by considering the magnetization vector components and magnetic field vectors as currents. Interconnections in such nanomagnet circuits are represented by non-energetic ideal transformers.

The circuit model is a tool for the design of systems composed of single domain nanomagnets. It enables the efficient numerical simulation of nanomagnetic systems and their integration with more conventional circuitry.

5 Surface Plasmon Waves in Nanoelectronic Circuits

Microelectronics could not explore the range of terahertz frequencies (from 0.1 to 100 THz), however, emerging nanotechnologies offer a hopeful solution. They enable us to generate and exploit the very fast oscillations of conduction electrons at conductor-insulator interfaces. In the conduction band of nanoscale metals the mean-free-path for electron-electron collision can be much smaller than the electron-mean-free-path for collisions with impurities and phonons. In materials with these properties, the electron's collective behavior is analogous to that of an electron gas, i.e. plasma waves can be generated and extremely fast plasma oscillations can be observed and utilized.

Plasma oscillations in bulk solid state materials have been studied for many decades. The relaxation time of bulk plasma oscillation is in the order of 10–18 s, thus they can not be used in devices and circuits. However, plasma waves at metal-dielectric or, in general, at conductor-insulator interfaces, called surface plasmon waves (SPW), can be generated and exploited [6, 7].

The circuit paradigm has been applied for modeling of surface plasmon waveguide modes, for the generation of surface plasmon modes with attenuated total reflection (ATR), and with tunneling in metal-insulator-metal junctions. Equivalent circuits for nanoparticles and arrays of field-coupled nanoparticle chains have been developed [8].

Nanoparticles behave as tiny antennas coupled by electromagnetic radiation. The coupling is not achieved by the far field of the antennas only, but by the near fields as well. For far fields they are radiation transmitters or sensors, the near field is interconnecting them in a field-coupled nanoelectronic circuit. Laser generated surface plasmon waves are very sensitive for the properties of the surface, and this phenomena has been used for bio-sensors [9, 10].

6 Quantum-Tunneling Nanoantennas

If two metallic nanoparticles are separated with a thin (0.1 to 2 nm thick) insulating layer, e.g. an oxide, electrons can quantum-tunnel between the two nanoparticles. A metal-insulator-metal (MIM) tunnel-diode is formed. If the two particles are continued in nanowires, a "nanoantenna" is formed, e.g. a dipole.

The quantum-tunneling nanoantenna can serve as the antenna and rectifier of a “radio receiver” in the THz frequency range. These “receivers” as sensors can be integrated with CMOS chips, because they are small enough, their fabrication is CMOS compatible, their properly perform at room temperature.

The quantum-tunneling nanoantenna integrated with a CMOS circuit is a real micro-nano “hybrid,” because a nanoelectronic sensor is built on top of a microelectronic circuit. In this paper we present the equivalent circuit of the quantum-tunneling nanoantenna, which enables us to design hybrid micro-nano circuits.

7 Single-electron Transistor (SET) Nenoelectronic Circuits

Single-Electron Tunneling (SET) transistors [11] have been suggested as candidates for ultra-dense and complex signal and image processing systems. Ultimately the goal has been to build SET transistors capable of operation at room temperature, and compatible with conventional CMOS process technology.

The World’s fastest and most sensitive electrometer is based on a few radio-frequency single electron transistors (RF-SET) [12, 13]. However, large-scale integration of SET based circuits at room temperature has not been achieved. The main disadvantage with SET devices is that it is difficult to realize structures with sufficiently small capacitances such that they function at room temperature, while device to device variations for present structures are quite large, an issue that has to be overcome by greatly improved process technology, or some scheme of self-assembly to realize uniform arrays of structures.

Nevertheless, the design of even simple integrated circuits requires the application of the circuit paradigm, i.e. the development of circuit models for the port-dynamics of SET transistors. Those simulation tools which analyze not only the port but as well as internal dynamics—such as e.g. SIMON [14]—are unnecessarily complex to simulate large-scale circuits. Without a proper hierarchy of models, large-scale systems can not be investigated and designed.

In this paper we review the hierarchy of circuit models of SET transistors, [15] and circuits composed of SET transistors, [16].

Very-Large-Scale Integrated circuits composed of metal-wired nanodevices have not been demonstrated. Interconnections limit the size of the circuits. Locally connected cellular architectures, such as Cellular Neural Networks (CNN) [17] are hopeful candidates for integrated SET circuits [18, 19].

8 Molecular and Mono-molecular circuits

Electronic devices based on single molecules has been proposed and demonstrated already in the 1970’s. It has been shown that metal-molecule-metal junctions can behave like rectifiers with only a single molecule embedded in the junctions. Later experiments with two- and three-terminal molecular devices have been demonstrated by bonding a few molecules between two or three metallic electrodes.

The goal of these experiments was to develop a molecular transistor. The current between the source and the drain electrodes flew through a molecule. The current could be controlled by the shift in energy of a given molecular level of the molecule relative to the Fermi level of the electrodes. This can be achieved by the closure of the HOMO-LUMO gap of the molecule or by a change of the molecule-source and/or molecule-drain electrode electronic coupling. The change in current is measured on an ammeter positioned away from the junction in the measurement circuit. The metal electrodes of the junction convert the electron transfer, which is a quantum property of the molecule, into a classical current intensity in the circuit.

The quality of the experimental transistors demonstrated so far are poor, and the size of the device is determined by the contacts and not by the molecule. It does not seem to be reasonable to insure three quantum-classical conversions for each molecular transistor in order to have classical currents and voltages at the terminals, which allows us the application of the circuit paradigm.

It has been suggested to integrate complex functions in large molecules, and instead of conversing the molecule's quantum behavior into classical currents and voltages, to integrate as many molecules as possible into a "mono-molecular" system [20].

In sections II, III and IV we have proposed and demonstrated an alternative solution, namely, to build integrated circuits by coupling the molecules with Coulomb-, magnetic- forces or electromagnetic radiation. We have presented techniques insuring the applicability of the circuit paradigm for field-coupled devices and also for hybrid micro-nano integrated circuits.

A concerted effort of the nano-device and the circuit design communities could significantly accelerate the development of nanoelectronics [21].

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