Nanotube-Based Interconnects for Nanotechnology Circuits: An Introspection

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As progress along the ITRS road map continues, physical and electromagnetic limitations make scaling of silicon FETs increasingly difficult. One solution is to replace FETs by completely new structures such as nanoscale molecular, biological or quantum devices. Before considering this changeover, an interconnect technology must be developed that is suitable for these new device concepts. To connect ultra-small devices, interconnects must be less than 10 nanometers (nm) in diameter. However, they still must be easy to fabricate, have low resistance, high maximum current carrying capacity and be isolated by low-k dielectric materials for applications in ultra-high density nanotechnology circuits. As the sizes of the active devices approach the nanometer dimensions, the wires that connect them must also be scaled down. Today, several IC manufacturers are in the process of commercializing 100 nm CMOS-based IC technologies and the research & development work for the 70 and 50 nm devices is well underway. Successful IC development below these feature sizes faces the fundamental challenges imposed by the basic lays of quantum physics. The surface scattering from the boundaries of ultra-narrow conductors as well as the grain boundary scattering would inhibit electronic conduction in the wires to an unacceptable level.

Nanotechnology circuits with devices on the sub 100 nm scale will require interconnects with sizes from 50 nm down to molecular and atomic dimensions. If metallic conducting lines such as copper are used for the interconnects then the miniaturization process will result in rise in the copper resistivity because the dimensions of the conducting lines will be of the same order of magnitude as the mean free path of electrons which is 39.3 nm in copper at room temperature. This rise in resistivity may dramatically slow the circuit's functioning and as a result jeopardize the ability to improve the circuit speed expected from miniaturization. Electromigration which is the result of momentum transfer from the electrons moving under the applied electric field to the ions making up the lattice structure of the interconnect material imposes another serious problem. Continuing miniaturization of the thin-film metallic interconnects results in increasingly high current densities leading to the open- and/or short-circuit electrical failures of interconnects in a relatively short time. The higher the temperature of operation, higher the electromigration-induced failure of the metallic interconnects is. Clearly, interconnects will play a crucial role in the development of the nanoscale integrated circuits and that, in addition to the development of the various nano devices, interconnects that will be used to connect these devices deserve a very special attention. In this paper, the applicability of carbon nanotubes (CNTs) as interconnects for nanotechnology circuits will be investigated.

Nanotubes are tiny tubes about 10,000 times thinner than a human hair and consist of rolled up sheets of carbon hexagons. They have the potential for use as minuscule wires in ultra small electronic devices. The electrical properties of CNTs are fascinating because they can exhibit metallic or semiconducting behavior depending on their structure and dimensions. This has made carbon nanotubes a unique candidate material for potential nanotechnology applications as nanoscale electronic devices and interconnections.

To a large extent, the unique electrical properties of CNTs such as their extremely low electric resistance are derived from their one dimensional character and the unique electronic structure of graphite. Resistance primarily occurs due to defects in crystal structure, impurity atoms or an atom vibrating about its position in the crystal. In the case of a CNT, the electrons are not so easily scattered. Due to the small diameter and the huge aspect ratio (length to width), nanotubes are essentially 1-D systems and therefore electrons have low chance of scattering giving rise to very low resistance. The electronic properties of perfect MWNTs are rather similar to those of perfect SWNTs because the coupling between the cylinders is weak in MWNTs.

Electrical transport in metallic SWNTs and MWNTs is ballistic, i.e., without scattering over long nanotube lengths enabling them to carry high currents with essentially no heating. In contrast, electrons in copper travel only 40-50 nm before they scatter. Phonons also propagate easily along the nanotube. Superconductivity has also been observed at low temperatures with transition temperatures of nearly 0.55 K for 1.4 nm diameter SWNTs and nearly 5 K for 0.5 nm SWNTs.

The low resistance ensures that the energy dissipated in carbon nanotubes is very small thereby solving the problem of dissipated power density that adversely affects silicon circuits. Current densities of more than 10^{10} A/cm^2 have been reported for the metallic configuration of CNTs. Since carbon nanotubes do not have any leftover bonds there is no need to grow a film on the surface in order to tie-up the free bonds and there is no need to restrict the gate insulator to silicon dioxide. This fact implies the use of other superior materials to insulate the gate terminal in a transistor which can result in a much faster device.

Carbon nanotubes have shown great promise for use as interconnections in nanotechnology circuit applications. This is particularly because they can conduct large currents of the order of a 10^6 A/cm^2 without any deterioration thus avoiding the electromigration problems characteristic of metallic interconnections. The scattering-free transport of electrons possible in defect-free carbon nanotubes is a very attractive feature of CNTs for microelectronic applications. The reduction in the thickness of conventional metallic or polycrystalline interconnections leads to additional scattering at the surfaces and grain boundaries thereby deteriorating the interconnection resistance. CNTs provide undistributed quasi-crystalline wire-like structure where pulses can travel uninterrupted by length dependent ohmic scattering. The approximate estimation of signal delays with a simple model proves that nanotubes would surpass classical wires with respect to signal delays. Plenty of work on using carbon nanotubes for building integrated circuits is in progress. Researchers are also trying to develop complex gates and circuits by fabricating devices along the length of a single CNT.

This work is based on research supported by a research contract from the U.S. Department of Defense.