Future Prospective of VLSI Technology

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ABSTRACT:-

As we are gradually migrating towards nano-technology, the interconnect width also reduces. This paper analyzes the use of carbon nanotubes(CNTs) and optical interconnects in the implementation of VHSIC/VLSI circuits in place of copper. The Optical interconnect is now-a-days more in demand due to its low latency, high bandwidth with low power dissipation as compared to VLSI technology. Reduction in cross-section of copper interconnect leads to increase in its resistivity causing increase in propagation delay and power dissipation. As a result, the continuous degradation of performance of copper interconnects is one of the major challenges to keep the Moore's law alive, thus, we are looking for future prospectives of VLSI Technology.

Keywords:- Optical interconnects, Copper interconnects, CNTs, VLSI etc.

1.INTRODUCTION:-

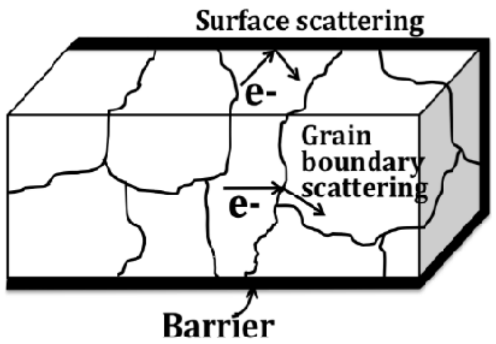
As we are entering into the golden era of electronics, the primary objective of chip design is to achieve highest performance-energy efficiency. The copper interconnects cannot keep pace with IC interconnects as the feature size scales down to nano-scale. The copper interconnects face great challenges in the nanometer regime such as higher power dissipation increased propagation delay and limited bandwidth. Thus, carbon based materials such as CNTs and optical interconnects have been proposed as alternatives for the VLSI circuits in the near future.

Carbon nanotubes (CNTs)are allotropes of carbon with a cylindrical nanostructure. These are graphene sheets rolled at specific and discrete angles and the combination of rolling angle and radius decides the nanotube properties, for example, whether the individual nanotube shell is a metal or semiconductor. Due to their extremely high mechanical and thermal stability, high thermal conductivity and large current carrying capacity, CNTs have emerged as an area of research for VLSI applications.

The performance of VHSIC/VLSI circuits is limited by communication capacity between gates, chips and boards. Optical interconnects can be a potential solution to this communication problem. Optical wires have the lowest latency, power consumption and highest possible bandwidth using Wavelength Division Multiplexing(WDM). While, a CNT has lower latency than copper. So far we have discussed the theoretical predictions of CNTs but technology should bridge the gap between theoretical prediction and what can be achieved with the current CNT technology.

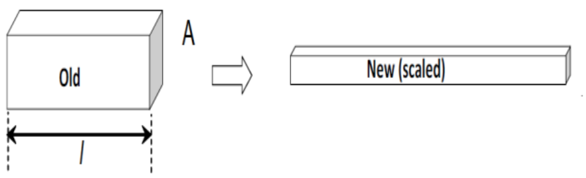
2.EFFECT OF SCALING ON COPPER INTERCONNECT

When the cross-section of wire and grain size becomes comparable to the mean free path of electrons in cu to phenomenon take place in current carrying copper, first being surface scattering and other being grain boundary scattering. These results in increase of resistivity of copper interconnects.



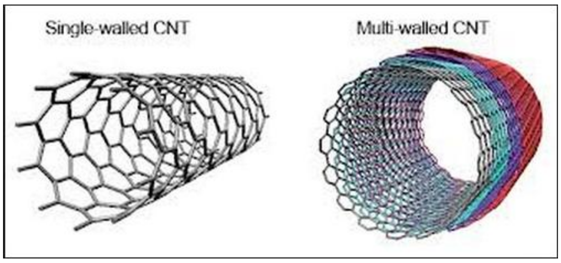
The increase in wire length(L) besides reduction in cross-sectional area(A) increases the resistance of wire, subsequently resulting in limiting the signal rise time, bandwidth, higher delay and more power consumption. This could be understood by the following relationship between the ideal bandwidth(B) and the cross-sectional area(A)

$$\mathbf{B} \propto A/L^2$$



3.ABOUT CNTs

CNTs were discovered in 1991 by Sumio Lijima. The CNTs are constructed in the form of seamless cylinders with the walls formed by one atom thick sheets of carbon. The diameters of these cylinders are of the order of nanometers. The chemical bonding of nanotubes is entirely composed of sp^2 bonds. These bonds stronger than sp^3 bonds provide nanotube with their unique strength. CNTs are classified as metallic or semiconductor depending on the chiral configurations but for VLSI interconnects, metallic once are preferred. There are two categories of CNTs, single-walled nanotubes(SWNTs) and multi-walled nanotubes(MWNTs).SWNTs have a diameter close to 1 nanometer. It constitutes of one atom thick layer of grapheme wrapped into a seamless cylinder. MWNTs consists of concentric tubes of graphene.



There are three unique geometries of CNTs which are armchair, zig-zag and chiral. Zig-zag is (n,0);armchair (n,n) and chiral (n, m) where (n, m) represents the manner in which the graphene is wrapped into the cylinder. The integers n and m represents the number of unit vectors along two directions of crystal lattice of graphene. The diameter D of an ideal carbon nanotube from its n and m is as follows

$$\mathbf{D = a/\pi * \sqrt{(n^2+nm+m^2)}}$$

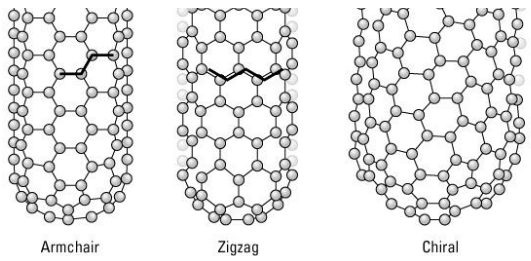
Where a=0.246 nanometers

One of the most interesting properties about CNTs is that if we have two of them which have slightly different physical structures and the two are joined together then the junction acts as an electronic device whose behavior depends upon the structure of the two tubes. If n=m then the nanotube is metallic and n-m is a multiple of 3 then the nanotube is semiconducting with small energy gap. Thus, all the armchairs are metallic and nanotube (6,3), (9,6) etc. are semiconducting.

CNTs are the strongest and the stiffest material in terms of tensile strength and this strength comes from the covalentsp^2 bonds between the individual carbon atoms. Through experiments, MWNTs have reached the tensile strength of 63 gigapascals (GPa), whilst SWNTs have reached nearly 100 GPa. CNTs have different properties in axial as well as radial direction. CNTs are very strong in the axial direction, while, in the radial direction they are rather soft.Overall, CNTs show a unique combination of stiffness, strength and tenacity compared to other fiber materials which may lack one or more of these properties.

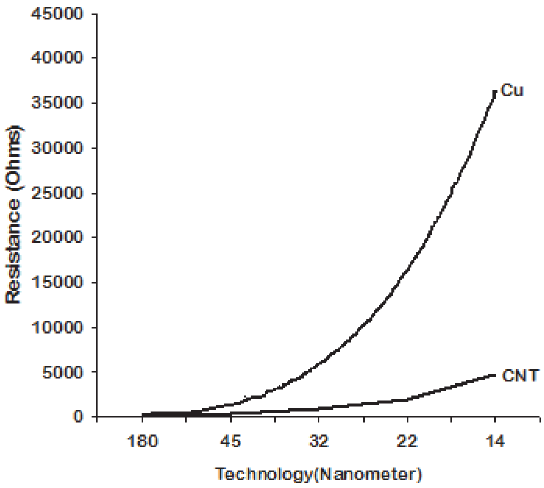
Theoretically, metallic nanotubes can carry an electric current density of $4*10^9$ A/cm^2 which is thousand times more than that of copper whose current density is limited by electro-migration. As we deal with nano-scale regime, electrons propagate along a axis of the tube only. So, CNTs are often are referred as one-dimensional conductors. All nano-tubes are excellent thermal conductors along a tube axis, whereas good insulator perpendicular to the tube axis. Experiments revealed that a SWNT has a thermal conductivity of 3500W/mK along its axis as compared to copper, which has thermal conductivity of 385W/mK. Whilst, MWNT has a thermal conductivity of 3000W/mK. Thermal conductivity in CNT is mostly due to phonon rather than electrons. Even in some experiments, CNTs were added to epoxy resin to double the thermal conductivity of resin.

Perfect CNTs have a crystalline structure formed by hexagonal network. The electrical properties of the CNTs are affected by the orientation of these hexagons. As discussed before, there are three geometrical configurations of CNTs of which the one labeled armchair has electrical properties similar to that of metals. When we apply voltage at its both ends, an electric current will flow. The other two configurations, zig-zag and chiral have properties similar to those of semiconductors. When we apply voltage at its both ends, an electric current will flow through it when extra energy in the form of light or electric field is provided to its free electrons from the carbon atoms.



In material sciences, the optical properties of CNTs refer to the absorption, photoluminescence and Raman spectroscopy of carbon nanotubes. Though the practical use of optical properties is yet unclear, but it is possible that CNTs could have application in the fields of optics, photonics, light-emitting diodes (LEDs), photo-detectors etc.

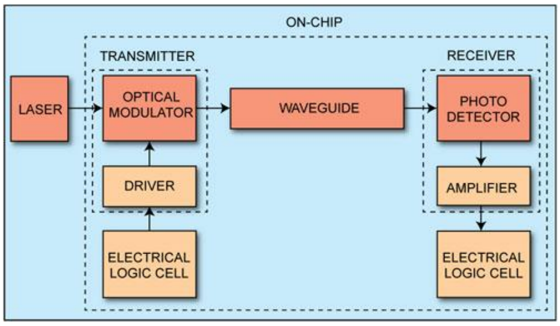
A graphical representation below shows the dependency of resistance on the technology regime used. It increases with increase in nano-scale meter.



4.OPTICAL INTERCONNECTS

An Optical Interconnect is a medium through which the signal flows through in the form of optical signals (light) and the medium being optical fiber, waveguide etc. In this, electrical signal is first converted into optical signal by led or photodiode followed by optical modulator. The signal propagates through optical cable/fibers. At the receiver side, the photo-detector reconstructs the electrical signal back from the optical signal. Optics does not put a limit on the density of information that can be sent over long distances as is the case of electrical wires where the limit for information density is put by Shannon's limit. Optics may be able to save energy in interconnects. Optical interconnect solves design problem such as bandwidth, crosstalk noise, power dissipation etc.

Optical interconnect is a way of communication through optical fibers/cables. The technology is currently introduced as a way to link computers to mobile devices, as well as in motherboards and devices within computers. A diagram of optical interconnect system is given below. It contains optoelectronic source such as lasers, optical modulator, optical demodulator and optoelectronic detector such as photo-detector, input and output channel coupler. Electrical logic cell shown in the block are actually input and output transducer. Waveguide means optical fiber communication channel. Amplifier here works as a repeater or regenerator.



4.1INFORMATION INPUT

Input can be in the form of data, video or voice. An input transducer is used to convert non-electrical input into electrical. Example: microphone converts sound into electrical current. Input must be in the form of electrical signal before it is transmitted through the fiber optic link.

4.2OPTICAL TRANSMITTER

An optical transmitter is required to convert the electrical signal into optical and to successfully launch it into the fiber optic link. This comprises of an optical modulator, optoelectronic source such as lasers and input channel coupler. Optoelectronic source generates an information carrier in the optical range nearly in the infrared part of the spectrum.

An ideal optoelectronic source should produce a stable monochromatic wave with sufficient power for long distance transmission. The favorable properties of this source include compact, light weight, easily modulated and consume moderate power. The optical signal is produced by modulating the electrical signal with the optical carrier wave.

The coupler is usually a micro-lens which collects the light signal from the optoelectronic source and send it efficiently to the optical fiber cable. In case of open channel communication such as in radio or tv broadcasting, the channel coupler is an antenna which collects the signal from the transmitter and directs it to the atmospheric channel, whilst, in case of guided channel communication such as in telephonic link, the coupler is a connector for attaching the transmitter to the cable.

4.3COMMUNICATION CHANNEL: OPTIC FIBER

Main purpose of communication channel in any system is to pass the input signal from the transmitter to the receiver without distorting it. Most light wave systems use optical fibers as the communication channel. Most important design issue for this channel is fiber dispersion which results in spreading of optical pulses with propagation. When optical pulses injected into the fiber spread in time domain such that they interfere with adjacent pulses, it results in Inter Symbol Interference or ISI. This reduces the system bandwidth or information carrying capacity of the system. This limits the bit rate, that is, how fast the information is transferred.

4.4REPEATERS

When optical signal travels through the length of the fiber, it gets attenuated due to scattering, absorption etc. and broadened due to dispersion. After a certain length, the cumulative effect of signal attenuation and broadening causes the signal to become weaker and indistinguishable. Thus, the shape and strength of the signal must be regained before this happens. This can be done by using repeaters or regenerators. Example: an erbium-doped fiber amplifier can be used at an appropriate point along the length of the fiber.

4.5OPTICAL RECEIVERS

An optical receiver is essentially required to convert optical signal received at the output end of the optical fiber back into the original electrical signal. It consists of optical demodulator, photo-detector and output channel coupler. At the end of the optical fiber link, again a coupler is used to collect the signal and redirect it to the photo-detector. The design of the demodulator depends on the modulation format used by the light wave system which mostly uses a scheme known as ‘’Intensity Modulation with Direct Detection (IM/DD)”.The current produced by the detector is proportional to the incident optical power and hence to the information input. The properties of these detectors include small size, linearity, low power consumption, linearity, long operating life and flat spectral response.

Demodulation is done by a decision circuit which identifies bits 1 or 0, depending on the amplitude of electrical signal. BER is bit error rate defined as the number of errors made per second which is important to characterize the performance of a digital light wave system. An important parameter for any receiver is the receiver sensitivity which is usually defined as the minimum average optical power required to realize a BER OF 10^{-9}. Receiver sensitivity depends on SNR which in turn depends on various noise sources that distort the received signal. An ideal receiver also introduces some noise by the process of photo-detection to the signal received. This is referred as quantum noise or shot noise as it has its origin in the particle nature of electrons. No practical receiver operates at this quantum limit due to the presence of several other noise sources such as thermal noise which are internal to the receiver.

4.6INFORMATION OUTPUT

Lastly, the output must be in the form that can be interpreted by a human observer. Example: transformation of electrical output into sound wave. For thee transformations, we require output transducers. In some cases, electrical signal can be directly used.

5.Conclusion

Optical interconnects and carbon nanotubes (CNTs) present promising options for replacing the existing copper based wires. We find that for a local wire, a CNT bundle exhibits a smaller latency than copper for a given geometry. Optical wires have the lowest latency and the highest possible bandwidth density using wavelength division multiplexing (WDM). CNTs can yield comparable performance to optical wires provided a certain mean free path and packing density is achieved. Semiconducting carbon nanotubes (CNTs) have gained immense popularity as possible successors to silicon as the channel material for ultrasonic performance field-effect transistors. We have found through experiments that optical interconnects have a performance that is competition with or better than electrical interconnects and can used for future interconnect needs. Optical interconnects have overcome problems of crosstalk, bandwidth as to attain higher data rates, reduced loss due to signal attenuation, security, reliability, impedance matching etc. Thus, an overview of using CNTS and optical interconnects is presented here as well as we discussed about the problems faced while using copper interconnects in nano-meter regime. We can conclude by saying that Optical interconnects and CNTs have potential to replace Copper interconnects in VLSI/ VHSIC applications.

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