Novel Designs For Nano-scale Inductors
California Institute of Technology, Computing Beyond Silicon Summer School
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1. INTRODUCTION

Power dissipation is an ever-increasing problem, as computer hardware is scaling down towards the atomic level and demand for high device density is rapidly increasing. Recent research papers have addressed this issue and purposed methods of improvement [1, 2, 3, 4, 6, 7, 17, 18]. A promising improvement, which is commercially used at the macro-scale by the Cambridge based company, Adiabatic Logic Limited, is adiabatic computation. If implemented at the nano-scale level (the next step in device size reduction), adiabatic computation could provide significant power dissipation reductions to the current nano-scale architecture. However, to efficiently apply the adiabatic computation at the nano-scale, the development of a high quality (*Q*) nano-scale inductor is necessary. Unfortunately, it gets considerably harder to produce high *Q* inductors as their size tumbles down to the nano-scale. This challenge stems from the fact that *Q* is proportional to L/R and physics dictates that the consequences of scaling down are a lower inductance and a high resistance.

Progress towards the development of high *Q* nano-scale inductors has started with the fabrication of inductors at the micro-scale. The traditional micro-scale inductor is a square, two-dimensional, copper spiral on a silicon-oxide substrate (Figure 1.). These inductors are fabricated with a top-down lithography approach process, and due to the high resistivity of copper at the micro-scale, and negative substrate coil interactions; the inductors have a very low *Q* (approx. 1, when approx. 100 is desired) [8, 17]. It appears that to succeed in producing a useful micro/nano-scale inductor a different fabrication approach and/or a new material is needed.

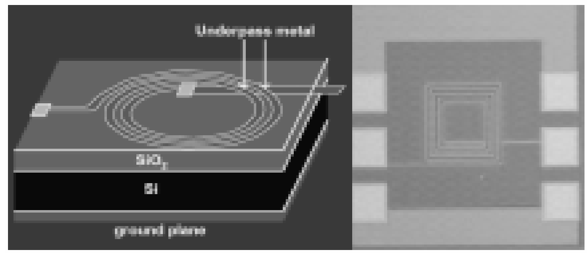

FIGURE 1. Two examples of traditional micro-scale inductors. [8].

The two types of nano-scale inductor designs that this paper discusses, are a coiled carbon nanotube inductor and an iron filled carbon nanotube inductor. Both types take advantage of a new conductive material and use a bottom-up, self-assembly approach. The easy growth, simple geometry, advantageous electron transport properties and high conductivity coupled with low resistivity of these two designs make them attractive as nano-scale inductors. Following the research, of the above properties, each design was simulated in a field solver computer program named *Fast Henry* [20]. Programmed with reasonable parameters of a purposed inductor design, *Fast Henry* can compute a theoretical quality factor for that inductor.

2. COILED CARBON NANOTUBES

2.1 Properties

Coiled Carbon Nano-Tubes, (*CCNT's*), have many properties that make them ideal for implementation as nano-scale inductors. The most obvious property is their traditional solenoid geometry (Figure 2.). The solenoid geometry provides a sufficient field area and prevents the possibility of current flow constraints that occur in the traditional square spiral, micro-scale inductor [10].

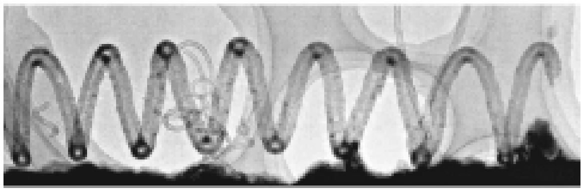

FIGURE 2. A Carbon Nano-Tube with an approximate diameter of 30nm. [19].

A second, relevant property of *CCNT's* is their ability to perform ballistic transport. Researchers have shown that in specific types of carbon nanotubes the mean free path of an electron increases with the diameter of the tube leading to one-dimensional and ballistic transport of electrons [13].

The aspect of ballistic transport supports the last important property of *CCNT's* - low and constant resistivity. The average literature value of the resistivity of *CCNT's* is approximately 10^{-7} Ω m [5]. This resistivity is comparatively low to that of the common copper metal used to manufacture current micro-scale inductors. The simple reduction of resistivity that is accomplished by the substitution of copper with carbon nanotubes also provides a two-fold benefit; considerable improvements in power loss (dissipation) leading to reduction of heat generation (resistance).

2.2 Growth Methods

Another beneficial property of *CCNT's* is their easy growth method that produces aligned coils. The method is very similar to that of the chemical vapor deposition (CVD) process used for regular carbon nanotubes. The general method for CVD begins with a substrate, usually Silicon, Si, or Silicon dioxide, SiO_2. Next, a thin catalyst film (usually a transition metal) is then placed on the substrate. The coated substrate is placed in the chamber of a CVD apparatus and the chamber is purged with a constant flow of hydrogen or argon gas. Finally, a gaseous hydrocarbon is flowed through the chamber at a constant speed, the chamber is heated to a temperature that decomposes the hydrocarbon, and carbon nanotubes self-organize onto the substrate. Zhoung, *et. al*., discusses a CVD method in which the substrate used was silicon, the catalyst was iron (III) oxide / iron (III) nitrate and a 90% yield was achieved.

2.3 Challenges

Even with all the advantageous properties of *CCNT's* for implementation as nano-scale inductors, there is one challenge that needs to be overcome - fabrication. The current fabrication methods for *CCNT's* are simple, but it is hard to produce coiled tubes with consistent walls thickness, tube diameter and coil diameter. Furthermore, once the *CCNT's* are grown, methods for transportation of them to the circuit, placement in the circuit (CCNT's are know for high elasticity) and interfacing with the circuit still need to be developed.

2.4 Theoretical Performance

'At best' literature value parameters were chosen to simulate the *CCNT* inductor's theoretical performance on "Fast Henry" (Table 1.).

TABLE 1. Parameters used for Fast Henry simulation and theoretical performance computation results.

Parameter	Value
Number of turns	200
Diameter of tube	30nm
Diameter of coil	300nm
Conductivity of CNT*	~10^7 / Ωm
Theoretical inductance	0.72μH
Theoretical quality factor	45

*Conductivity of CNT extrapolated from literature resistivity values [5].

3. IRON FILLE CARBON NANOTUBES

3.1 Properties

Watts, *et. al.,* discusses the innovative implementation of iron filled carbon nanotubes as nano-scale inductors. His model purposes that 'organized' chiralities in certain carbon nanotubes create a spiral path along the nanotube for electrons to travel (Figure 3.) and that the path of the electrons simulates a traditional solenoid inductor. The inductive effect of the spiral path traveled by the electrons is not individually significant, but it can be made useful if amplified. When an iron core is 'inserted' in the hollow center of the carbon nanotube, its inductance is amplified, just as a magnet enhances the inductance of a traditional solenoid.

The properties that result from Watt's model are simple yet valuable to the implementation of the iron filled carbon nanotubes as nano-scale inductors. First, as discussed above, they exhibit original electron transport properties that create an inductive phase. Second, due to the low resistivity of carbon nanotubes any nano-scale inductor constructed from iron filled carbon nanotubes will retain the benefit of low resistivity. Finally, since induction is accomplished with a simple nanotube the geometry of the nano-scale inductor design could be very basic (Fig. 3.).

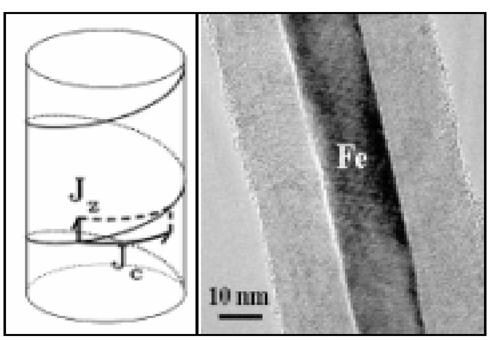

FIGURE 3. (Left) Path of electron in specific chiral carbon nanotubes [16]. (Right) Iron filled carbon nanotube with an approximate diameter of 30nm.

3.2 Growth Methods

In addition to their other useful properties, iron filled carbon nanotubes are easy to grow. The growth method is a modified version of CVD (outlined earlier), named catalytic prolysis. The modifications are as follows: the substrate is a thermally oxidized silicon wafer, the catalyst is an iron film, the CVD apparatus has two chambers [one to vaporize the hydrocarbon and metal material (usually ferrocene) and the other for the self-organization of nanotubes on the substrate] and the regulated gas flow acts as transportation for gaseous material between the two chambers [11, 12].

3.3 Challenges

Implementation of iron-filled carbon nanotubes as nano-scale inductors involves many of the same challenges as with the implementation of *CCNT's*. The growth of the tubes is easy, but consistent inner and outer diameter growth is the next step. The Lamber-Beer flow method can be used for placement of the nanotubes, but just as with the *CCNT's* a method of interfacing with the circuit is needed. Lastly, the construction of an iron filled carbon nanotube inductor is still unclear. Will it be made of one tube, several tubes, or a bundle of tubes?

3.4 Theoretical Performance

Since minimal research has been performed on the electron transport properties of iron filled carbon nanotubes, parameters that describe the path the electron follows can't be easily estimated, and its theoretical performance can't be simulated on "Fast Henry." Experiments have been run to test the conductivity of this design, but they were performed on polystyrene films of thousand of the nanotubes, not individual ones. The inductance of a film of volume 30mm X 15mm X 2mm was found to be 0.3□H [11, 12]. This is a significant conductance, however, it is hard to predict how the conductance will scale to one or several iron filled carbon nanotubes. The implementation of these iron filled carbon nanotubes has high potential and with further research could produce useful results.

4. CONCLUSION

Two designs of nano-scale inductors were presented in this paper. Advantageous properties and construction of the two design and challenges with the implementation of the two designs as nano-scale inductors as well as simulated performance results were included in the discussion of each design. Due to testing conditions, it is impossible to compare the performance of the designs with each other. However, each holds promise for success if a further effort in research is made.

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