The Potential of Carbon-based Memory Systems[1]

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Abstract

It seems likely that density concerns will force the DRAM community to consider using radically different schemes for the implementation of memory devices. We propose using nano-scale carbon structures as the basis for a memory device. A single-wall carbon nanotube would contain a charged buckyball. That buckyball will stick tightly to one end of the tube or the other. We assign the bit value of the device depending on which side of the tube the ball is. The result is a high-speed, non-volatile bit of memory. We propose a number of schemes for the interconnection of these devices and examine some of the known electrical issues.

1. Introduction

If the DRAM industry is to continue with its exponential rate of density improvement, it seems likely that there will need to be a radical change in the construction of memory devices at some point. Certainly quantum-dot [1] devices have possibilities in this role and significant R&D effort has been put forward to develop it. A different possibility is in the construction of a nanometer-sized memory device based on the self-assembly of buckyballs inside of carbon nanotubes. This "bucky shuttle" [2] memory offers nonvolatility and terahertz switching speeds. Also, each bit could require as little as two square nanometers. Extrapolating from the density needs laid out in "The National Technology Roadmap for Semiconductors" [3] this density would be sufficient well past 2030.

Our goal in this paper is to familiarize the reader with the basic issues involved in building a RAM out of carbon nano-structures. We start by discussing the carbon structures used. Next we describe the nanomemory device, followed by a discussion of possible interconnection schemes. Finally, we mention a few of the issues we are currently attempting to resolve.

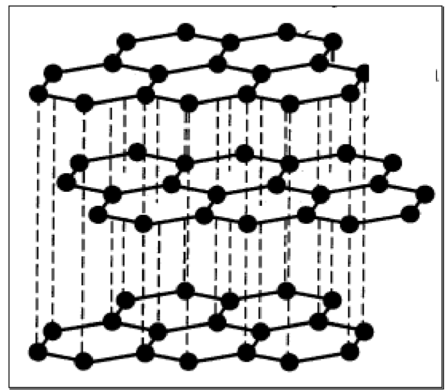

Figure 1 The atomic structure of graphite. The dashed lines indicate the weak connection between the planes of graphite.

1.1. Fullerine nanotubes

Carbon atoms can form a number of very different structures, two of the better known are diamond and graphite. A new carbon structure, the buckyball, was discovered in 1985. Soon after, the nanotube was discovered. These carbon structures, collectively known as fullerines, have been of great interest to the physics and chemistry communities. In the remainder of this section we will give a brief overview of these structures. Readers looking for additional details about fullerines are directed to an excellent overview article found in *American Scientist* [4].

Graphite consists of sheets of carbon atoms in a hexagonal arrangement (see Figure 1). The sheets are very loosely connected to each other. Now imagine taking a single sheet of graphite and cutting a long narrow strip. If that strip is rolled into a long, narrow tube, it would be a nanotube. The ends of the tubes usually form caps, as the dangling atoms will be receptive to forming bonds with their neighbors. The resulting structure is shown in Figure 2. The electrical properties of the newly created nanotube depend upon the exact angle at which the

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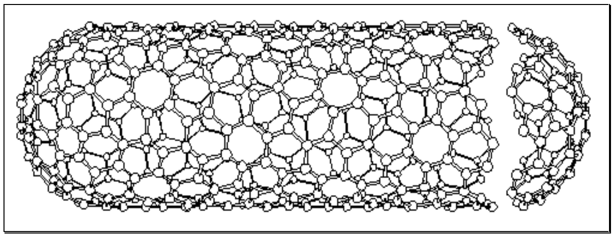

Figure 2 A carbon nanotube

graphite was cut. A cut along one of the edges of the hexagons would result in a conductive "armchair" nanotube. Other angles would result in semi-conductors and even insulators. This *chiral angle* can range from 0° and 30°.

A buckyball can be thought of as the smallest of the nanotubes. It is simply the connection of the two caps with no "tube" in between, and consists of exactly 60 carbon atoms (see Figure 3). Its combination of hexagons and pentagons is exactly the same as that found on a soccer ball. For historical reasons very short nanotubes with 70, or even 80 atoms are sometimes also called buckyballs. In this paper we will use the term only to describe C_{60}.

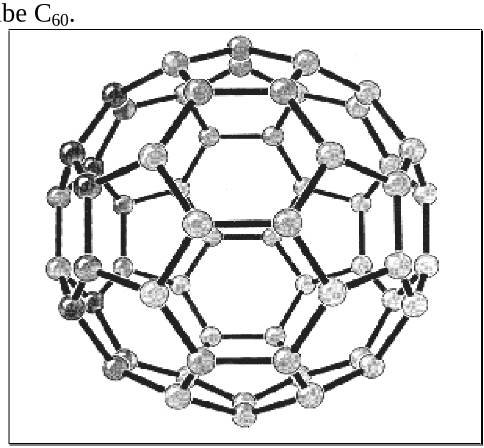

Figure 3 A buckyball

2. The Nanomemory Device

Our proposed nanomemory device (NMD) consists of two parts: the "capsule" which holds the much smaller, charged "shuttle." In Figure 4 we show an example where the capsule is a C_{240} nanotube while the shuttle is a buckyball. The buckyball contains a potassium ion (K^+) which gives the shuttle its charge. (The potassium ion is not shown in the figure.) The outer dimensions of this capsule would be about 1.4nm in diameter and about 2.0nm in length. This K^+ inside of a C_{60} inside of a C_{240} ($K^+@C_{60}@C_{240}$) structure is the smallest and simplest device we have considered. However we are also examining other options such as longer capsules which use other nanotubes as shuttles, as well as having many charged shuttles inside of each NMD.

The state of the memory device is determined by the location of the shuttle: if it is on one side of the capsule, we treat it as a '1'; on the other we treat it as a '0'. The Van der Waals forces between the tube and the shuttle will tightly bind the shuttle to one end of the tube or the other. There is an unstable equilibrium point when the shuttle is in the exact middle of the capsule, but our proposed scheme for writing to the device would prevent the shuttle from ever coming to rest there.

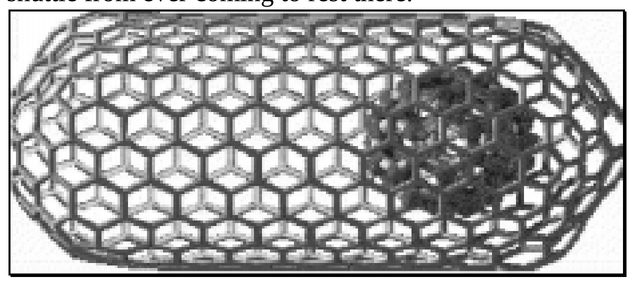

Figure 4 An example nanomemory device

2.1. Writing to the NMD

Figure 5 shows the potential energy of the shuttle at various locations in the NMD. The solid line indicates the potential energy curve when no electric field is applied. Notice that the two potential energy wells are found when the shuttle is on one side of the capsule or the other. These wells keep the shuttle bound to either side of the capsule.

The other two lines display the potential energy when a two-volt potential difference is applied. When such a voltage is applied there exists only one local minimum, and the shuttle will move to that side of the tube. It is with this two-volt potential difference that we can write to the NMD. In general the amount of voltage which needs to be applied depends upon the length of the capsule. A field of 0.1 volts/Å is sufficient to move the shuttle from one side of the tube to the other.

One important issue is how long it takes to perform a write to the NMD. Because of a bouncing effect observable in Figure 6 we have to wait for the buckyball to come to a stop. As the figure shows the time to settle will be about 20 picoseconds.

2.2. Reading from the NMD

Writing to the nanomemory devices is the easy part; reading from them is much more challenging. Somehow the state of the device must be sensed. We have proposed a number of ways to perform a read. The first requires three wires to be connected to the capsule: one on each end, and one in the middle. The position of the

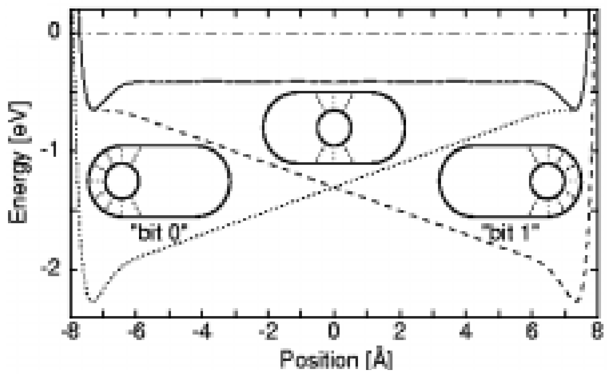

Figure 5 Potential energy of the shuttle at different locations in the capsule. The solid line is when no electric field is applied. The dashed lines are the potential energy when the two-volt potential difference is applied. [2]

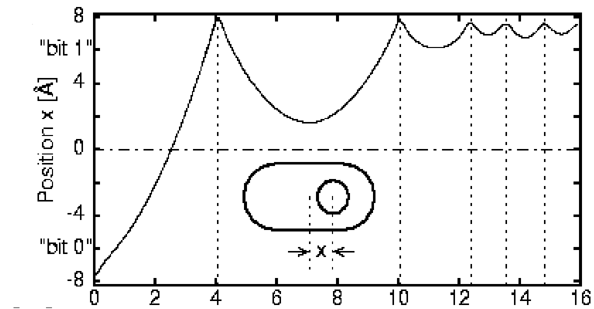

Figure 6 Location vs. time of the shuttle as a write is preformed. Time is in picoseconds. [2]

buckyball is detected by examining the resistance between the middle wire of the nanotube and the ends. A lower resistance will be found on the end that has the shuttle. This three-wire solution has a number of problems, not the least of which is that making a connection to the middle of a nanotube seems difficult. However, a long capsule and shuttle would perhaps make this solution viable.

A device without the middle wire would be easier to fabricate. The notion of a destructive read could be applied here. A read would then be performed in the same way as a write. During that write some current will flow if the shuttle moves from one side of the nanotube to the other. The total current that will flow is limited by the amount of charge held in the shuttles. It is for this type of a read that we would use many shuttles in our capsule to attempt to increase the amount of the current flow. Neither of these reading schemes is particularly satisfactory. We are currently working on other read schemes that appear to be more workable.

3. From NMD to RAM

Once the memory device is fabricated it will still be a challenge to integrate the devices into a large RAM cell. We currently foresee two possible implementations which we call "metal-wired" and "nano-wired." We view the metal-wired approach as the most viable implementation in the near term. However, it is equally useful as a stepping stone on the path to the nano-wired device which offers tremendous density improvements.

3.1. Metal-wired

The easiest device to fabricate would replace the traditional DRAM capacitor/transistor memory cell with a large number of nanomemory devices. We believe current VLSI fabrication techniques could be used, but with the addition of a layer of nano-devices. A “forest” of nanotubes has been already built [5], and a similar technique could be used to create a forest of memory devices between two conducting layers. Figure 7a is a representation of a 4-bit nanomemory device. Figure 7b shows a more detailed view of a single bit. Notice that a number of nanomemory devices are used to make up a single bit of memory. The number of devices per bit will depend upon the minimum line size of the lithography process used. With a 70nm wire width there could be nearly 1,000 nanomemory devices per bit.

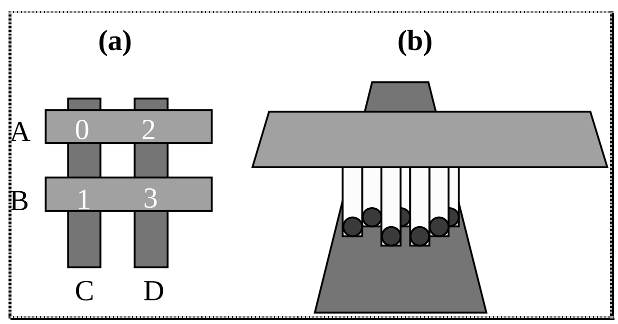

Figure 7 (a) 4-bit nanomemory device with wires A, B, C, and D. (b) a single-bit using forest of NMDs.

Consider how a write to the memory device in Figure 7 would work. Assume that a voltage differential of 2.0 volts will move the shuttles from one side of the capsule to the other. In order to write a ‘0’ to bit three we would have to apply a +1.0 volt potential to wire B while we apply a -1.0 volt potential to wire D. If all the other wires are held at ground, only at the addressed bit will there be a strong enough electrical field to the shuttles. We would write a ‘1’ by reversing the voltages. Writing to an entire row (or column) would be a two-stage process as the 1’s and the 0’s would have to be written at different times.

Now, consider a destructive read with a forest of nanotubes. Our forest of nanotubes would move a large number of charged ions. We should be able to detect if those ions moved or not. Clearly we will have destroyed the data in the process of doing the read. However, we can write it back later, much as it is handled in a traditional DRAM.

This metal-wired carbon nanomemory device has a number of useful features. It is non-volatile, the device itself switches very quickly, and it would seem to be just as buildable using 70nm lithography as it is using 350nm lithography.

3.2. Nano-wired

In this scheme, the memory array could be made entirely out of nanomemory devices and carbon nanowires. The metal wires would be replaced by conducting nanotubes. Each bit of memory would now use only a single NMD. The logic, sense-amps and pads would likely be made using traditional devices. (However, it should be noted that transistors can be built from nanotubes [4].) It would otherwise be similar to the metal-wired proposal. Nano-wires would allow for *very* high densities, with each bit fitting in about two square nanometers. Laying out this network of carbon would require self-assembly techniques well beyond anything we can do today. We believe that work in the area of carbon self-assembly is progressing well enough that this solution may be viable in 15 to 20 years.

4. Questions

Q: **How much heat is generated by the collision of the shuttle into the capsule?**

A: We aren't really sure yet. As shown in Figure 8, simulations at 0° Kelvin show an increase in temperature of 10 to 12 degrees. At room temperatures we expect a little more heat to be generated. However, nanotubes are excellent conductors of heat, and we expect to be able to dissipate that heat quickly.

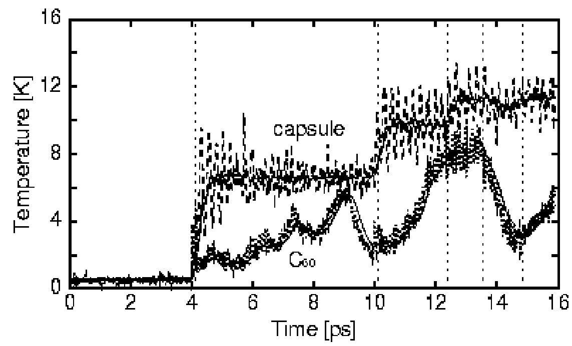

Figure 8 The heat generated by the shuttle slamming into the capsule during a write. [2]

Q: **Won't the nanotube act as a Faraday cage thus preventing an electric field from entering the nanotube?**

A: Yes. This means that we need an electrical connection to the capsule. Such a connection would greatly reduce or eliminate the screening effects.

Q: **Just how conductive are nanotubes?**

A: This is currently an issue under a great deal of study. As noted above, the conductivity depends upon the chiral angle of the nanotube. Measured resistivities of nanotubes have ranged from greater than 5 Ωcm to less than 5.1×10^{-6} Ωcm [6]. However, resistivity may be an irrelevant measure of a nanotube. Nanotubes have been experimentally shown to be quantum conductors [7]. Further, there is some early evidence that ballistic transport occurs along nanotubes. This would seem to indicate that resistance is independent of the length of the nanotube. In all honesty this result is a little difficult for those of us that are engineers to accept, but we recognize that quantum physics can lead to counter-intuitive results.

5. Conclusion

Our proposed nanomemory device is one candidate for carrying memory devices beyond the limits of current DRAM technology. It has three important characteristics: it is small, non-volatile, and fast. At this point the carbon nanomemory has been simulated and buckyballs inside of nanotubes have been created, but a working memory device does not exist. Building it will be a challenge, but self-assembling carbon nanotechnology is an active research area with continuous and promising advances. The feasibility of our device improves daily.

[1] K. Yano, "A 128Mb early prototype for gigascale single-electron memories," in *International Solid-State Circuits Conference (ISSCC)*, 1998.

[2] Y-K. Kwon, D. Tománek, and S. Iijima, "'Bucky shuttle' memory device: synthetic approach and molecular dynamics simulations," *Physical Review Letters*, vol. 82, pp. 1470-1473, 15 Feb 1999.

[3] Semiconductor Industry Association, *National Technology Roadmap for Semiconductors: Technology Needs,* 1997, http://notes.sematech.org/ntrs/PublNTRS.nsf.

[4] B. I. Yakobson and Richard E. Smalley, "Fullerene nanotubes: $C_{1,000,000}$ and Beyond," *American Scientist*, vol. 85, pp. 324-337, July-August 1997.

[5] M. Kusunoki, J. Shibata, M. Rokkaku, and T. Hirayama, "Aligned carbon nanotube film self-organized on a SiC wafer," *Japanese Journal of Applied Physics Part 2 - Letters*, vol. 37, Issue 5B, pp. L605-L606, 1998.

[6] T.W. Ebbensen, H.J. Lezec, H. Hiura, J.W. Bennett, H.F. Ghamemi and T. Thio., "Electrical conductivity of individual carbon nanotubes," *Nature*, vol. 382, pp. 54-56, 4 July 1996.

[7] S. Frank, P. Poncharal, Z.L. Wang, and W. A. de Heer, "Carbon nanotube quantum resistors," *Science*, vol. 280, pp. 1744-1746, 12 June 1998.