A Study of Nanomechanical Memory

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I. Introduction

Electronics are an integral part of modern society. Due to the miniaturization of electronics, more complex devices are produced at a rapid rate. This is responsible due to the invention of the integrated circuit. As devices get more complex, the size of parts increases. A founder of the company Intel, Gordon Moore, noted that the number of transistors on an integrated circuit increased exponentially. Since 1958, this relationship has held, due to the use of Complementary Metal-Oxide Semiconductor (CMOS) transistors [6]. Due to the nature of CMOS technology and the material properties of silicon, there is a limit to how small CMOS transistors can be made [7].

A number of technologies have been proposed to succeed CMOS, and the most promising ones have been compiled in a technological roadmap (ref needed). One of these technologies is nanomechanical memory. While CMOS uses doped transistors, nanomechanical memory uses the configuration of microscopic switches and levers to store information. The fundamental functionality of a mechanical computing system is fundamentally different than an electronic system. While mechanical components are the definite aspect of nanomechanical memory, there are always some sort of electronic components of the device. Even a switch that changes between “on” and “off” states can open or close a circuit. A purely mechanical system would be difficult to integrate with modern electronics. The device must be able to interface with electronics. Nanomechanical switches and nano-electrical-mechanical systems (NEMS) have drawn interest as an alternative to CMOS memory based devices. Types of nanomechanical memory are varied, and can include a carbon nanotube bridge [1], a carbon nanotube cantilever [2], a silicon dot charge storage device [3], and a silicon cantilever [4]. This paper will investigate the viability of a novel NEMS device, a carbon nanotube bridge, as a replacement for CMOS technology. This device was chosen due to its simplicity and ease of fabrication compared to other nanomechanical memory devices [1].

III. Nanomechanical Memory

A. History

The concept of mechanical devices as memory is not a new one. One of the first uses of mechanical devices as memory was Charles Babbage's difference engine. This early computer was an extremely complex machine, with no electronic components. The positioning of switches and mechanical devices served as the memory. While the difference engine was never produced, it was the springboard of several later designs. Computers of the early twentieth century would incorporate a combination of mechanical and electronic components. Magnetic tape, punched cards, and vacuum tubes characterized the bulky machines of the era. The production of electronic components, such as integrated circuits, meant that future computers would largely rely on electronics.

The dominant technology used in electronics was CMOS. However, CMOS has limits on how “small” it can become, due to the laws of physics and the properties of silicon. A replacement for CMOS is needed, and it must be small enough to function on the nanoscale. Revisiting the concept behind the difference engine, some have proposed the use of mechanical devices on the nanoscale. In short, this study will examine the viability of a nanomechanical memory device as replacement for CMOS-based devices.

B. Materials

Different materials have been used in nanomechanical systems. The two primary components in the CNT bridging device are two of the more common ones: silicon and carbon nanotubes. Carbon nanotubes are of potential interest for several types of devices, and nanomechanical memory is no exception. One type of experimental device, described later, used carbon nanotubes in its operation. CNTs are fullerenes, a group which also includes buckyballs. They are extremely strong fibers, having
a tensile strength much greater than steel. They are the strongest material known so far in terms of tensile strength and elastic modulus. All are cylindrical molecules made entirely of carbon. They are efficient conductors of heat. Two types of CNTs are single walled and multi-walled carbon nanotubes [8].

Single walled carbon nanotubes resemble a simple ‘tube’ of carbon atoms. Single-walled carbon nanotubes are a hollow cylinder. If a sheet of graphene was rolled into a tube, a SWCNT would be the result. The average diameter of a SWCNT is one nanometer. A SWCNT can work as a simple electric wire. Intermolecular logic gates and field effect transistors have been recently produced. However, there are high costs with producing SWCNTs. SWCNTs have unique electrical properties when compared with their multi-walled counterparts. They are considered a very likely material for manufacturing nanoscale electronics. Their mechanical and electrical properties make them of high interest for the fabrication of nanoscale devices [8].

Multi-walled carbon nanotubes are tubes with more than one wall. There are two models to describe different types of MWCNTs. One is the ‘Parchment’ one, and one is the ‘Russian Doll.’ If one single walled carbon nanotube was placed inside a larger one, a ‘Russian’ MWCNT would be the result. In the ‘Parchment’ model, the tube itself is rolled up similar to a rolled newspaper or scroll. A common issue that plagues MWCNTs is the possibility of sliding [8].

An issue that arises with multi-walled carbon nanotubes is sliding. Sometimes, an inside tube will slide around inside of the outside tube. When there is a significant difference in radius, there is less contact between the inner tube and outer tube. Carbon nanotubes do not have much friction, increasing the chance of slippage. For the design of mechanical devices, this must be taken into account. With moving parts included, unwanted motions must be taken into account. At times, the inner layers and outer layers may also have different electrical and structural properties. This difference makes MWCNTs difficult to employ in the design of devices. More on a device using MWCNTs is explained below.

C. Fabrication
Nanomechanical memory requires specialized fabrication techniques. The two “philosophies” are top-down and bottom-up. Conventional etching and lithography is “top-down.” Self-assembling materials and parts that form larger components are “bottom up.” Many NEMS have been etched by “top down” high-resolution etching and lithographic techniques. The inclusion of less conventional materials, such as carbon nanotubes, requires special considerations upon manufacturing. Fabrication of certain devices requires multi-walled carbon nanotubes and single-walled carbon nanotubes to be produced consistently. Improvements in fabrication technology are required for the carbon nanotubes. Specific types of carbon nanotubes must be fabricated in a consistent way to produce consistent results. Consistency in fabrication and manufacturing is necessary for the future production of any of these devices. During fabrication of the nanotech device, the nanotubes were grown directly on the device. This was a “bottom up” technique.

Carbon nanotubes are the key part of the nanomechanical memory device. Instead of using CNTs that had been ‘harvested’ earlier, they instead were grown on pre-patterned substrates. Three MWCNTs were grown at different points on the device using direct current plasma-enhanced chemical vapor deposition (dc-PECVD). Each of the MWCNTs has a diameter of seventy nanometers and a length of two micrometers. The CNTs were growing on top of a nickel catalyst, which itself was placed on a niobium (Nb) contact electrode. The electrodes themselves were made by electron beam lithography and sputtering on top of a silicon substrate. The lithographic and sputtering techniques used to fabricate the device were largely conventional. However, the technique of growing nanotubes directly on the device
may be applied to other types of NEMS devices in the future.

On the nanoscale, several forces must be taken into account when designing the device. Three key ones are the electrostatic force, the elastostatic force, and the van der Waals force. These three forces will determine a key parameter for the device, which is explained below. Electrostatic force is a field that deals with slow moving or stationary electric charges. When charge is built up on a surface, electrostatic forces are at work. In an electrostatic problem, any magnetic fields are assumed to be constant with respect to time, and are largely ignored. The electrostatic potential, or voltage, is how much work per unit charge is required to move a charge. For molecular devices, the charge between two points must be carefully controlled to ensure proper functionality. If too high a voltage is applied, the device could be damaged.

Elastostatic forces depend on the structural properties of the molecules. In materials science, the elastic range is the amount of elongation that can be applied to a substance before deformation. Elastostatic properties are the ability of a material to return itself to its original configuration after a force is applied. With nanomechanical memory, a moving part must be able to return to its original configuration when it is changed from “off” to “on” and vice versa. The elastostatic force \( F \) can be estimated by \( F_{\text{elas}} = 8E \cdot I \cdot d/L^3 \), where \( E \) is Young’s modulus, \( I \) is the moment of inertia, \( d \) is the distance between MWCNTs, and \( L \) is the length of the MWCNT [1]. The model assumes a one dimensional beam model.

Another force involved is the van der Waals force [5]. The van der Waals force is the attraction or repulsion between different parts of the same molecule. While weaker than traditional chemical bonds, van der Waals forces are an important considering for molecular devices. Attraction or repulsion of certain parts of a molecule could open or close a circuit when the opposite was desired. Thus, the van der Waals forces must be considered when designing a device. Any issues with one of these forces could seriously compromise the operations of the device. In addition to the materials involved, device design and fabrication must also take these forces into account.

D. Functionality
Nanomechanical memory utilizes a combination of moving parts and electronics. Unlike Babbage’s difference engine, memory in nanomechanical systems has both mechanical and electrical components. The configuration of different switches and levers can open and close different circuits. When an individual switch is in one configuration, a circuit would be opened. When it is in another configuration, the circuit same would be closed. Another option is when a switch is ‘off,’ for one configuration, it is ‘on’ for another circuit. Due to this, devices use a simple “on” or “off” configuration for an individual circuit. Nanomechanical memory systems with more than two configurations are possible, but are currently unstable and unreliable compared to simpler designs. The simplest types of nanomechanical memory are switches and levers. There are technical and economic considerations to keep devices simple. The more moving parts, the harder fabrication becomes, the greater chance of mechanical problems, and the higher costs rise.
With these concerns, a nanomechanical device was designed. An illustration of the device and its functionality are pictured in Figure 1 [1]. When off, each MWCNT stands alone. When the switch is on, the first and second CNTs become attracted and open a path for electrons to flow. The first carbon nanotube acts as the negative electrode relative to ground. The second and third carbon nanotubes are positive with respect to ground. The third CNT pushes the second CNT toward the first. This is due to electrostatic forces induced when the positive bias of the third nanotube increases, while maintaining a constant positive bias on the second carbon nanotube. Above a threshold bias, the second MWCNT makes electrical contact to the first MWCNT, establishing “on state.”

The threshold bias will be determined by three things. It must balance the electrostatic force, the elastostatic force, and the van der Waals force involved device operation. If the attractive van der Waals force between the first and second MWCNT is larger than the repulsive elastostatic force between the second and third, they would remain held even after the driving bias is removed. It would be stuck in the “on” state. Otherwise, the second nanotube would return to its original position when the driving bias is removed.
Figure 2-(a) [1] shows electron microscope images of the device in both on and off states. Figure 2-(b) shows the change in switching action for the device. Once 22.5 V is hit, the first and second MWCNTs attract. The increase in current between the first and second carbon nanotube marks the transition to the “on” state. The “off-state” current was found to be very low. This is because the leakage current flowed only through the insulating layer (the silicon wafer). Other nanoscale silicon-based memory has performance limited by a large gate tunnel leakage current, due to the gate insulator scaling. The low voltage (approximately 0.05 V) between the first and second MWCNT offers another important advantage for NEMS device operation, since possible damage caused by a large driving voltage, a previous problem from some other CNT-based systems, can be minimized. However, there is a higher turn-on voltage required in this device compared with typical memory systems. This is due to the large contact area in the device. Reducing this could lower the power requirements. The device turn-on voltage may also be lowered by optimizing device design. The first and second nanotubes remain connected to each other when the driving voltage is removed. This is likely due to the van der Waals forces, but further investigation is required. The off state can be restored by connecting the second MWCNT to a floating ground while the first one is also grounded.

This electromechanical system is simple in concept, and can even further be simplified, according to the researchers. The third carbon nanotube can be removed, simplifying fabrication costs and reducing the number of parts. A simplified device with two MWCNTs instead of three was fabricated.
The second device was built with two MWCNTs of similar size to the first device. The on state voltage is slightly higher than the first device, approximately 24 V. The two MWCNTs do not separate when the gate voltage is removed. The off state was re-established when the third electrode separated the second MWCNT from the first MWCNT, by pulling them apart while the gate voltage bias was varied between 20 V and 25 V. It is possible that the positive charges induced in the third electrode became large enough to separate the first and the second MWCNTs. An SEM image of the device is in Figure 3. This device was simpler, and less prone to failure than the three MWCNT device.

The feature of maintaining the “on” state connection even after the driving voltage is removed could be exploited for various novel applications. In some cases, this feature may not be useful. A switch device for random access memory (RAM) would require a complicated driving circuit if it were to be designed based on this feature.

![SEM image of MWCNTs](image1.jpg)

**Figure 3.** Electromechanical switch devices consisting of two MWCNTs (length is about 2 μm). (a) Left: SEM image of the electromechanical switch device made of two MWCNTs. Right: The second MWCNT remains stuck with the first MWCNT after the removal of applied bias. (b) Current vs voltage characteristics. The scale bar corresponds to 1 μm.
To resolve this issue and simplify design, a third device was constructed. The third device was similar to the second in that it had two MWCNTs, but the length for both was shorter, about 1.4 micrometers long. An SEM image of the device is shown in Figure 4 [1]. The threshold voltage was found to be approximately 24.6 V, higher than the previous two devices. Unlike the two previous devices, both MWCNTs returned to their original positions when the applied bias was removed. This should be obvious as the repulsive elastostatic force should be much higher than the attractive van der Waals force between the shorter MWCNTs. A ratio for the elastostatic forces in the third device to the second device was calculated to be 2.92. There is almost three times as elastostatic force in the third device as the second.

In this case, switching action can be easily performed by changing the gate voltage. This feature can be exploited for a replacement to silicon transistor-based switches in RAM devices. It should be also noted that the device structure consisting of only two MWCNTs and one gate electrode greatly simplifies the fabrication. This avoids the complicated lithographic, etching, and implantation processes required in making silicon transistor based switch devices.

IV. Comparison
The benefits and drawbacks of nanomechanical memory devices were compared to traditional CMOS memory devices. Nanomechanical memory has several notable obstacles to overcome. There are key issues that may fatally compromise nanomechanical systems. According to the ITRS roadmap [7], one of these is reliability. Because it is reliant on several moving parts, all of these parts most operate efficiently. Having defective parts would make a memory system using nanomechanical memory less reliable. If hundreds or thousands of moving parts were used, reliability would become a key issue.
Another issue with reliability is ensuring switches and levers are in a clearly defined “on” or “off” state. An issue with the three-MWCNT device was the device would sometimes remain in the ‘off’ state due to possible van der Waals attraction between them. The electrical force must be sufficient to keep the device in one state, without switching to another. In addition, the device must be able perform this change in states several times. The material comprising the device must be able to perform this change, and contain all the electrical properties necessary for the device. Any fabrication techniques must be extremely precise with these materials. Newer materials, such as carbon nanotubes, would require significant changes to existing fabrication techniques.

When most current CMOS memory devices are comprised of millions of parts, a large scale integrated nanomechanical memory device could easily require a large numbers of moving parts. Adopting new infrastructure for new fabrication techniques would be necessary. While some parts of the devices could be produced with existing technology, newer approaches would be needed for the less conventional materials. The current lack of control over the fabrication of CNT types is a key technical issue. Problems with the mass production of nanoscale devices with mechanical parts could yield significant reliability issues. Fabrication and reliability issues would be two key issues with a nanomechanical memory device.

The challenges associated with fabrication and reliability could raise issues with device compatibility. Due to its silicon base and electrodes, it is able to interface with existing technologies. The nanomechanical memory device demonstrated earlier still utilizes conventionally produced electrodes. However, the MWCNTs are horizontal with respect to the electrodes. An integrated circuit would require another dimension to it, and mass production of a large scale integrated device would require significant changes in manufacturing.

Scalability is another issue. As explained previously, the change in the length of the CNT produces significant results. Therefore, scaling the device down in size could also introduce problems. Since the purpose of the ITRS [7] is to find a technology able to operate on the nanoscale more efficient than silicon CMOS, this could be a critical issue.

Despite being designated as slightly worse than CMOS, it has advantages due to its mechanical nature. Despite these challenges, there are several advantages to nanomechanical memory. On the ITRS [7] roadmap for memory devices, nanomechanical memory scored the highest for operational temperature, and high in energy efficiency. While the MWCNT bridge device in the paper did not have an optimized design, it was mentioned that energy usage was efficient compared to silicon CMOS. The operational temperature of nanomechanical memory may provide it some advantages when compared with others. It can operate at temperatures comparable to CMOS, but has some compatibility issues. Nanomechanical memory may have an application in certain niche devices that operate outside of conventional temperature ranges. Coupled with higher energy efficiency, a nanomechanical memory device may work on certain specialized applications. Where another device cannot operate, a NEMS device may be able to, and on less power.

V. Conclusion
Despite its flaws and merits, nanomechanical memory has significant issues to overcome. While nanomechanical memory is a novel concept, other technologies may outperform it in several key criteria. If nanomechanical memory devices could be manufactured reliably on a large scale, it may become commonplace. Problems with reliability and scalability may make such an investment in technologies uneconomical, especially compared to other technologies. The devices were fabricated with a combination of top-down techniques for etching the electrode, and bottom-up techniques for
growing the MWCNTs in position. Compatibility with CMOS can be improved, and fabrication
techniques are almost likely to improve. However, critical issues with scalability and reliability are
innate problems with any mechanical system. Barring certain specialized device roles, other
technologies offer more potential for a successor to CMOS than NEMS.
VI. References

Papers:

Websites:
[6]: http://www.intel.com/technology/mooreslaw/