Computing after Silicon

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***Abstract*—Silicon is the second most commonly found element on the earth only behind oxygen. Silicon is the foundation on which we build all electronic circuits, it is an ideal semiconductor, which is great as it's extremely common too. But as we all know, every good thing must come to an end. As we keep decreasing the size of transistors silicon is starting to show issues as we are getting to sizes of 7nm and below. Currently we have 14nm in the commercial market, at this size there are only around 67 atoms per transistor. When we get to 7nm we only have around 33 atoms and this is where we start running into problems.**

I. Introduction

Silicon is building block of computing, but is it nearly at the end of its life? The first transistor was invented in bell labs in 1947 [5], and ever since we've been working to decrease its size to be ever smaller than the previous iteration. We've reached a point where the current consumer chips are at 7nm (Nanometre) and with silicon atom [1] being around 210pm (Pictometre) which is 0.21nm so a silicon transistor at 7nm contains only 33 atoms per transistor. And this size keeps getting smaller with 5nm being currently under development which would only contain 24 atoms. The size of transistors is getting smaller and smaller as the years go on, but we are now at a point where the limit on there size is not only constrained by refining manufacturing process but now also by size of atoms. Silicon has been used in all modern computers and mobile phones. Silicon is the best element on earth to use in chip manufacturing for two reasons. 1. It is a great semiconductor which is necessary for modern computing and 2. It is a highly abundant element on earth being the second most common after oxygen with around 28% of the earths mass. But even with these two properties it isn't enough. With researchers looking for alternate methods through software and hardware to improve performance. Other researchers realize the core issue is with the silicon production process we currently use is at an end, just like past technologies move to different technologies to keep up with current trends and technological improvement by changing so to do computers. Currently researchers are looking into Graphene [10] which is an allotrope of carbon consisting of a single layer of carbon atoms arranged in a hexagonal lattice. Graphene is stronger than any known material with a tensile strength of of 130 giga-pascals. Compare Graphene to steel which has a tensile strength of around 400 mega-pascals making Graphene 3.25x stronger than steel. This makes Graphene a great alternative to silicon as its strength would help keep transistors together when dealing with transistors in the atom size range. Due to Graphene's strength it also allows for higher speeds of 100GHz [7] and above. With current processors only going as high as 5GHz before having heat issues.

A. History of Silicon Use

In the early days of computing vacuum tubes [6] were used before in what were at the time super computers which were highly specialized. Most consumer devices with transistors were basic car radios which were still a major improvement over vacuum tube radios which was cheaper car radio and more efficient car radio as transistors 'bled' less heat.

A year after the introduction of the transistor in car radios in 1956 Bell Labs [5] developed a silicon transistor which was the beginning of what would become the basis of modern computing. This transistor was very basic using molten silicon.

In 1971 Intel developed the first silicon processor called the Intel 4004. Although it is very primitive in today's standards it was revolutionary. It was a 4 bit processor with a clock speed 740 kHz. The Intel 4004 only had 2300 transistors, compare this to the latest Intel i9 processor which contains somewhere around 100 million transistors per square millimeter, a big leap from their first microprocessor.

As time went on and multiple companies started developing more and more transistors the price fell and so did the process of manufacturing. By

B. Moore's Law

Moore's law [8] is more of a prediction made by Intel co-founder Gordon Moore. It states that the number of transistors in a dense integrated circuit doubles about every two years and the cost decreases by half. This observation was made in 1965 and has been true since it was made. Although the first time since it was made we are now seeing it come to and end. We are getting to a point where atoms are getting in the way of making transistors smaller and we have to rethink how we produce microprocessors [11].

C. Current progress with silicon

Today's silicon process is a more refined process than we used at the beginning of the development of microprocessors in 1971. We have refined the process to get around 2 billion to 3 billion transistors in one microprocessor. which is a big leap from the 2300 found in the first microprocessor.

Even with all these refinements we've slowed down in the last few years. Intel is staying with their 14nm manufacturing process while they develop a process to create a 10nm micro-processor. Intel have been using 14nm manufacturing process since 2015. Intel is expected to fully release their 10nm design in 2019 a full four years after releasing their 14nm line of microprocessors. This type of behaviour is expected as we make smaller and smaller transistors with transistors smaller than 7nm requiring new methods due to quantum tunneling. It is once we hit 5nm where experts from 10 years ago presumed it was the end of Moore's law. [11]

II. Current Silicon Development

As of 2018 transistors have gotten as small as 7nm with low powered machines such as the iPhone X. Intel and AMD (Microprocessor manufacturers) are both rumored to release new microprocessors under the current 14nm technology. Although this change has been long overdue with both manufacturers using the 14nm process for years (Intel since 2014). Intel has repeatedly delayed their 10nm chips [4] which has caused investors to question the current technology. Creating a stable silicon chip with transistors as small as 7nm requires a lot of challenges to be addressed and fixed before consumer roll-out. Intel are facing a much bigger issue than the small iPhone X such has keeping all current technology such as its Hyper-Threading Technology which are required by one of their biggest market bases, the cloud computing sector.

A. Quantum Tunneling

Quantum tunneling is a complex quantum mechanical phenomenon [9] but to save on time and limit it's scope to the silicon transistor it is the theory that particles that shouldn't go through a material do. The flaw with silicon transistors is that at 5nm and below this becomes a huge problem. Silicon transistors at below 7nm sit so close together that the effect called quantum tunneling occurs. This effect ruins computers as transistors cannot be reliably turned off and on and may just get stuck in an on position.

B. Status of Moore's Law

Moore's law has been correct since its inception, but only now are we reaching the limit of the size of a transistor.

III. Proposed Alternatives

With the end of Moore's law drawing ever closer researchers are looking into different ways to keep current progress going at the same rate as the last 50 years. There are many different solutions being talked about some software, some hardware. The hardware application are what will keep progress going. The software solutions just postpone the inevitable problem with silicon manufacturing process.

A. Silicon-Germanium Mix

Silicon-Germanium mix is an short term solution to the silicon transistor problem [2]. Germanium shares many of its properties with Silicon. They are both Metalloids, they both chemically similar to one another. The main reasons to add Germanium to the silicon transistor would be to solve the issue of quantum tunnelling through the oxide layer of the gate, which at transistors below 7nm would cause huge problems with machine performance. Germanium can be used on top of the traditional silicon chips as a bridge between gates to solve quantum tunneling [13]. We know Germanium works as early on germanium was used in transistors in the 50's but was later replaced by the cheaper and more abundant silicon semiconductor.

B. Graphene

Graphene is the long term solution for fixing the silicon issue with transistors. Graphene is the strongest known material, much stronger than silicon and even stronger than steel. Graphene would not completely replace silicon, much like the Silicon-Germanium solution graphene would be placed on a silicon chip to reduce costs. Graphene would be used in the essential parts of the computer like the central processing unit before being introduced later into other components [12].

Graphene is being proposed due to its strength as higher loads. The fastest graphene transistor is about ten times faster than the fastest silicon alternative [3]. Although users won't see near that kind of speed in commercial use, they will see a percentage of it and that is still much faster than our traditional silicon based transistors. Due to graphene's strength it is able to operate at a much higher rate than silicon transistors at a rate of 100GHz (Gigahertz) which is the transistors operating 100 Billion times a second much faster than the silicon transistors of today.

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