Brigham Young University Idaho

Interoffice memorandum

TO: Brother Phil Murdock
FROM: Derek Hildreth
DATE: July 3rd, 2007

SUBJECT: Transmittal for Research Paper Project

I am pleased to present the findings of my research on computer processor limitations and reasonings for why there there has been no increase in speed since 2005. Enclosed is the research paper package which includes an abstract, table of contents, a list of figures and tables, the research body, references, and an appendix.

My research has led me to a few different answers as to why there has been such a delay in releasing a processor with a speed of more than 4GHz. The answers include marketing strategies used by CPU manufactures, electrical migration, and electrical current jumps. All of these issues are related in one way or another, and I believe that they are the reason why CPU manufactures haven't released a processor of this power.

I also found that the future of the CPU is basically treading down a path that doesn't involve the same type of design methods used in traditional processor designs. New designs include processors with multiple cores, or processing units, used to distribute the work load that the average user demands. Other designs are even more radically different, including quantum computing which utilizes the laws of quantum physics to process information.

Thank you for allowing the research in this area to press forward. I think you will find that the work taken to complete this project satisfied the deadlines that were set while drafting the project. If you have any further questions or concerns, please contact me at HIL03015@byui.edu.

Sincerely,

Derek Hildreth

Encl: Research Paper

Running Head: HIGH-SPEED COMPUTER DEVELOPMENT

HIGH-SPEED COMPUTER DEVELOPMENT IN PARK: THE DELAYS OF A 4GHZ PROCESSOR

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ABSTRACT

This research focuses on the reasons behind the fact that there hasn't been a processor releasing to the public with clock speeds of over 4GHz. The current fastest commercial processor is 3.8GHz and has been that way for two years and counting. Reasons as to why this has occurred in the market today include Intel's marketing strategies, electrical migration (electromigration), and electrical current jumps (subthreshold voltage). A solution to these limitations includes building a smarter processor, rather than one with sheer strength. Processors like the recent Core Duo processor from Intel including multiple cores has stepped up to the challenge and has had huge success. Another way of smart computing is by the use of quantum mechanics, using the laws of physics to design a new type of processor. This research intends to investigate these findings.

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INTRODUCTION

Measuring CPUs

Traditionally, computer performance has been measured with a unit called Hz (hertz) which reports the clock speed of a CPU (central processing unit) in cycles per second. For example, a computer with a 1GHz processor will complete 1 billion cycles per second. The higher the clock speed of the CPU, the faster it can processes, which equates to less wait time when a user opens their documents and programs. Suggestively, consumers used this measurement to help them shop for a CPU with the highest clock speeds that would help them get things on their computer done faster.

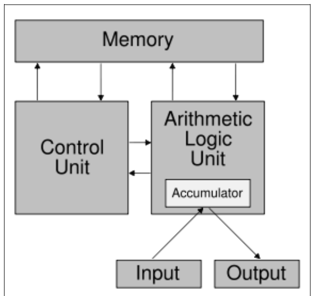

Figure 1: The von Neumann architecture.

CPU Construction

One CPU is made up of several different pieces that all work together including built-in memory (storage for instruction), a control unit (directs operations), an ALU (arithmetic logic unit that performs basic arithmetic operations), an accumulator (accumulates results of arithmetic operations), and an input and output (gathers command inputs and sends command outputs). These pieces form the basis for a traditional CPU design called the von Neumann architecture (see Figure 1). The speed at which these interact with one another is measured by the clock speed as discussed previously. There are two major CPU manufactures: Intel and AMD. Although it is important not to introduce bias, this research topic will focus on Intel, as they have excellent documentation of their processors and marketing. From 2000 to 2005, Intel had increased the clock speeds steadily from 2GHz to 3.8GHz (Intel, 2006, p. 1-6). However, clock speeds have been at a stand-still since 2005 and have not been released into the consumer market with speeds greater than 3.8GHz (see Figure 2).

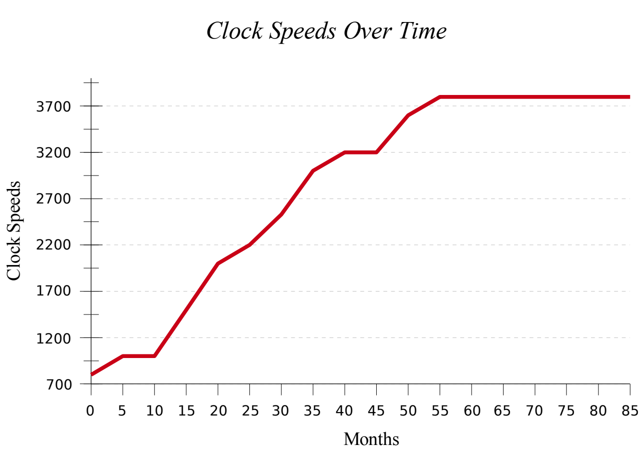

Figure 2: Timeline of Intel CPU speeds over 7 years (84 months) from 2000 to 2007.

Delay Reasoning

This stand-still has these three strong reasons to blame: (1) Intel's marketing strategies, which concentrates on smarter design rather than sheer clock speed brawn, (2) electronic migration, caused by the heat generated from faster CPUs and smaller wires, and (3) electric current jumps caused by ever-shrinking CPU components. It is important to understand these because they have changed the way consumers shop for computers. All three of these reasons may collectively be contributing to the stand-still of clock speeds and this research will more deeply explain these causes as well as touch upon the research being done in quantum computing.

INTEL MARKETING

Company Background

Intel is based out of Santa Clara, California in the heart of Silicon Valley where the major material of computer components, Silicon, is found. In April of 2007, they were producing 80.5% of CPUs in the computer industry (Krazit, 2007, *para.* 1). As with any company, the more market share you have the better off they are and Intel's marketing strategies have proved to be sufficient at doing so.

New Products

In 2005, Intel had released a new CPU technology that utilized radically different design than that of a traditional processor called the dual core processor (Intel, 2006, p. 4). These processors have two main processing units rather than the single one in the von Neumann architecture. With this new design, CPUs can out-perform a single core design with a higher clock speed because they are now able to execute more than one command at a time whereas before, only one command could be executed. Looking at an example comparison between an older single core Intel processor (Pentium 4 570) and a newer dual core processor (Core 2 Duo E6400) as shown in Table 1, one can clearly see the benefits of having two cores (Toms, 2006). For this reason, Intel simply gave the design of a multiple core processor more attention than breaking clock speed records. This has allowed them to produce a more cost effective CPU that out performs older designs that required higher manufacturing expenses to achieve the same performance.

Processor	Clock Speed	Score
Core 2 Duo E6400	2.1GHz	1892
Pentium 4 570	3.8GHz	1162

Table 1: Comparison of synthetic benchmark scores between a single core and dual core processor with a smaller clock speed.

Sales Figures

The change to dual core CPU design has also made reflections in the market sales and shares in the industry. Market share is essentially the percentage of sales in a specific business niche that a company has. AMD, Intels business rival, has had a competitive edge on Intel by steadily taking market share percent from Intel (Spooner, 2002, *para*. 2). It wasn't until 2007, when Intel's dual core processors started to become mainstream, that they were able to regain the market shares that AMD had taken from them. Also, looking at past levels of gross margin (or gross profit) from 2001 to 2006, Intel had the greatest change when the dual core processors were introduced in 2005, as shown in Figure 3 (Collantes, 2007, p. 1). Naturally, when sales increase, companies like Intel will keep selling the item that will bring them more profits. This evidence supports the conclusion that the reason a 4GHz

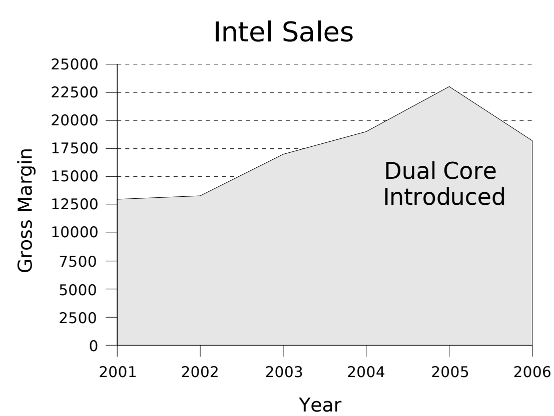

Figure 3: Intel gross marginal sales from 2001 to 2006.

processor has not been publicly released is because of Intel's marketing strategies. However, there are some physical roadblocks that almost forced Intel into re-designing the processor.

ELECTRONIC MIGRATION

Background

In designing a processor, there are a few different methods used to help increase clock speeds. One of them is to give the CPU a higher voltage from a power supply. This allows the electrical current to flow more freely, giving the CPU a higher clock speed. By closely monitoring the voltage on a CPU through the main control board of a computer, enthusiasts have been able to take a CPU from factory and change the settings forcing the clock speed to increase. Users have reportedly been able to boost their clock speeds up to 8Ghz (Andreas, 2007). At first, it sounds like a totally viable solution to breaking the 4GHz barrier and companies like Intel should just release these “overclocked” CPUs to the public. The problem is, these speed boosts come at the cost of an expensive cooling system and heavy modifications to the computer system, creating expenses that the consumer isn't willing to pay. One of the primary reasons for not releasing CPUs like these is because without the proper cooling (below 80°C), they are subjected to electronic migration, a phenomenon also known as electromigration.

Definition

Electromigration is officially defined as the “movement of atoms within a crystal.” (electromigration, 2000) This definition is very vague and seems incomplete. Polkowski (2007), a journalist for Toms Hardware, described electromigration in this way:

> Electromigration occurs as a result of metal atoms being moved via the momentum of electrons. Picture this as a sandblaster where the sand, at high velocity, is eroding the walls of the gun. In the case of electromigration, the electrons are moving the metal atoms away from one another. This can cause a circuit to fail by two means: either the atoms are moved apart breaking the circuit, or they are moved closer, so the circuit touches another causing a short. Either way, it is bad news for the components. (*para*. 2)

Electromigration Damage

A graphical representation of this occurrence is shown in Figure 4 where the horizontal pipe in the center is the “wall of the gun” that has been badly damaged due to electromigration. Notice that it looks similar to a badly damaged water hose with walls that are weak from wear and tear. When water is pushed through this hose, hardly any of it is going to make it to the other side. This is a similar situation for the interconnects, or inner wire connections,

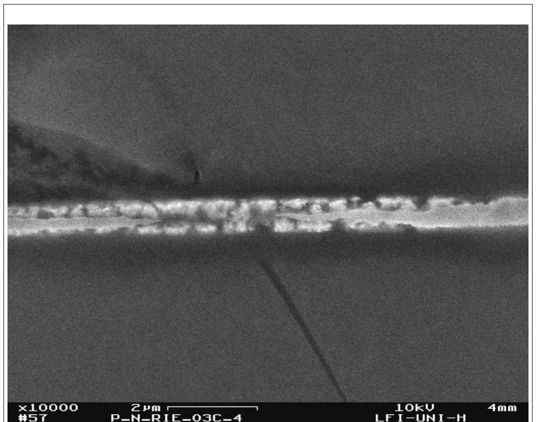

Figure 4: The effects of electromigration on a CPUs inner wire.

inside a CPU. The electrical current (compare to the water in a hose) is trying to flow through a damaged wire and will not succeed, thus rendering the CPU as non-functional. The process in which this occurs is highly technical and involves complex scientific laws of physics and chemistry. In "Failure is not an option," Lienig (2006) summarizes how this phenomenon occurs:

> The copper or aluminum interconnects of an electronic circuit are polycrystalline, that is, they consist of grains containing crystal lattices of identical construction but different orientation. As current flows through such a wire, there is interaction between the moving electrons – a sort of "electron wind" – and the metal ions in these lattice structures. Atoms at the grain boundaries especially will fall victim to the electron wind, that is, they will be forced to move in the direction of the flow of electrons. (p. 39)

In other words, the structural properties of the wire itself are shaped in such a way that they look similar to a beehive honeycomb, only not as uniform, as shown in Figure 5. As electricity passes through this structured wire, the honeycomb has a tendency to move with it. Compare it to a fast flowing river with loose rock on the bottom. The river is the electricity and the loose rock are the atoms of the wire. The rocks will move, or migrate, with the current of the river. This is also known as grain boundary diffusion (see Figure 5). Liening continues with an explanation of what grain boundary diffusion will do over a period of time:

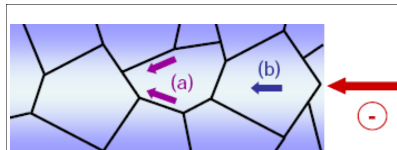

Figure 5: A drawing of an interconnect. The red arrow is the flow of electricity and (a) represents grain boundary diffusion.

> Thus, in time, copper or aluminum atoms will accumulate at individual grain boundaries, forming so- called "hillocks" in the direction of the current. At the same time, so-called "voids" can appear at the grain boundaries [Figure 6]. While the hillocks can short-connect adjacent interconnects, the voids reduce the current flow in particular locations until the point of interconnect failure. (p. 39)

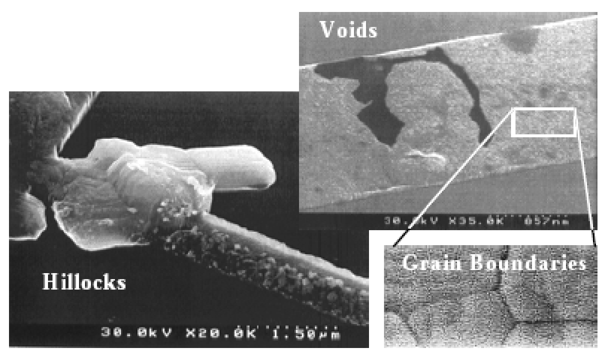

Figure 6: Two common effects of electromigration.

To paraphrase, there are two common side effects of electromigration: 1) Hillocks which are formed by an accumulation of atoms in the wire, and 2) voids, or dead spots, which occur when a cluster of atoms have migrated away from their original grain boundaries, much like a delta at the end of a river. As suspected, these common occurrences will eventually lead to hardware failure.

Solutions

In the 1960's, physicist J. R. Black derived a mathematical equation that will find the average life span of a CPU, taking electromigration into effect (see Figure 1). Without going into too much detail about the formula, a keen observation will see that the temperature (T) strongly effects the life span as it is in the exponent of the formula. Simply, in order to avoid CPU failure, adequate cooling is required as discussed earlier in this section. The stronger the voltage, the more susceptible the atoms of the inner connections will be to electromigration which will lead to CPU failure.

$$MTTF = \frac{A}{J^n} \cdot \exp\left(\frac{E_a}{k \cdot T}\right)$$

Figure 7: J.R. Black's formula for MMTF (mean time to failure).

ELECTRICAL CURRENT JUMPS

Background

Electrical current jumps (subthreshold leakage) occur within the “control center” of a processor causing unwanted CPU behavior. In order to better understand electrical current jumps, both the terms integrated circuits and nanotechnology must be understood.

Integrated Circuits

An integrated circuit is a tiny electronic circuit that is located on a block of material that can carry an electric current. They are primarily made up of components that help regulate the electric current. These components are connected together by small lines of metal called interconnects (as discussed earlier in electromigration). These circuits can be arranged to perform a variety of specific functions that a computer program can use (Integrated, 2002).

These integrated circuits are most commonly used to create what's called a logic gate. A logic gate is simply a gate that either allow or disallow a current from flowing through it. This is the foundation for why a computer runs on ones and zeros (on and off). An example of a logic gate is what's called an “AND” gate (see Figure 7). If there is an electric current flowing on both line A 'AND' B, then the gate will allow the current to flow through it. However, if there is only current flowing on line A and NOT B, then the gate will not allow any current to flow through it. So, the output is either on or off (one or zero). It is here where electrical current jumps occur, but still a review of nanotechnology is in order.

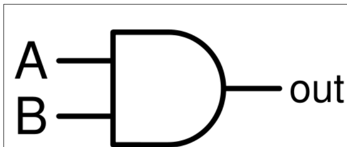

Figure 8: A schematics symbol representing an AND gate.

Nanotechnology

Nanotechnology is “the science and technology of building electronic circuits and devices from single atoms and molecules” (Nanotechnology, 2003). This is a very powerful technology where electronic circuits, like integrated circuits, are made so small, that millions of them can be included in a very small package the size of a postage stamp. The integrated circuits are measured in nanometers, or one-billionth of a meter. The most recent nanotechnology being used by Intel to build processors today is 45 nm. To put this into perspective, the width of a human hair is about 80,000 nanometers (National, *n.d.*). Understandably, the amount of integrated circuits and logic gates residing on one single 2.5" square is impressive. It is desirable to make smaller integrated circuits because the more a manufacture can fit into a CPU, the more powerful it will be. And, according to Moore's Law, the number of integrated circuits on a CPU will double about every two years (see Figure 8). The troubles that manufactures like Intel are facing are increased costs to produce these circuits, and the physical problems that appear like electrical current jumps.

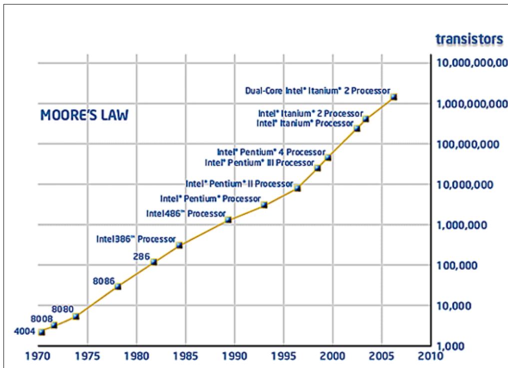

Figure 9: Intel Processors in comparison with Moore's Law.

How Subthreshold Leakage Occurs

Electrical current jumps (a.k.a. subthreshold leakage) occur when an electric current literally jumps directly from an inlet to an outlet of a logic gate because the distance between the two are so small (Subthreshold, 2007). In every circuit there is a current source, a logic gate to pass through, and a current drain (see Figure 9). Normally, the current will flow from the source into the logic gate, where it will either be allowed by the logic gate to pass through to the drain or not. Subthreshold leakage occurs when the current flows directly underneath the logic gate to the drain. This eliminates the logical set of instructions that the processor needs and leaves a direct current flowing through it all of the time. Instructions or commands are being executed incorrectly and essentially becomes the equivalent to pushing gasoline through an engine block with no pistons, spark plugs, or sensors to make the car move. However, in a computer, it does not render the CPU completely useless. The CPU will continue to work and execute commands, but the downside is that subthreshold leakage may account for up to 50% of total power consumption which is precious in such a power hungry device.

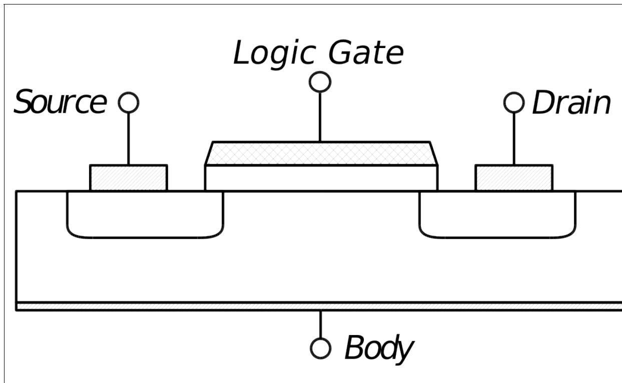

Figure 10: A visual representation of one typical circuit found on a CPU.

Solutions

In the past, this leakage was not a huge concern because computer components such as the CPU were made up of much larger components and they weren't built to tailor after the needs of voltage aware consumers. As of recently, the components used inside the CPU have reached the size of 45nm and are requiring much more voltage-aware design for applications such as mobile computing. When reducing the power consumption, engineers decrease the supply power (or the power required for the

CPU to operate). When the supply power is decreased, another voltage, known as the threshold voltage, must also be decreased in the same proportion. Threshold voltage is the amount of voltage necessary for a logic gate to detect a signal (Threshold, 2003, *para.* 2). Subthreshold leakage is exponentially dependent upon the threshold voltage . The smaller the threshold voltage, the higher the chance for leakage to occur (Dimitrios, 2002, p.20). Subthreshold leakage is also dependent upon the distance between the source and drain of the logic gate, but not as drastically as the threshold voltage. As CPUs get smaller, faster, and more power efficient, the risk of running into subthreshold voltage increases and the more inefficient CPUs become.

QUANTUM COMPUTING

One possible solution to computer processor limitations is by studying and implementing the laws of quantum physics within a computer. According to Moore's law, sometime between 2010 and 2020, the components that are used to construct the CPU will be so small that they would only consist of a few atoms each. When the components become this small, they will stop functioning reliably according to the laws of quantum physics (Computer, 2007a, *para.* 2). So, in order to design and produce a processor capable of running at higher speeds in a smaller package, the laws of quantum physics must be applied.

A computer processor only required two bits of information: on or off. And according to quantum mechanics, an electron also shares this property of having an on and an off value (In the quantum mechanics world, this is known as a spin). A system of these particles are called quantum bits or "qubits", as seen in Figure 10. This suggests that building a computer based on electrons and their properties is possible (Computer, 2007b, *para.* 1). This would allow engineers to build a personal computer in the future that will be faster than any supercomputer in existence today.

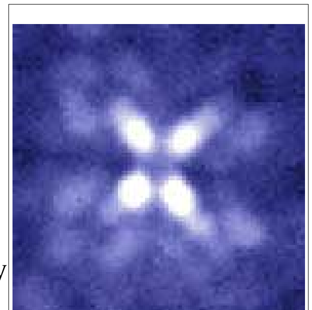

Figure 11: An image of qubits.

CONCLUSION

Review of Concepts

Recently, the CPU has been rethought and redesigned to accommodate the limitations found on traditional processors by using multiple cores or processing units to help alleviate the stress on single core processors. The stresses include electrical migration and electrical current jumps which have ultimately lead companies like Intel to disregard the von Neumann model and concentrate on more efficient designs like the multiple core or quantum computing.

Electrical migration, or electromigration is occurring in processors like the Pentium 4 (3.8GHz) because the voltage that is required to run at 3.8 billion cycles per second is creating much heat. This heat and fast stream of voltage going across the inter connections of the processor is forcing the atoms to move with it, causing damage to the line. Once enough damage has been done, the processor will be rendered useless and, depending on the voltage strength, can reach that point in as little as a few months. With only a few months expected time to live, marketing and selling these CPUs is worthless.

Electrical current jumps, or subthreshold leakage, is also a rising concern as the components (integrated circuits) to manufacture CPUs are growing smaller at a rate of 1:2 every two years. Between shrinking the integrated circuits and designing more energy efficient processors the tenancy for the electric current to jump from an inlet to an outlet and skipping the logic rises. This occurs frequently in processors running above 3.8GHz and leads to wasted energy and increased damage control done by the CPU, thus wasting precious time.

Solutions

Technology will continue to become more advanced and assist in making the integrated circuits on a processor smaller. The smaller they become, the more will fit into a CPU, giving it even more processing power. Eventually, however, they will become so small that they are only a couple atoms thick, making it impossible to mount a logic gate or any other component onto it. This has introduced a new kind of technology called quantum computing, which is still under research. Quantum computers will take advantage of the laws of quantum physics and provide a way to make an atom behave in a manner that the CPU will understand-- a zero and a one.

There are some problems in the world that can be solved by looking into the past, but the problems and limitations that surround the computing world will only be solved by looking ahead into the future. The future includes smarter processors with four or even eighty processing cores built in, each helping distribute the load, and quantum computing allowing incredibly fast supercomputer strength in a personal computer in somebody's office. These computers will be faster and better than processors running beyond 4GHz, only having a clock speed half the size, while avoiding the current problems that single core processors face today including electromigration and subthreshold leakage. These are the reasons as to why there has been a flat line on the timeline of processing speeds for more than two years since 2005.

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APPENDIXES

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