A Study of the Material Best Suited to Replace Silicon as the Principal Semiconductor In Computer Chips

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Abstract. Transistors made from silicon are more ubiquitous than ever, but the technology itself is not optimal. Some physical properties of silicon may hinder future technological progress. Two alternative semiconductor materials – diamond and gallium nitride (GaN) – are studied and their properties compared in order to find a suitable replacement. Speed is evaluated by using cutoff frequency and electron mobility; resistance to voltage and heat is evaluated by using the breakdown electric field, melting point, and thermal conductivity. It is found that diamond possesses superior characteristics in nearly every category. Of particular import are the cutoff frequency, the breakdown electric field, and the thermal conductivity of each transistor. The cutoff frequency of a silicon transistor is 0.055 GHz. For both the diamond and GaN transistors, it is 2 GHz. The breakdown electric field of silicon is 0.22 $V.cm^{-1}$; for diamond, it is 4.00 $V.cm^{-1}$; for GaN, 9.50 $V.cm^{-1}$. Finally, silicon's thermal conductivity at 300 K is 1.48 $W.cm^{-1}.K^{-1}$. Diamond easily bests its competitors with a thermal conductivity of 32.2 $W.cm^{-1}.K^{-1}$, while GaN's thermal conductivity is 2.53 $W.cm^{-1}.K^{-1}$. In light of these results, a diamond semiconductor has the potential to offer much faster and much more reliable transistors to many markets, ranging from professional applications to consumer-grade electronics.

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1. Introduction

The main driving force of the computer hardware market is performance; each year, companies strive to find ways to make computers faster and more efficient. A potential performance improvement is the replacement of silicon, the principal semiconductor used in computer chips. Therefore, the aim of this research paper is to examine which semiconductor material would be the most adequate substitute for silicon. Two solutions will be compared: diamond and gallium nitride (GaN). The semiconductor material chosen will affect the speed at which a transistor can turn on and off, which in turn affects the speed of a computer chip built using that type of transistor. Additionally, to replace silicon, a capacity to sustain high voltage is crucial; this implies that the semiconductor is able to dissipate heat efficiently.

First and foremost, a distinction between three terms that will be used frequently must be made to avoid confusion. Transistors are assembled from semiconductors. In other words, a transistor inherits the properties of the semiconductor that composes it. A semiconductor is a material, such as silicon, which can either conduct electricity or act as an insulator which prevents electricity from passing through. Transistors are the electrical components used when building an electrical circuit on a computer chip. Properties of a computer chip, such as its speed, depend on the transistors placed on the chip. The solutions to be compared are materials, but their properties will alter transistor performance. Accordingly, greater transistor performance will result in greater computer chip performance.

2. Overview of the Properties of Silicon

To understand the benefits of a semiconductor replacement, the criteria used to evaluate transistor performance must first be defined. A selection of the properties of semiconductors follows, along with their definitions. The performance of silicon transistors is also included in each section, to facilitate comparison with the alternative transistor types.

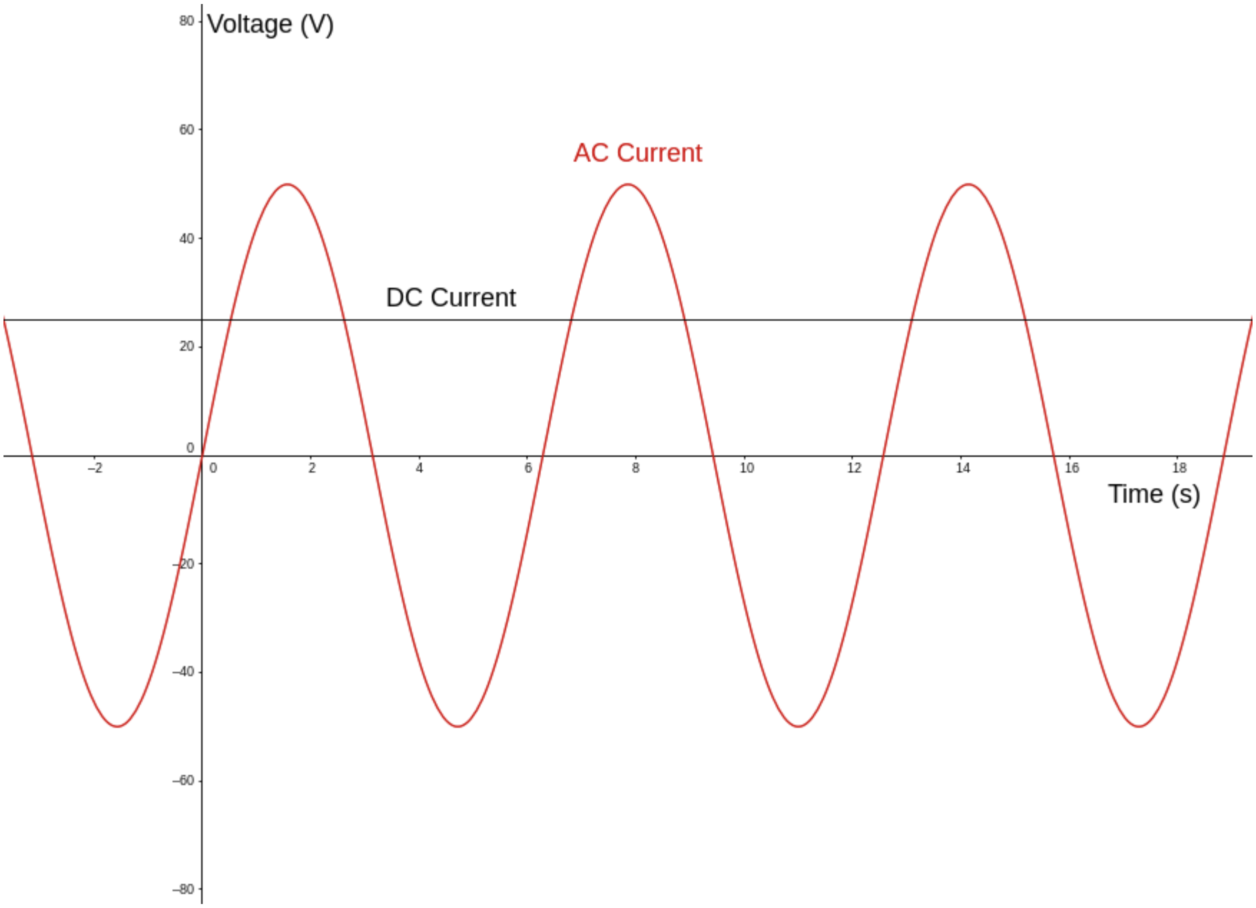
2.1. Transistor Speed

It is well known that modern computers use 1s and 0s to represent information. This binary system is used to move data, modify it, store it, and reinterpret it when needed. In order to do this, computer chips are composed of billions of transistors. As outlined above, semiconductor materials have a unique property: depending on the conditions in which they are placed, they will either act as a conductor or as an insulator. Due to this property, transistors can act as switches. They will turn on if they are supplied voltage above a set threshold; otherwise, they will stay off. To a computer, a transistor represents a value of 1 (on) if it conducts electricity, and 0 (off) if no electricity passes through.

The speed at which transistors turn on or off dictates the speed at which information moves through a computer chip. A fast transistor is more efficient at transporting data than a slow transistor. For an equivalent amount of supplied power, the fast transistor will be able to turn on and off more frequently, therefore representing more 1s and 0s in a set period of time. Greater speed also grants a finer degree of control over the state of each transistor across time.

High transistor speed is useful in many applications. For example, sensors would directly benefit from higher speeds, since they could operate at a higher frequency, and thus obtain more readings per second. High-speed sensors could then be placed in virtual reality helmets and self-driving cars, which act and react according to the information received from their sensors [1]. Power conversion systems would also profit from higher speeds. In most countries, power is supplied as alternating current (AC) to electrical outlets. As seen in Figure 1, an AC supply's voltage output alternates between positive and negative. However, many electronic devices, such as mobile phones and computers, do not possess the internal components required to interpret AC. Rather, these devices require direct current (DC) to charge their batteries or supply power to their electrical components – DC is constant, and easier to manage. Therefore, such devices use power adapters to convert AC to DC. Power adapters use transistors that operate at high frequency; a higher frequency allows the creation of a more efficient, smaller, lighter power adapter [1].

Figure 1. Sinusoidal behavior of alternating current compared to the static behavior of direct current

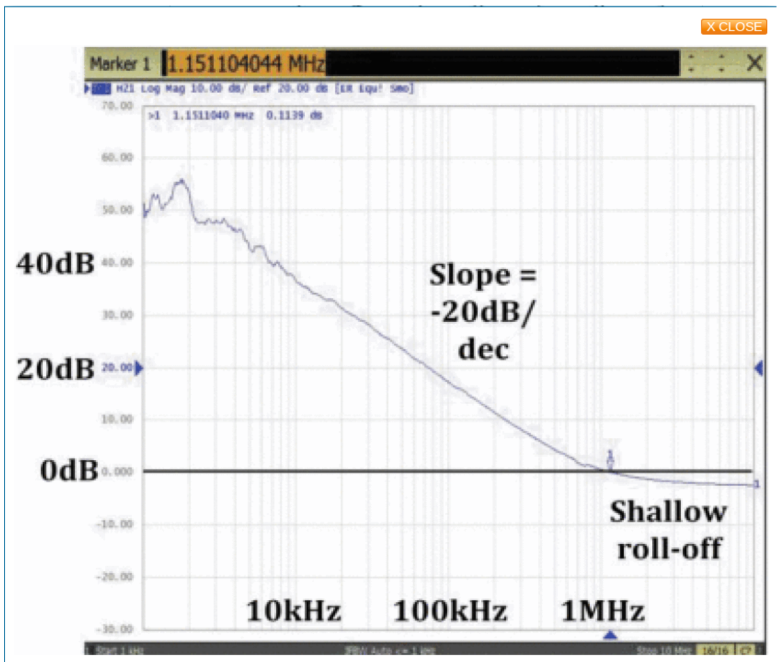


To evaluate transistor speed, its cutoff frequency is calculated or measured. The cutoff frequency is "an indicator of the intrinsic speed of a transistor, defined as the frequency at which the current gain of the transistor has fallen to unity" [2]. When a transistor is fully "off", it is in its "cutoff" state; when fully "on", it is "saturated". Current gain is defined as the ratio of the current at the transistor's output to the current at its input. Therefore, in cutoff state, the current simply goes through the transistor: the output and input are the same, thus the gain is 1. For the circuit to identify the transistor as being switched "on", the transistor has to amplify the current that it is receiving. The maximum amplification, or gain, of the transistor is reached when it is saturated. However, the transistor does not switch instantly. The transistor is "active" during the period of time where it is moving from "off" to "on" [3].

Transistor operation is not evaluated in the time domain (i.e. in seconds), but in the frequency domain (i.e. in Hertz), as is characteristic of any circuit component supplied with AC. This is due to the fact that the very current supplied to the transistor varies across time at a set frequency, as seen in Figure 1. Therefore, the cutoff point is evaluated as a frequency, and measured in Hertz (1/second). A high cutoff frequency implies high transistor speed.

Figure 2 represents an example of silicon transistor behavior. For this type of silicon transistor, cutoff frequency (when the current has an amplitude of 0 dB) was measured to be 1.15 MHz [2]. The cutoff frequency of the current type of silicon transistor is 55 MHz [4].

Figure 2. Amplitude of the current passing through a silicon transistor switching from "on" to "off" [2]



A cruder method of evaluating transistor speed is to rely on the electron mobility of the semiconductors themselves. Electron mobility is a chemical and physical property: it is the speed at which electrons, which are the particles representing current, move through the material. For silicon, this quantity is 1600 $cm^2.V^{-1}.s^{-1}$[5].

2.2. Resistance to High Voltage

Transistors may need to be operated at high voltages; for example, wireless charging requires a great transfer of voltage to be absorbed by transistors[1]. Therefore, a resistance to high voltage can prove to be essential. This resistance can be measured by using the breakdown electric field, which is the point where the behavior of a transistor becomes erratic, and where it risks damaging the rest of the circuit. A silicon transistor breaks down when its electric field is $2.2x10^5$ $V.cm^{-1}$. [4] [6]

While the breakdown electric field of a transistor is a useful value for specific applications, a more general approach to estimating transistor reliability is to evaluate a transistor's resistance to heat. A small portion of the current passing through any electrical component is turned into heat. Therefore, a semiconductor needs to be able to dissipate heat effectively before it transforms the semiconductor's material properties and, in turn, degrades its performance. One of the great challenges of silicon transistor development is finding insulators that can be placed onto the silicon wafer itself to help it dissipate heat better.[7] To get a general idea of a semiconductor's resistance to heat, its melting point is used; once it starts melting, it is permanently degraded. Silicon's melting point is 1683 Kelvins, or 1410 degrees Celsius.[8] The thermal conductivity of each semiconductor can also be used: this is a direct measurement of how well heat travels through a material. In practice, this means that "the higher the thermal conductivity, the more power a device can dissipate for the same temperature rise." [4] The conditions to damage a semiconductor with high thermal conductivity must be extreme. It is important to note that thermal conductivities are always evaluated at 300 K, which is considered room temperature (27 degrees Celsius).[4] Silicon's thermal conductivity is 1.48 $W.cm^{-1}K^{-1}$.[5]

3. Transistor Speed

3.1. Diamond

As described above, two properties can be used to predict transistor speed: cutoff frequency and electron mobility. The cutoff frequency of a diamond transistor is 2 GHz, which is over 35 times greater than a silicon transistor's cutoff frequency [4]. Its electron mobility is 2800 $cm^2.V^{-1}.s^{-1}$; this less rigorous metric confirms the interpretation that the much higher cutoff frequency results in a much faster semiconductor[5]. A consumer-grade computer made of diamond semiconductors would necessarily be faster and more responsive. Just as importantly, such transistors could be used for specific applications where high speeds are crucial.

3.2. Gallium Nitride

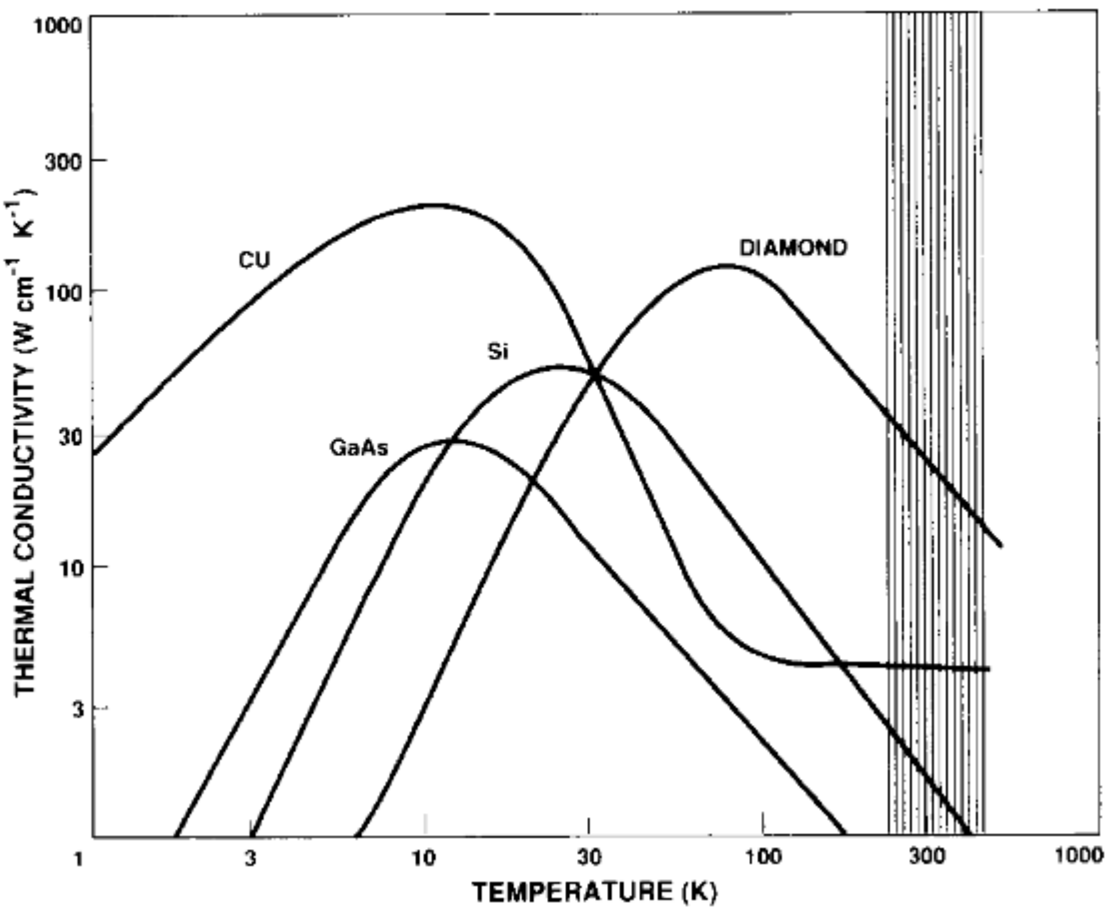
Just like the diamond semiconductor, a cutoff frequency of 2 GHz was measured experimentally for a cutting-edge GaN transistor. GaN's electron mobility is around 1400 $cm^2.V^{-1}.s^{-1}$. [9] An inconsistency can be observed: despite the same cutoff frequency, GaN's electron mobility is around 90% as much as silicon's electron mobility. This inconsistency could be caused by the advanced GaN transistor technology that was used to obtain a 2 GHz cutoff frequency. In other words, the difference in architecture, necessarily caused by the different chemical properties of each material (specifically at the electronic level), allows both transistors to effectively possess the same speed.

4. Resistance to High Voltage

4.1. Diamond

Three criteria for evaluating resistance to high voltage and heat were outlined above: breakdown electric field, melting point, and thermal conductivity. A diamond semiconductor will not break down until its electric field has reached 4×10^{-6} V.cm^{-1}, which is nearly 20 times as much as its silicon counterpart [4]. The breakdown electric field has been predicted to reach as much as 10×10^{-6} V.cm^{-1} by other sources [10]. As expected, diamond also has a higher melting point, at 3773 Kelvins – over two times silicon's melting point. Synthetic diamond is also the material with the highest thermal conductivity known: 32 W.cm^{-1}.K^{-1} at room temperature [11].This means that transistors made from diamond are much more resistant, and much more easily cooled, than silicon transistors. Figure 3 shows the variation of thermal conductivity across temperatures; diamond's superior conductivity is clearly shown, despite the sharp drop in conductivity when reaching temperatures around 300K.

Figure 3. Thermal conductivity of several solids as a function of temperature. The vertical lines around 300K represent the temperature range from -25 degrees Celsius to 125 degrees Celsius[4].



4.2. Gallium Nitride

The other considered solution, gallium nitride, has been demonstrated to break down with an electric field of 9.5 x 10^{-6} $V.cm^{-1}$, which is similar to diamond's anticipated value [12]. Its melting point is upward of 2773 K (2500 degrees Celsius) [13] and its thermal conductivity is 2.53 $W.cm^{-1}.K^{-1}$ [14]. While these properties are not as staggering as a diamond transistor's, they are still superior to silicon's.

5. Discussion Concerning the Cost of Fabrication

Silicon transistors are inexpensive because silicon is abundant and can easily be mined. The low cost of fabrication of silicon transistors has kept them firmly in place on most computer chips – an alternative will require competitive pricing. It is understood that businesses operate for profit. As a result, resistance to adopting a new technology will be significant, especially when considering the tremendous amount of hours and dollars spent to improve upon silicon technology. A solution should not only present an important technological improvement; it should be, from the onset, competitively priced and compatible with current technology. There are also concrete but intangible costs, such as the factories that may need to be built if it is impossible to adapt current factories for the adopted solution, or workers that will require training. The cost of synthesis of diamond and gallium nitride also needs to be considered. Indeed, though this could benefit from a complete study, it could be more profitable to synthesize diamond and GaN, rather than mine for the individual materials.

Moore's Law, which states that the number of transistors that can be placed on a computer chip will double every two years, is still valid as of 2015. However, as the limits of silicon are stretched more and more, the urgency to adopt a solution may rise. Also, adopting a new solution with better or altogether different properties may encourage innovation in the entire computer hardware field, and open up new possibilities. Finally, the solution could be adopted first in areas where high-power, high-speed transistors are crucial, only for it to reach a more widespread market when manufacturing processes improve [1] [15].

Since both gallium nitride and diamond technologies are being actively developed, predicting the market price of both types of transistors would require an in-depth study. However, they are not expected to be instantly competitive, because of the qualitative factors mentioned in this discussion. The prices that follow are meant to illustrate this point, though they are not directly comparable, as the transistors are used in different applications. In 2012, 20 million silicon semiconductors for use in common computer chips could be bought for $1 [16]. In stark contrast, EPC – a company making GaN transistors for high-power, high-speed applications such as self-driving cars or virtual reality helmets – is currently selling individual transistors for $0.49 and above[1]. It is clear that silicon transistors are much more inexpensive at the moment.

6. Summary of the Properties of Each Solution

Figure 4. Summary of all the properties considered to determine which semiconductor is best suited to replace silicon

	Silicon	**Diamond**	**GaN**
Cutoff frequency (GHz)	0.055	**2.00**	**2.00**
Electron Mobility ($cm^2.V^{-1}.s^{-1}$)	1600	**2800**	1400
Breakdown electric field ($MV.cm^{-1}$)	0.22	4.00 (or 10.0)	**9.50**
Melting point (K)	1683	**3773**	2773
Thermal Conductivity ($W.cm^{-1}.K^{-1}$) @ 300K	1.48	**32.2**	2.53

7. Conclusion

As the Figure 4 clearly shows, diamond is the most suitable replacement to silicon technology. The most significant advantage of silicon over the other types of transistors is its widespread use. The superior speed of diamond transistors was determined by using the transistor's cutoff frequency, and the semiconductor's innate electron mobility. Other material properties of semiconductor were used to determine that diamond transistors are able to dissipate heat more effectively. The one area where gallium nitride transistors shine is their breakdown electric field: they can sustain much higher voltages before breaking. However, even this property may be found to be in diamond's favor as technology develops, since the theoretical value of diamond's breakdown field is higher than what is reported.

Concretely, these properties would result in faster transistors that can withstand much higher voltage; revolutionary uses for transistors could be discovered by transcending silicon transistors. One has to keep in mind, nonetheless, that factors outside of pure performance dictate the needs of the computer hardware market.

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