FEASIBILITY AND APPLICATIONS OF GRAPHENE SPIN LOGIC

Thousand Oaks High School

AP Research

April 2019

Word Count: 4585

Abstract

The size of CMOS transistors are near their minimum size and Moore's law is near its limit, so it is paramount to look at different types of transistors to use for computer chips. One prominent type of transistor is the spintronic graphene transistor, which promises high performance and efficient energy conservation. In this report, the spin distance and spin lifetime of various graphene transistor models from peer-reviewed papers were gathered and analyzed to see if a correlation exists between the two variables. Various regression tests were performed as well as a standard error of regression test. All the R squared values and the S value indicates that there is little to no correlation between the variables.

Keywords: Graphene, Spintronics, Transistors, Spin Orbit Interactions, Moore's Law
Spin-lifetime, Spin-distance

Introduction

Transistors

A transistor is the most basic component of a computer central processing unit (CPU) (All about Circuits, 2018). The most common transistor in CPUs are metal oxide semiconductor field effect (MOSFET) transistors. It is similar to a switch that can be either be turned on or off, which either blocks or allows electrons through a passage. It has three main parts: a source, a gate, and a drain (All about Circuits, 2018). Electrons originate from the source and are either blocked or allowed through the gate. If they are blocked by the gate, they remain there. If they are allowed through the gate, they leave the transistor through the drain. And so the transistor can exist in two different states: one where electrons leave through the drain, and one where they are blocked by the gate. These states are represented by values called bits. If a transistor has a value of one, it means the electrons are at the drain. If it has a value of 0, it means the electrons are at the gate. A combination of several bits can be used to represent more complex information. Using a form of mathematics called boolean algebra, combinations of transistors are able to give a certain output, given the input. Groups of transistors form logic gates, which together form basic modules and then CPUs (All about Circuits, 2018). A CPU is the most important component of a computer because it is responsible for the majority of calculations done by the computer. The more transistors per CPU, the faster and smarter the circuit chip is (All about Circuits, 2018).

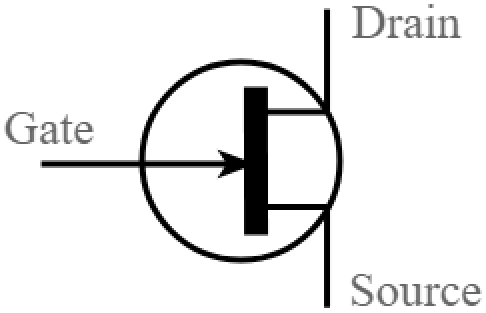


Fig 1. A diagram of a transistor (All about Circuits, 2018).. The gate is the part of the transistor that separates the drain from the source. This way, it can block incoming electrons from the source.

As of now, almost all transistors are made up of the element silicon. Silicon is one of the most abundant elements in the world and it is easy to manufacture (All about Circuits, 2018). More importantly, it has the ideal band gap of around 1 eV at room temperature (All about Circuits, 2018). A band gap represents the minimum energy that is required to excite an electron up to a state in the conduction band where it can participate in conduction. In other words, it is the value that determines if an electron will pass a gate or not. 1 eV is the ideal band gap because it is neither too high that silicon does not conduct, nor too low that it conducts too easily.

Moore's Law

Moore's law states that the number of transistors in a densely integrated circuits doubles around every two years (Aumnate n.d.). This is because transistors get smaller every year and more are able to fit in a silicon wafer. The number of transistors directly correlate with the processing power of a circuit. So, in other words, Moore's law states overall processing power for computers of the same size will double every two years. The law was first observed by Gordon Moore, co-founder of the semiconductor-based CPU company, Intel (Schaller,2018). Transistors are made smaller by using a process known as complementary metal–oxide–semiconductor (CMOS) scaling or device scaling. The process is a result of the reduction of the lateral and vertical dimensions of transistors. For the past few decades, transistors have roughly followed this law. We have seen computers shrink and get exponentially more powerful since the start of the Information Age and it has proven Moore's law to be true. To put things in perspective, an Apple iPhone 5 from 2012 has 2.7 times the performance of the 1985 Cray-2 supercomputer, the fastest computer of the time (Schaller,2018). Unfortunately, many experts predict that the law will soon come to a close and the advancements of technology will stagnate because of one simple problem: transistors are getting too small (Schaller,2018).

Currently, the average transistor is only 14nm long (da Costa et al., 2019). Creating a stable silicon transistor smaller than 14nm has either been too difficult or too expensive to create and market. As they get smaller, they become more difficult and expensive to research and manufacture. It becomes riskier to invest in research that may not be good enough. This ties in with the lesser known Moore's Second Law, also known as Rock's Law. Moore's Second Law states that the cost to manufacture chips doubles roughly every four years. And so, Moore's second law acts as a constrainer to Moore's first law.

Fig 2. (Schaller,2018) Moore's Law from 2009-2018 and size of the transistor from 2009-2018.

As can be seen in figure 2, in the last ten years, the size of a transistor is decreasing at a slower pace than predicted by Moore's law. Since there is a direct correlation between the size of a transistor and the speed of a CPU, CPUs have been getting faster at a slower pace in the past ten years. If we had followed Moore's Law, our electronics would be expected to run seven times as fast because a transistor would be 2 nanometers long, not 14. We should be able to fit in seven times as many transistors in circuits and expect a total calculations per second that is seven times as high .

Sadly, engineers face more than just an economic problem. It may be physically impossible to construct a transistor much smaller than fourteen nanometers. As transistors get smaller, quantum physics, the branch of physics that deal with the smallest scales of matter, play a larger role than traditional physics. Electrons may transfer themselves through the gate of a closed transistor, making transistors completely useless (Schaller,2018). Electrons will always take the path that requires the least energy. Normally, electrons would be provided energy when the transistor is in its "ON" state and cross the potential hill. Thus, when the transistor is in its "OFF" state, it would be impossible for electrons to get to the other side of the hill. A problem arises when the transistor gets smaller. A new path becomes available for electrons, quantum tunneling. They can tunnel through the hill rather than climb over it.

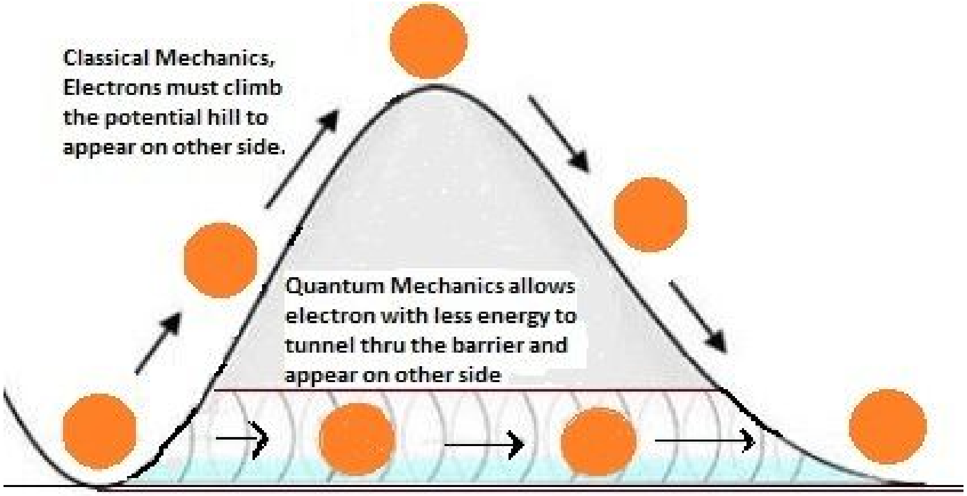


Fig 3. (Quora) Quantum tunneling requires a large amount of energy over large distances which makes it impossible in larger transistors but in smaller transistors, it is possible. This means that transistors can leak electrons and be considered "ON" when they should really be "OFF."

It is expected that transistors will be too expensive to manufacture as near as 2021 (Schaller,2018). If this hurdle is somehow passed, it is expected that the size of a transistor will reach its limit at 5 nanometers at 2026 (Schaller,2018). In the worst case scenario, we will see a complete stop in technological growth. To prevent this, it is critical that we look at different ways to compute information and move away from the traditional CMOS downscaling that has worked for us for the past half-century.

Spintronics

To prevent this technological plateau, many researchers have begun to look at different ways to store information that may make computing more efficient. Spintronics is a branch of electronics that holds much promise. Currently, in electronics, a transistor reads the charge of an electron. A spintronic device or component would read another property of an electron: its spin. Spintronic device's values of 0 or 1 depending whether an electron is spinning up or down rather than its charge, so it does not matter if the conductor is always transferring electrons (Cummings n.d.). In the gate of a spintronic transistor, the spin orbit coupling (SOC) of a material determines the state of the transistor or the value of the bit, not the band gap. SOC is a property of materials that defines the behavior of electron spin in the material. The benefits of spintronics over traditional are immense, including better performance and lower power consumption (Hirohata, 2015). Many scientists also predict that it will operate better in higher temperatures and pressures than electronics. It is also more resistant to radiation than normal electronics. Less energy is needed to change spin than to generate a current to maintain electron charges in a device, so spintronics devices use less power (Cummings n.d.). Spintronics may be more reliable in harsher environments such as space and high altitudes (Cummings n.d.). Spin can be measured because it generates tiny magnetic fields. Electronics require specialized semiconductor materials that are chemically doped in order to control the flow of charge through the transistors. But spin can be measured very simply in common metals such as copper or aluminum. Ferrous metals such as iron become magnetic, for example, when enough particles have their spin set in the same direction, generating a magnetic field of the same polarity as the spin.

Spintronics has already revolutionized the way storage is stored. The first application of spintronics to computers saw Professors Albert Fert and Peter Grünberg awarded the 2007 Nobel Prize in Physics for their discovery of giant magnetoresistance (Cummings n.d.). They realized it was possible to use electron spin to increase the rate at which information could be read from a hard disk drive and developed ground-breaking technology to harness this feature. A hard disk drive stores data as ones and zeros encoded magnetically on rotating disk platters within the drive. The magnetic field is generated when electrons flow through wire coils mounted in the drive write heads which move across the face of the platters, changing the alignment of the magneto-sensitive particles on the platter surface. Reversing the electron flow reverses the field; the two directions represent one and zero. To read from the disk, the process works in reverse. Spintronics researchers have since been working on introducing the same technology to computer memory, aiming to replace electric current-based dynamic random access memory (DRAM) with magnetic random access memory (MRAM) (Orwell 2009). Manufacturers such as Intel, Qualcomm, Toshiba, and Samsung are developing MRAM to use as processor cache memory, where by virtue of their smaller size, MRAM chips of greater capacity can be incorporated into smaller packages that will be faster, and use up to 80% less power than current cache memory (Orwell 2009). EverSpin has already created an MRAM module that is available commercially. Currently, it is used in planes and takes advantage of spintronics resistance to the pressure change in high altitudes (Orwell 2009).

The goal now is to apply already existing spintronic technologies into a different computer part: the CPU (Cummings n.d.). But first, to create a complete CPU, the most basic component, the transistor, must be built. The ideal spintronic will be efficient at room temperature, have an easily manipulatable spin injection and detection, long distance spin lifetime, and long spin distance. The spin injection is the manipulation of the spin of an electron and spin detection is the detection of the change of spin. Spin lifetime is the time the spin is held constant after it is manipulated. It needs to be long because if it is too short, spin detection would be impossible. Spin distance is the distance the electron travels after its spin is manipulated and held constant. This length also needs to be relatively long because spin distance needs to be long enough to pass through all three parts of a transistor.

Graphene

Graphene is a single, thin layer of graphite — the soft, flaky material used in pencil lead. Graphene was merely a theory, as scientists were unsure if it would ever be possible to slice graphite down to a single, atom-thin sheet. The first isolated sample of graphene was discovered by Andre Geim and Konstantin Novoselov (2004) at the University of Manchester. The two scientists discovered this material using simple scotch tape and later went on to earn the Nobel Prize in 2010. Being so remarkable in many ways, graphene has inspired scientists to think of a wide range of uses for the material, in fields as varied as consumer tech and environmental science (Hirohata, 2015).

Graphene’s high-speed conductivity makes it a strong candidate for high-performance electronics. A study by Birkner (2013) found that graphene has a theoretical charge carrier mobility higher than 200,000cm2/V·s while silicon only has a charge carrier mobility of

450cm2/V·s. Electron mobility characterizes how quickly an electron can move through a metal or semiconductor when pulled by an electric field. Because graphene can transport more electrons over a small course of time, it will speed up how fast electronics work. However, because of graphene's structure, it is impossible to use it in traditional computer chips. Graphene has a bandgap so small that many consider it to be nonexistent. It is a pure conductor, not a semiconductor like silicon. So, a transistor made out of graphene will only be able to have one value or state because it is impossible for transistors to change their state form on or off when the band gap is too low or too high. The material that CPUs are made up of must neither conduct electricity so readily nor reject every electrical charge. There have been attempts at chemically doping graphene to increase its band gap but in all the cases so far, the doped graphene has lost its incredible electron mobility (Cummings n.d.). As of now, it is impossible to use graphene in traditional electronics.

Graphene Spintronics

Graphene in spintronics, rather than electronics, however, holds much promise. It holds a very small SOC, which should theoretically lead to long spin relaxation times. It also has shown remarkable spin distance. Additionally, its high electron mobility would lead to it to be able to do more calculations per second. Lastly, it has a gate-tunable carrier concentration which allows for it to alternate the spin of electrons and thus strong spin manipulation.

Purpose

The purpose of this study is to investigate a way to increase the spin relaxation time of graphene transistor devices. Graphene is able to maintain spin conductivity over long distances very consistently. However, it is unable to maintain the spin distance for a measurable amount of time. Scientists have looked at increasing this spin lifetime by using different materials coupled with graphene and in some cases, have succeeded. However, it is still not long enough to be viable.

Theoretically, graphene should have a high spin lifetime. An estimate of spin relaxation can be found using the formula spin relaxation rate formula.

$$1/\tau_s \approx b^2/\tau_p$$

Fig 4. Formula spin relaxation rate formula (Cummings n.d.)

τ_s represents spin lifetime, b represents spin admixture, and τ_p represents momentum relaxation time. Graphene, however, does not seem to follow this formula, unlike all other materials. As of now, the reason for this is unknown. Experiments done on graphene flakes show that b $\approx 3.16 * 10^{10}$ and $\tau_p \approx 10$ fs which makes $\tau_s \approx 1$ µs. However, experimental values of are $\tau_s \approx .5\text{-}2$ ns (Cummings n.d.) .This shows that for an unknown reason the theoretical spin lifetime is much shorter than expected. The theoretical value is over two magnitudes higher than the experimental value. This suggests that the source of spin relaxation is of extrinsic origin (e.g. impurities, defects, static ripples, etc.) and the challenge is to identify the microscopic mechanism. Pristine graphene has been very difficult to manufacture in experiments and only small flakes can be created at the time.

But another possibility, one that is more likely actually, is that the equation used currently does not apply to graphene. This could be because graphene is fundamentally different from other materials since it is technically only two dimensional. The purpose of this paper is to derive a different equation that gives a more accurate value for the spin lifetime. The equation used for now is too inaccurate for an unknown reason and there is thus a major gap in the research. This of course, assumes that there is no problem with the graphene manufactured and used. A new equation will be derived by comparing two different variables to see if a correlation can be found. If an equation or correlation is found, it can be used to improve the efficacy of graphene spintronic transistors by providing ways to increase the spin-lifetime. For example, if a direct positive correlation is found, then increasing spin distance will increase spin lifetime.

Problem

Moore’s law is coming to an end soon and it is important to look for alternatives to silicon-based electronics. If Moore's law slows down as many experts predict, technology will simply stop growing at the rate that it has been growing in the past. Spintronics is one popular candidate to revive Moore's law. Graphene is a popular material for spintronics because it has high conductivity and high spin lifetime at room temperature. However, graphene has a low spin lifetime. If researchers are able to increase graphene’s spin lifetime, then it will be an even stronger candidate for spintronics than it already is.

Research Question

The questions this research paper will aim to answer: Are spin distance and spin lifetime related? Is it a positive or negative correlation? Is there a concrete equation relating these two variables? The reason I chose this paper is that many studies have suggested that a correlation exists between spin lifetime and spin distance (Cummings n.d.).

Hypothesis

Alternative hypothesis: Both spin lifetime and spin distance have shown a correlation to the spin orbital interaction of transistors and magnets. Therefore, there is a strong correlation between the spin lifetime of an electron and spin distance of an electron in graphene spintronic transistors. The correlation is most likely positive due to successful trials having both high spin lifetime and spin distance (Cummings n.d.). It is still unknown what kind of correlation this will be (ie. linear, exponential etc.).

Null hypothesis: There is no observable correlation between the spin lifetime of an electron and the spin distance of an electron in graphene spintronic transistors.

Methods

A systematic literature review was used for this paper. This method was chosen because I lacked the materials and experience to perform an experiment. Also, I did not have access to a lab at my school. I could not conduct a survey because that would not give me relevant information on this topic.

The databases to gather articles were Google Scholar, Nature, ResearchGate, ScienceDirect, and JSTOR. The College Board version of the database EBSCOhost was also used. Additional articles were also gathered from the reference section of already chosen articles. From these articles, quantitative data on spin-lifetime and spin-distance was extracted. To get more information on electrical engineering, important definitions were taken from passages of the “All about Circuits” textbook, which is available for free online. Another incredibly important source of information was the Graphene Flagship Program. The Graphene Flagship Program is the single largest research grant in the world (Graphene Flagship). The European Union commissioned a total of one billion euros to investigate the potential of graphene and to make it more usable and viable commercially. One of the many major fields the graphene flagship program is the field of spintronics. As such, I was able to find many peer-reviewed papers on the field. Lastly, information about graphene spintronics was used from Chapter 11 of the University of Cambridge's textbook on 2D materials, which focused on graphene spintronics.

The search results from the various databases provided over twenty-five thousand studies. 20 articles were identified to be useful based on title and abstract. All the papers data was gathered from were peer-reviewed. They are also from the last ten years in order to keep the data as current as possible. Lastly, the only papers considered were experiments and trials; systematic reviews, meta-analyses, and study protocols were all excluded. 12 articles were then excluded because the research papers were either too old or had an emphasis on enhancing other properties of graphene spintronic transistors, such as spin injection. The eight articles chosen were specifically trying to increase the spin life time of electrons. Spin lifetime and spin distance was extracted, recorded and analyzed.

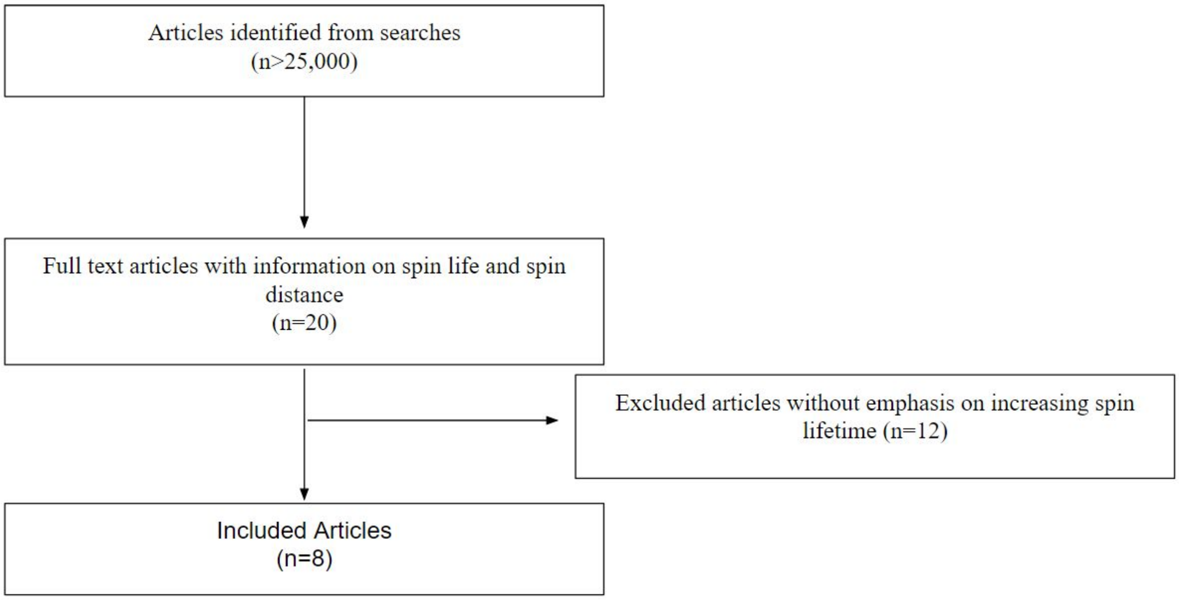


Fig 5. Diagram of the flow of studies throughout data collection.

Statistical Analysis

After data from the eight articles were extracted, the data was plotted in Microsoft Excel. Regression tests were then run for the graph to find the line of best fit for different types of equations. In total, five tests were run including linear, exponential, polynomial (second order), logarithmic, and power. The R squared value and equations for each line of best fit was recorded. Next, the standard error of regression was calculated based on the data points. Both R squared values and standard error of regression tests can be used to find the strength of correlation between two variables. The closer the R squared value is to 1, the stronger the correlation. The smaller the standard error of regression, the stronger the correlation. A standard error of regression under 2.5 is ideal. A standard error of regression test was also performed to see the correlation between the two variables. Microsoft Excel could calculate the R squared value but the standard error of regression had to be calculated by hand using the standard error of regression formula.

$$S_e = \sqrt{\frac{\sum (Y_i - Y')^2}{n - 2}}$$

Fig 6. The equation for the standard error of regression

ŷ is the point expected on the line of best fit while y is the actual y value observed. n represents the number of data points. The equation used for this test for the y values was the linear line of best fit.

Results

All the papers used attempted to increase the spin lifetime of electrons by applying a variety of methods. They introduced a different material near graphene and observed the effect it had on the spin lifetime. There was a wide consensus among all the articles that the greater the spin orbital interactions of the new material, the greater the desired result. The aim was that the large SOI of new material would increase the spin lifetime while the small SOI of graphene extends the spin distance. A majority of the papers used cobalt to test this because it had a high intrinsic SOI. Two papers also used Molybdenum Disulfide because it had a similarly high SOI. Lastly, two other papers used 2D materials for ease. One paper used a layer of silicene, a material similar to graphene except it is made of silicon atoms rather than carbon atoms, and another paper just used another layer of graphene.

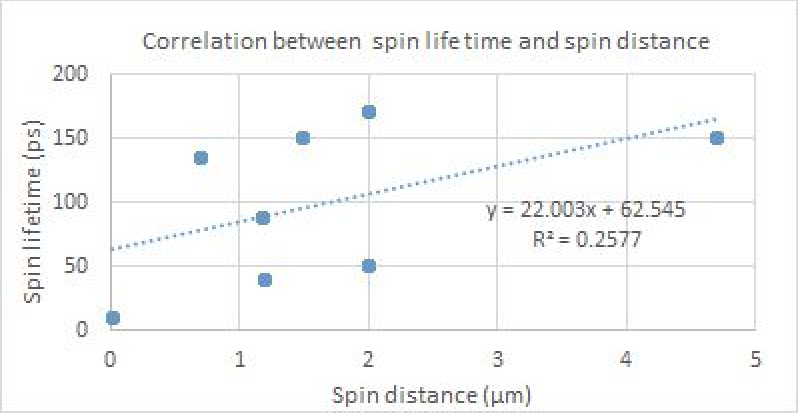
It appeared to seem that there were no major outliers in the data so all of the final eight papers were used in the graph.

Table 1. This table shows the data that was collected from eight different peer-reviewed research articles. Data includes complementary material used, spin lifetime, and spin distance.

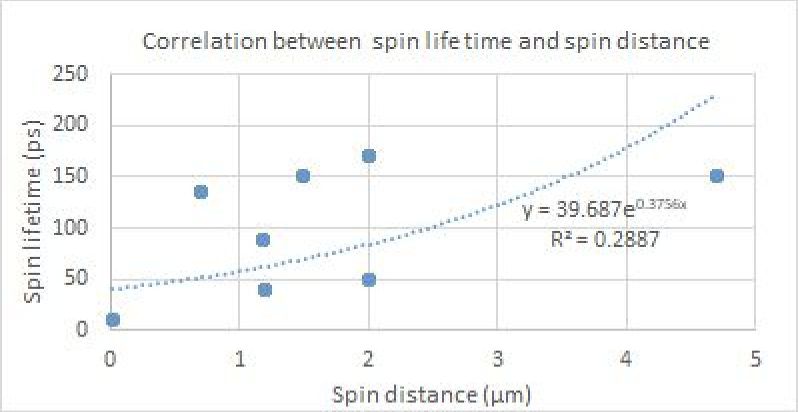
	Complementary Material	**Spin Lifetime(ps)**	**Spin Distance (μm)**
Tombros et al.	**Cobalt**	**170**	**2**
Yang et al.	**Bilayer Graphene**	**135**	**.7**
Guimarães et al.	**Cobalt**	**150**	**4.7**
Birkner et al.	**Epitaxial SiC (Graphene Silicene mixture)**	**88**	**1.18**

Józsa et al.	**Cobalt**	**150**	**1.5**
Dankert and Dash	**Molybdenum Disulfide**	**40**	**1.2**
Yan et al.	**Molybdenum Disulfide**	**10**	**.020**
Han et al.	**Cobalt**	**50**	**2**

.



a)



b)

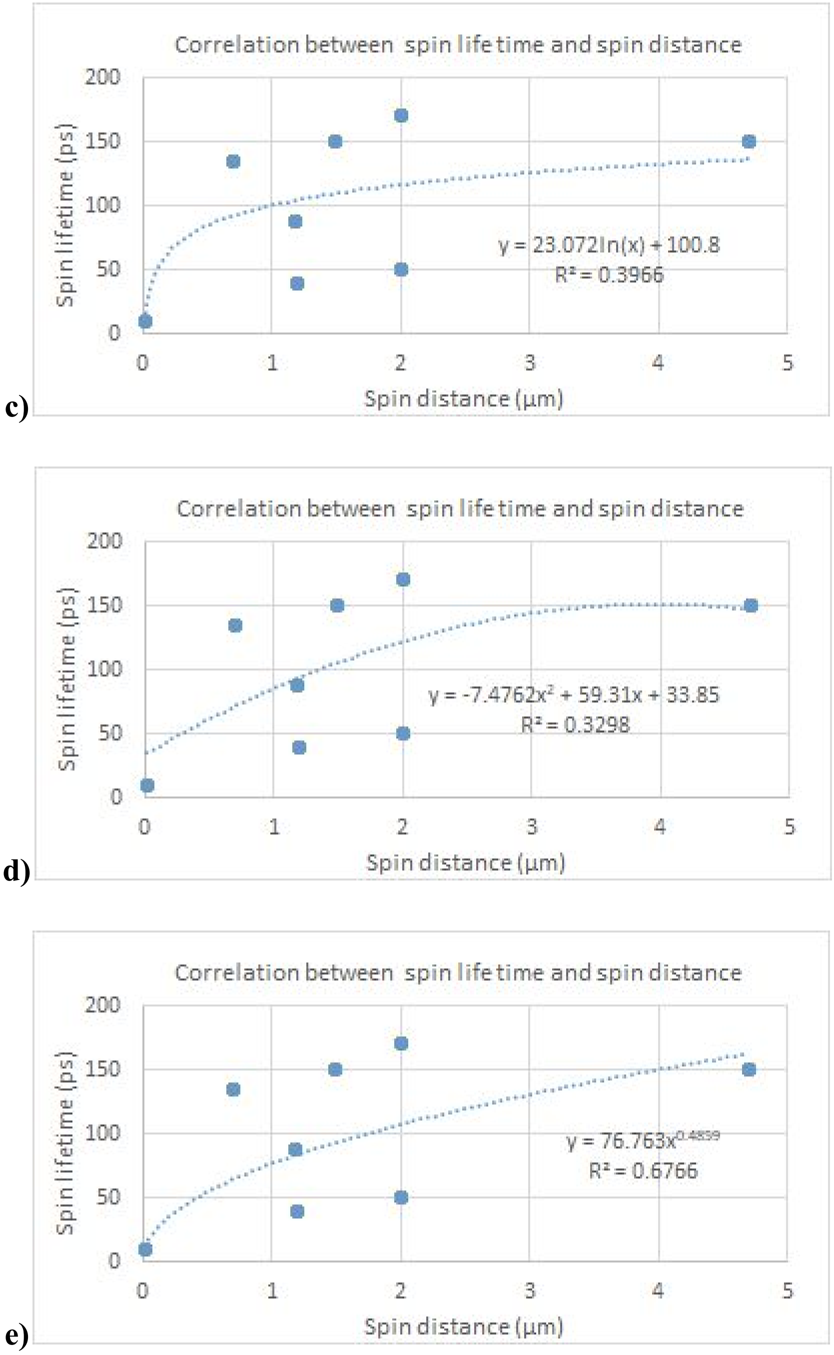


Fig 7. This figure is all the regression tests that were performed. a) is a linear test, b) is an exponential regression test, c) is a logarithmic regression test, d) is a second-degree polynomial test and e) is a power regression test. Included in the graph are the equations of the line of best fits, as well as the R squared values.

Table 2. This table shows all the R squared values and equations. It is organized from smallest to greatest R squared values. The greatest value observed was .6766.

Regression	R squared value	Equation
Linear	.2577	$y = 22.003x + 62.545$
Exponential	.2887	$y = 39.687e^{0.3756x}$
Polynomial (2nd)	.3298	$y = -7.4762x^2 + 59.31x + 33.85$
Logarithmic	.3966	$y = 23.072\ln(x) + 100.8$
Power	.6766	$y = 76.763x^{0.4859}$

Table 3. The table used to calculate the standard error of regression. X is the spin distance, y is the spin lifetime, and ŷ is the expected y spin lifetime based on the linear line of best fit.

x	y	ŷ	y- ŷ	(y-ŷ)^2
0.7	135	77.9471	57.0529	3255.033
4.7	150	165.9591	15.9591	254.6929
1.18	88	88.50854	0.50854	0.258613
1.5	150	95.5495	54.4505	2964.857
1.2	40	88.9486	48.9486	2395.965
0.02	10	62.98506	52.98506	2807.417
2	50	106.551	56.551	3198.016

From table 3, we can calculate the standard error of regression using figure 6. The sum of (y-ŷ)^2 equals 14,876.24 and (n-2)=6. After plugging everything in, we get an S value of 60.5.

Discussion

All the data compiled show that it is very likely that there is not a direct correlation between the variables being compared. As such, the null hypothesis should be accepted and the alternative hypothesis should be rejected. As seen in table 2, the highest R squared value was .6766 from a power regression test which indicates that there might be some correlation, but it is not a direct cause and effect. On the other hand, the lowest R squared value observed was .2577 which is incredibly low. However, it was unlikely from the start that the relationship would be linear.

A concrete equation relating spin distance to spin lifetime cannot be presented based on the results of these tests. This study shows is that there is a positive relationship. One possible reason for there being an erratic, but positive correlation is that there are multiple variables that affect the spin lifetime of an electron, not just spin distance. Some of these other variables could be voltage gate potential, spin orbital interactions, bond structure, and or conductivity and resistance of the complementary material.

Limitations

There are several limitations to my findings. The biggest one is the unreliability of comparing different transistor models. All the transistors analyzed in this paper were made differently and have different structures. There is no universal blueprint model that all the scientists followed. As such, it might be unfair to compare them amongst one another.

Secondly, papers used different materials alongside graphene. So a lack of correlation may be traced back to the use of different environments electrons existed in. Different materials, of course, have different voltage gate potential, spin orbital interactions, bond structure, and conductivity and resistance. However, papers with similar materials were chosen to limit this problem as much as possible

Also, the graphene that was used in each of these experiments may be of different quality. Pristine graphene has been very difficult to create and at most, only a few milligrams are able to be made at a time. Various experiments show that even graphene made through the same process can interact in slightly different ways.

A source of error could be that the data observed may be a slight margin. The measurements that were recorded were incredibly small in magnitude and thus have to be recorded very carefully, especially because the units were measured in picoseconds and microseconds. All the papers I used gave the average of a number of different trials, increasing the level of accuracy.

Lastly, the small number of data points could be a source of error. More data points are needed to have greater confidence in the results. Eight points are not enough to make a conclusion with complete certainty. But because this is still a relatively new topic, there were only so many papers that I could find.

Conclusion

This systematic literature review provides evidence supporting the null hypothesis proposed in this study that there is little correlation between spin lifetime and spin distance. Yet, there is still some positive correlation meaning that it is impossible to rule out that there is no correlation between them. All papers analyzed in this systematic review support this hypothesis, suggesting that there are likely other variables, not just spin distance, that affect spin lifetime. An equation could not be proposed relating the two variables because the R squared values are too low and the standard error of regression value is too high.

Further Work

If I was given more time, I would have researched more aspects of spintronics and included the voltage gate, interactions between orbitals within the electrons to my regression tests. I would perform something similar to what I did on this paper- perform regression tests except comparing these new variables to spin lifetime rather than spin distance. This way, I can see the way effect these variables have on spin lifetime. If they have a greater effect than spin-distance, then a new equation with these two variables should be proposed again.

Another finding of this study is that the study of Tombros et al is clearly the most efficient material paired with graphene so far. This finding was not part of the original research question, but it is easy to see that it has both the greatest spin lifetime and spin distance when compared with the rest of the studies in chart 1. As such I would analyze cobalt and look at why it had the most success. I would also look at this specific model transistor more closely to see what is different about it that maximizes spin lifetime because other transistors used cobalt as well but weren't as successful. In the future, when there are more papers published on this specific material and other materials as well, I would like to perform a t-test to prove or disprove that this cobalt is better.

Acknowledgments

I would like to thank my teacher, Dr. Malhotra, for guiding me through this project by helping me find my topic and giving me feedback for my paper. I also want to thank Dr. Dimitri for helping me understand my topic when I first started. He works directly with the Graphene

Flagship Program, so his feedback was incredibly valuable for this paper. Lastly, I would like to thank Nikki Razzal, an AP capstone alumni, for her help with conducting regression tests and providing feedback for my paper.

Bibliography

Arsalani, Nasser; Nasiri, Ramin; Zarei, Mahmoud. Chemical Engineering Research & Design: Transactions of the Institution of Chemical Engineers Part A. Aug2018 Part A, Vol. 136, p795-805. 11p. DOI: 10.1016/j.cherd.2018.06.024.

Aumnate, C.; Pongwisuthiruchte, A.; Pattananuwat, P.; Potiyaraj, P. Advances in Materials Science & Engineering. 11/6/2018, p1-9. 9p. DOI: 10.1155/2018/2830437.

Baladés, N.; Sales, D. L.; Herrera, M.; Raya, A. M.; Hernández-Garrido, J. C.; López-Haro, M.; Molina, S. I. Journal of Nanomaterials. 12/16/2018, p1-12. 12p. DOI: 10.1155/2018/4906746.

Birkner, B. et al. (2013) Annealing-induced magnetic moments detected by spin precession measurements in epitaxial graphene on SiC. Phys. Rev. B 87, 081405

Chengyang Peng, Fosong Liu, & Chunnian Chen. (2019). Synthesis of graphene/nano-sulphur/ polyaniline ternary nanocomposite for high-performance supercapacitor electrodes. Polymers & Polymer Composites, 27(1), 3–10. https://DOI.org/10.1177/0967391118809231.

Cummings, A. W., Valenzuela, S. O., Ortmann, F., & Roche, S. (n.d.). Graphene Spintronics. 2D Materials, 197–218. DOI:10.1017/9781316681619.012

da Costa, M. C. F.; Sousa, M. R. M.; Larrudé, D. R. G.; Fechine, G. J. M. Express Polymer Letters. 2019, Vol. 13 Issue 1, p52-64. 13p. DOI: 10.3144/expresspolymlett.2019.6.

Geim, A. . K. (2009). Graphene: Status and Prospects. *Science324*(5934), p. 1530. (Geim, 2009, p. 1530)

Ghasemi Yeklangi, Akbar; Khadem, S. E.; Darbari, Sara. Journal of Applied Physics. 2018, Vol. 124 Issue 22, pN.PAG-N.PAG. 8p. 4 Diagrams, 4 Graphs. DOI: 10.1063/1.5038729.

Guimarães, M. H. D. et al. (2012). Spin Transport in High-Quality Suspended Graphene Devices. Nano Letters 12, 3512-3517

Han et al. (2013) Large-Gap Quantum Spin Hall Insulators in Tin Films. Phys. Rev. Lett. 111, 136804

Józsa, C. et al. (2009) Linear scaling between momentum and spin scattering in graphene. Phys. Rev. B 80, 241403(R).

Kam, Kevin A.; Tengan, Brianne I. C.; Hayashi, Cody K.; Ordonez, Richard C.; Garmire, David G. Sensors (14248220). Sep2018, Vol. 18 Issue 9, p2774. 10p. DOI: 10.3390/s18092774.

Kikkawa, J. M. & Awschalom, D. D. (1998). Resonant Spin Amplification in n-Type GaAs. Phys. Rev. Lett. 80, 4313

Lane, J. R.; Zhang, L.; Khasawneh, M. A.; Zhou, B. N.; Henriksen, E. A.; Pollanen, J. Journal of Applied Physics. 2018, Vol. 124 Issue 19, pN.PAG-N.PAG. 6p. 1 Diagram, 4 Graphs. DOI: 10.1063/1.5047211.

Li, Yanan; Xing, Ruiguang; Zhang, Bangwen; Bulin, Chaoke. Polymers & Polymer Composites. Feb2019, Vol. 27 Issue 2, p76-81. 6p. DOI: 10.1177/0967391118817404.

Mikoushkin, V. M.; Kriukov, A. S.; Nikonov, S. Yu.; Dideikin, A. T.; Vul, A. Ya.; Vilkov, O. Yu. Journal of Applied Physics. 2018, Vol. 124 Issue 17, pN.PAG-N.PAG. 10p. 2 Diagrams, 1 Chart, 6 Graphs. DOI: 10.1063/1.5047045.

Nirumand, Ladan; Farhadi, Saeed; Zabardasti, Abedin. Acta Chimica Slovenica. 2018, Vol. 65 Issue 4, p919-931. 13p. 2 Black and White Photographs, 1 Chart, 9 Graphs. DOI: 10.17344/acsi.2018.4589.

Orwell, G. (2009). Lessons in Electric Circuits (1. Edition). Florida: All About Circuits.

Piñas, Jean A. V.; Andrade, Tatiana S.; Oliveira, Andreia T.; Salomão, Pedro E. A.; Rodriguez, Mariandry; Silva, Adilson C.; Oliveira, Henrique S.; Monteiro, Douglas S.; Pereira, Márcio C. Journal of Nanomaterials. 1/9/2019, p1-8. 8p. DOI: 10.1155/2019/5736563.

Schaller, R. R. (2018). Moore's law: past, present and future. IEEE Spectrum, 34(6), 52–59. DOI:10.1109/6.591665

Sharifi, S.; Banadaki, Y. M.; Nezhad, V. F.; Veronis, G.; Dowling, J. P. Journal of Applied Physics. 2018, Vol. 124 Issue 23, pN.PAG-N.PAG. 9p. 1 Diagram, 7 Graphs. DOI: 10.1063/1.5048332.

Tombros, N., Jozsa, C., Popinciuc, M., Jonkman, H. T. & van Wees, B. J. Electronic spin transport and spin precession in single graphene layers at room temperature Nature 448, 571 .

Yang, R. et al. (2013) Defect-Mediated Spin Relaxation and Dephasing in Graphene. Phys. Rev. Lett. 110, 156601 .

Yang, T.-Y. et al. Observation of Long Spin Relaxation Times in Bilayer Graphene at Room Temperature. Phys. Rev. Lett. 107, 047206.

Yu, Zhuying; Yan, Boteng; Li, Zhihong; Ruan, Xiukai; Zhang, Yaoju; Dai, Yuxing. Journal of Applied Physics. 2018, Vol. 124 Issue 18, pN.PAG-N.PAG. 6p. 1 Diagram, 5 Graphs. DOI: 10.1063/1.5060719