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Sophomore Research Project

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Beyond Silicon: The Next Frontier in Computing

When the ENIAC computer debuted in 1945, the first general purpose computer, it took up one thousand five hundred square feet, comparable to the size of a small home, and weighed thirty tons. It could execute five thousand operations per second, an operation being a calculation involving two numbers with decimal points. (Richey) Today, a new Macbook that weighs less than five pounds can compute ninety three trillion operations per second, a powerful reminder that the explosive and exponential growth of computers is driven by Moore's Law, the empirical formula that the number of transistors on a computer chip doubles approximately every 2 years. (Apple Inc) But as scientists continue to push the limits of traditional silicon based transistors making them smaller and smaller, reaching 2-3 nm, their performance begins to falter. At such a small scale, electron behavior causes instability, revealing fundamental limitations of silicon. As a result, researchers are pursuing alternatives to traditional silicon-based computing. The emergence of quantum computing and alternative transistor materials poses solutions to this problem. As these new solutions to surpass the limits of Moore's law emerge, the future of the technology looks

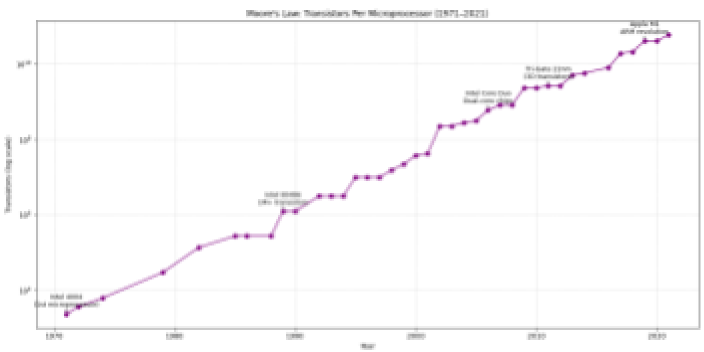


Figure 1: Moore's Law Transistor graph

(Rupp)

bright. These alternatives don't just have the potential to match silicon's performance, but to transcend it, breaking new ground in global economies, driving innovation globally.

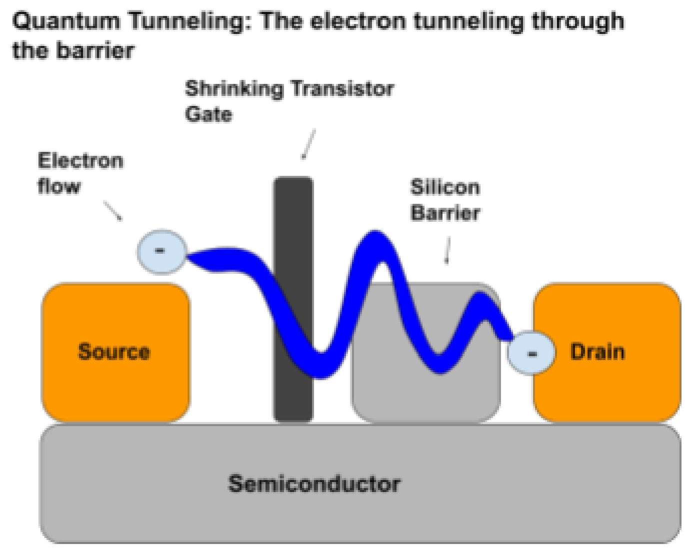


Figure 2: Transistor Gate/Electron Tunnelling (Roy, Kaustav, et al.)

As the semiconductor industry continues in relentless strides of progress, reaching the limits of transistor miniaturization, it faces an unavoidable problem: quantum tunnelling. Quantum tunneling occurs when electrons penetrate an insulating silicon barrier due to their wave-like nature, a process that becomes problematic at transistor scales around 3 or less nanometers. At these dimensions electrons can unpredictably tunnel though barriers and can cause electronics to behave unreliably and unexpectedly. This issue isn't just theoretical, it's been observed in real-world scenarios (Mittal and Huang).

"The Influence of Transistor Miniaturization on Quantum Tunneling in Semiconductor Devices" is a research paper published in the International Journal of Innovative Research in Technology by Aarav Mittal and Richard Huang. This article delivers an in-depth analysis of the implications of quantum tunneling on traditional computing and the challenges that future scientists and engineers will face associated with transistor miniaturization. They explain, "When transistors are produced at the nanometer scale, typically under 3nm, they experience leakage current between the two electrodes, a phenomenon known as quantum tunneling" (Aarav, Mittal

& Huang). This implies that the current methods of transistor miniaturization won't be feasible due to a loss of efficiency and reliability, as quantum tunneling causes uncontrolled current flow that disrupts normal transistor behavior. Mittal and Huang explain, "Under the lens of quantum mechanics, it is possible for particles to tunnel through transistors with barriers of thickness 1-3nm and smaller even if it doesn't have enough energy to pass through" (Aarav, Mittal & Huang). In other words, when given such a thin barrier the electrons can simply move right through the barrier instead of passing through and completing the circuit. This leads to a deviation of typical electrical behavior that computer systems are built on.

"Challenges and Opportunities in 2nm and Beyond" is a nanotechnology-focused article written by Ashwini H. from Abhiyantha, an engineering research website, exploring the technical hurdles and innovations in scaling transistors to sizes below 2 nanometers. This educative article raises many good points, reiterating that "As transistors approach atomic scales, quantum tunneling becomes a significant issue. Electrons can pass through barriers meant to contain them, leading to leakage currents, increased power consumption, and potential reliability issues" (H). This is because of the previously described concept of quantum tunneling, where An electron can bypass a barrier entirely due to quantum tunneling and that"..leading to leakage currents, increased power consumption, and potential reliability issues" (H).

The research presented by Aarav Mittal and Richard Huang, along with Ashwini H., clearly demonstrates that quantum tunneling poses a significant barrier to the continued miniaturization of transistors. As electrons leak and tunnel through barriers at the quantum level, traditional transistor functionality decreases, resulting in unreliable and unpredictable errors. This isn't a theoretical problem, it is a real and pressing challenge that the world's brightest minds work to answer, and as they race to overcome this issue, we can only wonder what the future holds for technology.

As the scaling of silicon based transistors pushes below the 3 nanometer threshold, scientists and engineers are increasingly running into issues due to the fundamental physical limitations of the material. As silicon falters, a global search for alternative materials has led scientists to suggest 2 promising candidates, one being graphene and one being MoS_2 (molybdenum disulfide). Both have merits in increased energy efficiency and scalability at lower transistor sizes, unlocking performance previously thought unachievable.

“Can MoS_2 Outperform Silicon?” is a nanoelectronics article written by Saptarshi Da and published in Circuit Cellar, exploring the potential of molybdenum disulfide as a next-generation alternative to silicon in transistor design. When writing about the sub-10 nm scale Da explains, “MoS_2 preserves all the important properties of silicon with the added advantage of an ultra-thin layer structure…. [allowing] scaling down to 2 nm and… the potential to outperform silicon beyond the 10-nm technology node” (Saptarshi Da). This quote emphasizes the advantages of MoS_2 in outperforming and maintaining normal behavior at extremely small scales, where traditional silicon based transistors begin to fail.

“Chemical Assembly of Atomically Thin Transistors and Circuits in a Large Scale” is a research article by Mervin Zhao, Yu Ye, and colleagues, published in arXiv, exploring the potential of 2D materials in next-generation electronics. Zhao et al highlights the integral fact that “two-dimensional (2D) gapless graphene and semiconducting transition metal dichalcogenides (TMDCs) have emerged as promising electronic materials due to their atomic thickness, chemical stability, and scalability” (Zhao et al). This emphasizes the emerging role of

2D materials such as graphene and MoS_2 in overcoming the limitations of traditional silicon based electronics.

“New transistors: An alternative to silicon and better than graphene”, published on Science Daily and based on research from the Ecole Polytechnique Fédérale de Lausanne, discusses the advantages of molybdenite (MoS_2) as a possible replacement for silicon in small scale electronics, offering the distinct advantage of efficiency, utilizing MoS_2 to create transistors that can consume 100,000 times less energy on standby, absolutely outshining silicon in its power efficiency (Ecole Polytechnique Fédérale de Lausanne).

The evidence from multiple scientific and engineering sources points clearly to the promise of MoS_2 and graphene as the future for transistor miniaturization. Whether in Saptarshi Da’s analysis of MoS_2’s structural advantages, Zhao et al.’s emphasis on the stability and scalability of 2D semiconductors, or the groundbreaking energy efficiency highlighted by the Ecole Polytechnique Fédérale de Lausanne a point is being made. The message is consistent: silicon is reaching the end of its dominance, and it has two very strong contenders for the throne. These alternative materials don't just offer continuity of progress but a substantial leap forward for the design of faster, smaller, and more efficient electronics. If developed strategically and adopted, these materials could power the next generation of technological progress.

While alternative materials like MoS_2 offer a continuation of silicon’s legacy of classical structure in computing, quantum computing represents a radical departure from traditional methods. However, both approaches aim to solve the same foundational issue: the limits imposed by transistor miniaturization. Comparatively MoS_2 is more immediately scalable with existing electronic infrastructure, quantum computing faces implementation hurdles but promises exponentially greater performance for specific applications.

As silicon transistors approach atomic scale dimensions, they face increasing instability due to quantum tunneling, making them unsustainable in the future of high performance computing. These challenges have led to the exploration of a more exotic form of computing: quantum computing, rather than a binary system with errors caused by quantum properties these computers will leverage quantum properties that allow for much faster and more complex computations. This is because they use qubits, which can represent 0 and 1 at the same time, in comparison to bits which can represent only 0 or 1 at a single time. This fundamental difference gives quantum computers the potential to solve problems in minutes that would take traditional computers years. Quantum computers leverage principles like superposition and entanglement to solve complex problems, marking a profound shift in how we solve computational problems, turning a setback into a step forward. (Schneider and Smalley).

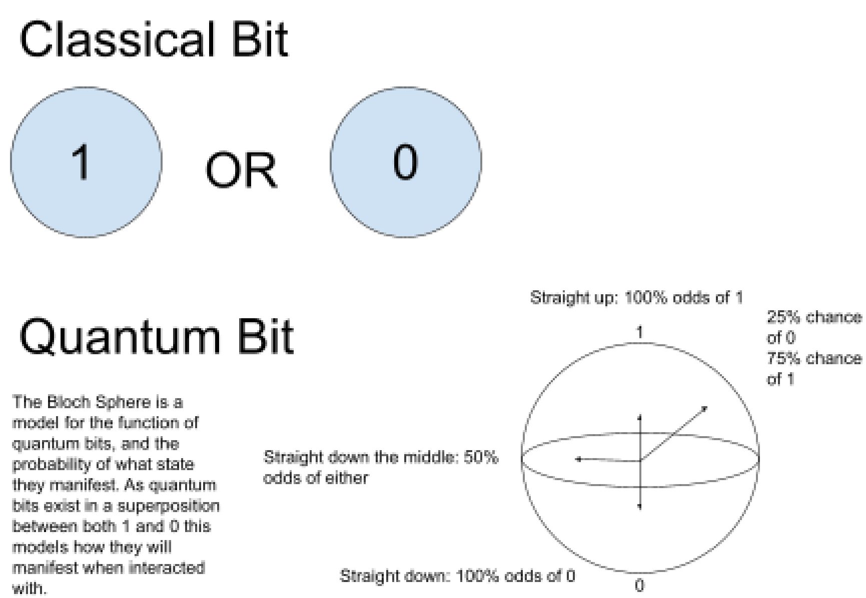


Figure 3: Classical vs Quantum Bits
(Viswanath)

“What Is Quantum Computing?” is an informational article published on the IBM Blog, authored by Josh Schneider, Senior Writer, and Ian Smalley, Senior Editorial Strategist, it outlines the basics of quantum computing and how the technology is equipped to overcome the difficulties of irregular behavior due to the quantum properties of electrons in sub 3nm silicon transistors. They state “By leveraging superposition and

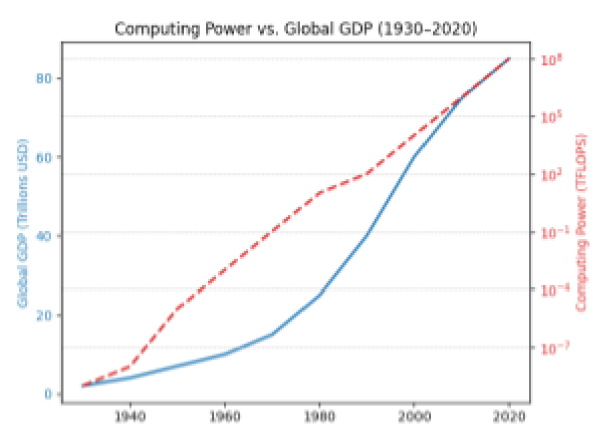
entanglement, quantum computing can perform complex computations in an instant compared to classical systems, potentially solving problems that would take classical computers thousands of years in just minutes" (Schneider and Smalley). Put in simple terms quantum computing can complete processes rapidly compared to regular silicon based computer chips due to their "qubits, which can store combinations of 0 and 1 simultaneously" allowing for "exponential scaling—two qubits can represent four values, and
three can represent eight." (Schneider and Smalley)

The article "Superposition and Entanglement" from Quantum Inspire, an online engineering resource, provides an accessible explanation of key quantum computing principles. The article notably focuses on how superposition and entanglement enable qubits to behave in ways fundamentally different from classical bits, and highlighting that because of that they can be exponentially faster than silicon processors. The author states "The superposition of states in quantum computing enables quantum systems to solve complex problems in parallel, performing many calculations at once, which classical computers cannot replicate" (Quantum Inspire). In other words the property of superposition allows for quantum computers to compute complex problems simultaneously, meaning that as quantum processors scale up they become far faster and more efficient in comparison to traditional silicon processors.

"Quantum Computing Explained," an article by the National Institute of Standards and Technologies, conveys the merits behind utilizing quantum computing as an alternative to traditional silicon based computer chips, highlighting its promise as a powerful tool for all. It's a good beginners concept level resource that explains the basics of quantum computing and its implications globally. Early in the article, NIST introduces the fundamental concept of quantum superposition: “Qubits can exist in multiple states at once, thanks to quantum superposition. This allows quantum computers to process many possible solutions simultaneously, providing a dramatic speed-up for certain types of calculations" (NIST). This quote conveys how quantum computing deviates from the path of traditional binary systems that are comparatively slower than quantum computers. This enables quantum systems to solve complex problems in parallel, dramatically increasing speed and efficiency (NIST). As a result, quantum computers can outperform traditional systems in specific tasks by several orders of magnitude, using complex quantum algorithms to produce huge human interpretable data, based on the properties of entanglement and superposition (NIST).

Quantum computing doesn’t just address the physical limitations of silicon-based systems, it completely reimagines what computers can do, creating a huge paradigm shift redefining limitations as strengths, and leveraging them to create a better future. With the possibility to process more possibilities simultaneously and using entanglement to build tandem systems that will transfer data faster than classical systems can, quantum processors are poised to overtake silicon based processors at every level. As explained by both IBM and Quantum Inspire, this leap in speed and complexity isn't a matter of minor improvements, it's exponential. As we move closer to the era of quantum and the limitations of silicon become more and more apparent, the adoption of quantum systems will be integral to the advancement of technology and to tackle the world's most complex computational challenges.

Moore's law, which has long served as a benchmark and pillar for the advancement of the semiconductor industry, is now reaching its physical limits, leading to economic stagnation. The predictable doubling of transistors



every two years is increasingly difficult to maintain, and as the costs of transistor miniaturization grow, along with R&D , the focus is shifting toward alternatives such as alternative materials and quantum computing. These developments don't just reshape the landscape of computing but also the economy, as most of the world's infrastructure now depends on computing. As industries and investors adapt to the shifting tides, new questions emerge in the value of speed and performance in comparison to accessibility of research on this technology and its development, along with sustainability.

The article, "Moore's Law and Its Practical Implications," written by Gregory Arcuri and Sujai Shivakumar of CSIS explores the immense change of national policy and economic security, along with innovation surrounding Moore's Law. They state that historically "Moore's Law has largely held true into the twenty-first century," yet the progress of transistor miniaturization is beginning to slow (Arcuri and Shivakumar). As "doubling of chip computing power requires a parallel doubling in capital investment," traditional silicon-based R&D is becoming less promising, pushing researchers toward quantum computing and alternative materials (Arcuri and Shivakumar). As the shifting focus of forward thinking investors turns to the future, they reflect on Moore's Law, stating "Moore himself admitted that 'the definition of 'Moore's Law' has broadened to refer to anything related to the semiconductor industry that, when plotted on semi-log paper, approximates a straight line" (Arcuri and Shivakumar) . They explore the fact that while Moore's original prediction may not apply in its strictest form, alternatively that its spirit lives on in the constant iteration and advancement of computing advancements that happen constantly. After all, transistor count isn't the only metric for the complexity and power of a computer system. The authors also propose the more niche reconceptualization of Moore's law, More than Moore, which focuses more on system complexity vs exclusively transistor count. (Arcuri & Shivakumar) If all scientists focused on shrinking old models without innovation, the result would be a more powerful machine with less practical utility. There are hundreds of components that play a part in a computer's speed, and all of them can be bottlenecks. It would be comparatively useless compared to a weaker computer with more real functionality.

In the opinion piece “Better, Faster, Stronger? Tech Titans’ Obsession with Turbocharged Computer Power Could Be Our Downfall” published by The Guardian, columnist John Naughton critiques the arrogance of the tech industry in its blind pursuit of ever-increasing computational power, and argues that this growth is driven by hubris. An example being the premier blue chip investor winner, and wall street's golden boy, the Nvidia Corporation, and their fanatic leader, Jensen Huang’s proclaimed “Huang’s law”(Naughton). It would be very easy to assume that graphics processors being the company's specialty that the law would be a mere copy of Moore's law, being that the amount of transistors in a graphics card would double every 2 years. Instead it poses the overconfident hypothesis that the performance of graphics cards will double every 2 years. This promise to investors has driven individuals and large funds alike to throw money at the company in a speculative frenzy. As Naughton points out, “irrational exuberance about AI took over the tech industry, fuelling a gold rush in which Huang was the premier supplier of picks and shovels, and his company is now the second most valuable corporation on the planet, just behind Apple” (Naughton).

In the article “Can we build a safe and inclusive 'quantum economy'?” published by the World Economic Forum, writer Victoria Masterson explores how quantum technologies can reshape global industries and emphasizes the importance of equitable access through responsible development to close technological gaps. Masterson gives credit to the size of the quantum market, stating “Quantum science and technology currently attracts around $40 billion globally, in research and innovation funding from the public sector; the number is continually rising” (Masterson). He states that quantum technologies impact will be very multifaceted, impacting a variety of sectors from economy, to healthcare, to finance, and even green energy. (Masterson). By stressing the need for collaboration and public awareness, the article conveys that quantum innovation must be pursued not just for the economic benefit but also for the possibility of an increase in quality of life and a global good.

As Moore's law begins to come to stagnation, the push towards alternatives such as different materials and quantum computing signals a new era of computing, leading to a global economic transformation. This shift isn't just technical but deeply economic, affecting research and development costs along with industry practices and education.

For decades, scientific and economic advancements have been propelled by Moore's law. Future computing faces a difficulty when silicon falters owing to quantum phenomena, resulting in unpredictable and unreliable behavior as transistors decrease to the 2-3 nanometer threshold. Because of this, scientists are now investigating substitute materials like MoS_2 and graphene as well as quantum computing, which uses subatomic physics to get around silicon's drawbacks. But this isn't just a technical issue; it also represents a larger change in the global economy and technological advancement. As the limits of silicon-based computing become unavoidable, the next generation of technologies, ranging from quantum to material based, will not simply extend the past but redefine the future.

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