Proceedings of the 4th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/84/20240893

Comparative analysis of silicon and steel technologies: Shaping societal evolution and prospects

Pengcheng Zhang[1,4,5], Jiahong Yang[2,6], Yu Zhai[3,7]

[1]Department of Physics and Astronomy, University College London, London, United Kingdom
[2]Gaoqiao Middle School, Shanghai, China
[3]Zhenhai High School, Ningbo, China
[4]Corresponding author

[5]pengchengz30@gmail.com
[6]jiahongyang0918@163.com
[7]zhaiyu0829@163.com

Abstract. Lives have completely changed in the past few decades in light of the application of integrated circuits which are based on silicon. This paper conducts a comparative analysis of the impact of silicon technology and steel on human societies, both pivotal in advancing social productivity. It delves into their evolution, highlighting the transformation from antiquity to modernity for steel and the maturation of silicon from a natural element to a semiconductor cornerstone. Key developments in steel, such as the Bessemer process and electric arc furnaces, are explored alongside silicon's journey from basic electronic components to complex integrated circuits. The paper also investigates the influence of these materials in various industries, notably the automotive sector, where steel's structural integrity complements silicon's role in digitization and automation. Furthermore, it examines the future prospects of these industries, emphasizing sustainable practices in steel production and the potential of silicon in emerging fields like quantum computing. The analysis aims to underscore the similarities and interplay between the roles of silicon and steel in shaping modern society, providing insights into their enduring significance and evolving applications.

Keywords: Integrated Circuit, Silicon Technology, Steel Industry, Historical Evolution, Semiconductor, Digital Automation

1. Introduction

1.1. Historical Evolution of Steel: From Antiquity to Modernity

The emergence of steel can be dated back to 4000 years ago when steel started to replace bronze and as a more widely used metal due to the higher hardness [1]. During the past thousands of years, the quality of iron mainly depended on ore available, then the production methods, i.e., the productivity became more crucial. By the 1850s, the increasing speed and weight of train traffic were placing extraordinary demands on their railway infrastructure [2].

DOI: 10.54254/2755-2721/84/20240893

Bessemer process, named after Sir Henry Bessemer, an English inventor and engineer, aimed to remove impurities from pig iron by injecting air into molten iron. Oxygen in the air is used to initiate a reaction with the impurities, converting them into oxides which can be separated as slag. This process was conceived independently and almost simultaneously by both Bessemer and William Kelly [3].

After 1890, the Bessemer process began to be progressively replaced by open-hearth steelmaking, and by the mid-20th century, it was completely obsolete [4].

By 1900, the electric arc furnace had been modified for use in steelmaking, and by the 1920s, the decreasing consumption of electricity enabled it to largely supplant the crucible process for producing specialty steels [5].

In the 1910s and 1940s, the two world wars were imposing a higher demand on steel which is essential to manufacture cars, tanks, artillery, ships, and aircrafts [6-7].

During the post-war era, steel still plays an indispensable role in several industries and people's daily life [8].

1.2. The Evolution of Silicon: A Material Transformed

Similar as iron, silicon is also one of the most abundant elements in the crust of Earth. It can be found in various forms, including quartz, sand, and various minerals. It had not been isolated until 1823, but it does not imply a short history.

Before silicon was isolated by Jöns Jacob Berzelius, people used silicon compounds for various purposes, including making glass and jewelry. After that, further studies concerning its properties and ability to form compounds with other elements were studied by scientists. In the late 19th century, applications of silicon began to expand, especially in the field of metallurgy, where it was utilized as an alloying element to enhance the properties of iron and steel [9].

In 1940s, with the development of semiconductor industries, scientists found silicon's distinctive electrical characteristics which could be used in many electronic components. In the mid-20th century, the electronic devices were still using discrete transistors. The devices at that time were bulky and consumed much power. Thus, people were seeking a solution which is more efficient.

In 1958, Jack Kilby, an engineer at Texas Instruments, had the idea of combining multiple electronic components onto a single semiconductor material, which led to the creation of the first integrated circuit. He used germanium as the semiconductor material to make this invention possible [10].

Concurrently, Robert Noyce, co-founder of Fairchild Semiconductor and Intel, developed a similar concept. Noyce's used silicon as the semiconductor material. His design had the advantage of being more scalable and suitable with mass production [11]. Thus, he was nicknamed the Mayor of Silicon Valley.

Nowadays, silicon still plays a pivotal role in various technological areas. It is widely used in the semiconductor industry since it is the fundamental material to produce chips.

2. Steel Industry and its prospects

2.1. The definition of steel

Steel is an alloy made of iron combined with other elements, among these, the most common element is carbon, which in today's society is also one of the most widely used metal materials. At the same time, the carbon content also determines its different properties and possible uses. In addition, there are alloy steels made by combining iron with other metal elements such as manganese, chromium, vanadium, and tungsten [12]. For the most common carbon alloys, high carbon content means good ductility and cross-hardness, while low carbon steel means excellent hardness, as well as good rust resistance and weldability, but poor ductility. These carbon or other metallic elements in the bonding of iron act as hardeners, preventing the dislocation from moving. In pure iron, the crystal structure is less resistant to the sliding of iron atoms, which leads to strong ductility.

2.2. The origin of the steel

At the beginning of the development of steel, bloomery and crucibles were used to assist in iron making. The most obvious role in this is the crucible. The crucible dates to the fifth or sixth millennium BC in Iran and Eastern Europe [13]. Crucible in the following stone, Bronze, Iron Age, and until the 17th century was gradually replaced by blast furnace steelmaking. Crucible in the smelting of alloy technology in the Roman period had a breakthrough. The shape of the crucible became round or conical, very similar to the modern style. These designs gave greater stability within the charcoal [14]. In this period, the cementation process appeared, initially applied to the refining of bronze alloys, but later similar methods were applied to the refining of steel.

2.3. Modern steelmaking technology

As time went by, until the 17th century, Europe's steelmaking technology entered an era of leap development, which was due to the large demand for steel and related technological breakthroughs brought about by the economy, population, and industrial revolution. From the initial crucible steelmaking to the later Bessemer converter steelmaking method, followed by the open-hearth steelmaking method, and finally, the electric arc furnace and basic oxygen steelmaking that dominate the modern ironmaking process. Among them, the most promising, the most advantageous should be electric arc furnace.

2.4. Development and practical application of electric arc furnace

Since the 19th century, many people have begun to study arc steelmaking technology. From Sir Humphry Davy's first public demonstration, various scientists continued to improve the research over the next few decades, and Sir William Siemens applied for a patent for it. It was not until 1888 that James Burgess Redman invented the first working electric arc furnace, although it was used to produce phosphorus [15-16]. Commercialization came in 1907, when the Sanderson Brothers Steel Company began using the first electric arc furnace. But it was not until the end of the Second World War that electric arc furnaces began to be used on a real scale, and at the same time it greatly reduced the production cost of steel mills. However, it is mainly used in the manufacture of long products, and others such as heavy steel plates are still manufactured by alkaline oxygen furnaces. After the first generation of electric arc furnaces came out, the recovery rate of scrap steel increased greatly, because electric arc furnaces can theoretically make steel from 100 percent of scrap metal raw materials.

2.5. The prospects of steel

For the steel industry, the general trend of future development must be towards green environmental protection development and comprehensive realization of intelligence. As the era of heavy industrialization became history, people got rid of the disadvantages of relying on steel to develop the economy. Therefore, the protection of the environment is put on the agenda. Due to the serious pollution caused by conventional steelmaking methods such as coke, people have focused on reducing toxic emissions and reducing energy consumption, and the mentioned electric arc furnace is a good solution. At the same time, with the advent of the information age, the steelmaking industry will no longer need a large number of labors to operate the machine, which can greatly reduce the cost and improve the speed of operation, but also reduce the risk in the process of steelmaking.

3. Silicon Industry and its prospects

3.1. Early Silicon Pioneering

In the mid-20th century, people discovered silicon's incredible potential as a semiconductor. Engineers and scientists began to make transistors and diodes by using silicon. Until this innovation, electronics were primarily dominated by the bulky and inefficient vacuum tube technology. It promoted a revolution in technology, which reduced the size of electronic components and finally leaded to the modern computing era [17].

3.2. Moor's Law and Precision Scaling

Moor's Law, a fundamental principle in the semiconductor realm, boldly asserted that the count of transistors on a single chip would double roughly every two years. It was proposed by Gordon Moore who held the position of Director of Research and Development at Fairchild Semiconductor in 1965 [18]. This audacious prediction became a reality through unwavering dedication to meticulously reducing the dimensions of transistors. The journey took us from measurements in micrometers to the exquisite precision of nanometers. As a result, contemporary cutting-edge chips now proudly host transistors in the astonishing single-digit nanometer range, unleashing computational capabilities that were once unimaginable.

3.3. The Rise of 3D Stacking for Performance Enhancement

In pursuit of increased performance and efficiency, engineers embarked on a journey of innovation, investigating thoroughly the realm of three-dimensional stacking techniques. This ingenious approach involved the strategic layering of multiple semiconductor chips atop one another, meticulously interconnected through cutting-edge packaging technology [19]. This breakthrough not only dramatically boosted processing power but also substantially expanded memory capacity, all achieved within a remarkably compact physical footprint.

3.4. Exploration of Diverse Semiconductor Materials

While silicon continues to be the foundation of semiconductor manufacturing, researchers have sought alternative materials like gallium arsenide and silicon carbide. These materials show distinctive properties that render them exceptionally suitable for some specialized applications, especially in the domains of high-frequency and high-power devices [20]. This innovative approach is charting new horizons in semiconductor technology.

3.5. Cutting-Edge Semiconductor Packaging Techniques

Emphasizing the critical role of packaging in safeguarding and optimizing semiconductor performance cannot be overstressed. Recent breakthroughs in packaging technology have resulted in solutions specifically designed to tackle challenges related to thermal management, signal integrity, and efficient power delivery. These advancements are instrumental in ensuring the unwavering reliability and seamless functionality of integrated circuits across a diverse array of environmental conditions.

3.6. Quantum Computing and Silicon's Leading Role

Beyond the realm of classical computing, silicon technology stands at the forefront of the rapidly advancing field of quantum computing. Researchers are harnessing silicon-based platforms to delve into the potential of achieving computational paradigms that are exponentially faster and more efficient. This exploration holds the promise of ushering in revolutionary changes across industries, from cryptography, where security could be transformed, to material science, where discoveries could be accelerated.

3.7. Sustainable Technology and Enhanced Energy Efficiency

As the global pay more attention on environmental issues, the semiconductor industry is taking more proactive steps to reduce the environmental footprint of semiconductor manufacturing, optimize energy consumption, and develop energy-efficient devices, which aim at achieving global sustainability goals.

4. Common Contributions

4.1. Automotive industry

The steel industry paves the foundation of vehicular structural integrity, ensuring passenger safety, and furnishing robust engines, while the silicon industry propels the digitization of vehicles [21-23]. An important component within modern vehicles is the Electronic Control Unit (ECU), which organizes a vast array of functionalities. At the heart of the ECU are microprocessors and microcontrollers, predominantly crafted using silicon technology. These silicon-infused chips meticulously process data harvested from an extensive network of sensors and execute commands to govern various vehicular systems. Silicon-based constituents such as Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) and voltage regulators are quintessential in ECUs, proficiently managing and disbursing power, thereby ensuring the seamless operation of all electronic systems within the vehicle [24-25]. This integration enables drivers to customize driving modes. For instance, in a sports mode, the ECU orchestrates a more agile but energy-intensive driving experience, and vice versa.

Silicon technology extends its tentacles into the realm of sensor fabrication, engendering a suite of sensors that convey critical data to the ECU. Micro-Electro-Mechanical Systems (MEMS) sensors, rooted in silicon technology, are deployed to gauge variables like pressure, temperature, and acceleration, forming a data nexus indispensable for the ECU's real-time decision-making process [26-28].

Delving into the autonomous driving frontier, silicon-based chips and processors emerge as the linchpins in autopilot systems' operation. Tesla, a vanguard in the autonomous vehicle arena, is renowned for architecting its own silicon, a venture aimed at propelling its Artificial Intelligence (AI) and self-driving technologic prowess [29]. Through silicon technology, a bridge is built between the physical robustness accorded by steel and the digital acumen ushered in by silicon, embodying a symbiosis that drives the automotive industry's evolution into an era of enhanced safety, efficiency, and automation.

5. Conclusion

Comparing the impact of silicon technology to that of steel on human societies reveals intriguing parallels and divergences in their historical evolution and contemporary prospects. Steel, with its ancient origins and crucial role in shaping infrastructure and industries, has been the cornerstone of societal progress for millennia. Its evolution, from bloomery and crucible methods to modern electric arc furnaces, underscores its enduring significance. In contrast, silicon's journey as a transformative material has been relatively brief but exceptionally influential. Initially employed in metallurgy to enhance the properties of iron and steel, silicon found its true calling as a semiconductor in the mid-20th century. The advent of integrated circuits, pioneered by Jack Kilby and Robert Noyce, catalyzed a technological revolution, shrinking electronic components and ushering in the era of modern computing.

The automotive industry exemplifies the complementary roles of steel and silicon; steel provides the structural integrity and durability necessary for vehicle construction, while silicon drives the technological advancements, enhancing vehicle performance, safety, and efficiency. Through innovations like Electronic Control Units (ECUs) and autonomous driving technologies, the collaboration between steel and silicon is enabling a new era of smart, efficient, and environmentally friendly transportation solutions.

Looking ahead, both industries face distinct trajectories. Steel seeks a more environmentally sustainable future, reducing emissions, conserving energy, and embracing automation. In contrast, silicon technology remains at the cutting edge of quantum computing, promising exponential advancements in computational capabilities.

The steel and silicon industries, while divergent in their historical paths, stand as testaments to human innovation. Steel symbolizes the enduring foundations of society, while silicon represents the ever-evolving frontier of technology. Together, they continue to shape our world, reflecting the dynamic interplay of tradition and progress.

References

[1] Bell, T. (2020, August 21). The history of steel. ThoughtCo. https://www.thoughtco.com/steel-history-2340172
[2] David Brooke, "the Advent of the Steel Rail, 1857-1914," Journal of Transport History (1986) 7#1 pp 18-31
[3] Britannica, (2019, August 27). Bessemer process. Encyclopedia Britannica https://www.britannica.com/technology/Bessemer-process

[4] Lloyd-Jones, R., & Lewis, M. J. (1998). British industrial capitalism since the Industrial Revolution. UCL
[5] Milward, A. S., & Saul, S. B. (2012). The development of the economies of continental Europe 1850-1914. Routledge
[6] The National Archives. End of the First World War. https://www.nationalarchives.gov.uk/cabinetpapers/themes/end-of-the-first-world-war.htm
[7] Federal Steel Supply. (2014, December 10). The Role of Steel in WWII and Beyond. https://www.fedsteel.com/insights/role-steel-wwii-beyond/
[8] Kim, J., Sovacool, B. K., Bazilian, M., Griffiths, S., Lee, J., Yang, M., & Lee, J. (2022). Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science, 89, 102565. https://doi.org/10.1016/j.erss.2022.102565
[9] Segal, M. (2012). Material history: Learning from silicon. Nature, 483, S43–S44. https://doi.org/10.1038/483S43a
[10] Deffree, S. (2019, September 12). Kilby demonstrates the 1st IC, September 12, 1958. EDN. https://www.edn.com/kilby-demonstrates-the-1st-ic-september-12-1958/
[11] Benson, D. K., & Kessler, J. F. (2018). The silicon chip. Nature Electronics, 1(9), 512–514. https://doi.org/10.1038/s41928-018-0145-6
[12] Ashby, M. F., & Jones, D. R. H. (1992). Engineering Materials 2 with corrections. Pergamon Press. (Original work published 1986)
[13] Pigott, V.C. (1999). The Development of Metal Production on the Iranian Plateau: An Archaeometallurgical Perspective. In V.C. Pigott (Ed.), The Archaeometallurgy of the Asian Old World (pp. 73-106)
[14] Bayley, J., & Rehren, T. (2007). Towards a functional and typological classification of crucibles (pp. 46-55). Archetype Books
[15] Redman, J. B. (Inventor). (1889, December 24). Process of manufacturing phosphorus (U.S. Patent No. 417,943). United States Patent and Trademark Office. https://patents.google.com/patent/US417943A
[16] Toy, A. D. F. (1973). The Chemistry of Phosphorus (1st ed., Vol. 3). Pergamon Texts in Inorganic Chemistry. Elsevier
[17] Computer History Museum. 1953: Transistorized Computers Emerge. The Silicon Engine. https://www.computerhistory.org/siliconengine/transistorized-computers-emerge/
[18] Britannica, (2023, September 29). Moore's law. Encyclopedia Britannica. https://www.britannica.com/technology/Moores-law
[19] Cheng-Ta Ko, & Kuan-Neng Chen. (2010). Wafer-level bonding/stacking technology for 3D integration. Microelectronics Reliability, 50(4), 481-488. https://doi.org/10.1016/j.microrel.2009.09.015
[20] All About Circuits. (2019, August 23). Gallium Arsenide: Another Player in Semiconductor Technology. https://www.allaboutcircuits.com/news/gallium-arsenide-another-player-in-semiconductor-technology/
[21] American Iron and Steel Institute. Automotive. Retrieved October 11, 2023. https://www.steel.org/steel-markets/automotive
[22] AZoM. (2016, January 14). The Future of Steel In The Automotive Industry. AZoM.com. https://www.azom.com/article.aspx?ArticleID=10538
[23] Bharat Steels. (n.d.). Role Of Steel In The Automobile Industries. Retrieved October 11, 2023, from https://www.bharatsteels.in/blog/role-of-steel-in-the-automobile-industries/
[24] Xu, S., Huang, A. Q., Lucía, Ó., & Ozpineci, B. (2017). Review of Silicon Carbide Power Devices and Their Applications. IEEE Transactions on Industrial Electronics, 64(10), 8193-8205. https://doi.org/10.1109/TIE.2017.2652401
[25] Ding, X., Cheng, J., & Chen, F. (2017). Impact of Silicon Carbide Devices on the Powertrain Systems in Electric Vehicles. *Energies, 10*(4), 533. https://doi.org/10.3390/en10040533

[26] Esashi, M. (2021). MEMS development focusing on collaboration using common facilities: A retrospective view and future directions. *Microsystems & Nanoengineering, 7*(60). https://doi.org/10.1038/s41378-021-00290-x
[27] Abdelghani, L., Nasr-Eddine, M., Azouza, M., Abdellah, B., & Moadh, K. (2014). Modeling of silicon MEMS capacitive pressure sensor for biomédical applications. In *2014 9th International Design and Test Symposium (IDT)* (pp. 263-266). Algeries, Algeria. https://doi.org/10.1109/IDT.2014.7038625
[28] Nemec, D., Janota, A., Hrubos, M., & Šimák, V. (2016). Intelligent Real-Time MEMS Sensor Fusion and Calibration. *IEEE Sensors Journal, 16*(19), 1-1. https://doi.org/10.1109/JSEN.2016.2597292
[29] Talpes, E., et al. (2020). Compute Solution for Tesla's Full Self-Driving Computer. *IEEE Micro, 40*(2), 25-35. https://doi.org/10.1109/MM.2020.2975764