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Flexible Silicon: Status, Opportunities, and Challenges

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Abstract— **The rise of the Internet of Everything has spurred the need for flexible and stretchable electronic devices, particularly in biomedical applications. Monocrystalline silicon, a key material in the semiconductor industry, must be adapted to meet these demands. This article explores various thinning techniques to fabricate flexible silicon wafers, methods for transferring silicon to flexible substrates, and the importance of enhancing silicon's stretchability. Furthermore, it discusses the impact of flexible silicon on sectors such as biomedical sensing, electronics, and power systems, highlighting the role of the Internet of Things (IoT) platform in interconnecting devices. Finally, the article examines current progress and future prospects in flexible silicon technology, paving the way for further advancements in this rapidly evolving field.**

Index Terms— **Flexible Electronics, Flexible silicon, Ultra-thin chips fabrication, progression**

I. INTRODUCTION

With the rapid advancements in technology, we saw the growth of the Internet of Things, where many devices became interconnected. Today, we see a growth in the Internet of Everything, where data, hardware, and living beings are being integrated. Electronic devices are being placed inside the human body to record and transmit data and assist in the organs' proper functioning. When such devices are placed under the skin, and near various other organs, they need to confirm to the movement of the region they reside in, i.e, they need to bend and stretch as well [1]. This is where the need for smaller, thinner, and flexible electronics arises. Most devices today are made of bulk monocrystalline silicon. While it is not naturally the most optimal semiconductor, many studies and investments have gone into using this in CMOS technology. This makes it the best material to utilize today.

CMOS has helped realize Moore's law over the last few decades, consistently improving upon device density, switching speeds, reducing delays, all while keeping the power dissipation energy low. Various lithographic techniques have made it possible to fabricate high precision metal patterns.

Instead of making the chips flexible themselves, we can also place rigid chips on a flexible substrate. This is done in practice and these devices are said to be semi-flexible. In such cases, the radius of flexibility is constrained by the chip dimensions. This radius of curvature can be further reduced by making the chips thinner and flexible themselves. Additionally, a neutral axis of bending is created at the interface when the substrate and the chip are of similar thickness. In this region, there is no stress induced, making it easier to find a bonding agent.

A. Progression and Current Status

Silicon, as a bulky rigid material, has been in use for thousands of years, for various purposes. It included making beads and vases, silica in glass, etc. It was only in the late 19th and early 20th century that it began to be used to make semiconductors and led to the start of the Digital Age. Today, silicon is used in every aspect of our lives, from the electronic devices we use, to the biomedical implants placed inside us. To appreciate the current status of flexible silicon devices, and to predict future trends, we must study how flexible silicon came to be developed, and the various fields it has impacted along the way. In this section, we start from the first flexible substrate that was made and talk right up to some of the latest discoveries.

As space exploration gained momentum in the mid-20th century, a need arose for lightweight power sources to replace bulky, traditional systems. Solar power emerged as an ideal solution, leading to research on thin crystalline solar cells. In the 1970s, NASA designed lightweight, flexible solar cells using Teflon [2], which provided durability and stability across various temperatures. During this time, small silicon solar cells were used in handheld calculators, and polycrystalline silicon ribbons [3] achieved 5% conversion efficiency. In the 1980s, amorphous silicon on flexible substrates resulted in 9% conversion efficiency [4].

Lightweight solar cells remained the major focus for the thin silicon industry until the mid 1980s. In the mid-1980s, thin silicon was studied for flexible integrated circuits (ICs) and biomedical applications. One notable study involved using silicon ICs for cancer treatment via hyperthermia [5]. Flexible polyimide (PI) substrates and gold interconnects were used to create these devices.

Later, in 1997, the first micro-electromechanical system (MEMS) shear stress sensor [6] was developed for skin application, using Si islands connected by PI films. Research also explored flexible silicon for retina implants in the human eye [6]- [7]. Thin silicon islands were connected by flexible silicon bridges, with bridges sometimes perforated for increased flexibility. As innovations progressed, MEMS systems were fabricated using complementary metal-oxide semiconductor (CMOS) circuits at low temperatures for compatibility. These systems were divided into functional

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blocks placed on separate islands.

In the early 2000s, researchers focused on using thin, flexible silicon to develop transistors and microprocessors [8]–[11]. Often, but not always, these devices used crystalline silicon. New fabrication methods allowed for thinner and more bendable silicon wafers. In 2004, a breakthrough was achieved with flexible, visible light-transparent transistors made using amorphous silicon oxide semiconductors [10].

By 2005, a technique called selective transfer of micro-structured silicon was gaining traction. This involved using a specific type of stamping on Silicon-on-Insulator wafers [9]. Later, an 8-bit microprocessor [12] was fabricated using low-temperature technology, improving upon previous designs. In 2006, a flexible silicon-based microelectrode was successfully implanted in a rat’s brain [13]. Another development involved using low-temperature polysilicon in active-matrix organic light-emitting diode displays [14], showcasing high performance and resolution. In 2008, researchers created intelligent textiles [15] by integrating silicon islands on a substrate. Compatible with standard technologies, these islands were connected using metal wires. The resulting material could bend, twist, and stretch, making it suitable for applications like health monitoring.

Later, polysilicon technology was used to create an 8-bit central processing unit for radio frequency integrated circuits in RFID tags [11]. The flexible material allowed for manual bending and offered benefits such as lower power consumption. In 2010, a high-performance transistor was developed using a silicon nanomembrane [16]. With a maximum frequency of 12 GHz, the device enabled high-speed operations while maintaining performance during bending.

Over the past decade, flexible silicon technology has made remarkable strides in various applications. In 2013, a flexible silicon-based thermal energy harvester was developed [17], demonstrating improved efficiency and reduced power consumption compared to traditional devices. This innovation paved the way for the exploration of thin and bendable materials in the field of electronics. In 2015, researchers made advancements in solar cell technology by developing an ultrathin solar cell with single crystal silicon [18]. When bent into a concave shape, this cell trapped more light, leading to a significant increase in conversion efficiency compared to flat cells.

The medical field also benefited from advancements in flexible silicon technology. In 2017, an ultrathin silicon dioxide layer was used in cardiac electrophysiology [19], providing a stable and biocompatible barrier for medical devices within the body. Moreover, flexible silicon contributed to the development of stretchable micro light-emitting diodes (microLEDs), showcasing the versatility of this technology. As smart electronics gained popularity, researchers shifted their focus to smaller and thinner solar cells suitable for wearable devices. In 2019, the first flexible photodetectors using hyperdoped sulfur on ultrathin silicon [20] were developed. These devices exhibited strong potential for various applications due to their broadband response to visible and infrared wavelengths, light trapping structures, and stable electrical performance when bent. Numerical simulations during the same year demonstrated that 15μm crystalline silicon solar cells with inverted micro pyramid structures and interdigitated contacts [21] could potentially achieve over 30% power conversion efficiency, marking a significant milestone in solar cell technology. In 2021, a thin solar cell was designed to fit commercial contact lenses [22], offering transparency and efficiency under indoor lighting conditions. This innovation has significant implications for the future of wearable technology and renewable energy harvesting. Furthermore, flexible silicon technology has also contributed to advancements in acetone detection. Silicon nanowires fabricated on a thin layer demonstrated the ability

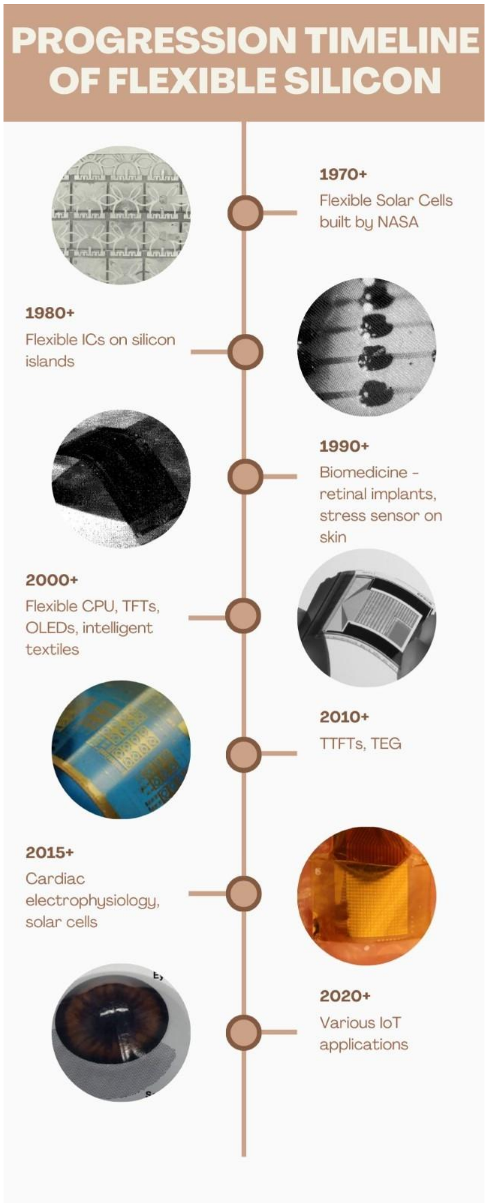

Fig. 1. Timeline showing the progression of Flexible Silicon.

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to detect low concentrations of harmful acetone [23], with improved performance when bent. The compatibility of these sensors with standard processes in the electronics industry makes them promising candidates for various applications.

We can see that flexible silicon has come a long way since interest was first created in it, in the 1960s. With the growing popularity of wearable electronics, and requirements in the biomedical, and other industries, we can expect to see many more methods to enhance and improve the properties of thin silicon wafers, as well as gaining new opportunities in several different applications.

II. FABRICATION

Silicon wafers are generally of much greater thickness than is needed to be able to bend and stretch it, to give it its flexible properties. For this, various fabrication techniques have been developed over the years, making the final wafer obtained thinner, to below 50µm. We start this section with a broad classification of these techniques. Next, we discuss some methods to transfer this thinned silicon to other flexible substrates, as the situation may demand. A few specific examples of the latest fabrication techniques have been covered as well. The last section of the chapter covers stretchability, a mechanical property similar to flexibility that is desired in silicon.

A. Fabricating Thin Silicon

There are several ways to obtain thin wafers of silicon on a flexible substrate. These can be classified as shown in Fig.2.

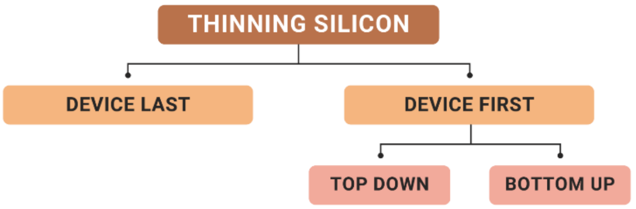

Fig. 2. Classification of methods to obtain flexible silicon devices.

In the device last approach, a layer of silicon is first thinned down, and placed on a flexible substrate. After this, the device is fabricated directly on the substrate in post processing steps. Using Silicon on Insulator (SOI) substrate is one such common method to obtain thin, flexible monocrystalline silicon. This process is easy to implement, is not expensive, and takes place at low temperatures. However, a considerable amount of silicon is lost. In addition, any post-processing steps must take place at low temperatures as the substrate cannot often withstand heat. More complex metallization and contacts cannot be designed either.

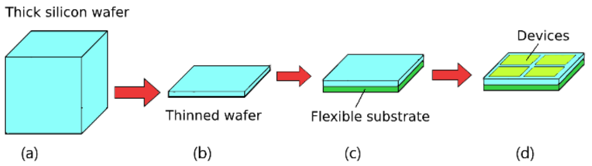

Fig. 3. Device-last approach. (a) a thick wafer of silicon is used as the starting material. (b) the thick wafer is thinned down using various methods to obtain a thin, flexible wafer of silicon. (c) the thin wafer is bonded to a flexible substrate. (d) devices are fabricated on the silicon in the last step.

In the device first approach, the device is first fabricated on silicon. This is then thinned down and transferred to the destination substrate. This can be further divided into two methods - the top-down method and the bottom-up method.

In the top-down method, the fabricated device is removed as a silicon layer and placed on the destination substrate. The device can be fabricated at high temperatures, but post fabrication, only low temperatures are required. One method here is the trench-protect-etch-release (TPER) method. This allows you to control the thickness of silicon, and makes the wafer semi-transparent, hence making it useful in optical applications, such as LEDs. It also supports 3D architectures to be built. In another such process, called the SlimCut Process, the wafer is fractured parallel to the device surface and removed. This is used to make CMOS logic circuits and photovoltaic cells.

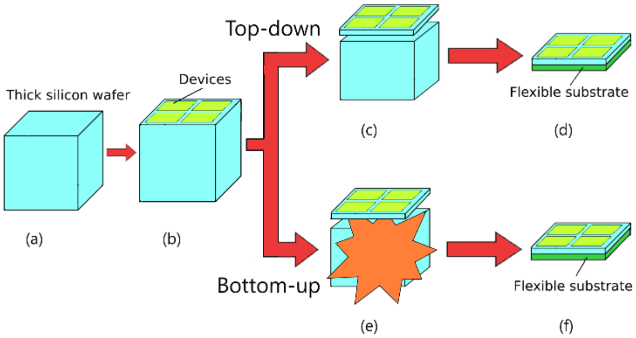

Fig. 4. Device-first approach (a) a thick wafer of silicon is taken as the starting material. (b) the devices are fabricated at the top of the thick wafer. (c) taking the top-down approach, the fabricated device is removed as a silicon layer. (d) the layer is placed on the destination substrate. (e) taking the bottom-up approach, the excess silicon is removed/destroyed to obtain a thin silicon layer with the devices. (f) the thin layer is placed on the destination substrate.

In the bottom-up approach, the silicon substrate has the device at the top and the excess silicon is removed from the bottom to form a thin layer. This is then transferred to the destination substrate. For larger coarse removal, mechanical grinding is used. For finer, more precise removal, chemical etching is used. Chemical Mechanical Process (CMP) uses

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both these methods to etch at speeds faster than chemical processes alone, but with better precision than back grinding.

B. Handling, Transfer and Bonding

Thinned silicon wafers are too weak to be used on their own and need to be bonded to a substrate. For this, both the bonding agent and the destination substrate need to be flexible as well.

A carrier substrate provides support to the thinned silicon wafer that needs to be transferred in the device last approach, or when the top layer is removed during grinding in the bottom-up approach. Often, polydimethylsiloxane(PDMS) is used as the carrier substrate. Some methods to transfer silicon include the transfer printing process, the flip-chip technique, controlled spalling technique, etc. The TPER method discussed earlier does not need any handler substrates.

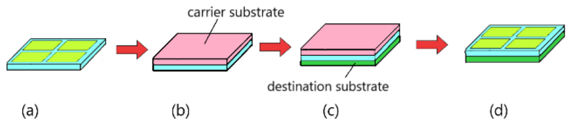

Fig. 5. Transfer of a flexible silicon device. (a) a thin silicon wafer has been obtained. (b) a carrier substrate is bonded to the wafer. (d) a destination substrate is bonded to the wafer. (d) the carrier substrate is removed, giving the desired final product.

Destination substrates play an important role in the properties of the final device being fabricated. Some desirable features of these substrates are: high flexibility, high chemical tolerance, lightweight, easily manufactured in bulk, non-toxic for bio-medical and wearable applications, transparent for photovoltaic applications, preferably thermally conductive and the coefficient of thermal expansion (CTE) must be close to silicon in the operating temperatures. The CTE match between the two materials is particularly important since any mismatch could result in the formation of mechanical stress, leading to cracks, delamination, or peeling off layers [24]

Bonding materials are ones that help keep the thinned silicon in place on the destination substrate. Their properties influence the final device as well. The properties an ideal bonding material must possess includes; controllable stiction with silicon, transparency, chemical resistance, thermal stability, and conduct heat from silicon substrate to destination substrate.

SU-8 photoresist is a commonly used bonding material. It forms large 3D molecules that make it mechanically and chemically stable. They are also thermally stable and chemically inert to most solvents.

PDMS can also be used as a bonding material. The process to prepare this varies from the process to prepare it as a destination substrate. Kapton tapes are inexpensive and easy to use. However, only the parts covered in tape have low stiction, and this adhesive nature is not controllable.

TABLE I

DESTINATION SUBSTRATES

Substrate	Advantages	Disadvantages
Polymer-based plastic substrates (PEN, PET)	Good chemical resistance Mechanical flexibility Transparent Non-toxic Inexpensive for bulk fabrication	Mechanically unstable at high temperatures Low CTE
Polyimide (Kapton)	Higher glass transition	Not transparent PDMS has large CTE
Glass Foils	Trent in Transparent in visible region Chemical resistance Non-toxic CTE similar to silicon Largely temperature resistant visible	Very fragile
ITO	Transparent	Expensive

C. Latest Trends in Fabrication

In this section, we will discuss a few of the latest techniques and methodologies to fabricate thin silicon wafers to obtain the required mechanical properties.

1) *Growth of Ultrathin Silicon Wafer via a Self-releasing Seed Layer:* A new bottom-up approach has been proposed as a waste-free alternative in the thinning process of flexible silicon [25]. This method employs plasma-assisted epitaxial growth of silicon to generate controlled nanogaps that serve as separation planes. In this process, nanoscale voids are deliberately induced in the plasma-epitaxial silicon when grown on a high-quality crystalline silicon substrate. These voids are manipulated to form a nanogap, which acts as a designated separation plane. The surface produced serves as a suitable seed layer for subsequent high-temperature epitaxy (HTE) growth. The technique demonstrates that profiled gas flow performs better than constant gas flow, as the latter leads to more crystalline distortions. The resulting wafers have a thickness of $50\mu m$.

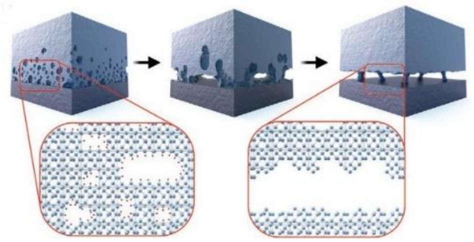

Fig. 6. Separation of a thin wafer of silicon via the formation of a self-releasing layer. Reproduced with permission [25].

This approach has several advantages:

- Substrate Reusability: The substrate can be reused, potentially decreasing waste and costs.
- Reduced Diffusion Issues: The process experiences minimal diffusion-related problems.
- Improved Material Quality: The method avoids impurity diffusion into the substrate, contributing to enhanced bulk material quality.

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In summary, this novel bottom-up approach introduces a waste-free alternative for fabricating flexible silicon, with potential applications in various industries, such as flexible electronics and solar cells. Further research and development may explore its efficacy and scalability.

2) *By crystal-ion-slicing using BCB Bonding Layer:* A new hydrogen ion implantation method has been introduced for creating flexible silicon [26]. This approach involves bombarding a silicon substrate with H^+ ions, which become implanted at a specific depth beneath the surface. The depth of implantation increases linearly with the energy of the ions. Subsequently, a polyimide layer is deposited, and a BCB bonding layer is spin-coated onto the surface. The structure is then annealed, causing the hydrogen ions to form H_2 molecules, creating holes within the substrate. As the H_2 molecules expand, the holes enlarge, eventually separating the upper layer from the rest of the substrate.

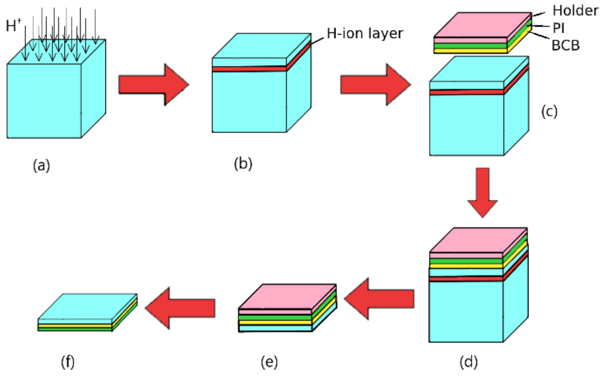

Fig. 7. Crystal ion slicing to form thin silicon. (a) a thick silicon wafer is bombarded with H^+ ions. (b) a layer of H^+ ions is formed at a certain depth, depending on the energy of the bombarded ions. (c) a holder, with polyimide substrate and BCB bonding layer is bonded to the wafer. (d) the structure is annealed in vacuum at 400 ^{o}C. (e) the H^+ ions combine to form H_2 molecules and separate from the bulk wafer. (f) the holder is removed. (g) the required final wafer is obtained.

This method has successfully produced 1 μm thick wafers. The resulting thin film exhibits good quality and flexibility, with no significant holes or cracks and a bending degree of 3 cm. However, this technique relies on hydrophilic bonding, which requires initial substrates with very flat surfaces, potentially limiting its applicability. In summary, this novel hydrogen ion implantation method presents an alternative approach to fabricating flexible silicon, with potential applications in various industries. Further research and development may explore its efficacy and potential solutions to address the limitations posed by the hydrophilic bonding requirement.

3) *Exfoliation of Thin-Film Transistors from Bulk Wafer:* A new wafer-scale exfoliation method has been developed to produce thin silicon wafers for flexible electronics [27]. This approach involves fabricating devices on a bulk silicon wafer and depositing a plasma-enhanced chemical vapor deposition (PECVD) silicon nitride film as an isolation layer. A nickel seed layer is evaporated and electroplated on top, followed by mechanical exfoliation of the top silicon layer.

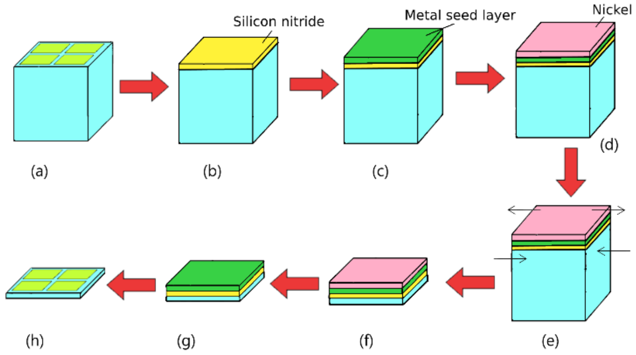

Fig. 8. Exfoliation of thick wafers. (a) devices are fabricated on a thick silicon wafer. (b) silicon nitride is deposited on the surface of the wafer. (c) a metal seed layer is deposited. (d) a layer of nickel is deposited using electroplating. (e) the top and bottom layers are placed under stress as indicated. (f) the film is exfoliated from the wafer. (g) the nickel foil is removed. (h) the other layers are removed to obtain the final device.

This process results in wafers with thicknesses ranging from 10 to 80 μm. The method exhibits a slightly lower saturation current and gate leakage voltage compared to traditional techniques. It also offers several advantages, as listed below.

- Speed and simplicity: The process is fast and straightforward.
- Temperature flexibility: The operating temperature is not limited by plastic substrate constraints.
- High-quality crystals: The method produces high-quality silicon crystals.
- Enhanced substrate ruggedness: Residual strain improves the substrate’s durability and yield.
- Minimal transistor degradation: No significant degradation of transistor characteristics is observed.

In summary, this high-yield silicon wafer exfoliation method provides an efficient and effective approach to fabricating flexible electronics. Further research and development may explore its potential applications in various industries and optimize its performance.

D. Stretchability

The bendability of a substrate alone is not enough for most flexible applications. When stress is applied laterally, the strain experienced depends on the mechanical properties of the lattice. Organic semiconductors are made of long entangled chains of polymers that align themselves when stretched, making them inherently stretchable. However, they do not

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have very good conductive properties. Hence, we use them along with other compounds that show good electrical properties. However, in many semiconductors, the strain causes a change in bandgap, leading to changes in its electrical properties. This must be taken care of while designing structures that are stretchable.

Monocrystalline silicon, on its own, is a brittle and stiff material. It must be used in conjunction with a more stretchable substrate to gain deformability. This integration with a suitable substrate can considerably alter the mechanical properties of intrinsic silicon. This can be seen from the stress-strain studies for monocrystalline silicon [28], which demonstrate the brittle nature of intrinsic silicon. On the other hand, Silicon-on-Polymer strain gauges [29], and other stretchable electronics on PDMS substrates [30] have been developed and show significantly better stretchable nature.

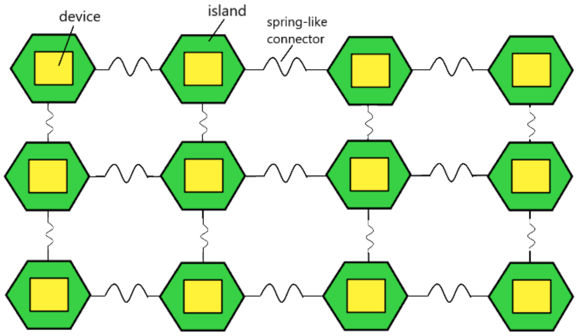

Fig. 9. Silicon islands connected using springs for stretchability.

Silicon springs can be used to impart stretchability to a device. Electronic devices are housed on discrete islands. Surrounding these islands are silicon springs, connecting the islands to one another. When the material is stretched, the springs unravel, storing the strain as potential energy. As the strain is removed, the original shape of the spring is retained. This process uses the epitaxy process to obtain thick SOI for thick springs, making it expensive, with low throughput.

Such use of silicon springs can lead to some mechanical failures. For instance, if the spring design does not account for the concentration of stress at certain points, localized stress can lead to the creation and propagation of cracks, leading to spring failure. Additionally, excessive stretching beyond the spring's elastic limit can result in permanent deformation or fracture.

Pre-straining a substrate can also be used to make a device stretchable. In this method, the substrate is stretched, and flat nanoribbons are bonded to the surface. When the strain is released, the ribbons come out of the plane to form a wave-like structure. When strain is applied once more, the ribbons stretch and become planar again in a reversible process.

This technique can significantly affect the mechanical properties of the device. The wavy configuration of the nanoribbons allows the device to accommodate larger strains without compromising the functionality of the electronic components. However, if the pre-strain is not properly controlled, it can induce residual stresses in the nanoribbons, potentially causing buckling, wrinkling, or cracking.

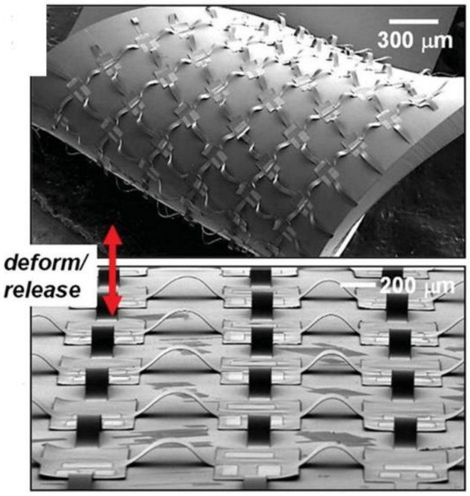

Fig. 10. Pre-straining a substrate to impart stretchability. Reproduced with permission [31].

We can also use metallic interconnects between the islands of flexible silicon in two ways - using metallic springs and by using conductive polymer composites. In the first method, a thin film of metal is deposited on a polymer backing and both are made into spring structures. These interconnects are used to connect device islands as done previously. It can either be a free-standing device or can be placed on a final destination substrate. In the free-standing configuration, the interconnects absorb all the stress. If a destination substrate is used, the substrate needs to absorb the stress on its layer, while the stress on the device layer is mostly absorbed by the interconnects. An important property these interconnects must possess is constant resistance when subjected to strain.

Usage of conductive polymer composites is another method to achieve stretchable electronics. Here, metal nanoparticles and nanowires are dispersed in a polymer, giving it conductive properties. Polymers are inherently stretchable materials, but the conductors are not. But metals have the desired electrical properties, while polymers do not. A balance must be obtained between the two to obtain the final desired product that is both flexible and conductive.

Elastomeric structures may also contain liquid metals inside them, to provide stretchability. However, this is not widely used due to the toxicity and prohibitive costs of the metals involved.

III. OPPORTUNITIES

The flexibility of semiconductors, particularly silicon, can impact various aspects of our lives in major ways. Instead of having bulky, rigid components in different systems that hinder motion, thinner, lighter, and more flexible ones are preferred. This brings in more freedom of movement, lesser

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area occupied, easier portability, etc. These new properties have proven to be useful in various applications such as biomedical sensing (as e-skin, and in medical implants), electronics (as transistors and microprocessors), power related applications(to store lithium, as electrodes, as solar cells), sensing applications(to form a better substrate in Surface-enhanced Raman Spectroscopy, SERS),and in optoelectronics(to make a substrate more or less transparent to certain wavelengths of light). All of these can be interlinked or connected using the Internet of Things (IoT) platform, which is rapidly picking up pace in today's world.

In the previous section, we discussed the various properties and methods to fabricate flexible silicon. These wafers must be lesser than 50 µm in thickness to be flexible. As we reduce the thickness, the radius up to which the silicon wafer can bend without breaking reduces as well. Depending on the application, there are different methods to fabricate it, each showing its own advantages and disadvantages in the final product and costs and complexity involved. Here, we discuss some of the opportunities that having the additional flexibility in silicon has introduced and the progress that has been made in this field over the last few years.

A. Biomedical

The field of biomedicine has one of the greatest needs for high-performance flexible electronic systems. Wearable and implantable electronics can be placed and integrated with different organs of the human body to detect, diagnose and treat diseases. These need to have properties similar to those of the organs they are attached to so that they may produce good readings spatially and temporally. One major factor here is their flexibility [32]. The electronic systems that are implanted must move along with the organ, and bend, stretch and fold. This is so that they may be able to be sufficiently integrated along with the bio tissues. Any impedance in natural movement may lead to significant risks and create newer problems to solve.

In the healthcare sector, continuous monitoring of the heart and associated blood vessels is crucial for patient wellbeing. To achieve this, invasive soft cardiac monitoring sensors are often utilized. These sensors need to maintain good contact surface area and apply appropriate pressure without hindering normal activities like heartbeat, necessitating flexibility. Silicon-based materials have proven effective in creating such sensors, as well as epidermal devices that monitor blood flow variations.

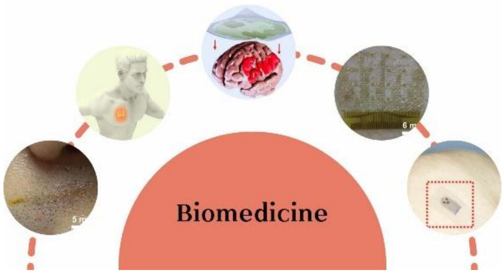

Fig. 11. Applications of flexible silicon in biomedicine.

Wireless Body Area Networks (WBANs) play a vital role in remotely monitoring patient health by connecting sensors placed under the skin or inside the body to a network [33]. These sensors measure vital signs such as blood pressure, pulse rate, and temperature. For this purpose, small antennas operating at specific frequencies are designed using thin, high-resistance silicon and Inkjet printing techniques.

A notable development in biodegradable implants is a NOx gas sensor fabricated using a single crystal silicon nanomembrane [34]. Its ability to dissolve after use makes it ideal for biomedical applications. The device is transferred onto a degradable substrate and features serpentine bridges between islands for enhanced stretchability. It exhibits a bending radius of 5 mm, stretchability of 40%, and stable electrical properties upon deformation.

Most current implantable electronic systems lack barriers to prevent biofluid infiltration, thus reducing their operational lifespan. To address this issue, highly doped Si pads create a bio-interface that serves as both an encapsulating structure and a conductively coupled interface to tissues [19]. This results in stable operation and prevents delamination, unlike metal electrodes.

The COVID-19 pandemic brought attention to the need for continuous body temperature monitoring. In response, an ultrasensitive and stretchable epidermal sensor array was developed using Au-doped silicon nanomembranes [35]. The high temperature coefficient of resistance, mechanical loading, and isolated island structures contribute to the sensor's sensitivity. These nanomembranes are transferred to flexible substrates, forming a mesh-like structure that is both flexible and stretchable, ensuring effective performance even when placed at joints that experience frequent deformation.

Flexible silicon has contributed immensely to healthcare advancements, enabling continuous monitoring of vital organs and parameters. Its biocompatibility, durability, and adaptability make it an invaluable material for creating innovative healthcare solutions that enhance patient wellbeing and treatment outcomes.

B. Consumer Electronics

Flexible electronics has a large market in the consumer electronics industry. Smaller, thinner, and more portable electronic devices are becoming increasingly popular. Industry competitors are developing newer devices that are flexible, without compromising on the functionality of their non-flexible counterparts. The integrated circuits and transistors used in these are often made of silicon substrates, and this must be thinned down to match the shape and size of the rest of the device. These include microprocessors, batteries for smart watches, solar cells and other similar devices.

Flexible microprocessors, such as the PlasticARM [12], have demonstrated the potential for improved gate density and reduced cell area size, offering exciting possibilities for the future of compact devices. Despite facing some manufacturing challenges, this technology continues to evolve and holds promise for a new generation of microprocessors.

Solar cells made from thin, flexible crystalline silicon have

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emerged as an eco-friendly power source for wearable devices. These solar cells [36] efficiently convert light to energy and can be integrated into clothing or accessories, providing a sustainable energy solution for the growing wearable technology market.

Flexible lithium batteries with composite silicon and carbon electrodes [37] are another breakthrough in the realm of wearable electronics. These batteries offer stability, low resistance, and durability, addressing the need for rechargeable power sources in flexible devices. As researchers continue to improve these materials, the potential for enhanced battery performance grows.

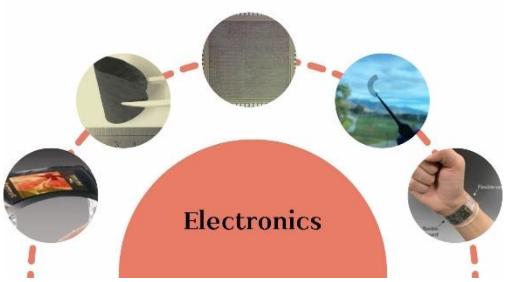

Fig. 12. Applications of flexible silicon in consumer electronics.

In the field of lithium-ion batteries, the development of silicon-carbon composites with a yolk-shell structure [38] has led to improved electrical conductivity and structural integrity. By addressing the issue of silicon's short lifetime in battery applications, this innovation holds significant potential for further advancements in battery technology.

Flexible silicon technology has opened the door to a new era of smaller, more efficient, and adaptable devices. Ongoing research and development efforts strive to refine these materials and address challenges, ensuring the continued advancement of flexible electronics and their positive impact on the consumer electronics industry.

C. Sensing

Surface-enhanced Raman Spectroscopy (SERS) is a technique used to detect low concentrations of substances by analyzing how light scatters when it interacts with molecules. The efficiency of this detection method relies on the type of material, or substrate, used in the process. Typically, non-uniform materials pose challenges due to their instability. In contrast, uniform materials with 3D structures have shown better detection capabilities compared to 2D structures, with the inverted pyramid shape being particularly effective [39] as it can trap light from one side. Flexible silicon has emerged as a promising substrate for SERS, demonstrating improved detection sensitivities.

A method known as metal-assisted chemical etching (MACE) has been developed to create porous silicon for use in SERS [40]. Silicon wafers are prepared using MACE, and the resulting structures are transformed into thin, flexible substrates through a peeling mechanism. This process creates nanopores that are beneficial for light manipulation and sensing. The flexible silicon substrate is lightweight and easy to handle, making it ideal for integration into portable devices used in pharmaceutical and forensic laboratories.

Flexible silicon substrates offer numerous advantages for SERS detection methods. Their uniformity and unique geometry enhance detection sensitivity, enabling accurate identification of low concentrations of substances. Moreover, their lightweight and flexible nature makes them suitable for portable devices, facilitating on-site analysis and real-time results.

As researchers continue exploring the potential of flexible silicon in SERS detection methods, we can anticipate further advancements in spectroscopy. These innovations will likely lead to more accurate and efficient detection techniques, ultimately benefiting various industries, including pharmaceuticals and forensics.

B. Optoelectronics

The demand for flexible and transparent optoelectronic devices has grown significantly in recent years, driven by their potential applications in the Internet of Things (IoT), flexible screens, and electronic devices. Silicon, a widely used material in electronics, can be made flexible by thinning it down to below 50 µm. However, this process makes it transparent to visible light while remaining opaque to ultraviolet (UV) and infrared (IR) wavelengths. This property can be advantageous or disadvantageous, depending on the specific application. Researchers have developed various structures of flexible silicon to cater to these different requirements.

One such structure is the single-crystalline silicon framework [41], designed to increase the transparency of thin silicon to UV and IR light. Fabricated using a combination of wet etching and microfabrication technologies, these frameworks can be integrated with asymmetrical electrodes to form robust Schottky junctions, exhibiting diode characteristics. Key features of these frameworks include their self-supporting nature, modulated transparency, high photocurrent, fast response speed, and stability over various frequencies. Despite their low theoretical bending radius of 0.5 mm, crystal imperfections and surface defects increase the practical bending radius to about 5 mm. These microstructures can be used in multi-band photo detecting systems without affecting other components. To enhance the photocurrent in thin Si substrates, researchers have introduced light-trapping structures such as pyramids, inverted pyramids, and nanowires [42]. Nanowires, with a lowered density, provide the highest photocurrents among these structures. These nanowires exhibit excellent anti-reflective properties and maintain photo response under various bending radii. The use of polystyrene sulfonate (PSS) and dimethyl sulfoxide (DMSO) during fabrication helps counteract the reduced conductivity of the films.

The development of flexible silicon technology has significantly impacted the optoelectronics industry by

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enabling the creation of flexible and transparent devices. Ongoing research and development efforts continue to refine these innovative materials, addressing challenges and improving performance.

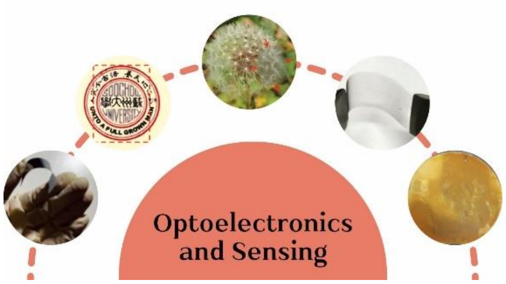

Fig. 13. Applications of flexible silicon in optoelectronics and sensing.

IV. CONCLUSION

This article began by looking at the time when the need for flexible silicon arose, and how it was achieved then. From here, we saw its progression over the last few decades, and the status. Then, we discussed the various methods to obtain thin wafers of silicon, and how to handle and transfer them to other substrates as needed. The current opportunities for using flexible silicon in various fields was also discussed.

From this discussion, we see the wide range of applications flexible silicon has, and it is only picking up pace faster. With the advent of Internet of Things, electronics are becoming a vital part of wearable devices. This requires flexible materials that conform to the shape of the surface they are placed on. Despite the challenges of fabricating, handling, and usage of such thin materials, it has been gaining ground rapidly and further rising. As these advancements progress, we can expect further growth in the applications and capabilities of flexible devices.

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