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SILK PROTEIN-INFUSED SMART DEVICES - A REVIEW

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Abstract: An emerging progress of the Internet of Things (IOT) and 5G wireless technology boosts widespread applications of flexible electronics in diverse fields. On other side, the unwished outcomes of electronic wastes includes toxic matters causes environmental contaminations. Hence, researchers found biomaterial as an alternate for conventional electronic devices. Among diverse biomaterials, silk is discovered as an excellent fiber material in view of its mechanical robustness, better affinity with conductive materials, good biocompatibility and biodegradability used for designing the flexible electronic devices. In this article, we emphasize on an overview of Silk Fibroin (SF)-infused flexible electronics and their utilization in different areas. Silk protein can be amalgamated with flexible electrons evolved into progressive materials like membranes, hydrogels, conductive fibers and scaffolds for smart wearable gadgets comprising sensors, e-skin, energy storage devices, silk based memristors and energy harvesters. SF even being unified with sensors such as food sensors and wearable body sensors for bio-monitoring. The broad applications of SF based devices in medical industry includes wearable devices, resorbable gadgets for therapy and drug release, e-skin, blended SF for ocular lens, biosorbable screws for fracture fixation and brain interfaces made from silk film. Eventually, the critics and prospects of developing silk infused flexible electronics were contemplated.

***Index Terms* -** Silk, flexible electronics, sensors, wearable smart devices.

I. INTRODUCTION

Need for flexible electronic devices

Advances in various semiconductor technologies have led to a colossal production of silicon-based electronic devices for applications in high-speed computers, high-efficiency photovoltaic cells and portable consumer electronics, which have drastically transformed our traditional ways of communication, work, and entertainment. Although the devices contribute much convenience to our daily routine, unfortunately, they would also result in:

i) Rapid depletion of natural nonrenewable resources

ii) Production of mass of electronic waste that often contains toxic and/or nondegradable substances leads to ecological smog (Tanskanen, 2013; Karthick *et al.* 2022)

iii) The undesirable outcomes are becoming ubiquitous now as the operating lifetime of electronics gradually becomes shorter (Irimia-Vladu, 2014).

Flexible electronic devices are necessary for applications involving unconventional interfaces, such as soft and curved biological systems, in which traditional silicon-based electronics would confront a mechanical mismatch. There is thus a great demand to sustainably develop silicon-based electronics. After five decades of continuous and extensive research and development efforts (Franklin, 2015) conventional silicon technologies are approaching their fundamental limits and it is thus very difficult to further improve their performance. In the last two decades, organic nanomaterials have revealed great promise to address the scientific challenge by building complementary electronics, which not only ameliorates electronic and mechanical characteristics competitive with their inorganic counterparts, but also renders the production of emerging flexible and thin-film devices possible (Klauk, 2010). In order to make electronic devices applicable in unconventional environments at biotic/abiotic interfaces where conformal and intimate integration with biological systems is required, electronic devices with high mechanical flexibility are demanded to conquer the mismatch between rigid silicon wafers with soft and curved biological surfaces (Rogers *et al.*, 2010).

Natural biomaterials have offered lasting inspirations and attractive building blocks for developing next-generation flexible and biosustainable electronics, such as organic thin film transistors (Chang *et al.*, 2011), organic displays and light-emitting devices (Nogi and Yano, 2008), and organic photovoltaics (Barr *et al.*, 2011), thus endowing them with environmental benignity and high performance, together with large-scale fabrication capability at low cost (Wang *et al.*, 2015). At the same time, due to their appealing properties including their biocompatibility, biodegradability, bioresorbability, and natural abundance, as well as their light weight, biomaterials have emerged as excellent candidates for the development of biointegrated electronic devices for biological-related applications, such as sensor skins (McEvoy and Correll, 2015), biomedical diagnosis and therapy (Tao *et al.*, 2014) and brain–machine interfaces (Kim *et al.*, 2013). Most of these applications require that the electronics not only possess high mechanical flexibility and robustness, so as to conform to curved and dynamic surfaces and interface with soft and curvilinear biological tissues/organs harmoniously for seamless fidelity, but also to be biocompatible and innocuous, to alleviate allergic reaction or inflammatory responses and relieve potential

detriment
(Kim *et al.*, 2015). More noteworthy, flexible devices in thin and lightweight formats would moderate the discomfort of users and thus enable continuous and long-term use of wearable and implantable systems for biomedical, surgical, and health-monitoring applications (Kaltenbrunner *et al.*, 2013). Biological polymers offer new opportunities for flexible electronic devices by virtue of their biocompatibility, environmental benignity, and sustainability, as well as low cost.

Biopolymers

Biopolymers are polymers produced by living organisms; in other words, they are polymeric biomolecules. Biopolymers contain monomeric units that are covalently bonded to form larger structures. The main natural polymers are silk, chitosan, collagen, keratin and elastin. Based on their biological and mechanical properties (Table 1), silks from silkworms (e.g., *Bombyx mori*) and orb-weaving spiders (e.g., *Nephila clavipes*) have been explored to understand the processing mechanisms and to exploit the properties of these proteins for use as biomaterials. Silks from silkworms and orb-weaving spiders have impressive mechanical properties (Vepari and Kaplan, 2007). However, spider silk have not been domesticated or commercialized because spiders have a predatory nature so they cannot be raised in high densities, and the level of silk production by spiders is much lower than silkworm (Altman *et al.*, 2003). Silk is attractive, compared to other biodegradable polymers such as polyglycolic acid, polylactic acid and collagen, because of its robust mechanical properties, the ability to tailor the dissolution, and/or biodegradation rates from hours to years, the formation of non-inflammatory amino acid degradation products, and the option to prepare the materials at ambient conditions to preserve sensitive electronic functions. Silks represent a unique family of structural proteins that are biocompatible, degradable, and mechanically superior, offer a wide range of properties, are amenable to aqueous or organic solvent processing, and can be chemically modified to suit a wide range of biomedical and electronic applications (Arai *et al.*, 2004).

Table 1. Mechanical properties of biodegradable polymeric materials

Source of Biomaterial	Modulus (GPa)	Ultimate Tensile Strength (MPa)	Strain (%) at break
Bombyx mori silk (with sericin)	5–12	500	19
B. mori silk (without sericin)	15–17	610–690	4–16
B. mori silk	10	740	20
Nephila clavipes silk	11–13	875–972	17–18
Collagen	0.0018–0.046	0.9–7.4	24–68
Crosslinked collagen	0.4–0.8	47–72	12–16
Polylactic acid	1.2–3.0	28–50	2–6

II. AN OVERVIEW OF SILK-BASED DEVICES

Advancements in fabrication technologies are opening new avenues for engineering silk materials in applications beyond traditional usages of textile and suture. The endeavors in recent decades to produce silk fibroin in a variety of material formats through various fabrication techniques such as printing and stenciling, and to utilize silk materials for applications ranging from biomedical devices to optics, photonics, and optoelectronics, have been described in recent reviews (Hota *et al.*, 2012; Altman *et al.*, 2003; Koh *et al.*, 2015; Tansil *et al.*, 2012). More recently, a tremendous increase in the use of silk fibroin for applications in flexible electronic devices has been witnessed due to its biosustainable and biodegradable nature, configurable mechanical robustness, and excellent optical and electronic properties (Muller *et al.*, 2011). Silk is an extensively used biomaterial for the core of conductive fibers owing to its excellent mechanical veracity and better affinity with conductive materials (Hwang and Matteini, 2023).

Unique properties of Silk Fibroin toward flexible electronic devices were,

- Mechanical robustness
- Solution processability
- Physical properties of silk can be modified

III. SILK BASED ENERGY STORAGE DEVICES

Microporous carbon nanoplates from regenerated silk proteins for supercapacitors

Supercapacitors and lithium-ion batteries (LIBs) are both attractive energy-storage devices in the present electronic market. To meet the requirements for future high-power applications, it is critical to improve the performance of current energy-storage systems by employing materials with high electrical conductivity, large surface area, and well-developed nanostructures for fast transport of ions and electrons. Carbon materials (e.g. active carbon, carbon nanotubes, and graphene) are regarded as important electrode materials for supercapacitors and LIBs because of their high surface area, light weight, low cost, and electrochemical stability. Numerous strategies have been developed to fabricate carbon or carbon-based composites with a wide range of precursors. In particular, silk has emerged as a promising class of biorenewable carbon source due to its natural abundance and the copious amount of functional groups contained in its structure. With simple heat treatment and activation of the natural silk, nitrogen-doped “silk carbon” with controllable pore sizes can be synthesized. By breaking the peptide bonds in the silk fibroin, the resulting nitrogen-contained carbon has endowed the electrode with better electrical conductivity and excellent stability against electro-oxidation when applied as an electrode material in supercapacitors. Moreover, the morphology and porous structure of the as-synthesized carbon materials can be further tuned through chemical activation of the silk fibroin. The lamella-like layer structure of silk fibroin has tended to produce 2D carbon nanoplates or nanosheets upon the carbonization and activation processes, which would endow an electrode with a large specific surface area.

Yun *et al.* (2013) revealed that carbon-based microporous nanoplates containing heteroatoms-N (H-CMNs) have been fabricated from silk fibroin and used as electrodes in supercapacitors, which display high specific capacitance of 264 F g^{-1} at a current density of 0.1 A g^{-1} in aqueous electrolyte (1 M H_2SO_4), and 168 F g^{-1} at 0.8 A g^{-1} in an organic electrolyte, 1-butyl-3-methylimidazolium tetrafluoroborate (BMIMBF4)/acetonitrile. These supercapacitors were also characterized by a specific energy density of 133 W h kg^{-1}, which is comparable to that of lithium-ion batteries, a specific power density of 217 kW kg^{-1}, and a stable cycle life over 10,000 cycles.

IV. SILK BASED MEMORY DEVICES

Natural silk fibroin protein-based transparent bio-memristor

The recent discovery of nanoelectronics memristor devices has opened up a new wave of enthusiasm and optimism in revolutionizing electronic circuit design, marking the beginning of new era for the advancement of neuromorphic, high-density logic and memory applications. In this study, a highly non-linear dynamic response of a bio-memristor (resistor with memory) is demonstrated using natural silk cocoon fibroin protein of silkworm, *Bombyx mori*. A film that is transparent across most of the visible spectrum is obtained with the electronic-grade silk fibroin aqueous solution of ca. 2% (wt/v). The memristive transition is elucidated by a physical model based on the carrier trapping or detrapping in silk fibroin films and this appears to be due to oxidation and reduction procedures, as evidenced from cyclic voltammetry measurements. Hence, silk fibroin protein could be used as a biomaterial for bio-memristor devices for applications in advanced bio-inspired very large-scale integration circuit design as well as in biologically inspired synapse links for energy-efficient neuromorphic computing (Hota *et al.*, 2012).

V. SILK BASED ENERGY HARVESTERS

Transient, biocompatible electronics and energy harvesters based on ZNO

Semiconducting oxides are of growing interest as replacements for silicon in thin film transistors for active matrix display backplanes; they are also of potential use in transparent, flexible electronics and energy harvesters. Zinc oxide (ZnO), in particular, has favorable combination of properties, including excellent transparency in the visible wavelength range, high electron mobility, and strong piezoelectric response. Sheets of silk fibroin provide substrates and, in certain cases, encapsulating layers.

A top encapsulating layer of silk can be applied by spin casting. All constituent materials, i.e. Mg (electrodes, contacts and interconnects), MgO (gate and interlayer dielectrics), ZnO (active material for the TFTs and energy harvesters/ strain gauges) and silk (substrate and encapsulant), dissolve in water. The products of this dissolution include Mg $(OH)_2$, Si $(OH)_4$ and Zn $(OH)_2$. The trace completely disappears after 15 hours, in DI water at room temperature. The mechanisms of dissolution of ZnO can be analytically described by reactive diffusion models, in which water diffusion into the materials is the rate limiting process.

Additional experiments on dissolution, monitored by measurements of thickness as a function of time during immersion in several different types of solutions. All electronic materials, i.e. Mg, MgO and ZnO, completely dissolve in 15 h after immersion in DI water at room temperature, in a controlled manner, without cracking, flaking or delamination. This study suggested that these compounds, and the device materials themselves, are biocompatible and environmentally benign (Dagdeviren *et al.*, 2013).

VI. SILICON ELECTRONICS ON SILK AS A PATH TO BIORESORBABLE, IMPLANTABLE DEVICES

The combination of silicon electronics, based on nanomembranes of silicon, with biodegradable thin film substrates of silk protein, to yield a flexible system and device that is largely resorbable in the body. The use of silicon provides high performance, good reliability, and robust operation. The doped silicon nanomembranes were transfer printed onto a film of polyimide (PI), cast onto a thin sacrificial layer of polymethylmethacrylate (PMMA) on a silicon wafer i.e., carrier wafer for processing. After printing, a series of fabrication processes, including photolithography, reactive ion etching, plasma enhanced chemical vapor deposition of oxides, and electron beam evaporation of metals, formed silicon metal oxide field effect transistors connected by metal lines.

Transfer printing delivered the devices to either a spin cast film of silk on a silicon substrate or a freestanding silk membrane. This process yielded a system in which the substrate is water soluble, and resorbable, but the devices are not. To examine this issue directly, samples were implanted subcutaneously in mice and retrieved after two weeks. The results showed that the partial dissolution of the film in this time frame, as well as the lack of any inflammation around the implant site. The mice did not exhibit any sign of abscessing or liquid buildup, and initial integration of the silk carrier into the subcutaneous layers could be observed. The size of the implant is estimated to be between 15%–20% smaller than the originally implanted device and detachment of a few transistor structures can be observed (Kim *et al.*, 2009).

VII. SILK BASED SENSORS

Silk-Based Conformal, Adhesive, Edible food sensors

Food safety is an increasingly important public health issue for both the consumer and food industry. Characteristics such as color, firmness, odor, texture, etc., are routinely used in the quality control of agricultural and biological food products. Early analytical techniques used in the food quality control required isolation of the food component of interest, which inevitably caused the damage to the tested samples. Recent progress in the development of non-destructive approaches/instruments, for example gas chromatography, mass spectrometry, electronic noses and electronic tongues that could detect and recognize odors and tastes, has shown some success for food quality evaluation. Though these techniques are of considerable interest to the food industry, oftentimes such analyses require sophisticated instrumentation and data processing software, which could be time-consuming and are relatively expensive for daily use.

Tao *et al*. (2012) proposed a concept for making wireless passive antennas on silk substrates across multiple regions (Megahertz (MHz), Gigahertz (GHz), Terahertz (THz)) of the electromagnetic spectrum. These antennas can be easily applied to curved objects (i.e., food in this work) and adhere conformally. The devices were tested for function by monitoring their resonant responses continuously during the spoilage process to assess the potential to monitor changes in food quality. Proof-of-principle demonstrations for this type of approach are demonstrated by monitoring fruit ripening with a conformally attached Radio Frequency Identification (RFID) like silk sensor transferred onto the fruit skin, and spoilage of dairy products through surface contact (in the solid case) or immersion (for liquid goods). These types of passive, chip-less sensor, consists of an antenna or an array of antennas/resonators made of only a sub-micron thickness of gold, a level equivalent to common edible gold leaf/ flakes used on cakes and chocolates. The resonators are fabricated on pure-protein silk film substrates and can be used as sensing platforms that safely interface with consumable goods or can be in direct contact with food (and can potentially be consumed) for different applications

Silk fibroin-based sensor for the detection of explosive nitroaromatic vapours (picric acid and trinitrotoluene)

The detection of ultra-trace amounts of high energetic nitro aromatic compounds (NACs) *viz.* 1,3,5-trinitroperhydro-1,3,5-triazine (RDX); 2,4,6-trinitrotoluene (TNT); 2,4,6-trinitrophenol (TNP) etc. has recently emerged as an important area of research particularly in the field of material science. It has an important significance in the field of homeland security, environmental monitoring and minimization of health hazards. Among the aforementioned analytes, TNP and TNT vapour sensing requires special attention particularly due to the severe health hazards and environmental effects associated with its exposure. Herein, they have chosen silk fibroin (SF) scaffold as a template of their choice for sensor preparation. Recently, SF has demonstrated its potential role in electronic and photonic devices. Carbon nano particles impregnation on 3D porous scaffolds of silk fibroin protein make the composite electrically semiconducting. This led to the development of new sensory material with further application towards vapour sensing of model nitroaromatic explosives-TNP and TNT (Chakravarty *et al.*, 2016).

VIII. SILK SUBSTRATE FOR BIO-COMPATIBLE FLEXIBLE SOLAR CELLS

The most common flexible substrates used for flexible solar cells so far have been synthetic polymers such as polyethylene terephthalate (commonly known as PET) and polyethylene naphthalate (PEN). However, if organic solar cells are to be applied onto clothes and other soft surfaces – some of which come into direct contact with skin – they are required to be human-compatible, non-toxic and non-irritable. One possible solution for such a substrate could be silk. "The natural silk fibroin – extracted from the silkworm (*Bombyx mori*) cocoon – is a promising alternative material due to its good biocompatibility, biodegradability, non-toxicity, non-irritability and advantageous mechanical properties, as well as high optical transmittance (90-95%) of films. Furthermore, the biodegradable and mechanical properties of silk fibroin substrates can be tailored by controlling the fabrication process, such that they match the desired requirements for some specific application. In this study, they integrated a biocompatible silk fibroin with a mesh of silver nanowires to achieve a flexible, transparent, and biodegradable substrate for efficient plastic solar cells.

IX. GOLD NANOPARTICLE-EMBEDDED SILK PROTEIN- ZNO NANOROD HYBRIDS FOR FLEXIBLE BIO-PHOTONIC DEVICES

Silk protein has been used as a biopolymer substrate for flexible photonic devices. ZnO is one of the promising metal oxides with a wide band gap (3.34 eV) and large exciton binding energy (60 meV) exhibiting multifunctional applications. In particular, ZnO nanostructures have been widely investigated for UV photodetectors with higher on/off current ratio and having potential for flexible electronic applications. The realization of novel photodetectors using aligned ZnO nanorod arrays on biocompatible silk protein/glass or polyethylene terephthalate (PET) substrates using a low temperature process. The proposed novel hybrid ZnO nanorods on silk protein can provide a pathway for new opportunities towards low cost, biocompatible, biodegradable, flexible and lightweight photonic devices (Gogurla *et al*., 2017).

X. SILK BASED WEARABLE DEVICES

Silk could improve sensitivity, flexibility of wearable body sensors

There is a whole world of possibilities for silk sensors at the moment. Silk is an ideal material for fabricating sensors that are worn on the body. One possibility the researchers foresee is for them to be used as an integrated wireless system that would allow doctors to more easily monitor patients remotely so that they can respond to their medical needs more rapidly than ever before. Body sensors, which are usually made with semiconductors, have shown great potential for monitoring human health. But they have limitations. For instance, strain sensors, which measure changes in force, cannot be highly sensitive and highly stretchable at the same time. Silk, a natural material that is stronger than steel and more flexible than nylon, could overcome these problems. The fiber is also lightweight and biocompatible. However, silk doesn’t conduct electricity very well. To address this challenge, Zhang and colleagues at Tsinghua University in China sought to find a way to boost the conductivity of silk so it could be successfully used in body-sensing devices. In this approach, they treated the silk in an inert gas environment with temperatures ranging from 1,112 degrees to 5,432 degrees Fahrenheit. As a result, the silk became infused with N-doped carbon with some graphitized particles, which is electrically conductive. Using this technique, the scientists have developed strain sensors, pressure sensors and a dual-mode sensor capable of measuring temperature and pressure simultaneously. Silk sensors might be used to build more realistic robots that can sense touch, temperature or humidity and can even distinguish between different people’s voices (Zhang *et al.*, 2017).

Lu *et al.* (2024) produced silk fibroin-based ionic hydrogel (SIH) fibers which retain excellent fracture strength (55 MPa), extensibility (530%), stable and good conductivity (0.45 S·m–1) due to oriented structures and ionic incorporation.

Pang *et al.* (2024) developed silk fibroin based wearable electronics (SFWE) for on-body monitoring. A combination of rose petal templating and hollow carbon nanospheres endows as-fabricated SFWE with good sensitivity (5.63 kPa−1), a fast response time (147 ms) and stable durability (15,000 cycles). The degradable phenomenon has been observed in the solution of 1 M NaOH, confirming that silk fibroin based wearable electronics possess degradable property.

XI. SILK BASED DEVICES IN BIOMEDICAL FIELD

Bio-integrated Electronics can be classified into two groups,

1) Epidermal electronics - Epidermal electronic system is a class of hair thin, skin soft, stretchable sensors and electronics capable of continuous and long-term physiological sensing and clinical therapy when applied on human skin.
2) Bio-integration within the body – Integration of sensors within the body tissues

Biotransferable graphene wireless sensor based on silk fibroin

A graphene-based wireless sensor on a silk fibroin film was devised, which can be wrapped onto a variety of biological tissues, such as teeth and muscles. After functionalizing graphene film with biorecognition peptides, the device is capable of biological sensing with detection limits down to a single bacterium. The bacteria-detection performance of the sensor relies on the electrical conductivity changes of graphene films, which can be monitored remotely through integration with a wireless coil. By transferring the sensor onto a tooth, intimate contact was achieved between the sensing elements and the tooth after the dissolution of silk substrate, which enabled the sensor to respond rapidly to exhaled breath. This renders the device as promising for noninvasive biomedical diagnosis (Mannoor *et al.*, 2012**)**.

Silk-based resorbable wireless heating devices for therapy and drug release

The fabrication of a fully dissolvable wireless heating device was reported, which consists of a serpentine resistor and a power-receiving coil, both made of Mg, on the silk substrate. The Mg heater was protected through being encapsulated in a silk "pocket", which can be used to program the lifetime of the device. The device could be remotely activated for thermal treatment in the infection area. It could also be further modified into a wireless therapeutic device by entraining ampicillin in the silk substrate. The ampicillin release can be remotely triggered and the release rate can be efficiently controlled by altering the crystallinity and molecular weight of the silk films. Such external control could effectively avoid the challenges encountered in in vivo operation, such as mechanical handling, sterilization, and mechanical stability at the biopolymer–device interface. In the aforementioned work, silk films mostly act as a reliable carrier that is biodegradable and bioresorbable without leaving hazardous remnants within the body (Tao *et al.*, 2014).

Silk E-Skin

- Carbonized silk nanofiber membranes (CSilkNM) into pressure sensors for electronic skin (E-skin).
- Low-cost fabrication
- Biocompatible and environmentally benign.
- After electrospinning and carbonization, SF is made into a highly conductive material that can be integrated with a PDMS film to obtain a flexible sensor.
- Functioned consistently in real-time
- When worn on the wrist and chest - detected pulse and breathing rate, respectively.
- When attached to the neck - deep-lying jugular venous pulse (JVP)
- To detect subtle muscle movements made during speech.
- An array of CSilkNM sensors spatially resolved the distribution of pressure from a collection of small objects (Flogeras, 2017).

Silk-molded flexible, ultrasensitive, and highly stable electronic skin for monitoring human physiological signals

Monitoring human physiological signals such as wrist pulse and muscle movement when a person is speaking, which may broaden their potential applications for disease diagnosis and voice recognition. E-skin exhibited high sensitivity and distinct patterns when the speaker spoke different words and phrases such as

"Hello", "Nanotechnology", "Inspire a generation", and "One world one dream", respectively. To further investigate its repeatability, the word "Hello" and the phrase "One world one dream" were recorded for three times. It is clear that the obtained *I-t* curves have similar characteristic peaks and valleys when the tester spoke the same words or phrases. The E-skin provides an interesting and effective method for voice recognition through sensitive and fast pressure sensing, which is mainly caused by the deformation of epidermis and muscles around the throat during speech. It might be usefully for people with damaged vocal cords to recover their speech ability by training to control their throat muscle movement. The E-skin will also bring promise for remote control of human/machine interfaces (Wang *et al.,* 2016).

Preliminary study of blended silk fibroin for contact lens

Silk fibroin, a natural fiber polymer produced by the silkworm, *B. mori*, has excellent properties for ocular drug delivery systems, i.e., biocompatibility, chemical and mechanical stability, wetting ability, high oxygen permeability. The light transparency and mechanical properties of silk fibroin blended films were measured using UV–VIS spectrophotometer and texture analyzer, respectively. The dry film prepared with SF/PVA at a ratio of 10/90–50/50 showed good light transparency, >90%. However, light transparency of SF/PVA films decreased about 10% when films were wet (Jeencham *et al*., 2016).

The use of silk-based devices for fracture fixation

Metallic fixation systems are currently the gold standard for fracture fixation but have problems including stress shielding, palpability and temperature sensitivity. Recently, resorbable systems have gained interest because they avoid removal and may improve bone remodeling due to the lack of stress shielding. However, their use is limited to paediatric craniofacial procedures mainly due to the laborious implantation requirements. Gabriel *et al.,* (2014) prepared and characterized a new family of resorbable screws prepared from silk fibroin for craniofacial fracture repair. *In vivo* assessment in rat femurs showed that the screws to be self-tapping, remain fixed in the bone for 4 and 8 weeks, exhibit biocompatibility and promote bone remodeling. The silk-based devices compare favourably with current poly-lactic-co-glycolic acid fixation systems, however, silk-based devices offer numerous advantages including ease of implantation, conformal fit to the repair site, sterilization by autoclaving and minimal inflammatory response (Perrone *et al.,* 2014).

Brain interfaces made of silk

- Measures electrical activity from the surface of the brain in cats.
- Silk is mechanically strong – films can be rolled up and inserted through a small hole in the skull–yet can dissolve into harmless biomolecules over time.
- When it's placed on brain tissue and wetted with saline, a silk film will shrink-wrap around the surface of the brain, bringing electrodes with it into the wrinkles of the tissue.
- Conventional surface electrode arrays can't reach these crevices, which make up a large amount of the brain's surface area (Bourzac, 2010).

XII. CHALLENGES AND PROBLEMS IN SILK INFUSED DEVICES DEVELOPMENT

- Development of silk-based electronics is still at a rudimentary stage
- Molding, imprinting, and transfer printing - fabricate complex silk features
- Integration with electronic components is still a challenge
- Require metals films, metal nanowires, or conducting polymers as conductive components, thus limiting their biodegradability and bioresorbability
- Requires expensive composite materials

XIII. CONCLUSION

Biocompatible and biosustainable silk materials revolutionize the state-of-art electronic devices. Advances in silk-based electronic devices used for the design and integration of high-performance biointegrated electronics for future applications like consumer electronics, computing technologies, biomedical diagnosis and human–machine interfaces. Silk based devices reshape the future manufacturing techniques toward environmental benignity and sustainability.

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