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Implantable neural recording devices for brain-machine interfaces: A review

Junhao Lin

The University of California, Davis

jhalin@ucdavis.edu

Abstract. BMIs provide individuals with neuromuscular illness with communication and management options. The capture and analysis of signals are critical. BMIs enable people to engage with their environments, giving patients optimism. In this overview, we will discuss embedded sensors for collecting data from our bodies, such as chemical sensors and electrophysiological sensors. We will also discuss some general aspects of implantable sensors, such as why they are helpful and the various kinds of electrodes for BMI. We also discuss new methods for miniaturizing devices, such as microfabrication and microfluidics.

Keywords: BMI, implantable probes, neural interface, biosensors, microfabrication

1. Introduction

Brain-machine interfaces (BMIs) have the potential to offer control and communication options to individuals suffering from disabling neuromuscular conditions like amyotrophic lateral sclerosis (ALS), brainstem stroke, cerebral palsy, and spinal cord injuries because they are not dependent on neuromuscular coordination. [1]. The goal of BMI research and development is to allow these people to communicate their requests to caretakers, use word processing and other applications, and even control a robotic arm or a neuroprosthesis. BMIs may be beneficial to those with minor, or even no, motor impairments, according to the current hypothesis. Researchers have proposed numerous BMI designs. The signal acquisition and signal processing units are the key components of the BMI system [2].

Until recently, the concept of directing one's surroundings with one's thoughts was considered science fiction. However, technological breakthroughs have resulted in a new reality: people may now use electrical impulses generated by brain activity to interact with, affect, or modify their environment. Individuals who are unable to speak or move their limbs may be able to interact with or operate assistance devices for walking and moving items owing to the rapidly evolving field of BMI technology. People with disabilities may be able to restore their capacity to move in the near future. The field of brain-computer interface research is well-known even there is a lot of curiosity and interest in a subject that might soon help a lot of individuals with disabilities, as seen by YouTube videos and news reports in the popular media [3].

In this review, we will talk about implantable sensors for acquiring information from our body, including chemical sensors and electrophysiological sensors. We will also mention some common about implantable probes such as why they are useful and different types of electrodes for BMI.

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Furthermore, we describe advanced technologies to miniaturize the devices–microfabrication, and microfluidics.

2. Implantable sensors

The electrochemical biosensor is one of the common sensing devices that converts biological processes to electrical impulses. An electrode is a crucial component for the immobilization of biomolecules and the flow of electrons in this sort of sensor [4]. A common configuration for electrochemical biosensors involves an enzymatic catalytic process that either generates or consumes electrons. Typically, the biosensor's substrate contains three electrodes, typically categorized as working, reference, and counter electrodes [5]. The desired substance to be analyzed engages in a process that takes place at the active electrode's surface, and this process may also make the transfer of electrons through a potential double layer. The magnitude of the current can be determined at a specific potential [5].

For electrophysiological sensors for BMI, we often use probes. According to [6], there are three common neural probes: tetrode, Utah Array, and Michigan Probe.

2.1. Tetrode

Tetrodes are frequently employed to capture extracellular electrical signals within brain systems. These tetrodes consist of four electrodes that record neural impulses from the same source, albeit at slightly different spatial positions [6]. In the rat cortex, a single tetrode can monitor extracellular potentials from more than 1,100 neurons within a 140-meter radius [6]. This method offers several advantages over single-channel electrodes, including the capacity to distinguish extracellular potentials of nearby neurons through a clustering algorithm [6]. However, to directly assess spatially multi-dimensional extracellular potential distributions, it is essential to accurately implant and space multiple tetrodes at regular intervals. Tetrodes have found application as implanted brain probes in BMI platforms, especially for small creatures [6].

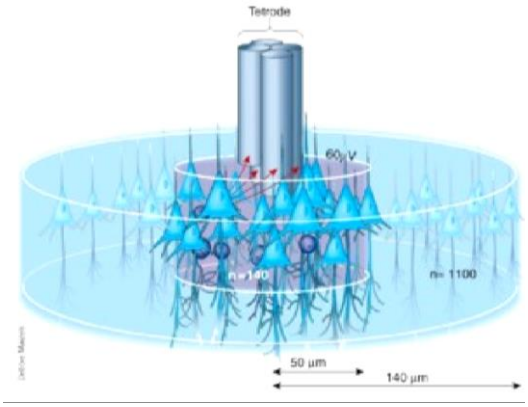

Figure 1. A diagram that shows the brain activity that a tetrode can detect. The tetrode can see neuronal activity in regions of neural assemblies with 280 m diameters using better clustering and spike sorting algorithms [6].

2.2. Utah Array

The Utah array, a type of intracortical electrode array, consists of as many as 100 silicon needle-shaped electrodes. It is manufactured using microscale production techniques such as metal deposition, thermomigration, mechanical and chemical micromachining, and encasing the electrodes in a polymer composed of imide monomers [6]. Unlike the tetrode, which is often used in small animals, the Utah array has primarily been utilized in larger animals, predominantly non-human primates, owing to its extensive array of electrodes [6].

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2.3. Michigan probe

Users of the two earlier neural probes can record neural activity from various brain regions. However, their capacity to focus on axially deep neuronal structures is constrained [6]. Compared to the Utah array's (0.5 to 1.5 mm for research), the Michigan probe's electrodes (2 to 15 mm) are longer. Therefore, for recording from deeper cortical areas, the Michigan probe may be more appropriate [6].

3. Commons about implantable probes

Neural probe technologies have significantly advanced our comprehension of the brain by clarifying the functioning of biological neuron networks. These probes are implanted into different brain regions to both record and stimulate specific areas. In numerous medical scenarios, neural probes serve diagnostic purposes, aiding in the identification of conditions like seizures, epilepsy, migraines, Alzheimer's, and dementia affecting the brain [7].

3.1. Wire Electrodes

Microwire arrays (MWAs), also known as wire electrodes, have a rich historical background and find extensive use in neural interfacing. The utilization of metal wire electrodes in neural studies dates back to the early 20th century when silver probes were first introduced. Today, MWAs are widely applied in the investigation of neural activity across various species, including rodents, non-human primates, mammals, and humans. They are particularly valuable for tasks requiring long-term and dependable performance or for reaching deeper regions of the brain. Researchers have achieved remarkable success in recording single and multi-unit activity, as well as local field potentials (LFPs), over extended durations, with notable examples including over 9 months in the guinea pig cerebral cortex, over 18 and 84 months in the macaque motor cortex, and even up to seven years in monkeys [8].

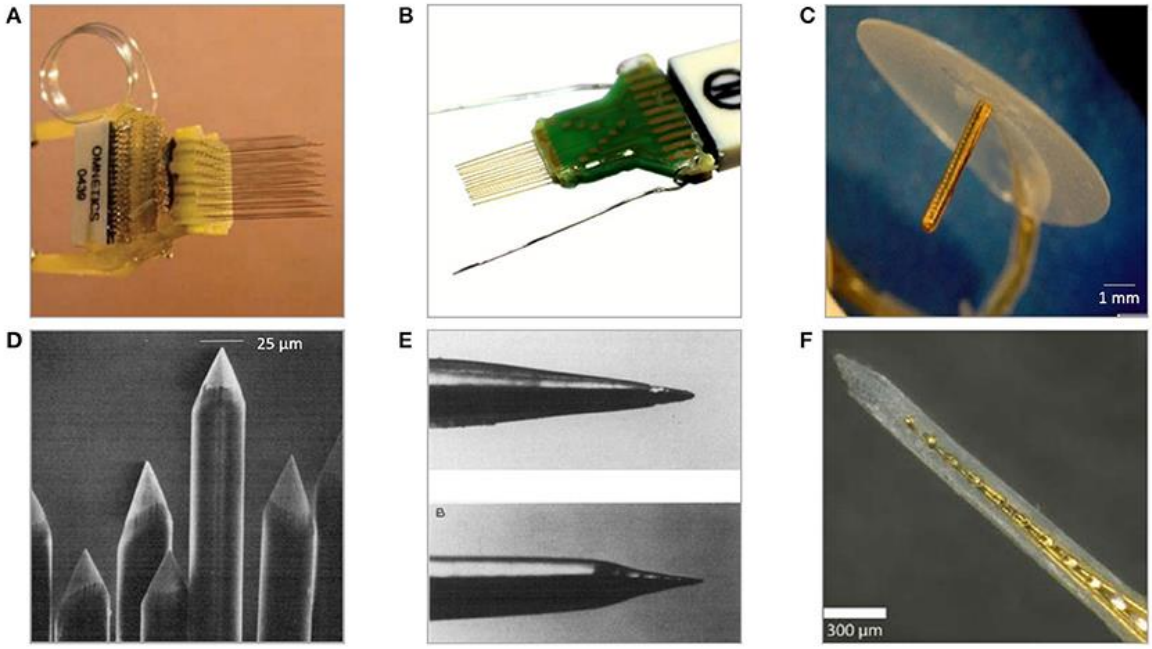

Figure 2. Examples of brain electrodes using microwire technology (A) A connection established using a detached 8 by 8 microwire electrode grid containing 64 channels. (B) The 32-channel multi-layer array of tungsten wires insulated with polyimide was developed by Tucker Davis and affixed to a distinct PCB (Printed Circuit Board). (C) The 24-channel linear Thumbtack microelectrode array from Plexon. (D) Insulated microwire tips were mechanically sharpened on grinding wheels. (E) Electrochemically honing a microwire yielded a variety of alloy tip morphologies. (F) The 32-channel shank microelectrode array is made of gold microwires and manufactured by the University of California [8].

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The advancement of silicon-based neural probes of the latest generation was instigated by the emergence of photolithography and the subsequent progress in micromachining technology. Wafer-scale microfabrication methods allow for flexible design of 2D geometries, unmatched accuracy with small minimum feature sizes, integration with circuits for signal processing, and reliable large-scale fabrication [8]. The most extensive and varied class of penetrating brain probes is made up of micromachined microelectrodes. Numerous two- and three-dimensional geometries, using a variety of materials and coatings, have been suggested and tested in non-human primates for durations of up to 81 and 300 weeks, respectively [8]. The ability of micromachined probes to incorporate multiple recording sites provides valuable insights into the spatial mapping of brain activity and improves the discernment of recorded signals. This stands as a key benefit of these probes [8].

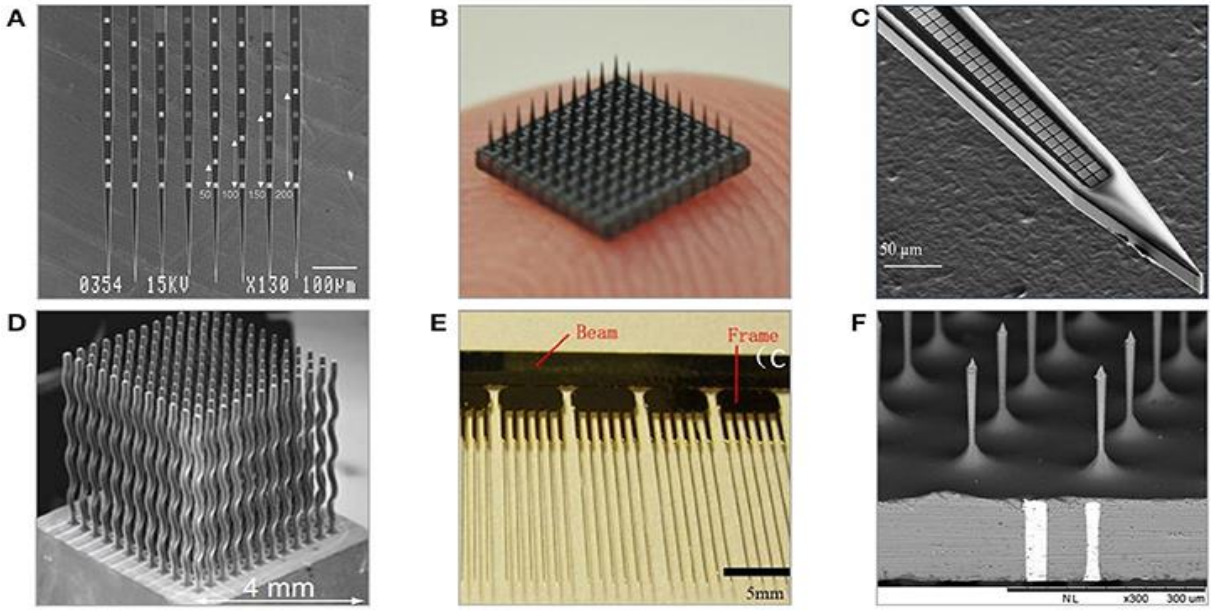

Figure 3. Examples of silicon substrate-based brain microelectrodes made using micromachining techniques. 64-channel planar probes in the Michigan electrode style (A), mostly specified by photolithography. (B) A Utah electrode array measuring 4 mm by 4 mm is constructed from robust substrates using cutting and chemical etching methods, and it features an array size of 10 by 10. (C) A silicon microelectrode with 1000 channels was made using an electron beam and conventional photolithography. (D) Wire electron discharge machining was used to create a multi-needle electrode array that allows for non-3D needle shaping. (E) Electrodes made of just silicon wire have undergone both wet and dry etching operations. (F) Silicon microneedle array with TSV integration [8].

The dimensions and disparities in mechanical properties between silicon-based and wire microelectrode arrays and the brain present two significant obstacles that restrict the quality of neural recordings [8]. Polymers may be used to circumvent the drawbacks of rigid materials and provide conformal contact with delicate, uneven brain tissue. Stretchable and having a lower Young's modulus, polymers put less tension on the tissue, which reduces secondary inflammation [8].

The challenge of inserting pliable, flexible structures into the brain lies in the potential impact on the precision and depth of implantation. In response to this issue, various strategies have been devised, including the creation of removable rigid supports, the addition of extra dissolvable layers, or preliminary tissue penetration using other devices prior to the actual implantation [8].

3.2. Polymer-based neural microelectrodes

Polymer-based neural implants are frequently crafted with slender shank designs and incorporate multiple metallic recording locations, resembling the characteristics of silicon-based implants [8].

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Nevertheless, due to the unique mechanical properties and fabrication options of polymers, they can also feature distinctive geometries [8].

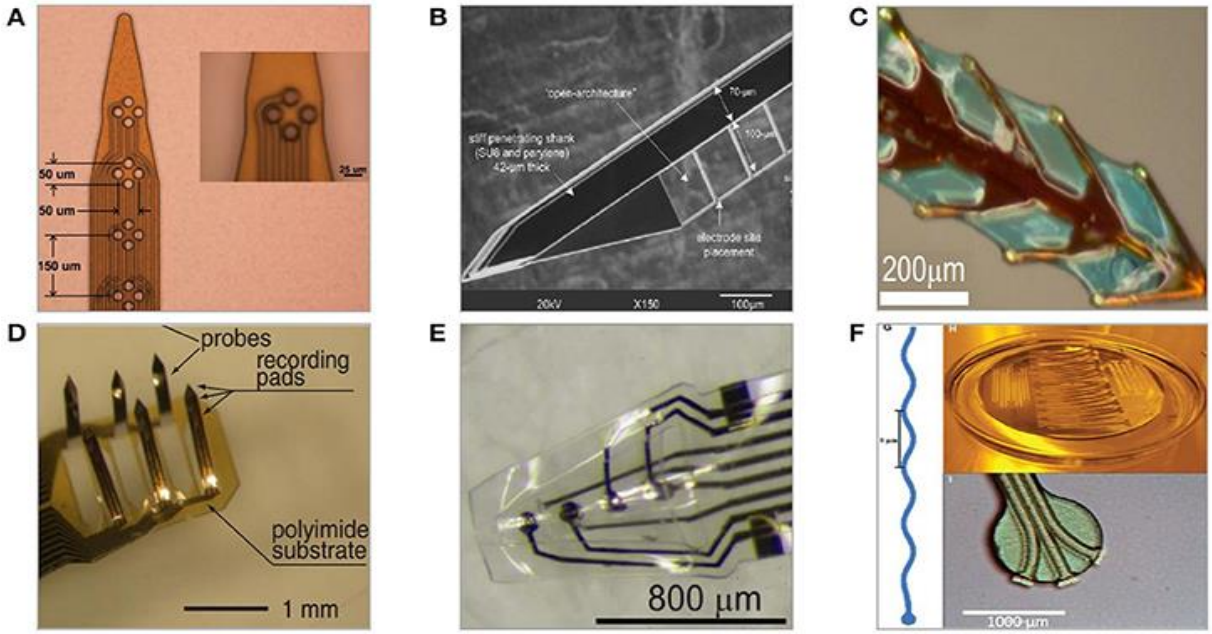

Figure 4. Polymer-based neural microelectrodes are created using host substrates and microfabrication methods. Flexible planar multisite shank electrode made of polyimide (A). (B) A flexible microelectrode with thin lateral arms that may compensate for mechanical mismatch. Microelectrode in the form of a fishbone made of polyimide (C). (D) A three-dimensional, multichannel electrode made of polyimide. (E) Cone polymer sheath electrode with a three-dimensional thermoformed Parylene-C base. (F) A sinusoidal electrode built on parylene-C [8].

A neural interface must meet several requirements for the design, size, form, and material qualities in order to limit the impacts of FBR and function flawlessly for a long time. The implant must be built of materials that can interface with the tissue as it will be in direct touch with it. These materials must also be susceptible to attacks from body metabolic products and able to execute their job for an extended period of time [8]. Mechanical qualities, chemical composition, microstructure, and surface features all affect how biocompatible an implant is. Research conducted on the response of the feline cortex to minute wires made of diverse metals has demonstrated that variations in reactions to different materials can become apparent within a week following the initial surgical procedure [8]. Therefore, the substrate, encapsulation, and recording site materials used in the creation of brain implants should all exhibit high levels of biocompatibility, particularly if they are intended for long-term use. Additionally, implant materials must be vulnerable to breakage, corrosion, delamination, and connectivity failure [8]. It is crucial that none of the materials implanted generate or release additional chemical byproducts like oxidative compounds or solvents, as these could potentially accelerate material degradation and have an adverse impact on recording functionality. [8].

4. Fabrication Methods

Implantable probes are very small and very challenging to fabricate. We will need advanced technologies to miniaturize the devices. Microfabrication is the technique of creating tiny, micrometer-scale, and smaller structures [9]. A group of technologies is used in microfabrication, which is used to create microdevices. Some of them, like lithography and etching, have extremely ancient roots unrelated to manufacturing [9]. Many vacuum procedures are derived from 19th-century physics research, while polishing was taken from the manufacture of optical devices. Along with other

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stamping and embossing methods, electroplating is another 19th-century technology modified to create structures at the micrometer scale [9].

The realm of miniature devices, particularly those incorporating movable components, encompasses microelectromechanical systems (MEMS) [10]. The convergence of MEMS and nanotechnology at the nanoscale has given rise to nanoelectromechanical systems (NEMS). In Japan and Europe, MEMS are also referred to as microsystem technology (MST) and micromachines [10].

Microfluidics is a multidisciplinary field concerned with examining the behavior, precise control, and manipulation of fluids at minuscule scales, typically below a millimeter, where surface forces take precedence over volumetric forces [11]. It proves particularly valuable in crafting compact fluid processing systems that facilitate multiplexing, automation, and high-throughput screening. Microfluidics took shape in the 1980s and is now instrumental in the development of various technologies such as inkjet printheads, DNA chips, lab-on-a-chip systems, micro-thermal devices, and micro-propulsion technology [11].

Microfluidics has rapidly evolved in the last decade, leading to the proliferation of microscale bioreactors and complex analysis systems. These advancements allow for customized microenvironments, automated experiments, and the integration of cell culture with high-throughput analysis. However, transitioning from traditional macroscopic culture platforms on polystyrene to microfluidic devices made of materials like PDMS presents challenges, as various cell types respond differently to this shift [12]. Generalizations are challenging since device designs are as varied as the cell lines that are cultivated inside of them. Negative outcomes, such as less-than-ideal cell development in a particular device or other problems, are also probably underestimated in the literature [12].

Various techniques, such as wet etching, reactive ion etching, photolithography, and more, are employed to produce microfluidic devices. Replication techniques encompass the production of molds or master templates using various mechanical methods like micro-cutting and ultrasonic machining, energy-assisted approaches such as laser ablation and electron beam machining, traditional MEMS processes, and methodologies for manufacturing molds on curved surfaces [13]. To create microfluidic devices, a combination of low-volume manufacturing techniques and high-volume production methods is employed [13].

Early microfluidic devices were commonly constructed using well-established microfabrication techniques such as photolithography, etching, and deposition. These devices were often made from materials like silicon, quartz, or glass. Quartz and glass were patterned using isotropic wet etching with hydrofluoric acid, whereas silicon was usually patterned through anisotropic wet etching techniques involving potassium hydroxide (KOH) and tetramethylammonium hydroxide (TMAH), or dry etching methods like reactive ion etching (RIE) and deep reactive ion etching (DRIE) that included the use of hydrofluoric acid (HF) [13].

5. Conclusion

While subsequent processing stages play a vital role in ensuring the functionality of these systems, the enduring quality of brain recordings holds paramount importance for the efficacy of BMI systems [6]. Furthermore, a BMI system should encompass decoding algorithms for the accurate analysis of captured neural signals and encoding techniques for relaying external information to the brain. In the development of high-performance BMI systems suitable for real-world applications, the integration of high-speed computing and wireless signal processing is also imperative [6]

The primary hurdle for BMI systems incorporating optogenetic stimulation revolves around safety issues. To surmount this challenge and attain top-tier neural probes and BMI systems, it will be essential to embrace pioneering materials, advanced integrated technologies with high resolution, and leverage nanotechnology [6].

The biocompatibility and mechanical appropriateness of implanted brain probes are among the most significant problems facing developers. Mechanical and material science developments will help

in the development of methods for reducing brain scarring while keeping appropriate electrode contact [6].

When creating brain probes for commercial and practical usage, mass manufacturing and security issues should also be taken into consideration. Because the electrode must be put into the brain, correct mass manufacturing techniques must be used without jeopardizing the probe's quality during the whole manufacturing process [6].

The tissue reaction that results from a neurological injury that affects the implanted neural probe's long-term functionality is arguably the biggest obstacle to the adoption of neural implants. Many groups have noted signal degradation shortly after array implantation. In order to enable self-contained and self-governing brain-machine interfaces, these devices should ideally continue to work indefinitely [7]. The brain's overall immunological reaction to the presence of an unfamiliar item has been linked to signal degradation. The electrode's insertion causes the vasculature to burst and kills every neuron in its path. An initial immunological response is triggered immediately after the array is implanted, which helps to attract glial cells. Enzymes produced by activated glial cells will start to break down cellular waste. The relationship between probe size, shape, and surface roughness determines the response's magnitude [7].

This initial reaction transitions into the chronic response, in which brain scarring triggers the start of probe encapsulation.

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