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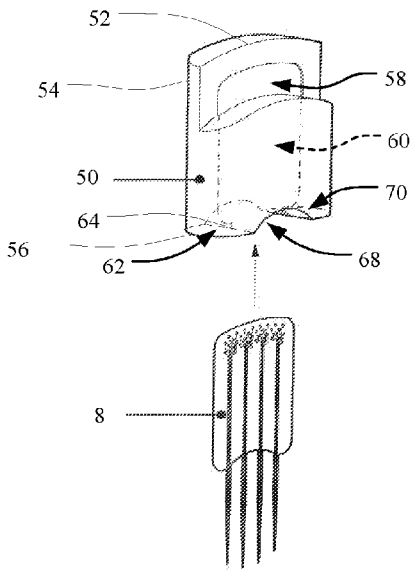

FIG. 2

(57) Abstract: An electrode device and related methods of use and manufacture are described. The electrode can be configured to be securely mounted to a patient's nerve and so that individual contacts are put in electrical communication with individual nerves in a nerve bundle.

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NEURAL ELECTRODE AND RELATED METHODS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Application No. 63/511,101, filed June 29, 2023, which is incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure generally relates to medical devices and more specifically to apparatus and related methods for an implantable neural electrode.

BACKGROUND

[0003] Implantable neural interfaces (INIs) are devices configured to connect with the human nervous system through electrical means. Advantageously, such devices allow electrical recording and stimulation of the nervous system and can contribute to developing effective treatments for various nervous system diseases (e.g., chronic pain, arrythmia, Parkinson's, Alzheimer's, and poliomyelitis).

[0004] However, the materials used for conventional INIs (e.g., silicon and noble metals) suffer from many limitations. For example, due to a relatively low impedance and small detection window, noble metals and silicon-based INIs have limited application during neural stimulation. Additionally, long-term implantable performance with such devices is poor due to the foreign body response, loss of target neurons, and scar formation (i.e., gliosis). In some instances, a base material, such as Si, has been known to make contact with the neural environment and trigger the body's immune system response. In some instances, this has led to undesirable device encapsulation with glial scar tissue resulting in reduced device performance and patient discomfort.

[0005] Furthermore, metals can introduce irreversible dissolution during neurostimulation, which can cause undesirable damage to the human body. Accordingly, new implantable device materials for biomedical applications are desirable.

[0006] With rapid improvements in bionic limbs (prosthetic hands, arms and legs) new challenges arise in the efficient and transparent operation of these advanced devices. Electromyography (EMG) sensors can be used to detect and measure electrical signals in a patient's muscle, however, this does not allow for specific neural interfacing. Performance

using these sensors is limited due to the large number of neural signals that are picked up, sometimes all at the same time. In addition, this type of interface does not lend itself to accurate and effective neural stimulation, for instance to individual nerves, and thus bionic limb feedback signals cannot be fed back to the user. A solution is desired that allows for an increase in the number of individual neural recording/stimulation points that are available, along with reliable, long-term electrode implantation in the peripheral nervous system (PNS). Such a device would preferably improve the number of bionic limb degrees of freedom possible, and also both reduce latency and improve accuracy, as contemporary interfaces require a software algorithm and lengthy training to assess and estimate the patient's intent.

[0007] Microelectrode (MEA) arrays, developed for use in the central nervous system (CNS), are known, but available devices are not suitable for long-term implantation in the peripheral nervous system (PNS). Reliability of implanted devices can be affected by a variety of factors, including the degradation of the implant itself, the immune response, and patient motion in an in-vivo environment.

SUMMARY

[0008] In some embodiments of the present disclosure, an implantable neural device is provided for placement in the body of a patient for transmitting electrical signals. The device can include a probe that has one or more elongated electrode shanks, which can be formed from silicon carbide, extending from a panel. The electrode shanks can include one or more electrode traces that can electrically couple a respective electrode contact. The electrode shanks can be adapted and sized to engage one or more peripheral nerves such that the electrode contacts can electrically couple with the nerve. The surface of the probe can be covered in a silicon carbide coating that can act as an insulator, for instance an amorphous silicon carbide coating with the electrode tip contact uncovered to allow for electrical coupling to the neural environment.

[0009] In some embodiments, an implantable neural device can include signal control electronics attached to the at least one elongated electrode shank and in communication with the at least one electrode contact.

[0010] In some embodiments, an implantable neural device a plurality of elongated electrode shanks can be arranged into a matrix.

[0011] In some embodiments, an implantable neural device matrix can be a two-dimensional matrix.

[0012] In some embodiments, an implantable neural device matrix can be a three-dimensional matrix.

[0013] In some embodiments, each shank can have a plurality of electrode traces, each electrode trace can be configured to electrically couple a respective electrode contact disposed on the surface of the respective elongated electrode shank.

[0014] In some embodiments, an implantable neural device each electrode contact can be a terminal end of one of the plurality of electrode traces.

[0015] In some embodiments, an implantable neural device one or more electrode traces can be configured from at least one of carbon, doped 3C-SiC, 4H-SiC or 6H-SiC or pyrolyzed photoresist film.

[0016] In some embodiments, an SiC coating can be configured as an insulator. The insulator can comprise at least one of an amorphous-SiC coating, a polymer coating, or a ceramic coating.

[0017] In some embodiments, a polymer can be a parylene C.

[0018] In some embodiments, a ceramic coating can be aluminum oxide (Al_2O_3).

[0019] In some embodiments, each electrode trace can terminate in an electrical bonding pad configured to enable an electrical connection to a data cable.

[0020] In some embodiments, a silicon carbide coating can be configured as an insulator. In some embodiments, the insulator does not cover the surface of an electrical bonding pad.

[0021] In some embodiments, an implantable neural device can include a housing having an inner surface defining a cavity. The cavity can be sized to house a panel of a probe while a plurality of elongated electrode shanks extend from the cavity outside of the housing.

[0022] In another embodiment of the present disclosure, a method for detecting electrical signals from a peripheral nerve is provided. The method includes deploying an implantable neural device, which includes a probe. The probe can have one or more elongated electrode shanks that can engage a peripheral nerve and include one or more electrode traces that can electrically couple a respective electrode contact, which can electrically couple to an individual nerve fascicle or a nerve bundle. The electrode can be formed from silicon carbide, including from multiple layers of silicon carbide epitaxial films of alternating electrical polarity (e.g., n- and p-type), and coated with an amorphous silicon carbide film that can act as an insulator. When the device is deployed, the electrode contacts can come into electrical contact with one or more nerve fascicles. The method further includes receiving or transmitting electrical signals by a computer processor in conjunction with electronic circuitry. Signals can be received from the nerve or sent to the nerve through the implantable neural device.

[0023] In another embodiment of the present disclosure a method for sending electrical signals to stimulate a peripheral nerve is provided. The method can include deploying an

implantable neural device. The device can include a probe comprising a plurality of elongated electrode shanks adapted and sized to engage a peripheral nerve. Each shank can have at least one electrode trace. Each electrode trace can be configured to electrically couple a respective electrode contact disposed on the surface of the respective elongated electrode shank and each electrode contact can be arranged to electrically couple with the nerve. The at least one elongated electrode shank can be formed from silicon carbide, and a coating comprising at least one of an amorphous silicon carbide or a crystalline silicon carbide configured as an insulator. The device can be deployed so that a plurality of electrode contacts can be in electrical contact with one or more nerves. The method can include sending electrical signals to the nerve through the implantable neural device. The sending can be partly performed by a computer processor.

[0024] In another embodiment of the present disclosure an implantable peripheral nerve system is provided. The system can include a probe. The probe can include a panel including an electrical contact that is positioned on a surface of the panel, and a shank coupled to and extending from the panel. The shank can include an electrode contact. The electrode contact can be electrically coupled to the electrical contact. The system can include a housing having an inner surface defining a cavity. The cavity can be sized to house the panel of the probe while the shank extends from the cavity outside of the housing. The probe can be adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to the electrode contact of the shank.

[0025] In some embodiments, when a probe is positioned within a cavity of a housing, the housing can constrain movement of the probe relative to the housing.

[0026] In some embodiments, a housing can include an opening at a bottom of the housing. When a probe is positioned within the cavity of the housing, the shank can extend through the opening of the housing.

[0027] In some embodiments, a panel can include a concave portion. An opening can include a concave region that can align with the concave portion of the panel, when the probe is positioned within the cavity of the housing.

[0028] In some embodiments, a housing can include a mechanical stop that can engage with a panel of a probe to prevent movement of the panel past the mechanical stop.

[0029] In some embodiments, a mechanical stop can be an extension that can extend into an opening of a housing in which a shank extends through.

[0030] In some embodiments, an electrical contact of a probe can be exposed when the probe is positioned within a housing. The system can include a cable configured to be coupled

to a panel, such that when the cable is coupled to the panel, the cable electrically couples to an electrical contact of the probe.

[0031] In some embodiments, the system can include a cable with a boot coupled to an end of the cable. A housing can include a cut-out or recess that can expose an electrical contact when the probe is positioned within the housing. The boot can mechanically engage with the housing thereby coupling the cable to the housing to secure the cable to the housing and electrically couple the electrical contact to the cable.

[0032] In some embodiments, a probe, a housing, and a cable can be configured to be implanted within a subject.

[0033] In some embodiments, an electrical contact can be a first electrical contact. A shank can be a first shank. An electrode contact can be a first electrode contact. A panel can include a second electrical contact that can be positioned on a surface of the panel. A probe can include a second shank coupled to and extending from the panel. The shank can include a second electrode contact. The second electrode contact can be electrically coupled to the second electrical contact.

[0034] In another embodiment of the present disclosure an implantable peripheral nerve system is provided. The system can include a probe. The probe can include a panel including an electrical contact that can be positioned on a surface of the panel, and a shank coupled to and extending from the panel. The shank can include an electrode contact. The electrode contact can be electrically coupled to the electrical contact. The system can include a housing having an inner surface defining a cavity. The cavity can be sized to house the panel of the probe while the shank extends from the cavity outside of the housing. The system can include a support adapted to engage with a peripheral nerve of a subject. The support can have a slot sized to house the housing with the probe therein. When the housing is inserted into the support, the support can constrain movement of the housing relative to the support. The probe can be adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to the electrode contact of the shank.

[0035] In some embodiments, a support can include a collar that can be configured to surround a peripheral nerve of a subject. A slot can be positioned on top of the collar.

[0036] In some embodiments, the system can include a lock that when engaged can constrain movement of a housing relative to a support.

[0037] In some embodiments, a support can include a lock and the lock can include one or more feet that contact a housing to block movement of the housing.

[0038] In some embodiments, a probe, a housing, and a support can be configured to be implanted within a subject.

[0039] In another embodiment of the present disclosure an implantable neural device is provided. The device can include a probe. The probe can include a panel having a length, and a first shank coupled to and extending from the panel. The first shank can include a first electrode contact. The first shank can have a length that can be greater than the length of the panel. The probe can include a second shank coupled to and extending from the panel. The second shank can include a second electrode contact. The second shank can have a length that is greater than the length of the panel. The probe can be adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to at least one of the first shank or the second shank.

[0040] In some embodiments, a ratio of a length of a panel to a length of a first shank can be greater than or equal to about 1. A ratio of the length of the panel to the length of the first shank can be greater than or equal to about 1.4. A ratio of the length of the panel to the length of the first shank is greater than or equal to about 1.7.

[0041] In some embodiments, a probe can be adapted to engage a peripheral nerve bundle of a subject thereby electrically connecting a first peripheral nerve fiber of the peripheral nerve bundle to the first shank and electrically connecting a second peripheral nerve fiber of the peripheral nerve bundle to the second shank.

[0042] In some embodiments, a thickness of a panel can be substantially the same as a thickness of a first shank and a thickness of a second shank.

[0043] In some embodiments, a first shank and a second shank are integrally formed with a panel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0044] Features of the present invention will become apparent to those skilled in the art from the following description with reference to the figures, in which:

[0045] Figure 1A is a plan (i.e., top) view of an example probe according to certain embodiments.

[0046] Figure 1B shows example arrangements of electrode shanks forming 1D, 2D, and 3D matrices.

[0047] Figure 2 shows a housing before an implantable neural device is inserted.

[0048] Figure 3 shows a housing with an implantable neural device inserted.

[0049] Figure 4 shows a cable boot assembly, including a cable boot and a data cable in accordance with certain embodiments.

[0050] Figure 5 shows a housing with an implantable neural device before the housing and implantable neural device are inserted into a support including a collar body and before a cable boot and data cable are attached.

[0051] Figure 6 shows a cut-away view of a housing with an implantable neural device before the housing and implantable neural device are inserted into a support including a collar body and before a cable boot and data cable are attached.

[0052] Figure 7 shows a block diagram of a nervous system interface system.

[0053] Figure 8 shows an example of a specific configuration of the present disclosure where the subject has a missing hand.

[0054] Figure 9 shows a flowchart that illustrates a method for using the electrode design as described herein.

[0055] Figure 10 shows a cross-sectional view of neural implant material layers for different example electrodes.

[0056] Figure 11 shows a cross-sectional view of example neural implant layers similar to Figure 9 with portions of an N^{++} layer being etched away to form a semi-metallic N^{++} electrode mesa.

[0057] Figure 12 shows a cross-sectional view of example neural implant layers similar to Figures 10 and 11 with an *a*-SiC insulator conformal coating.

[0058] Figure 13 shows a cross-sectional view of example neural implant layers similar to Figures 10-12 with the electrode tip having been exposed.

[0059] Figure 14 shows a cross-sectional view of example neural implant material layers similar to Figures 10-12 with the exposed electrode bonding pad coated with a metal layer to facilitate device connection to the outside environment through a cable boot assembly.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0060] For simplicity and illustrative purposes, the principles of the present invention are described by referring to various example embodiments thereof. Although the preferred embodiments of the invention are particularly disclosed herein, one of ordinary skill in the art will readily recognize that the same principles are equally applicable to, and can be implemented in other systems, and that any such variation would be within such modifications that do not part from the scope of the present invention. Before explaining the disclosed embodiments of the present invention in detail, it is to be understood that the invention is not

limited in its application to the details of any particular arrangement shown, since the invention is capable of other embodiments. The terminology used herein is for the purpose of description and not of limitation.

[0061] As used herein and in the claims, the singular forms include the plural reference and vice versa unless the context clearly indicates otherwise. Other than in the operating examples, or where otherwise indicated, all numbers expressing quantities of ingredients or reaction conditions used herein should be understood as modified in all instances by the term "about."

[0062] All patents and other publications identified are expressly incorporated herein by reference for the purpose of describing and disclosing, for example, the methodologies described in such publications that might be used in connection with the present invention. These publications are provided solely for their disclosure prior to the filing date of the present application. Nothing in this regard should be construed as an admission that the inventors are not entitled to antedate such disclosure by virtue of prior invention or for any other reason. All statements as to the date or representation as to the contents of these documents is based on the information available to the applicants and does not constitute any admission as to the correctness of the dates or contents of these documents.

[0063] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as those commonly understood to one of ordinary skill in the art to which this invention pertains. Although any known methods, devices, and materials can be used in the practice or testing of the invention, the methods, devices, and materials in this regard are described herein.

[0064] In one embodiment, the present disclosure provides a mainly silicon carbide (SiC) or even an all-SiC neural interface in the form of an electrode or, preferably, multielectrode device which is preferably chemically inert and/or does not contain any metals or polymers inside the neural tissue thus greatly reducing the probability of neural tissue immune system activity. In certain embodiments this can be accomplished in various forms. Table I summarizes optional materials that can be used for the support (base), conductive and insulating layers of the device, as will be described in detail below. The electrodes can be formed from multiple layers of varying materials.

Table I: Material options for system layers

Material Property	Possible Materials
Insulator	Amorphous silicon carbide (α-SiC)
	Parylene C
	Polyimide (PI)
	Ceramic coating (e.g., aluminum oxide (Al_2O_3), silicon nitride, etc.)
	Other electrical insulating material
Conductor	Silicon carbide (SiC)
	Heavily-doped (e.g., N++, P++) Silicon carbide epitaxial films on top of opposite electrical polarity layers/bulk SiC
	Doped (e.g., N+, P+) or heavily-doped (e.g., N++, P++) SiC (doped with e.g., phosphorous, nitrogen, aluminum, boron, etc.)
	Monocrystalline SiC (e.g., 4H-SiC, 6H-SiC, 3C-SiC, etc.)
	Polycrystalline SiC
	Carbon trace
	Conductive C film (e.g., PPF, glassy carbon, graphene, etc.)
Conductive Bonding Pads	Au, Au on Ti, Cr, etc., e.g. where Ti and Cr facilitate adhesion of Au to SiC
Support (Base)	Silicon substrate (any orientation such as (100), (111), etc.), Monocrystalline bulk SiC (e.g., 4H-SiC, 6H-SiC, 3C-SiC, semi-insulating,etc.), 3C-SiC on Silicon, 3C-SiC on SOI, a-SiC on Si, a-SiC on SOI, a-SiC on oxide coated Silicon, etc.

[0065] The electrodes can be formed from silicon carbide epitaxial films. The electrodes can include various layers of doped SiC, which can have alternating electrical polarity (e.g., N, P, N, etc.). For example, the electrode can be formed from a doped or heavily doped 'semi-metallic' conductive SiC electrode, for instance a micromachined mesa electrode. In one case the electrode has one type of electrical polarity, formed on top of another SiC layer doped with the opposite polarity. A SiC heavily doped mesa electrode can be formed on a SiC base layer doped with the opposite polarity and capped and/or coated with an outer layer of amorphous SiC that can act as an insulator. In one case the SiC materials can be monocrystalline (such as 4H-, 6H-, or 3C-SiC) or polycrystalline. Alternatively, or additionally, some or all of the SiC insulating layer materials can be amorphous SiC (a-SiC). The SiC solid-state form used in device construction can depend on the specific implantation specifications required, which can

be application specific. Some devices can utilize more than one SiC type, including more than one SiC solid-state type. For instance, in one embodiment *a*-SiC can be used as a surface coating or insulation layer, while internal layers and/or a core can be formed of crystalline SiC. Alternatively, internal layers and/or a core can be formed of SiC formed on single crystal silicon, which is removed after device fabrication, and contains a surface coating or insulation layer formed using *a*-SiC.

[0066] In other embodiments, the probe is made of monocrystalline SiC, such as cubic silicon carbide (3C-SiC), or hexagonal SiC (i.e., 4H- or 6H-SiC). In addition, the 3C-SiC embodiment can be formed directly on a bulk Silicon (Si) substrate or on silicon-on-insulator (SOI). In one case, an amorphous SiC (*a*-SiC) layer is deposited on bulk Si upon which conductive carbon traces are formed, which are then capped with a second *a*-SiC layer that serves as the surface conformal insulating layer. *a*-SiC can serve as the capping layer to electrically insulate the conductive electrode from the neural environment except at the electrode recording tip, which is in electrical contact with the neural environment. In addition, the packaged end of the device can be coated with a metallic bonding pad that directly contacts the conductive mesa layer. For example, metal coatings can include Au on Ti, Au on Cr, etc. to facilitate electrical connection to the outside environment.

[0067] A significant advantage of using SiC is that it can be possible to reduce or even eliminate gliosis (glial scarring). The use of SiC also allows for a superior signal to noise ratio (SNR) as compared to contemporary penetrating interfaces to the PNS. Silicon carbide (SiC) provides a single, robust material system, to enhance device reliability in-vivo. SiC has excellent bio- and hemocompatibility, is chemically inert and physically robust, and electrically customizable. It has a fracture toughness 4-5 times greater than silicon making it possible to create extremely thin structures (Reddy et al., 2008, Locke et al., 2009). In addition, Euler's Buckling Formula predicts that a SiC probe with a thickness of 6 μm would have the same buckling characteristics of a 15 μm thick Si INI probe with the same architecture. Thus, SiC probes, which are physically robust, can be thinner and more compliant than contemporary Si INI devices, which can lead to a reduced biotic response. Prior work by Stice et al. (2007) showed a statistically significant reduction in inflammatory markers for 12 μm thick versus 25 μm thick implants. Therefore, the thinner implants achievable with SiC can reduce the tissue response during long-term or chronic implantation. In addition, SiC interfaces can exhibit reduced protein absorption, a factor associated with the biotic response. As mentioned, devices comprised of SiC would be inert or perhaps nearly chemically nonreactive and this can help to blunt or reduce the long-term inflammatory processes that contribute to the biological response

of traditional implanted neural probes. Our research demonstrates that: 1) it is possible to create electrode-like structures with electrochemical properties consistent with metallic microelectrodes and, 2) the aforementioned forms of SiC are tolerated by neural tissue in-vivo.

[0068] One embodiment provides an implantable neural device for placement in the PNS of a patient for any and/or all of receiving and sending electrical signals, stimulating or activating (for instance muscle movement), simulating sensation (for instance sending signals directed to the CNS), or facilitating bi-directional communication, for instance sending and receiving electrical signals.

[0069] One embodiment provides a multi-shank design with the shank dimensions allowing for better form-fit with the circular cross section of a human peripheral nerve bundle. This provides a significant improvement over the insertion of traditional CNS probes into the nerve bundle of the PNS, which generally results in non-uniform cross-section capture and stimulation of nerve fascicles. For instance, insertion of traditional CNS probes into the nerve bundle can disadvantageously result in electrical contact being made with multiple individual nerves simultaneously. Indeed, the traditional probe can even result in the undesirable result of individual nerves being put in electrical contact with one another. For example, conventional CNS arrays have shanks that are entirely conductive (e.g., formed out of metal), which can result in multiple nerves, nerve fibers, etc., being in electrical contact with a given shank. In other words, the metal shank contacts multiple (e.g., a great number) of nerve fibers along its length when the metal shank is inserted into the site. This can undesirably result in the given metal shank picking up all these resultant nerve signals at the same time, which can be difficult if not impossible to decouple from each other (e.g., decoupling a combined signal into signals derived from individual nerves). This disclosure, however, can address such a problem by providing relatively small electrode contact sizes, where each electrode contact can have a dimension that is less than or equal to substantially 25 μm. The devices and methods of the present disclosure are configured to avoid the probe serving as an electrical bridge putting individual nerves in direct electrical communication.

[0070] Other objects, advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

[0071] Figure 1A depicts an implantable neural device 8 for placement in the body of a patient for receiving and sending electrical signals. The device 8 can be provided in the form of a probe with one or more elongated electrode shanks 18 each adapted to engage one or more peripheral nerves. For example, Figure 1A shows electrode shanks 18, 20, 22, 24 extending

along a longitudinal axis 27 of the probe. In particular, each shank 18, 20, 22, 24 can extend along the longitudinal axis 27 of the probe in a substantially (i.e., deviating from less than or equal to 30 percent from, in this case, from straight) line. Thus, in some case, each shank 18, 20, 22, 24 can be substantially parallel to each other.

[0072] Each electrode shank 18, 20, 22, 24 can include one or more respective electrode contacts. For example, the shank 18 can include an electrode contact 26. Similarly, the probe can include an electrode trace 12 that extends along the shank 18 and along a panel 14, described in more detail below. In some cases, each shank 18, 20, 22, 24 can include a plurality of electrode contacts, each of which are axially separated from each other along the longitudinal axis 27 of the probe or along the length of the respective shank. In other words, each electrode contact can terminate at a different location along the length of the respective electrode shank. For example, the shank 18 includes eight electrode contacts, which are positioned at different locations along the length of the shank 18. Although each shank 18, 20, 22, 24 is shown in Figure 1A as having eight electrode contacts, in other configurations, each shank can have other numbers of electrode contacts (e.g., one, two, three, etc.). In some configurations, having multiple differently spaced axial electrode contacts for a shank can be advantageous in that when the shank is inserted into a peripheral nerve, each electrode contact can be electrically coupled to different individual peripheral nerve fibers of the peripheral nerve. In this way, many more peripheral nerve signals can be acquired (e.g., to be used to operate a prosthesis, alert an individual, etc.).

[0073] As shown in figure 1A, the probe, and more specifically, each electrode shank 18 has at least one electrically conductive electrode trace 12, and each electrode trace 12 is configured to electrically couple a respective electrode contact 26 (e.g., disposed on the surface of the respective elongated electrode shank 18). For example, the probe can include one or more electrode traces that can electrically connect an electrode contact to a corresponding electrical contact. As a more specific example, the probe 8 can include an electrical contact 28, with the trace 12 extending along the shank 18, extending along the panel 14 and reaching the electrical contact 28. Although the electrical contact 28 terminates at an end of the trace 12, in other configurations, the electrical contact 28 can be positioned at a different location along the trace 12. In some cases, each electrode contact 16 can be arranged to electrically couple with the nerve and can simply be the exposed end of the electrode trace 12 or can be an electrically conductive contact member affixed to the electrode trace 12 and outer surface of the electrode shank 18. In addition to the electrode contact 16, each electrode trace 12 can also have an electrical connector or bonding pad for putting the electrode trace 12 in electrical

coupling with a separate electrode housing, signal control electronics, and/or a cable bundle. Preferably each electrode shank 18, 20, 22, 24 is formed from silicon carbide or SiC on Si, or SiC on SOI, and can include a polycrystalline SiC or conductive carbon trace as the electrode material with an amorphous SiC coating configured as an insulator. In certain embodiments, both the electrode shanks 18, 20, 22, 24 and the upper portion of the implantable neural device 8 (e.g., the panel 14) are formed from a core or include a layer of silicon carbide, and can include a SiC coating configured as an insulator. As used herein, the SiC can be amorphous SiC, polycrystalline SiC, or single crystal SiC.

[0074] In some embodiments, each shank 18, 20, 22, 24 can include multiple electrode contacts. Correspondingly, each shank 18, 20, 22, 24 can then include multiple electrode traces, with each electrode trace being electrically coupled (e.g., electrically connected) to a respective electrode contact of the shank 18, 20, 22, 24. In this way, the number of multiple electrode contacts, number of multiple electrode traces, etc., can be adjusted based on, for example the number of nerves that a given shank is to electrically interact with.

[0075]

[0076] In the embodiment shown, in Figure 1A, a flat, planar or generally (or substantially) flat member or panel 14 is provided as a support for or as part of the electrode shanks 18, 20, 22, 24, the one or more electrode traces 12, and the one or more electrical bonding pads. The panel 14 is preferably formed of a chemically inert or nearly inert or chemically nonreactive material. In one embodiment the panel is configured from SiC, which can be monocrystalline (such as 4H-, 6H-, or 3C-SiC) or *a*-SiC. The panel 14 can be multi-layer, for instance with several layers sandwiched together, and one or more layers can be formed from the same or different materials such as monocrystalline SiC (such as 4H-, 6H-, or 3C-SiC) or *a*-SiC. In one embodiment, the panel 14 is formed with a core having one or more layers surrounding the core. For instance, in an embodiment with multiple layers sandwiched together, such as layers X-Y-Z, each of the layers X, Y, and Z can be formed of monocrystalline SiC (such as 4H-, 6H-, or 3C-SiC) or *a*-SiC (as well as amorphous SiC, polycrystalline SiC, or single crystal SiC). Additional layers of SiC or another suitable material such as an inert polymer can also be utilized.

[0077] Each electrode shank 18, 20, 22, 24 can be formed with, for instance, simultaneously with and/or as a part of, the panel 14, or can be formed separately and attached to the panel 14. The electrode shanks 18, 20, 22, 24 can be adapted and sized to engage a peripheral nerve bundle. Each electrode shank 18, 20, 22, 24 has at least one electrically conductive electrode trace 12, and each electrode trace 12 is configured to electrically couple

a respective electrode contact 26 disposed on the surface of the respective elongated electrode shank 18. The electrode traces 12 can be provided in the form of a conductive SiC electrode that is doped or heavily doped so that it is "semi-metallic", for instance a micromachined (mesa) electrode, or in the form of a carbon electrode. Suitable dopants for the doped SiC electrode include phosphorous, nitrogen, aluminum, or boron. The electrode traces 12 can be covered on the outside or surface with a nonconductive insulator. For example, the insulator can include amorphous SiC, parylene C, polyimide (PI), a suitable ceramic coating, such as aluminum oxide (Al_2O_3) or silicon nitride, or another electrical insulating material. The electrode traces 12 can also be configured in a channel or simply between layers which can be the same or similar to the material used to the form the panel 14.

[0078] As shown in Figure 1A, each electrode shank 18, 20, 22, 24 extends longitudinally away from the main body of the panel 14 and has a generally (or substantially) flat cross-sectional shape with an outer surface. The cross-sectional shape can also be rounded, square, triangular, or rectangular. The electrode shank 18 can be configured so that the various electrode contacts 26 along the length of the electrode shank 18 will be in contact with individual nerves or individual nerve fibers in a peripheral nerve bundle. Where a plurality of electrode shanks are provided, such as the shanks 18, 20, 22, 24, they can extend the same, similar, or different lengths away from the panel 14. As shown in Figure 1A, the length of the surface or surfaces that extend longitudinally away from the panel 14 on each electrode shank 18, 20, 22, 24 are larger than the width of each electrode shank 18, for instance the length is from or between 3X-20X, 5X-15X, 10X-12X, or any of the individual values within these ranges, including their end points, for instance, 3X, 4X, 5X, 6X, . . . 20X, etc.

[0079] The panel 14, or stated differently a plate, can be fixed or installed, including removably installed, inside a housing in such a way that electrical contacts are exposed on opposite longitudinal ends with contacts on the panel and the electrode shanks.

[0080] In one embodiment one or more electrode contacts 26 is the exposed end of the respective electrode trace 12. One or more electrode contacts 26 can be formed by removing the insulator at the location of the desired electrode contact 26. Or one or more electrode contacts 16 can be formed with a removable covering at the location of the desired electrode contact 16 so that upon removal of the removable covering the electrode contact 16 is exposed. Additionally, or alternatively, a connector (not shown) can be provided at the location of the desired electrode contact 16 to facilitate electrical connection and conductivity.

[0081] In some embodiments, and as illustrated in Figure 1A, each shank 18, 20, 22, 24 includes a plurality of electrode contacts, each of which is configured to be electrically coupled

to a specific peripheral nerve, such as, when the shanks 18, 20, 22, 24 engage with a peripheral nerve bundle (e.g., the shanks 18, 20, 22, 24 puncturing the peripheral nerve bundle). As described above, each electrode contact (e.g., the electrode contact 26) is disposed at a different location along the longitudinal dimension of the respective shank. In some cases, none of the electrode contacts of a shank are positioned at a tip of the shank. For example, a tip 30 of the shank 18 is free of any electrode contacts. In this way, the relatively small surface area of the tip 30 can be insufficient for proper electrical connection with a peripheral nerve. Further, when the shank 18 is inserted into a peripheral nerve bundle, the tip can be positioned at a sheath of the peripheral nerve bundle. In this case, then, having an electrode contact at the tip would not be desirable (e.g., because it would be electrically connected to the sheath, an insulator). In some cases, the probe 8 can include a plurality of groups of electrical contacts 32, 34, 36, 38 each of which can correspond to a respective shank 18, 20, 22, 24. Each group of electrical contacts 32, 34, 36, 38 can include a plurality of electrical contacts, each of which can be similar to the electrical contact 28. Each electrical contact within each group of electrical contacts 32, 34, 36, 38 can be electrically coupled to a corresponding electrode trace of the respective shank 18, 20, 22, 24. For example, an electrical contact of the group of electrical contacts 32 can be electrically coupled to an electrode contact of the shank 18. In some cases, as described above, each electrical contact can be electrically coupled to a corresponding electrode contact by a trace (e.g., the trace 12). In this case, each trace can extend along the respective shank and the panel 14.

[0082] Although the plurality of electrode contacts on a respective shank can be positioned on one side of the shank (e.g., one longitudinal side of the shank), in other configurations, the plurality of electrode contacts can be disposed on various surfaces around the shank (e.g., if the shank is not planar, if the shank is planar, etc.). Further, the plurality of electrode shanks can be positioned on opposing longitudinal sides of the shank. For example, a first plurality of electrode contacts can be positioned on a first longitudinal side of the shank 18 shown in FIG. 1A, and a second plurality of electrode contacts can be positioned on a second longitudinal side of the shank 18 (e.g., a rear side of FIG. 1A). In some cases, a plurality of electrode contacts can be positioned on opposing lateral sides of each shank (e.g., right and left sides of the shank 18 in the view of FIG. 1A). For example, a first plurality of electrode contacts can be positioned on a first lateral side of the shank 18 and a second plurality of electrode contacts can be positioned on a second opposing lateral side of the shank 18. Therefore, in some cases, the plurality of electrode contacts can surround a portion of a shank (e.g., the plurality of electrode contacts can be positioned around the shank, such as circumferentially). In this way,

with more electrode contacts dispersed at different locations on a shank, more unique neural signals can be harvested from the nerve, or can be used to stimulate the nerve.

[0083] In some configurations, each shank 18, 20, 22, 24 can include a number of electrode contacts, such as one, two, three, four, five, six, seven, eight, nine, ten, etc., with each electrode contact being configured to electrically couple (e.g., electrically connect) to a unique nerve fiber for receiving a unique nerve signal therefrom or for transmitting a signal to the nerve fiber. In some cases, each shank 18, 20, 22, 24 can include an electrode contact that is a recording electrode contact. The recording electrode contact can be electrically coupled to a nerve (e.g., a peripheral nerve) and can receive a nerve signal from the nerve (e.g., a unique nerve signal). Correspondingly, each shank 18, 20, 22, 24 can include an electrode contact that is a stimulation electrode contact. The stimulation electrode contact can be electrically coupled to a nerve (e.g., a peripheral nerve) and can transmit a nerve signal to the nerve (e.g., for stimulating the nerve, or a portion thereof, including a particular nerve fiber). In some cases, each shank 18, 20, 22, 24 can include a plurality of recording electrode contacts and a plurality of stimulation electrode contacts.

[0084] In some embodiments, the electrode contacts as disclosed herein can be advantageous as compared to prior configurations (e.g., including those in CNS applications). For example, each electrode contact does not span the entire surface of a given shank that the electrode contact is on. Therefore, each electrode contact can be relatively small, which advantageously, can allow for better targeting particular nerves to receive nerve signals therefrom or transmit nerve signals to (e.g., for stimulation). To that end, each electrode contact, which can be substantially planar, substantially flat, etc., can have a dimension (e.g., width, diameter, radius, etc.) that is substantially less than or equal to 1 mm, 900 μm, 800 μm, 700 μm, 600 μm, 500 μm, 400 μm, 300 μm, 200 μm, 100 μm, etc. Further, desirably, each electrode contact can be made even smaller, and thus each electrode contact can have a dimension that is substantially less than or equal to 100 μm, 90 μm, 80 μm, 70 μm, 60 μm, 50 μm, 40 μm, 30 μm, 20 μm, 10 μm, etc. In some cases, including when a dimension is a width or a diameter, each electrode contact can have the dimension that is substantially less than or equal to 25 μm.

[0085] In some embodiments, again, having smaller electrode contacts can be desirable to better interface with specific nerves or components thereof (e.g., to isolate a nerve or a component thereof). In some cases, each electrode contact (e.g., which can be substantially planar, substantially flat, etc.) can have a surface area that is substantially less than or equal to 1000 μm^2, 900 μm^2, 800 μm^2, 700 μm^2, 600 μm^2, 500 μm^2, 400 μm^2, 300 μm^2, 200 μm^2, 100

μm^2, etc. In some cases, stimulation electrode contacts can have a larger dimension (e.g., width, diameter, surface area, etc.) than a corresponding dimension of a recording electrode contacts, because, for example, a larger surface area can be needed to provide the stimulation current required to stimulate the target nerve. Therefore, including when each shank includes a recording electrode contact and a stimulation electrode contact, a surface area of the stimulation electrode contact can be greater than a corresponding surface area of the recording electrode contact.

[0086] In some embodiments, the material used in the probe 8 can advantageously permit smaller stimulation electrode contacts while still allowing adequate simulation of the target nerve at the stimulation electrode contact. For example, when the panel 14, a given shank (e.g., each shank 18, 20, 22, 24), and a given electrode contact are formed out of Silicon Carbide, the electrical properties of Silicon Carbide can permit the smaller size of a stimulation electrode contact. Therefore, the stimulation electrodes can be formed using the dimensions described previously when, for example, Silicon Carbide is used.

[0087] Although each electrode contact is shown as being circular, in other configurations, each electrode contact can have other shapes. For example, each electrode contact can be a square, triangle, rectangle, hexagon, octagon, etc.

As shown in Figure 1A, each group of electrical contacts 32, 34, 36, 38 is positioned at a top end 15 of the panel 14 opposite a bottom end 17 of the panel 14 in which the shanks 18, 20, 22, 24 extend out from. Each electrical contact of each group of electrical contacts 32, 34, 36, 38 can be positioned on a surface (e.g., the same surface) and the same side of the panel 14. In this way, the groups of electrical contacts 32, 34, 36, 38 are positioned at the same location, which can make interfacing with an electrical connector easier (e.g., an electrical cable). In some cases, each group of electrical contacts 32, 34, 36, 38 can be an electrical connector or bonding pad. Therefore, each electrical connector or bonding pad can couple with a respective electrical connector or bonding pad of a different component (e.g., an electrical cable).

[0088] As shown in Figure 1A, a length 40 of the panel 14 (e.g., at its smallest dimension, such as a local minima), can be greater than a length of each shank 18, 20, 22, 24. Stated another way, the panel 14 can be longer than each shank 18, 20, 22, 24. In some cases, a ratio of the length 40 of the panel 14 to a length 42 of a shank (e.g., in this case the shank 24) can be greater than or equal to about (i.e., deviating by less than or equal to 30 percent from) 1, greater than or equal to about 1.4, greater than or equal to about 1.7, etc. This relatively stocky configuration of the panel 14 relative to the shanks can be advantageous particularly in the PNS system environment. For example, rather than in the CNS environment where movement of

electrodes are less common (e.g., due to being able be located within the skull or otherwise coupled to the skull for rigid support), the PNS environment is more prone to movements (e.g., limbs moving around). This requires electrodes to be more stable, and as such the length of the shanks should be confined to maintain structural integrity due to movements. Further, as opposed to the CNS where the axial distance of the brain is quite large (e.g., particularly for reaching deep desired structures of the brain including a cortex of interest, such as the motor cortex), the PNS, and in particular a peripheral nerve bundle of the PNS, is far smaller in cross-section than the brain. This, then, allows for far smaller shanks. Therefore, in some configurations, the length of each shank 18, 20, 22, 24 can be less than substantially 1 centimeter, less than a diameter (or a thickness) of a peripheral nerve to be engaged with the shanks 18, 20, 22, 24 (e.g., which can be far, far smaller than the length required for CNS applications). For example, an average nerve bundle thickness in the arm (e.g., a peripheral nerve bundle) is about 4 mm. Therefore, the length of each shank 18, 20, 22, 24 can be substantially less than or equal to 4 mm. Conversely, in CNS applications, probes typically are much longer so as to reach deep portions of the brain. For example, these CNS probes can have lengths that are greater than 5 cm. Accordingly, the length of each shank 18, 20, 22, 24 can be less than 5 cm. Although the average nerve bundle thickness of an arm was described, the sizing of the length of each shank can be appropriately tailored to other PNS nerves, such as, for example, a leg nerve having a thickness of 2 cm.

[0089] In some cases, each shank 18, 20, 22, 24 can be integrally formed with the panel 14. In other words, each shank 18, 20, 22, 24 and the panel 14 can form a single monolithic component. In this way, advantageously, since each shank 18, 20, 22, 24 is not coupled to the panel 14, the mechanical integrity between the shanks and the plate is further bolstered by providing a single component (e.g., a coupling interface is removed, which can provide for a weakness between a shank and the plate). Further, an integrally formed configuration is advantageous, particularly in the neural interface field, because this allows for a better electrical interface between each shank 18, 20, 22, 24 and the panel 14 (e.g., the groups of electrical contacts 32, 34, 36, 38) because an electrical connector between a shank and the plate can be omitted. Still further, the integrally formed configuration can be desirable from a manufacturing perspective. For example, when the components are integrally formed, they can be formed out of the same material (e.g., silicon carbide), which can make manufacturing easier. Correspondingly, then, with a substantially same material, creating the electrical components in the probe 8 can be easier (e.g., doping portions of the probe).

In some configurations, the integrally formed configuration (and relative dimension of the shank relative to the plate, such as the lengths) can advantageously minimize some dimensions due to the improved mechanical stability of the shanks. Therefore, a thickness of the panel 14 (e.g., transverse to the axis 27) can be substantially the same as a thickness of each shank 18, 20, 22, 24. This can advantageously minimize the overall footprint of the probe 8. In some configurations, each shank 18, 20, 22, 24 can be substantially coplanar with the panel 14. In some cases, the panel 14 can have a substantially flat surface and each shank 18, 20, 22, 24 can have a substantially flat surface. These flat surfaces can be substantially coplanar with each other. In some configurations, this decreasing the thickness of the probe 8 including components thereof, such as, for example, the panel 14 and the shanks 18, 20, 22, 24 can be advantageous to minimize trauma to the insertion site. Therefore, some or all of the components of the probe 8, such as the panel 14 and each shank 18, 20, 22, 24 can have a thickness that is less than or equal to substantially or exactly 45 μm, less than or equal to substantially or exactly 30 μm, less than or equal to substantially or exactly 15 μm, less than or equal to substantially or exactly 10 μm. In some cases, when the probe 8 is formed out of Silicon Carbide, the thickness can be made advantageously small, while still providing relatively good strength, fracture resistance, etc., when compared to say, Silicon based probes. To that end, when the probe 8 is made out of Silicon Carbide, the probe 8 (e.g., the panel 14, each shank 18, 20, 22, 24, etc.) can have a thickness that is equal to substantially or exactly 10 μm, which can not only provide for an advantageously thin probe, but can also maintain good structural integrity while also being able to be inserted into the peripheral nerve bundle (e.g., through a sheath of the peripheral nerve bundle). In some embodiments, each shank 18, 20, 22, 24 can have different or the same lengths. For example, as shown in Figure 1A, the shanks 18, 24 and the shanks 20, 22 have substantially the same length. Each shank 18, 24, which is positioned between the shanks 18, 24 can be longer than each shank 18, 24. Stated another way, when the probe 8 includes a plurality of shanks, a shank that is positioned between a pair of shanks (e.g., the shank 22 between the shanks 18, 24) can be longer than the pair of shanks. Therefore, shanks provided on the periphery can be the shortest shanks of the plurality of shanks, whereas shanks provided internally (e.g., not on the ends) can have lengths that are longer than the shanks on the periphery. As described below, having longer shanks positioned internally and having shorter shanks on the outer periphery (e.g., side ends of the probe 8, and in particular the panel 14) can be well suited for the PNS as opposed to the CNS. For example, PNS nerve bundles can be idealized as cylinders, such that the lengths of the shanks of the probe 8 can generally follow a transverse cross-sectional dimension of the peripheral nerve

bundle (e.g., because the width of the peripheral nerve bundles changes along its transverse cross-section). Therefore, in some cases, then, each shank of the probe 8 can extend substantially through a peripheral nerve bundle.

[0090] In some cases, the probe 8 can have a concave portion 44 and a convex portion 46. In particular, as shown in Figure 1A, the panel 14 can include the concave portion 44, while the shanks 18, 20, 22, 24 can include the convex portion 46. This concave portion 44 can be positioned at a bottom end 17 of the panel 14, and in some cases, the shanks 18, 20, 22, 24 can also define the concave portion 44. For example, each proximal portion of each shank 18, 20, 22, 24 (e.g., the proximal portion being located closer to the panel 14), can follow a concave pattern (e.g., when viewed in the view of Figure 1A). In some cases, this concave pattern and the concave portion 44 can be a circle (e.g., can substantially be a circle). Similarly, each distal tip of each shank 18, 20, 22, 24 can follow a convex pattern, which again, can be a circle (e.g., can be substantially a circle). Stated another way, when the distal tip of each shank is connected a convex pattern forms that can be circle. This is shown in Figure 1A. These portions 44, 46 can be advantageous in PNS applications. For example, the concave portion 44 can follow the curvature of a peripheral nerve bundle.

[0091] In addition to the planar arrangement shown in Figure 1A, the implantable neural device 8 can be provided in a three-dimensional arrangement, for instance with the electrode shanks 18 in a staggered, box, triangle, circle, matrix, random, or other configuration, (relative to one another, for instance) rather than being linearly arranged as shown in Figure 1A.

[0092] As shown in Figure 1B, the placement of one or more electrode shanks 18 can create a matrix of electrode shanks 18, 20, 22, 24 within the nerve (e.g., a peripheral nerve bundle). Such placement can be determined by the application or the anatomy or physiology of the target nerve or nerve bundle. For example, the electrode shanks can form a 1D matrix of electrode shanks 18, 20, 22, 24 arranged in a line along a right-left axis of the implantable neural device 8, in which the electrode shanks can be of equal length and evenly or otherwise spaced. A 2D matrix of electrode shanks can be formed by varying the length or position of each electrode shank. Additionally, electrode shanks can be arranged on both surfaces of the panel of the implantable neural device 8 or along the anteroposterior axis of the 3-dimensional implantable neural device 8. Further, electrode shanks can be arranged along both the anteroposterior and left-right axes of the implantable neural device 8 with varying lengths along the longitudinal axis to form a 3D matrix of electrode shanks 18, 20, 22, 24. Further localized specificity can be achieved based on the placement of electrode contacts 16 along the electrode shanks. Such

placement can be varied along the length of the shank or varied around the front or back surface of the shanks.

[0093] The electrode shanks 18, 20, 22, 24 can also have a 3-dimensional shape, such as cone-like, pyramid-like, prism-like etc. In this way, electrode traces 12 can be located on any of the surfaces of the electrode shanks 18, 20, 22, 24. For example, in the planar case, electrode traces 12 can be located on either planar side of the electrode shank 18. As another non-limiting example, if one or more of the electrode shanks 18, 20, 22, 24 are conical, the electrode traces 12 can be evenly or otherwise spaces around the cone surface of the electrode shanks 18, 20, 22, 24. As another non-limiting example, if one or more of the electrode shanks 18, 20, 22, 24 are pyramid-shaped, electrode traces 12 can be located on one or more of the tapered faces of the pyramid.

[0094] Figures 2 and 3 show a housing 50 for the implantable neural device 8. The housing 50 can provide structural support and stability to the implantable neural device 8 and can be helpful when deploying or removing the implantable neural device 8. Further, particularly within PNS applications, portions of the probe 8 can be quite thin, which is advantageous, but which can limit the structural integrity of the probe 8. With the housing 50, however, the probe 8 can be secured, which can not only prevent translation of the probe 8 (e.g., downward translation), but can also avoid the probe 8 from flexing (e.g., the panel 14) or otherwise deviating from a planar configuration.

[0095] The housing 50 can have a generally rectangular shape, and can have curved or rounded external surfaces. These rounded exterior or peripheral surfaces can be advantageous in that they can avoid interacting undesirably with the surrounding tissue. For example, edges that have been removed, such as by rounding can avoid puncturing surrounding tissue including skin, muscle, etc. This can be particularly helpful because the probe 8 and the housing 50 (and other components) are temporarily or permanently implanted into the patient, under the skin of the patient. Therefore, avoiding issues with undesirable interactions between the housing 50 and the surrounding tissue can prevent the need for further surgical interventions. Figure 2 shows the housing 50 having various edges 52, 54, 56 that are curved (e.g., are not sharp, or do not end at a point). Particularly, the edge 52 is positioned at a top of the housing 50 (e.g., and extends laterally along the housing 50), the edge 54 is positioned along a side of the housing 50 (e.g., and extends longitudinally along the housing 50), and the edge 56 is positioned along the bottom of the housing 50 (e.g., and extends laterally along the housing 50).

[0096] In some embodiments a data cable or bundle may be provided with a cable boot configured to engage a complimentary fitting, which may be on the housing 50 or on a separate

collar body, for instance with a conventional snap or friction-based attachment mechanism such as projections, tabs, ridges or fittings. The separate collar body may can include a collar configured to hold he nerve and facilitate placement of the implantable neural device 8 in the nerve.

[0097] Additionally, the housing 50 can allow for attachment of a data cable or bundle to connect to the plurality of groups of electrical contacts 32, 34, 36, 38 (e.g., each group being an electrical bonding pad) and the housing 50. To that end, the housing 50 can include a window 58 or aperture for a cable (e.g., a data cable) to connect to the electrical contacts on the implantable neural device 8. In some cases, the window 58 can be sized, such that when the device 8 is positioned within the housing 50 (e.g., positioned within a cavity or recess within the housing 50), each group of electrical contacts 32, 34, 36, 38 are exposed, or otherwise positioned within the window 58, while other portions of the device 8, such as the panel 14, are surrounded by the housing 50.

[0098] As shown in Figures 2 and 3, the implantable neural device 8 can be inserted into a cavity 60 defined by an inner surface in the housing 50 so that the implantable neural device 8 is partially covered by the housing 50. The housing 50 can provide structural support and stability by way of the inner surface defining a slot or pocket that is sized to provide a close, snug, or secure fit around the panel 14. The housing 50 can be provided with features to hold the panel 14 in place such as a snap fit with projections, tabs, ridges or fittings that hold a bottom edge surface of the panel 14. To that end, the housing 50 can include a mechanical stop 62, which can engage with the probe 8 (e.g., the bottom end 17 of the panel 14 at one side) to block relative movement between the probe 8 and the housing 50 (e.g., block downwards translation of the probe 8, away from the bottom of the housing 50). For example, the housing 50 can include a hole 68, which can be directed into the bottom of the housing 50 and can be fluidly coupled to the cavity 60. When the probe 8 is positioned within the housing 50, the panel 14 can be retained within the housing 50, blocked from falling out of the housing 50 by the mechanical stop 62, while the shanks 18, 20, 22, 24 can extend through the hole 68 and out of the housing 50. As shown in Figure 2, the mechanical stop 62 can be implemented as an extension 64 (or a protrusion) that extends into hole 68 and which engages a side of the panel 14 to prevent the panel 14 from falling out of the housing 50. Although a mechanical stop 62 has been described, the housing 50 can include multiple mechanical stops, each of which can be situated at an opposing end of the housing 50 and which are configured to engage an opposing end of the panel 14 of the probe 8. To that end, Figure 2 also shows a mechanical stop implemented as an extension positioned opposite to the extension 62.

[0099] In some embodiments, the housing 50 can include a recess 70, which can be directed into the bottom of the housing 50. As shown in Figure 2, the recess 70 can have a shape that substantially corresponds to the shape of the concave region 44 of the probe 8. In this way, when the probe 8 is inserted into the housing 50, the recess 70 aligns with the concave region 44, such that the shanks 18, 20, 22, 24 are free to engage with the peripheral nerve bundle. Further, as described below, this recess 70 provides a mechanical engagement feature to provide coupling with other components of the broader system.

[00100] Additionally, or alternatively, the slot or pocket of the housing 50 can be sized such that it provides a tight or friction fit, optionally including projections, tabs, ridges or fittings so that, once installed, the panel 14 is prevented or inhibited from sliding out of the housing 50. In a preferred embodiment the housing 50 partially surrounds the implantable neural device 8 and, as noted, the housing 50 can have an aperture or window 58 defined by an aperture surface. The aperture or window 58 allows for attachment and electrical engagement with a data cable or bundle or other signal control electronics (not shown) and can be provided with projections, tabs, ridges or fittings, so that the data cable, bundle or other signal control electronics are held in place against the panel 14 and/or can be attached to the housing 50.

[00101] The cable (e.g., data cable), bundle or other signal control electronics can electrically couple with the electrical contacts (e.g., bonding pads) to send or receive electric signals to or from the electrode traces 12 and electrode contacts 16. In this way, the data cable can provide access to stimulate or measure signal received at each electrode contact 16 with specificity. In a non-limiting example, the data cable can include a flexible printable circuit board. The data cable can provide electrical connection to an external computer system or to a wireless transmitter that can send or receive signals to an external computer system.

[00102] Figure 4 shows an example of a cable 80 that can be engaged with and electrically coupled to the device 8. In particular, the cable 80, which can be a data cable, bundle, etc., including one or more wires to carry electrical signals to opposing ends of the cable 80, can be provided with a cable boot 82 configured to engage a complimentary fitting, which can be on the housing 50 or on a separate collar body, for instance with a conventional snap or friction-based attachment mechanism such as projections, tabs, ridges or fittings. As shown in Figure 4, the cable boot 82 can have a substantially similar shape to a cutaway on the housing 50, which is in alignment with the window 58. In other words, the cutaway can be substantially the negative of the cable boot 82. In this way, when the cable boot 82 is engaged with the housing 50 at the cutaway, the cable boot 82 mechanically couples with the housing 50 and a periphery of the cable boot 82 is flush with a corresponding periphery of the housing 50.

Correspondingly, when the cable boot 82 is mechanically coupled to the housing 50, the cable 80 electrically couples to the device 8 (e.g., the groups of electrical contacts 32, 34, 36, 38). In this way, such as during monitoring, electrical signals can flow from each electrode contact, along the corresponding trace to the corresponding electrical contact and through the cable 80. Similarly, such as during stimulation, electrical signals can flow in the opposing direction - from the cable 80, to each electrical contact, along the corresponding trace, and to the corresponding electrode contact.

[00103] In some embodiments, a separate collar body can include a collar configured to hold the nerve and facilitate placement of the implantable neural device 8 in the nerve. For example, the collar can form a mechanical or compliant hinge that is configured to wrap circumferentially around a nerve to hold the collar body in place, allowing for the probe to be inserted into the nerve. The housing 50 is provided with a surface configured to engage with a complimentary surface on the collar body. When assembled together, the combination of the housing 50, implantable neural device 8, collar body, and cable boot can form a sealed or nearly-sealed structure that prevents, reduces or inhibits a patient's body fluids from reaching the exposed collection of electrical bonding pads on the implantable neural device 8, as well as any exposed portions of the data cable or bundle.

[00104] In a preferred embodiment, the housing 50 and panel 14 are configured such that when engaged to the cable boot and/or the data cable and/or a nerve collar, the panel 14 is held in a fixed position, and in a further preferred embodiment, the panel 14 is held in a fixed but moveable position for instance where the panel 14 can be manually moved but otherwise remains in a fixed position relative to the cable boot and/or the data cable and/or a nerve collar. In particular, any of the housing 50, panel 14, cable boot, data cable and/or nerve collar, can each be provided with their own surfaces and/or apertures that accommodate complimentary adjacent surfaces of the housing 50, panel 14, cable boot, data cable and/or nerve collar, as applicable to assist in maintaining the relative position of these components. Additionally, the surfaces can be provided with conventional snap or friction-based attachment features such as projections, tabs, ridges or fittings to assist in or facilitate maintaining the relative position of these components.

[00105] In some embodiments, the collar body includes an inner surface that fits to the outer surface of the housing 50. When the housing 50 is inserted into the collar body the electrode shanks can extend into one or more nerves. At the same time, the outer surface of the housing 50 presses against a collar grip foot so that they rotate, moving a lower end of the collar grip

foot so that teeth or other projections on the collar grip foot can engage collar grip teeth on the collar, temporarily (or for prolonged usages), locking the collar in place around the nerve.

[00106] Figure 5 shows an example of an implantable peripheral nerve system 100 for placement in the body of a patient for receiving and sending electrical signals. This implantable peripheral nerve system 100 can be an implantable neural collar system. The system 100 can include an electrode housing 50, a support 108 that can engage with an support the electrode housing 50 and can surround a peripheral nerve (e.g., a peripheral nerve bundle) when implanted. In some cases, the support 108 can include a collar neck 114, and a collar 116, described more below. For the purposes of this description, a longitudinal axis 101 extends in the longitudinal direction that travels through the collar, aligned with the nerve axis when a nerve (e.g., a peripheral nerve bundle) is in place. A vertical axis 103 extends in a proximal/distal direction, where the distal end engages the nerve bundle in use and the proximal end provides access to control the device. The collar neck 114 and electrode housing 50 can be considered to be located at the proximal end of the device along vertical axis 103 and the collar 116 can be considered to be located at the distal of the device along the vertical axis 103. The axis 105 describes the circumferential direction that loops around the collar 116 or around the circumference of a nerve or nerve bundle, when in use. The radial axis 107 describes any radial axis extending perpendicularly and radially from the longitudinal axis 101.

[00107] The electrode housing 112 can be implemented in a similar manner as the housing 50 and can include a probe 120 positioned therein, which can include one or more electrodes 122 (e.g., electrode shanks) each of which being configured to contact one or more nerves (e.g., peripheral nerves, a peripheral nerve fiber, etc.) to transmit electrical signals while the system is in use. The probe 120 can be fixed inside the electrode housing 112 in such a way to leave electrical contacts exposed on both ends. For example, the probe 120 can include one or more elongated electrodes 122 each adapted to engage a peripheral nerve (e.g., the same peripheral nerve bundle). Each electrode 122 has at least one electrically conductive electrode trace, and each electrode trace is configured to electrically couple a respective electrode contact disposed on the surface of the respective elongated electrode 122. Each electrode contact can be arranged to electrically couple with the nerve and can simply be the exposed end of the electrode trace or can be an electrically conductive contact member affixed to the electrode trace and outer surface of the electrode 122. The electrode contact can transmit electrical signals to and/or from the nerves in use. In addition to the electrode contact, each electrode trace can also have an electrical bonding pad 124 for putting the electrode trace in electrical contact with a data cable 132 and/or cable bundle. Preferably, the at least one elongated electrode 122 is formed from

silicon carbide, and can include an SiC coating configured as an insulator. In certain embodiments, both the electrode 122 and the base of the probe 120 are formed from silicon carbide, and can include an SiC coating configured as an insulator.

[00108] The collar neck 114 can include a collar package 130 sized to receive the electrode housing 112. For example, the collar package 130 can include an opening, or slot 136, in the proximal end through which the electrode housing 112 can slide down into place, for example along axis 103. The slot 136 can be defined by an interior surface 138 and can have an oval or square cross sectional shape, or other shape complementary with the electrode housing 112, with or without or curved or right angled corners. The slot 136 within the collar package 130 can be sized to provide a close, snug, or secure fit around the electrode housing 112 to keep it in place and the interior surface can be vertical or tapered with the opposite sides of the vertical surface coming together. The collar package 130 can also include features to hold the electrode housing 112 in place, such as a snap fit with projections, tabs, ridges, or fittings that hold a distal edge surface of the electrode housing 112. The slot 136 can also provide a tight or friction fit, optionally including projections, tabs, ridges, or fittings, such that the electrode housing 112 is prevented from sliding out of the collar package 130 once in place.

[00109] As will be described in further detail, when the system 100 is in place, the electrodes 122 of the probe 120 can be embedded into the target nerve (e.g., a peripheral nerve) as the electrode housing 112 is placed into the collar package 130. The collar package 130 can further include a fitting that is configured to engage a cable boot 134 coupled to a data cable 132. The cable boot 134, which can snap into the collar neck 116 to provide secure contact between the probe 120 (e.g., the bonding pads 124) and a data cable 132, which can send and/or receive signals to and/or from the probe 120. The fitting can create a seal between the cable boot 134 and the collar package 130 to protect the electrical connections from the surrounding environment. The collar neck 114 can further include collar grip feet and one or more grip hook recesses, which will be described in further detail below.

[00110] The collar neck 114 can be fixed to or detachably coupled to a collar 116 that is configured to receive a nerve or nerve bundle in use. The collar 116 can connect to the collar neck 114 at a subset or first portion 144 of the length of the collar neck 114 along axis 101. For example, the collar 116 can connect to the collar neck 114 by connecting to the collar package 130, which can be centered within or otherwise located along the collar neck 114 along longitudinal axis 101. The collar package 130 can extend further along vertical axis 103 towards the distal end of the device (i.e., towards the collar 116) to make contact with the collar 116 while leaving a gap or space 142 between the bottom surface of the collar neck 114 and

proximal surface 140 of the proximal end of the collar 116. In this way, the collar 116 can be spaced from a second portion of the collar neck 114 to create the space 142 or gap configured to receive the collar 116. The space 142 can have a thickness or height defined from the distal surface of the collar neck to the proximal surface of the proximal end of the collar. The thickness of the space 142 can be larger than the thickness of the distal end of the collar 116. In use, the space 142 will be able to receive the distal side of the collar 116 when the collar 116 is deployed, during which the distal end of the collar 116 can wrap over the proximal surface of the proximal end of the collar 116.

[00111] The collar neck 114 can have a circumferentially rounded distal surface, especially within the first portion 144 of the collar neck 114 where the collar 116 connects to the collar neck 114. This rounded surface can provide a rounded backbone to fit against the collar 116 when the collar 116 is coupled to the collar neck 114. Such rounded shape of the collar neck 114, and thus the distal end of the collar 116, can provide a rounded generally cylindrical space inside the collar 116 that can receive the nerve when in use. This proximal end of the collar 116 can provide a part of the coiled collar 116 that wraps around the nerve when deployed and can wrap to overlap the opposite side of the collar 116.

[00112] In general, the collar 116 can be flexible with one or more flexible fingers 150 that extend from the main body of the collar 116. The collar 116 can at least partially wrap around a circumference of one or more nerves (e.g., a peripheral nerve). The collar 116 can fully wrap around a circumference of one or more nerves such that parts of the collar 116 overlap. In some cases, the fingers 150 can hook around one or more nerves or nerve bundles (e.g., a peripheral nerve, or a peripheral nerve bundle).

[00113] The body of the collar 116 can further include an electrode tip slot 152, which can receive the distal tips of the electrodes 122 when the system is in the engaged with a peripheral nerve. The electrode tip slot 152 can be defined by an interior surface defining a slot or divot within the collar 116. The electrode tip slot 152 can be dimensioned to receive the distal ends of the electrodes 122 and can include several slots to receive each electrode 122. The electrode tip slot 152 can extend partially through the thickness of the collar 116. Thus, in use, the electrode tip slot 152 can protect the distal tips of the electrodes 122 from contacting other nerves or anatomy (e.g., muscles, bones, connective tissue, etc.) that are not targets of the electrodes.

[00114] The fingers 150 can be spaced apart along the longitudinal axis 101, providing a gap 158. The gap 158 can be dimensioned to fit the first portion of the length of the collar neck 114 along longitudinal axis 101, without limiting circumferential movement of the collar 116.

For example, the gap 158 can be dimensioned to fit the collar package 130, which attaches the collar neck 114 to the collar 116. In this way, the distal end of the collar 116 is permitted to wrap around the proximal end of the collar 116 while the fingers 150 insert into the space 142 between the proximal surface of the proximal end of the collar 116 and the collar neck 114. One or more of the fingers 150 can include a fastener 182, which can be used to hold the collar 116 in a closed configuration, as will be described in further detail below. For example, the fastener 182 can line the inner surface of each finger 150 adjacent to the gap 158.

[00115] Referring now to Figure 6, a perspective cut-away view of the system 100 is shown, which can include a housing (e.g., housing 50), a collar body, and a collar. In Figure 6, it is shown that the collar package 130 of the collar neck 114 has a slot 136 that is configured to receive the electrode housing 112. The distal end of the collar package 130 can also have one or more holes or spaces 154 that are dimensioned so that the electrodes 122 can pass distally through the collar neck 114. The holes 154 can extend from the slot 136 through the distal end of the collar neck 114 to the distal surface of the collar neck 114 and can be defined by one or more interior surfaces. For example, a distal side of the collar package 130 can include a single hole (e.g., 154) that fits all of the electrodes122, several separate holes that each receive one of the electrodes 122, or multiple holes that receive a subset of electrodes 122. The holes 154 can be smaller in area than the proximal opening of the slot 136 such that the distal end of the collar package 130 can hold the electrode housing 112 in place.

[00116] Similarly, the proximal end of the collar 116 can include holes 156 that allow the electrodes to pass distally through the collar 116. The collar holes 156 can extend through the full thickness of the collar 116 from the proximal surface of the proximal end of the collar 116 to the distal surface of the proximal end of the collar 116. The collar 116 can include a single hole (e.g., 156) that fits all of the electrodes 122, several separate holes that each receive one of the electrodes 122, or multiple holes that receive a subset of electrodes 122. The collar package holes 154 can align with the collar holes 156 such that the electrodes 212 can pass through both the distal end of the collar package 130 and the proximal end of the collar 116. However, while the collar package holes 154 and collar holes 156 can be the same size and shape, they are not required to be so, as some or all of the holes 154 or 156 can be larger than the size of the electrode 122 cross-sectional area. Holes 154 or 156 can be defined by an interior surface and can be vertical or tapered and be oval shaped or squared with rounded or right angled corners.

[00117] In use, the electrode housing 112 can be slid distally into the slot 136 while the electrodes 122 can pass distally through the collar package holes 154 and the collar holes 156

such that the electrodes 122 engage with the nerve 160, when the nerve 160 is in place. The collar neck 114 can further include one or more locking feet 170. The locking feet 170 can have a back side facing the inner portion of the slot 136 and a front side opposite of the back side and facing away from the slot 136. The front side can retain a fastener 172. For example, the front side of the locking feet 170 can be lined with grip teeth that are configured to engage with grip teeth lining a portion of the collar fingers 150, as will be described further below.

[00118] The locking feet 170 can be flexible and biased towards the slot 136. For example, the locking feet 170 can have flexible legs 174 that extend proximally from the locking feet 170 to connect the locking feet 170 to the collar neck 114 and bias the locking feet 170 towards the slot 136, such that they protrude into the slot 136 when the electrode housing 112 is not in place. The flexible legs 174 can be constructed with a spring or with a flexible material, such as plastic. The flexible legs 174 can allow for the locking feet 170 to be pushed away from the slot 136 when the electrode housing 112 is slid into the slot 136, whereby an outer surface of electrode housing 112 presses against the back side of the locking feet 170, thereby pushing the locking feet away from the slot 136. Such motion can cause the fastener 172 to engage with a complimentary fastener 182 on the collar 116, as will be described in further detail below.

[00119] Because the locking feet 170 are biased towards the slot 136, removing the electrode housing 112 can cause the locking feet to retract back into or towards the slot 136, which can disengage the fastener 172 from its complimentary fastener 182. Further, the bias towards the slot 136 of the locking feet 170 creates inward pressure from the back surface side of the locking feet 170 onto the outer surface of the electrode housing 112. This pressure helps maintain the position of the electrode housing 112 relative to the collar neck 114. The electrode housing 112 can include ridges, teeth, or a frictionally engaging outer surface to engage a similar feature on the back surface side of the locking feet 170 and further hold the electrode housing in place relative to the collar neck 114.

[00120] The complimentary fasteners 182 can be located on the collar fingers 150, for example along the inner surface of the fingers 150 adjacent to the gap 158. The fasteners 182 can extend along the whole length of the inner surface of the fingers 150, which allows for a variable diameter of the collar 116 in the deployed position (i.e., coiled and wrapped around the nerve 160). When the collar 116 wraps around the nerve 160, a portion of the collar fasteners 182 will align with the collar neck fasteners 172 allowing the fasteners to engage with one another to lock the collar 116 in the coiled and engaged position. These fasteners help to arrest further movement of the collar 116, allowing a surgeon to select a preferred diameter of the deployed collar 116 before instance based on the diameter of the target nerve or nerves 160.

[00121] Placement of the electrode housing 112 within the slot 136 can lock the collar 116 into an engaged configuration. The locking function can be achieved by fasteners (e.g., 172 and 182) coupled to the collar 116 and the collar neck 114. In particular, the collar neck 114 can have one or more fasteners 172. For example, the fasteners 172 can include grip teeth, as shown in Figure 6. The grip teeth can protrude from a surface in a pattern that is inverse to the complimentary receiving fastener 182. As a non-limiting example, the grip teeth surface can have a zig-zagged pattern, wherein the protrusions have a triangular cross section shape, for instance with 60° angles at their peaks, and the grooves are triangular with 60° angles at their base. In this example, the complimentary fastener 182 can include grip teeth with the same pattern, such that the protrusions of fastener 172 are received by the grooves of the fastener 182, and vice versa. The grip teeth can also have a triangular pattern of different angles. Such triangular shaped protrusions and grooves of the grip teeth can advantageously allow for slight motion in the circumferential direction as the fasteners engage together. In this way, the grip teeth are not required to be aligned with the complimentary grip teeth when the locking process begins, and they will align by sliding or passing along the surfaces of the triangles. However, the grip teeth can alternatively have protrusions, ridges and grooves of other shapes and sizes, or another frictionally engagement which can be complimentary (i.e., opposite) on the receiving fastener 182.

[00122] As previously described, the collar 116 can be provided in an open, hook-like position when undeployed. For example, in the undeployed position, the collar 116 can have a "C"-like shape with round proximal and distal ends connected by a nearly straight mid-section. The collar 116 can be flexible and biased towards the undeployed, open position. It can be constructed from a layer of flexible material with a thickness that can be constant or vary along the length of the collar. In this undeployed positioned the hook-like fingers 150 of the collar 116 can hook a nerve 160 or nerve bundle to begin engaging the nerve 160. Once the nerve 160 is in place within the open collar 116, the collar 116 can be wrapped around the nerve 160 in a circumferential direction. The collar 116 can be pushed in a circumferential direction, which can cause the collar 116 to coil or wrap around the nerve 160 (e.g., like a spiral), fitting the collar fingers 150 into the space 142 defined by the proximal surface of the proximal end of the collar 116 and the distal surface of a portion of the collar neck 114. The collar 116 can fully surround the circumference of the nerve 160 to keep it in place within the system 100.

[00123] When the collar 116 is wrapped around the nerve 160, the collar fastener 182, or at least a portion of the collar fastener 182, will be aligned within the space 142 to receive the collar neck fastener 172, thus locking the collar 116 into place around the nerve 160. The

electrode housing 112 can be inserted into the slot 136 using a plunger. The insertion of the electrode housing 112 will push the locking feet 170 into an engaged position in which the collar neck fastener 172 engages with the collar fastener 182, as previously described. This will maintain the collar 116 in the wrapped position while the electrode housing 112 is in place within the slot 136. Also, while the electrode housing 112 is positioned in the slot 136, the electrodes 122 can engage with the nerve 160 that is positioned within the collar 116. The tips of the electrodes 122 can be received by the electrode tip slot 152 on the distal end of the device. Referring again to Figure 6, the collar neck 114 can further include one or more grip hook recesses 184 that can receive a portion of a surgical device for deployment.

[00124] In some embodiments, as described above, the support 108 can be configured to at least partially surround the nerve 160 (e.g., a peripheral nerve), when deployed. Although the above description includes references to coiling the collar 116 of the support 108 around itself (e.g., in a spiral) with the nerve 160 positioned therein (e.g., with the collar 116 surrounding the nerve 160), in other configurations, the collar 116 can engage the nerve 160 in a different manner. For example, the one or more fingers 150, being compliant can be flexed (or hinged) in a distal direction prior to deployment of the collar 116. Then, with the collar 116 positioned around the nerve 160 (e.g., the nerve 160 positioned within a bore defined by the collar 116), the fingers 150 can retract back to surround the nerve 160. In this way, with the fingers 150 in the position shown in Figure 5, the fingers 150 can prevent the nerve 160 from falling out of the collar 116 (e.g., translating in a distal direction).

[00125] In some embodiments, the support 108 can ensure that that the housing 112 (with the probe positioned therein 120) is deployed in the desired position. As described above, inserting the probe 120, such that the electrodes 122 are positioned at different locations along a transverse axis of the support 108 (e.g., relative to the longitudinal axis) can ensure that the electrodes 122 engage the nerve 160 at the same cross-section (e.g., an axial cross-section, which can be generally circular). In this way, rather than having the electrodes 122 engage the peripheral nerve with each electrode being at a different longitudinal position along the peripheral nerve 160, having the electrodes 122 engage the nerve 160 at substantially the same longitudinal location can be advantageous for maximum signal harvesting. For example, the electrodes 122 being positioned at different longitudinal locations can cause corresponding electrode contacts (e.g., contacts on different electrodes 122 but at the same axial distance) to harvest the same neural signal from the same neural fiber. Conversely, with the electrodes 122 engaging the nerve 160 at substantially the same longitudinal location of the nerve 160 can ensure that each electrode is in electrical contact with its own fiber, which can allow the probe

120 to harvest more unique nerve signals. To that end, the support 108 can include a slot (e.g., the slot 136) that has a width that extends in a transverse direction to the nerve 160 (e.g., when the nerve 160 is secured by the support 108). Correspondingly, the slot can extend in a transverse direction relative to the longitudinal axis 101. This slot can then receive the electrode housing 112, with the width of the electrode housing 112 aligning with the width of the slot. In some embodiments, this slot can be formed as within a package (e.g., the collar package 130). In this case, the slot can include a protrusion that can engage with the recess of the electrode housing 112 (e.g., the recess 70), which can ensure correct engagement between the electrode housing 112 and the support 108. Similarly, this slot can include one or more flat surfaces that provide an abutment for engagement with corresponding lower surfaces of the electrode housing 112 (e.g., surfaces on the opposing ends, not include the recess 70).

[00126] In some embodiments, the location of the slot of the support 108 can be advantageous. For example, the slot being positioned above the nerve 160 when the support 108 engages with the nerve can provide an relatively easy access point for insertion of the housing 112 (and the probe 120 positioned therein) and can ensure that the electrodes 122 are in the desired orientation (e.g., being coplanar with a cross-section of the nerve 160). Correspondingly, then, a component that forms the slot of the support 108, such as, the collar package 130, can be positioned above the nerve 160 (e.g., when the support 108 secures the nerve 160). Similarly, this component can be positioned on a top of the support 108 (e.g., above or integrally formed with the collar 116).

[00127] In some embodiments, and as shown in Figure 6, the support 108 can include a lock 190 that engages with the electrode housing 112 to constrain movement between the electrode housing 112 and the support 108. For example, when the lock 190 is engaged, such as the lock 190 contacting one or more sides of the electrode housing 112, the lock 190 blocks the electrode housing 112 from exiting the slot (e.g., the slot 136), such as by blocking translation out of the slot. The lock 190 can be implemented in different ways. For example, as described above, the lock 190 can be implemented as one or more locking feet (e.g., the locking feet 170). Specifically, Figure 6 shows a first locking foot on one side and second locking foot on an opposing side, each of which are biased towards a locking position, such that when the housing 112 (e.g., with the probe 120 positioned therein) is inserted into the slot, the feet retract, but are otherwise forced against the housing 112 to ensure the housing 112 does not move significantly. In some cases, the housing 112 can include respective recesses, each of which being configured to receive a portion of a locking foot. In this way, the locking foot can, after retracting, be forced into the recess, which can provide a better securing of the housing 112

relative to the support 108. As another example, the lock 190 can be implemented as a threaded fastener, such as a bolt that threadingly engages the housing 112 to the support 108. As yet another example, the housing 112 can include a magnet (or can be partially formed out of a magnetic material) and the support 108 (e.g., at the slot, such as the slot 136) can include a corresponding magnet (or magnetic material). In this way, not only can the magnets help align and constrain the housing 112 relative to the support 108, but the attraction of the magnets can help facilitate insertion of the probe 120 into the nerve 160. Stated another way, the magnets can provide a semi-automatic deployment mechanism.

[00128] In some embodiments, portions of or the entire system 100 can be implanted in the subject. For example, after the support 108 engages with and surrounds the nerve 160 and with the electrodes 122 engaging the nerve 160 (e.g., puncturing the nerve 160), and with the cable boot 134 engaging the support 108 (e.g., the collar package 130 and the housing 112) thereby electrically coupling the cable 132 (e.g., a data cable) to the probe 120, these components can remain in the subject during usage of the system 100. For example, in some cases, the cable 132 can be implanted under the skin of the subject. This implantation of the system 100 can allow for prolonged usage of the system 100. In other configurations, the implantation of the system 100 can be temporary, such as during harvesting of neural signals.

[00129] Figure 7 shows a block diagram of a nervous system interface system, which provides a non-limiting example of a system that can be used to stimulate and receive signals from nerves using an electrode design as described herein. The system includes a probe 302 that is capable or recording neural activity and administering electrical stimulation to a target. For example, the probe can include the device 8 as previously described. The probe 302 can be in communication with a controller 304 via electrical or wireless connections 306a and 306b. For example, the connections 306a and 306b can include data cables coupled to the probe 302 via a cable boot, as previously described.

[00130] As shown in Figure 7, the controller 304 can generally include a processor 308, a memory 310, such as flash or other type of memory, a communication module 312, signal generation modules 314, signal detection modules 324, a clock module 316, a power source 320, and a control module 318. The controller 304 can also include various connections, terminals, or wireless communication connection, for transmitting signals generated by the signal generation module 314 or the control module 318, or signals measured by the signal detection module 324. Any or all of these elements can be implanted into a patient's body, carried/worn externally to the body, otherwise outside of the body, or some combination thereof with appropriate connections (such as wired or wireless) between elements.

[00131] In some implementations, the controller 304 can also include an input for accepting user selections, operational instructions and information, as well as an output or display for providing a report. Specifically, the input can include various user interface elements, such as a mouse, keyboard, touchpad, touch screen, buttons, and the like. The input can also include various drives and receptacles, such as flash-drives, USB drives, CD/DVD drives, and other computer-readable medium receptacles, for receiving various data and information. To this end, the input can also include various communication ports and modules, such as Ethernet, Bluetooth, WiFi, etc. for exchanging data and information with various external computers, systems, devices, machines, mainframes, servers or networks.

[00132] The processor 308 can be configured or programmed to perform a variety of functions for operating the controller 304 using instructions stored in memory 312, in the form of a non-transitory computer readable medium, or instructions received via input. In some implementations, the processor 308 can control the sending and receiving of instructions and operational parameters (for example, via a wireless transcutaneous link in the communication module 312), the storage of the operational or stimulation parameters and instructions in memory 310, the transmission of the operational parameters to signal generators in the signal generation module 314, the selective triggering of the signal generators to provide electrical, and other stimulations, to various regions of the nervous system or tissues of a subject, as well as synchronizing various functions using the clock module 316. For instance, the processor 308 can communicate with the clock module 316 to determine the timing, phase lag, and synchronization of various stimulations. The processor 308 can also communicate with the clock module 316, as well as other hardware and digital logic circuitry, to accurately store activation times in memory 310 and provide activation counts. By way of example, the processor 308 can be a programmable microprocessor or microcomputer.

[00133] The signal generation module 314, in communication with the processor 308, can include a number of signal generators for providing activating signals to the probe 302. In some implementations, each of the electrode traces of the probe 302 can be individually controlled using separate signal generators. The signal generators can be independently operated, either sequentially or concomitantly, by the processor 308, to provide stimulation signals with various intensities, frequencies, phases, pulse widths, durations, and waveforms. In some aspects, the signal generators can be controlled to provide stimulations to various nerves or nerve regions substantially concurrently, using selected inter-pulse time delays. For instance, a first stimulation can be provided to a first region in the subject's nerve, while a second stimulation can be provided to a second region. In addition, in some implementations, the signal generation

module 314 can include an output sensing circuit to monitor contact output, as well as other fail-safe mechanisms.

[00134] In some aspects, the stimulation sequence determined or selected by the processor 308 can be a pulsed stimulation sequence that includes first stimulation to the first region and a second stimulation to the second region, with the stimulations being timed to be substantially concurrent and separated by a controlled inter-pulse time delay. Herein, substantially concurrent generally refers to the stimulations being initiated at approximately the same starting time. In some aspects, the stimulations can be initiated within 5 seconds or less of each other, although other values can be possible (e.g., between about 0 to 100 milliseconds, and in some cases, more). The processor 308 can then direct the signal generation module 314 to deliver the pulsed stimulation sequence.

[00135] In some aspects, the processor 308 can receive signals corresponding to neuronal activity in a first region and a second region of a subject's peripheral nervous system as input. The processor 308 can use the received signal to localize each of the electrode traces or electrode contacts within the subject's nerve. The processor 308 can also analyze the signals to determine a level of connectivity between the regions, for example, by computing various metrics indicative of connectivity. Based on the analysis, as well as other provided or determined information, the processor 308 can then determine or select a stimulation parameter configured to control, increase, decrease, or otherwise alter the connectivity. In some aspects, the connectivity can be increased or decreased until the measured connectivity levels pass a predetermined threshold. In some aspects, the processor 308 can receive such information from various input elements configured on the controller 304, as described, or alternatively from an external or remote device, computer or system, by way of the communication module 312. The processor 308 can also access a reference or database, as described, stored locally in the memory 310, or at a storage location. In some implementations, the processor 308 can operate in an open-loop or a closed-loop fashion to control connection activity between PNS regions in a subject.

[00136] The processor 308 can also use the measured signal to determine instructions for one or more external devices 322 and control the external device 322 using the control module 318. For example, the external device 322 can include a robotic or bionic limb and the control module 318 can be used to control motion of the robotic limb.

[00137] The signal detection module 324 can include various hardware and be configured to detect neurological signals acquired using the probe 302. For instance, the signal detection module 324 can include various analog-to-digital converters, voltage/current meters, optical or

magnetic or physical sensors, amplifiers, filters, and other elements. Signals from the signal detection module 324 can then be provided as input and processed by the processor 308. Alternatively, the signals can be stored in the memory 310 and subsequently accessed/processed by the processor 308.

[00138] The signal detection module 324 can receive sensory data from the probe 302 or from another external device 322. For example, the sensory data can include electrical signals measured by the probe 302. The sensory data can also include data measured by one or more external devices 322 that provide additional signal inputs to the system. For example, the external devices 322 can include a pressure sensor, microphone, accelerometer, gyroscope, camera, etc. As a non-limiting example, the sensory data can include pressure data measured by a bionic hand, indicating the pressure with which the bionic hand touches an object. The external device 322 can also include a muscle probe that measures excitatory signals in the muscle, which can be related to signals in the PNS. The external device 322 can also include a central nervous system probe that measures electrical activity in the central nervous system. Such sensory signals can be processed by the processor 308 and returned to the nervous system via the signal generation module 314 and probe 302, for example. The sensory signals can also be used to provide feedback to the external device 322 (e.g., bionic hand) via the control module 318.

[00139] In some implementations, the controller 304, along with the probe 302, can be part of a standalone stimulation system. Alternatively, the controller 304 can be a wearable or implantable unit that is programmable or configurable using an external device, computer or system. To this end, the communication module 312 can be configured to send and receive various signals, as well as receive power. Specifically, the communication module 312 can include an antenna, or an input-output wire coil, a receiver and transmitter, data converters, as well as other hardware components. As a non-limiting example, the receiver and transmitter can be configured to receive and transmit radio-frequency (RF) signals. In some implementations, the antenna can be configured for transcutaneous wireless two-way communication with an external wearable device, sending and receiving signals when the external wearable device is placed in close proximity. The communication signals can be transmitted through magnetic induction and include information for operating and/or programming the processor 308. For instance, the communication signals can include triggers or command signals for generating stimulations. In some aspects, transmitted signals can also be configured to power or recharge battery components powering the controller 304. The antenna can be connected to a receiver and transmitter, which in turn can be connected to serial-

to-parallel and parallel-to-serial data convertors, respectively. Any information sent or received, as described, can then be processed by the processor 308.

[00140] The controller 304 can be powered by an internal and/or external power source 320. For example, an internal source can include a standard rechargeable battery, comparable to batteries used in implantable devices (e.g., pacemakers). Alternatively, or additionally, the internal power source can include a capacitor in combination with a regulator, such as a single ended primary inductor converter or dc-dc converter, that together can generate a constant current or voltage output for short periods of time. In some implementations, the capacitor can be charged by an external wearable device. As such, the controller 304 can include an induction coil, or thin, tightly wound wire that allows for RF telemetry and/or battery recharge by an external wearable device, configured either as part of the communication module 312, or as separate hardware. Other methods of charging can also be utilized.

[00141] Figure 8 shows an example of a system 400, which can be specific implementation of the various devices and systems described herein. For example, the system 400 can include components, features, etc., of the systems 100, 300. The system 400 can include an implantable peripheral nerve system 402, a computing device 404, and a prosthetic limb 406. The system 402 can be implemented in a similar manner as the system 100. For example, the system 402 can include a probe including one or more electrodes, an electrode housing securing the probe, and a support that surrounds the peripheral nerve 408. As shown in Figure 8, the one or more electrodes of the probe are inserted into the peripheral nerve 408. The computing device 404 can be implemented in a similar manner as the controller 304 and can be in communication (e.g., wireless communication) with the system 402 and the prosthetic limb 406. For example, the computing device 404 can receive a signal (e.g., information) from the system 402 indicative of one or more peripheral nerve signals (e.g., motor signals, temperature signals, pressure signals, etc.), can analyze the signal (e.g., information), and can cause the prosthetic limb 406 to move, based on the signal. In some embodiments, the prosthetic limb 406 can be a robotic limb, which can include one or more moveable components to cause movement of the prosthetic limb 406. For example, the prosthetic limb 406 can include appendages 410, 412. Each appendage 410, 412 can include one or more motors, actuators, etc., configured to move the appendage 410, 412 with various degrees of freedom. Although Figure 8 shows each appendage 410, 412 having two motors, each appendage 410, 412 can have other numbers of motors (e.g., corresponding to other numbers of degrees of freedom for the specific appendage).

[00142] Figure 8 illustrates a specific configuration where a subject has a missing hand. In this case, the system 402 engages with the peripheral nerve 408 that is the radial nerve of an arm 414 of the subject. Correspondingly, the prosthetic limb 406 is a prosthetic hand where each appendage 410, 412 is a finger. In this case, the probe of the system 402 receives a peripheral nerve signal from the radial nerve. Then, the system 402 (e.g., a controller of the system 402) can transmit the peripheral nerve signal to the computing device 404, where the peripheral nerve signal can be analyzed (e.g., by the computing device 404). At this point, the computing device 404 can cause the prosthetic hand to move (e.g., an appendage), based on the peripheral nerve signal (e.g., an analyzed peripheral nerve signal). For example, the peripheral nerve signal can be a motor signal, and thus the computing device 404 can cause the prosthetic hand to move. As another example, the peripheral nerve signal can be a pressure signal, and thus the computing device 404 can cause the prosthetic hand to grip an object more tightly. Although the system 400 has been illustrated with respect to the specific configuration of a missing hand, these systems are applicable to various other prosthesis (e.g., a leg, an arm, a knee, a foot, etc.). Further, although a prosthesis is described and shown, in other configurations, the prosthesis can be replaced with another external device, such as a robotic arm (e.g., separate from the subject). In this way, the subject can, for example, move an object without having to wear a prosthesis. In some embodiments, the computing device 404 can be incorporated within the prosthetic limb 406 (or other external device, such as a robotic arm). In this way, the system 100 can communicate directly with the prosthetic limb 406 (or other external device), which can simplify the system and avoid requiring the subject to carry around, wear, or be implanted with the computing device 404.

[00143] Figure 9 shows a flowchart that illustrates a method for using the electrode design described herein for nerve stimulation and/or measurement of nerve signals. An example process 800 is shown for interfacing with the nervous system of a subject. The implantable neural device can be deployed in block 802. For example, the implantable neural device 8 can be implanted into a subject such that the electrode shanks 18, 20, 22, 24 engage one or more peripheral nerves. The collar can be used to maintain the device in place. Such deployment can include a surgical procedure to access the PNS of the subject.

[00144] Localization of the electrode contacts (e.g., 16) of the deployed device can optionally occur in block 804. For example, the system 300 can be used to alternatingly stimulate the nerve using each of the electrode contacts individually and measuring the response. For example, the response can be measured by the device using the system 300. Additionally, or alternatively, the response can include a verbal or physical response from the

subject that can be manually recorded by the subject or other user or automatically recorded by an external device, such as a pressure sensor, microphone, accelerometer, etc. The response can also be measured with another external device used to measure electrical signals that indicate neuronal responses, such as electroencephalogram (EEG) or another tool.

[00145] In block 806 the implantable neural device can be used to send or receive electrical signals to or from one or more nerves. For example, each electrode can be used to stimulate the nerve or nerves in contact with the electrode contact. As a non-limiting example, stimulation or activation can be used to induce muscle movement or simulate sensations, in which the signals can be received by the nerve and sent to the CNS. The ability to send and receive signals to and from the nerves can also facilitate bi-directional communication between, for example, the localized nerves and the CNS, a control system, an external device, etc. Signal transmission can be localized such that signals can be sent or received from each individual electrode trace, providing high degrees of freedom in the stimulation pattern and high specificity in the feedback measurement. Electrical stimulations can be monophasic or biphasic, with pulses having any waveform shape. Also, stimulations can be pulsed, continuous, or intermittent in the form of current or voltage, light, magnetic, thermal, or sonic energy, and so on, having various amplitudes, frequencies, periods, waveforms, durations, phases, polarities, and so on, which subsequently produce an electrical impulse within the nerve. The electrical signal can be in the form of a voltage. The voltage can be a function of time with amplitude and/or frequency modulation. Neuronal responses can also be measured by measuring the current through, or voltage across, the nerves.

[00146] In one embodiment, methods of manufacturing an implantable neural device are provided. The methods can include one or more steps including: providing an electrode with at least one conductive layer composed of polycrystalline or monocrystalline SiC; and layering over the electrode an insulator, such as an α-SiC coating as described herein. The insulator can be provided in such a way that it also creates the electrode shanks as described herein. The electrode shanks can be formed or provided with an exterior surface having a cross sectional area that is greater near the top or proximal end of the shank than at the distal end. The shanks can have a pointed distal end. The shanks can be conical, pyramidal, generally flat with optional rounded longitudinal edges, or that has a cross section that is circular, square, triangular, pentagonal, hexagonal or oval-shaped. The methods can also include etching or removing a portion of the SiC coating to reveal one or more electrode contacts.

[00147] Figures 10-14 show steps for creating electrodes and, in particular, show cross-sectional views of neural implant layers for four different example electrodes. Depicted are:

4H-SiC Neural Implant, 3C-SiC on Si Neural Implant, 3C-SiC on SOI Neural Implant, and C sandwiched in *a*-SiC Neural Implant.

[00148] As shown in Figure 10, the 4H-SiC Neural Implant includes an N^{++} electrode mesa layer over a p-type base layer over a bulk substrate. As a non-limiting example, the bulk substrate can include an N bulk substrate, as shown. The bulk substrate can also be configured from a P, or semi-insulating type bulk substrate.

[00149] The 3C-SiC on Si Neural Implant can include an N^{++} electrode mesa layer over a P-type base layer over an N or P Si substrate.

[00150] The 3C-SiC on SOI Neural Implant includes an N^{++} electrode mesa layer over a P-type base layer over an SOI layer over an N or P Si substrate.

[00151] The C sandwiched in *a*-SiC Neural Implant includes a C conductive film, such as pyrolyzed photoresist film (PPF) over an *a*-SiC (on Si or SOI) layer over an N- or P-type Si substrate. Here the C layer can be replaced with heavily doped polycrystalline SiC. This C layer can also be a glassy carbon or graphene layer – the main idea being that a conductive C film, very thin with respect to the *a*-SiC top and cap layers, is used to conduct electrical signals to and from the nerve.

[00152] Figure 11 shows the etch of the electrode (top) layer on each of the four example electrodes resulting in removal of portions of the electrode layer to form a mesa-type conductor. In particular, Figure 11 shows a cross-sectional view of example neural implant layers similar to Figure 10 with portions of the N^{++} layer or C conductive film etched away to form the electrode mesa. The mesa provides a flat surface of the N++ layer or C conductive film along a portion of the electrode cross-section. In this way, the mesa structure protrudes from the p-type base layer

[00153] Figure 12 shows a cross-sectional view of example neural implant layers similar to Figures 10 and 11 with an *a*-SiC insulator coating. In particular, Figure 12 shows the *a*-SiC insulator coating and device thinning process steps. In particular an *a*-SiC insulator coating layer is provided as the top layer. In addition, the device support layer, either bulk SiC or Si/SOI substrates, is removed and/or thinned, for instance by back lapping, DRIE etching, Si etching (dry + wet etching, etc.), etc., as the case can be.

[00154] Figure 13 shows a cross-sectional view of example neural implant layers similar to Figure 10-12 with the electrode tip having been exposed. In particular Figure 13 shows a cross section of a portion of the electrode where the electrode is to be exposed, for instance for contact with a nerve fascicle. In this case the insulator window can be etched, for instance via RIE (reactive ion etching) resulting in the electrode tip being exposed to form a recording tip.

During this step the electrical bonding pad (as shown, for example, in Figure 1A) can also be exposed for metal deposition to facilitate electrical connection of the electrode to the outside world.

[00155] Figure 14 shows a cross-sectional view of example neural implant layers similar to Figures 10-13 with the electrode bond pad region having been exposed. The exposed bonding pad is then metalized, using standard metal film deposition methods such as evaporation, e-beam evaporation, sputtering, etc. to form a conductive metal film to facilitate packaging and signal transduction into/out of the probe. The metal coating can include Ti, Au, Cr, etc., or some combination thereof. Note this portion of the probe resides outside of the nerve and is thus not in contact with neural tissue and facilitates connection to a data cable.

[00156] While the invention has been described with reference to certain example embodiments thereof, those skilled in the art can make various modifications to the described embodiments of the invention without departing from the scope of the invention. The terms and descriptions used herein are set forth by way of illustration only and not meant as limitations. In particular, although the present invention has been described by way of examples, a variety of devices would practice the inventive concepts described herein. Although the invention has been described and disclosed in various terms and certain embodiments, the scope of the invention is not intended to be, nor should it be deemed to be, limited thereby and such other modifications or embodiments as can be suggested by the teachings herein are particularly reserved, especially as they fall within the breadth and scope of the claims here appended. Those skilled in the art will recognize that these and other variations are possible within the scope of the invention as defined in the following claims and their equivalents.

REFERENCES

[00157] US Patent No. 10136825 filed January 14, 2014 titled "Long-term implantable silicon carbide neural interface device using the electrical field effect".

[00158] US Patent No. 9211401 filed Can 24, 2012 titled "Cubic silicon carbide implantable neural prosthetic".

[00159] International Application No. PCT/US2022/014632 filed January 31, 2022 titled "Electrode device and related methods".

[00160] Graphene electrodes on a planar cubic silicon carbide (3C-SiC) long term ...WO US US8751015B2 Stephen E. Saddow University of South Florida

[00161] Implantable biocompatible SiC sensors WO US WO2013138275A1 Stephen E. Saddow University of South Florida

What is claimed is:

1. An implantable peripheral nerve system comprising:

a probe comprising:

a panel including an electrical contact that is positioned on a surface of the panel;

a shank coupled to and extending from the panel, the shank including an electrode contact, the electrode contact being electrically coupled to the electrical contact;

a housing having an inner surface defining a cavity, the cavity being sized to house the panel of the probe while the shank extends from the cavity outside of the housing; and

wherein the probe is adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to the electrode contact of the shank.

2. The system of claim 1, wherein when the probe is positioned within the cavity of the housing, the housing constrains movement of the probe relative to the housing.

3. The system of claim 1, wherein the housing includes an opening at a bottom of the housing; and

wherein when the probe is positioned within the cavity of the housing, the shank extends through the opening of the housing.

4. The system of claim 1, wherein the panel includes a concave portion;

wherein the opening includes a concave region that aligns with the concave portion of the panel, when the probe is positioned within the cavity of the housing.

5. The system of claim 1, wherein the housing includes a mechanical stop that engages with the panel of the probe to prevent movement of the panel past the mechanical stop.

6. The system of claim 5, wherein the mechanical stop is an extension that extends into an opening of the housing in which the shank extends through.

7. The system of claim 1, wherein the electrical contact of the probe is exposed when the probe is positioned within the housing; and further comprising a cable configured to be coupled to the panel, such that when the cable is coupled to the panel, the cable electrically couples to the electrical contact of the probe.

8. The system of claim 1, further comprising a cable with a boot coupled to an end of the cable;

wherein the housing includes a cut-out or recess that exposes the electrical contact when the probe is positioned within the housing; and

wherein the boot mechanically engages with the housing thereby coupling the cable to the housing to secure the cable to the housing and electrically couple the electrical contact to the cable.

9. The system of claim 1, wherein the probe, the housing, and the cable are configured to be implanted within a subject.

10. The system of claim 1, wherein the electrical contact is a first electrical contact, the shank is a first shank, and the electrode contact is a first electrode contact;

wherein the panel includes a second electrical contact that is positioned on the surface of the panel; and

wherein the probe includes a second shank coupled to and extending from the panel, the shank including a second electrode contact, the second electrode contact being electrically coupled to the second electrical contact.

11. An implantable peripheral nerve system comprising:

a probe comprising:

a panel including an electrical contact that is positioned on a surface of the panel;

a shank coupled to and extending from the panel, the shank including an electrode contact, the electrode contact being electrically coupled to the electrical contact;

a housing having an inner surface defining a cavity, the cavity being sized to house the panel of the probe while the shank extends from the cavity outside of the housing;

a support adapted to engage with a peripheral nerve of a subject, the support having a slot sized to house the housing with the probe therein, wherein when the housing is inserted into the support, the support constrains movement of the housing relative to the support; and

wherein the probe is adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to the electrode contact of the shank.

12. The system of claim 11, wherein the support includes a collar that is configured to surround the peripheral nerve of the subject; and

wherein the slot is positioned on top of the collar.

13. The system of claim 1, further comprising a lock that when engaged constrains movement of the housing relative to the support.

14. The system of claim 13, wherein the support includes the lock and the lock includes one or more feet that contact the housing to block movement of the housing.

15. The system of claim 12, wherein the probe, the housing, and the support are configured to be implanted within a subject.

16. An implantable neural device comprising:

a probe comprising:

a panel having a length;

a first shank coupled to and extending from the panel, the first shank including a first electrode contact, the first shank having a length that is greater than the length of the panel;

a second shank coupled to and extending from the panel, the second shank including a second electrode contact, the second shank having a length that is greater than the length of the panel; and

wherein the probe is adapted to engage a peripheral nerve of a subject thereby electrically connecting the peripheral nerve to at least one of the first shank or the second shank.

17. The device of claim 16, wherein a ratio of the length of the panel to the length of the first shank is greater than or equal to about 1;

wherein a ratio of the length of the panel to the length of the first shank is greater than or equal to about 1.4; or

wherein a ratio of the length of the panel to the length of the first shank is greater than or equal to about 1.7.

18. The device of claim 16, wherein the probe is adapted to engage a peripheral nerve bundle of a subject thereby electrically connecting a first peripheral nerve fiber of the peripheral nerve bundle to the first shank and electrically connecting a second peripheral nerve fiber of the peripheral nerve bundle to the second shank.

19. The device of claim 16, wherein a thickness of the panel is substantially the same as a thickness of the first shank and a thickness of the second shank.

20. The device of claim 16, wherein the first shank and the second shank are integrally formed with the panel.

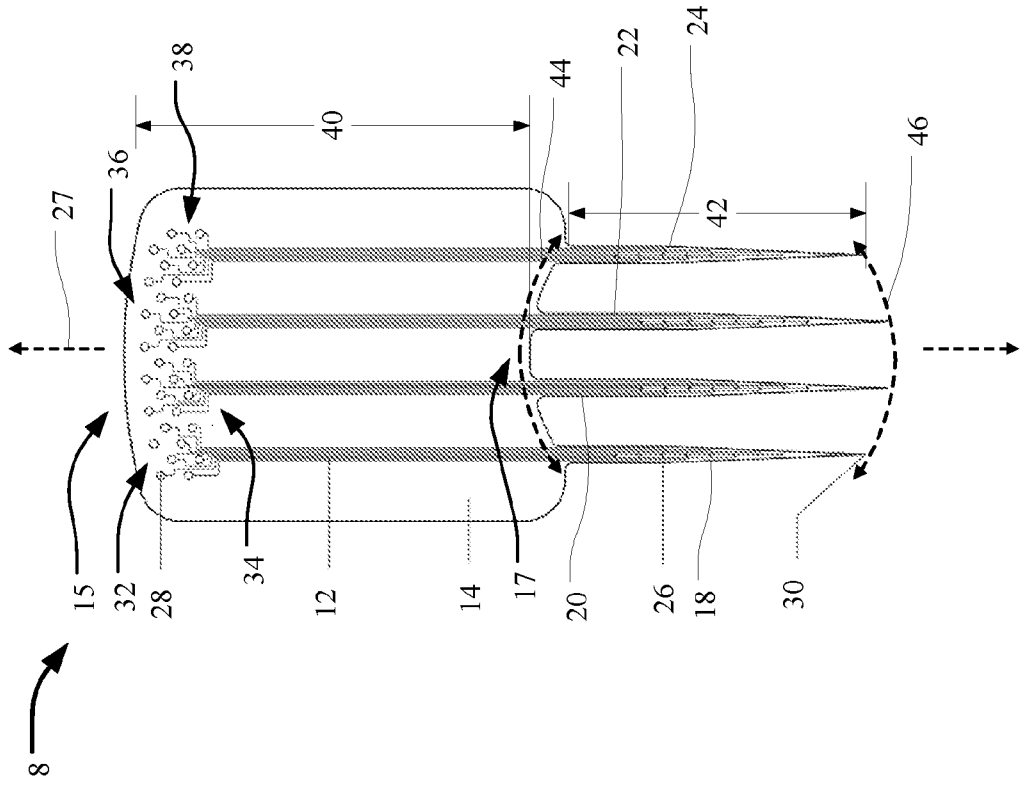


FIG. 1A

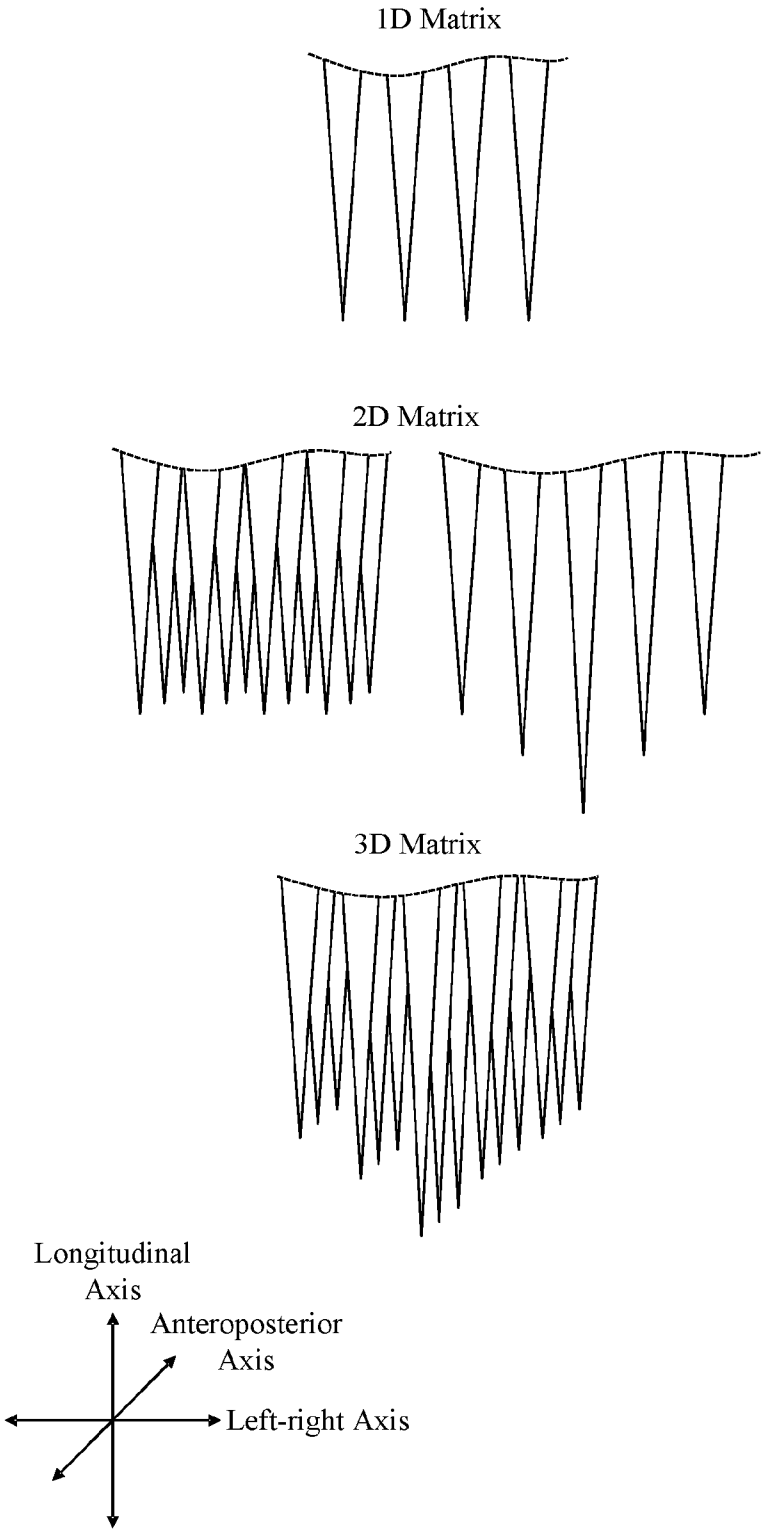

1D Matrix
2D Matrix
3D Matrix
Longitudinal Axis
Anteroposterior Axis
Left-right Axis

FIG. 1B

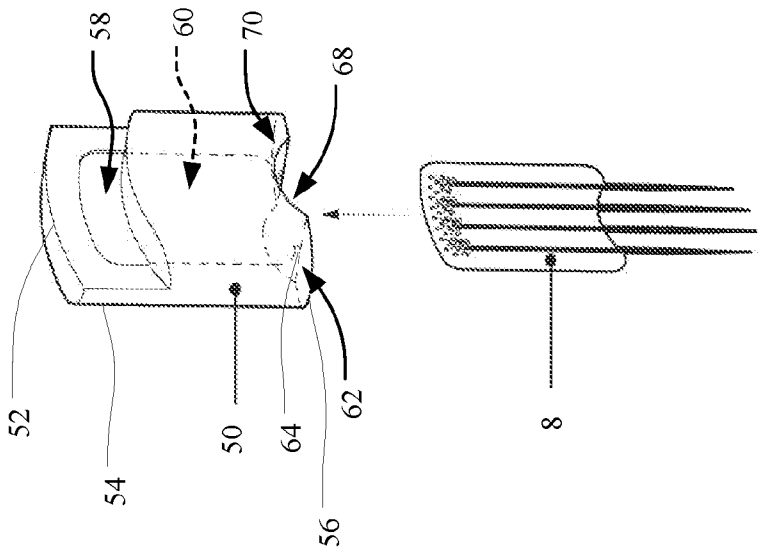


FIG. 2

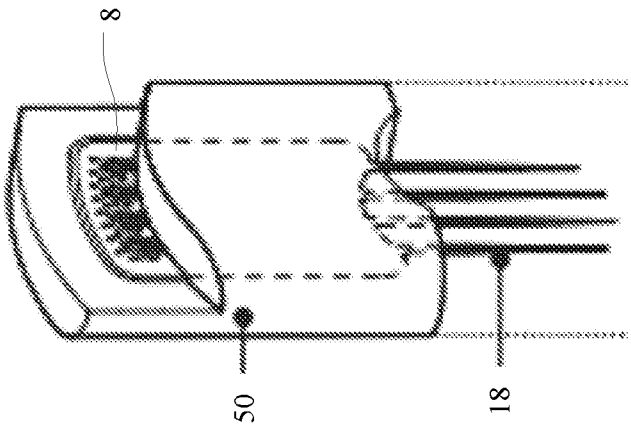


FIG. 3

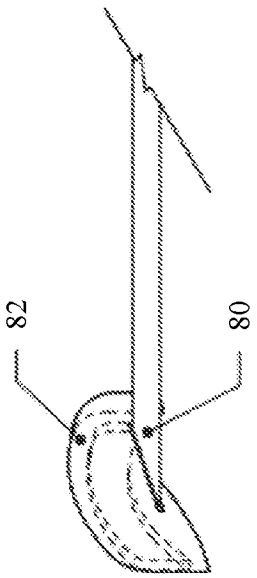


FIG. 4

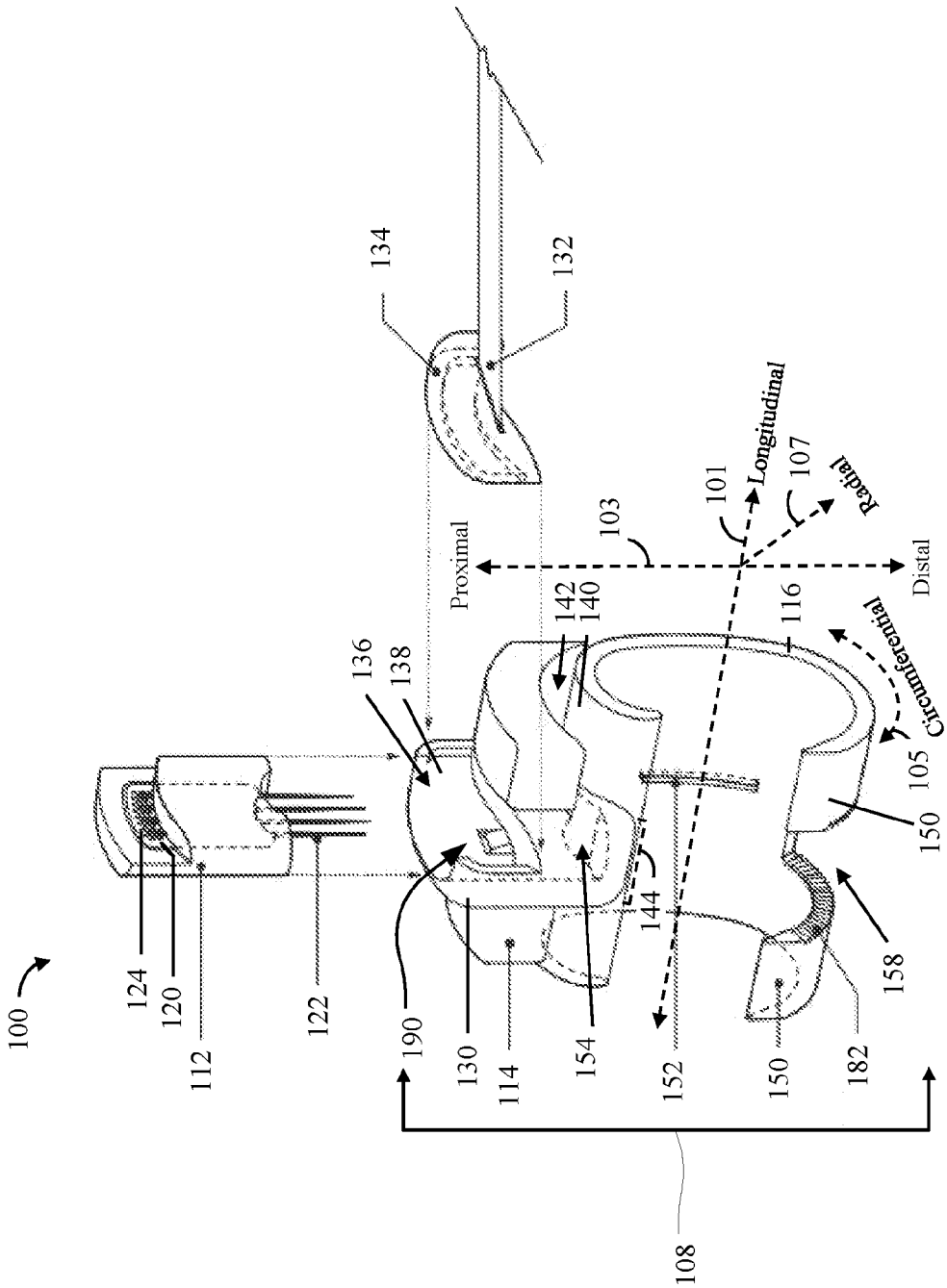

100
124
120
112
122
190
130
114
154
152
150
182
158
144
150
105
Circumferential
116
142
140
136
138
Proximal
103
Distal
101
Longitudinal
107
Radial
134
132
108

FIG. 5

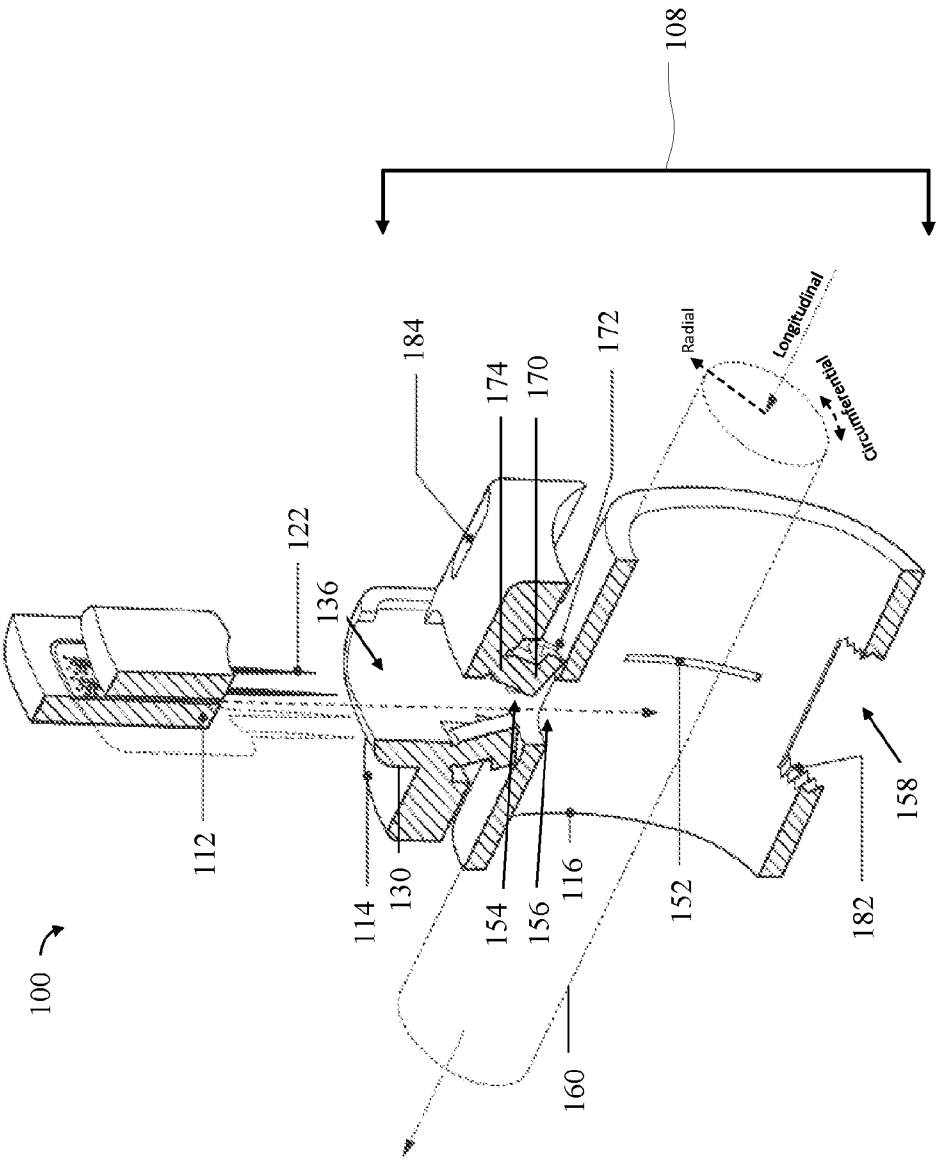

108
184
174
170
172
Radial
Longitudinal
Circumferential
122
136
112
114
130
154
156
116
152
182
158
160
100

FIG. 6

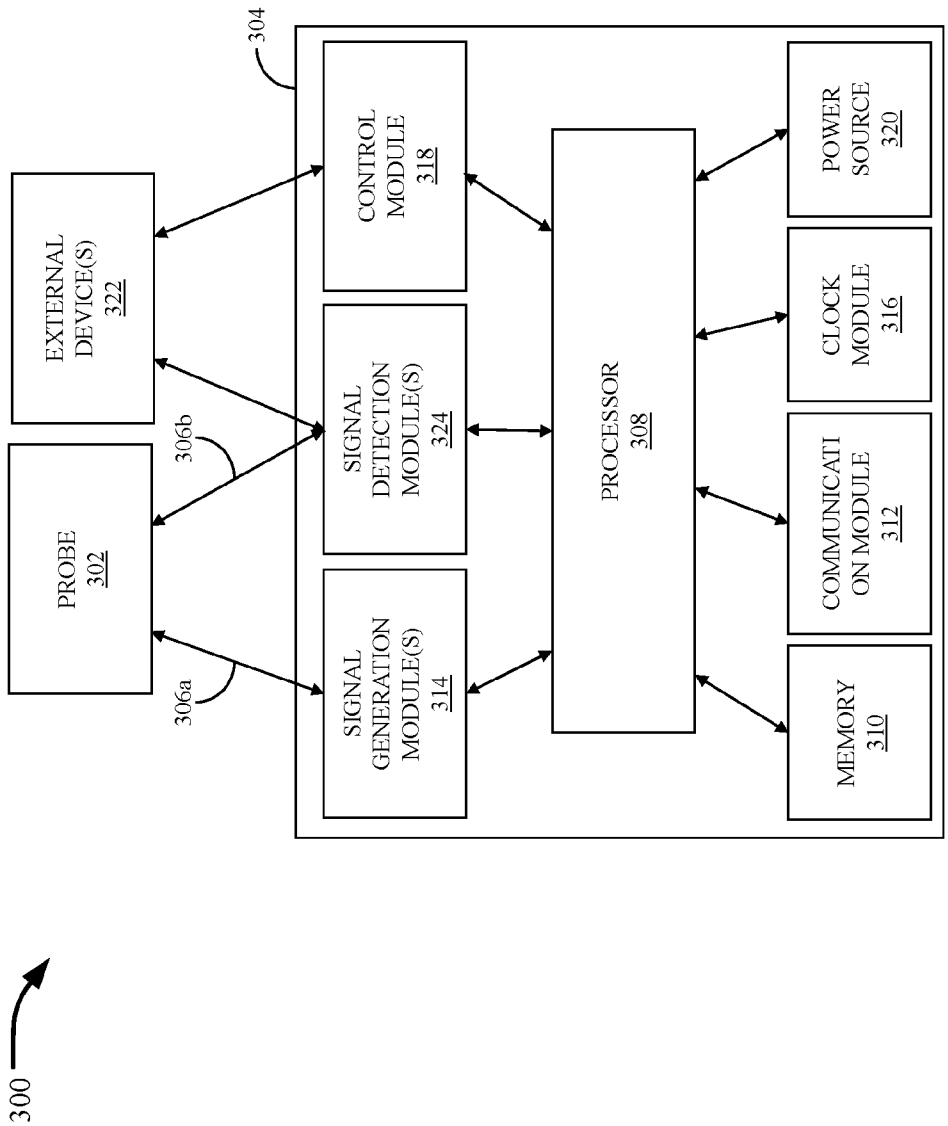

300
304
EXTERNAL DEVICE(S) 322
PROBE 302
306a
306b
CONTROL MODULE 318
SIGNAL DETECTION MODULE(S) 324
SIGNAL GENERATION MODULE(S) 314
PROCESSOR 308
POWER SOURCE 320
CLOCK MODULE 316
COMMUNICATION MODULE 312
MEMORY 310

FIG. 7

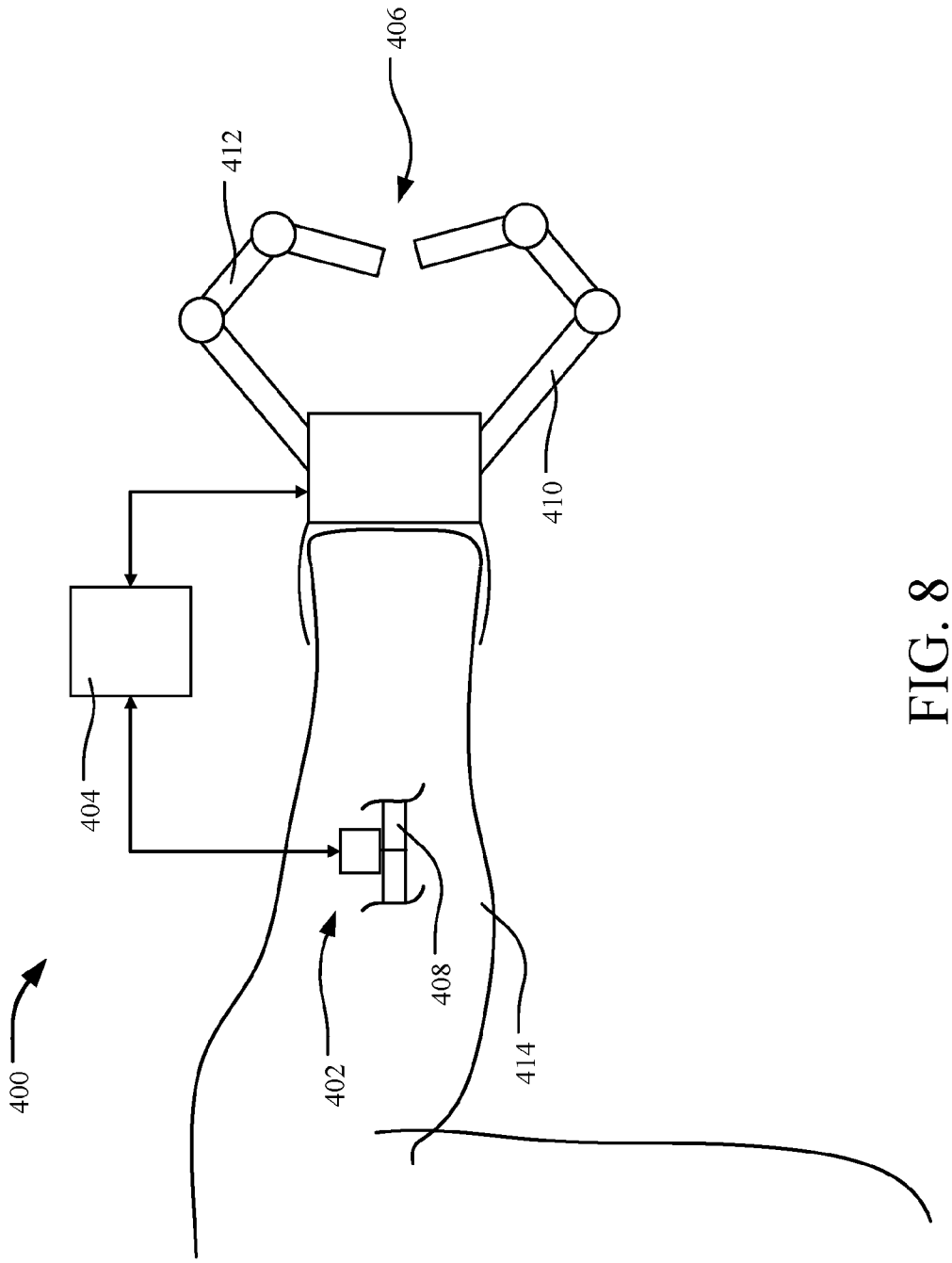


FIG. 8

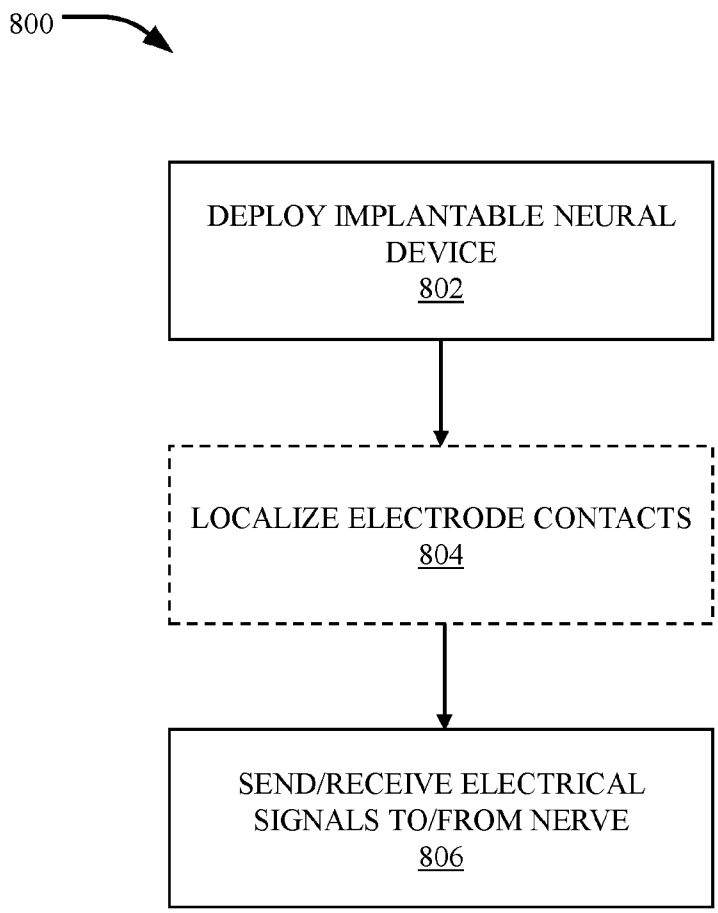

800
DEPLOY IMPLANTABLE NEURAL DEVICE
802
LOCALIZE ELECTRODE CONTACTS
804
SEND/RECEIVE ELECTRICAL SIGNALS TO/FROM NERVE
806

FIG. 9

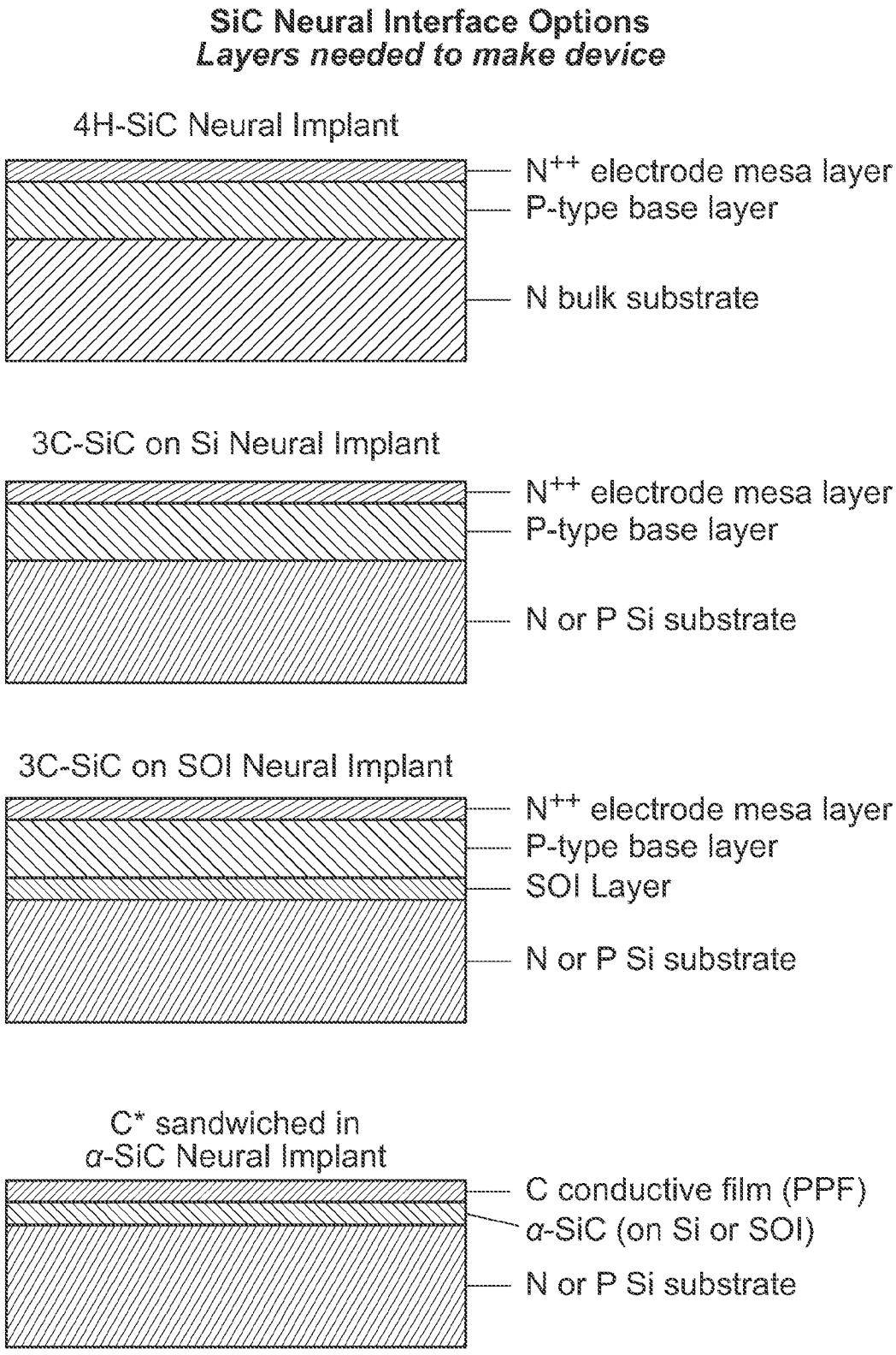

SiC Neural Interface Options
Layers needed to make device
4H-SiC Neural Implant
N++ electrode mesa layer
P-type base layer
N bulk substrate
3C-SiC on Si Neural Implant
N++ electrode mesa layer
P-type base layer
N or P Si substrate
3C-SiC on SOI Neural Implant
N++ electrode mesa layer
P-type base layer
SOI Layer
N or P Si substrate
C* sandwiched in
α-SiC Neural Implant
C conductive film (PPF)
α-SiC (on Si or SOI)
N or P Si substrate
C* layer can be replaced with heavily doped polycrystalline SiC

FIG. 10

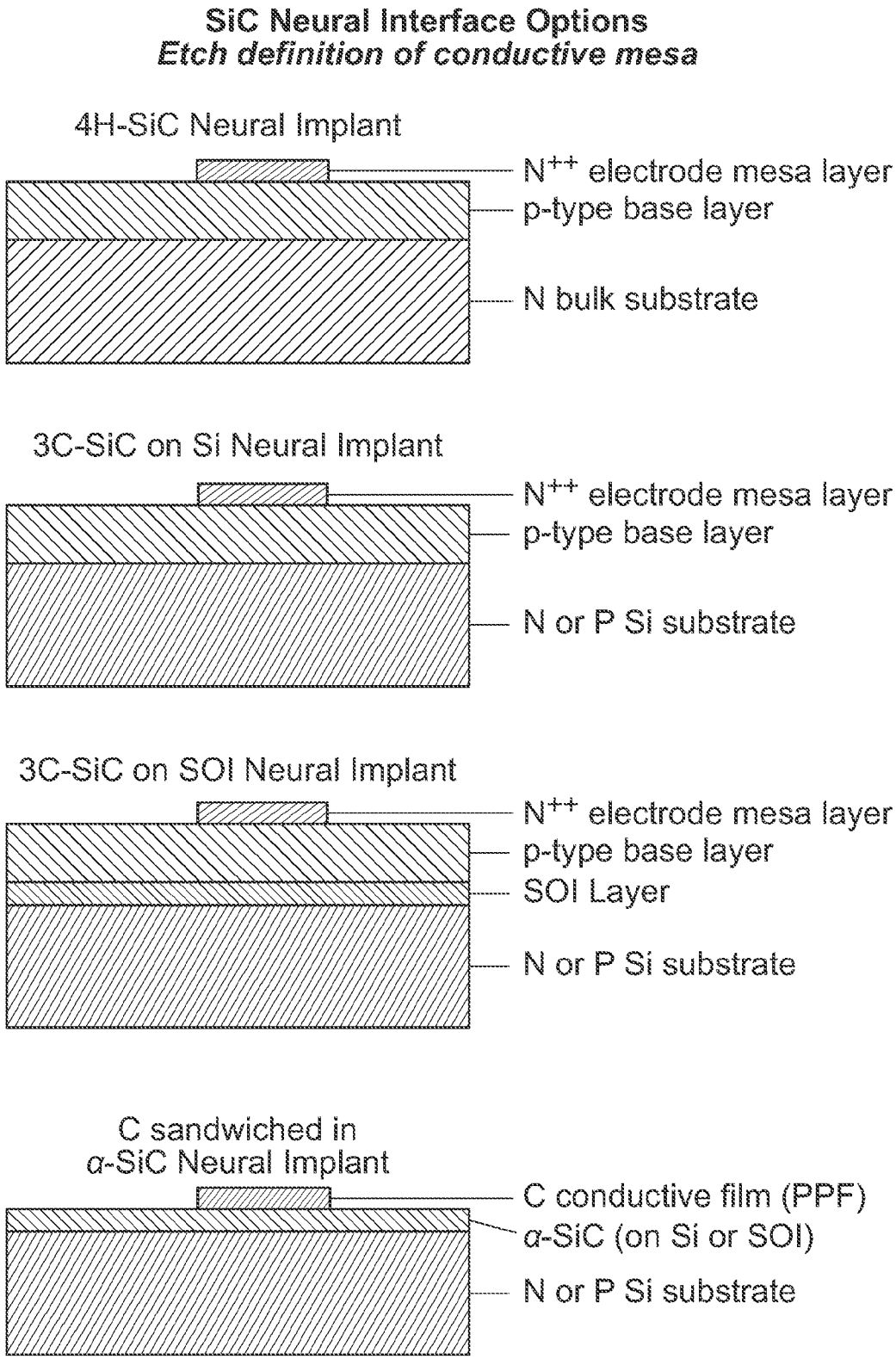

SiC Neural Interface Options
Etch definition of conductive mesa
4H-SiC Neural Implant
N++ electrode mesa layer
p-type base layer
N bulk substrate
3C-SiC on Si Neural Implant
N++ electrode mesa layer
p-type base layer
N or P Si substrate
3C-SiC on SOI Neural Implant
N++ electrode mesa layer
p-type base layer
SOI Layer
N or P Si substrate
C sandwiched in
α-SiC Neural Implant
C conductive film (PPF)
α-SiC (on Si or SOI)
N or P Si substrate

FIG. 11

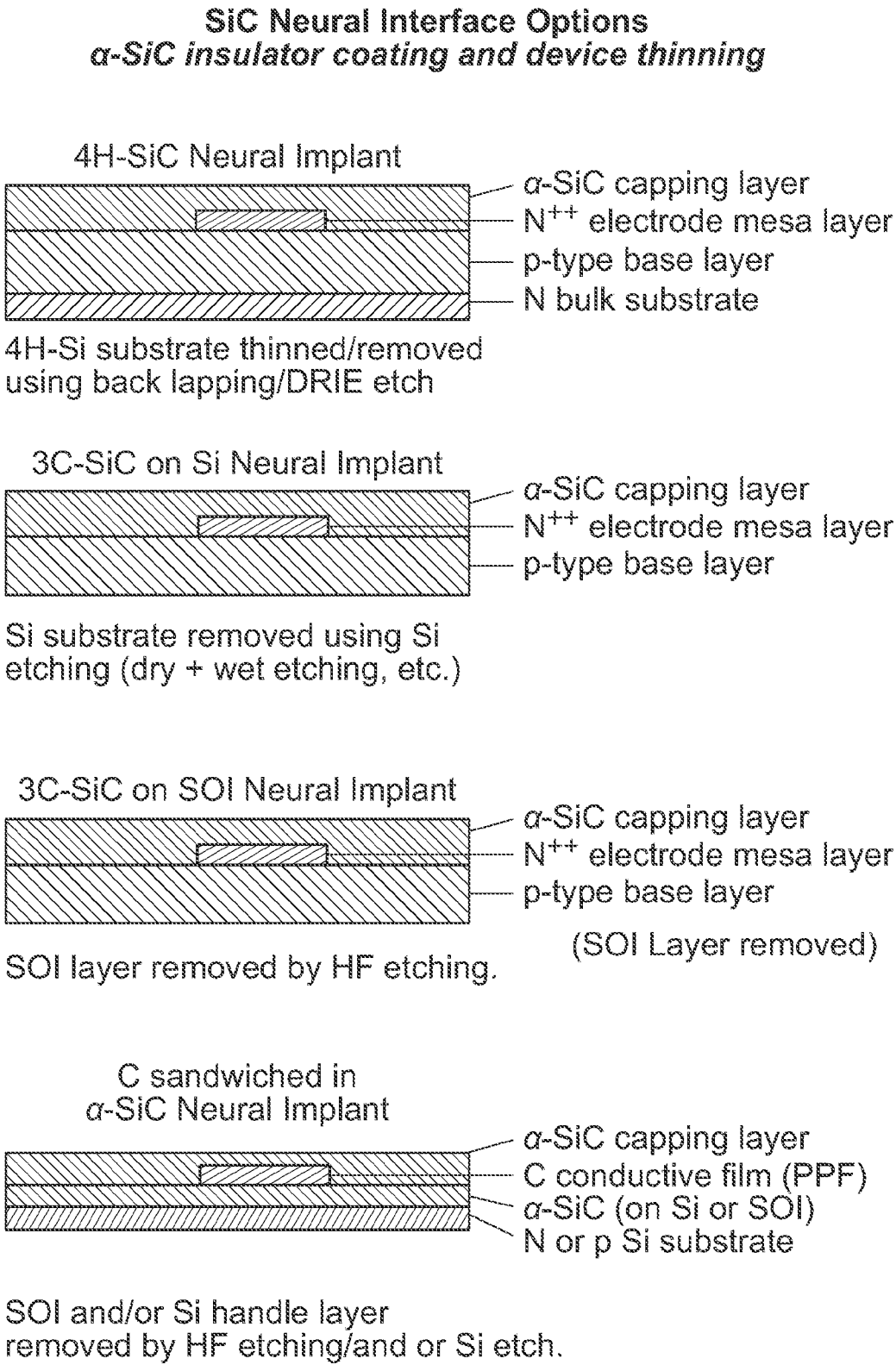
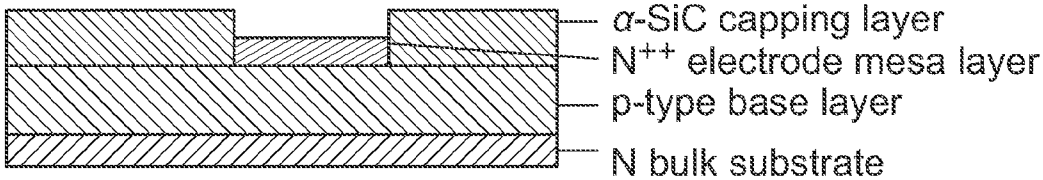

SiC Neural Interface Options
α-SiC insulator coating and device thinning
4H-SiC Neural Implant
α-SiC capping layer
N++ electrode mesa layer
p-type base layer
N bulk substrate
4H-Si substrate thinned/removed using back lapping/DRIE etch
3C-SiC on Si Neural Implant
α-SiC capping layer
N++ electrode mesa layer
p-type base layer
Si substrate removed using Si etching (dry + wet etching, etc.)
3C-SiC on SOI Neural Implant
α-SiC capping layer
N++ electrode mesa layer
p-type base layer
(SOI Layer removed)
SOI layer removed by HF etching.
C sandwiched in α-SiC Neural Implant
α-SiC capping layer
C conductive film (PPF)
α-SiC (on Si or SOI)
N or p Si substrate
SOI and/or Si handle layer removed by HF etching/and or Si etch.

FIG. 12

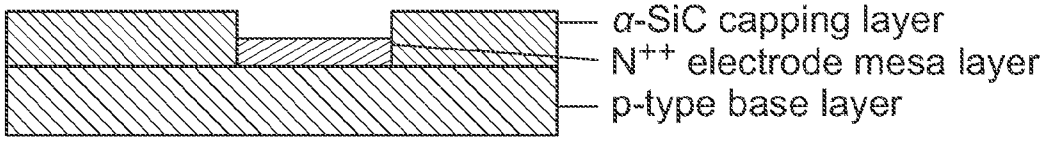
SiC Neural Interface Options
Insulator window etch*: bonding pads and recording tip**

4H-SiC Neural Implant



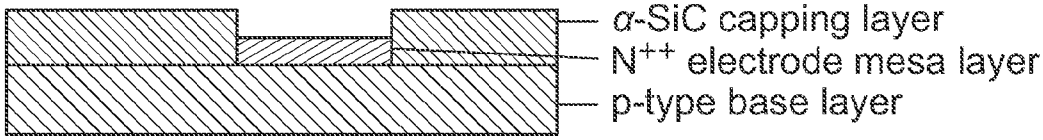
Electrode tip exposed via RIE

3C-SiC on Si Neural Implant



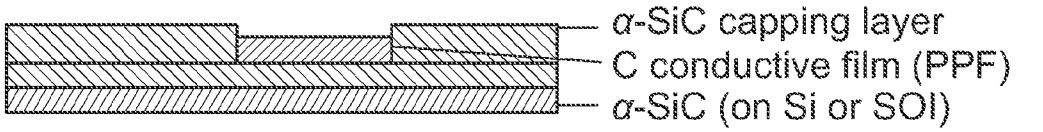
Electrode tip exposed via RIE

3C-SiC on SOI Neural Implant



Electrode tip exposed via RIE (SOI Layer removed)

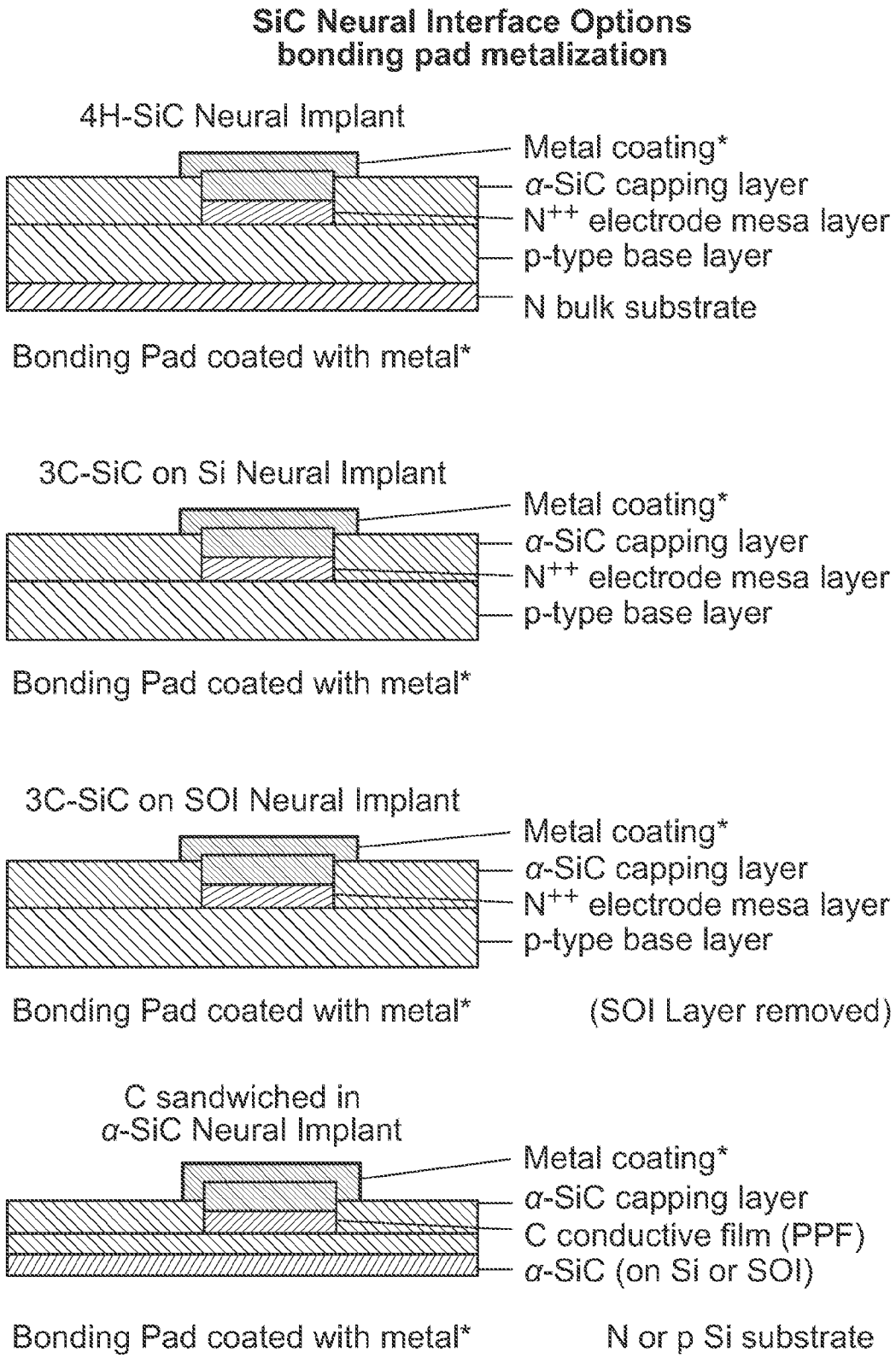
C sandwiched in
α-SiC Neural Implant



Electrode tip exposed via RIE N or p Si substrate

* RIE (reactive ion etching) step done before wafer thinning
** Bonding pads not shown here, only recording tip window

FIG. 13



* Typically Ti/Au or similar layers. Ti layer facilitates metal adhesion to SiC while Au is the conducting layer to facilitate packaging

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/035903

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61N1/05 A61N1/375
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61N A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8 255 061 B2 (PERLIN GAYATRI EADARA [US]; CASEY BRENDAN E [US] ET AL.) 28 August 2012 (2012-08-28) abstract; figures 3A-5 column 1, lines 21-23 column 2, lines 54-67 column 3, lines 24-37 column 5, line 35 - column 9, line 17 column 10, lines 14-63 column 13, line 30 - column 17, line 3	1-3,5-7, 9,10, 16-20
X	EP 2 870 980 A2 (NEURONEXUS TECHNOLOGIES INC [US]) 13 May 2015 (2015-05-13) abstract; figures 1-16 paragraphs [0002], [0009], [0010], [0015] - [0035]	11-15

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
13 September 2024	26/09/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Molina Silvestre, A

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INTERNATIONAL SEARCH REPORT

International application No
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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1 726 329 A1 (MANN ALFRED E FOUND SCIENT RES [US]) 29 November 2006 (2006-11-29) the whole document	1-20
A	US 2018/353750 A1 (HETKE JAMILLE F [US] ET AL) 13 December 2018 (2018-12-13) the whole document	1-20

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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