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(71) Applicant (for all designated States except US): **UNIVERSITY OF SOUTH FLORIDA** [US/US]; 3802 Spectrum Blvd. Ste.100, Tampa, Florida 33612 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **REGISTER, Joseph** [US/US]; 819 Ambassador Loop, Tampa, Florida 33613 (US). **SADDOW, Stephen** [US/US]; 15002 Lakeside Cove Court, Odessa, Florida 33556 (US). **FREWIN, Christopher** [US/US]; 14605 Gilligan's Way, Apt. 7, Tampa, Florida 33613 (US). **WEEBER, Edwin** [US/US]; 5407 Conch Shell Place, Apollo Beach, Florida 33572 (US).

(74) Agent: **ZHAO, Wanhua**; 180 Pine Avenue North, Oldsmar, Florida 34677 (US).

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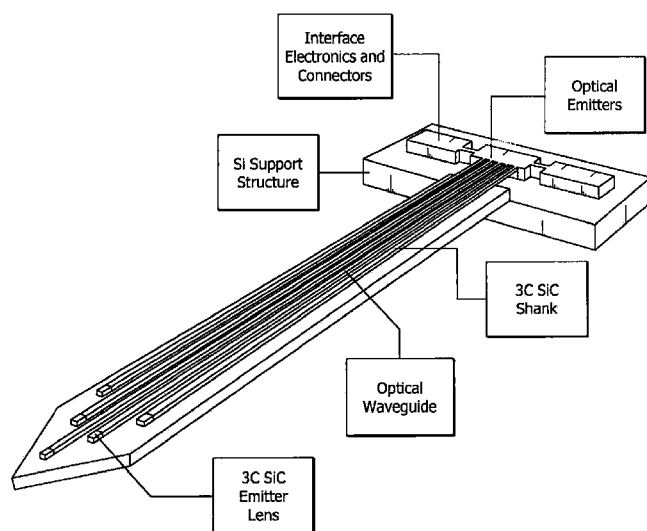


FIG. 1

(57) Abstract: The microfabricated prosthetic device uses local, direct, and wavelength-specific optical stimulation to achieve an action potential from a single or small group of neurons within the central nervous system (CNS). The device is biocompatible, mechanically flexible, and optically transparent. The device can also use integrated electrodes for additional input/output (IO) locations, signal verification, feedback, wireless communication, and characterization of the electrochemically-evoked potential received from the activated neuron. The purpose of the device is to act as a neural interface prosthetic. The prosthetic is designed as the central component of a Brain machine interface (BMI).

5 **OPTICAL NEURON STIMULATION PROSTHETIC USING SiC (SILICON CARBIDE)**

CROSS REFERENCE TO RELATED APPLICATIONS

10 This invention claim priority to United States Provisional Patent Application No. 61/437,346 filed January 28, 2011 entitled "Optical Neuron Stimulation Prosthetic Using SiC (Silicon Carbide)". The content of which is incorporated herein by reference.

FIELD OF THE INVENTION

 This invention relates to a device and method for optical neuron stimulation prosthetics using SiC (silicon carbide).

15 **BACKGROUND OF INVENTION**

 The importance of controlling action potentials in certain cell types was emphasized first by Francis Crick in his Kuffler Lectures at the University of California in San Diego 2002. Soon after this talk, an explosion of genetic targeting experiments culminated in the Deisseroth group genetically isolating a photosensitive ion channel called
20 Channelrhodopsin-2 (ChR2). The team then used standard genetic engineering techniques to insert the needed DNA sequence into a neuron using an AAV virus. The process resulted in the world's first mammalian neuron with a blue-green light controlled action potential. ChR2 is still the most commonly used modification in optogenetics, but several other ion channels have now been discovered. Most notably, the antithesis to
25 ChR2, Natronomonas pharaonis halorhodopsin (NpHR) is an ion pump for chlorine ions. When this structure is illuminated with yellow light an inhibitory current is created that effectively silences the neuron. Between these two ion-channel structures total bipolar state control over the action potential can be realized. This type of optical targeting and stimulation provides a great advantage over traditional electrical stimulation (See
30 Alexander M Aravanis, Li-Ping Wang, Feng Zhang, Leslie A Meltzer, Murtaza Z Mogri, M Bret Schneider and Karl Deisseroth. "An optical neural interface: in vivo control of rodent motor cortex with integrated fiberoptic and optogenetic technology" J. Neural Eng. 4, S143, 2007). Precise light control by lenses and other optical structures results in high spatial resolution while the genetic targeting technique provides neuron differentiation.
35 Using a localized light emitter, CNS cells can be activated, inhibited, and intercell signaling can be controlled on an individual neuron level with millisecond temporal resolution. Currently, these devices are extremely lifetime limited. Neural prosthetics have

5 to survive the rigors of the body's harsh environment and better materials are warranted if implants are to have design-lifetimes on the order of a human lifetime.

The Implantation of a prosthetic device in the brain leads to a "foreign body" response mounted by the immune system. This immunologic response, coupled with the chemically harsh environment of the body, quickly degrades neural prosthesis in-vivo. Beginning
10 from the moment of implantation, performance begins to degrade and eventually terminates in total failure. This process usually happens in a matter of weeks to years. Previously, the effect could only be mitigated temporarily using a careful selection of encapsulation materials. In order to enhance device lifetimes and reduce inflammation designers utilize materials such as sapphire, ceramics, glass, and polymers to fend off
15 device destruction. To complicate the issue, electrically active prosthesis such as wireless and optoelectronic devices use these materials as a protective coating to encapsulate otherwise poisonous electronic components.

The specialized biomaterials used to build neural prosthesis have a dual purpose. First, The materials reduce the amount of immunologic response caused by the prosthesis.
20 Second, these materials provide a barrier between the body and the prosthetic in an attempt to save the body from undue exposure to otherwise toxic substances. In the case of an optical neural prosthesis, the most devastating of these effects is a glial scar that forms around the device effectively encapsulating it in dense fibrous tissue.

The glial scar disrupts the light transmitted from the device causing both optical path loss and degraded spatial resolution. Common biomaterials, such as sapphire, some
25 ceramics, and glass may not dissolve or dissolve in the body but result in a large immunologic response when implanted in neural tissue. Polymers, such as polyimide, work well initially but eventually crack and fail. Our invention addresses these concerns by using carefully selected polytypes (crystal structures) of single crystalline silicon carbide (SiC) material. It has been shown that 3C-SiC does not crack or swell over time
30 like many polymers and its use can result in a device that is wholly biocompatible and mechanically rigid enough to withstand chronic implantation. In addition 3C-SiC has an exceedingly low immune response in chronic cortical implantation.

Single crystal SiC has been shown to have a very low immune response, high
35 mechanical resilience, and possess optical transparency at certain key wavelengths currently used in optogenetics therapy (Gary Lynn Harris: "Properties of silicon carbide" , INSPEC, Institution of Electrical Engineers, 282pp, ISBN 0 85296 870 1, pp. 16-17, 1995 and Garret D Stuber "Dissecting the neural circuitry of addiction and psychiatric disease with optogenetics" Neuropsychopharmacology, 35, pp. 341-342, 2010). Using silicon

5 carbide as a primary construction material for the optical stimulation prosthesis we allow for device lifetimes that are orders of magnitude greater than current standards.

SUMMARY OF INVENTION

The present invention provides a microfabricated prosthetic device that uses local, direct, and wavelength-specific optical stimulation to evoke an action potential from a single or
10 small population of neurons within the central nervous system (CNS). The device topology is based off of a preexisting design developed by researchers at the University of Michigan (John Seymour, Mayurachat Ning Gulari, Joerg Lahann, Daryl Kipke "Method for Manufacturing an Implantable Electronic Device", US Patent Application 20100145422) and drastically improved by our novel application of SiC biomaterials. The
15 invention is presented in multiple topologies demonstrated as embodiment's herein. The purpose of the device is to act as a neural interface prosthetic whereby the prosthetic is a central component of a brain machine interface (BMI) system.

Using the previously established ISO-10993 standard it has been established that 3C-SiC can be used as a highly biocompatible material with little immune response (Christopher
20 L. Frewin, "The neuron-silicon carbide interface: Biocompatibility study and BMI device development" PhD dissertation, University of South Florida, 2009). It has also been established that other polymorphs of SiC such as 4H-SiC and 6H-SiC show low toxicity to immortalized mammalian cells in tests (See C. Coletti, M. J. Jaroszeski, A. Pallaoro, A. M. Hoff, S. Iannotta, and S. E. Sadow, "Biocompatibility and wettability of crystalline SiC and Si surfaces", IEEE EMBC Proceedings, vol. 22-26, 2007, pp. 5849-5852). Using
25 these polymorphs of silicon carbide in concert can render a device that is functional, non-toxic, and extremely resistant to mechanical failure.

Single crystal SiC has several properties that make it well suited for optical neuron stimulation. It can be used to create integrated electronic circuitry, light emitters, and on-
30 chip optical waveguide structures, and by using doped regions of epitaxial SiC light emitting junctions can be realized. Conductors can be formed on/within the device by using a high temperature process to create epitaxial graphene or through the creation of highly doped n^{++} or p^{++} regions. Overall, the material properties of SiC can be harnessed to create a long-term optostimulation and neural recording solution for the invention
35 presented. Therefore, SiC is used not only due to its superior biocompatibility, but also because it can produce the desired light and provide the necessary the heat dissipation.

The first aspect of the device involves the transmission and delivery of light to the targeted neural tissue. One embodiment of the device uses micromachined layers of

5 single crystal SiC polytypes to form long, thin, longitudinal waveguides that carry at least a portion of the light from a source near the support down the longitudinal axis to targeted neural tissue along the length of the device (FIG. 1). The optical waveguides are fabricated with a combination of grown epitaxial films consisting of 6H-SiC, 4H-SiC, 3C-SiC polytypes with the 3C-SiC polytype always used as the outer most device layer to
10 ensure the highest level of biocompatibility (See Christopher L. Frewin, "The neuron-silicon carbide interface: Biocompatibility study and BMI device development" PhD dissertation, University of South Florida, 2009).

In this embodiment either standard LED emitters are fabricated onto the Si support, i.e., not in direct contact with neurons, or outside the dura but still beneath the skull or micro
15 fabricated semiconductor lasers are utilized as emission sources.

Yet another embodiment of this device uses light emitters directly fabricated at points along the length of the prosthetic (FIG. 2). This configuration eliminates the need to guide light down the length of the prosthetic using waveguides but requires conductive traces to power each light emitting diode (LED) structure to run along the length of the device.
20 Commonly, optical stimulation prosthetics with integrated LEDs are made using cytotoxic semiconductors such as GaAs. Often, these materials are coated in biocompatible polymers such as polyimide, but this leads to device failure due to the swelling and cracking that these coating materials undergo in the long-term. This failure causes the eventual release of toxic materials into the body.

25 Another aspect of the device involves electrical feedback taken directly from the optically activated neural tissue. The electrical neuronal feedback can be sensed by direct electrical conduction of a microelectrode or induced by other means such as micro induction coil or similar device in place of the microelectrode. Each voltage or field effect sensor is connected to a conductive trace providing a feedback path.

30 In another embodiment, the device employs an array of electrical feedback microelectrodes to detect the presence of electrical neural activation potentials evoked by the light emitters. Each microelectrode is connected to a conductive trace providing a feedback path. It is envisioned that each optical emitter (LED or waveguide) will have at least one microelectrode nearby, typically less than 20um or less than the average width
35 from the targeted neuron type and each microelectrode will have a conductive return trace to route the electrical signal down the length of the device terminating near the top support structure.

5 Another aspect of the device is the processing, communication, and drive circuitry that is all located in the device support structure. Here, optical outputs are sent down the length of the prosthetic and electrical feedback from recording electrodes can optionally be recorded or passed on to an external interface.

10 Many embodiments of the of the device contain general processing and support circuitry that handles the addressing and control of light emitters as well as the processing of feedback emanating from the microelectrodes on the device which we refer to henceforth as an application specific integrated circuit (ASIC).

15 In some embodiments of the invention, the transmission circuitry can include means such as inductive coupling or a RF subsystem of wireless communication. In addition, the invention may include a receiver allowing bi-directional RF communication. The same system may be used for both transmitting and receiving. Also we envision that the same RF subsystem used for communication, can wirelessly transmit power to the prosthetic's drive circuitry powering the unit through inductive coupling. Such circuitry would be kept outside the dura and not in direct contact with neural tissue.

20 In this same aspect, an embodiment would contain a method of communication by using an external wire (or wires) exiting the prosthetic and subject's body where it is to be connected to further interface systems. With this embodiment long-term power and communication would all be conducted through the wire.

BRIEF DESCRIPTION OF THE DRAWINGS

25 For a fuller understanding of the invention, reference should be made to the following detailed description, taken in connection with the accompanying drawings, in which:

FIG. 1 is an illustration of a SiC Prosthetic device that uses SiC waveguides to direct the light from the support structure to the tip emitter apertures.

30 FIG. 2 is an illustration of a SiC Prosthetic using electrical conductors to power SiC LED emitters.

FIG. 3 is an illustration of the first of two methods for incorporating GaN. It shows the processing steps required to generate a 3C-SiC/AlN/GaN stack.

FIG. 4 is an illustration of the second of two methods for incorporating GaN. It shows the processing steps required to generate a 3C-SiC/6H-SiC/AlN/GaN stack.

5 FIG. 5 is a figure from Philip G. Neudeck, David J. Larkin, Jonathan E. Starr, J. Anthony Powell, Carl S. Salupo, and Lawrence G. Matus, "Electrical Properties of Epitaxial 3C- and 6H-SiC p-n Junction Diodes Produced Side-by-Side on 6H-SiC Substrates", IEEE Transactions On Electron Devices, Vol. 41, No. 5, May 1994, showing a dual color SiC LED structure. Using only 3C- and 6H-SiC highly biocompatible LEDs can be realized.

10 **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT**

 In the following detailed description of preferred embodiments, reference is made to the accompanying drawings, which form a part hereof, and within which are shown by way of illustration specific embodiments by which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made
15 without departing from the scope of the invention.

 As used herein "dura" refers to the fibrous covering over the brain and inside the skull; also, the term "shank" refers to the long thin SiC structure on the device that pierces the dura and makes intimate contact with the neural tissue; and "support" refers to the top region of the prosthetic that remains outside the dura and contains the majority of the
20 prosthetics electrical subsystems; "ASIC" refers to an application specific integrated circuit and the general purpose processor used on the device. The ASIC can handle some or all of the functions of the circuitry on the device and can work in conjunction with other circuitry on the device. For simplicity, all of these circuits collectively will be referred to as the "Interface Electronics"; "light emitter" refers to either a microfabricated LED or
25 optical facet emitter on an optical waveguide onboard the device; The design for the optical neural probe comprising two main structural components. A "support structure" serves as the central communications, processing and power hub as well as a mechanical platform where the shank connects to the prosthetic. The ASIC subsystem is located on the support and is capable of handling communication and drive of optical
30 devices onboard the prosthetic. The ASIC, typically fabricated from a silicon substrate with standard CMOS processing, is the general purpose processor for the prosthetic and handles all executive processes such as; **(a)** Stimulation control with temporal and spatial precision through emitter selection **(b)** Communication control of collected electrical impulses and received commands pertaining to (but not limited to) optical stimulation **(c)**
35 amplification, filtering, and otherwise processing of received electrical signals.

 The long, thin, silicon carbide shank structure attached to the support makes direct contact with the targeted neural tissue (FIG. 1). The shank contains optical facets and lenses capable of direct interface between the prosthetic light emitters and the

5 surrounding neurons. Once implanted, the device interacts with the neural cells by providing wavelength specific light to the membrane of the targeted neural cells.

The generated light emerging from the shank (in either architecture) interacts with the genetically introduced ion channels on (i.e. directly with the membrane ion channels), whereas many other devices are more indirect and evoke electrical changes across large
10 regions of space (e.g. DBS devices). Due to the size and density of the optical emitters on the presented invention it is possible to activate single neurons (FIG.1). In addition, this high density will make treating disorders such as epilepsy much more possible with the ability to find and treat small foci in the brain with long-term optical stimulation. This device increases longevity and reliability of the current standard due to the dramatic
15 increase in biocompatibility that 3C-SiC provides over other similar biomaterials.

With little to no glial scar formation, the presented device maintains its light-to neuron interface long-term far exceeding the lifetime of similar designs. There are two variations of the shank emitter system. Each uses 3C-SiC as the outer most layer of the device and gallium nitride (GaN) as an inner buried layer. The buried GaN provides the active layer
20 to realize a direct band gap blue LED which is needed for improved efficiency, whereas 3C-SiC allows direct interaction with the body environment as well as providing the material for the generation of a green/ yellow LED.

The first variation, shown in FIG. 3, begins with 3C-SiC grown on a Si substrate using CVD. GaN is then grown on 3C-SiC using vapor phase deposition by way of a thin (~200
25 nm) aluminum nitride (AlN) buffer layer. After GaN growth the Si substrate is removed, leaving a GaN/AlN/3C-SiC layer stack. PN junctions will be formed to realize the LED's in both the GaN and 3C-SiC through either epitaxial growth of doped layers or through post-growth ion implantation/ thermal annealing. Handle wafers will be used to allow processing of each side of the GaN/AlN/3C-SiC stack. Epitaxial growth and annealing
30 temperatures must be below 1200 °C to avoid thermal damage to the GaN layer. When the devices have been finished, they will be bonded to the optical waveguide emitter structure using processes described later earlier in this document. The final stage will be to make sure that the exposed AlN/GaN is hermetically sealed as these materials do not have an established biocompatibility level commensurate with neural implantation. The
35 hermetic seal layer can be composed of amorphous SiC, diamond, or another biocompatible ceramic.

The second variation, illustrated in FIG. 4, generates 6H-SiC/AlN/GaN as a substrate for the growth of 3C-SiC. We DRIE the 6H-SiC substrate to a thin layer (~1 um to 500 nm). The 6H-SiC surface is then mechanically polished flat and hydrogen etched. This will

5 provide the surface for the growth of 3C-SiC. This will leave a 3C-SiC/6H-SiC/AlN/GaN material layer stack. Again, each side of the stack (the 3C-SiC and GaN) can be processed to generate PN junctions through epitaxial growth and ion implantation/ thermal annealing as was stated in the previous section. The exact methods of attaching the stacks are examined in the next section. As with the previous section, any exposed
10 GaN must be hermetically sealed from the body environment.

In one embodiment, the support, normally fabricated from silicon with standard CMOS techniques, is connected to the shank through a high temperature anodic bonding process. A small region of the Si substrate is oxidized as well as the backside of the SiC shank assembly. The two oxidized surfaces are pressed together under a high voltage
15 potential in excess of 8kV applied by external plate electrodes and temperatures above 350° C while clamped together. The process joins the two pieces tightly together. The shank includes an optical waveguide or integrated SiC light emitters that will deliver the light to the neural tissue. The shank portion of the device will be implanted within neural tissue with the support portion residing just above the dura. The shank may also support
20 microelectrodes and conductive traces for electrical feedback from surrounding neurons.

In the same embodiment, the support structure is held to the shank using a biocompatible adhesive such as methyl 2-cyanoacrylate or ethyl-2-cyanoacrylate (Cyanoacrylate). Due to this union existing outside the dura, neurons would not come into contact with the adhesive preserving the neuron interface. Cyanoacrylate is a proven biocompatible
25 adhesive and is often used in modern surgery.

SiC Optical Waveguide Shank Architecture

It has been previously established that SiC is optically transparent across a wide range of light wavelengths. This property is utilized in the architecture of the emitter design of the present invention to create a waveguide structure. Light is generated from emitters
30 located on the prosthetic's support structure (by LEDs or laser emitters) and is directed down the length of the shank and out into the environment using several SiC waveguides and lens assemblies that are formed through lithography and dry etching on the surface of the shank. Near the end of each waveguide is a small lens structure that guides the light directly to the neuron to be activated (FIG.1).

35 Described herein is an example of how biocompatible waveguide structures can be made from layers of SiC. First, construction of the waveguide starts with a 6H-SiC or 4H-SiC substrate which is first patterned with photoresist to serve as a mask for an ion etching process. Then, using ion etching, rib waveguides are made by removing substrate

5 material to the desired depth. Then, 3C SiC is grown over the top of the 6H sample using a hotwall CVD process conducted at/near 1300° C in the presence of flowing gas precursors containing Si (commonly SiH₄) and Carbon (commonly C₃H₈) (See P.G. Neudeck, A. J. Trunek, D. J. Spry, J. A. Powell, H. Du, M. Skowronski, X. R. Huang, M. Dudley "CVD Growth of 3C-SiC on 4H/6H Mesas Chemical Vapor Deposition" Special
10 Issue: Silicon Carbide CVD for Electronic Device Applications, Volume 12, Issue 8-9, pp. 531–540, September, 2006).

The next step is using another lithography patterning step whereby the waveguide is etched to include conventional and/or Fresnel lens assemblies as well as other optical facets for light emission.

15 This architecture includes embodiments for feedback electrodes previously mentioned.

Integrated Emitter Architecture

In another embodiment of the device biocompatible LED emitters are directly fabricated on the shank portion of the prosthetic through the clever use of SiC polytype selection and fabrication techniques. This configuration eliminates the need to guide light down the
20 length of the prosthetic using waveguides but requires conductive traces to power each light emitting diode (LED) structure to run along the length of the device.

SiC is a wide-bandgap semiconductor with bandgap ranging from 2.17eV to 3.26eV depending on polytype and doping concentration. Using a P-N junction arrangement light emitting diodes that range in wavelength $\lambda = \frac{hc}{E}$ 570nm (yellow) to 380nm (ultraviolet) can
25 be created using 3C-, 6H-, and 4H-SiC polytypes. This is ideal as the most commonly used ion channel proteins are channelrhodopsin-2 and the halorhodopsin ion pump structures which are manipulated through wavelengths within this range. A wide range of colors on a single shank can be made of SiC, thereby facilitating a multitude of options in optical stimulation techniques. This multi-color, multi-channel, multi-mode capability
30 allows for excitation and inhibition of multiple neuron types in-vivo.

LED emitters can be constructed using layered SiC biomaterials. Having this aspect of the neural prosthesis made from SiC polytypes resulted in a wholly biocompatible prosthetic. Even if the device suffered catastrophic mechanical failure the material exposure will not be detrimental to the subject.

35 Described herein is an example of how biocompatible LEDs can be made from layers of SiC. First, construction of the emitter starts with a 4H- or 6H- (p type) SiC substrate. Next,

5 p and n regions are ion implanted to form junctions in the substrate. Commonly, ion
implantation of SiC uses aluminum and boron ions for “p” regions while Nitrogen and
Phosphorus ions are used as “n” dopants. Then, the substrate is annealed at 1200°C-
1700°C to activate the dopants and repair the damage done to the material by ion
10 implantation. Next, 3C-SiC (n-type) epitaxial film is grown over the top of the substrate
using a hotwall CVD process conducted at/near 1300° C in the presence of flowing gas
precursors containing Si (commonly SiH₄) and Carbon (commonly C₃H₈). (See P. G.
Neudeck¹, A. J. Trunek, D. J. Spry, J. A. Powell, H. Du, M. Skowronski, X. R. Huang, M.
Dudley “CVD Growth of 3C-SiC on 4H/6H Mesas Chemical Vapor Deposition” Special
15 Issue: Silicon Carbide CVD for Electronic Device Applications, Volume 12, Issue 8-9, pp.
531–540, September, 2006)

Once the 3C epitaxial layer is formed it is also ion implanted with n and p dopants forming
p-n junctions. Then, topside contacts are applied to the 3C-SiC film directly over the ion
implanted regions using either electron-beam evaporation or sputtering deposition. Next,
20 these contacts are patterned using either lift-off or wet etch processes. Finally, these
contacts are then annealed at 600°C for 20 min to form an ohmic contact that can be
connected to conductive traces that carry current to the LED.

Another embodiment of the invention uses the base material stacks mentioned in the
emitter section (3C-SiC/AlN/GaN or 3C-SiC/6H-SiC/AlN/GaN) and generating the LED's
as detailed there. The only processing difference is we would not be attaching the final
25 product to the emitter or electronic section, but they would be standalone devices
generated into a shank form using DRIE. To allow the GaN LED to interact effectively
with the neural environment, we will need to create a window in the 3C-SiC via DRIE
processing. This window must leave a very thin (only 10 to 20 nm) layer of 3C-SiC so as
to allow the blue light to pass through into the neural environment without significant loss.
30 We will use the previously mentioned bonding techniques to connect two shanks together
at the GaN layers, generating an implantable planar device with 2 active sides. The
remaining exposed layers of GaN/AlN or GaN/AlN/6H-SiC can be hermetically coated
with amorphous SiC or diamond so as to maintain the required level of biocompatibility.

35 In another embodiment, LED emitters are made of an alternating combination of 3C- and
6H-SiC materials. The junctions are layered so that multiple wavelengths can be realized
from the same junction point. For biocompatibility reasons the 3C-SiC is grown on top of
the 6H-SiC layer (FIG. 5).

In summary, the present invention offers a highly compact, biocompatible, and frequency
agile light source with electrical feedback that is well suited for a number of *in vivo*

5 optogenetics applications. The materials and methods used for its construction can be optimized as new ion channels and light stimulation techniques are discovered. The primary material of its construction, single crystal cubic silicon carbide (also known as β -SiC or 3C-SiC), is a highly biocompatible material that elicits a very low immune response and can be used in many ways to form all of the structures required to perform optical
10 neural stimulation and feedback (light emitters, conductors, structural supports, and waveguides). Other such optogenetics-based prosthetics have not yet fully utilized this material for optogenetics.

It will thus be seen that the objects set forth above, and those made apparent from the foregoing disclosure, are efficiently attained. Since certain changes may be made in the
15 above construction without departing from the scope of the invention, it is intended that all matters contained in the foregoing disclosure or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein disclosed, and all statements of the scope of
20 the invention that, as a matter of language, might be said to fall therebetween.

5 What is claimed is:

1. An implantable neuronal prosthetic device for optical neuron stimulation, comprising:

a support structure made from 6H- or 3C- silicon carbide (SiC);

an electronics system disposed on the support structure to generate light
10 and connections between the prosthetic device to the outside world;

at least one shank structure mounted on the support structure, wherein said shank is formed on a layer of single crystal cubic silicon carbide, single crystal diamond or gallium nitride is deposited on the surface of the substrate; and

15 an optical system disposed on the shank to generate a direct interface between the prosthetics device and surrounding tissue neurons.
2. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, further comprising reference electrodes integrated into the shank to provide feedback from targeted neurons.
- 20 3. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the electronic system comprising at least one light-emitting diode to generate light.
- 25 4. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the electronic system comprising at least one laser emitter to generate light.
5. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the optical system comprising at least one optical light emitting P-N junction.
- 30 6. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the optical system comprising at least one waveguide structure and at least one optical lens.

- 5 7. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 6, wherein the waveguide structure is fabricated from silicon carbide.
- 10 8. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 5, wherein the optical light emitter P-N junction is made of materials including gold, platinum, platinum-iridium alloys, iridium oxide, stainless steel, tungsten, titanium nitride, graphene, or heavily doped silicon carbide.
9. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 5, wherein the optical light emitter P-N junction comprising at least one epitaxial layer of silicon carbide.
- 15 10. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 9, wherein at least one epitaxial layer is a single layer of 3C-SiC.
11. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 9, wherein at least one epitaxial layer comprising a bottom layer of 6H-SiC and 3C-SiC directly deposited on the top of the bottom layer.
- 20 12. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the single crystal cubic silicon carbide comprising β -SiC (i.e., 3C-SiC), 4H-SiC, 6H-SiC.
13. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the electronic system comprising a circuitry for wired communication.
- 25 14. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, wherein the interface electronic system comprising a circuitry for wireless communication.
15. The implantable neuronal prosthetic device for optical neuron stimulation as in claim 1, further comprising a plurality of said shanks, with at least one, being arranged into a two- or three-dimensional matrix.
- 30 16. A method of manufacturing an implantable neuronal prosthetic device for placement in a patient for optical neuron stimulation, comprising the steps of:

- 5 forming a supporting structure;
- depositing a layer of single crystal cubic silicon carbide, single crystal diamond or gallium nitride on the supporting structure;
- disposing an electronic system to generate light and connection between the prosthetic device and outside world on the support structure;
- 10 forming at least one shank structure on the support structure; and
- disposing an optical system on the shank to generate a direct interface between the prosthetic device and surrounding tissue neurons.
- 15 17. The method of claim 16, wherein step b) is achieved by heteroepitaxially growing the substrate layer on the supporting structure.
18. The method of claim 16, wherein step b) is achieved by chemical vapor deposition.
19. The method of claim 16, wherein step e) is achieved by forming at least one silicon carbide waveguide and at least one lens by dry etching and photolithography techniques.
- 20 20. The method of claim 16, wherein step e) is achieved by forming at least one optical light emitting P-N junction.
21. The method of manufacturing an implantable neuronal prosthetic for optical neuron stimulation as in claim 16, further comprising the step of attaching at least one electrode to at least one said shank structure to receive feedback from surrounding neurons.
- 25 22. The method of manufacturing an implantable neuronal prosthetic optical neuron stimulation as in claim 16, further comprising the step of arranging a plurality of at least one said shank into a matrix.

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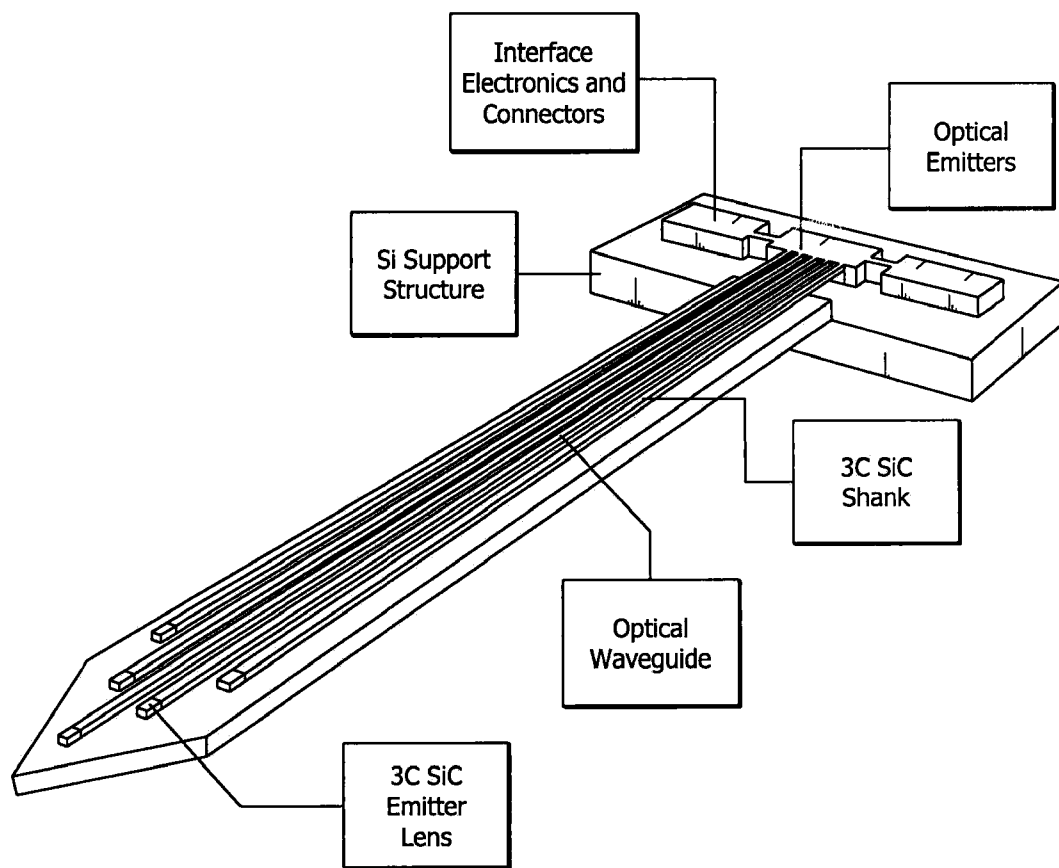
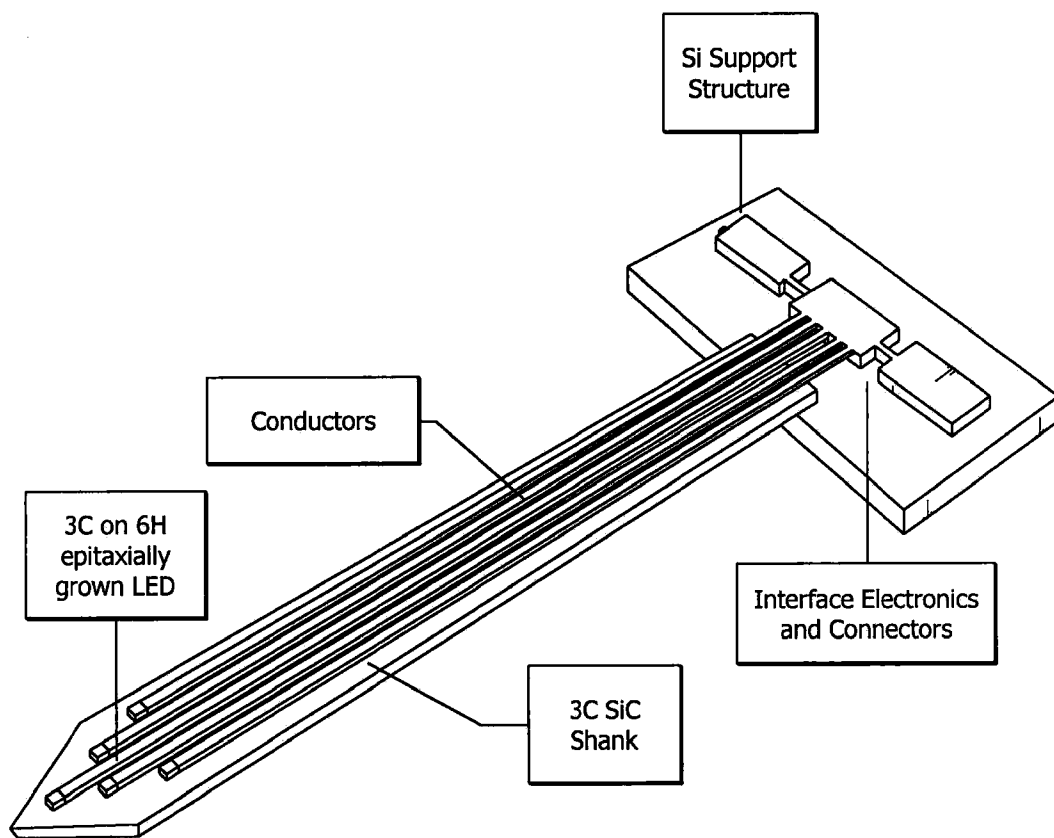
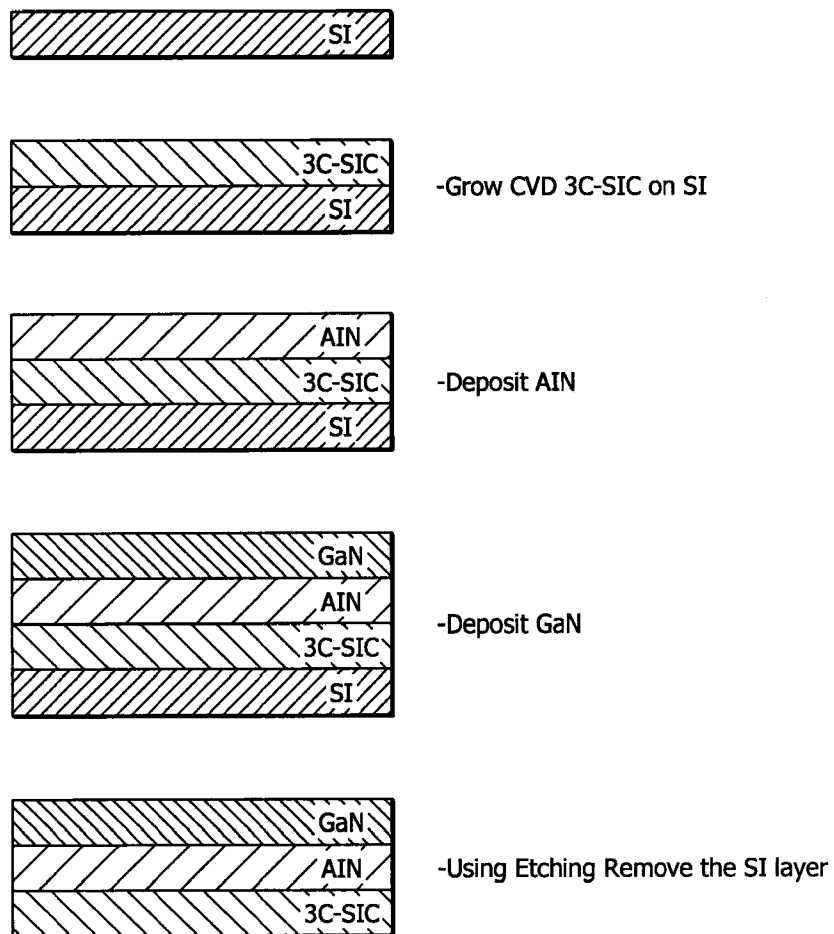


FIG. 1

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*FIG. 2*

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*FIG. 3*

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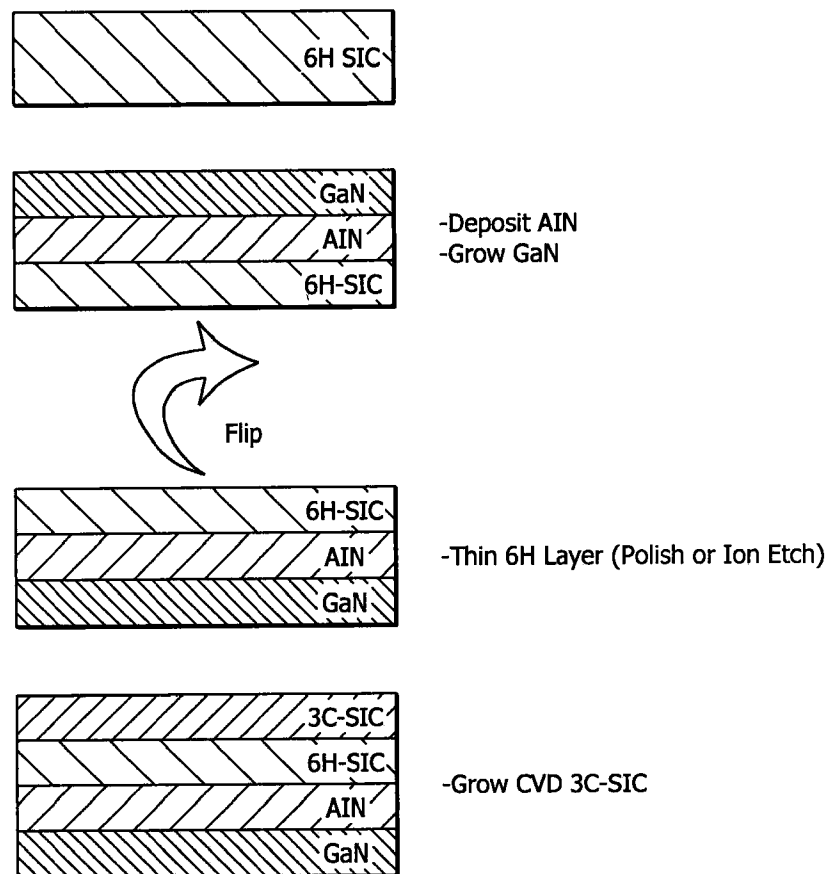
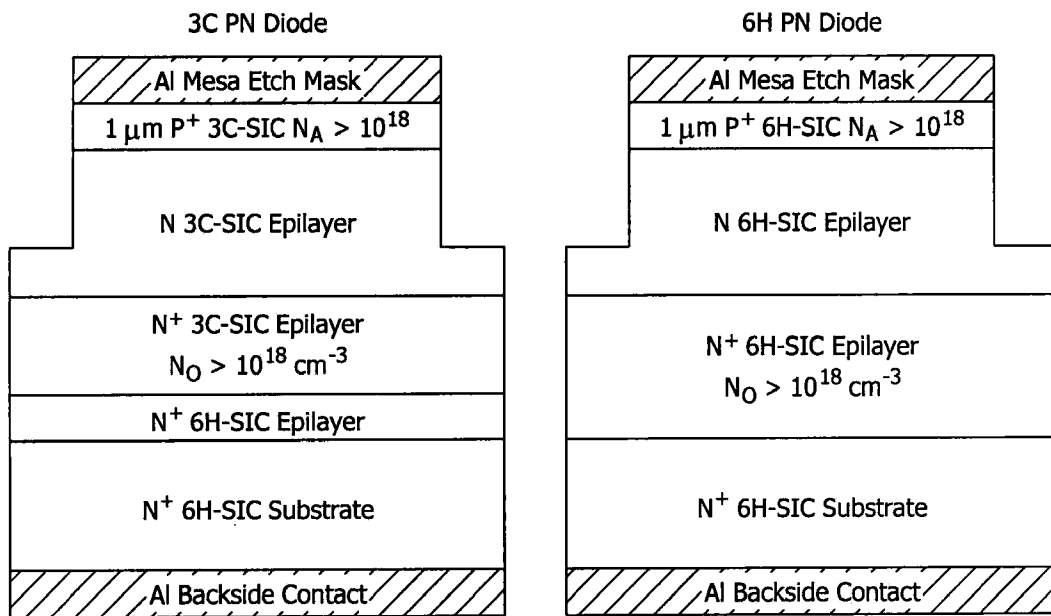
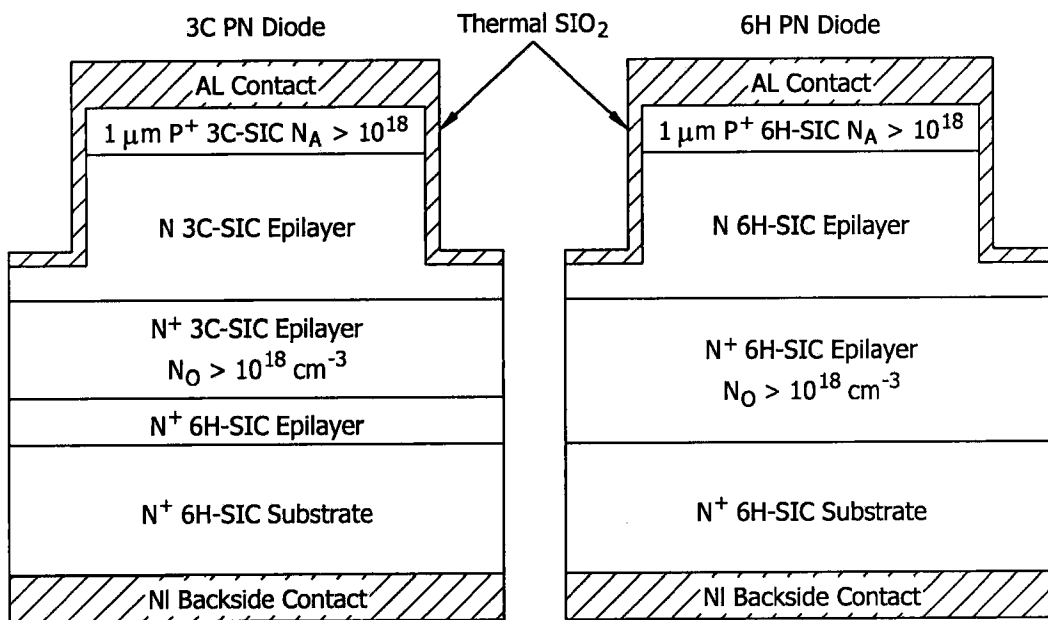


FIG. 4

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Partially Fabricated Diodes

FIG. 5A

Oxide Passivated Diodes

FIG. 5B