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Recording and Processing of Brain Waves using Nanotechnology

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Citation: Jaydeep Bhadra (2018) Recording and processing of Brain waves using Nanotechnology. J Nanotech Smart Mater 3: 1-9.

Abstract

In this project, our aim is to suggest a plausible method for recording dreams using nanotechnology. Dreams are a series of thoughts, images, and sensations occurring in a person's mind during sleep. They are a manifestation of brain waves (during sleep). Thus, we are using nanotechnology to create a sensor which can enable efficient recording of brain waves, that is, mapping the neural activity of human brain. The method proposed here is the following: First, the use of a 3D macroporous flexible electrical network embedded with nanoFET sensors which can be placed inside the brain and enable mapping of neural activity. Second, the signals obtained from the nano-based sensor are collected to an output device and further processing of the brain signals are carried out.

Keywords: Dreams; Neural activity; Neurons; NanoFET sensor; (biocompatible) Electrical tissue; Circuit diagram; Electrical devices

Introduction

Dreams: The aim of our project is to design a Nano based device which can decode Dream. Dreams are successions of images, ideas, emotions, and sensations that occur involuntarily in the mind during certain stages of sleep. Dreams can be about: a cherished aspiration, ambition, or ideal, or may be sometimes dangers, sad and bad events etc. However what dreams are or why do we dream is not so sure to the scientists till today. The scientific study of dreams is called oneirology. In the Greek and Roman periods, people believed that dreams were direct messages from one and/or multiple deities, from deceased persons, and using that signals they tried to predict the future. Sigmund Freud explained dreams as manifestations of our deepest desires and anxieties, often relating to repressed childhood memories or obsessions. With the development of science today, scientists can find out when we dream, what happens to our body during dreaming. But it is a surprising thing that we forget most of the dreams we see just after our awakening from sleep. That is, the more we try to recollect, the more we forget! We all have experienced that dream appears like a movie.

What if using nanotechnology we can record the movies in a similar way like a video recorder or at least the images like a snapshot, and then watch it in an output device like television or computer, that will be a better way to interpret the dream. If this kind of a thing is developed interpretation of Dreams will be far easier.

Dreams are generated inside the brain. Recent studies show that during dreaming the Theta waves (frequency range: 3-8 Hz), from the brain, predominates. Hence our target is to catch the theta waves and then process them, to convert them into image forms and if possible into video output forms with the help of Nano-scale devices. Now we'll discuss in short about the structure of brain, neuron: nerve cell forming the neural network which is responsible for generating various brain signals.

Structure of Brain [2]: The Basic parts of the brain are depicted below:

Among the parts of the Brain shown in Figure.1, the Brain Stem Part is responsible for automatic survival functions. The brainstem also contains networks of neurons, known collectively as the reticular formation, that project up into the cerebral cortex and basal ganglia and affect general arousal. The reticular formation is also involved in inducing and terminating the different stages of sleep. The Theta waves generated during sleep steps are originating from the Parietal and Temporal Lobe.
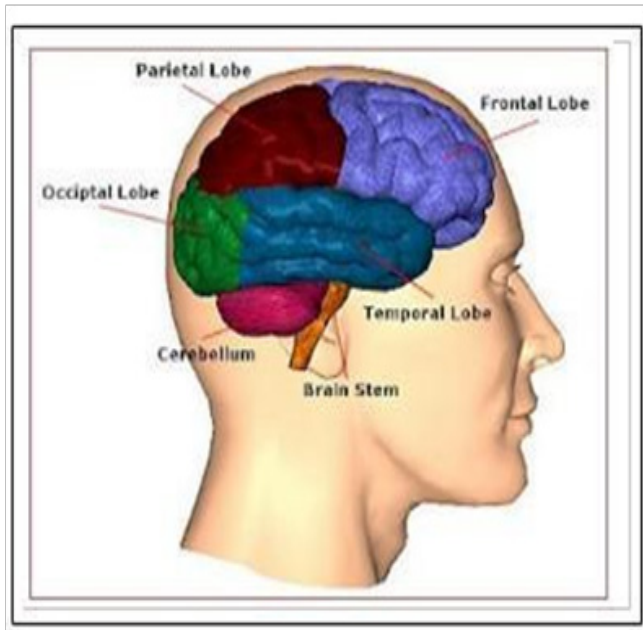
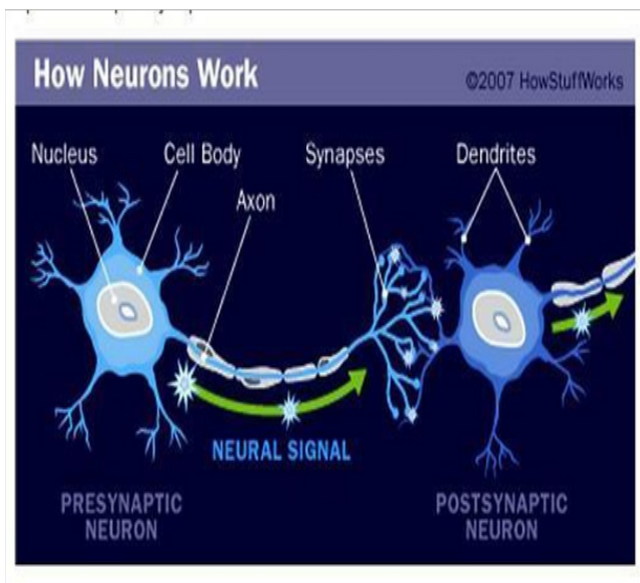Figure 1: Brain structure

Neuron and Neural Network:

Figure 2 : Neural network (between 2 neurons).

[3,5] The neural network inside our brain is formed by connections between various neurons. Neuron (nerve cell) serves as the basic unit for signal transmission in our brain. It consists of a cell body (soma), dendrites and one axon. Signals are transmitted from one neuron to several neurons via junctions called synapses. Various functions of the neural network are: to receive information from outside (environment) via sensory neurons, process the information and finally generate signals which get transformed into various mechanical actions, thoughts, emotions, dreams & consciousness.

Key features of neural network: it consists of an average of 86 billion neurons. Each neuron has an average 7000 synaptic connections to other neurons. Adult brain has of the order of 1014 synapses. This network lies in the brain and reaches out to the body as well. The neuron's cell membrane at rest has voltage which is around -70 mV. This is known as the Resting Potential. It implies that the neuron at rest is electrically charged (due to difference in charge carriers (ions) inside and outside the cell membrane). When a neuron fires, it sends out an electrical signal (via it's axon to other neurons) called Action potential. The action potential is a roughly 100 mV fluctuation in the electrical potential across the cell membrane that lasts for about 1ms.

Types of Brain Waves

[6]Brainwaves are produced by synchronized electrical pulses from masses of neurons communicating with each other. Our brainwaves change according to what we're doing and feeling. Brainwave speed is measured in Hertz (cycles per second) and they are divided into bands delineating slow, moderate, and fast waves. The typical Brain Waves during different times of sleep can be presented as above. It is a proven fact that dreams occur during light sleep or REM sleep. Our aim is to record and process the Theta waves.

Project Description

Recording and Processing Brain waves

The various brain signals generated from the neural activity results in the various phenomenas such as thoughts, emotions, dreams and consciousness. Here we are going illustrate how we can use nanotechnology to map out the neural activity. Now two things have to be kept in mind while designing the sensor:

1)   Sensor sensing action potential from individual neurons, i.e., probe the cellular or subcellular region with high resolution.

2)   Sensor detecting signals from the neural network in large, which means the sensor spanning out (or should probe) a large number of neurons simultaneously, covering the neural network at the maximum scale possible.

The size of a neuron ranges from 4 microns to 100 microns in diameter. Length of the axon varies from an inch to several feet. Thus, with nanotechnology, it is possible to create a nanometer sized probe that can potentially probe inside a cell membrane. Our purpose is to record this action potential from as many neurons as possible simultaneously.

TABLE 3

Alertness and Sleepiness may be quantitatively measured by noting the changes in the electroencephalographic (EEG) power spectrum. The lower the number (Hz), the slower is the brain pattern.

	Delta	Theta	Alpha	Sigma	Beta
Frequency (Hz)	0.5-4	4-7	8-13	11-15	13-40
Sleep	deep	light	12-14 REM sleep		
Alert			focused concentration	vigilant (anxiety)	arousal

Figure 3: Types of brain-waves

After the signals have been detected/collected by the sensor, they have to be stored in a memory device and then the signals can be processed further in the following way:

Block Diagram

Required signal selected	Collection of Brain waves	Signal stored in memory device	Output the signal to a device	Decode the selected wave	Image of the selected wave

Figure 4: Block diagram: Further processing of Collected Brain Signals.

As per the block diagram the complete procedure may be divided into following steps:-

Collection of Brain Waves : All kinds of brain waves (of any frequency & amplitude) generated from different parts of the brain are collected using nano-based sensor.

Store the wave : Here a memory device stores the waves as the signal forms.

O/P to a device : The stored signals from the memory element are sent to some electronic device for further processing.

Selection of the required wave : During dreaming Theta waves (frequency: 3-8 Hz) dominate, hence they are sorted out with the help of a filter

Decoding the Selected wave: The selected wave is converted to a digital form and then decoded for further processing.

Imaging the Selected wave: The digitized waves (after decoding) can be compared to some earlier set values of data for imaging the waves.

Brief procedure for collection of brain waves may be explained as follows:

Fabrication of Nano-Scale Device

Here we present Ist part of designing the sensor: nanoFET based sensors which can potentially record the active potential of a single neuron (intracellularly). A FET device is a voltage-sensitive device. Whenever the voltage across gate terminal changes, it allows conduction to occur via the source-drain channel.

(A) Kinked Nanowire Probes: [8,9] Conventional linear geometry FETs cannot probe into the sub-cellular level efficiently. Therefore, the structure of the FET device has to be modified in order to probe within cells. One way is to use kinked Silicon nanowires in a V or U shape and the nano FET is introduced at the kink tip. It represents an ideal geometry for intracellular insertion. Si nanowires are being chosen because very small probe devices can be created with diameter in the range 10nm – 50 nm.

Features: [9,10] The nanoFET is encoded near the probe tip (kinked structure) directly during synthesis. This allows the highly localized FET at the kink tip to be inserted into the cell without damaging it. These devices when coated with phospholipid layers (similar in structure to the cell membrane) penetrate the cell membrane very easily and ensure highly sensitive transmembrane action potential recording.
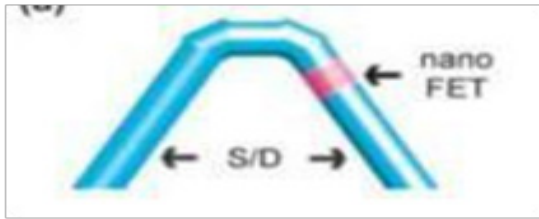
Figure 5: [9] Kinked nanowire probe. Pink: nanoFET, blue: nanoscale source, drain electrodes.

Synthesis: [9,11] These nanowires can be synthesized using gold nanocluster catalyzed vapor-liquid-solid (VLS) growth mechanism in a (CVD) chemical vapor deposition system . Light doping modulation is used to encode the nanoFET channel very close to the probe tip directly during synthesis. The arms of the nanowire are heavily doped to serve as nanoscale source, drain electrodes. A cell probe can then be fabricated by connecting the nanoscale S/D arms to strained microscale metal interconnects as shown below:

(B)Branched Intracellular Nanotube Fet Probe (BIT-FET) [9] :

Another sensor that can be used for highly sensitive, high resolution intracellular recording with absolute smallest probe size which can probe into sub-cellular structures: neuronal dendrites and dendritic spines, is the following: Branched Intracellular Nanotube FET Probe (BIT-FET).

Features: [9] This sensor consists a vertical silicon dioxide nanotube integrated on top of a FET channel (a Si NW channel). When the nanotube enters the cell membrane, the cytosol fills the nanotube and activates the FET channel which enables recording: intracellular action potentials.
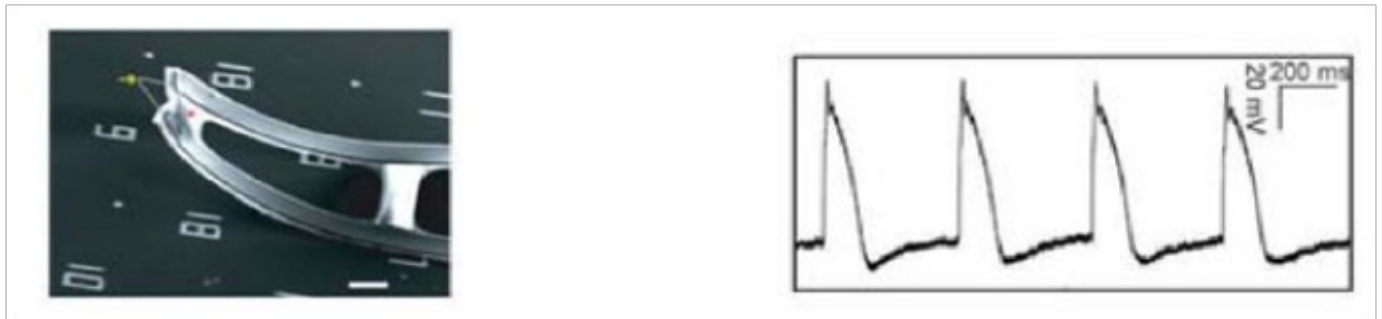

Figure 6: Left :- a 3D free-standing kinked nanowire FET bent probe. Yellow arrow (at the tip of V nanowire) marks the nanoscale FET. Scale bar: 5 micrometer. Right:- Steady-state intracellular recording [9].
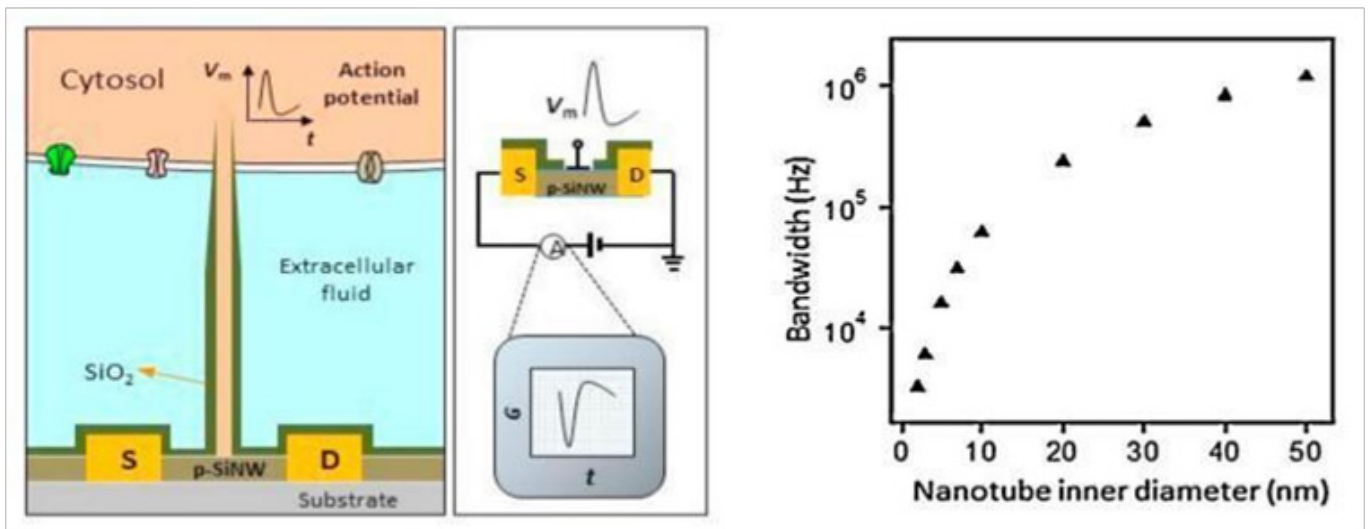

Figure 7: a) BIT-FET nanoprobe b) Calculated bandwidth of the device vs nanotube inner diameter for a fixed nanotube length of 1.5 ìm [9].

This nanodevice too is functionalized with phospholipid layers which allows nanotube to enter the cell membrane with ease and also allows a tight seal between the nanotube probe and the (interior) cell membrane. Because the probe is of ultra small size, it allows minimal invasiveness into the membrane without disrupting cell structures. Also it allows repeated recording of potentials at the same cell site which makes it reliable for long term, stable recordings and a robust nanosensor. It is a highly sensitive probe that can even probe into sub-cellular structures which makes it an ideal intracellular probe for recording (neuron cell) membrane potentials.

Thus, the above two nanosensors can be utilized for recording intracellular cell membrane action potentials with very high resolution.

Now, we shift our focus on the 2nd part of designing the sensor: sensor detecting signals from multiple neurons simultaneously, covering most of the neural network. One of the ways to do that efficiently, is to integrate the above nanoFET sensors to a 3D macroporous flexible electronic network.

3D Macroporous Nanoelectronics Networks [9,11]

Features: [9,11] It is macroporous which enables 3D interpenetration of neuron cells. With it's large area and embedded with high density of nanoscale probes yields high spatio-temporal resolution and high density of neural recording (i.e., large number of neurons in the neural network probed simultaneously). The structural elements have nanometere to micrometer scale dimensions comparable to biomaterial scaffolds. It has 3D interconnectivity and mechanical properties similar to natural tissue. The nanoscale probes within the network offer minimal perturbation to cells and tissues.

Concept of merging nanoelectronic networks with living tissues seamlessly [9,12]

- The nanoelectronic network in 2D is fabricated with underlying sacrificial layers and substrate support. The above mentioned nanoFET probes are incorporated in it (Figure.8, step A). This yields a 2D electronic network with multiple nanoprobes attached to it.
- The sacrificial layers are removed to release the nanoelectronic network and yield 3D, free-standing macroporous nanoelectronic scaffolds (nanoES). The nanoES have nano- to micro-meter features with high (>99%) porosity, highly flexible and biocompatible. The nanoES can be used alone or combined with tissue scaffold materials which makes them suitable for tissue culture (Figure.8, step B).
- Cells are seeded & cultured in the nanoES to yield 3D nanoelectronic-tissue hybrids (Figure.8, step C).
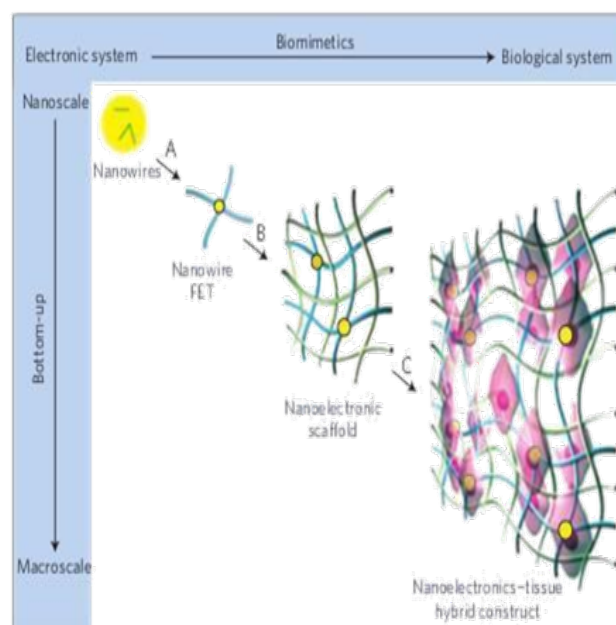

Figure (8): Coneptual steps for merging nanoelectronics with artificial tissues seamlessly in 3D [11].

Fabrication [11]: of the nanoES (using kinked Si NW FET as the probe) in brief : a layer of negative resist (SU-8) is coated on a nickel sacrificial layer, a solution with kinked nanowires are deposited onto the SU-8 layer and allowed to evaporate, and then SU-8 is patterned by lithography to immobilize nanowires and to provide the basic framework for nanoES. Extra nanowires are washed away during the development process of the SU-8 structure. Metal contacts are patterned by lithography and deposition. Finally, a layer of SU-8 is deposited and lithographically defined as the upper passivation layer on the interconnects.

Using the above concept and fabrication method, Reticular nanoES [9,11] was designed. These are made by electron beam lithography (EBL). The metal interconnects in the 2D structure are stressed such that on removal of the sacrificial layer, it self-organizes into a 3D structure. The 3D structure resembles the fibrous meshwork of the brain tissue.

Embryonic rat hippocampal neurons [11] were cultured in the reticular nanoES/Matrigel for 7-21 days. Reconstructed 3D confocal micrographs from a two-week culture (Figure.9) showed neurons with a high density of spatially interconnected neurites penetrating the reticular nanoES seamlessly, often passing through the ring structures supporting individual nanowire FET sensors (Figure.9b).
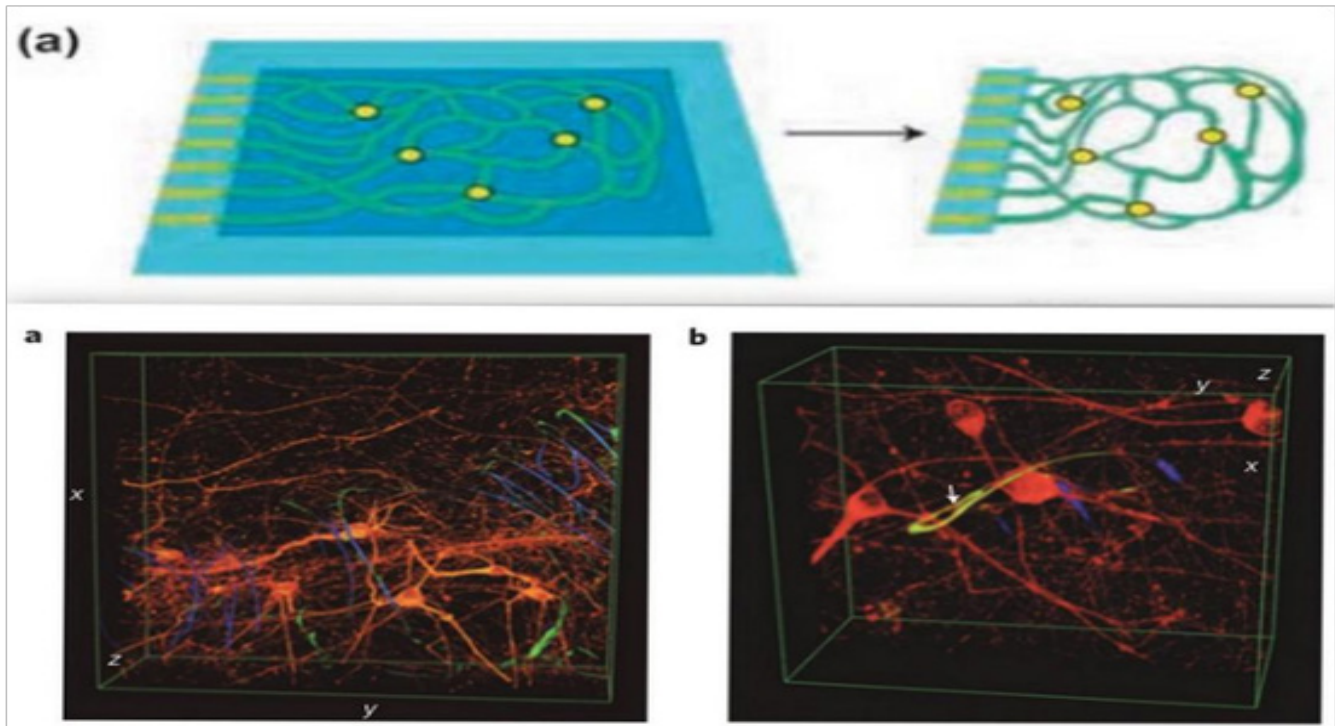
Figure.9: Top: Reticular nanoES: a) Device fabrication schematics for reticular nanoES. Light blue: silicon oxide substrates; blue: nickel sacrificial layers; green: nanoES; yellow dots: individual nanowire FETs. Bottom:3D tissue hybrid/ nanoelectronics:3D reconstructed confocal images of rat hippocampal neurons after a two-week culture on a reticular nanoES. a) Red: neuronal â-tubulin; yellow: epoxy ribbons. The metal interconnects are false coloured in blue. b) The white arrow highlights a neurite passing through a ring-like structure supporting a nanowire FET[11].

The above example demonstrates that a 3D macroporous nanoelectronic network represents a powerful platform for neural activity recording and mapping.

Placement of the Device: Finally, we would like to place this (sensor) 3D macroporous flexible electronic network inside the brain in a minimally-invasive manner for recording neural activity. There are two possible ways of implanting the electronic network inside the brain [12]

• First the flexible nanoelectronic network device can be transferred to the surface of a biodegradable polymer layer and then through direct mechanical insertion as is used with conventional neural probes is carried out. Inside the brain, the sacrificial support dissolves and the nanoelectronic device network remains inside the brain giving a seamless nanoelectronics/neural network interface [12].

• The highly-flexible nanoelectronic network is injected via a syringe needle directly into the brain. Post-injection, the nanoelectronic network is expected to yield a seamless nanoelectronics/neural network interface [12].

After implanting the 3D electronic tissue inside the brain as mentioned above, the brain signals obtained from the sensor are collected to an output device in the following way, as shown in Figure. (11):

A -- Sensor: 3D macroporous flexible electronic network is placed inside the brain (preferably in the temporal & parietal region) for detecting brain signals.

B -- The memory device is embedded in the 3D electronic network to record brain waves [9].

C -- Functionalized Carbon nanowires (modified on the surface to make the CNWs biocompatible and CNW have excellent electrical properties – conductivity much superior to copper wires) are used for transferring the signals from memory element (present in 3D electronic tissue) to our finger tips. Figure. (11)

D -- Recorder probes, placed on finger tips which then transfer the signals to an output device via an outside circuitry as shown in Figure. (11)-right.
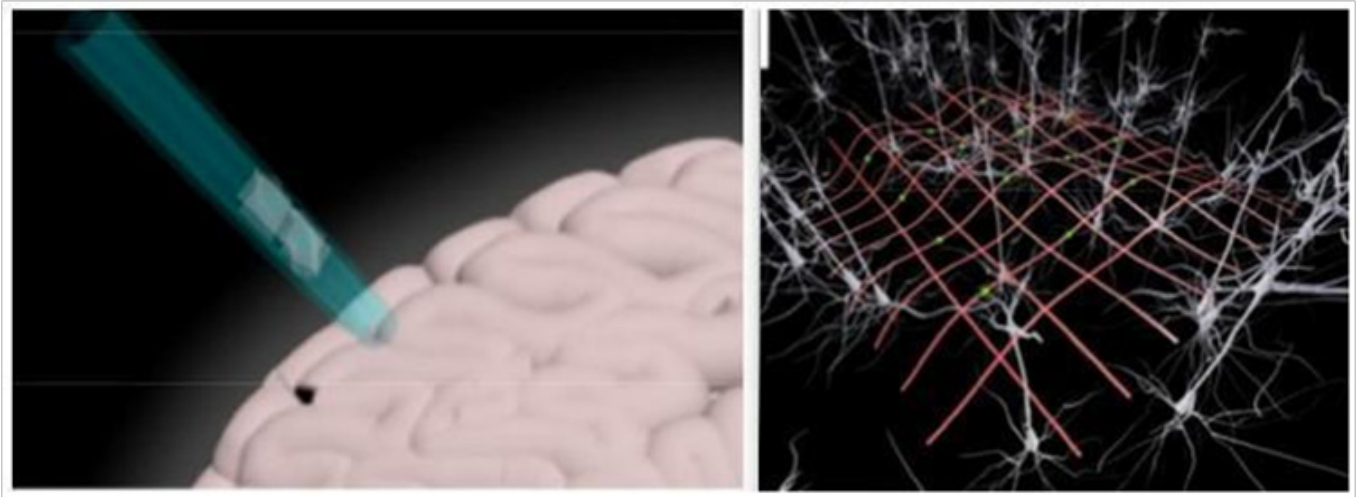
Figure (10): Left:- The highly flexible nano-electronic network is delivered into the brain by either injecting through a needle inserted into the brain (shown) or inserting supported on a removable or biodegradable rigid support probe. Right: - Depiction of the nanoelectronic network merged with a brain neural network after implantation in a minimally-invasive manner. The green dots indicate positions of the nanoelectronic devices, and the red lines correspond to both encapsulated electronic interconnects and structural elements [12].
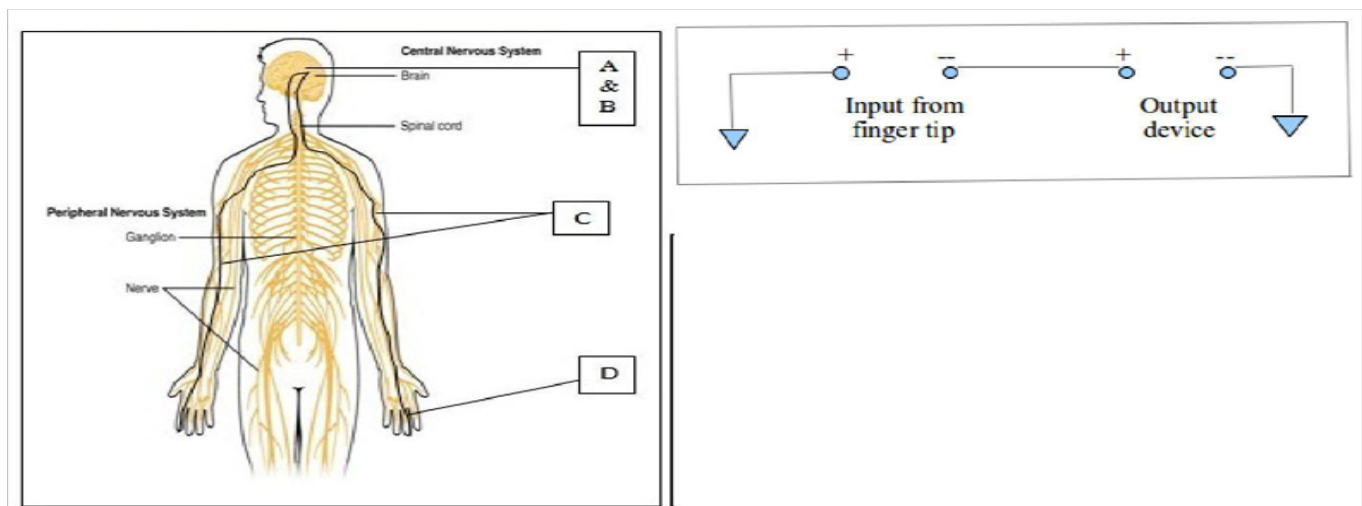

Figure (11): Left:- A&B – 3D electonic tissue (embedded with nanoFET sensors & memory element) placed inside brain. C – CNWs carry signal from sensor to finger tips. D – Recorder probes placed on finger tips, from where signals are sent to an output device. Right:-Circiut diagram: showing how brain signals are collected outside the human body. Brain signals from the recorder probes (on finger tips) sent to an output device via an outside circuitry.

Thus, the above procedure illustrates a mechanism for collecting and recording brain-waves. Now, we'll discuss how the recorded brain-waves can be processed further to (possibly) convert them into image forms.

Processing of Brain-Waves: - [7]

A Machine learning based method is chosen for this application. The motivation is that the highly stochastic uncertainty of the signal received makes deterministic decision making erroneous. Also the noise corrupting the signal which is picked up by the sensors is taken care of in the analysis part.

Denoising Module: Firstly the recorded signal is denoised to make the Signal-to-Noise ratio of the signal high. Our assumption here: is the noise associated are mainly high frequency noise. So a low pass filter will serve the purpose. The cut off frequency is selected quite methodically so that no information is lost.

Training Module: In the training phase we need to collect a reliable dataset. Experiments are conducted in a controlled environment where the subject is stimulated with a particular genre of dream and the response is recorded using above procedure. This data is denoised as described above and standard datasets for training a learning algorithm is generated. As the problem here deals with learning a highly non-linear response we select a strong classifier like Random Forests or Multi Class SVM with Gaussian kernels. The Classifier is trained with the generated dataset. The Data should be very large to make the model robust, generalized and to prevent over fitting.

Cross Validation Module: The Training Dataset is divided into 2 parts. The training is accomplished in 80% and validated in 20%. This is to validate whether the training model is robust enough or not. This is done in an iterative fashion until the error is very less.

Performance Analysis Module: The performance of the learning model is evaluated by testing on new datasets. Its Receiver Operating Characteristics (ROC) is plotted and the Area under the Curve (AUC) is evaluated to see the generalizability and sensitivity of the learnt model. If all the parameters are good enough it is deployed at the end of the proposed framework for reliable dream decoding.

Conclusion and Recommendation

Therefore, 3D macroporous flexible electronic networks provide a brand new way of studying neural activity. They have been used for 3D culture of rat's neurons. Very recently these electronic networks have been implanted into a mouse brain via a syringe needle [13]. Inside the brain the mesh opens up and melds with the brain tissue. The mouse remained brain-healthy for a full 5 weeks after implantation, thus enabling long-term recording of neural activity [13].

This potentially offers a strong platform for in vivo neural activity recording and mapping in humans as well. Such 3D electronic tissues offer unique capabilities such as high spatio-temporal resolution, high neural density recording and stability of long-term recordings [12] .They will potentially serve as an excellent brain-machine interface for diagnosing various neurological problems like epilepsy and brain disaeases such as Parkinson's disease [12].
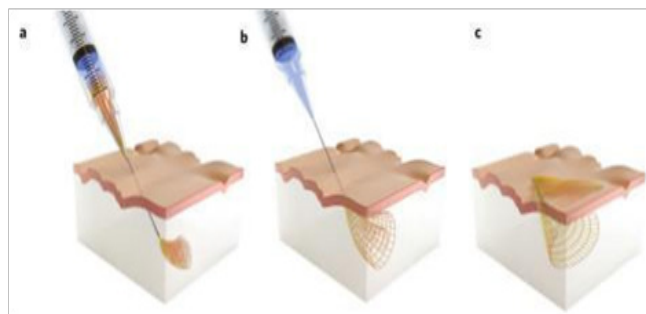

Figure 12: A rolled up 3D electronic mesh that is injected into a mouse brain. Once there, it unfolds and melds with the brain tissue [13].

Thus, by implanting the 3D electronic tissue (containing nanoFET sensors and memory device) selectively in the temporal and parietal region of the brain, theta waves (mainly) responsible for dreams can be recorded and using the appropriate machnine learning algorithm, the data (brain signals) can be converted into meaningful patterns and hence image plots. This recommended framework by us can surely be applied in the near future (which uses nanotechnology) to decode dreams in an unprecedented manner.

References

1) Wikipedia

2) Wikipedia

3) A Course on Foundational Neuroscience for Perception and Action, Leonard E. White, Duke University.

4) A Course on Computational Neuroscience, Rajesh P.N.Rao & Adrienne Fairhall, University of Washington, Seattle, USA.

5) Theoretical Neuroscience, Computational & Mathematical Model of Neuron System, Peter Dayan and L.F. Abbott.

6) Journal: Type of Brain waves, EEG sensor and brain wave – UK.

7) Abhijit Guha Roy, Instrumentation and Signal Processing, IIT Kharagpur.

8) Chapter 6: Nanowire-based Sensors from the Book: 'Nanotechnology and Nanosensors' by Prof. Hossam Haick.

9) Duan X, Lieber CM (2013) "Nanoelectronics meets biology: From new nanoscale devices for live-cell recording to 3D innervated tissues," Chem. Asian J. 8: 2304-2314.

10) Kruskal P, Jiang Z, Gao T and Lieber CM (2015) "Beyond the patch clamp: Nanotechnologies for intracellular recording," Neuron 86: 21-24.

11) Tian B, Liu J, Dvir T, Jin L, Tsui JH, et al (2012) "Macroporous nanowire nanoelectronic scaffolds for synthetic tissues". Nature Mater. 11: 986-994.

12) Duan X, Lieber CM (2014) "Nanoscience and the nano-bioelectronics frontier," Nano Research.

13) Liu J, Fu TM, Cheng Z, Hong G, Zhou T, et al. (2015) "Syringe-injectable electronics," Nature Nanotechnol.