Utilizing Quantum Dots for a High Resolution Vestibulocochlear Nerve Interface

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Abstract

“In order to replicate the effect of current electrical microelectrode arrays, we will identify the use of quantum dot photoelectrode arrays implanted into the cochlea to achieve photovoltaic stimulation delivered through optic fibers at a higher resolution than electrical stimulation. Our aim is to achieve a higher spectral resolution and greater electrode insertion depth with minimal trauma as compared to current microelectrode implants. Reducing the electrode array diameter allows for a greater depth of insertion, and reducing the size of the electrodes allows for a greater electrode density on the array within the cochlea. Current cochlear implants do not allow for complete insertion to the cochlea as there is a high risk of trauma. Allowing for increased insertion depth along with higher spectral resolution may allow for vastly improved speech and music perception for patients with severe to profound hearing loss. “

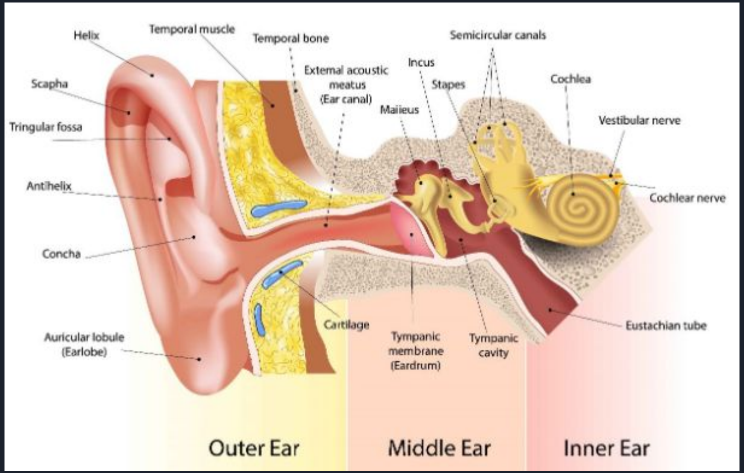
Auditory Physiology

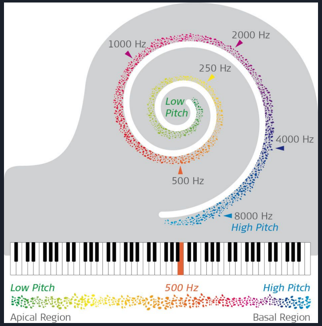
- Pressure waves from sound transduced to vibrations from the tympanic membrane (eardrum) that propagate through ear bones

- Vibrations induce endolymph fluid oscillations in the basilar membrane of the cochlea, deflecting hair cell stereocilia to activate the auditory nerve; region of cochlear activation depends on frequency of vibrations (and thus frequency of sound)

- Auditory nerve sends sound signals to auditory cortex for perception of sound

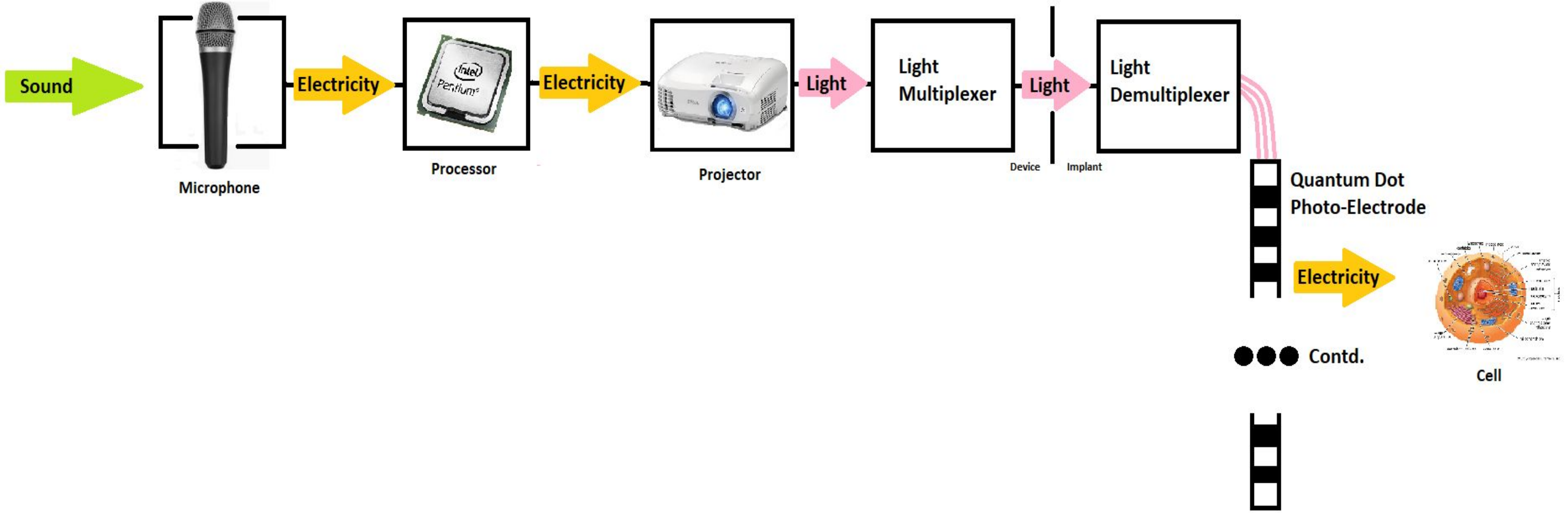
- In patients with severe/profound hearing loss, hair cells are damaged or missing





Our Proposed MEMs device

Indium phosphide based quantum dots for a high resolution vestibulocochlear nerve interface and limited implantation damage.



Similar Devices/Methods

- Current cochlear implant devices use metal strips to electrically stimulate the cochlear nerve
    - These receive their input from a constant current source which stimulates each of the 16/22 electrodes based on the frequency of the sound
- These typically use platinum tipped electrodes to depolarize local neural tissue
- Research in optogenetics and stimulation in other regions of brain
- Limitations with spectral resolution and frequency range

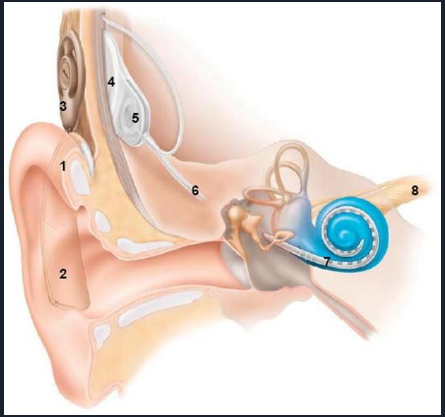


Image source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2782849/#!po=39.1566

Purpose of Device Concept

- This would allow for a higher frequency resolution cochlear implant
  - This is important since current frequency resolutions for cochlear implant users is significantly lower than normal hearing
    - This is critically important for music perception
  - Improvements in electrode insertion depth which allow for lower frequency sound perception
- This concept would also reduce long term damage to the vestibulocochlear nerve caused by corrosion of electrode and by insertion damage

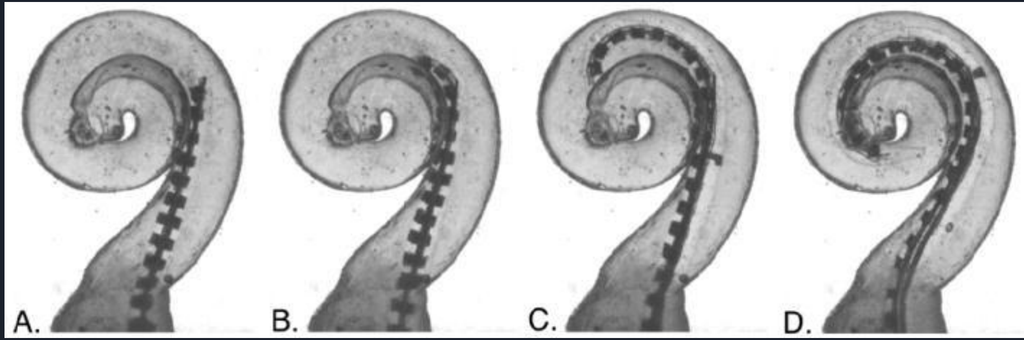
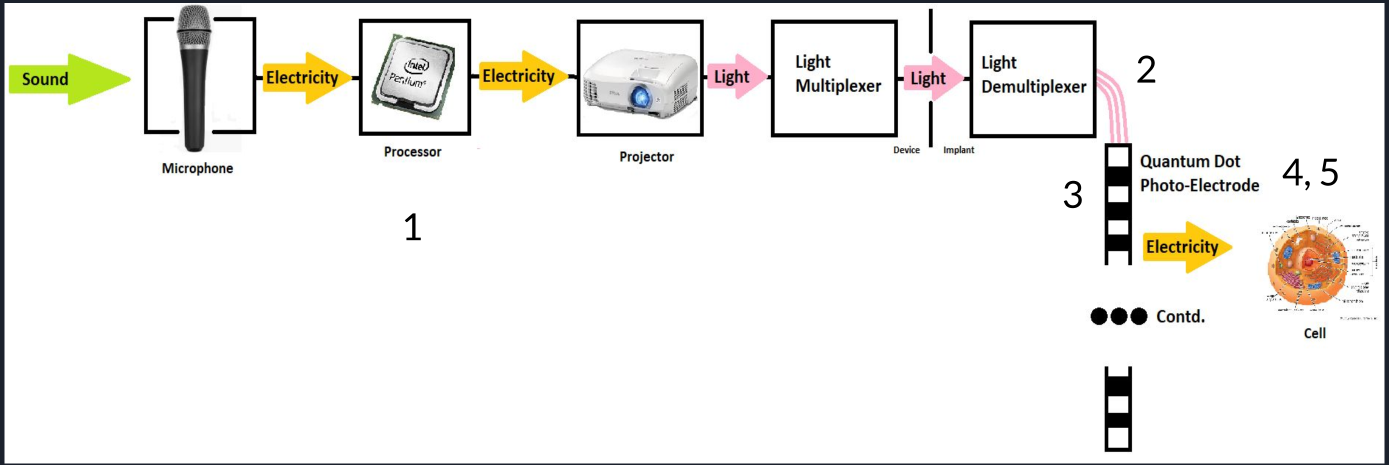


Image source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2782849/#!po=39.1566

Theories behind Device Concept

1. Digital Signal Processing
2. Fiber Optic Cables: Lossless optical transmission
3. Quantum Dots: Photoelectrode array
4. Anodic Break Stimulation
5. Photovoltaic Stimulation of Cochlea

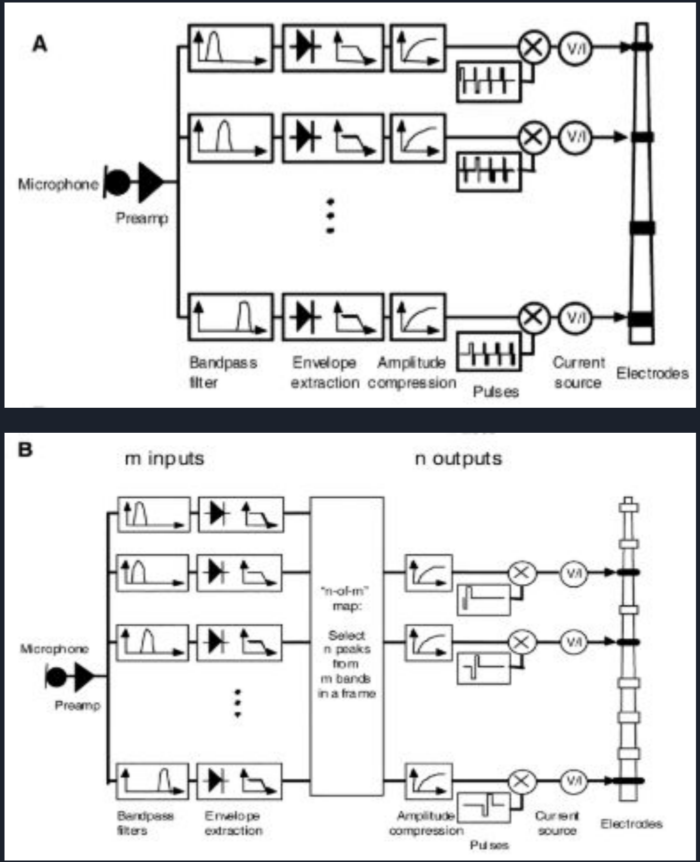


Digital Signal Processing Theories

Continuous Interleaved Sampling (CIS)

N-of-m

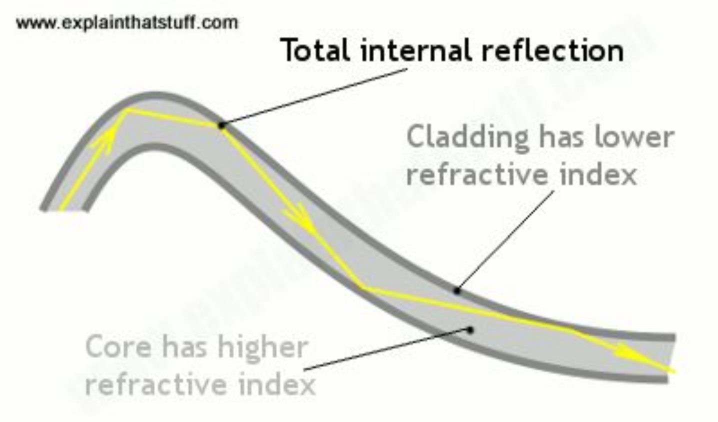
Simultaneous Analog Stimulation (SAS)

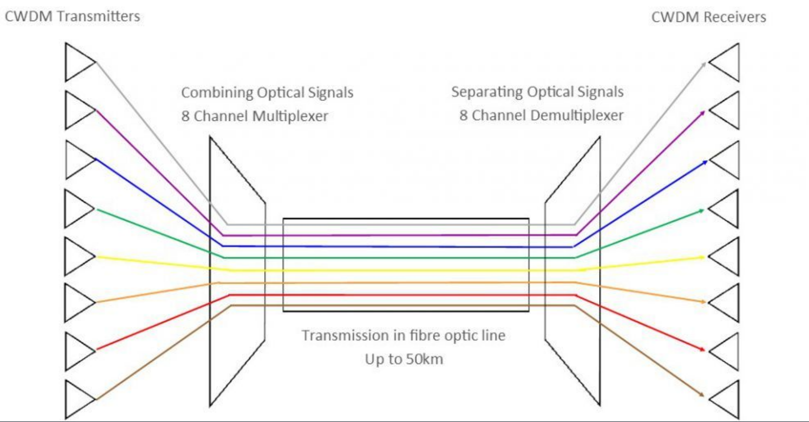


Zeng et al

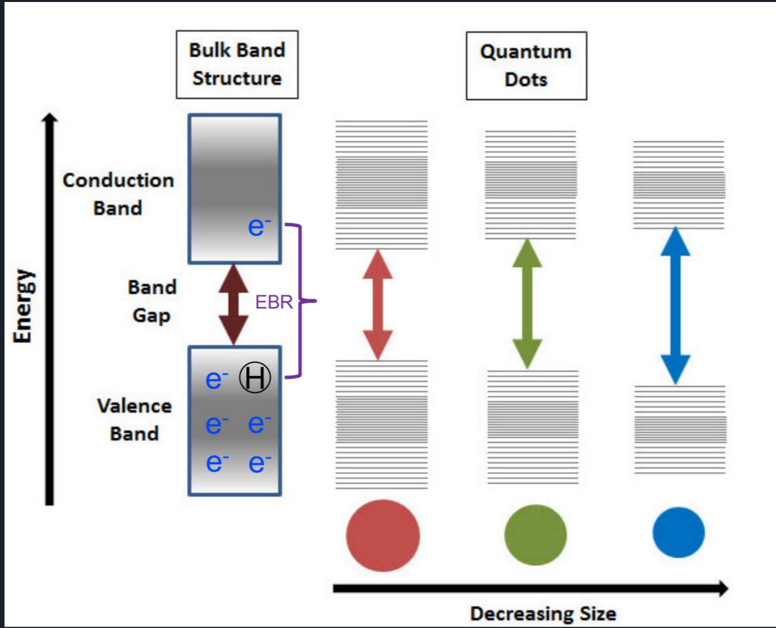
Optical Transmission through Fiber Optic Cables

- Optical fibers transmit nearly all light down their long axis
    - This is possible as they are composed of very pure glass about the diameter of a human hair which is clad with highly reflective coating which reflects over 99.9% of the light back to carry on
    - There is then a buffer coating which protects this fiber from the elements
- This allows for transmission of light nearly losslessly
- Multiple wavelengths of light can be put into a single fiber optic cable with optical multiplexing



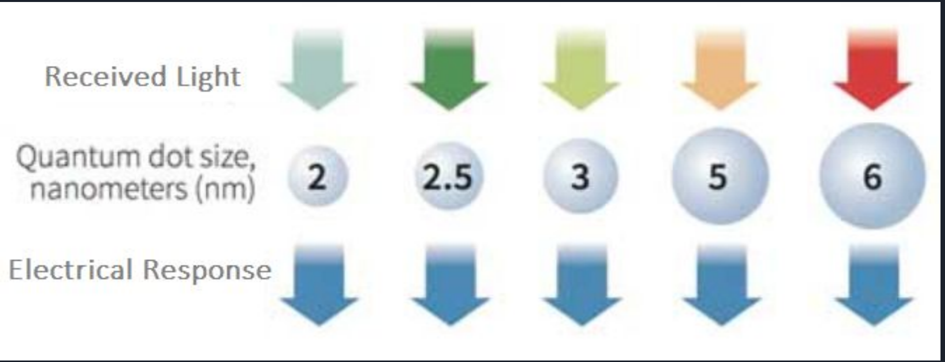


Quantum Dots: Light and Electricity



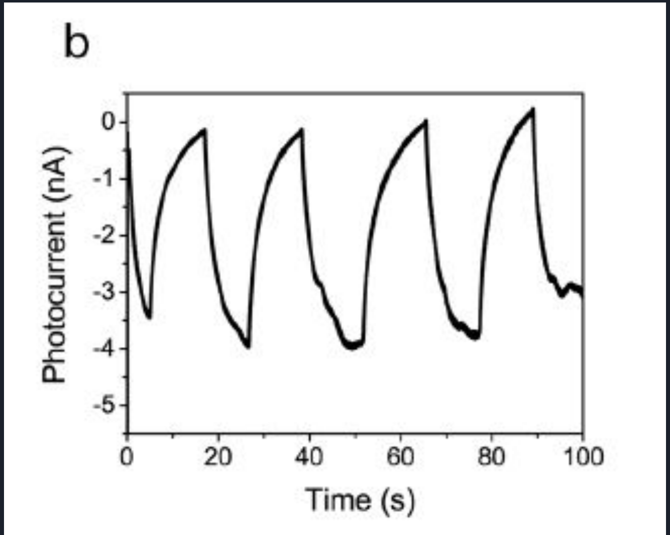
https://www.nanowerk.com/what_are_quantum_dots.php

Light → Quantum Dots → Electrical Signal



Electricity is emitted when valences return to ground state.

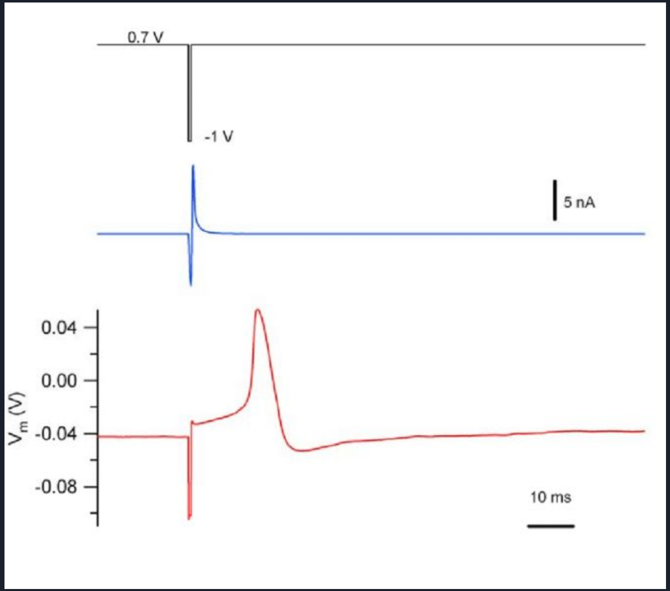
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2782849/#!po=39.1566

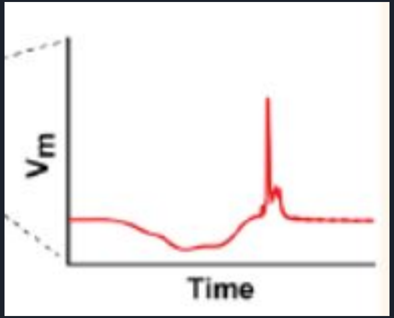


A stimulus hyperpolarizes the QD crystal.
A depolarization occurs when returning to its ground state.

Anode Break Stimulation of Neurons

- Anode break stimulation entails a very strong anodic stimulus which, when removed, will elicit an action potential.
    - This is theorized to work by the cell attempting to return its voltage to resting potential, but overshooting past the threshold voltage





https://www.researchgate.net/figure/Anode-break-excitation-of-action-potential-using-a-carbon-fiber-electrode_fig20_308928623

Photovoltaic Stimulation of the Cochlea

- Cochlear implant current range is typically 0 - 1.2 mA
  - Cochlear implant electrode impedances are higher than QD photoelectrode impedances
- QD photoelectrode induces neural activation at 4 μW/mm^2 (0 - -4 nA)
  - Power requirements to activate spiral ganglion cells with QD photoelectrodes should be comparable to Neuro2A cells

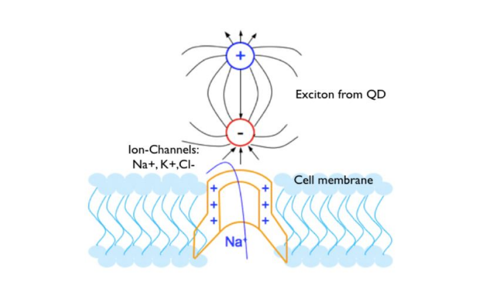
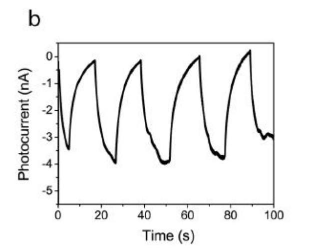


Fig. 1. Interaction of a QD with a cell membrane.



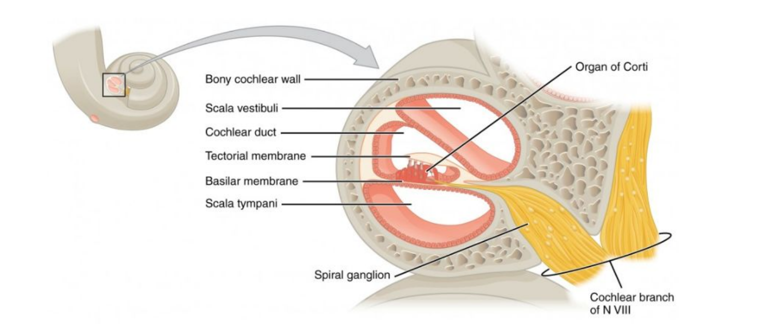
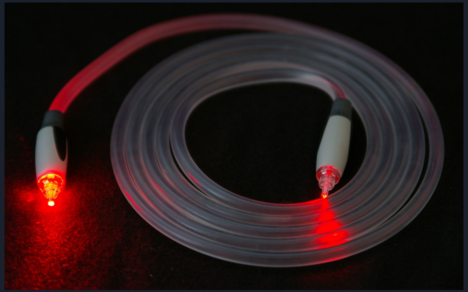
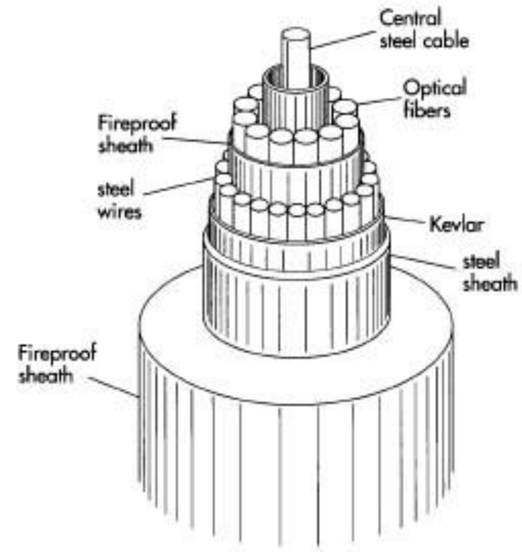


Image source: https://www.osapublishing.org/boe/abstract.cfm?uri=boe-3-3-447

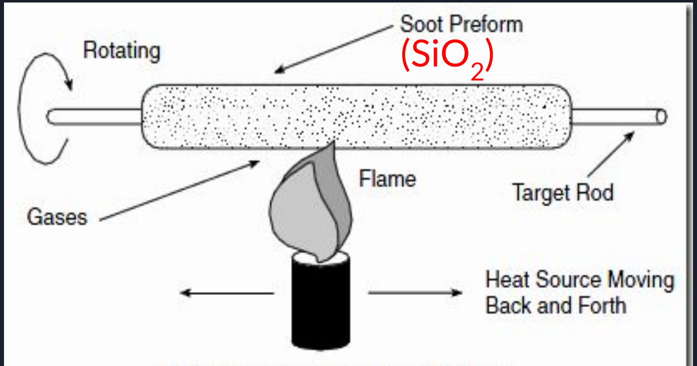
Fiber Optic Material & Fabrication



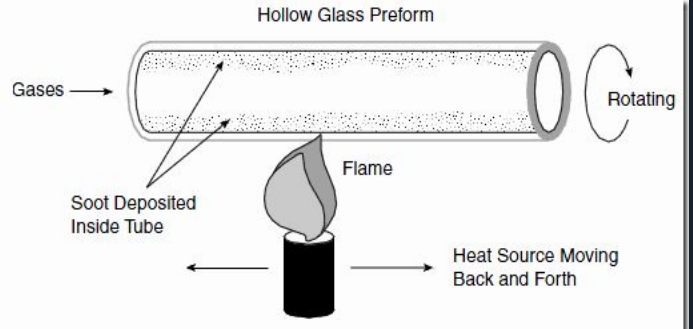


Glass, Polymer, or Photonic Crystal

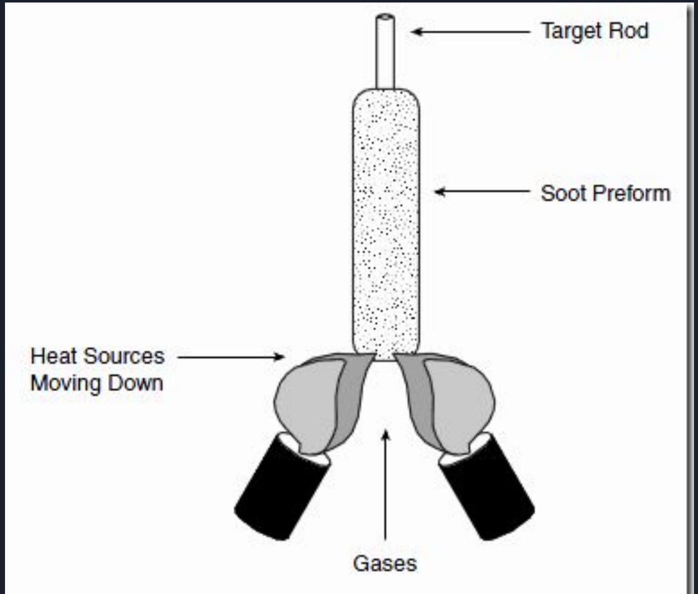
Glass Fiber Construction Methods



Outside vapor deposition (OVD).



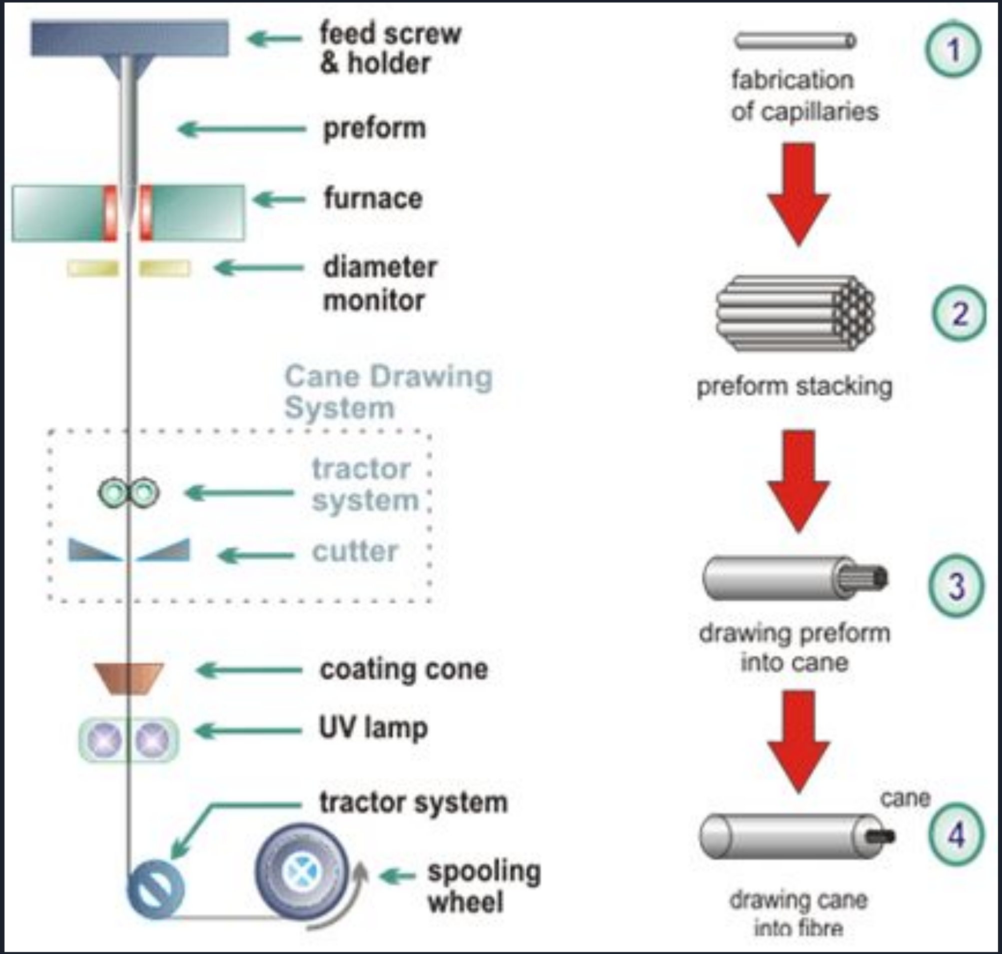
Modified chemical vapor deposition (MCVD)



Vapor axial deposition (VAD).

https://www.fiberoptics4sale.com/blogs/archive-posts/95051590-optical-fiber-manufacturing

Coating provides mechanical stress and water protection.



Individual Glass Fibers

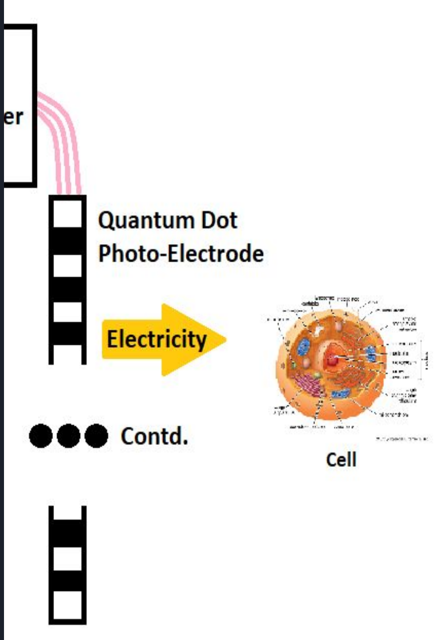
Stack Necessary Amount of Fibers

Draw Fibers to Correct Length and Size

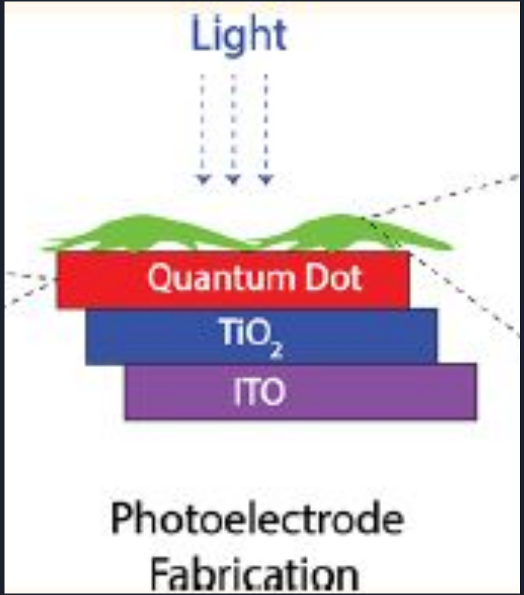
Insert Into Sheath/Jacket and Draw Jacket to Correct Length

https://www.slideshare.net/sagarpatel3720/fiber-fabrications

Photoelectrode Materials

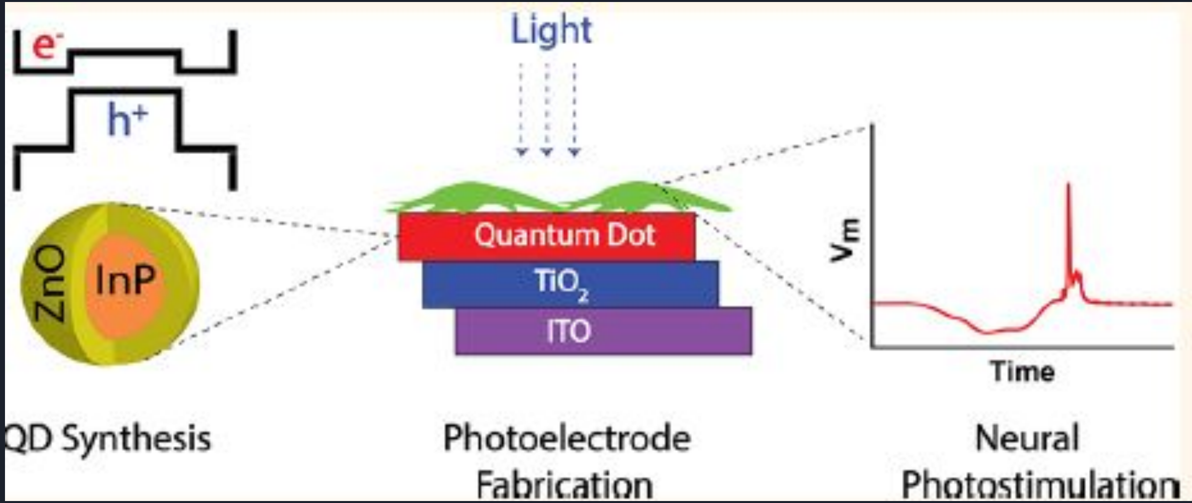


- ITO (Indium Tin Oxide) substrate
- TiO_2
- Acetonitrile Solution
- InP/ZnO QD Solution

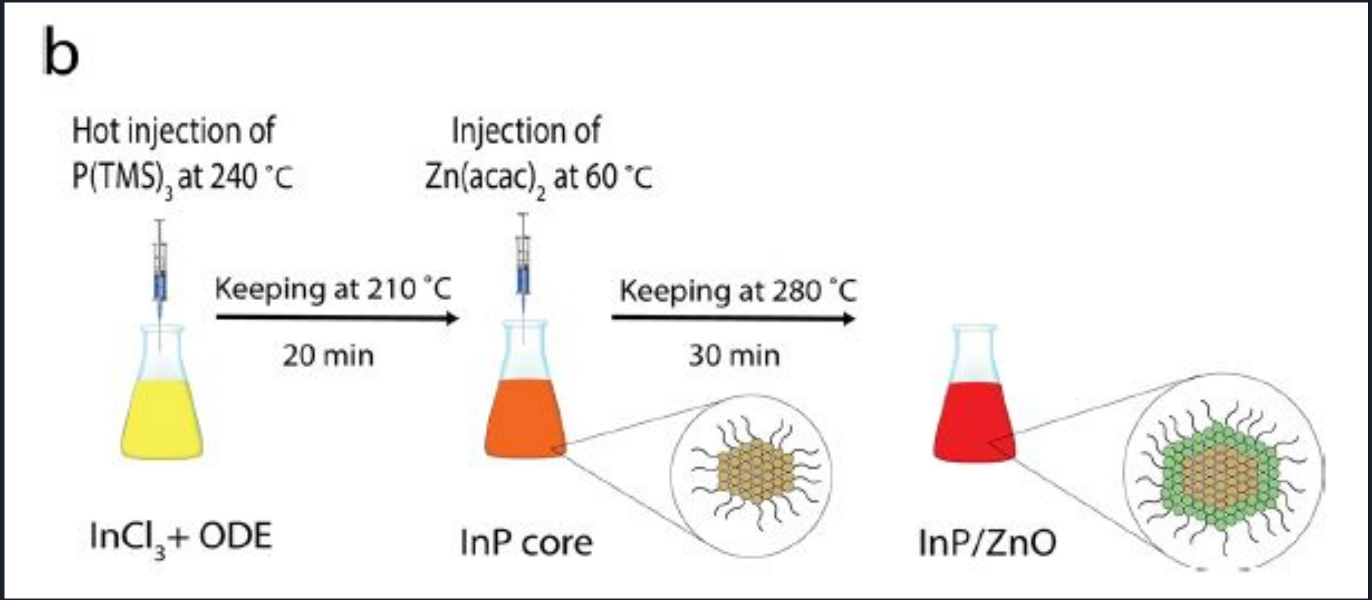


Useful Methodology in Manufacturing

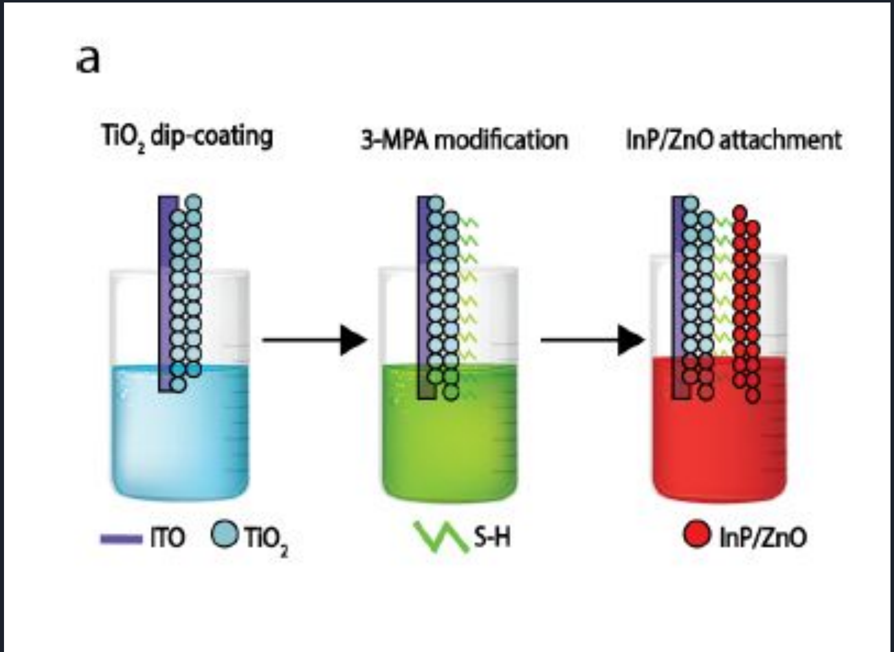
1. Quantum dot fabrication of InP/ZnO Core/Shell
2. Create electrode substrate & absorb QD onto substrate
3. Link Electrode Substrate to Fiber Optic Wire



Quantum Dot Fabrication



Create Electrode Substrate & Absorb QD



Connect Electrode Substrate to Fiber Optic Wire

- Create manufacturing process to connect ITO electrode substrate to the fiber optic wire.
  - ITO - spin coating
  - Fiber optic cable - heat and strain

Testing

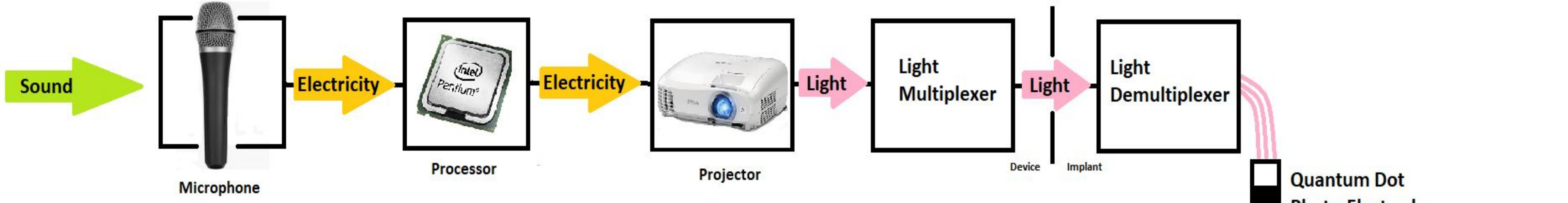
- Device Testing
    - Stress Testing
    - Testing for placement
    - Biocompatibility
    - Electrical Testing
- Animal Model
    - Neural Response
- Clinical Trials
    - Speech Performance

Biocompatibility

- Previous testing showing
  - Appropriate cell growth
  - Lack of cytotoxicity
  - LDH Leakage Assay
- Additional ISO 10993 testing for implanted device in contact with tissue/bone for a permanent duration.
  - Sensitization
  - Irritation
  - Acute systemic toxicity and subchronic toxicity
  - Genotoxicity

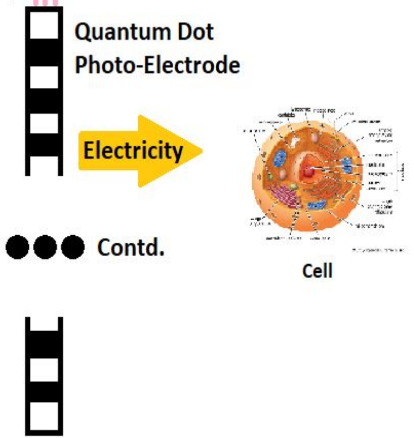
Limitations

- QD Lifespan
- Electrical Stimulation from QDs
- Closed Loop Feedback
    - Telemetry might not be possible
        - Monitoring QD impedances to ensure safe and effective stimulation
- Cost/Benefit



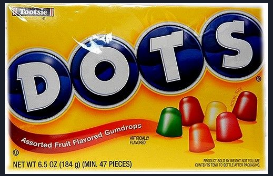
Utilizing Quantum Dots for a High Resolution Vestibulocochlear Nerve Interface

- Limited current spread due to QD
- Decreased cochlear damage due to smaller, more nimble electrode/electrode substrate



Summary

References



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