Diamond as an Electrode Material for Neural Stimulation

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The implanted stimulating electrode is one of the most critical design elements of a neural prosthesis since it is in direct contact with physiological tissue. Therefore, a desirable electrode material must exhibit electrochemical properties that allow the prosthesis to function effectively and safely. Conductive diamond electrodes offer unique properties that may enhance the efficacy of these devices: biocompatibility (1,2,3), low reactivity with dissolved oxygen (4), and the lack of an oxide layer (4). We can also take advantage of these unusual properties and use diamond to provide a context for understanding ongoing issues of electrode design in the clinical field of neural stimulation. The focus of this work is to evaluate, under simulated and/or actual physiological conditions, the diamond electrode as a neural stimulator, using a combination of bench-top and *in vitro* measurements.

To be effective stimulators, electrodes must offer sufficient charge-injection densities and avoid potentially toxic electrochemical reactions during current pulsing. Such reactions include gas evolution, oxidation of organic and inorganic species, production of metal salts, and metal dissolution. Under chronic stimulation, some of these reactions can cause irreversible tissue and electrode damage and inhibition of cell division. Because of diamond's advantageous characteristics, it is likely to provide effective stimulation with minimal side effects.

Polycrystalline, boron-doped diamond electrodes were grown by hot-filament assisted chemical vapor deposition using established methods (5); the diamond films were deposited onto tungsten wires (0.5-mm diam.). Diamond quality was verified by slow-scan cyclic voltammetry, Raman spectroscopy, and scanning electron microscopy. Voltammetry also determined the cathodic and anodic charge-storage capacity (CSC) of diamond and metal electrodes in phosphate-buffered saline purged with nitrogen or oxygen gas. A large CSC typically correlates with a greater relative amount of charge an electrode will inject during stimulation. The CSC's reversibility (*i.e.*, net charge transferred) provides insight into irreversible electrochemical processes that may be detrimental to the tissue and electrode during chronic stimulation.

Preliminary measurements show a higher CSC for platinum than for diamond electrodes in nitrogen (Fig. 1) or oxygen-rich (Fig. 2) environments. This is not surprising because diamond's lower double-layer capacitance leads to less capacitive charging, one of the primary charge-injection mechanisms. Yet, these data also show that charge transfer on diamond is more reversible than on platinum and much less affected by dissolved oxygen. This suggests that diamond may avoid irreversible reactions that lower the stimulation efficiency and potentially damage tissue; the effect is especially significant in the oxygen-rich environment typical of biological tissue.

As mentioned previously, the CSC is an indicator of the capability of an electrode as a neural stimulator, but the measurement timescale is 3 orders of magnitude slower than actual stimulating protocols, and therefore, may misrepresent the electrochemical dynamics of this process. To study the electrochemical behavior of the diamond electrode at the fast timescale of neural stimulation, a high-frequency pulse-clamp technique is being utilized, following the procedures of Merrill *et al*. (6). We will present our latest comparisons of diamond and other electrodes using this method.

Extracellular stimulation by diamond electrodes was performed *in vitro* on several motor neurons of the invertebrate *Aplysia californica*. Diamond was able to induce, inhibit, and record action potentials on these neurons (not shown). Currently, the effectiveness and durability of diamond electrodes are being compared to electrodes typically used in neuroscience research.

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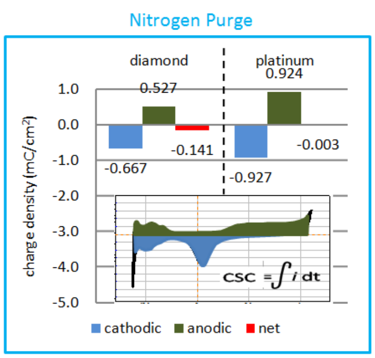

Figure 1: CSC in PBS purged with nitrogen gas; inset – calculation of cathodic and anodic CSC of Pt.

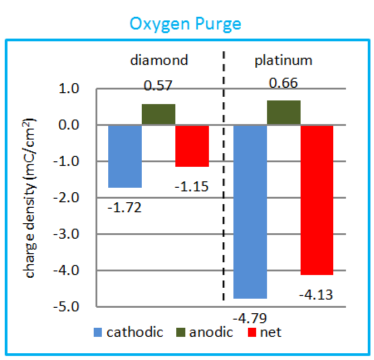

Figure 2: CSC in PBS purged with oxygen gas.