Neural Probe Utilizing Micro-Coil Magnetic Stimulation with CMOS Technology Integration for Spatially Programmable Neurostimulation

CNF Project Number: 2847-19

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Primary CNF Tools Used: Oxford ALD FlexAL, AJA sputter deposition, ABM contact aligner, Unaxis 770, PT770 etcher, Oxford 100

Abstract:

Neural prostheses have been effective in treating neurological disorders using electrical stimulation through micro-electrodes [1]. However, micro-electrode neurostimulation suffers from the inability to selectively activate neurons based on orientation [2] as well as maintaining long-term functionality [3]. Magnetic stimulation produced by micro-coil devices avoid these issues as the induced electric fields are asymmetric and magnetic fields can pass through biological materials allowing for complete encapsulation [4,5]. Mixed-signal circuitry is integrated into the proposed micro-coils by fabricating the design in a 180 nm CMOS technology process. Further nanofabrication techniques are applied to release the proposed micro-coils from the original chip packaging to produce a neural probe with spatially programmable micro-coil magnetic stimulation sites. Preliminary *in vitro* patch-clamp recordings of retinal tissue with programmed micro-coil magnetic stimulation sites has shown controlled neural behavior. Further research exploring the programmable stimulation site regions are ongoing.

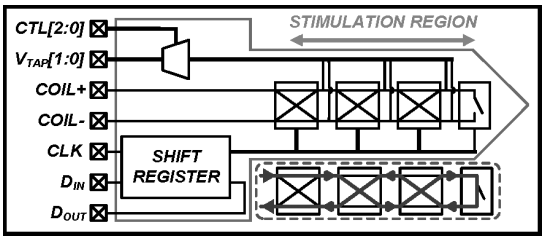

Figure 1: High-level diagram of the proposed programmable micro-coil neural probe with an example of programmed current direction.

Summary of Research:

The proposed micro-coil system is shown in Figure 1. The programmable stimulation sites are implemented by using a programmable switching network to direct the micro-coil current flow. The switching network can be programmed into four states: pass straight through, cross over, short-circuit, or open-circuit. The switches are implemented as pass gates with the NFETs sized at W/L of 1.5 mm/180 nm and PFETs sized at W/L of 2 mm/180 nm. The switches are sized to have a maximum resistance of 2W. With the trace resistance approximately 4W, the maximum coil resistance is 18W, allowing safe operation of the FETs while driving the micro-coil with 100 mA of current. The micro-coil is programmed using a shift register where the programming bits are buffered and routed down the probe to the switching networks. For electrical verification the coil segments are broken out to a multiplexer and brought off-chip to validate the current direction based off the voltage drop throughout the micro-coil.

The micro-coils are released and thinned down from the original chip packaging through a series of nanofabrication steps. Aluminum oxide and chrome are deposited (to serve as silicon etching and oxide etching masks respectively) and patterned using conventional photolithography and a combination of wet-etch and plasma etching. The oxide is etched in a CHF_3/O_2 oxide plasma etch using the Oxford 100 to expose the silicon surface. The exposed topside silicon is etched in the Unaxis 770 using a deep reactive-ion etching (DRIE) process down to the desired thickness of the neural probe (75 μm). The chips are flipped upside-down and the bulk silicon is etched in the same DRIE process until the micro-coils are released from the rest of the chip. The nanofabrication process to release the micro-coils is shown in Figure 3. The released micro-coils are then wire bonded to a carrier PCB, the wire bonds are protected with epoxy, and the entire assembly is coated with around 2 μm of Parylene-C to further encapsulate the micro-coil.

The micro-coils were fabricated in a 180 nm 1P6M CMOS process with a probe length and width of 1.9 mm and 0.1 mm respectively. A micrograph and scanning electron microscope (SEM) image of the micro-coil is shown in Figure 3.

Preliminary biological testing has been done using a patch clamp recording electrode in conjunction with the micro-coil in mouse retinal tissue. The recorded neuron was located at the tip of the micro-coil probe. Stimulation trials were done by driving the micro-coil with twenty ramp current waveforms spaced 200 ms apart. Figure 4 shows the neural response of the clamped neuron at the first and fourth stimulation sites (next to the neuron and 750 µm away). The data shows that stimulation near the neuron elicited indirect stimulation as there was immediate suppression of neural activity for 100 ms followed by a spike train for all twenty stimulation pulses. Stimulation further away from the neuron showed neural behavior that was more akin to natural behavior than evoked responses.

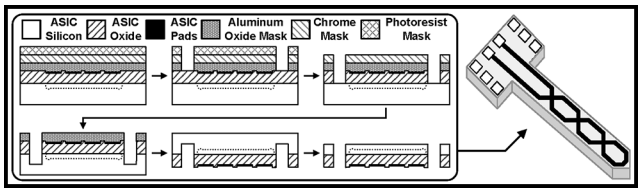

Figure 2: Nanofabrication process to release the micro-coils from the rest of the chip. Mask layers that are no longer being used are etched away between the shown process steps.

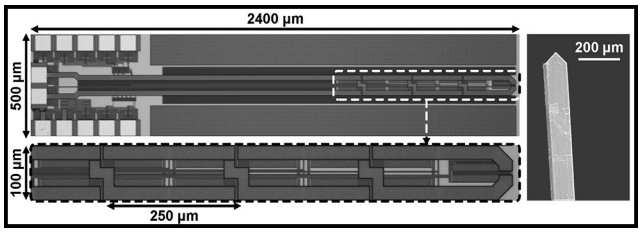

Figure 3: Unreleased micro-coil die photo with enhanced view of the stimulation region as well as an SEM image of a released micro-coil.

Conclusions and Future Steps:

Through the use of CMOS technology and nanofabrication techniques an insertable neural probe utilizing micro-coil magnetic stimulation with spatially programmable stimulation sites has been created. Preliminary biological testing with patch clamp measurements has shown repeatable evoked neural responses, however further testing utilizing a multi electrode array needs to be done to characterize the stimulation site regions. Future designs are also being created to utilize micro-coils with more turns to decrease the necessary stimulation current as well as incorporating current driving circuitry to independently drive each micro-coil.

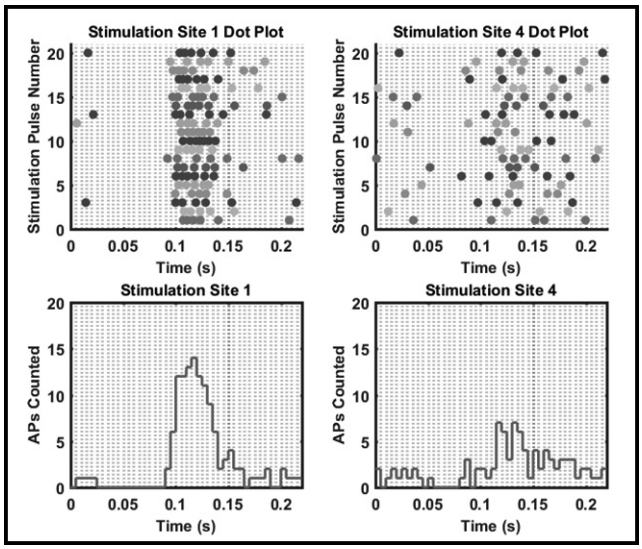

Figure 4: Dot plot and action potential count of patch clamp measurements from one neuron during stimulation at two different programmed sites. (See pages vi-vii for full color version.)

References:

[1] S. J. Bensmaia and L. E. Miller, "Restoring sensorimotor function through intracortical interfaces: progress and looming challenges," Nature Reviews Neuroscience, vol. 15, no. 5, pp. 313-325, 2014.

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[5] S. W. Lee, K. Thyagarajan, and S. I. Fried, "Micro-coil design influences the spatial extent of responses to intracortical magnetic stimulation," IEEE Transactions on Biomedical Engineering, vol. 66, no. 6, pp. 1680-1694, June 2019.