# CMOS Neural Probe with Multi-Turn Micro-Coil Magnetic Stimulation

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*Primary CNF Tools Used: ABM contact aligner, AJA sputter deposition, Oxford 81, Oxford 100, Oxford ALD, PT770 etcher, P7 profilometer, Unaxis deep silicon etcher, Parylene coater, Westbond 7400A ultrasonic wire bonder*

## Abstract:

**Micro-coil magnetic stimulation has been shown to be an effective method of neurostimulation while circumventing the issues that limit the effectiveness of the more commonly used implantable electrodes [1,2]. This is due to the micro-coils not needing direct contact to the biological tissue allowing for complete device encapsulation. This allows for the stimulation effectiveness to be maintained over long periods of time while eliminating the electrode-tissue interface that is prone to electrochemical effects that can damage the probe or tissue [3]. Recent work has developed programmable micro-coil neural probes integrating complementary metal oxide semiconductor (CMOS) technology with the micro-coil design [4]. However, the design did not utilize multi-turn micro-coils to reduce the necessary stimulation current. This work proposes a neural probe that co-optimizes the micro-coil design with CMOS micro-coil current drivers to maximize the induced electric field gradients. A four-wire interface is used to supply power, deliver the stimulation current, and program the micro-coil current directions using four terminals. Preliminary *in vitro* testing with mouse olfactory bulb slices and a commercial MEA show the probes are capable of producing changes in neural behavior.**

## Summary of Research:

The circuit implementation of the proposed neural probe is shown in Figure 1. A four-wire interface is implemented to reduce the number of necessary pads to power the probe, drive the micro-coils, and program the location of the stimulation sites by using the supply and differential current inputs as the programming clock and data signals respectively. The clock is generated by a comparator comparing VDD to a bias voltage. The programming data is extracted from the common-mode of the differential input current using a pair of unity gain, high output impedance amplifiers with the outputs connected together. The current drivers use a push-pull topology operating with the bias transistor pairs operating in class AB to balance between the maximum input current range and the quiescent bias current. The output of the current driver is the parallel outputs of cascoded PFET and NFET current mirrors. Cascoded outputs are used to ensure accurate current mirroring over the wide range of coil voltages present during stimulation.

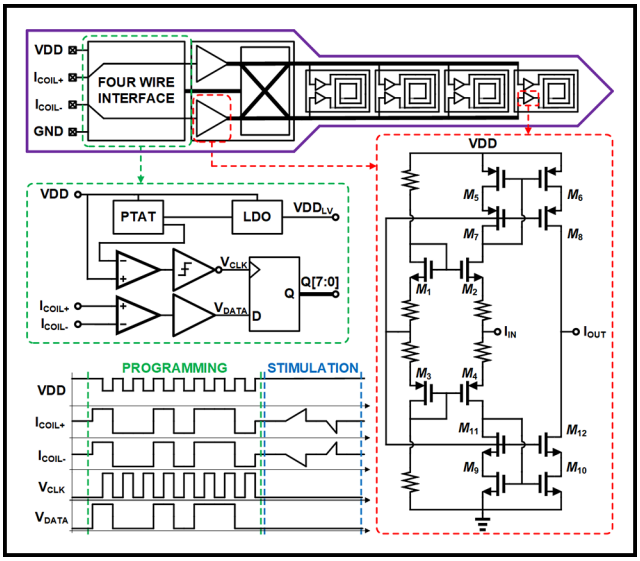


*Figure 1: Circuit implementation of the proposed neural probe.*

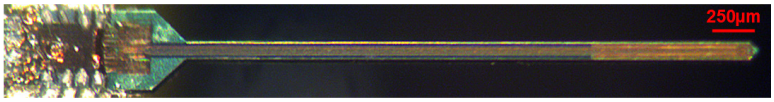


*Figure 2: Micrograph of a released and fully encapsulated neural probe.*

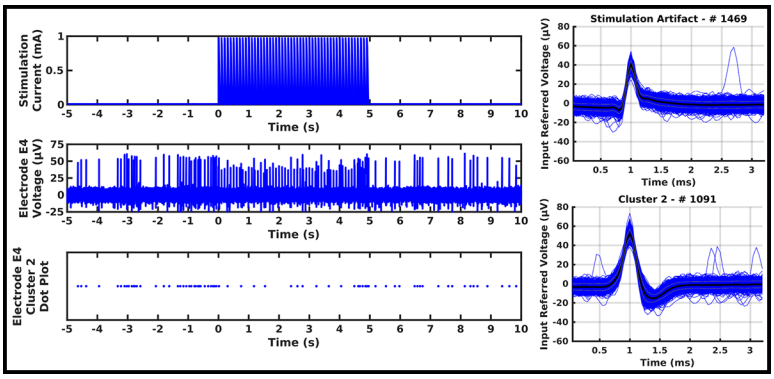


*Figure 3: Preliminary data showing inhibitory neural response to stimulation train and time aligned neural spikes and stimulation artifacts.*

The neural probes are thinned down and released from the original chip packaging through a series of nanofabrication steps. The neural probes are initially embedded in 5 mm × 5 mm die of foundry CMOS with a thickness of 330 $\mu$m. Aluminum oxide and chrome are deposited (used as silicon etching and oxide etching masks respectively) and patterned using conventional photolithography and a combination of wet etching and plasma etching. The oxide is etched in a $CHF_3/O_2$ plasma sto expose the silicon surface. The exposed topside silicon is etched in a deep reactive-ion etching (DRIE) process down to the desired thickness of the neural probe of 70 $\mu$m. 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 released probes are mounted to a carrier printed circuit board using conductive silver epoxy and electrically connected using the Westbond 7400A ultrasonic wire bonder. The wire bonds are protected using a clear epoxy before the entire assembly is coated with approximately 4 $\mu$m of Parylene-C.

*In vitro* testing is done on 300 $\mu$m-thick mouse olfactory bulb slices with a commercial MEA. Spikes and LFPs are recorded using a 120-electrode microelectrode array with titanium nitride electrodes. The probe is placed on the surface of the slice with the micro-coils located over the region of tissue with visible activity. Testing consisted of driving the micro-coils with stimulation trains of fifty 10 Hz ramp waveforms spaced ten seconds apart while observing changes in neural behavior.

Figure 3 shows preliminary results where the micro-coils are configured to have the two inner coils run current in opposite directions to generate the strongest gradient in the electric field while the outer coils are turned off. The dot plot shows that the stimulation waveform has an inhibitory effect on the recorded activity which is consistent with the results found in [4].

## Conclusions and Future Steps:

This work proposes a neural probe that co-optimizes the micro-coil design with CMOS current drivers to maximize the electric field gradients and reduce the necessary stimulation current. Independently driven multi-turn micro-coils allow for spatially programmable neurostimulation sites between adjacent micro-coils. A four-wire interface is used to reduce the number of pads on the probe backend by using the supply and differential current inputs as the programming clock and data signals, respectively. Preliminary *in vitro* testing of the neural probe is done with slices of a mouse olfactory bulb in conjunction with an MEA showing changes in neural behavior.

Future work looks to explore neural probe designs utilizing micro-coil magnetic stimulation with recording electrodes to allow for a closed-loop neuromodulation.

## References:

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