MANDUCA SEXTA OLFACTORY NEURAL INTERFACE

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ABSTRACT

We present wireless transmission of neural signals from an insect based hybrid bio-electromechanical sensor. Previous work demonstrated the feasibility of creating an insect-based olfactory sensor with integration of a microfabricated silicon microprobe. By expanding this system to include wireless transmission, we can move towards taking full advantage of tapping into an insect's olfactory system to serve as a gas sensor. Moth species have one of the most sensitive gas sensors available with parts-per-quadrillion sensitivity to pheromones. A 0.35- μm technology application specific integrated circuit is integrated with a silicon microprobe neural interface. The chip provides a 40-dB amplification over a 10 kHz bandwidth and wirelessly transmits the input signals with a voltage controlled oscillator. The microprobe sensor, with a weight of ~ 80 mg can be integrated with the hawk moth *Manduca sexta*, using Early Metamorphosis Insertion Technology (EMIT). The moth is able to emerge successfully with the microprobe intact, demonstrating a pathway towards a tetherless hybrid flying insect gas sensor.

INTRODUCTION

Typical olfactory sensors function by monitoring a change in a given sensor device property (mass, strain, resistance, etc.) as odorant molecules adhere to the sensor. Strain based microcantilever detectors are able to detect odorants down to parts per trillion, while chemiresistive sensors are able to detect with very low powers of 0.1-1 mW [1, 2]. In this work, we draw upon a natural insect olfactory system which is capable of detecting odorants down to parts per quadrillion sensitivities [3]. By interfacing to this system and detecting neural responses to given

Airborne System Component	Weight
6-mil thick polyimide PCB	32 mg
ASIC neurochip	13 mg
Microprobe	42 mg
TOTAL	87 mg

Figure 1: Photograph of silicon microprobe, without metal lines, inserted into *Manduca sexta* pupae, and insect emergence to adult stage with probe intact. The table shows the estimated weight for an airborne interface system without batteries.

Figure 2: Prototype integrated ASIC neurochip and microprobe. The probe and ASIC were integrated with a custom printed circuit board, and surface mount inductors, capacitors, and resistors were used for the Colpitts oscillator.

odorants, this opens up the possibility of a low power, high system sensitivity environmental gas detector. Previous work presented at MEMS 2009 demonstrated the feasibility of an insect sensor with a silicon microprobe inserted in the pupal brain of the moth *Manduca sexta* [4]. By inserting the probe early during the pupal stage with Early Metamorphosis Insertion Technology (EMIT), we can achieve better mechanical coupling with the tissue than if the probe were inserted later in the adult stage [5]. The inserted silicon microprobe, with outputs fed to an external amplifier, captured extracellular neural signals in the antennal lobe stimulated in response to specific odors incident upon the insect's antenna. In this work, we demonstrate an extension of the previous work by incorporating a specially designed application specific integrated circuit (ASIC) consisting of an amplifier and a radio that can be integrated on an airborne moth. Previous work from our group has demonstrated using muscle embedded microfabricated electrodes for flight control [6]. By incorporating neural sensing of insect responses to various gases at very high sensitivity with the technology for flight control in the future, we demonstrate a pathway to a low-cost wireless airborne neural interface to serve as a gas sensor node.

TETHERLESS NEURAL INTERFACE SYSTEM

Figure 3: Equivalent circuit parameters of silicon microfabricated probe electrode-electrolyte interface. The interface consists of an interfacial capacitance Z_{CPA} from the double layer, a charge transfer resistance R_{CT} that serves as a DC path, and the spreading resistance R_s . The electrode impedance was also measured with electrochemical impedance spectroscopy in (a) and the fit values to the equivalent circuit are shown in (b).

Integration: Survivability, Weight, and Power Considerations

Using Early Metamorphosis Insertion Technology (EMIT), polyimide-reinforced silicon microprobes were first inserted into pupal stage *Manduca sexta* to confirm the survivability of insects. The weight of the silicon microprobe and polyimide reinforcement was approximately 80 mg. As shown in Fig. 1, the insects were able to successfully emerge to adulthood and the probes remained intact. For a functional airborne system, the components would compose of the silicon microprobe, the newly developed ASIC neurochip, and a thin flexible polyimide printed circuit board to form electrical connections. The estimated weight of such an airborne wireless system without batteries would be 87 mg. Studies on *Manduca sexta* indicate their payload capacity is ~ 1 g indicating the need for integration with light battery power and/or power harvesting from the insect. A recent paper has shown the ability to scavenge power of 1 mW from moth flight vibrations using a magnet in a wire coil [7]. Additionally, higher payloads may be possible with larger moths. Based on these considerations, it is possible to realize an insect behaving in its natural environment while providing wireless transmission of gathered sensor data. This could potentially include visual cues as well as olfactory cues, as there are specific neurons which relay signals for looming or receding objects, and for lateral and vertical motion [8, 9]. In comparison, micro-aerial vehicles (MAVs) with corresponding capabilities would require much higher power consumption with feedback control systems for avoiding obstacles and guiding flight, as well as on board sensors to capture visual and olfactory information from the environment.

Figure 4: Schematic of ASIC neurochip. The circuit includes a 40 dB amplifying stage, a buffer stage, and a voltage controlled oscillator (VCO). The VCO components L , C_1 , and C_2 are surface mount components.

Figure 5: CADENCE layout and microphotograph of designed ASIC. The chip has four complete amplifier, buffer, and VCO channels and one set of individual channel components for testing.

Silicon Microprobe Neural Interface

The neural interface is composed of a microfabricated neural probe, as shown in Fig. 2. This probe has platinum lines to ensure biocompatibility, and an insulating material of silicon nitride. The equivalent circuit parameters of the electrode-electrolyte interface including the interfacial capacitance Z_{CPA} , the charge transfer resistance, R_{CT} , and the spreading resistance, R_s , are shown in Fig. 3, as well as the measured electrochemical impedance spectroscopy data for the interface.

ASIC Neurochip Design and Measured Performance

An integrated circuit was designed in AMS 0.35- μm technology with an amplifier and voltage controlled oscillator (VCO). This circuit is designed to interface with the microfabricated neural probe for wireless transmission of the captured signals. The schematic of the chip is shown in Fig. 4. The neurochip consists of an amplifier and radio and occupies a 9 mm^2 design area for four fully assembled channels, plus one channel of individual test components. The CADENCE layout and a microphotograph of a single channel are shown in Fig. 5.

The amplifier is composed of a differential first stage followed by a common source stage to allow large output swings. The amplifier is maintained in resistive feedback to give a 40 dB gain over 10 kHz. The simulated phase margin is 104° and the simulated input referred noise is $7.47 \mu\text{V}$. The measured and simulated gain-frequency curves of the amplifier are shown in Fig. 6. Additionally, the chip incorporates a DC offset filtering component to remove DC potentials from metal-electrolyte half

Figure 6: Simulated and measured amplifier performance. The amplifier has a 40 dB gain over a 10 kHz bandwidth, which is the expected bandwidth of interest for biological signals.

Figure 7: (a) Amplifier input stage used in combination with electrode-electrolyte interface to high pass filter incoming signals and remove DC offset (highlighted in box). (b) Equivalent circuit of electrode-electrolyte interface and amplifier input.

cell potentials that form spontaneously when metals are immersed in electrolytes. These potentials can be several hundred millivolts and would otherwise saturate the amplifier. The high pass filter incorporates a subthreshold transistor which serves as a megaohm resistance at the amplifier input [10]. In combination with the interfacial capacitance of the microfabricated probe, as shown in Fig. 7, this forms a high pass filter to remove DC offsets. It is designed for $f_{3dB} = 12$ Hz. The buffer stage serves to isolate the amplifier and voltage controlled oscillator (VCO).

The VCO is designed using a Colpitts topology with an oscillation frequency as shown in Fig. 7. Since L , C_1 , and C_2 are surface mount components, these can be used to easily adjust the carrier frequency of the VCO in the FM range 88-108 MHz. The variable capacitance C_{VAR} is adjusted by the input signal V_{TUNE} which modulates the capacitance over the MOSCAPs. The VCO stage simulated and measured tuning curves are shown in Fig. 8. The measured data is fit to a model which takes into account parasitic inductances and capacitances arising from the antenna and metal lines. Using a best-fit regression curve, the parasitic inductance is estimated to be 10^{-13} H and the parasitic capacitance is 5.42 pF. These values are added as parasitic components and used to re-simulate the expected oscillation frequencies, as shown in Fig. 8. It is seen that the simulated and measured curves match well, within the $\pm 5\%$ error tolerance limits of the surface mount devices.

The ~ 100 -MHz FM wave is fed to a 2-cm wire antenna, and

Figure 8: Schematic of voltage controlled oscillator with Colpitts topology. The ideal oscillation frequency, as well as surface mount components values used are listed above.

Figure 9: Simulated and measured voltage controlled oscillator (VCO) change in frequency for given tuning voltages.

signals can be detected at a range of 3-m, although a range of 100-m is possible with increased power consumption. For example, by increasing the gate-source voltage over the voltage controlled oscillator transistor, we can increase the g_m and improve oscillator gain, at the cost of consuming more current. The system uses ± 1.5 V and is compatible with power harvester and flexible battery voltages [7, 11].

The ASIC was interfaced with the microfabricated silicon probe with a custom printed circuit board, as shown in Fig. 2. To characterize the VCO tunability when integrated with the microprobe, the probe was immersed in saline. An Ag/AgCl wire was used to feed a generated square wave from an Agilent 33250A function generator to the system. The VCO tunability was measured to be 150 kHz/mV input to the probe neurochip system.

WIRELESS TRANSMISSION OF SIGNALS

Transmission of Simulated ECG Pulses

To demonstrate wireless transmission of signals with the radio, an Agilent 33250A arbitrary function generator was first used to generate a 1.2 mVpp, 1-Hz electrocardiogram (ECG) signal. The signal was fed into insect saline with an Ag/AgCl electrode. A microfabricated probe interfaced with a radio chip was immersed in the saline, and a FM radio was used to receive and demodulate the signal. The audio output was fed into a National Instruments data acquisition card, and a custom LabVIEW program was used to record the data. The received waveform is shown in Fig. 10.

Transmission of Potentials from Insect Brain

A late pupal stage male *Manduca sexta* insect was first chilled on ice to anesthetize it. A Pt wire was inserted in the insect's

Figure 10: An 1-Hz ECG signal (top) was fed through an Ag/AgCl wire into saline. The microprobe was immersed in saline and outputs were wirelessly transmitted with the newly design neurochip. The signals were picked up with an FM receiver and demodulated, as shown in the bottom trace.

abdomen to serve as a ground. The microfabricated probe interfaced to the radio chip was inserted into the head of the insect, and first interfaced with an external Dagan Corp. amplifier. Insect neuronal responses to external stimuli of tobacco and air were recorded. The system was then switched to wirelessly transmit recorded pulses from the insect. The recorded signals are shown in Fig. 11.

CONCLUSION

In this paper, we have demonstrated the incorporation of a newly designed radio chip with a microfabricated neural probe to serve as a neural interface sensor of insect responses to olfactory cues in the environment. This allows us to potentially tap into the parts-per-quadrillion olfactory sensitivity of insects. Future work and challenges include fully miniaturizing the system and integrating the system with sufficient power at a low enough weight to be carried by the moth during flight.

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Wirelessly Transmitted Extracellular Signals from Insect Brain

Figure 11: Wirelessly transmitted signals from coupled microprobe radio system inserted in *Manduca sexta* brain.

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