Characterization and Design of Organic Field-Effect Transistor Circuits for Sensing Bioelectromagnetism

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ABSTRACT

Current scanning technology for the brain and heart requires electrodes to be placed on the surface, with a wire connected to each electrode. Because the electrodes are large, it is impossible to achieve a high sampling resolution of the signals from the tissue being scanned. Silicon based structures are not very suitable for this application. They have a rigid planar surface which prevents them from capturing a high degree of information from the three dimensional structure of the brain or the heart. However, an organic transistor, fabricated on flexible plastics, should be able to conform to and output a high degree of information from a three-dimensional structure. To test the ability of organic transistors to read data, an organic field-effect transistor was placed in a common source configuration. This configuration, when used with an organic transistor, allows the electrodes to conform to the structure, appear in higher density, and cover a larger area. A 50µm channel length transistor was able to operate with a low frequency gain of 0.97V/V and with a cutoff frequency of 91Hz. Organic field-effect transistors fabricated into circuits that are more complex were analyzed so that they could be considered for amplification purposes. A 6µm channel length inverter showed a low frequency gain of 3.2V/V and a cutoff frequency of 145Hz. A 10µm channel length cascode showed a low frequency gain of 2V/V with a cutoff frequency of 220Hz. These results suggest that organic field-effect transistors have the ability to measure and amplify a small signal and become an effective tool for mapping high-density signals of the brain and the heart.

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1. INTRODUCTION

Organic field-effect transistors (OFETs) are relatively new devices that have not yet been optimized and employed in a large variety of electronics. However, OFETs show great potential and could emerge as a dominant presence in electronic applications. OFETs, through low cost fabrication, have the potential to become an inexpensive source of electronics [1], [2]. OFETs can be mounted on plastic substrates providing a new area of functionality that current transistor technology does not possess. The new functionality in OFETs is largely due to the flexibility that this structure provides. The flexible plastic substrate employed allows for a sensor that uses flexible electrodes. These electrodes have potential to conform to and then more effectively map the electrical signals produced by an organ. They should also be able to apply voltages to stimulate nerves in that area.

One possible use of OFETs is to characterize disorders of the brain. The current approach to mapping the electric fields of the brain uses large electrodes in an array whose size is on the order of square millimeters with a wire connected to each electrode. The size of these electrodes along with the need to have a wire connected to each one prevents them from forming a high-density array of electrodes that can sample the signals with high spatial resolution. The OFET circuit should be capable of mapping brain signals more easily and safely than currently possible. The flexible electrodes would be able to conform to the shape of the brain, appear in higher density, and cover a larger area of the brain than possible with current electrodes. In order to realize this utility an OFET must be able to function in a circuit with low input reference noise to deal with small signals of approximately 30μV in amplitude and enough range to deal with large spikes up to 2mV in amplitude. This requirement is necessary because normal brain waves are on the microvolt scale while neural spikes are measured in millivolts. The circuit must have higher input impedance than the electrical tissue interface in order to prevent the signal from being compromised and it must block DC offsets in order to prevent saturation of the circuit [3].

2. BACKGROUND

2.1 Field-effect transistors

A field-effect transistor (FET) has terminals that are identified as the drain, the source, and the gate. The fabrication of an FET is accomplished by depositing layers of different materials. The first layer deposited is the gate. The gate controls the flow of electrons between the source and the drain. In an n-type FET, (positive) current enters through the drain and leaves through the source. In a p-type FET, (positive) current enters through the source and leaves through the drain. All FETs are made up of some basic components including a semiconductor layer, electrodes for the source and drain, a dielectric layer and a metal gate. These layers are fabricated onto a substrate as seen in Figure 1. An important characteristic of a transistor is its *mobility*. The mobility of a transistor is its ability to transport charge. This value is proportional to the current through the drain of the transistor. The drain current of a transistor is important because the transconductance of the transistor is proportional to the square root of the drain current while in saturation. The transconductance of a circuit controls the gain so a high transconductance is important for the creation of an amplifier circuit.

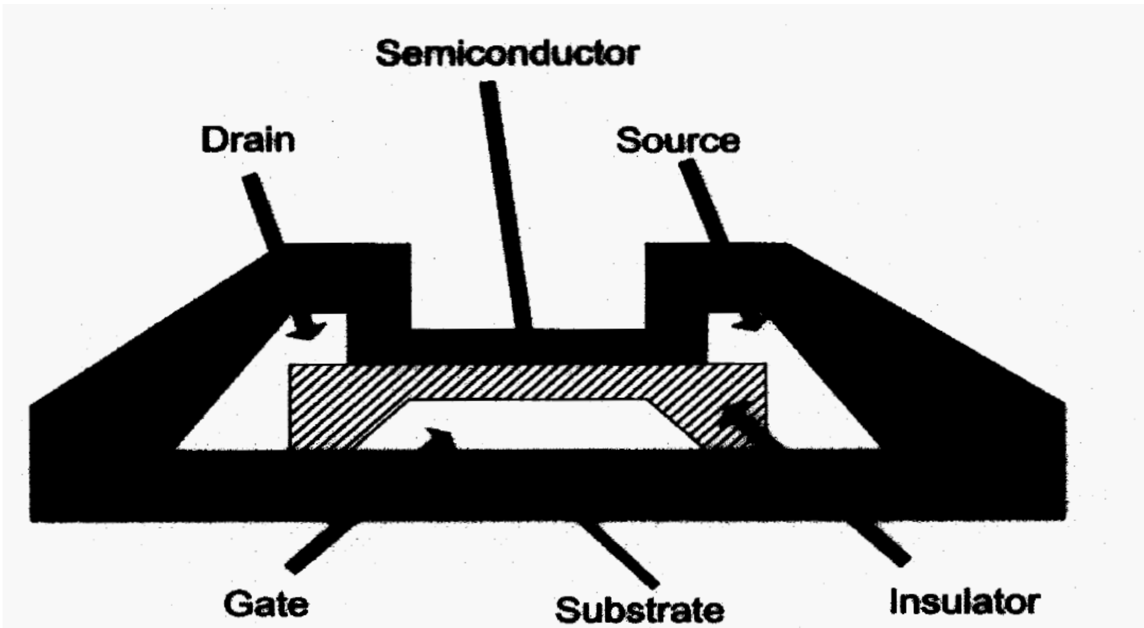

Figure 1: Transistor Diagram [4]

2.1.1 Organic field-effect transistors

Organic field-effect transistors differ from normal FETs in that they use an organic semiconductor. They also have the ability to be fabricated on plastic substrates, which imparts a characteristic flexibility that is not seen in other FETs.

In order for the OFETs to be placed in an intracranial circuit, they need to be both stable and non-harmful in the environmental conditions created within the skull. Kagan, Afzali, and Graham have demonstrated that reduced power and limited air exposure could create the necessary stability to integrate OFETs into electronic circuits [5].

2.2 Circuits for small signal amplification testing

Like other transistors, OFETs can be used for amplification. One type of OFET amplifier circuit is the common source. This configuration has the source connected to ground, with a resistor connected between a DC voltage and the drain, and a signal supplied to the gate. The output of this circuit is taken between the drain and the resistor. The gain of this circuit is controlled by the transconductance and the drain resistor. This makes it necessary to use large resistors when the transconductance is small. Another important characteristic of this circuit is its frequency response. The cutoff frequency for the circuit is inversely proportional to the product of the dominant capacitance and output resistance of the circuit.

Another circuit that can be used for amplification is the inverter. A diode inverter with a diode-connected load consists of two transistors with the source of the first connected to the drain of the second when one type of transistor is used. The first transistor has its drain connected to the gate, which causes it to act like a resistor. This allows this circuit to operate in a similar manner to the common-source configuration. The gain for this circuit is related to the ratio of the transconductance of the two transistors. Assuming the two transistors have similar mobility values this expression can be simplified to the ratio of the W/L values, as each transistor will have the same current flowing through it. An inverter outputs a large voltage for a small input voltage and outputs a small voltage for large input voltages.

An important circuit for measuring signals is the source-follower. Source-followers use two transistors similar to the inverter. However, unlike the inverter, the source-follower has the gate of the second transistor connected to its source. This configuration functions like a unity-gain buffer. It provides a gain of approximately 1V/V while converting high impedance to low impedance. This allows readings to be taken without changing the output resistance of the circuit.

A cascode is a more complex circuit used for the amplification of signals. The cascode used consists of three transistors. The first transistor has its drain connected to the gate and functions as a resistor. The second transistor has its drain connected to the source of the previous transistor. The output of the circuit is taken at this point. The gate of the second transistor is supplied a bias voltage and its source is connected to the next transistor. The final transistor has its drain connected to the source of the previous transistor and receives an input signal at the gate. The source of this transistor is connected to ground. An important characteristic of the cascode is its increased frequency response. This is due to its elimination of the Miller effect, which means that the capacitance between the input and the output is not increased.

A ring oscillator is a circuit that consists of an odd number of inverters connected without the input of an inverter coming from the output of the previous inverter. If the output from the previous stage was a high voltage, the next inverter will convert it to a low voltage and if the output of the previous inverter was a high voltage, the next inverter will switch it to a low voltage. This characteristic causes the output of the ring oscillator to look like a sine wave.

2.2.1 Noise in Circuit Design

Noise is a substantial issue when dealing with circuits that receive small input signals. If noise is not properly filtered, it causes distortion and prevents an accurate measurement of the signal being read. One source of noise is the 60 Hz AC noise found in the United States and 50 Hz found in other countries. In order to filter this noise a notch filter is often used. A notch filter allows all the components of a signal to pass except for those falling in a specific frequency range. In the case where only the data from a specific frequency range is relevant, high-pass and low-pass filters can be added to further filter out noise. A high-pass filter allows signals at high frequencies to continue through the circuit, while signals at frequencies below the chosen cutoff frequency are reduced. A low-pass filter works based on the same concept as a high-pass filter but it attenuates high frequencies above the cutoff frequency and allows low frequency signals to pass through the circuit.

2.3 Neurological Signal Sensing

2.3.1 Electroencephalography (EEG)

Electroencephalography, also known as EEG, is defined by C. E. M. van Beijsterveldt and D. I. Boomsma to be "a recording, from the scalp, of the electrical activity of the brain over a short period of time"[6]. Typical brain waves studied by an EEG occur within the range of less than 1 Hz to 100 Hz. The brain signals are divided according to the frequencies they occur at and then classified as alpha waves, beta waves, gamma waves, delta waves, or theta waves. Waves occurring between 8 and 13 Hz are considered alpha waves. Alpha waves are responsible for taking in and amplifying information sent to the brain. Waves occurring between 12 and 30 Hz are considered beta waves. Continuing in this pattern, gamma waves have a frequency between 30 and 100 Hz, delta waves have a frequency up to 4 Hz and theta waves have a frequency between 4 and 7 Hz. An EEG can be used to detect an abnormality within the brain by displaying the brain signals. This information allows for the successful diagnosis of brain disorders.

2.3.1. Electrocorticography (ECoG)

Electrocorticography is similar to electroencephalography in that it is used to measure brain signals; however, in place of measurements being taken from the skull, they are taken intracranially. Electrocorticography is used to determine a specific area of the brain where an abnormal signal originates before surgery is performed. This can be done on seizure patients before the abnormal tissue is removed. Electrocorticography can also be used to provide a stimulus to an area of the brain. The current approach for an ECoG is to use a device called the Utah Electrode Array as seen in Figure 2. The Utah electrode array consists of a 10 x 10 array of platinum tipped silicon electrodes with 4 x 4 x 1.5 mm^3 dimensions [3]. These dimensions limit the density of the signal and the amount of brain surface area that can be covered.

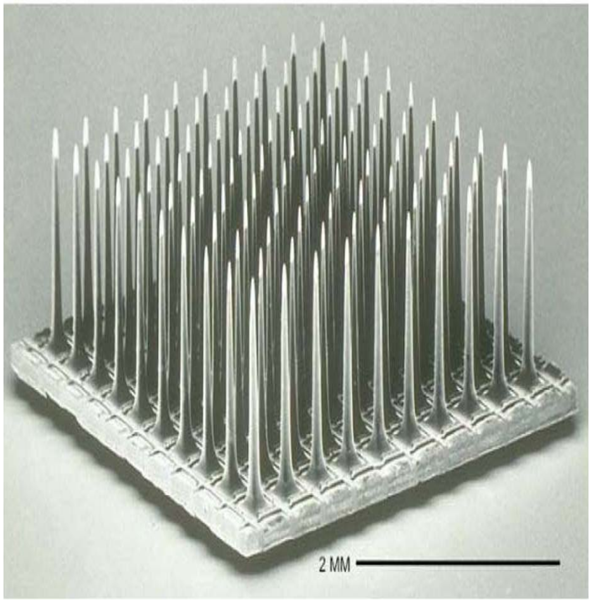

Figure 2: Utah Electrode Array [3]

2.4 Electrocardiography (ECG)

Electrocardiography is an important tool for studying heart arrhythmias and disorders. An electrocardiogram is performed by placing electrodes on the chest. It is used to measure the electrical activity of the heart over time. An electrocardiogram should have a bandwidth of 100 Hz and be able to measure signals as small as 20μV [7]. The signal must also show little error to ensure that there is no cause for misdiagnosis. The signal from an ECG consists of a P wave, a QRS complex and a T wave. The P wave is the result of the depolarization, which occurs from the sinoatrial node to the atrioventricular node. The QRS complex corresponds to the depolarization of the right and left ventricles. The T wave represents the repolarization of the ventricles.

3. MATERIALS AND METHODS

3.1 Organic Device Characterization

All measurements of organic transistors and organic transistor circuits were performed with devices kept in a controlled nitrogen environment. The transistors used throughout the experiments use pentacene as the organic semiconductor with each transistor being fabricated on a Kapton substrate. Throughout the experiments, measurements were taken with a Keithley 2420 source meter, an Agilent E3620A voltage supply, an Agilent 4156C parameter analyzer, an Agilent 3320A function generator, and a Tektronix TDS2014B oscilloscope.

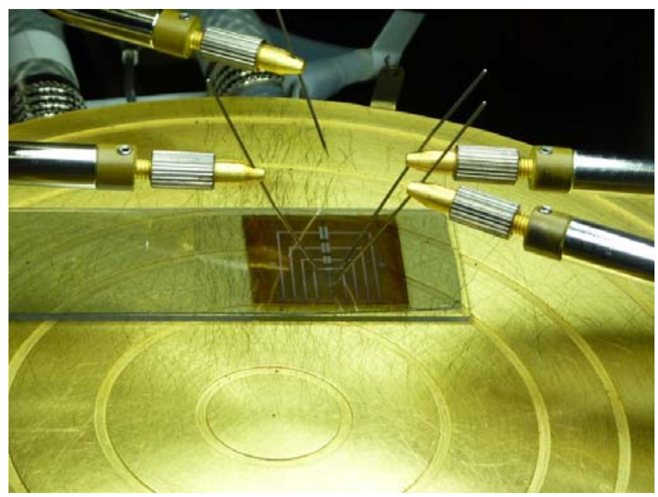

Figure 3:Probe Connections from within the glove box

In order to connect the circuit to our electrical supplies as well as other circuit components, we made connections directly in the glove box using probe tips as seen in Figure 3. These probe tips were connected to BNC connector cables through a feed-through, which allowed the stages of the circuit to be connected.

When working with the basic organic transistors we began by measuring the drain current against the voltage between the drain and the source. We measured this curve for varying values of the gate voltage as seen in Figure 4. These gate values ranged between -50V and 0V and increased with a step size of 10V. This graph shows the voltage necessary for the transistor to be operating in the saturation region where it will have consistent current levels. It was necessary to push the transistor into the saturation region so that it would have consistent gain throughout the experiments. The drain current was also measured against the voltage between the gate and the source as seen in Figure 4. This was done for a voltage of -50V between the drain and the source. From this data, we extracted the transconductance of the transistor, which was taken as the slope of the

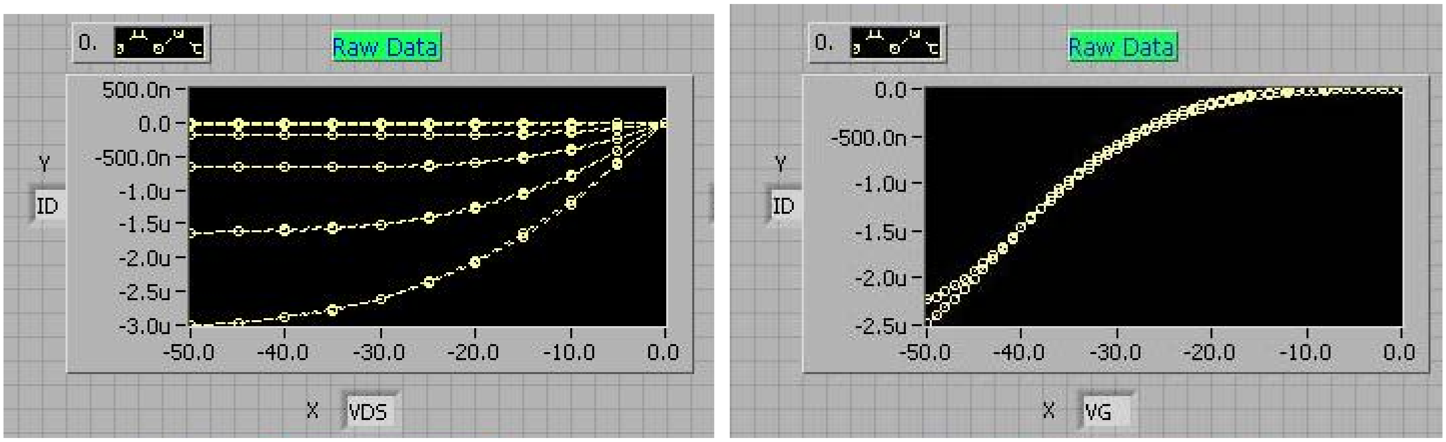

Figure 4:50µm DC Characteristics; W/L = 750µm/50µm

linear portion of the graph. These characteristics were run at the beginning and end of every experiment to monitor the stability of the organic transistors.

3.2 Cardiac and Neurological Sensor Design

With this data taken, the organic transistor could be connected to other electrical components. A multi-staged circuit was designed in order to read and output biological signals. The first stage of the circuit utilized a 50µm channel length organic transistor in a common source configuration. For this configuration, a resistor of value 10MΩ was connected between the drain of the transistor and a voltage source, V_{DD}. The source of the transistor was connected to another voltage source to help create a voltage difference between drain and source that would allow the transistor to operate in the saturation region. The signal was simulated by a function generator, that was connected to the gate of the transistor.

The output of this stage was taken between the drain and the resistor. This output was then connected to an op amp configured as a unity gain buffer. Throughout the experiments, only op amps with impedance greater than 10^{12} were used. The unity gain buffer consisted of the output from the last stage going into the non-inverting end of an op amp while the inverting end was connected directly to the output. This stage reduced the impedance before the next stage of the circuit, which utilized an inverting op amp. The final stage of the circuit connected the output of the unity gain buffer to a resistor, which was connected to the inverting end of another op amp. The inverting end of the op amp was then connected to the output through a resistor. The non-inverting end of this op amp was connected directly to ground. The full circuit can be seen in Figure 5.

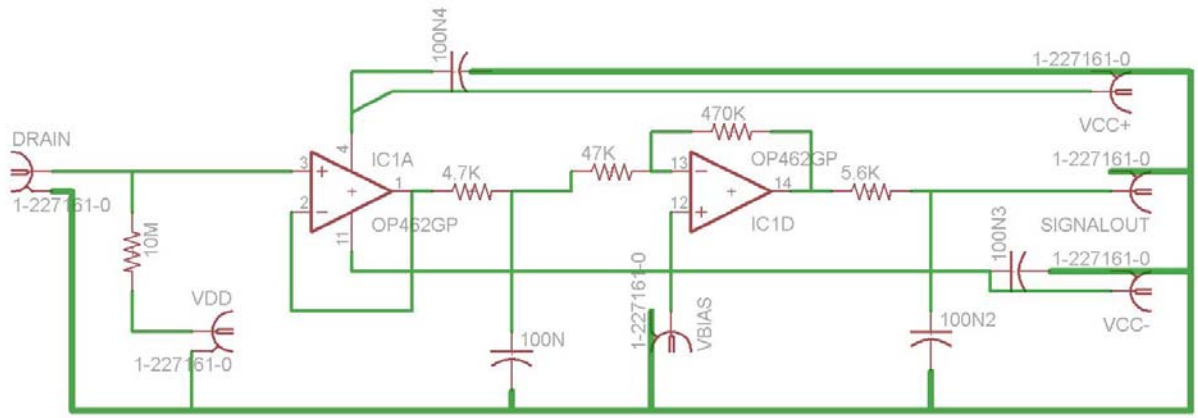

Figure 5: Circuit Schematic

This circuit to analyze biological signals was first tested using a breadboard. The organic transistor was maintained in the nitrogen environment while the electrical equipment, breadboard, resistors, and op amps were left outside in an ambient air environment. The drain, source, and gate of the organic transistor were connected to the electrical devices outside of the glove box using BNC cables connected to the feed-through of the glove box. The drain and the source of the transistor were connected to voltage supplies while the gate was directly connected to a function generator. The function generator was setup to create a sine wave at different frequencies and amplitudes. The op amp supply-voltages were provided by the parameter analyzer that was setup to generate a constant DC voltage. The output of the circuit was taken from the output of the op amp in the third stage using a digital oscilloscope.

After testing the completed circuit, low-pass filters were added after the unity gain buffer and after the inverting amplifier. The low-pass filter used was designed as a series combination of a resistor and a capacitor with the output taken between the capacitor and ground. The values of the resistor and capacitor were chosen so that the cutoff frequency created by the filter would be higher than the cutoff frequency of the first stage common source circuit. The capacitors used both had a value of 100nF. The resistor used for the first low-pass filter had a value 4.7kΩ, which corresponds to a cutoff frequency at 339Hz. The resistor used for the second low-pass filter had a value of 5.6kΩ, which corresponds to a cutoff frequency at 284Hz.

After analyzing the circuit on the breadboard, a printed circuit board (PCB) was fabricated in an attempt to reduce the effects of noise on the circuit. The design of the PCB was accomplished using the software Eagle. The PCB design used 90^{o} BNC connectors for all of the inputs and outputs. The schematic of the board the board was made identical to the circuit on the breadboard and the board layout was designed with the goal of minimizing space. After designing the board layout, the file was sent to 4PCB.com for fabrication. The completed board layout along with the fabricated PCB can be seen in Figure 6.

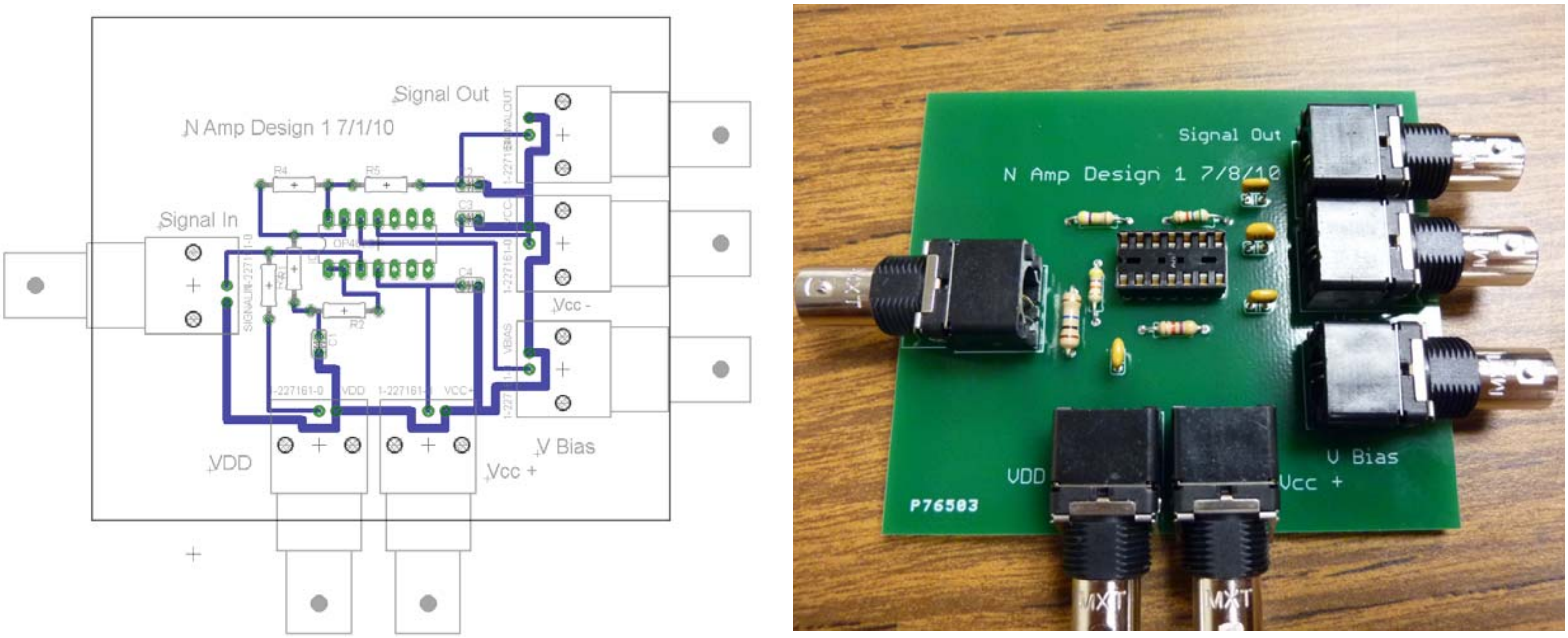

Figure 6: Board layout and fabricated PCB

The PCB was tested, like the breadboard, by connecting the voltage sources to the circuit and reading the output from the digital oscilloscope. The peak-to-peak output voltage was taken for sine waves created from the output of the circuit. The input sine wave was varied by amplitude and by frequency. This output voltage was graphed as a function of frequency to measure the trend in gain and the cutoff frequency for this circuit configuration. It was then found that a BNC cable connected to the output with AC coupling severely reduced the gain. Readings were then retaken with the oscilloscope set to DC coupling.

The PCB was also tested from within the glove box. For these measurements, the probe cable for the drain was connected directly to the PCB. The source and gate probe cables as well as BNC cables for V_{CC}+, V_{CC}-, V_{Bias}, V_{DD}, and the output were connected to the feed-through of the glove box

3.3 Organic Transistor Circuit Analysis

Completed organic circuits fabricated on a plastic substrate were also analyzed. These fabricated circuits were treated with thiophenol to lower their contact resistance. The circuits included single transistors, inverters, source followers, cascodes and ring oscillators. The circuits were kept in a nitrogen environment glove box and connections were made with probe tips.

3.3.1 Single Transistor Analysis

The single transistors treated for contact resistance were analyzed in a similar manner to the previous set of transistors. A DC scan was first run to measure the drain current against the voltage between the drain and the source. The drain current was then measured against the voltage between the gate and the source. After this was done, the single transistors were connected to the PCB. This used the single transistors in a common source configuration and sent the output to the unity gain buffer, followed by a low-pass filter, an inverting amplifier, and another low-pass filter.

3.3.2 Inverter Analysis

A series of inverters were also analyzed. The inverters each had a different channel length. The channel lengths tested included 2µm, 4µm, 6µm, 8µm, 10µm and 30µm. Figure 7 shows the glove box probe tips connected to the 6µm channel-length inverter.

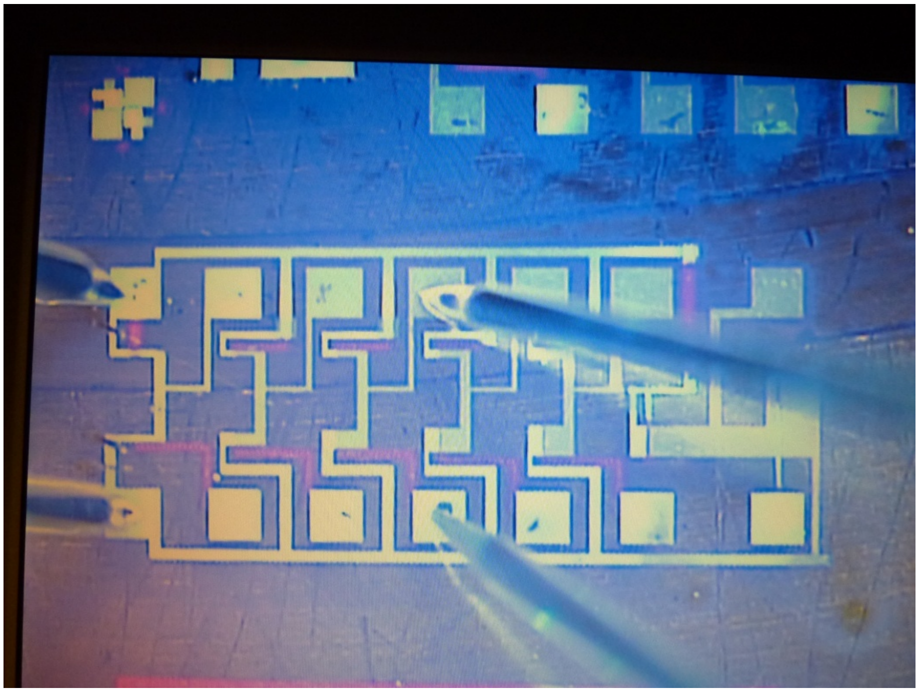

Figure 7:Inverter probe connections

The top left probe supplies a voltage, V_{DD} to the drain of the inverter. The bottom left probe is connected to the ground for the inverter circuit. The bottom right probe supplies the input signal for the inverter while the top right probe is used to measure the output of the inverter. The inverter was tested using the parameter analyzer. The parameter analyzer was setup to supply a constant V_{DD} value and to provide a common ground for the circuit. This inverter was analyzed for both a V_{DD} of -80V and -100V. The input signal was varied from 0V to -100V with a step size of -1V and the output voltage was taken at each point.

AC analysis was then completed on the inverters. For the AC analysis, V_{DD} and V_S were both connected to voltage sources. The sources were used to supply a voltage between the drain and the source that would cause the transistor to operate in the saturation region. V_S was chosen to provide the necessary offset to the input signal and then V_{DD} was selected as the value to create the necessary V_{DS} value. V_S was chosen as a value that would offset the input signal allowing the circuit to be biased in the linear region where the gain would be the highest. After selecting an experimental value, the values for V_{DD} and V_S were adjusted through testing different values and monitoring the gain. The optimal value for V_{DD} was found to be -84V while the optimal value for V_S was found to be 16V. The input was connected to a function generator through a BNC cable and the output was connected to a PCB with a unity gain buffer through another BNC cable. To reduce the effect of noise a 1V peak-to-peak input signal was used. The output was read from a digital oscilloscope with the oscilloscope probe set to 10x attenuation. The connections from the inverter to the PCB were all made inside the nitrogen environment glove box.

3.3.3 Source Follower Analysis

DC analysis was run for the source follower. For this analysis, five probes were used. Two probes were connected with a T-connector and then connected to a feed-through. These both provided the same value, V_S. The remaining three probes were each connected to an individual feed-through. The four feed-through were connected to the parameter analyzer. V_S was set to a common ground. V_{DD} was set to a constant voltage. For our experiments we used V_{DD} at -60V, -80V, and -100V. V_{In} was setup to vary between 0V and -100V with a step of -1V. The fourth channel was used to measure the output from the source follower.

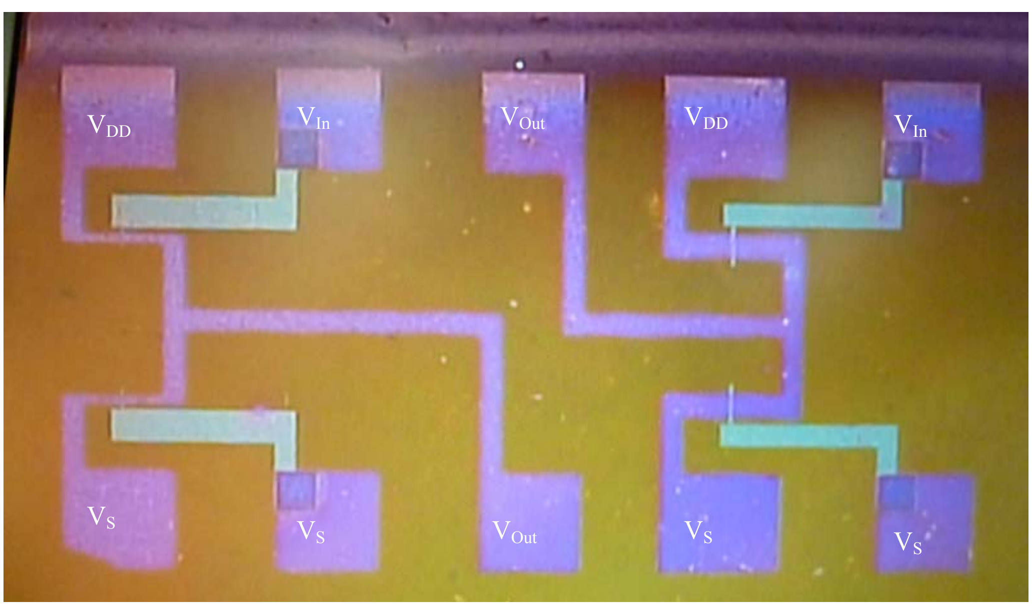

Figure 8:Fabricated source-follower

3.3.4 Cascode Analysis

In order to test the cascode, five different probes were needed to make connections to the pads. In order to run DC analysis the probes connected to V_{Out}, V_{DD}, V_{In}, and V_S were connected to the parameter analyzer. The probe connected to V_{Bias} was connected to a voltage source. A scan was setup using the parameter analyzer with a constant voltage supplied to V_{DD}. For our analysis, we used a V_{DD} of -100V. The input voltage, V_{In}, was varied from 0V to -100V in a step of -1V. V_{Bias} was set to different values for each scan with a voltage source. V_{Bias} was tested at -30V, -40V, -50V and -60V.

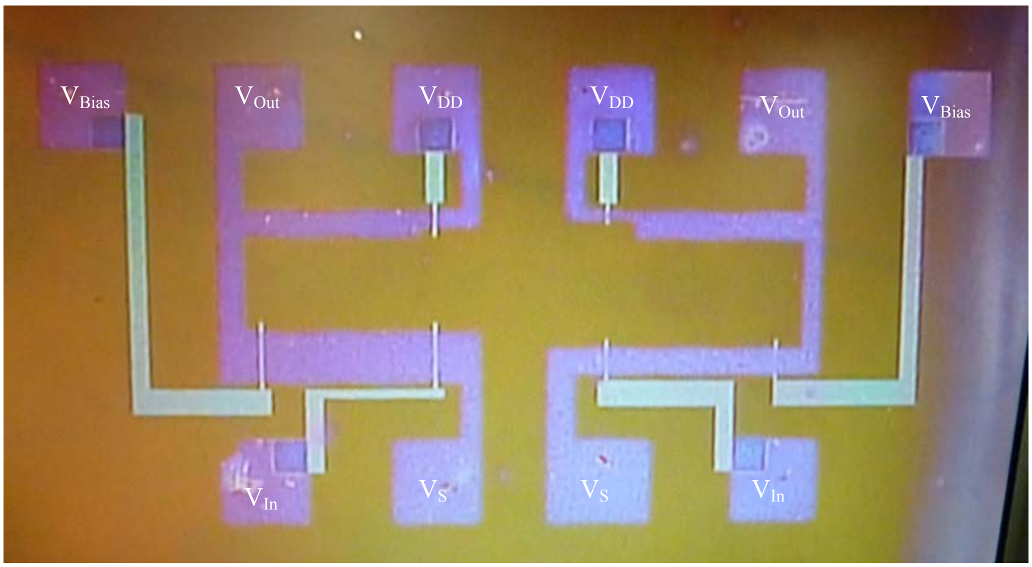

Figure 9:Fabricated cascode

AC measurements of the cascode were then taken. For the AC analysis V_{DD} and V_S were each connected to a voltage source. The voltage between the drain and the source was chosen to allow the transistors to operate in the saturation region and the source voltage was chosen to offset the input signal into the linear region of the circuit. V_{DD} was set to -83V and V_S was set to 17.18V throughout the experiment. V_{Bias} was chosen as -50V after examining the DC characteristics of the circuit. A 1V peak-to-peak input was supplied by the function generator and the output was connected to a PCB containing a unity-gain buffer. The output was measured by a digital oscilloscope using a probe set to 10x attenuation directly connected to the output of the unity gain buffer.

3.3.5 Ring Oscillator Analysis

A ring oscillator consisting of five inverters was tested. For these tests a voltage of -100V was supplied as V_{DD} to all the inverters and the ground was kept as 0V. The output was connected to a unity gain buffer that was fabricated onto a PCB and the signal was read using a digital oscilloscope. Figure 10 shows the structure of the ring oscillator. The triggering transistor was bypassed for the measurements that were taken.

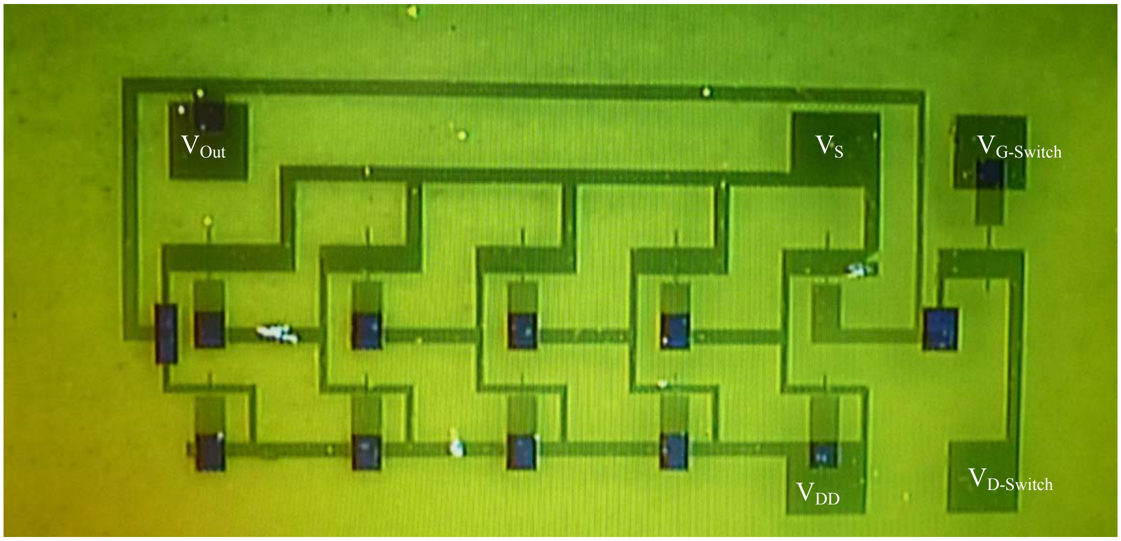

Figure 10:Fabricated ring oscillator

4. RESULTS

4.1 Neural and Cardiac Circuit

The third stage of the circuit was isolated and tested by using a function generator to provide an input to the unity gain buffer and bypass the common source stage. The amplifier has shown a gain of approximately 8.8V/V. The third stage also has a cutoff frequency of 180Hz. This differs from the expected cutoff frequency of 300Hz. This is likely a result of the two low-pass filter poles around 300Hz. These poles run together and cause the cutoff frequency to be much lower than expected.

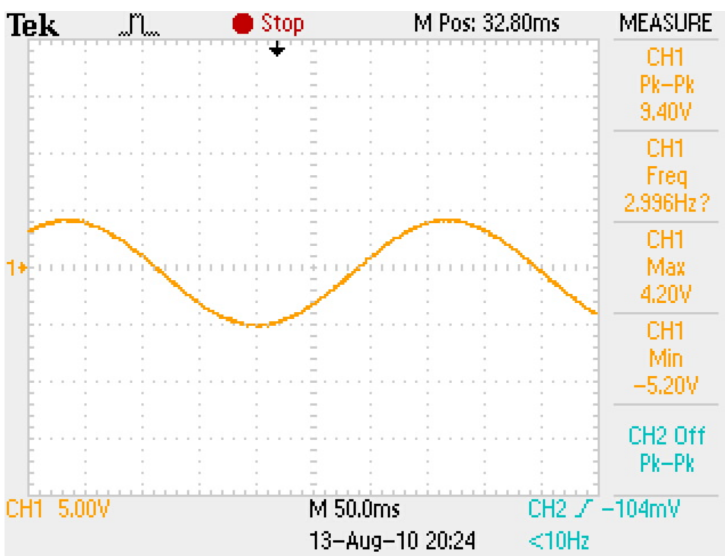

Figure 11: Output signal taken from 3rd stage of circuit; the transistor had a W/L= 750µm/50µm

Figure 11 shows the output of the third stage of the circuit connected outside of the glove box with an input signal of 1V peak-to-peak at a frequency of 3Hz. This corresponds to a gain of approximately 9.4V/V. This gain is produced by the amplifier stage multiplied by the common-source stage.

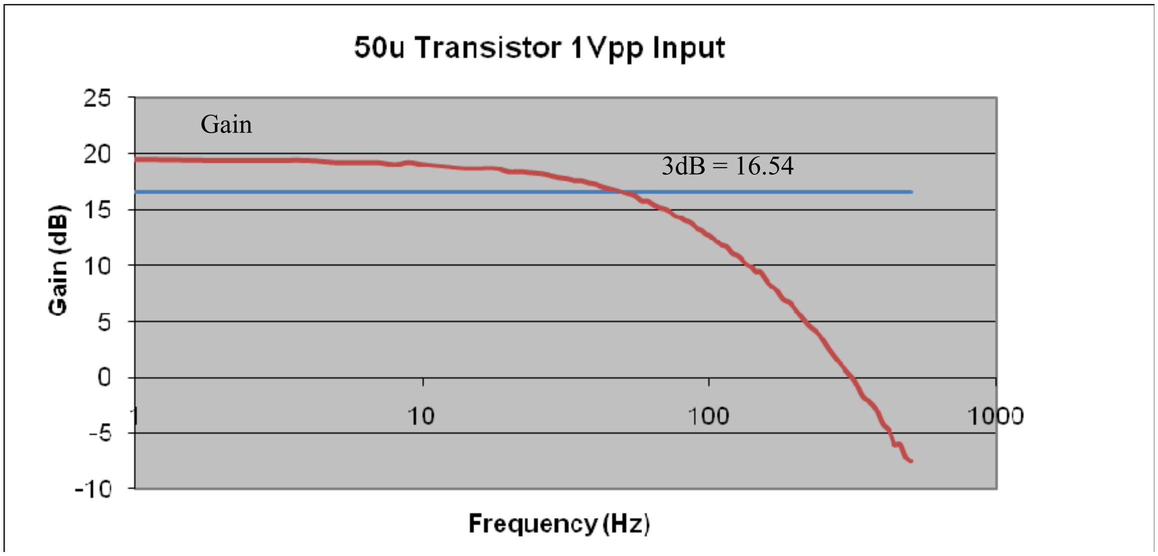

Figure 12:50µm common-source configuration outside glove box

Figure 12 shows the gain from the third stage of the PCB plotted against frequency with a 1V peak-to-peak input signal. At low frequencies the circuit shows a gain between 9.5V/V and 9V/V. However, the circuit reaches its cutoff frequency by 52Hz. This is a result of the extra capacitance supplied to the output by the BNC cables.

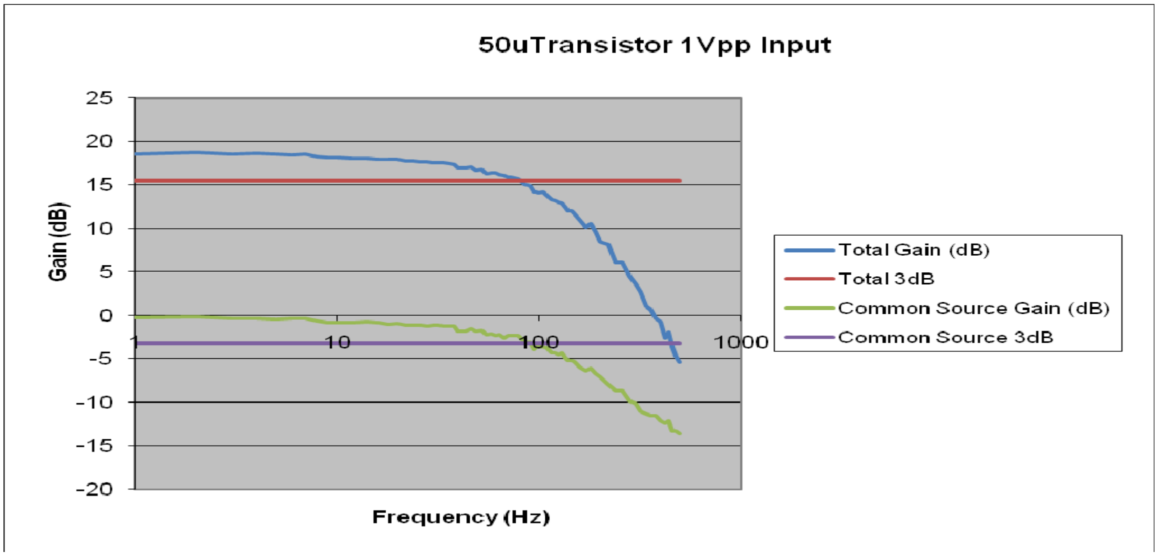

Figure 13:50µm common-source configuration inside glove box

Figure 13 shows a plot of gain versus frequency for the same transistor with all connections made inside the glove box. This allowed shorter BNC cables to be used. For this setup the output from the final stage of the PCB and the output directly after the unity gain buffer were both read. At low frequencies, the unity gain buffer shows that the common-source configuration is creating a gain between 0.9V/V and 0.984V/V. The final output from the PCB is showing a gain between 7.92V/V and 8.64V/V. This gain matches the theoretical gain of the common-source stage multiplied by the amplifier's gain of 8.88V/V. The common source stage shows a cutoff frequency of approximately 91Hz while the total circuit has a cutoff frequency of approximately 82Hz. By connecting the PCB within the glove box, the cutoff frequency was increased from 52Hz to 82Hz. This indicates that the long BNC cables used to make connections outside of the glove box provided the dominant output capacitance. By changing the length of the cables used it was possible to increase the frequency response. The lower cutoff frequency of the total circuit can be explained by the closeness of the poles lowering the overall cutoff frequency.

4.2 Organic Transistor Circuit Analysis

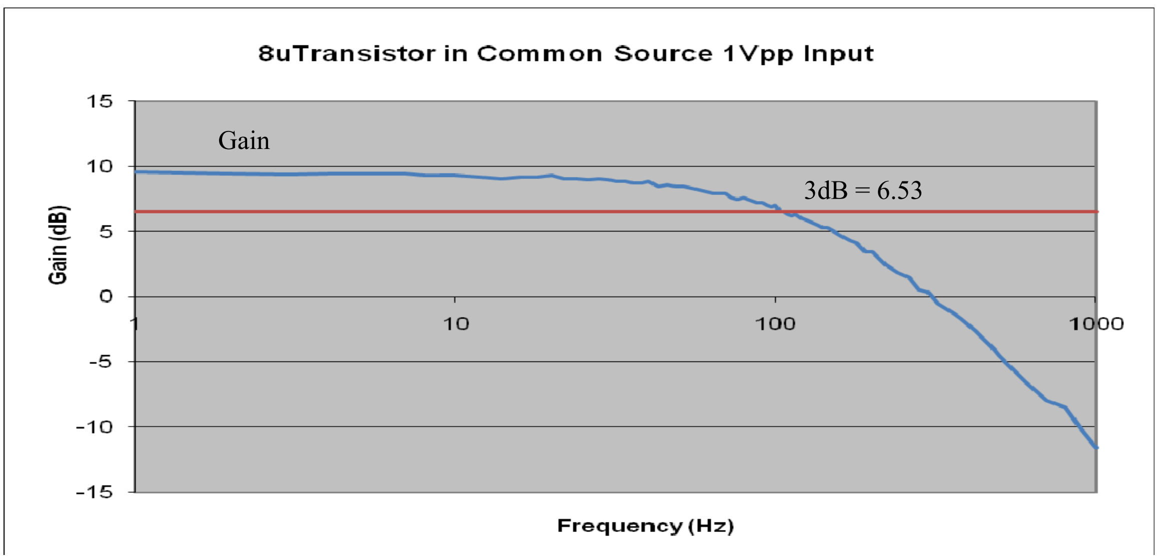

Figure 14:8µm common-source configuration inside glove box

Figure 14 shows the gain of the 8µm single transistor configured in a common-source configuration. This value is taken after the unity-gain buffer and before any additional filtering or amplification is done. At low frequencies, this configuration shows a gain between 2.92V/V and 3V/V. The cutoff frequency for this stage appears at 106Hz.

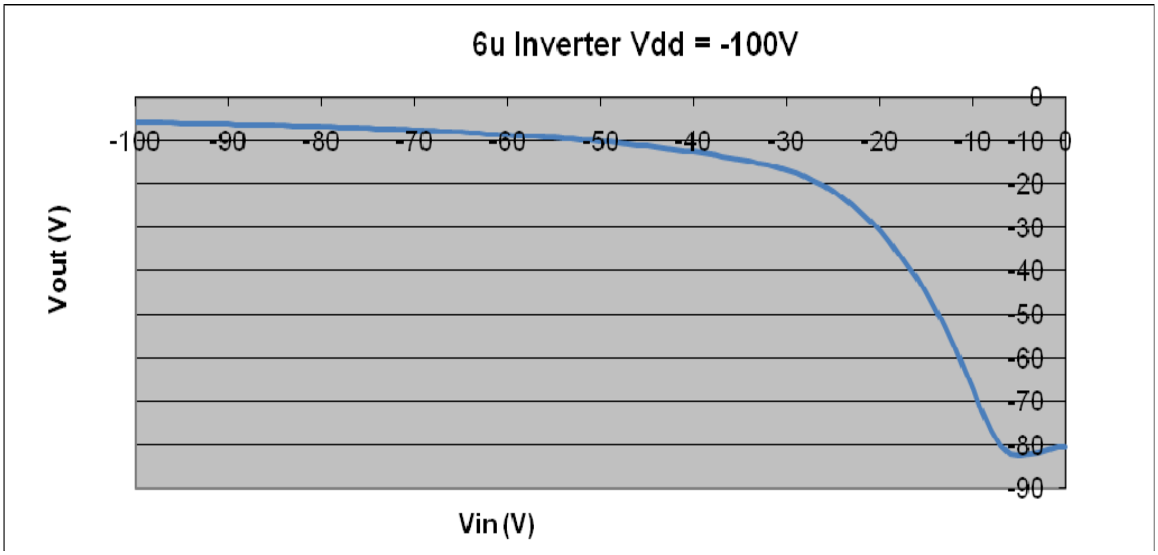

Figure 15: DC response of 6μm inverter

The magnitude of the ideal gain for this inverter is 3V/V. This value was approximated using the W/L values for the transistors involved in the circuit. The inverter is showing an actual gain of 3.2V/V when biased in the linear region. This was found by taking the slope of the linear region.

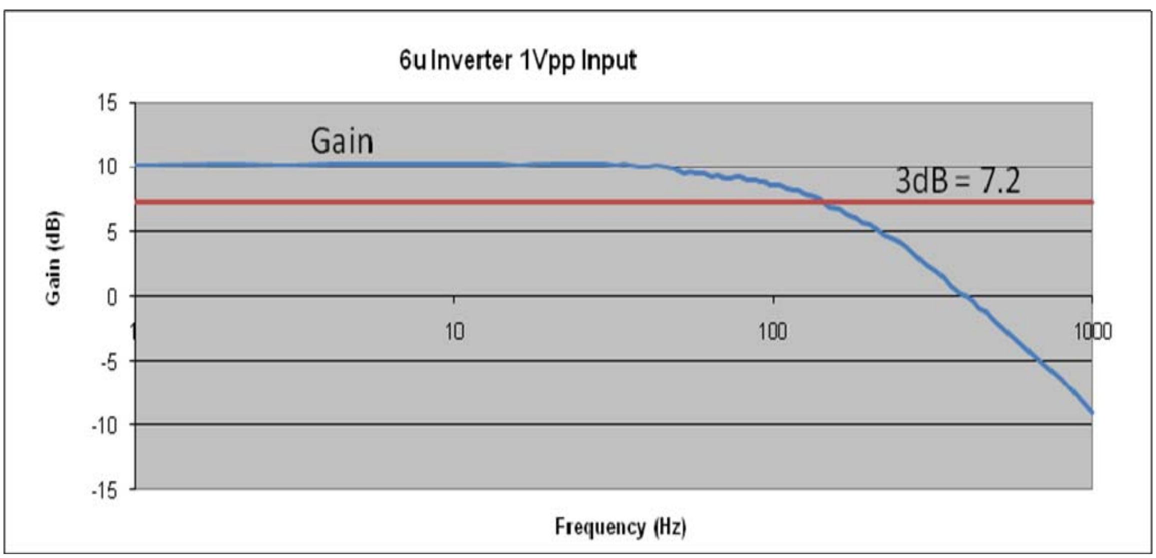

Figure 16: AC response of 6μm inverter

Figure 16 shows the gain for the 6μm channel length inverter plotted against the frequency of the input signal. At low frequencies, the inverter shows a gain of 3.2 V/V. The cutoff frequency for this circuit is approximately 145Hz.

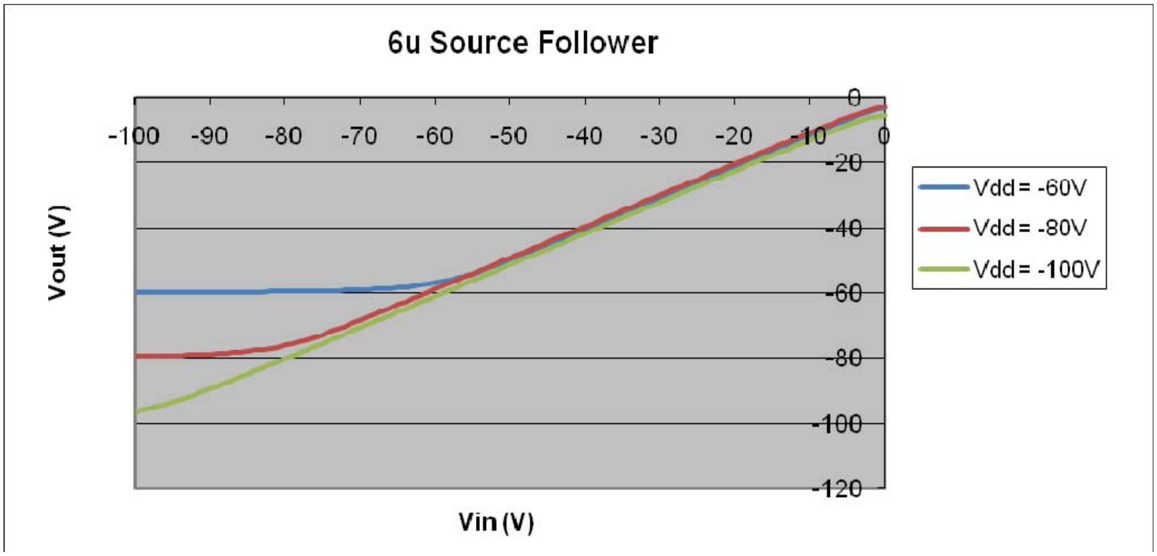

Figure 17: DC Characteristics of 6µm source follower

The source-follower circuit configuration has an ideal gain of one. The fabricated devices showed an average gain of 0.94V/V in the linear region. As the V_{DD} used in the source-follower is increased, the linear region of operation is also increased.

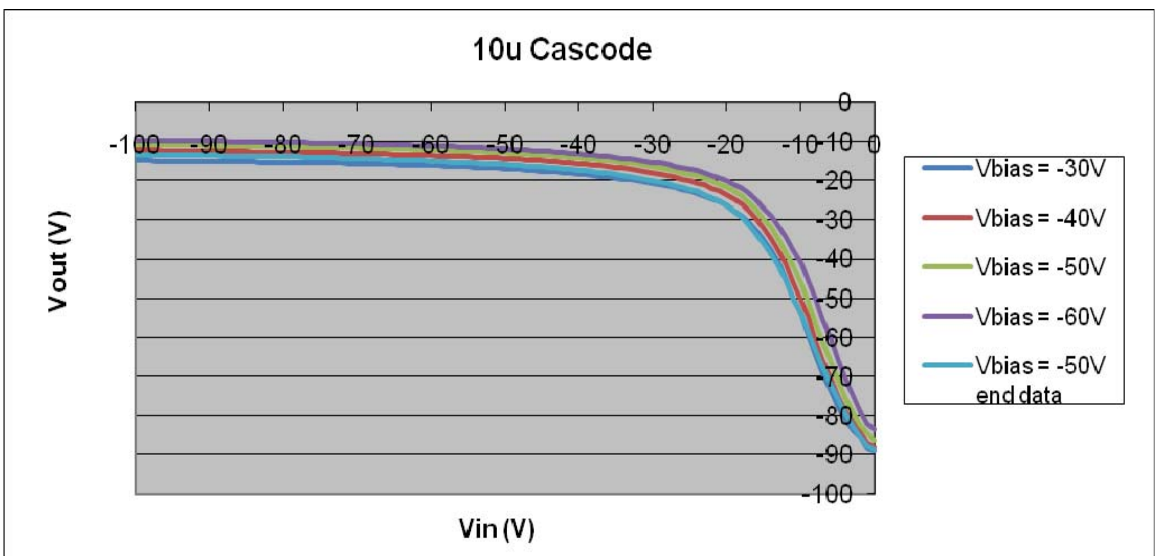

Figure 18: DC Characteristics of 10µ cascode

The cascode was analyzed for an input signal that varied between 0 V and -100 V. The output was tested with the bias set to -30V, -40V, -50V and -60V. The cascode showed a gain in the linear region of approximately 2V/V.

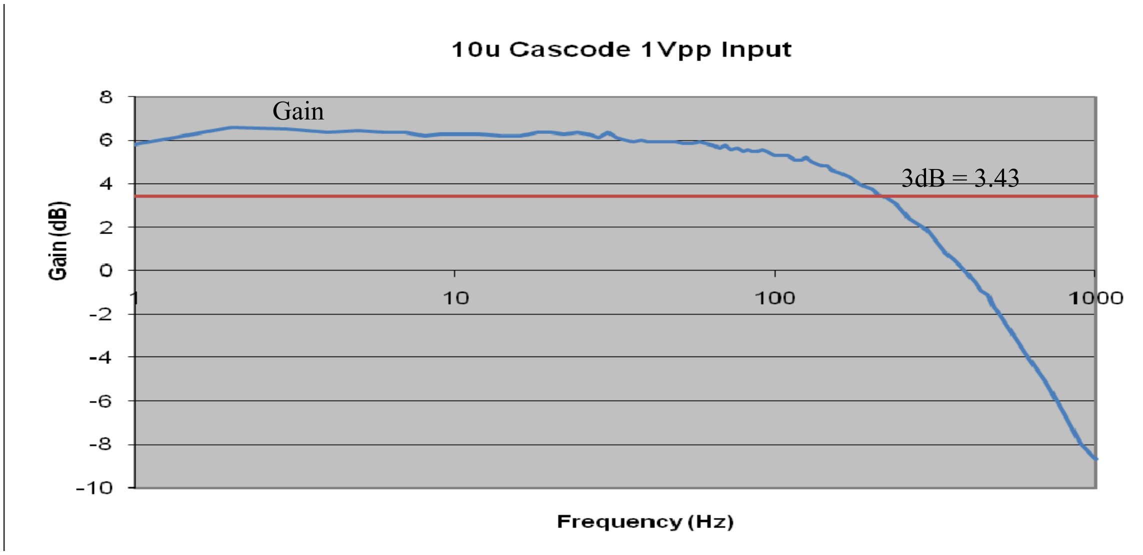

Figure 19: AC response of 10μ cascode

Figure 19 shows the AC response of the cascode with the 10μm channel length load. At low frequencies the cascode has a gain between 2V/V and 2.14V/V. The cascode shows a cutoff frequency at aprroximately 220Hz.

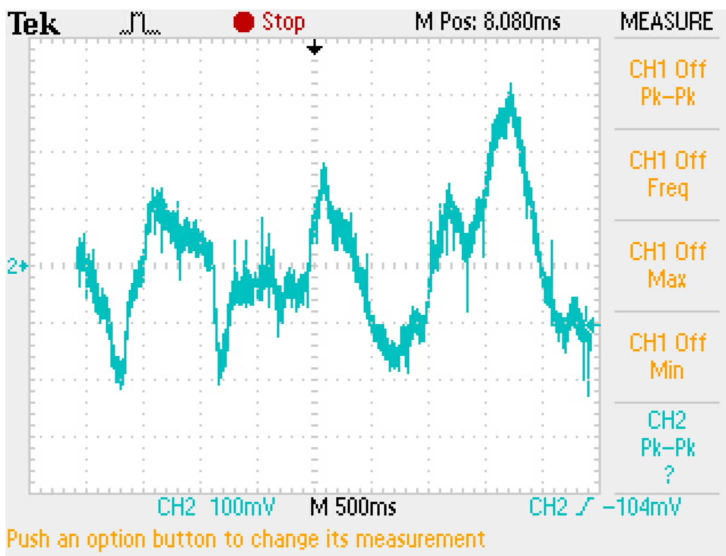

Figure 20: Output from ring oscillator

Figure 20 shows the output of the ring oscillator. This circuit is producing oscillations; however, the wave is inconsistent and varies in amplitude and shape.

5. DISCUSSION

In this study, we were able to employ OFETs as amplifiers through fabrication and circuit techniques. The circuit-configurations used were designed to test if OFETs could be used to read and amplify a small signal without heavily compromising the circuit bandwidth. The three-stage circuit designed with a 50μm channel-length transistor in a common-source configuration shows a low-frequency voltage gain of approximately 8V/V. With all connections made outside of the glove box, the final stage shows a bandwidth of approximately 52Hz. When connections are made within the glove box the final stage shows a bandwidth of 82Hz. This improvement in bandwidth is due to the lower output capacitance made possible by the shorter BNC cables used to make connections from within the glove box. The common-source stage alone shows a gain of approximately 0.95V/V. The common-source stage has a bandwidth of 67Hz when connections are made outside of the glove box and a bandwidth of 91Hz when connections are made within the glove box. The fact that the bandwidth is higher in the first stage than the total circuit indicates that the poles created in the later stages could be decreasing the frequency response. Through use of the common-source stage and the unity-gain buffer alone, there should be sufficient bandwidth for the analysis of the local field potentials of the brain and the electrical signals passed through the heart.

The more complex transistor circuits also show promise for the amplification of signals from the brain. The 8μm channel-length transistor, inverter, and cascode all show a higher gain than the 50μm channel-length transistor. Because of the elimination of the Miller effect, the cascode is also able to produce a greater bandwidth than possible with the single transistors or the inverters. The ring oscillator still does not show a consistent sine wave. This is likely due to the lack of uniformity between the inverters in the ring oscillator and insufficient time to invert the signal from the previous stage.

The use of a PCB was important for the reliability of the data. When data was taken from the circuit-configuration built on a breadboard there was a high degree of noise. This noise makes it impossible to distinguish the true peak-to-peak voltage of the output signal and prevents the accurate analysis of the gain and cutoff frequency. This noise was caused by the nature of the breadboard. In order to make connections on a breadboard wires needed to be employed. These wires become an issue because they can act as antennas and pick-up the noise generated by the components and the surrounding electronics. If this noise were left unfiltered, the output signal generated would be too unreliable to make any diagnostic decisions. By using a PCB, all wires were eliminated and the amount of noise was greatly reduced.

6. RECOMMENDATIONS

The first thing that needs to be done is to ensure that the OFET circuits can accurately output brain signals. In order to do this an electrode should be inserted into the brain and connected to the circuit through a wire. The output from the circuit should be connected to a unity gain buffer and be measured so that it can be compared to an output that is taken directly from an electrode. This test should be done with the common-source, inverter, and cascode being used for amplification. If the source-follower shows that it can function properly as a unity-gain buffer then it should be possible to fabricate a complete circuit for reading signals from the brain and heart without additional components needed.

For neurological and cardiac applications of OFETs, the next step is to ensure that the materials used are safe and non-toxic while interacting with living tissue. The circuit would also become safer if the dielectric were to be scaled so that the transistor can operate at lower voltages. Once these two precautions are covered, an OFET with electrodes that come in direct contact with the brain should be tested.

The next step after improving the ability of OFETs to sense signals of the brain and heart would be to be able to generate a stimulus under certain pre-defined conditions. This could create a circuit that more easily conforms to tissue and serves diverse roles including being used as a pacemaker for the heart.

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