Append E: Sensor Neuron Simulations[1]

E.1 Introduction

Modeling the electrical performance of the sensory neurons is an important first step in validating the Electrolytic Theory of the Neuron and the Activa. The Activa operates at unusually low voltages compared to most man-made transistor circuitry. As a result, simulation programs like Pspice do not contain the appropriate standard files in their repertoire. The initial efforts relied upon scaling the potentials used with the PNP Activa and applying those potentials to one of the easily available NPN transistors. Later efforts are expected to develop the appropriate file. Eventually that file will also accommodate the avalanche breakdown effect as well. Only in this way can the actual overall gain of the biological circuit be properly simulated.

E.2 First attempt at simulation

Dr. Rodney Staples of Melbourne, Australia was the first to perform a simulation of the sensory neurons based on the Electrolytic Theory of the Neuron and the Activa. The simulation, using PSpice, was performed by scaling the operating regime of the PNP Activa to match the operating regime of a typical NPN transistor (type 2N2222). The simulation circuit did not include the Avalanche Breakdown feature found in the biological circuit. As a result, the maximum voltage gain did not exceed 100:1 (voltage gain of 40 dB). The simulation circuit is shown in **Figure E.1.1-1**

[1]Released: May 8, 2005

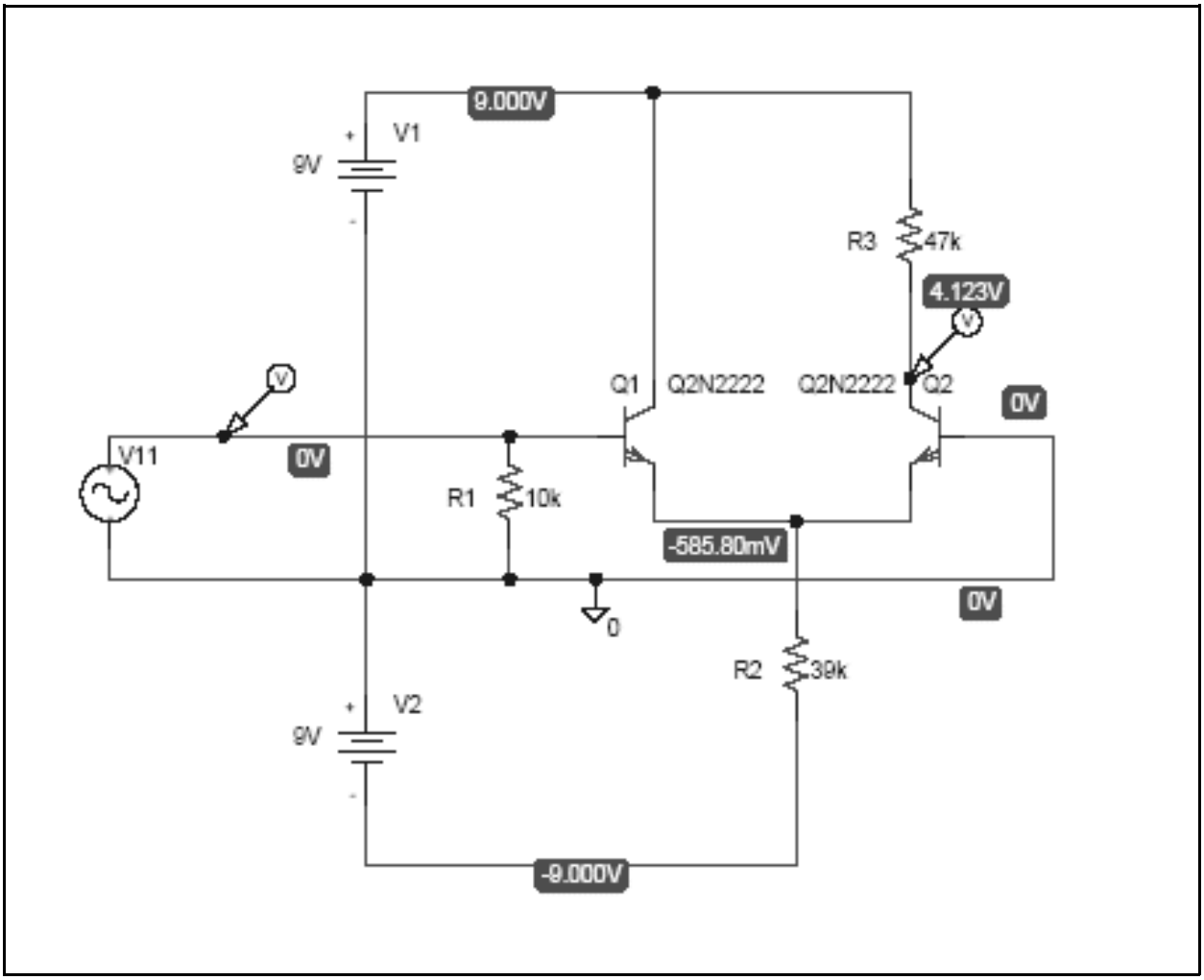

Figure E.1.1-1 Initial simulation of the sensory neuron circuit using scaling in PSpice.

His initial results speak for themselves.

E.2.1 The Experiment

I promised a modelling exercise based on a semiconductor version of anActiva. Here it is.

I'm surprised how simple it is, and how good for its simplicity.

I started with the active model in Ch 5 of hearing, taking one supply at 135 mV, and the other at about 20 mV, added them together and scaled up by 100 to give my starting point with silicon semiconductors. (With a Si transistor Vbe in the order of 600mV I thought the scaling was reasonable.)

I then took nearest standard values: e.g. *9V supplies, standard switching transistors (2n2222) and nearest standard value resistors. I set the emitter current at about 100mA,

which is around the optimum for noise performance in this kind of BJT. That set R2 at 39k ohms, and for the collector resistor R3 to set the output voltage in the middle of the available swing range that set R3 at 47k ohms (39k ohms works too, but at a reduction in gain and a slight increase in bandwidth, as you would expect). The attached pdf file has the circuit I used, and the outputs from the simulation.

R1 is included for biasing if the signal source is isolated with a capacitor (a possibility if the loss of energy in the visual photoreceptors is coupled capacitively into the activa), but it could be dispensed with (replaced with an open circuit) if there is a DC coupled drive in the hearing mechanism. (I haven't really read the details of how the coupling works yet, so forgive me if I get this bit wrong.)

With this circuit, the quiescent level of Q2 collector is about 4 volts above the reference. That could be a problem in coupling to later circuits and I haven't gone into that bit yet, but I think by rearranging the power supplies more in line with your biochemical model I think this difficulty might be overcome. I haven't tried that yet.

The gain of this version of the circuit was about 93, and the upper frequency limit was about 700 kHz. In other versions I had gains from about 50 to typically 70 or 80 with a very similar frequency limit. If I included a base resistor for Q2, it unbalanced the circuit (as you would expect with a voltage source directly coupled to the other input) but the gain remained remarkably similar, although the effect of Miller capacitance in Q2 was obvious with the upper frequency limit reduced to about 60 kHz. (The modelled Collector Base capacitance in Q2 is about 3 pF in this simulation, but the frequency limitations suggests a maximum capacitance of only about 1.8 pF for the pole shown. I wonder if there is a zero earlier in the circuit?) The distortion was remarkably low for what is a rather large signal output, at about 1-1.5 percent at 1V p/p out. Again as you would expect, the output began to clip as it approached the supply limitation, and saturation of Q2, giving about a 7V p/p maximum output, although the
distortion obviously increased with increasing level.

I'm surprised a little by the combination of gain, linearity and large-signal capacity of the circuit. With the single stage and two stage circuits I'm more familiar with, I'm used to seeing this kind of linearly with outputs in the 10's of millivolts range but not at the large signal range without copious feedback, and I'm not used to reliably getting such large gains so close to the maximum gain of the device.

I tried a version with *5 V supplies as well. The results at similar currents were remarkably similar.

Dr. Staples noted the high quiescent potential of the second amplifier circuit, the distribution amplifier. This would be unusual in a circuit passively DC coupled to the next stage. This would be of particular concern if the stages used a common power supply. However, the coupling used in neural circuits is not passive and each stage is independently powered. The coupling is provided by an Activa operating in a grounded base configuration. Operationally, the coupling Activa acts as a diode between the input and output circuits under normal conditions.

E.2.2 Analysis

This experiment was exploratory, no effort was made to emulate the detailed parameters of the Activa. Instead, scaling was used to make the operating parameters, primarily the voltages, compatible with silicon transistor technology. The stated scaling of 100:1 is probably too high. The

V_{BE} (at V_{BE} > V-sub γ) of the Activa is approximately –44mV (Section 5.3.1) compared to the 600 mV for silicon. Thus, a ratio of 15:1 appears more appropriate based on a cutoff voltage criteria.

The transistor chosen, 2N2222, is a general purpose device used for both "medium speed switches and as amplifiers from audio to VHF frequencies." The simulation circuit operated at a low impedance relative to the actual circuit. As a result, the bandwidth of the circuit must be interpreted.

In both vision and hearing, energy is applied to the sensory neuron by a quantum-mechanical process. For purposes of modeling, the application can be considered to be by direct coupling as opposed to capacitive coupling. Alternately, the first transistor in the simulation can be an open base photo-transistor. Virtually any silicon transistor in a transparent case is a photo-transistor.

The observed simulation bandwidths are very large compared to the target biological circuits. The typical sensory neuron exhibits a low pass filter characteristic with a pole at 600-1000 Hz. This difference is due primarily to the large maximum current capability of the 2N2222 transistor (an indication of the physical size of the device). Ideally, future simulations would use a data file for a much smaller device, such as might be found within the low level amplifiers of integrated circuit based operational amplifiers. The maximum average collector current in a sensory neuron is less than 100 pA (compared to the 800 mA of the 2N2222). The use of a significantly smaller device would allow circuit operation at an impedance level in the 1000 Megohm range (rather than the 10Kohm to 100Kohm range).

The collector to base capacitance of the Activa is largely unknown at this time. Future experiments will provide guidance in uncovering any significant Miller Effect in the Activa. This experiment does emphasize the importance of limiting the impedance in the base lead of the second Activa. In the biological circuit, the independent power supply to this lead probably exhibits a very low impedance.