Negative Capacitance – Using Positive Feedback to Compensate for Microelectrode Capacitance

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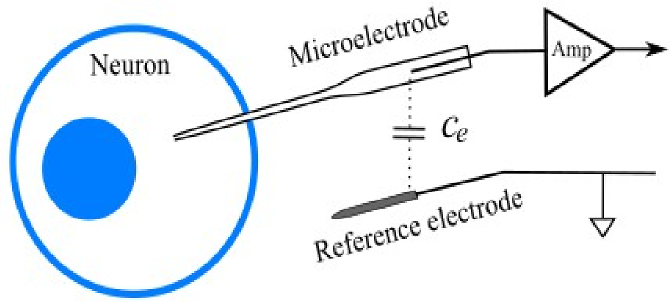
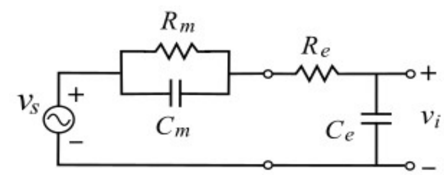
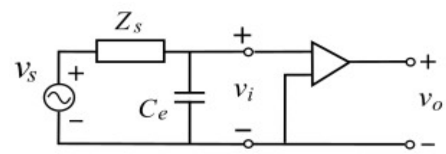
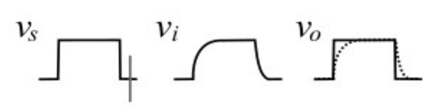
The standard technique for recording action potentials from a neuron is to insert a microelectrode, which is made from a glass pipette by using an electrode puller. The microelectrode tapers and becomes very small at the tip (~1 μm). The microelectrode has a large resistance R_e as well as a large stray capacitance C_e with respect to the surrounding bath solution.



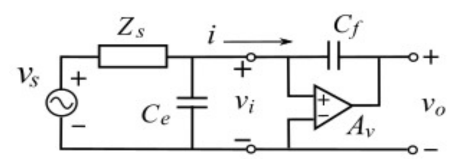
The equivalent circuit is shown on the right, where R_m = membrane resistance, C_m = membrane capacitance, v_s = voltage signal to be measured, and v_i = input voltage to the amplifier. The equivalent circuit can be further reduced, where the source impedance Z_s includes R_e, R_m and C_m. If v_s is a square pulse, v_i would show a low-pass filtered waveform because of the presence of C_e. To recover the lost higher frequency components, an amplifier is designed such that the output voltage v_o resembles v_s, as illustrated.







A technique typically used for this situation is based on a positive feedback circuit that creates a "negative capacitance" to cancel out C_e. As shown in the equivalent circuit, the gain of the amplifier is A_v , where $v_o = A_v \times v_i$. A positive feedback is created by connecting C_f from the output to the positive input terminal of the amplifier.



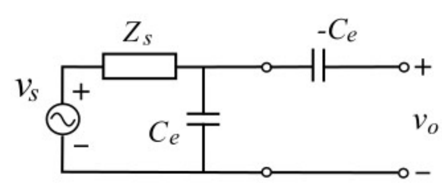
Let *i* be the current through C_f, we have

$$v_i = v_o + \frac{1}{C_f}\int i\,di = A_v v_i + \frac{1}{C_f}\int i\,di$$

$$(1-A_v)v_i = \frac{1}{C_f}\int i\,di \Rightarrow v_i = \frac{1}{(1-A_v)C_f}\int i\,di$$

Choose $A_v = 1 + \frac{C_e}{C_f} \Rightarrow \frac{1}{(1-A_v)C_f} = \frac{1}{-C_e}$.

The final equivalent circuit is shown on the right, where the negative capacitance $-C_e$ cancels out the electrode capacitance C_e, if the gain of the positive feedback A_v is properly set.



The gain should be set at $A_v = 1 + C_e/C_f$ in order to reproduce the square wave. Too low or too high a gain would affect the wave shape as shown on the right.