Lab 7

March 28, 2004

Current–Divider and Diffusor

The objectives of this lab are to:

- Test a current–mode "resistor," called a diffusor, and understand its operation in terms of the current–divider concept.
- Explore the behavior of an elegant current-mode implementation of a *resistive network* called a *diffusor network* and understand some of the things that these circuits are used for.

Resistive networks are often used in biological systems for a variety of tasks. In particular, they can be used to perform *local spatial averaging.* Such averaging is used to improve the signal-to-noise ratio or to obtain a *local reference* to which signals can be compared.

In this lab, we will examine a one-dimensional resistive network made up of diffusors. The diffusor relies on the exact linear relationship between channel current and the carrier concentration in subthreshold conduction.

7.1 Reading

Read over your notes from class on the current–mode circuits. The operation of the diffusor circuit is much easier to understand in terms of the two components that make up the channel current rather than the saturating I_{ds}–V_{ds} characteristics we measured earlier. Forward and reverse currents are the current–mode counterpart to the ohmic/saturation dichotomy you used to think about voltage–mode circuits. Try to resist the temptation of resorting to the voltage–mode way of thinking.

Also, review your notes on the diffusor circuit and read the section of Chapter 7 (Aggregating Signals) on resistive networks (pp. 107-116) and Appendix C (Resistive Networks) for some more of the mathematics involved in treating the continuous approximation.

7.2 Prelab

1. This question ask you to rethink the transistor in a "current–mode" way and compare it with the voltage–mode view.

   a. Draw an n–fet, define the direction for the channel current, and label the drain and source accordingly.

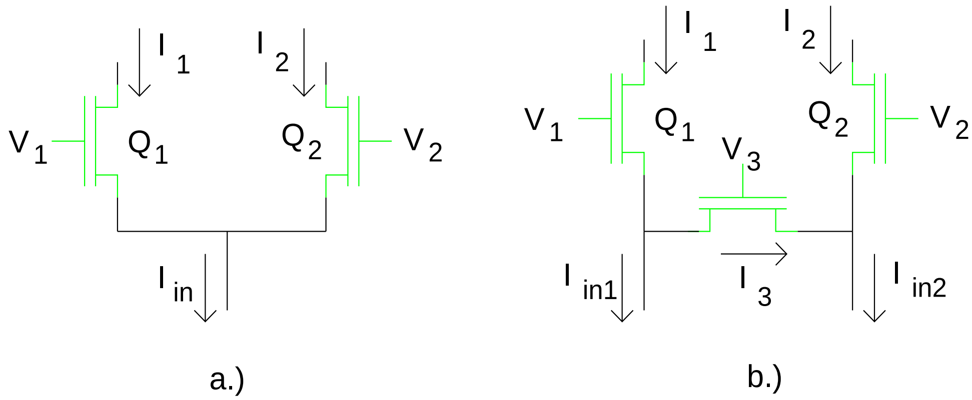

Figure 7.1:
Current divider and Diffusor. The (a) current–divider and (b) diffusor circuits.

b. Write down an expression for the subthreshold current and show that it can be expressed as the difference of a forward current I_f, in the same direction as the channel current, and a reverse current I_r, in the opposite direction.

c. How does decreasing the source voltage affect (i) the forward current and (ii) the reverse current. What about the effect of changing the drain voltage?

d. What are the relative magnitudes of the forward and reverse currents when the transistor is in (i) the ohmic region and (ii) the saturation region.

2. Derive an expression for the ratio I_1/I_2 between the currents in the current–divider circuit shown in Fig. 7.1a in terms of the voltage difference $V_1 - V_2$ and the W/L ratios of the transistors, denoted by w_1 and w_2. Assume subthreshold operation and $I_f \gg I_r$.

3. **a.** For the diffusor circuit in Fig. 7.1b, show that the relationship between the current through the diffusor Q$_3$ and the current difference[1] across it is

$$\frac{I_3}{w_3 e^{\kappa V_3}} = \frac{I_2}{w_2 e^{\kappa V_2}} - \frac{I_1}{w_1 e^{\kappa V_1}} \tag{7.1}$$

where w_i is the W/L ratio of Q_i. Note that the currents that are relevant here are the currents in Q_1 and Q_2—not the input currents. First, use the current–divider formula from **3a** to compute the forward and reverse components of I_3 and then combine them. Assume Q_1 and Q_2 have $I_f \gg I_r$. As usual, subthreshold operation is assumed with voltages in units of kT/q.

b. If Q_1 and Q_2 have the same effective width, i.e. $w_1 \exp(\kappa V_1) = w_2 \exp(\kappa V_2) \equiv w \exp(\kappa V_{\text{ref}})$, Equation 7.1 simplifies to

$$I_3 = \alpha(I_2 - I_1)$$

where α is the ratio of effective widths. Give an expression for α in terms of $V_3 - V_{\text{ref}}$ and w_3/w.

4. **a.** Read about resistive networks and derive the differential equation governing a continuous approximation to a resistive ladder. Observe how the space constant of the network falls out of the equation.

[1] This is the analog of the voltage difference across a resistor.

b. When the conductance into the network G and the lateral conductance $1/R$ depend exponentially on the bias voltages V_g and V_r, how will the space constant depend on their difference $V_g - V_r$?

5. **a.** Consider a continuous two–dimensional resistive sheet (there is no conductance to ground) with sheet resistance ρ/δ, where ρ is the resistivity and δ is the thickness. An extrinsic current $I(x, y)$ is injected at position (x, y) and $V(x, y)$ is the resulting voltage. Show that

$$\nabla^2 V(x, y) + \frac{\rho}{\delta} F(x, y) = 0$$

where $F(x, y)$ is the current per unit area and $\nabla^2 \equiv \partial^2/\partial x^2 + \partial^2 \partial y^2$ is the laplacian—the 2–D counterpart of the second derivative. Hint: Consider a small square element of size $\Delta x \times \Delta y$ and find the relationships between the currents across its four sides and the partial derivatives there.

b. Suppose we wanted to take the laplacian of an image (why might this be useful?) with a discrete resistive network. Let the internode resistance be r and the internode spacing be ϵ. By considering this network as an approximation to the continuous sheet, use your previous result to find the relationship between the laplacian of the voltage and the current injected into the nodes.

6. Let us consider how to transform a voltage–mode network into a current–mode one.

a. Draw a resistive voltage divider and a resistive current divider with the same ratios—these circuits are duals.

b. Using this example, come up with the current–mode version of the resistive network shown in Figure 7.5 of Mead (page 110).

c. Can you see a pattern in transforming a linear circuit from voltage–mode to current–mode?

d. How would you build the current–mode network using diffusors?

7. Draw the set–ups you will use for the experiments.

7.3 `Mathematica` tool for taking data with Scanners

This week, you will be using a new `Mathematica` tool called `DiffusorPlot` which facilitates taking static data from scanner projects using the 6517 electrometer. The program measures a voltage or current signal at various positions along a scanned 1-D array and returns a signal *f(x)* vector versus a position vector *x*. The program will output a plot of the scanned data in the `Mathematica` notebook. Please remember that this plot is only meant to give you an idea of what the output currents look like. In order to really assess the diffusor network, you should subtract the output currents you find with uniform inputs from your data (i.e. all nodes set to 0.6v for example). To run the program, simply go to *E:/BE526/Diffusor/* and open up the `Mathematica` notebook *DiffusorPlots*. Select the cell containing the `Mathematica` code (a cell is delineated by a blue bracket on the right side of the screen) and hit Shift-Enter to run the code. `DiffusorPlot` will scan the 25 output nodes of the chip and plot them both linearly and logarithmically on the `Mathematica` notebook. The output data is stored in the text file *data.txt* (in mA) in the same directory, but you can look at the data in `Mathematica` by looking at the `Mathematica` variable currdata (in Amps). Before running the program, make sure you power up the 6517 Electrometer, the 2400 Sourcemeter, the potbox, and the DC power supply (outputting 5v DC).

If the program doesn't work, verify your connections and check to make sure that the clock voltages and number of stages are set properly. Also, make sure that PDBIAS (pin 24) is set appropriately.

Caveat emptor! This code is not completely bullet-proof. Please report any bugs to me!

7.4 Experiments

For this lab, the chip you will be testing (N4BG-BZ2) is the same chip you used for the adaptive neuron lab. A schematic of the diffusor network is shown in Fig. 7.2. Recall from the adaptive neuron lab that V_{dd} is pin 15, and ground is pin 5. Note that the inputs to the diffusor network come in in seven independent groups to conserve pins. V_1 is pin 16, V_{2-11} is pin 12, V_{12} is pin 11, V_{13} is pin 10, V_{14} is pin 9, V_{15-24} is pin 8, and V_{25} is pin 14.

You can check the values that you set these voltages to by turning on the corresponding switch, which will connect that particular potentiometer to the fluke.

Experiment 1: Set Up

Connect power and ground to the chip. Following the pinout of Fig. 7.2, connect a potentiometer to each of the inputs of the diffusor network. Follow the arrangement described above, but if some of the potentiometers are not working, feel free to tie some diffusor inputs together. Also, make sure to connect a potentiometer to V_r and V_g (pins 22 and 23, respectively) and a potentiometer to PDBias (if you are running out of working pots, you can set PDBias to roughly 2-2.5V with a resistive voltage divider).

The `Mathematica` code uses the 6517 and 2400, so we have to connect these devices to the potbox. Connect the rear input triax on the 6517 to one of the triax ports on the potbox. On the potbox itself, you should wire the positive side of this triax line to *diffuseout* (pin 37). This will be where we will read off our output currents. The negative side of this line should be tied to some DC voltage that you can create with another resistive voltage divider (2v). Pin 38 on the chip (*diffusdumm*) should be tied to this same voltage (for an explanation, see the accompanying scanner handout).

The 6517's voltage source should be set to five volts and tied to CLK (pin 28). To get a better idea of how the scanner works, look at SYNC, pin 27, on the fluke. Normally, it will be near Gnd . When a sync pulse occurs, it is pulled to $\mathrm{V_{dd}}$. To clock the scanner once manually, press the "operate" button on the 6517 voltage source twice in succession. This has the effect of switching the output voltage from ground (clock low) to 5V (clock high). Repeat this until the SYNC line goes from ground to 5V.

Finally, hook up the 2400 to the potbox. Set the current source on the 2400 to 0 Amps (use the rear current input/output port) and set the 2400 to measure voltage. On the potbox, tie the 2400's line to pin 27 (SYNC). The 2400 should read off 0v until a SYNC pulse occurs, at which point you will see 5V on the 2400 (just like you did with the fluke).

When running the Mathematica code, the SYNC and CLK signals will be automatically aligned such that the data is recorded from nodes 1 to 25. There is additional code at the bottom of the `Mathematica` notebook that facilitates normalizing the data. Simply run the initial code once with your uniform inputs. Then execute the "testdata=data" cell - this

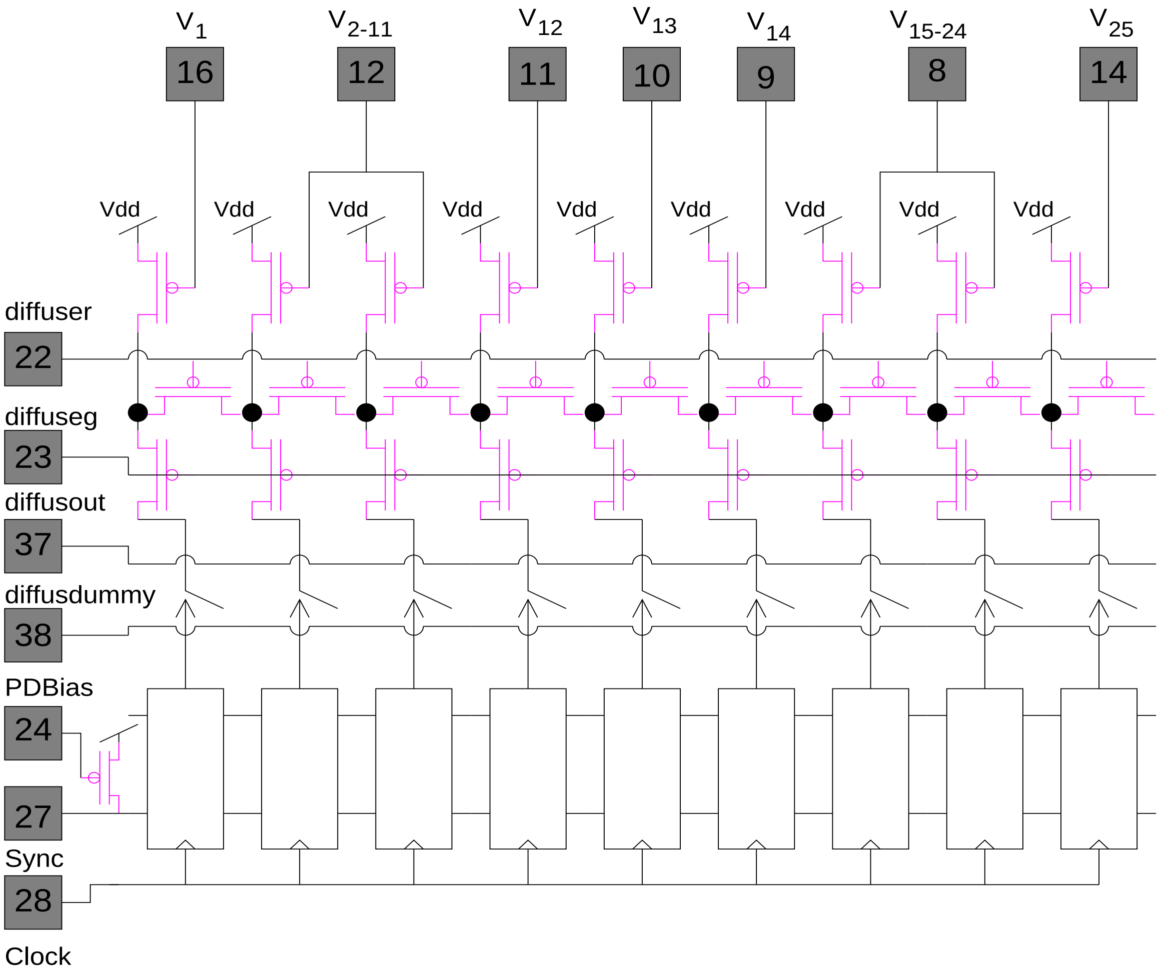

Figure 7.2:
Diffusor–based resistive network.

should store your initial data in the variable testdata. Rerun the initial code again with your new settings. Run the code at the bottom of the notebook which will subtract your testdata from your new data and will plot the results.

Experiment 2: Diffusor Network

Current sinks (native transistors controlled by the input voltages) provide inputs to the diffusor network. The output currents are multiplexed onto diffusdummy (pin 38) and diffusout (pin 37). The effective widths of the lateral and vertical devices are controlled by diffuser (pin 22) and a diffuseg (pin 23). We will refer to these biases as V_r and V_g, respectively; they determine the space constant of the network.

Experiment 2.1: Space constant

Set all the inputs to zero except the one in the center. Observe the effects of the input level on the output level. Vary V_r and V_g and observe how the signal spreads.

Obtain the responses to a subthreshold input current for different values of $V_r - V_g$. Plot your results on a semilog plot and extract the space constant. Over how many decades is the response exponential? Is the deviation due boundary effects or offsets? You might want to apply the input at one end instead of the middle to avoid boundary effects. Also try subtracting the leakage currents, i.e. the outputs for zero input current. Plot the measured space constants versus $V_r - V_g$ and check agreement with theory.

Experiment 2.2: Operating Range

Obtain the responses to input levels ranging from subthreshold to above threshold for a fixed value of V_r and V_g. Over what range is the space constant actually constant? When and why does it begin to change?

Experiment 2.3: Smoothing

Try putting a small step edge into the network. Look at the output as you change the height of one side with respect to the other. Is the network linear? How can you test that?

Explore varying the space constant with V_r and V_g. What effect does it have on the smoothing? Corrupt the clean edge with noise and see how well the network still recovers the edge in the presence of noisy data. Is there an optimum setting for the space constant for a given noise level?

7.5 Postlab

1. Let us look at how things work above threshold. Repeat Question 1b-d in the Prelab for the above–threshold current. You can simply say ‘Same as subthreshold’ if the answer is the same.

2. Read through the chapter on the silicon retina and come up with a current–mode version of Misha’s circuit. You need not understand how the HRES circuit works in detail–only that it is a voltage-mode implementation of a resistive network and that it requires six transistors per pixel for a bias circuit and six pass transistors per pixel for the resistive network. Also compare the number of transistors required by each implementation.