A retina/V1 simple cell chip for physiology experiment design or classroom demonstration

Tobi Delbrück*, Shih-Chii Liu, Elisabetta Chicca, Gian Marco Ricci, Simon Bovet
Institute of Neuroinformatics (INI), Univ. of Zürich and ETH Zürich
Winterthurerstr. 190, 8057 Zürich, Switzerland
* tobi@ini.phys.ethz.ch, http://www.ini.unizh.ch/~tobi

Abstract

This chip provides retinal and simple cell responses to visual stimuli. It can be used by visual physiologists to debug and test their experimental setups and by instructors to demonstrate the responses of the early visual system. The chip has a hexagonal arrangement of 7 photodiodes. Subsequent processing produces the chip's outputs: An adaptive photoreceptor cell, a retinal horizontal cell, *on*- and *off*-type spiking retinal ganglion cells, and two spiking simple-type cells of *odd* and *even* type. The membrane potentials of some of the cells are also available. The 5 mm^2 chip was built in a 1.6 µm CMOS technology. All parameters are set by an on-chip bias generator.

I. Motivation

Modern visual physiology requires synchronization of multiple computers that generate visual stimuli, record responses, and perform on-line data analysis. These custom-built setups are usually ridden with irritating bugs that take months to expunge. There exist no commercially available animal "stand-in" devices that allow vision physiologists to test the complete experiment design from visual stimulus to on-line analysis of neural responses. Such a device would be valuable for debugging the setup *before* an animal is sacrificed for an experiment. Lecturers could also demonstrate compellingly the operation of retina and visual cortex. The aim of this work was to fabricate a *practical* device to fulfill these requirements, with battery-powered stand-alone operation, a number of easily selectable outputs, and preset operating point.

II. Chip Architecture

Fig. 1 shows the schematic of the core of the chip corresponding to the layout shown in Fig. 2. A discrete array of 7 hexagonally-arranged photodiodes feed their photocurrents to a linear array of 7 adaptive photoreceptor circuits (Fig. 3) [3]. The receptor outputs connect to the horizontal/bipolar layer circuits shown in Fig. 4. The horizontal cell circuit computes the average photoreceptor output using a follower-aggregator [5]. An antibump circuit [4] in each pixel splits the difference between photoreceptor and horizontal cell outputs into rectified *on* and *off* currents. These *on* and *off* currents drive 14 spiking adaptive ganglion cells (Fig. 5) [1]. These cells connect with excitatory and inhibitory synapses (Fig. 6) to two simple-type V1 cell somas (same circuit as ganglion cell). The connections are arranged to create the push-pull models of *odd* and *even* simple-type receptive fields shown in Fig. 7. For example, the *odd* simple cell is excited by *on* ganglion cells on the right and by *off* ganglion cells on the left. It is also inhibited by *off* ganglion cells on the right and by *on* ganglion cells on the left. The *odd* simple cell is maximally excited by the black and white edge shown overlaying it in Fig. 7. A PCB (Fig. 8) carries the chip with its lens, and provides a built-in speaker, volume control, output selection, and BNC or 3.5mm audio plug outputs for connection to standard physiology rigs or external speakers.

III. Bias Generator

The on-chip bias circuit generates 12 internal bias currents and reference voltages. They are nearly independent of threshold and supply voltage variations. The bias circuit is based on a β-multiplier loop that generates a known master reference current [6] using a single external resistor. A pseudo-resistive divider based on Bult and Geelen's [2] current splitter derives the other bias currents from this master current. The ratio of the largest current (10 µA) to the smallest (100 pA) is 10^5.

IV. Operation

Fig. 9 shows representative outputs from the *odd* type simple cell in response to drifting sinusoidal grating patterns with varying orientation.

Power consumption of the 9V battery powered system is 10 mA. Chip power consumption is 1 mA at 5V.

Conclusion

This chip is being used at INI on a regular basis for experiment design, student training, and lectures. The audio output is particularly effective for demonstrations to large classes. We are planning production of an expanded design for distribution to laboratories and teachers.

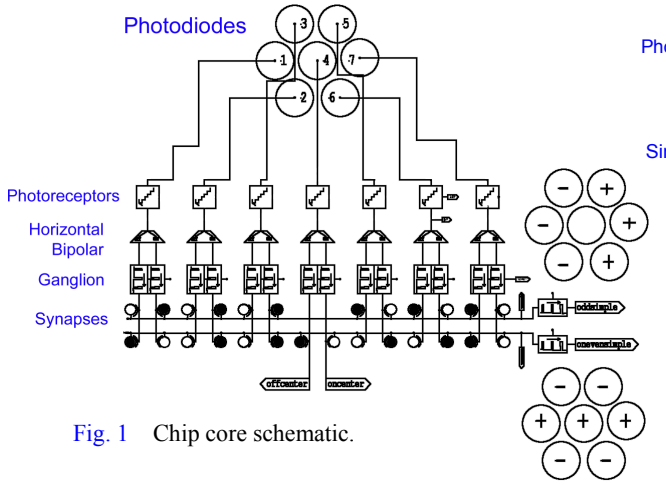


Fig. 1 Chip core schematic.

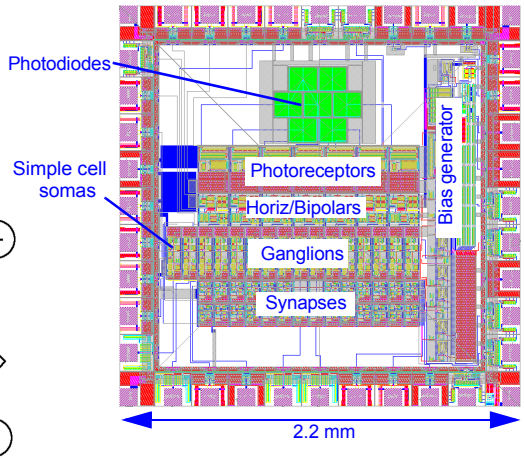


Fig. 2 Chip layout.

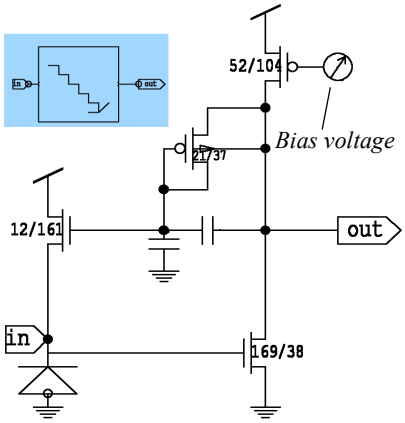


Fig. 3 Adaptive photoreceptor. *Out* drives the Horizontal/Bipolar stage.

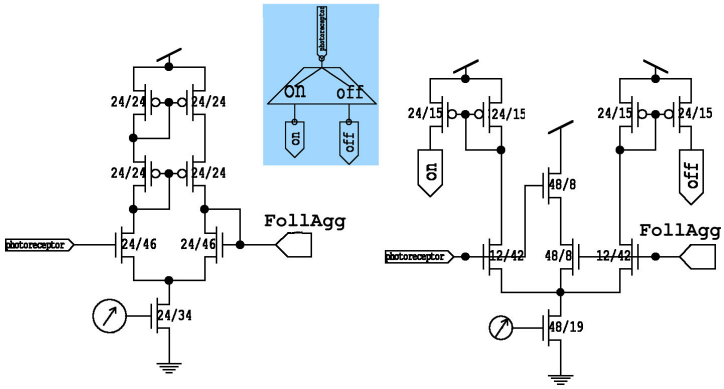


Fig. 4 Horizontal and bipolar cells. Global node *FollAgg* is the average photoreceptor. *On* and *off* drive the ganglion cells.

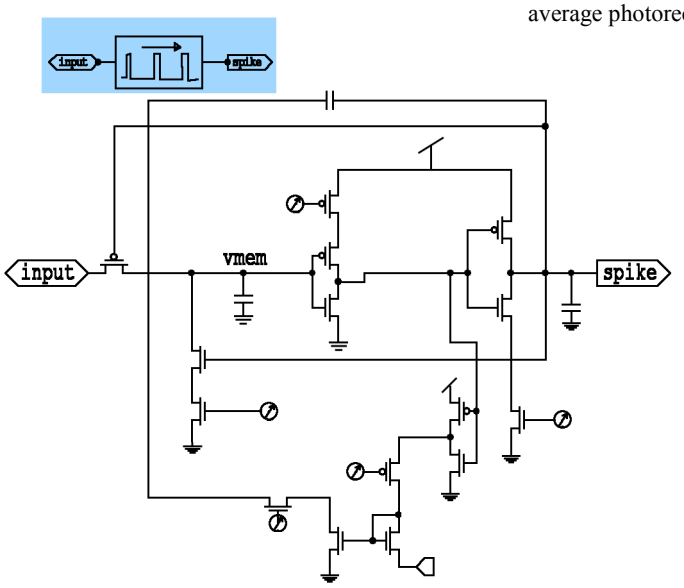


Fig. 5 Integrate-and-fire ganglion cell and simple cell soma. Lower circuitry provides spike adaptation.

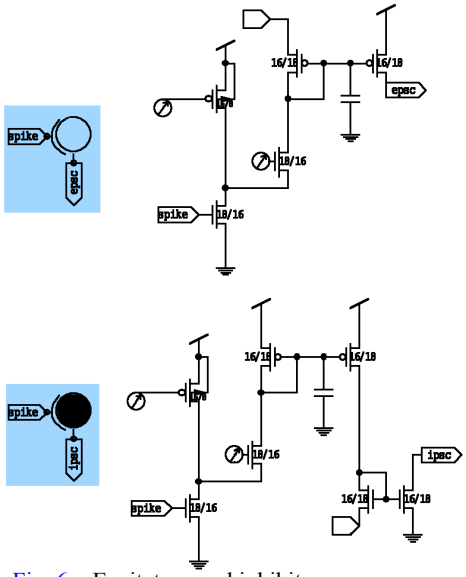


Fig. 6 Excitatory and inhibitory synapses. *Epsc* and *ipsc* drive the simple cells.

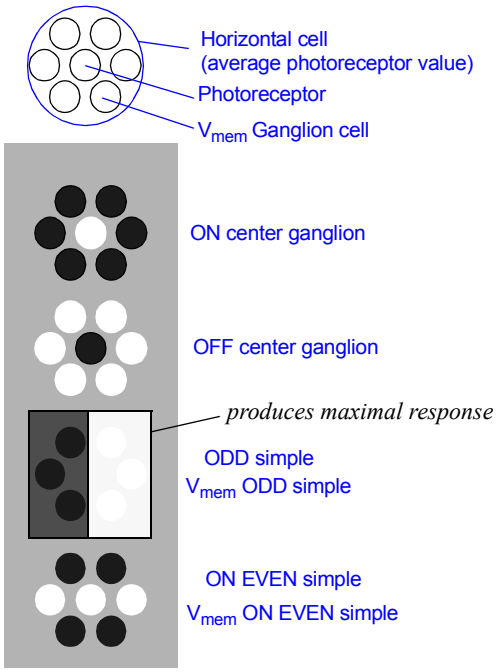


Fig. 7 Chip outputs and their receptive fields.

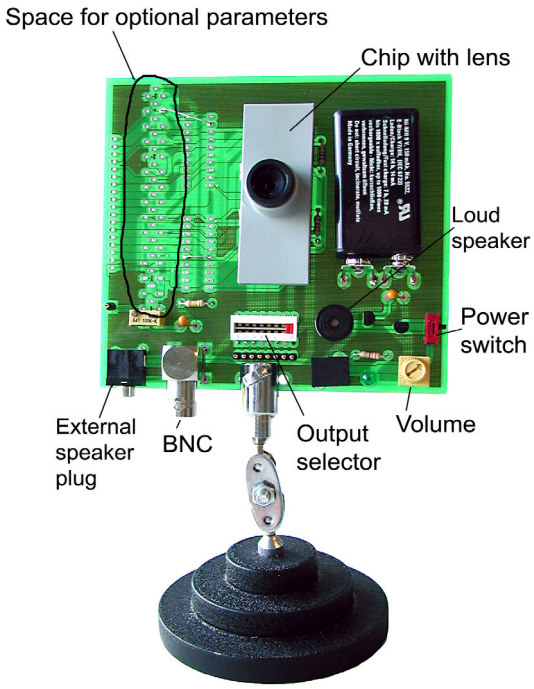
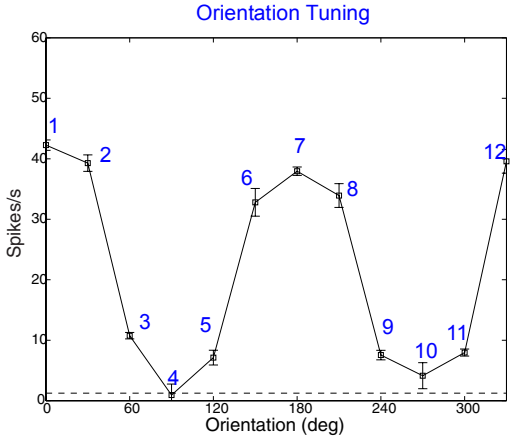


Fig. 8 PCB.



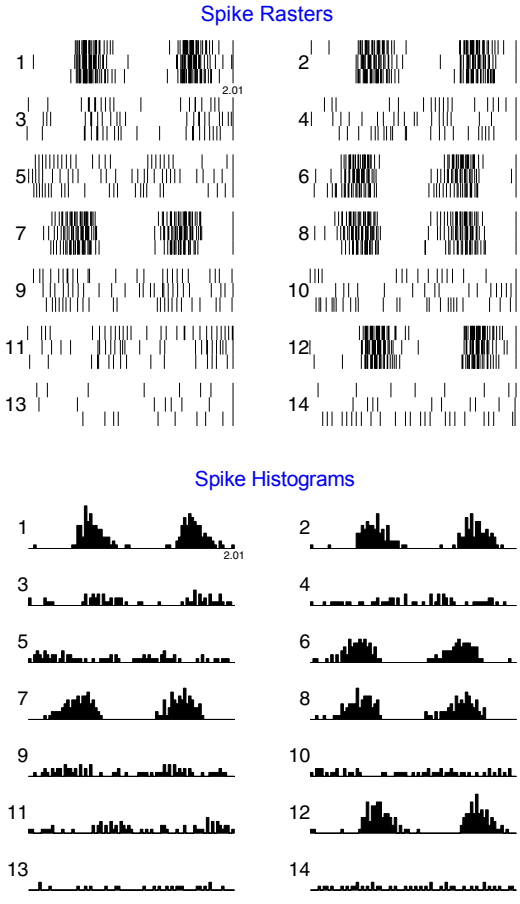


Fig. 9 Representative measured responses from *odd* simple cell. Orientation tuning curve, spike rasters, and histograms in response to a drifting sinusoidal grating with varying orientation; contrast 100%, temporal frequency 2 Hz, spatial frequency about 1 pixel, 3 repeats. Orientation tuning (above) shows first harmonic response. Stimuli 1 (0^o) and 7 (180^o) are horizontally drifting vertical gratings. Stimuli 13 and 14 are a blank screen.

Acknowledgments

M. Carrandini provided impetus by using S.C. Liu's direction-selective fly model chip to help debug and calibrate his physiology setup. Students in our aVLSI course at INI and students at the Telluride Workshop on Neuromorphic Engineering also contributed to the design. A. Van Schaik, O. Landolt, and B. Schediwy, helped with the bias generator design. M. Carrandini measured the responses in Fig. 9 using his physiology rig. This work was funded by the Swiss National Science Foundation.

References

[1]. Boahen KA (1997). "The retinomorphic approach: pixel-parallel adaptive amplification, filtering, and quantization," *Analog Integrated Circuits & Signal Processing,* vol. 13, no.1-2, May-June 1997, pp.53–68. http://www.neuroengineering.upenn.edu/publications/papers/kwabena/retinomorp.pdf

[2]. Bult K. and Geelen G. (1992). "An inherently linear and compact MOST-only current division technique," *IEEE Journal of Solid State Circuits*, vol.27, pp.1730–1735.

[3]. T. Delbrück and C.A. Mead (1994). Analog VLSI Phototransduction by Continuous-Time, Adaptive, Logarithmic Photoreceptor Circuits. Caltech CNS Memo #30 http://www.pcmp.caltech.edu/anaprose/tobi/recep

[4]. Delbrück, T. (1993). "Bump circuits for computing similarity and dissimilarity of analog voltages," Caltech CNS memo #26. http://www.pcmp.caltech.edu/anaprose/tobi/bump

[5]. Mead, C.A. (1989). *Analog VLSI and Neural Systems.* Reading, MA: Addison-Wesley.

[6]. Vittoz, E.A. and J. Fellrath (1977). "CMOS analog integrated circuits based on weak inversion operation," *IEEE Journal of Solid State Circuits,* vol. SC-12, no. 3, June 1977, pp. 224–231