Dichromatic self-timed spectral measurement circuit with digital output in vanilla CMOS

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Prior work [1-4] has shown that ordinary (vanilla) CMOS can spectrally separate photons using the shallow source-drain and deep well junctions (Fig 1) and that a color imaging sensor and self-timed readout structure can be built to read out these signals Here we show our first implementation of a self-timed circuit with digital output that encodes the spectral content (long vs. short wavelength content) as PWM duty cycle and the total photocurrent as PWM frequency, as in [4], but using vanilla CMOS instead of a bipolar process. This circuit is a step towards building color sensitive vision sensors using commodity CMOS processes. The potential advantage of vanilla CMOS is that it avoids the use of high-cost, low availability specialized process flows with integrated color filters, thus allowing more rapid and affordable prototyping of experimental circuits and faster evolution of new architectures.

Longer-wavelength photons penetrate more deeply. The shallow diode (U) is more sensitive to short wavelength light and the buried diode (L) is more sensitive to longer wavelengths. The ratio of the two different photocurrents is a strong function of wavelength and can provide information about the color. Because U and L diodes share the n-type region (well) and one node is "hardwired" to ground (substrate), it is hard to separate the two currents. The current of the U diode is available at the active node. The only other available current is the current at the well node, which is the sum of U and L photocurrents. If both currents were allowed to flow continuously, the photocurrent of the L diode would have to be calculated by somehow subtracting the upper current from the summed current. Because such a calculation is mismatch-prone, we measure the ratio of photocurrents by reverse-biasing both photodiodes and then letting the photocurrent discharge the U and then the L diode (Figs. 2&3). We output a signal that is low during the discharge of the U diode and high during the discharge of the L diode. The duty cycle of this signal contains the information about the long versus short wavelength content of the incident light. To generate this signal we use a self-timed control circuit (Fig. 4). This circuit implements the comparators that determine state transitions and the state machine. The design of the circuit ensures that it cannot get stuck in a parasitic state. The control circuit outputs the switch signals ϕ_n and ϕ_p.

This circuit was fabricated in a 0.5u 3M 2P 5V process. Fig. 5 shows a die photograph and Fig. 6 shows the layout of the 100x100 um^2 photodiode and control circuit, along with two poly capacitors used for characterization.

Fig. 7 shows the measured spectral response and Fig. 8 shows that the duty cycle is invariant to absolute illumination over at least 5 decades, while the frequency is proportional to illumination. Under 500 lux fluorescent illumination, the duty cycle is about 25%, while the frequency is about 150 Hz. The duty cycle varies from 50% to 7% over a wavelength range 400 nm to 750 nm. Fig. 9 shows scope traces of circuit nodes with two different pure spectral illumination conditions; the discharge rate of the A node increases when wavelength is decreased.

Circuit power consumption is about 20 uW under indoor illumination conditions; at this bias level, the circuit can run up to 90 kHz. Mismatch in response duty cycle and frequency as measured over 5 chips is under 1%. This low mismatch is due to low variability of capacitance values and independence of behavior on absolute threshold voltages.

Future developments will integrate small arrays of these circuits with self-timed readout and processing circuits for applications in low-resolution color-based visual recognition tasks.

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[1] R. F. Wolffenbuttel and P. P. L. Regtien, "A novel approach to solid state color sensing," *Sens. Actuators*, vol. 9, pp. 199-211, 1986.
[2] R. F. Wolffenbuttel, "Color filters integrated with the detector in silicon," *IEEE Electron Device Letters*, vol. EDL-8, pp. 13-15, 1987.
[3] R. F. Wolffenbuttel and G. D. Graaf, "Performance of an integrated silicon color sensor with a digital output in terms of response to colors in the color triangle," *Sens. Actuators A*, vol. 21-23, pp. 574–580, 1990.

[4] R. F. Wolffenbuttel and G. d. Graaf, "Light-to-Frequency Converter Using Integrating Mode Photodiodes," *IEEE Journal of Solid State Circuits*, vol. 46, pp. 933-936, 1997.

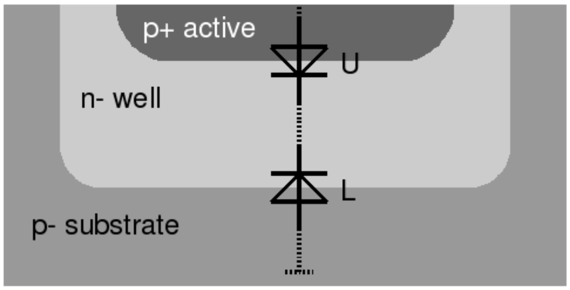
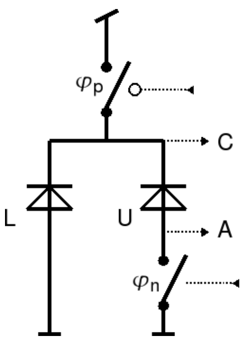


Figure 1. CMOS cross section.



Phase	φ_p	φ_n
Tc - Charge	on	on
Tu - Discharge U	on	off
Tl - Discharge L	off	off

Figure 2. Control states.

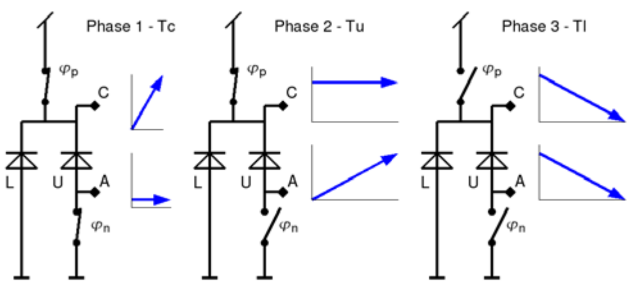


Figure 3. Cyclic operation phases.

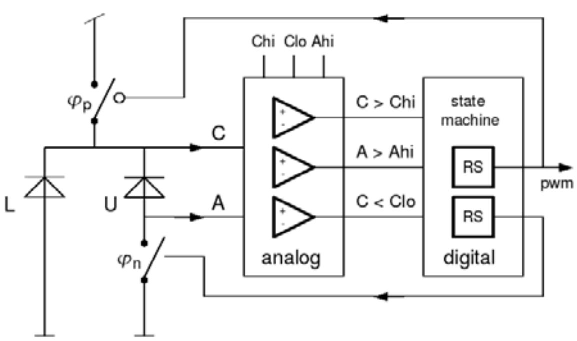


Figure 4. Control circuit schematic.

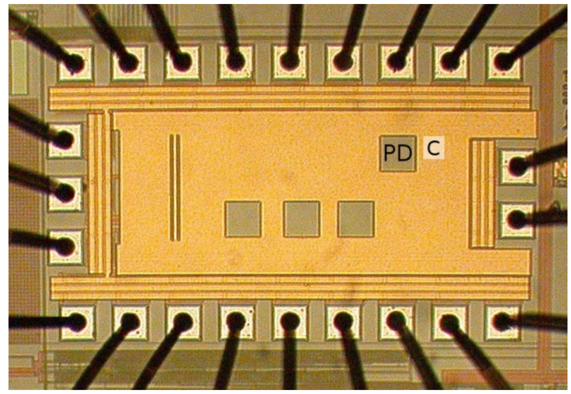


Figure 5. Die photo. PD=photodiode, C=control circuit.

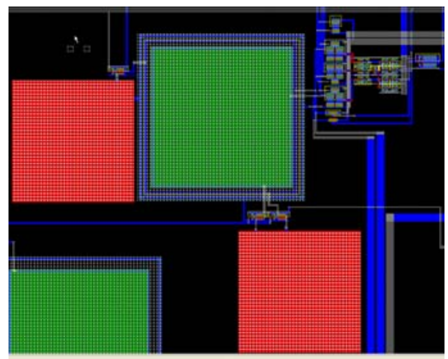


Figure 6. Layout including test capacitors.

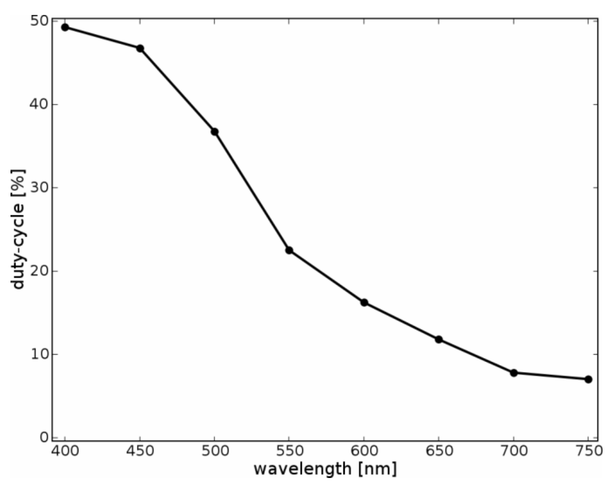


Figure 7. Spectral response.

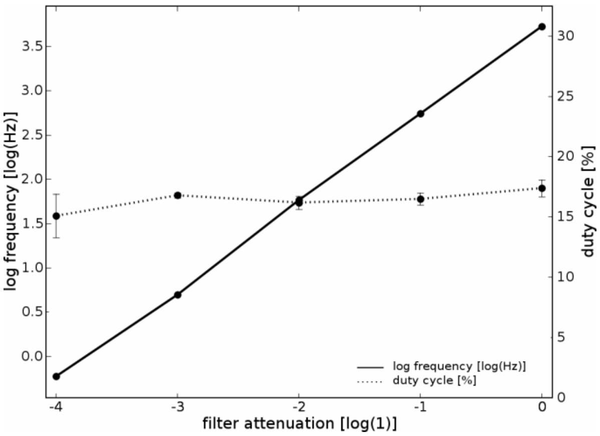


Figure 8. Invariance of duty cycle to illumination.

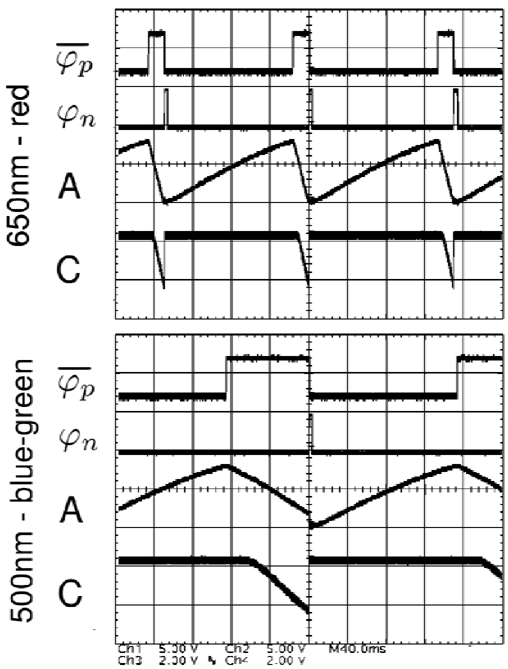


Figure 9. Scope traces.