Light-to-Frequency Converter Using Integrating Mode Photodiodes

Ger de Graaf and Reinoud F. Wolffenbuttel

Abstract—**An optical sensor for operation in the visible spectrum with integrated electronic readout circuits has been realized in a BIFET process. The output signal is a pulse series with a frequency proportional to the intensity of the incident light. Furthermore, the duty-cycle of the output pulses depends on the spectral distribution of the incident light, enabling the measurement of color. The electronic circuits have been designed for operating with a large dynamic range, while using only a relatively small chip area. No internal or external capacitor is needed for the current-to-frequency conversion, since the photodiode operates in the charge integrating mode. This enables fabrication of arrays of smart image detectors where a large area can be used for the photodetector.**

Index Terms— **Charge integrating photodiode, color sensor, light-to-frequency conversion, optical detector, smart sensor.**

I. INTRODUCTION

LIGHT is generally characterized by its intensity (luminance) and its spectral distribution (chrominance). Utilizing the very large dynamic range of silicon photodiodes in analog systems would require an expensive high-performance AD converter. Therefore, several sensor interface circuits with a frequency output both in MOS [1], [4] and bipolar technology [2], [3] have been recently introduced. A frequency output generally allows a high dynamic range since frequencies from a few hertz up to several megahertz can be easily counted using simple logic. Modern microcontrollers have on-chip counter/timer logic allowing a direct interface to these type of sensors. Also a digital output of the sensor allows simple interface with bus systems. Commercially available light-to-frequency converters realized in MOS technology [4] consist of a current amplifier covering an input current range of about four decades followed by a current-to-frequency converter. The current amplifier is programmable in three steps of one decade to cover the entire dynamic range of the detector (10^{-9}–10^{-1} W/cm^2). These devices perform very well in terms of dynamic range and linearity, but in many applications, e.g., object recognition, also the spectral distribution of the incident light is needed.

The circuit presented here uses the photocurrents of two stacked junction diodes in the epitaxial layer of a bipolar integrated circuit process. Due to the wavelength-dependent absorption of light in the epilayer, these currents can be used to extract information on the spectral distribution of the impinging light [7].

Manuscript received June 3, 1996.

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Publisher Item Identifier S 0018-9456(97)06498-X.

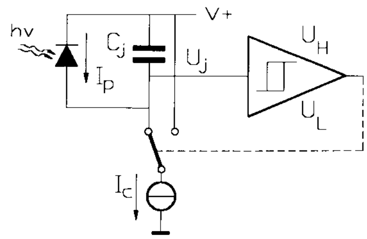

Fig. 1. Integrating mode oscillator.

II. INTEGRATING MODE OPERATION

One of the photodiodes in this novel sensor system is used in the integrating mode [5], [6]. Fig. 1 shows the basic circuit of the diode as the timing element in an astable oscillator configuration. The current source I_c charges the junction capacitance of the reverse-biased photodiode. The voltage U_j across the diode can be derived from

$$\frac{dQ}{dt} = C_j \frac{dU_j}{dt} + U_j \frac{dC_j}{dt} = -I_c + I_{ph}. \qquad (1)$$

The depletion capacitance C_j of the diode depends on the voltage across the junction by the following relation: $C_j = kA_jU_j^m$, where A_j is the diode area, k is a constant and m is a constant depending on the doping gradients of the P and N side of the junction ($m = -1/2$ for an abrupt junction). Substitution in (1) yields

$$-I_c + I_{ph} = kA_jU_j^m \frac{dU_j}{dt} + U_jkmA_jU_j^{(m-1)} \frac{dU_j}{dt}$$
$$\Rightarrow -I_c + I_{ph} = kA_jU_j^m(1+m)\frac{dU}{dt}.$$

If U_H and U_L are the high and low threshold voltage of the comparator, the charge time t can be derived from

$$\Delta Q = \int_{t=0}^{t=t_c} (I_c - I_{ph})\,dt = (I_c - I_{ph})t_c$$
$$= kA_j(1+m)\int_{U_j=U_H}^{U_j=U_L} U_j^m\,dU_j$$
$$\Rightarrow t_c = \frac{kA_j}{(I_c - I_{ph})}(U_H^{m+1} - U_L^{m+1}). \qquad (2)$$

After reaching U_L the comparator will switch and connect I_c to ground and the photocurrent I_{ph} will discharge the

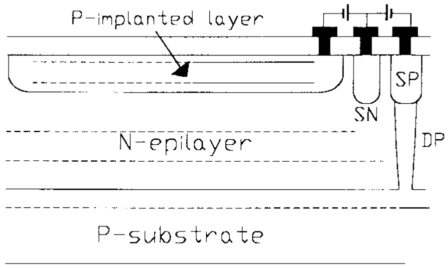

Fig. 2. Sensor structure.

junction capacitance again to the high threshold voltage U_H. The discharge time t_d can be found by substitution of $(I_c - I_{ph})$ by

$$I_{ph} = \frac{PA_j \lambda \eta_e}{\hbar c} \tag{3}$$

with

- P optical power [W];
- A_j junction area;
- λ wavelength;
- η_e external quantum efficiency;
- $\hbar$ Planck's constant;
- c speed of light.

in (2) giving

$$t_d = \frac{k\hbar c}{\lambda \eta_e P}(U_H^{m+1} - U_L^{m+1}). \tag{4}$$

Therefore, the discharge time t_d is inversely proportional to the light intensity P. Also note that the discharge time t_d does not depend on the diode area A_j, and the voltage across the junction is nonlinear. However, since the threshold voltages U_H and U_L are constant this does not influence the linearity in the current-to-frequency conversion. A disadvantage of this circuit is that the fixed current I_c must always be larger than the photocurrent I_{ph} to be able to charge C_j again. This results in a large difference between the charge- and discharge times at a low photocurrent, meaning a very low duty-cycle of the output pulses at low illumination levels. The circuit and sensor combination described in the next paragraph avoids this problem.

III. Light-Sensor Structure

The structure of the sensor is shown in Fig. 2. It is a vertical PNP device consisting of a P-implanted layer, the epilayer and the substrate. The epilayer is 4-μm thick and the P-implantation forms a neutral layer at about 2 μm depth in the epilayer. A more detailed description of the operation of this type of color sensor is given in [7]. Fig. 3 shows measured the spectral responses of the reverse biased upper (a) and lower (b) photodiode.

Fig. 4 shows the basic readout circuit. The shallow PN diode is used in the charge integrating mode. The sum of both photocurrents $I_e = I_{ph} + I_s$ is mirrored twice and fed to the current switch, replacing the fixed charge current I_c of Fig. 1. Substitution of $I_e = I_s + I_{ph}$ in (2) results in a discharge time t_d inversely proportional to the photocurrent generated in

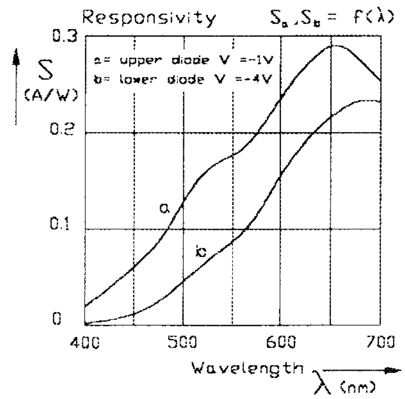

Fig. 3. Sensor responsivity.

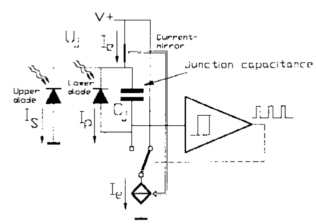

Fig. 4. Block diagram of the readout circuits.

D_2, while the charge time t_c is inversely proportional to the photocurrent in the shallow junction D_1. From Fig. 3 can be seen that the responsivity for short wavelengths of the shallow PN junction is much higher than that of the epilayer-substrate junction. Since both the charge- and the discharge current are proportional to the incident light, the duty-cycle of the output pulses remains constant at a varying luminous intensity. Due to the wavelength-dependent absorption of light in silicon the ratio of these currents will change with the wavelength [8]. This results in a varying duty-cycle as a function of the average wavelength (color) of the light on the sensor.

IV. Electronic Circuit

The circuit is shown in Fig. 5. The junction FET input pair $(Q_1 - Q_2)$ of the comparator features a very-low-input current and a good noise performance. The positive feedback loop to the gate of Q_2 introduces the required hysteresis for astable oscillator operation. The fixed current sources I_1 and I_2 are used to bias the JFET's. The comparator threshold voltages are given by: $U_L = R_1(I_1 + I_2)$ and $U_H = R_1 I_1$. A level-shift stage formed by transistors Q_7 and Q_8 drive the output switches Q_5 and Q_6. The NPN current mirror $(Q_{11} - Q_{12})$ and the output switches $(Q_5 - Q_6)$ do not operate well at a collector current (= the total photocurrent I_c) lower than 1 nA. Therefore, the fixed current I_f is added. Fig. 6 shows the L-shaped photodiode with the electronic circuits in the lower left corner made in a BIFET process.

V. Measurement Results

Fig. 7 shows the measurement results on the output frequency of the converter using 2×2 mm^2 photodiode as a function of the light intensity. The lower and upper limit of

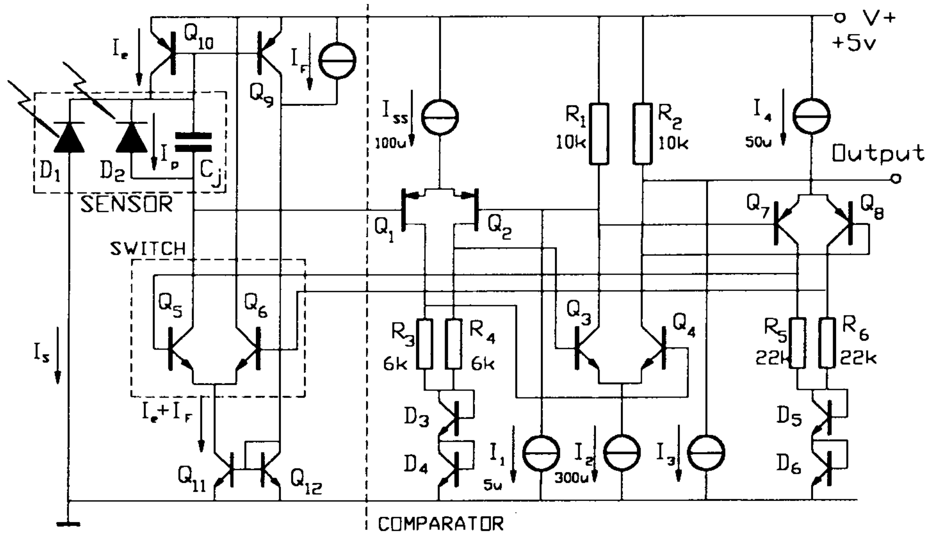

Fig. 5. Electronic circuits.

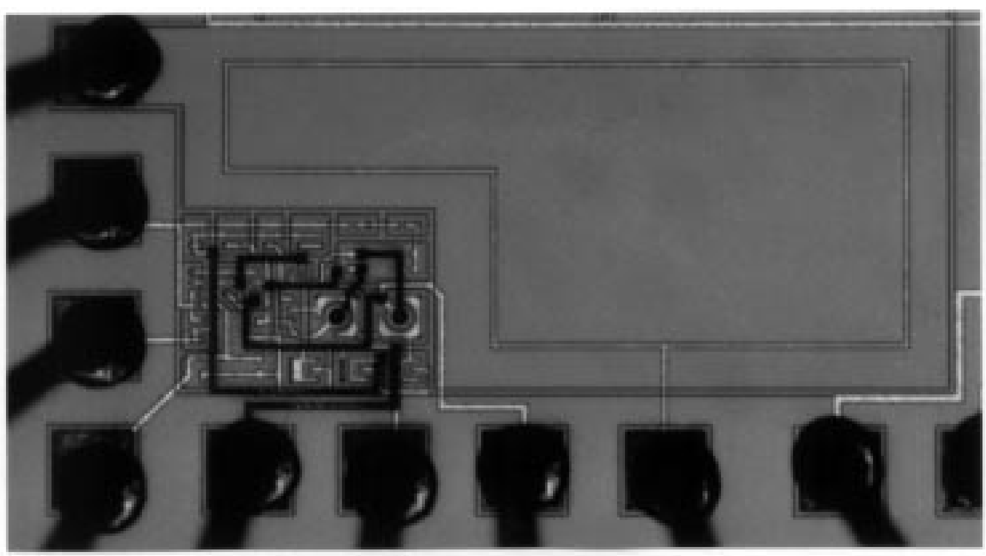

Fig. 6. Photo of the sensor with electronic circuits.

the output frequency have been measured to be 0.1 Hz and 120 kHz respectively. Frequency scaling is possible by adding external capacitors.

The dynamic range mainly depends on the photodetector characteristics. The large series resistance of the epilayer, limits the charge- and discharge-time of the junction capacitance (≈500 pF at 3V) resulting in an upper frequency limit. Devices with a lower series resistance would allow operation limited merely by the speed of the comparator. The lower limit of the output frequency is determined by the leakage current of the PN junction (≈65 pA). Fig. 8 shows that the duty cycle of the output signal has an unambiguous spectral response from 450 nm to 700 nm. Since the spectral response of both photodiodes is wavelength dependent, the output frequency, which is proportional to the sum of both photocurrents, will also depend on the wavelength of the incident light. This is a basic property of silicon photodiodes and is also present in other commercially available light-to-frequency converters

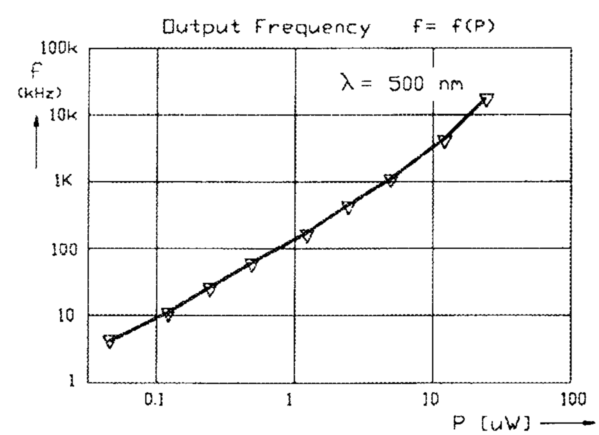

Fig. 7. Output frequency = f(P).

based on these devices. Fig. 8 shows the measured response of the output frequency as a function of wavelength. A flat

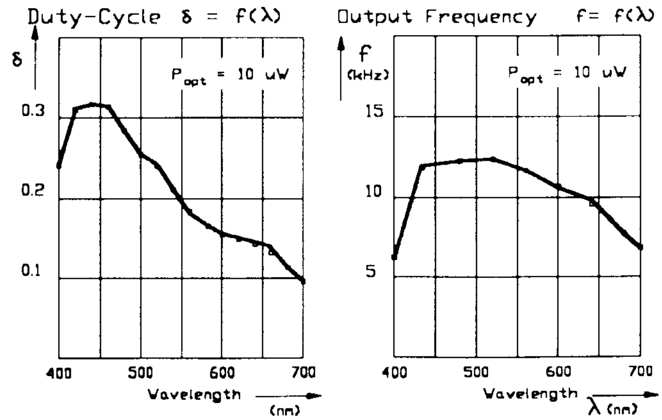

Fig. 8. Duty cycle and output frequency = f(λ).

response can be obtained in a limited spectral range when using different active areas for the upper and the lower junction or by changing the average reverse voltages across the junctions. The reverse voltage across the junction changes the width of the depletion layer resulting in a different spectral response curve for the diode.

VI. Conclusions

A fully integrated silicon light-to-frequency converter has been realized in a BIFET process without an external capacitor. Batch production is possible since no external components are needed and color can be measured without the use of optical filters or extra mask steps. The system covers a measurement range of about five decades of intensity. Temperature compensation may be a next step in the development of the system and bias circuits also have to be added. As many applications in the future require "plug-and-play" sensor systems, an interface for a bus system will be integrated on the same chip.

Acknowledgment

The authors would like to thank the IC processing section of the Delft Institute for Micro-Electronics and Submicrontechnology (DIMES) for fabrication of the devices.

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