A Buried Triple-Junction Self-Reset Pixel in a 0.35µm High Voltage CMOS Process

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ABSTRACT – Light to frequency converters are used to sense the photocurrents of a buried triple-junction pixel achieving high dynamic range and low dark current colour sensing without the use of colour filters. The pixel is realised in a high voltage 0.35µm CMOS enabling sample manipulation by electrowetting and spectral sensing for a FRET biosensor.

I. INTRODUCTION

Colour sensing without the need for surface optical filters has been achieved by using buried p-n junction structures in various CMOS processes [1-3]. In addition to reducing process costs, this increases overall photon collection efficiency and eliminates the colour aliasing introduced by conventional Bayer pattern sub-sampling [4-5]. BiCMOS processes provide several p-n junctions at different depths which can be employed to realise stacked triple-junction photodiodes [6]. In this paper, we present the use of a 0.35µm high voltage CMOS process for the realisation of such buried triple-junction (BTJ) photodiode structures (Fig. 1). High voltage handling and optical filterless colour sensing are required for electrowetting and spectral sensing for FRET-based biosensors [7-8]. The pixel itself employs light-to-frequency (L2F) techniques, and is presented in section II.

II. CIRCUIT OPERATION

BTJ sensors generally employ integrating mode photodiodes (Fig. 2) whereby the three junctions are reset to various potentials to keep the photodiodes reverse-biased. The diodes then integrate at different rates dependent on the spectral content of the light and their respective responsivities. Because the junctions are coupled, they will become forward biased if the signal in one spectral band is particularly high relative to the others, resulting in crosstalk between colour channels. Moreover, the stack of voltage levels uses up voltage headroom and requires careful management.

Self-resetting L2F converters are a popular means of realising very high dynamic range image sensors [9-11]. In the sensor proposed here, L2F converters are employed to sense the currents through each of the reverse-biased p-n junctions of the BTJ structure (Fig. 3). The virtual ground of the amplifiers allows the junction potentials to be held constant at arbitrary levels during operation. In this case, the charge amplifier bias voltage, V_{CM}, is chosen to be 1.6V; approximately half of the 3.3V supply. Thus, the blue and green junctions have zero potential across them, resulting in minimal dark current [12]. A 1V swing was chosen for the integrators, resulting in V_{CP}=2.6V (Fig. 4). The charge amplifier of the middle junction integrates in the opposite sense, and so the comparator has been inverted, and its voltage threshold set to V_{CN}=0.6V. The output frequencies of the top and bottom charge amplifiers are given by (1) and (3), while that at the output of the middle charge amplifier is given by (2), shown below:

$$f_b = \frac{I_{blue}}{2C_f(V_{CP} - V_{CM})} \tag{1}$$

$$f_{bg} = \frac{I_{blue} + I_{green}}{2C_f(V_{CM} - V_{CN})} \tag{2}$$

$$f_{gr} = \frac{I_{green} + I_{red}}{2C_f(V_{CP} - V_{CM})} \tag{3}$$

Note that the L2F output frequencies represent the I_{blue}, I_{blue}+I_{green}, and I_{green}+I_{red}, respectively because of the summations of currents into the amplifier virtual earths. The frequencies are directly proportional to the photocurrents. 100fF poly-poly capacitors have been chosen as integrating capacitors setting the sensitivity of the sensor. The high linearity of these capacitors assures a linear relationship between photocurrent and frequency.

The denominator terms in (1), (2) and (3) are designed to be identical by choosing matched integrating capacitance and $(V_{CP}-V_{CM})=(V_{CM}-V_{CN})$. This allows the contributions of the individual I_{blue}, I_{green} and I_{red} photocurrents to be dissociated by simple subtraction of the frequencies. A convenient hardware implementation is possible using up-down counters clocked by the output transitions of the blue/green or red/green L2F outputs.

An extremely high dynamic range is obtained (>150dB). Saturation does not occur regardless of the spectral content of the illumination leading to good colour detection over a very high dynamic range.

In Fig. 5, an L2F structure is proposed with improved full scale-range. A switched-capacitor feedback structure allows independent choice of the photodiode voltage level and the comparator threshold voltage. The full range of the power supply can thus be used (between V_{CN} and V_{CP}), maximising SNR and full-well capacity.

IV. MEASURED RESULTS

The chip micrograph is shown in Fig. 6. The die has had the polyimide passivation removed by oxygen plasma, providing around 3-5x increase in quantum efficiency in the 500nm range. Four different BTJ structures were implemented using the various junction depths available. Fig. 7 shows a typical set of outputs of the L2F converters. The spectral response curves of photocurrents corresponding to the n-diffusion, p-well, deep n-well BTJ structures are shown in Fig. 8. The sensor performance is summarized in Table. 1. Dark current of the blue and green diodes with 0V reverse bias is not measurable while the dark current of the red photodiode with 1.6V bias is $2nA/cm^2$. A dynamic range of >150dB with frequencies ranging from 1mHz to 5MHz is obtained.

V. CONCLUSION

Self-reset loop structures can be applied to buried triple junction photodiodes to provide high-dynamic range, filterless colour sensing. Low dark current with simple digital colour outputs are beneficial for biosensor applications.

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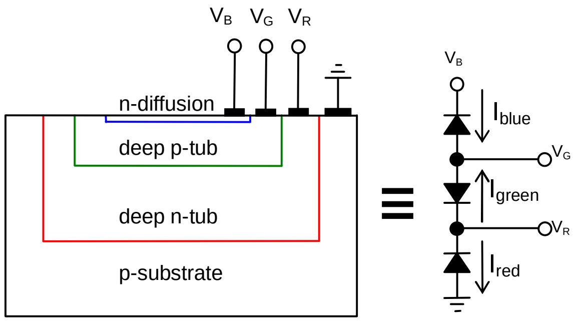

Fig. 1 Diagram of buried triple structure showing junctions and diodes

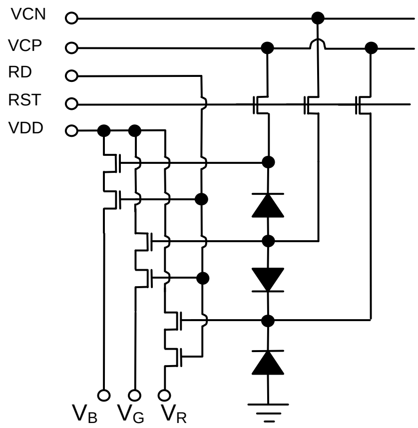

Fig. 2 BTJ source-follower readout

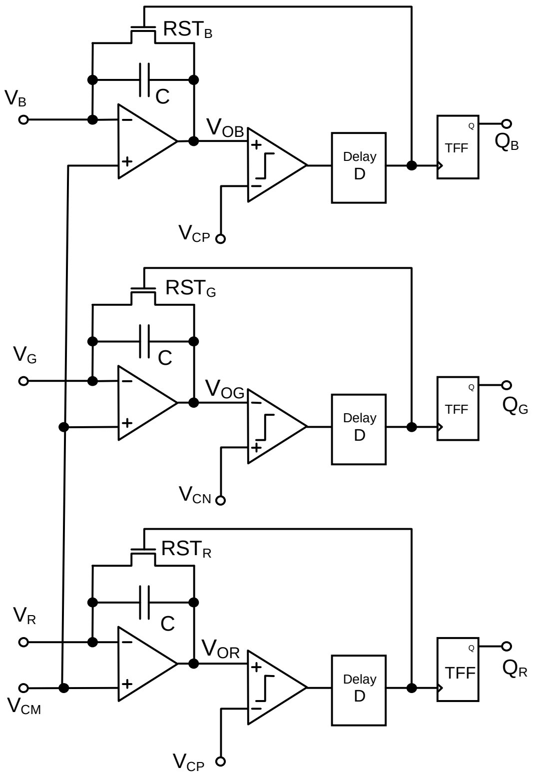

Fig. 3 BTJ readout using three L2F converters

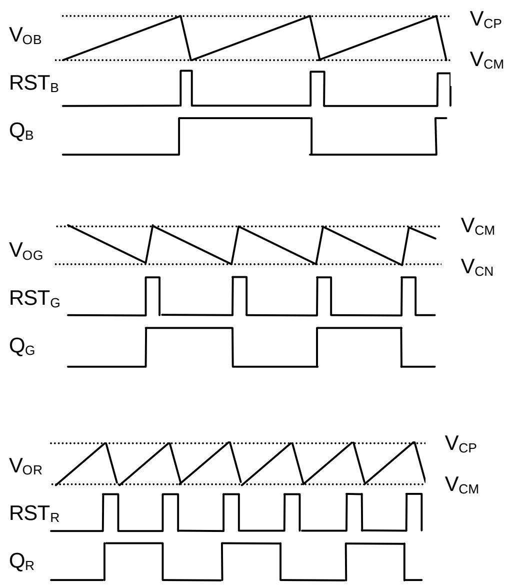

Fig. 4 Timing diagram showing the operation of the L2F readout

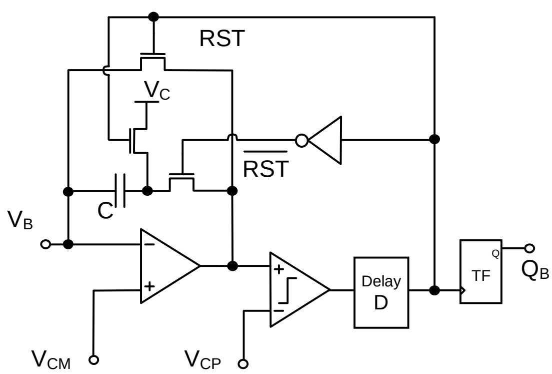

Fig. 5 L2F converter with optimised output swing

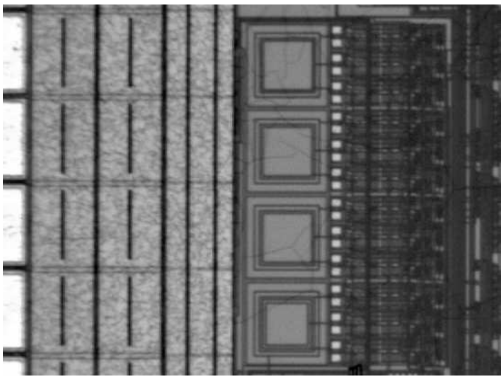

Fig. 6 Chip micrograph showing four 80µm x 80µm BTJ diode structures with L2F readouts

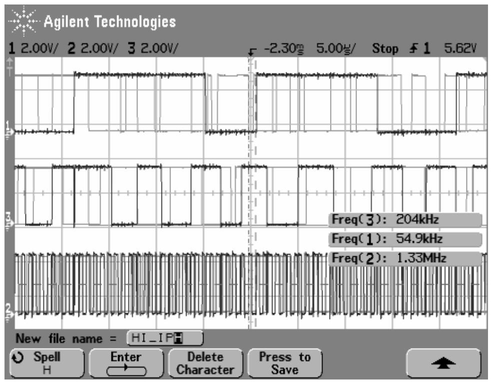

Fig. 7 Oscilloscope trace showing the three L2F outputs

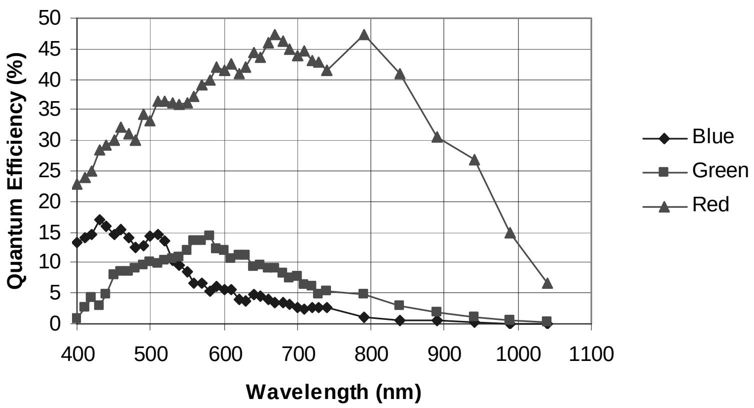

Fig. 8 Quantum efficiency versus wavelength for the three junctions

Parameter	Value	units
Process	0.35µm 50V 4LM 2P	CMOS
Dynamic Range	>150	dB
Dark current (red)	2	nA/cm^2
Dark current (blue, green)	Not observable	nA/cm^2
Capacitance	100 (poly-poly)	fF
Area	0.016	mm^2
Current consumption	500	µA
Supply voltage	3.3	V
Full well	625k	e$^-$
Maximum frequency	5	MHz

Table 1 BTJ Sensor Performance Summary