An Artificial Iris ASIC with High Voltage Liquid Crystal Driver, 10nA Light Range Detector and 40nA Blink Detector for LCD flicker removal

Bogdan C. Raducanu, Samira Zaliasl, Stefano Stanzione, Chris van Liempd, Andrés Vásquez Quintero, Herbert De Smet, Johan De Baets, Chris van Hoof, Nick Van Helleputte

Abstract— In a normally functioning eye, the iris controls the pupil diameter to regulate the amount of light reaching the retina. Various iris deficiencies exist, manifesting as defects in the iris or an absence of one which result in too much light reaching the retina. Some iris deficiencies such as aniridia or leiomyoma can be mitigated with fixed or adaptive artificial irises [1]. As an alternative, adaptive transparency glasses may also alleviate this situation, however both solutions do not mimic the other normal functionality of the natural iris: adaptive aperture. To address this, we developed a fully encapsulated, self-contained artificial iris embedded in a smart contact lens. The control ASIC of the contact lens is developed in 0.18 μm 16 V BCD TSMC and has a typical power consumption of 1.9 μW from a 3 V supply voltage at office light condition.

Index Terms— contact lens, artificial, iris, light range detector, blink detector, ultralow power.

I. INTRODUCTION

The human eye can function over a wide range of illuminance levels, reaching from bright sunlight all the way down to night vision. Two mechanisms exist to facilitate vision across a high dynamic range: the pupillary light reflex and retina adaptation. Retina adaptation [1] is the ability of the retina to adjust to lower or higher levels of light covering a broad range, however this is a slow process which is often times insufficient. The other mechanism of the eye is to control the amount of light that reaches the retina through the pupil by adjusting the diameter [2]. The iris contains muscles used to change the pupil diameter and different deficiencies can render this adjustment mechanism inefficient or completely absent (aniridia).

Various methods exist to replicate some of the functionality of the damaged iris, such as artificial iris implants, contact lenses or glasses with adaptive transparency. These methods provide a way to limit the amount of light reaching the retina, either in a fixed or adaptive way.

Additionally, another role of the iris and pupil is that they function as an aperture, which also impacts the depth of field perceived [3] which can influence the quality of the perceived image. The depth of field is the corresponding distance range within which objects appear in focus and it is influenced by the diameter of the aperture: the smaller the diameter, the larger the depth of field [4]. For this reason, a larger depth of field can improve eyesight in certain conditions.

A drawback of existing solutions for iris problems is that they cannot provide a variable depth of field, just like the natural iris.

Manuscript received Aug. 15, 2020.

B. C. Raducanu, C. van Hoof and N. Van Helleputte are with imec, Leuven, Belgium (e-mail: raducanu@imec.be).

S. Zaliasl, S. Stanzione and C. van Liempd are with imec/Holst Centre, Eindhoven, the Netherlands.

A. Vásquez Quintero, H. De Smet and J. De Baets are with CMST/Ghent University and imec, Ghent, Belgium.

C. van Hoof is with KU Leuven, Heverlee, Belgium.

Thus, we propose to replicate the functionality of the iris by providing a variable aperture implemented with a multi ring liquid crystal display (LCD). The artificial iris LCD is embedded within an artificial contact lens that contains the additional elements to make it functional: a power source, control circuits and sensors, a charging method and electrical interconnects as shown in Fig. 1. The electronics are interconnected using thin film and embedded in a thermoplastic carrier which will be thermoformed to achieve the required curvature to fit the eye shape [5].

Fig. 1 Smart contact lens and internal components in flat format before thermoforming on top of an NFC charging coil; Smart contact lens ASIC block diagram along with the external NFC and PMIC.

II. PROPOSED SOLUTION

The artificial iris contact lens and its block diagram comprising of an embedded guest-host LCD [6], [7], a control ASIC and embedded near field communication (NFC) powering are shown in Fig. 1.

The variable iris aperture is implemented using 4 concentric rings on the LCD [8] which turn opaque depending on ambient light levels measured by the control ASIC with integrated photodiodes (PD). Alternatively, the center LCD ring may be designed as a disc. Considering the volume available for a battery as power source, a μWh level consumption is required to run the lens for a full day. The embedded battery (3-3.6V) is charged overnight by a power management IC (PMIC) using power received by an NFC IC, while the user sleeps.

The primary function of the ASIC is to generate the appropriate LCD control signals based on ambient light levels using the core blocks: an ambient light range detector (LRD), an eye blink detector (BD) and an LCD driver which are supported by additional functions (oscillators, registers, logic and bias circuits).

III. AMBIENT LIGHT RANGE DETECTOR

To properly control the LCD, the ambient light readout does not need to be continuous over a broad range but rather be able to distinguish the light level ranges corresponding to the closure (i.e. darkening) of the LCD elements. Considering that a large number of factors influence the pupil diameter of a specific user [2] it is

desirable to cater for individual user needs by providing adjustability of the artificial iris behaviour.

Fig. 2 The light range detector block diagram. I_{PD} is successively compared with 4 level I_{DAC} using a clocked comparator. The digital MAX detector rejects the light flickering and blink events by providing a maximum out of 12 consecutive samples.

An ultra-low-power ambient LRD quantizes the incoming light into 5 consecutive light ranges (corresponding to 0-to-4 opaque rings) to control the 4-ring iris. On-chip integrated PDs are used to measure the light level, therefore the naked die is directly embedded into the lens. Typically, a transimpedance-based readout is too power-hungry in high light-level conditions (>100 klux) and alternatively measuring the PD open voltage has a high PVT spread and very low signal levels under low-light conditions (1 lux). Therefore, to achieve a low-power solution covering the wide dynamic range of light intensity, the LRD in Fig. 2 is proposed.

To determine which LCD rings should be opaque, the photodiode current is compared to a current corresponding to photodiode current at the desired brightness. Thus, for each of the 4 rings, the photodiode current I_{PD} is successively compared to four increasing and programmable I_{DAC} currents, starting at the lowest level (400 pA for ~ 6.4 lux) and continuing through the 4 levels until the comparator indicates $I_{PD} > I_{DAC}$ ($V_{OUT} < 0$). A simple clocked comparator with 0 V reference can be used, since the input will saturate to either $-V_{OP}$ (photodiode current I_{PD} is larger) or to V_{DD} (I_{DAC} current is larger). For the low current level, a 4.8 kHz clock generates the timing accounting for the large PD capacitance ($C_{PD} \sim 19$ pF) and an 80 kHz clock is used only for a more precise timing at the top 3 high current ranges. This wide range LRD consumes an average of ~ 10 nA under office light levels with 43 ms conversion time. To account for user and ASIC variability, a 4-bit Trim setting is available for each of the I_{DAC} currents.

The artificial light flicker (50/60 Hz) [9], [10] and eye blinks (nominal duration <200 ms) result in a variable light level at the LRD. To remove these variations, the 24 s/sec output of the readout is down sampled to 2s/sec by a MAX Detector circuit which selects

the maximum out of each group of 12 samples (Fig. 2 bottom).

Although this is not expected, if a particular user requires a light threshold that is larger than the maximum range of the I_{DAC} (~ 4.1 klux) a smaller photodiode is used which expands the dynamic range of the circuit up to 190 klux using control bit *High_range* which disconnects the large PD (Fig. 2).

IV. LCD DRIVER

Based on the LRD output *Light_level<3:0>*, the LCD driver turns on the right LCD rings. These LCD elements require >10 V_{pp} bias voltage to achieve sufficient light blocking. As shown in [11], the LCD needs AC drive signal to have reasonable lifespan, as a DC component will electrochemically damage the cell. Given the power budget and the large LCD capacitance of 33pF/ring on average, such AC driving is not possible. Therefore, to save power low frequency AC (<0.1 Hz) can be used which avoids the drastically short life of DC driving [11].

Fig. 3 LCD driver consisting of 8 charge pumps using high voltage components to boost the voltage and iris LCD showing the first segment opaque along with associated drive waveforms, indicating the polarity reversal due to eye blinks or timeout.

Four independently controlled charge pumps (V_{CP}) are used to drive each of the rings, with the LCD itself acting as the storage capacitor as shown in Fig. 3. The positive half is achieved with a grounded common electrode and a V_{CP} applied to the required segments, while during the negative half V_{CP} is applied to the common electrode using 4 parallel charge pumps while the opaque segments are grounded. During the transition between the two halves of the AC drive, the LCD element is first discharged and then charged to the opposite polarity, which reduces the overall transition time.

V. BLINK DETECTOR

As the LCD transitions between the two polarities, it becomes transparent for a short time (i.e. when the applied voltage crosses zero) which can result in perceived flicker. To make the flicker unperceivable, the LCD polarity switching is aligned with eye blinks. The time variation of the light level behind the eyelid expected to reach the eye during a blink event is shown in Fig. 4. The expected level drops sharply during the eyelid closing (typ. 75 ms) and raises slower during the eyelid opening [12] at around 150ms. Considering the latency of the circuits and the duration of the LCD polarity swapping, the blink detector will detect the falling edge (eyelid

closing).

Fig. 4 Blink detector block and timing diagram. The log amplifier in the feedback outputs a voltage proportional to the relative variation of light level, which is high pass filtered to detect a blink event.

Since the eyelid blocks ~95% of the incoming light [13] and the ambient light levels vary across multiple orders of magnitude, an eye blink detector circuit cannot rely on a fixed threshold to detect a closed eye. Therefore, the blink detector in Fig. 4 detects a sudden light level drop as opposed to a single absolute I_{PD} threshold. Hence I_{PD} is fed into a logarithmic current-to-voltage converter created by the diode-feedback amplifier which generates an output voltage proportional to the relative variation. Only fast signals filtered by the high-pass filter reach the comparator and are detected. To achieve sufficient speed despite the high photodiode parasitic capacitance C_{PD} , the PD is biased with a constant voltage bias. The LRD is used to determine when the light level is low, and a larger photodiode is used to provide more sensitivity. In brighter scenes, only a smaller PD is used to save power. Under typical indoor lighting, the eye blink detection circuit consumes 40 nA.

A timer inside the Blink detector control block monitors the blink detection. In case a blink is not detected for 14 seconds, a fail-safe triggers the generation of an extra pulse on the Blink flag, forcing an LCD polarity reversal.

VI. FABRICATION AND MEASUREMENT RESULTS

The electronics platform is composed of two main parts: the thin-film based circuitry and the guest-host liquid crystal (GH-LCD) cell. The circuitry was realized by encapsulating thin layers of gold inside spin-coated polyimide (PI) following photolithography and chemical etching steps described in [5]. The 5 μH , 10 μm thick RF antenna was designed in a multi-loop configuration compatible with the contact lens format and input impedance of the NFC IC. The antenna was plated from a seed layer of gold (100 nm) until the desired final thickness, as visible in Fig. 5. The ASIC and NFC IC were integrated to the main circuitry by a modified flip-chip technique and bonded by thermo-compression. Fig. 5 shows the top view of the integrated smart platform including the ASIC, NFC, RF antenna, stretchable interconnections and GH-LCD cell. The components are integrated while the platform is flat which is compatible with industrial standards. Thermoforming is performed after the lamination and laser ablation of top and bottom thermoplastic polyurethane (TPU) [5], which converts the 2D shape into a 3D spherical one, compatible with the curvature of a contact lens. The thermoforming of an active device is an ongoing step that would enable the embedding of the platform inside a conventional contact lens, as presented in [14].

Fig. 5 top right shows the laser ablated concentric rings and the location of the SU-8-based spacers used to keep a constant distance between the top and bottom electrodes, which ensures a homogeneous transmittance of the LC cell.

Fig. 5 Top view image of the integrated smart contact lens with an artificial iris including the ASIC, NFC, RF antenna, stretchable interconnections and GH-LCD. The hand-right side insert shows a close-up image of the GH-LCD with the distribution of the space. Bottom: SEM images of the Au-based RF antenna, view of the Au antenna at the pad and loops, respectively.

The darker spots around the border of the GH-LCD cell (orange dotted ovals) are provoked by particle impurities which alter the alignment layer of the LC, while the one close to the cross-over vias (light-blue dashed-dotted oval) is triggered by a difference in cell gap due to the extra ICA used for the electrical contact.

The ASIC was fabricated in a 0.18 μm 16 V BCD TSMC technology. The micrograph is shown in Fig. 6 together with the main blocks highlighted: the LCD driver charge pumps and the photodiodes take up most of the area.

Fig. 6 Die micrograph and test setup (right).

Testing the smart contact lens ASIC requires the ASIC to be exposed to a controllable light source which is used both to generate a precise light level at the integrated PDs and to generate a specific light level pattern to simulate different conditions such as an eye blink or artificial light flicker. The test setup uses a high power white LED controlled by a function generator and a high speed voltage to current converter as shown in Fig. 6.

The key performance measurements are shown in Fig. 7. The response of the emulated pupil diameter is compared to a natural one at typical thresholds. Given personal preference, each of the thresholds is tuneable (1.2 lux to 4.1 klux). The typical total power consumption at 3V supply starts at 184 nW in near dark, while at indoor light levels which uses 2 LCD segments it is 1.9 μW and increases to a maximum of 4.2 μW with all 4 LCD segments on.

Table 1 also shows a comparison with ASICs containing similar functions: an ambient light detector [15] and a contact lens LCD driver [8]. The BD was tested with a controllable light source and it reliably triggers when the illuminance drops at least 65% for 50 ms while the background level is varied over a 15 lux to 5 klux range. The LCD driver achieves typ. 13 Vpp drive with 3 ms rise time for 3 V supply voltage.

Fig. 7 key performance measurements at 3 V supply: blink detector test with controllable light source and LCD output voltage showing polarity reversal at blinks and timeout; measured power consumption of chip during ambient light level readout showing 80 kHz clock duty cycled usage; measured artificial pupil diameter and table with measured performance compared with artificial lens LCD driver and ambient light sensor.

Table 1 Parameters comparison

	[3]	[5]	This work
LCD segments	1	-	4
Supply range [V]	5 - 9	1	3 - 3.6
Active power with LCD off [W]	-	125 μ	184n
Active power 1/2/3/4 LCD segments on [μ W]	25	-	0.93/ 1.9/ 2.2/ 4.2
LCD drive typ. [Vpp]	10	-	13
LCD flicker removal	No	-	Yes
Ambient light range [lux]	-	100-25k	1.2-190k
Blink sensitivity, max [%]	-	-	-65
Active chip area [mm ²]	0.75	0.046	1.45
Technology node [μ m]	5 μ m TFT	0.13 CMOS	0.18 μ m BCD

VII. CONCLUSION

This work demonstrates a fully integrated artificial iris in a contact lens form factor, providing a variable aperture using a 4-ring LCD. With the artificial iris both the light level control and the depth of field control can be achieved, similar to a normally functional eye. The ASIC demonstrated in this work contains a nW power light range detector with on-chip photodiodes to automatically limit the amount of light entering the eye by appropriately darkening the respective LCD rings using charge pumps. A low frequency LCD driving method is used where the polarity switching is aligned with the blinks, ensuring a 1.9 μ W typical power consumption.

REFERENCES

- [1] R. Shapley and C. Enroth-Cugell, "Chapter 9 Visual adaptation and retinal gain controls," *Progress in Retinal Research*, 1984.
- [2] C. J. K. Ellis, "The pupillary light reflex in normal subjects," *Br. J. Ophthalmol.*, 1981.
- [3] P. Bernal-Molina, R. Montés-Micó, R. Legras, and N. López-Gil, "Depth-of-field of the accommodating eye," *Optom. Vis. Sci.*, vol. 91, no. 10, pp. 1208-1214, 2014.
- [4] W. N. Charman and H. Whitefoot, "Pupil diameter and the depth-of-field of the human eye as measured by laser speckle," *Opt. Acta (Lond.)*, 1977.
- [5] A. Vázquez Quintero, R. Verplancke, H. De Smet, and J. Vanfleteren, "Stretchable Electronic Platform for Soft and Smart Contact Lens Applications," *Adv. Mater. Technol.*, vol. 2, no. 8, 2017.
- [6] J. De Smet, A. Avci, R. Beernaert, D. Cuypers, and H. De Smet, "Design and wrinkling behavior of a contact lens with an integrated liquid crystal light modulator," *IEEE/OSA J. Disp. Technol.*, vol. 8, no. 5, pp. 299-305, 2012.
- [7] C. Vanhaverbeke, R. Verplancke, J. De Smet, D. Cuypers, and H. De Smet, "Microfabrication of a spherically curved liquid crystal display enabling the integration in a smart contact lens," *Displays*, vol. 49, pp. 16-25, 2017.
- [8] F. De Roose *et al.*, "An active artificial iris controlled by a 25- μ W flexible thin-film driver," in *Technical Digest - International Electron Devices Meeting, IEDM*, 2017, pp. 32.1.1-32.1.4.
- [9] R. Inger, J. Bennie, T. W. Davies, and K. J. Gaston, "Potential biological and ecological effects of flickering artificial light," *PLoS One*, 2014.
- [10] IEEE Power Electronics Society, *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers*, 2015.
- [11] J. Pirš, D. Ponikvar, B. Marin, and M. Chambers, "Low power consumption driving for liquid crystal light modulators," *Displays*, vol. 25, no. 4, 2004.
- [12] K. A. Kwon *et al.*, "High-speed camera characterization of voluntary eye blinking kinematics," *J. R. Soc. Interface*, 2013.
- [13] K. Ando and D. F. Kripke, "Light attenuation by the human eyelid," *Biol. Psychiatry*, 1996.
- [14] A. V. Quintero, P. Pérez-Merino, and H. De Smet, "Artificial iris performance for smart contact lens vision correction applications," *Sci. Rep.*, no. Accepted, 2020.
- [15] S. Sengupta, H. Ouh, and M. L. Johnston, "An all-digital CMOS ambient light sensor using a single photon avalanche diode," in *Proceedings of IEEE Sensors*, 2017, vol. 2017-Decem.