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RESPONSE PROPERTIES OF A FOVEATED SPACE-VARIANT CMOS IMAGE SENSOR

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ABSTRACT

A new foveated CMOS image sensor has been designed and fabricated. The photocell elements transform the light into current, and then, in a continuous way, into voltage without charge integration. This kind of sensing cell has been already employed in image sensors for normal cameras, but never in foveated sensors. The presented sensor tries to emulate the human eye pixel resulting in a sensor with a space variant distribution of pixels. Consequences of this distribution are the different size of the sensing elements in the pixel matrix, the non orthogonal shapes of the different elements that integrate the pixel, and, as a result, the different response of every cell in the sensor. A scaling mechanism is needed due to the different pixel size from circumference to circumference. A mechanism for current scaling is presented. This mechanism has been studied along with other effects, as the narrow channel effect on submicron MOS transistors, and the influence of the logarithmic response of these special kind of sensing cells. The chip has been fabricated using standard 0.7 μm CMOS technology.

1. INTRODUCTION

The spatial distribution of pixels in the human eye has very interesting properties for image processing. The main advantage of using a space variant structure for the pixel distribution in a sensor, is the selective reduction of image data. The concentration of pixels is high in the center (also called *fovea* like in the human eye) reducing the number of photocells toward the periphery (also called *retina*). This structure has good resolution for image processing in the interesting parts of the scene (usually in the center), while still keeping enough resolution in the periphery allowing a wide view field. The result is a reduction of the image data to be processed, making these kind of sensors specially interesting for image communications, real-time image systems, and also robotics navigation [1].

There are many possibilities for space-variant distributions, but probably the most interesting, from a mathematical point of view, is the log-polar transform, also called log-spiral mapping. This transformation is defined in equation (1) and graphically shown in figure 1, where the *retinal* plane corresponds to the image plane showing the pixel structure. The log polar transform converts the retinal pixel distribution in a squared matrix known as computational plane or also *cortical* since this is the distribution that the human cortex has of the eye image information. Some interesting mathematical properties include the conservation of the pixel aspect ratio among different circumferences, the transformation of object scalings in the retinal plane to horizontal translations in the cortical plane, and the transformation of rotations in vertical translations.

$$\begin{cases} \xi = \log r = \log\left(\sqrt{x^2+y^2}\right) \\ \gamma = \theta = \tan^{-1}\left(\frac{y}{x}\right) \end{cases} \quad (1)$$

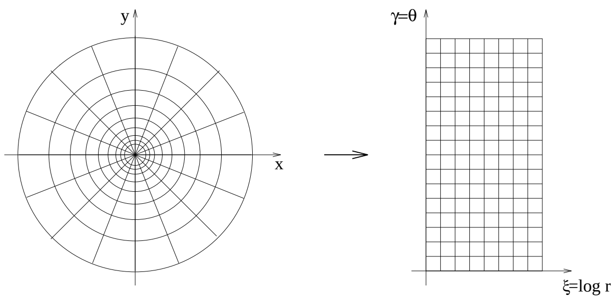

Figure 1. *The log-polar mapping*

The retina, periphery of the sensor, is the biggest part of the chip and it follows the log-polar mapping explained before. The fovea, central part, is always a problem in this kind of sensors, since it has to follow the same structure of the retina while still keeping image processing capabilities without design rule violations. For this retinal sensor, a different approach for the fovea was taken. Instead of just putting a squared matrix in the middle of the sensor, as any other existing foveated sensor did, we preferred to follow the structure of the retina, keeping the circular distribution of pixels, while linearly reducing the radius of the circumferences, instead of the exponential reduction that is not possible to be implemented due to the design rule limits. The result is a fovea with decreasing number of pixels per circumference, ending in a single cell in the middle of the sensor.

The resolution of the retina is 56x128, (56 circumferences with 128 pixels each), being the foveated sensor with more resolution designed to date [2]. The fovea consist of 20 rings more with decreasing number of pixels; there is one ring with one pixel (the central pixel), one with 4 pixels, another one with 8 pixels, two with 16 pixels, five with 32, and ten with 64 pixels. The sensor has been designed at IMEC, Belgium, and the microphotograph of the layout is shown in figure 2.

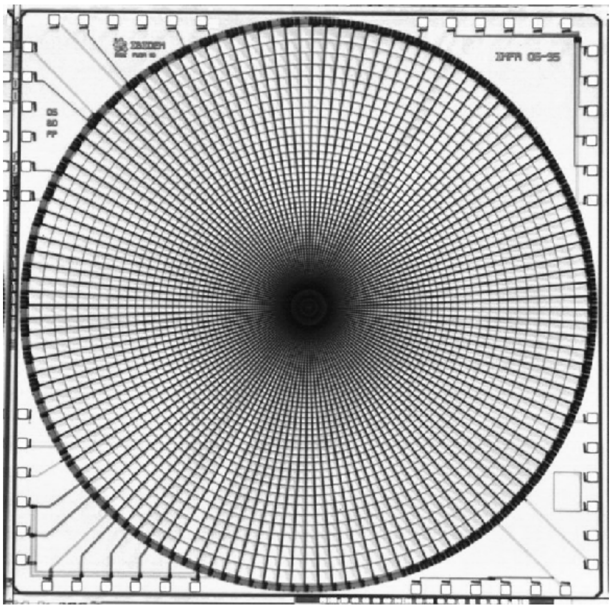

Figure 2. *Microphotograph of the sensor layout*

2. THE BASIC SENSING CELL

There are many possibilities for light capture using CMOS technology. The most extended is to integrate the incident light in a photodiode that is charged during an integration time. This is the way in which light is captured in CCD cameras. Quality is best than other methods, but this is always supposing a squared pixel matrix where every pixel has the same size and shape. In other pixel distributions and shapes, this method has not been so successful. The main problem is the charge scaling depending on the pixel size. There exists one retinal CCD sensor [3], the only designed using this technology, where a post normalization of the image was necessary since the normalization circuit, inside the chip, did not scale properly. There exist another retinal sensor, designed at the McGill University, Canada, in CMOS technology using integration cells [4]. The scaling in that chip is made outside of the sensor, though in that case the problem was not so big since the number of rings (16) was not very high.

2.1. Basic sensing cell response

For the reasons presented before, and others [5], a different aproach was taken for the design of the foveated sensor presented in this paper. The figure 3 shows the basic sensing cell. Incident photons in the photodiode, are converted in electron-hole pairs producing a current proportional to the incident light intensity and the photodiode area [6]. This current is very small (from pico to nano amperes) polarizing the M1 transistor in its weak inversion region. In this region of operation, the voltage between gate and source V_{gs}, follows a logarithmic dependency with drain current. The second transistor M2 is just a source follower. The third transistor M3 is a switch to individually select the cell. Outside of the photocell matrix there are current mirror circuits to properly polarize the source follower M2.

Supposing big size transistors, the expression for the gate to source voltage as function of the drain current can be

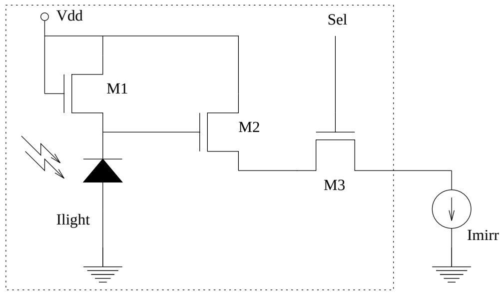

Figure 3. *Basic sensing cell of the foveated sensor*

simplified to the following equation:

$$V_{gs} = \frac{kT}{q} ln \left(\frac{L}{W} \frac{I_d}{I_{do}} \right) \quad (2)$$

where V_{gs} is the gate-source voltage, I_d is the drain current, W and L are the width and length of the channel, T is the temperature, and k, q and I_{do} are constants. From this expression it is simple to see the constancy of the slope of V_{gs} against $ln(I_d)$, since the term $\frac{kT}{q}$ is independent of the technology, shape, position, etc. This term only depends on the temperature, but T is suppose to be constant for the whole chip.

All other parameters of expression (2) are included in the logarithm as product terms. It has a straight forward meaning: any change of any parameter as the length, substrate doping, etc., produces a change in the offset of the curve that defines the dependency between light intensity and output voltage. This is specially interesting since it is easier to perform offset corrections than slope corrections that usually also implies an offset correction. These interesting characteristics are always true if transistors are big enough to discard second order effects, that for small size transistor are specially important.

2.2. Scaling the response of the cell

The foveated sensor, presented here, has 56 rings in the retinal part following a exponential growing of the radius. This exponential growing of the radius means a exponential growing also for the pixel area. The growing factor depends on the shape of the cell, etc. Supposing a squared shape for the pixel, and 56 rings, the outer cells are about 250 times bigger than the inner cells. This number is really a big difference, meaning that the response of the outer cells should be attenuated by a factor 250 to obtain the same response than the inner cells. Nevertheless the problem is even worst. This factor has been calculated supposing that the photodiode occupies all the area of the pixel, and this is not true. For the outer cells the photodiode covers most of the pixel (around 95%), but for the inner cells, the photodiode is a small part (around 20%) since the source follower and the selection transistor and other elements cover most of the pixel. Therefore, the photodiode size (and not pixel size) of the outer cells is around 900 times bigger than the inner cell size. Supposing integration cells, as CCD or some CMOS, thus with linear response with light intensity, a mechanism for charge scaling is vital. This mechanism should handle differences of 900 from cell to cell. It is easy to realize that it is not simple at all, specially since the scaling is referred to the slope of the response.

With the cell used in the foveated sensor presented here, the problem is not so big. Since the output is proportional to the logarithm of the incident light and photodiode size, the growing area has less effect in the output since it is included inside of the logarithmic term. In the other hand, the growing factor becomes an additive term instead of a multiplicative term, so the difference from one cell to another is an offset while the slope of the curve remains constant. In the example above, there was a proportional factor of 900 between inner and outer cells; this proportion, after the logarithmic expression, is converted to an offset of only 6.8, that is less traumatic than the 900 multiplication factor.

Though the logarithmic response of the cell minimizes the scaling effects, it is still interesting to provide a mechanism for automatically scale the different response among rings. To see the contribution of different sizes in the output equation (2), it is possible to re-write the current I_d as $I_{dl}a^2$ where I_{dl} is the drain current of the smallest pixel, and a^2 is the area in smallest pixel size units, supposing a square shape for the photodiode with side length a. The contribution of the factor a is therefore:

$$V_{gs} = \frac{kT}{q} ln\left(\frac{L}{W}\frac{I_{dl}}{I_{do}}\right) + 2\frac{kT}{q} ln(a) \qquad (3)$$

The slope of this curve is about 60 mV/dec. Linearity inside the weak inversion region of the transistor remains for about 4 light intensity decades. It means a total band from black to white of around 240 mV. Offset differences due to area growing is the factor $2\frac{kT}{q}ln(a)$. Taking $a^2 = 900$ the offset difference is about 170 mV that is around the same order as the response, so it is simple to scale it outside the chip.

Nevertheless, though the offset problem is not so big due to the logarithmic response, it is still interesting to minimize this effect. The expression (2) gives a straight forward way of scaling the growing size, it is as simple as changing the factor $\frac{L}{W}$ in the same way as the pixels grows. It is not possible to scale the length L since it can not be reduced beyond the design rule limits, so it has been constant for every pixel. The only parameter that is possible to change is the width W. A complete offset compensation is obtained scaling the width with the same factor as the area, nevertheless, it has not been possible to do so since the area scales quadratically. The only possibility was to linearly increase the width with the factor a. So we can substitute W for Wa in equation (3) giving the expression:

$$V_{gs} = \frac{kT}{q} ln\left(\frac{L}{W}\frac{I_l}{I_{do}}\right) + \frac{kT}{q} ln(a) \qquad (4)$$

where the offset due to the growing pixels is now half. For the present design, no other compensation mechanisms were adopted. The reason is that it is simple to correct this offset outside the chip, and this correction has to be performed anyway since there are other sources of offset non uniformity that cannot be corrected inside the chip.

2.3. Random offset non uniformity

Mismatching propertiers of MOS transistors are always a problem in any analog design using this technology. It is specially an important design issue in image sensors since every sensing cell should yield the same response. The presented cell for light sensing has been already employed in other CMOS sensors with typical squared orthogonal matrix of cells [7]. In those devices, mismatching of MOS transistors produced an offset non uniformity, or Fixed Pattern Noise (FPN), at the output of every cell. The mismatching properties of transistors in those previous sensors have not been deeply studied, but they have been studied in the new retinal sensor with some interesting conclusions for further image sensors designs using this kind of cell.

There are several sources for the transistor mismatching. Some technological parameters, as doping concentration, oxide thickness, etc. are different depending on the wafer region where the transistor is located. These parameters are basically technological, so there are not many things a designer can do about it, other than follow some rules to avoid non uniformities along the wafer, as putting matching transistors nearby, with same orientation, etc. There are other parameters that also influences the transistor mismatching and those we can change them. These are geometrical transistor design parameters, specially the length (L) and width (W) of transistor channels.

It is difficult to give an estimation of the influence of each parameter on the offset mismatch, specially when the technological parameters dispersion is unknown, but it is possible to measure the offset dispersion of the response and get some conclusions from it.

3. EXPERIMENTAL RESULTS

Many measures has been made with the retinal sensor, specially studying the problem on the offset non uniformity. The retinal image sensor yields a good response but the high offset non uniformity needs a correction that is performed outside. This correction consist of a simple subtraction of the offset fixed pattern. In the figure 4 is possible to see the image taken directly from the sensor, and other image just subtracting the fixed pattern noise from the original image.

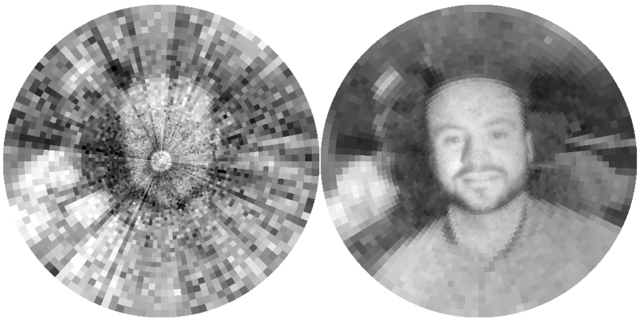

Figure 4. *Left: original image. Right: corrected image*

3.1. Non uniformity

In figure 5 we can see the response of a gray uniform image along the rings of the sensor. We see that there is a large dispersion of the output around a mean value. The continuous line of the figure 5 is the mean value of all pixels on each ring, and we can see that it follows a growing law for the outer rings. First rings, (0-19) correspond to the fovea, that has a different structure and therefore different behaviour. Last rings, (20-75) corresponds to the retina and we see a dependency that is linear for the last rings.

Equation (4) shows an offset growing that is logarithmic respect to the pixel area. The pixel area grows exponentially with the ring, thus the offset grows linearly with the ring. In figure 5 the linearity is only shown for rings above 30 or so, while for the inner rings the growing law is opposite to the expected. The first explanation for this behaviour is the different photosensing area. While the pixel area follows exactly an exponential law, it is not so for the photodiode area since, as it was already explained, the photodiode not covers all the pixel area, and this covering depends on the ring. It could be a good explanation, but it is not the reason

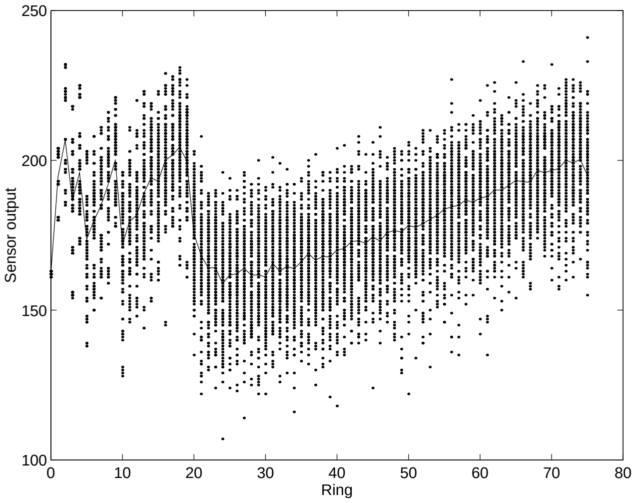

Figure 5. *Non uniformity among rings*

since we have the same effect on the transistor width, and both effects (it has been studied and evaluated) compensate each other, giving the same response as a theoretical pixel.

The reason for this behaviour, of the inner rings of the retina, is the narrow channel effect of MOS transistors. Short channel effects have been very well studied in the past, also narrow effects though not that much due to the fact that, in most analog designs, the width is kept maximum. The retina designed is an example that narrow channel effects exist and give significant different response than wide channels.

In the retina design, the smallest width was 3 μm, that it is not a very high value. It was possible to design a smaller width even with smaller pixel size thus reducing total sensor size, but it was decided to use this size since simulations showed a big fixed non uniformity under 3 μm channel width. The experimental results showed a smaller narrow effect than simulated. To study this difference, the equations for the Spice LEVEL 2 model were collected and evaluated. This study showed that the DELTA parameter (fitting factor for the Narrow-width effect) was overstimated by the foundry. Taking DELTA=1.0, instead of the 2.0 from the foundry, produces a perfect matching between experimental and theoretical data.

Though the narrow channel effect can be very negative for most analog circuits, it has something good for the retinal sensor; this effect compensates the fixed non uniformity due to pixel growing, so the pixel size differences are less important than expected. The conservative 3 μm width value, taken for the first design, can be changed to something narrower, thus reducing total chip size, though this effect grows very quickly with the width reduction.

These non uniformities are referred to the retinal rings. It is possible to make a similar study of non uniformity along different orientations. The result is that there is no evidence of privileged pixel orientation since the non uniformity dispersion is uniform among radii. In any case, the dispersion among radii is different from the dispersion among circumferences. The dispersion among radii is almost double and the reason is very simple: For the radial non uniformity there are two contributions, one is the random pixel non uniformity, and the other is the random amplifier non uniformity, that non only gives a FPN but also a non uniformity of the response slope depending on the amplification scheme used outside the chip.

4. CONCLUSIONS

A retinal sensor with increasing area pixels has been designed and fabricated. The sensor has a logarithmic response instead o the typical linear of CCDs and CMOS integration cameras. The most critical problem on space variant sensor is the pixel response scaling among different size pixels. With the logarithmic response and a half compensation, using convenient transistor width scaling, the effects of the existence of different pixel sizes are minimized.

Non uniformities in the sensor have been evaluated. The random non uniformity is of the same order as the fixed non uniformity due to pixel growing.In the case of the retina, the transistor or pixel mismatching, source of the random non uniformity, is mainly due to geometrical parameters, specially channel length. The cause of radial non uniformity is produced by the difference among the radial amplifiers, that is not only due to geometrical parameters but technological. A reduction for the pixel mismatching is acomplished making longer channels. The solution for the radial non uniformity is even simpler, instead of using an amplifier for every radius, it is better to use a single amplifier common to every pixel.

5. ACKNOWLEDGEMENTS

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