Analysis of Photosensor Properties for Visual Neural Stimulators

Naser Pour Aryan and Albrecht Rothermel
Institute of Microelectronics, University of Ulm, Ulm, 89081, Germany

Keywords: Dark Current, Epitaxy Process, Photodiode, Retinal Illuminance, Subretinal Chip.

Abstract: Photodiodes are important elements in subretinal visual stimulation chips (Rao et al., 2006)(Rothermel et al., 2009). This paper quantifies the advantages of using a process involving a low photodiode dark current per unit area for fabricating these devices. Such a technology needs an epitaxy process to optimize the substrate material lattice properties as also mentioned in (Cinguino et al., 1985) and (Inada et al., 2009). In the following we show that the illumination on the retina is in a range that an epitaxy process ensuring low dark current becomes beneficial. To the authors' knowledge, this is the first study of its kind in open literature.

1 INTRODUCTION

Subretinal stimulator chips are among the devices giving rise to hope in curing blindness in people suffering from Retinitis Pigmentosa (RP) or Age-related Macular Degeneration (AMD) (Rao et al., 2006)(Rothermel et al., 2009). Light sensing in these devices is done through photodiodes. Among the important parameters in designing these photodiodes is the retinal illuminance.

Retinal illuminance has been investigated before (Mactier et al.,)(Atchinson and Smith, 2000). Unfortunately these studies relate the retinal illuminance to the luminance incident on the eye pupil. This approach has little significance in practice because photodiode current is proportional to the illuminance (or the irradiance) incident on the photodiode. Moreover, compared to illuminance, devices used for luminance measurement are much more expensive.

In the following we relate the retinal illuminance to the illuminance incident on an object with a distance r from the eye. We assume that the object is white and reflects all of the incident light. This method enables us to apply the measured photosensor voltage versus illumination characteristic to a retinal chip and evaluate the interesting illuminance range. Then, we show that regarding this range, photodiodes fabricated in an epitaxy process which have a low dark current per unit area are beneficial in subretinal devices.

2 PHOTOSENSOR STRUCTURE AND THE FABRICATED DEVICE

A photosensor circuit with a structure similar to the one in (Rothermel et al., 2009) (Fig. 1) is fabricated in CMOS technologies on bulk and epitaxy substrates. Here V_{dda} is equal to +2V and V_{ss} is -2V. The current source I_{Photo} models the photodiode's current induced by the incident light and does not exist in the actual structure. This current is linearly proportional to the illuminance of the incident light. The two NMOS

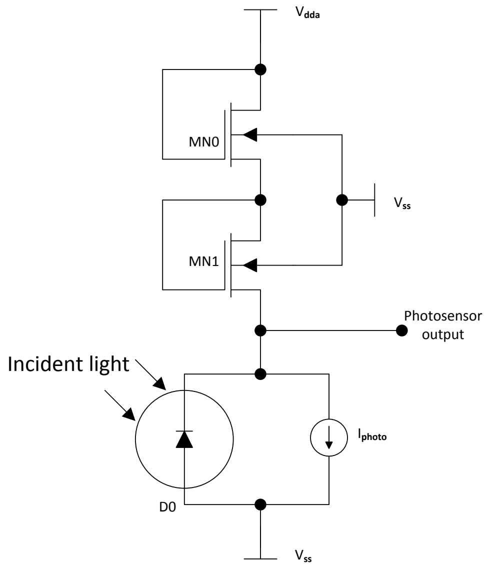

Figure 1: The photosensor circuit fabricated and investigated in this study.

Pour Aryan N. and Rothermel A..
Analysis of Photosensor Properties for Visual Neural Stimulators.
DOI: 10.5220/0004312400400044
In *Proceedings of the International Conference on Photonics, Optics and Laser Technology* (PHOTOPTICS-2013), pages 40-44
ISBN: 978-989-8565-44-0

transistors MN0 and MN1 operate in the subthreshold region, in which the MOSFETs exhibit an exponential current-voltage characteristic. So this structure can be used to logarithmically compress a large range of the photocurrent. Moreover, it has a logarithmic response which mimics the photoreceptor's behavior in the human retina. For a MOS diode operating in the subthreshold region, if the substrate effect is ignored and it is assumed that its drain-source voltage is much higher than the thermal voltage for simplicity, the drain current I_D is written as (Allen and Holberg, 1987):

$$I_D = \frac{W}{L} \cdot I_{D0} e^{\frac{V_{GS}-V_{th}}{nV_t}} \quad (1)$$

with

$$I_{D0} \cong \beta \frac{L}{W} \frac{2(nV_t)^2}{e^2} \quad (2)$$

Thus, the voltage drop on the diode V_{GS} is

$$V_{GS} = nV_t ln(\frac{I_D L}{I_{D0} W}) + V_{th} \quad (3)$$

Here W is the gate width of the MOSFET, L the gate length, n is the subthreshold slope factor which is a process parameter with typically $n = 1.14 \rightarrow 1.5$. The thermal voltage V_t is about 27mV at body temperature. k is Boltzmann's constant. T is device temperature in Kelvins and q is the elementary charge value.

This photosensor circuit is fabricated together with the rest of the stimulator chip in a silicon based 0.35μm CMOS process. A chip micrograph is illustrated in Fig. 2. The chip has 1600 pixels. A single pixel is marked in Fig. 3 in the green rectangle. Every pixel has an octagonal electrode with a diameter of 15μm (in the dotted red circle) and a photodiode with an area of 15μm x 48μm (in the red solid oval). This chip is fabricated both in an epitaxy substrate based process (Fig. 2) and a process without an epitaxy layer (not shown here, fabricated as a test-chip with extra pads to measure the internal signals, including the output voltage of the photosensor). The thickness of the epitaxy substrate is 14μm.

In addition to the electrode and the photodiode there are other amplifying and conversion circuitry in the pixels which are not detailed further here.

3 MEASUREMENT RESULTS

The photosensors fabricated in the bulk and epitaxy substrate based processes were measured indirectly. The output electrode current of the pixel depends on the photosensor voltage. By measuring this current, photosensor voltage versus illuminance characteristics in both processes were determined. The two photosensor characteristics are illustrated in Fig. 4. Because of measurement setup limitations, the illuminance range was confined to 0.01 lux to 10 klux.

The test-chip with the bulk substrate provided the voltage directly via a pad, so we could verify the indirect measurement method. The voltage of this pad had to be measured with an op-amp (used as buffer) having a very low input bias current, because the photodiode current is very small in low illuminances (1pA at 1 Lux). The option used here was LMC6044 from National Semiconductor, having an input bias current of only 2 fA. The measured photosensor characteristic was the same as in the indirect measurement.

The illuminance was measured by a Minilux luxmeter from Mx-electronic.

As is seen in Fig. 4, while the epitaxy process based photosensor output remains linear over the whole measurement range, the bulk based photosensor saturates at lower illuminances. At low illumi-

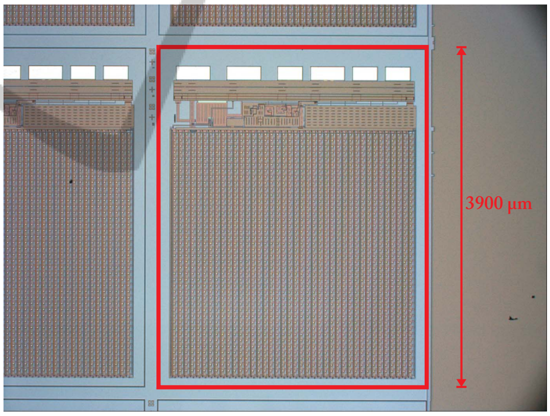

Figure 2: The chip micrograph: A single chip is inside the red rectangle.

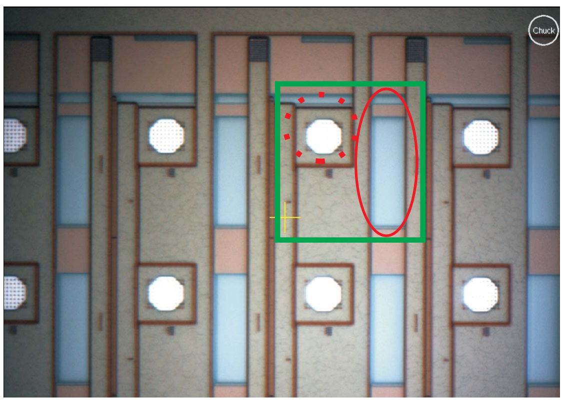

Figure 3: Photo of a single pixel. The vertical and horizontal pitch is 70μm.

nances, photodiode current drops below photodiode's dark current, so no sensitivity to illuminance is available any more.

We could determine the photodiode dark current by comparing the measurement results with the simulations. For the epitaxy based process a dark current of 600fA (corresponding to 0.83 nA/mm^2) could be determined. Note that a completely linear photosensor characteristic does not mean a zero dark current, because the MOSFETs have some leakage current which compensates for the effect of photodiode dark current. The transistor models used in the simulations take this into account. The bulk substrate based process had a higher dark current: 2pA (corresponding to 2.77 nA/mm^2).

4 RETINAL ILLUMINANCE CALCULATION

In order to determine if an epitaxy process is beneficial for a subretinal stimulator chip application, it is necessary to calculate the retinal illuminance. This is done in the following.

We consider the eye looking at an object illuminated by an illuminance value I. We assume that the object is 100% reflecting, is infinitesimally small but has a definite area A (Fig. 5), thus it is practically a point.

A corresponding image point with an area B emerges on the retina. The luminous flux radiated from the point into the whole right half-space is $I \cdot A$ $[lm]$. The spatial angle spanning the half-space is equal to $2\pi sr$. So the luminous intensity into the half-space (which is uniform because the point is very small) is:

$$Intensity = \frac{Flux}{Angle} = \frac{I \cdot A}{2\pi sr} \quad (4)$$

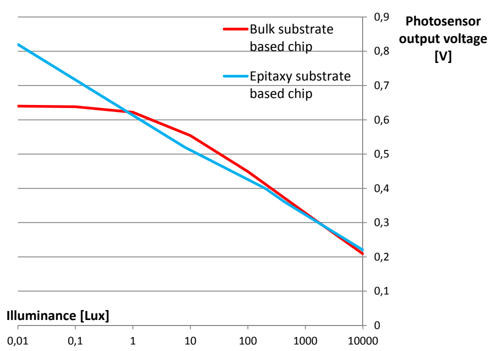

Figure 4: The characteristics of the photosensor output voltage versus illuminance for bulk and epitaxy substrate based chips.

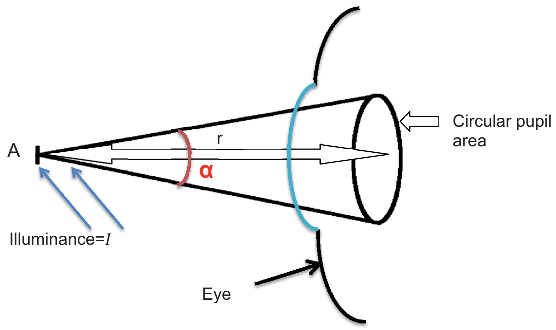

Figure 5: The eye looking at an infinitesimally small point with an area of A.

The (luminous) flux into the eye is only the part of the total flux radiating inside the angle α as in Fig. 5. So:

$$Flux\ into\ the\ eye[lm] = I \cdot A \cdot \frac{\alpha}{2\pi sr} \quad (5)$$

So for the retinal illuminance:

$$Retinal\ illuminance[lux] = T \cdot I \cdot \frac{A}{B} \cdot \frac{\alpha}{2\pi sr} \quad (6)$$

T is the transmittance of ocular media and is on the average 0.75 (Atchinson and Smith, 2000). Geometric calculations give:

$$\frac{\alpha}{2\pi sr} = \frac{Pupil\ area}{Area\ of\ a\ hemisphere\ with\ radius\ r} = \frac{d^2}{8r^2} \quad (7)$$

Where d is the pupil diameter. The pupil diameter range depends on the individual and age. The pupil diameter is between 3 to 5mm when the environment is bright. At the age of 15, the dark adapted pupil can vary from 4mm to 9mm (Atchinson and Smith, 2000). r is the object(point)-pupil distance.

We can approximate the transparent part of the eye as a sphere having a constant refraction index of $n' \cong 1.34$, because the constituting material is similar every where (Meschede and Gerthsen, 2003) (see Fig. 6). So the ratio of the point area to its image on the retina can be calculated by the optical formula corresponding to spherical transparent surfaces with a refraction index different from 1. It depends on the distance r, eye diameter a(image distance from the cornea, where most of the refraction occurs, about $2\,cm$) and n' (Hering et al., 2007):

$$\frac{A}{B} = (\frac{n'}{n})^2 \cdot (\frac{r}{a})^2 \quad (8)$$

Here n is the air refraction index, which is 1. Mathematical calculations considering above assumptions result in the following formula for retinal illuminance at the point on the retina:

$$Retinal\ illuminance[lux] = T \cdot I \cdot n'^2 \cdot \frac{d^2}{8a^2} = 420.8m^{-2}Id^2 \quad (9)$$

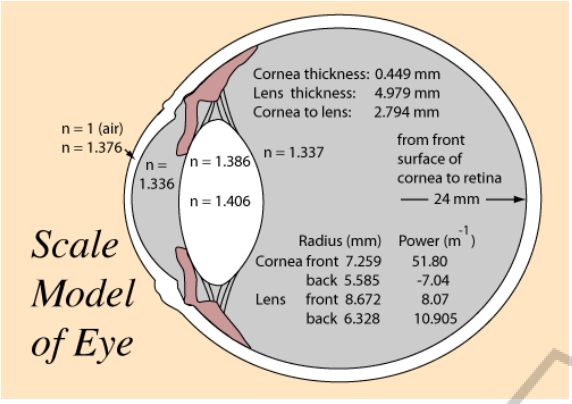

Figure 6: The refraction index of different eye organs, from (eye, http://hyperphysics.phy-astr.gsu.edu/).

A real white object which is uniformly illuminated can be considered as a superposition of plenty of points. The corresponding calculation should be done through integration. The object is considered to be large, i.e. its angular size is much larger than the human eye angular resolution, which is 4 minutes of arc. A good example is a uniformly lit white wall. Therefore the effects of straylight (Vos et al., 1976) and dullness of the retinal focus are canceled. The resulting retinal illuminance is the same as above.

Therefore an object illuminance of 1 klux results in a retinal illuminance of only 15.1 lux for $d = 6mm$. This means that the retinal illuminance is about 2 orders of magnitude lower than the illuminance of the observed object. Table 1 lists the calculated retinal illuminance values for various conditions. From the table we read a retinal illuminance range between 0.034 mlux to 736.4 lux.

5 DISCUSSION

As we see from Fig. 4, the bulk substrate based photosensor enters saturation in retinal illumances between 1 and 10 lux. Table 1 shows that this is already problematic for vision in living room and in street light. For retinal illuminances below 1 lux, the photosensor output voltage is not sensitive to illuminance changes, so no contrast (for example edges) can be perceived any more. The epitaxy based photosensor remains to be linear in darker environments. However, because of measurement setup limitations, we were unable to verify its functioning for illuminances lower than 0.01 lux. Anyway, the necessity of using epitaxy based photodiodes with low dark current is revealed.

Table 1: The calculated retinal illuminance in different conditions, the observed object is white and 100% reflective.

Situation	Environment Illuminance	Retinal Illuminance
Sun, summer, d=5mm	70 klux	736.4 lux
Cloudy day, d=6mm	2 klux	30.3 lux
Well lit office d=6mm	1 klux	15.1 lux
Living room d=7mm	120 lux	2.47 lux
Street light d=8mm	16 lux	0.43 lux
Full moon d=9mm	0.25 lux	8.5 mlux
Stars but no moon, clear night, d=9mm	0.001 lux	0.034 mlux

6 CONCLUSIONS

We have fabricated photosensors containing photodiodes with an area of 15μm x 48μm on both a bulk and an epitaxy substrate based CMOS process. Our measurements showed that while the epitaxy based photosensor is linear in the range of 0.01 to 10 klux, the photosensor fabricated on bulk substrate loses linearity below 10 lux and enters saturation around 1 lux. We developed a mathematical method to calculate the retinal illuminance using optics and anatomy knowledge. By comparing these results and the measured photosensor characteristics, we discovered the advantage of an epitaxy based process for photodiode fabrication in subretinal neural stimulator devices.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Walter G. Wrobel and Mr. Johannes Groeger for their support on this work.

REFERENCES

http://hyperphysics.phy-astr.gsu.edu/.

Allen, P. E. and Holberg, D. R. (1987). *CMOS Analog Circuit Design*. Oxford University Press.

Atchinson, D. A. and Smith, G. (2000). *Optics of the human eye*. Butterworth-Heinemann Ltd.

Cinguino, P., Genova, F., Rigo, C., and Stano, A. (1985). Low dark current ingaas pin photodiodes grown by molecular beam epitaxy. *Electronics Letters*, 21(4):139 –140.

Hering, E., Martin, R., and Stohrer, M. (2007). *Physik für Ingenieure*. Springer-Lehrbuch. Springer.

Inada, H., Miura, K., Nagai, Y., Tsubokura, M., Moto, A., Iguchi, Y., and Kawamura, Y. (2009). Low dark current swir photodiode with ingaas/gaassb type ii quantum wells grown on inp substrate. In *Indium Phosphide Related Materials, 2009. IPRM '09. IEEE International Conference on*, pages 149 –152.

Mactier, H., Maroo, S., Bradnam, M., and Hamilton, R.

Meschede, D. and Gerthsen, C. (2003). *Gerthsen Physik:*. Springer-Lehrbuch. Springer.

Rao, C., Yuan, X., Zhang, S., Meng, L., and Peng, C. (2006). Cmos artificial subretinal chip for natural light illumination. *Electronics Letters*, 42(15):849 – 850.

Rothermel, A., Liu, L., Aryan, N., Fischer, M., Wuenschmann, J., Kibbel, S., and Harscher, A. (2009). A cmos chip with active pixel array and specific test features for subretinal implantation. *Solid-State Circuits, IEEE Journal of*, 44(1):290 –300.

Vos, J., Walraven, J., and Meeteren, A. V. (1976). Light profiles of the foveal image of a point source. *Vision Research*, 16(2):215 – 219.