Near-100 % fill factor standard CMOS active pixel

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1. Introduction

One major drawback of active pixel sensors and, to a lesser extent, of CMOS passive pixels or photo diode arrays too, is that a significant part of the pixel's surface is used for readout circuitry, which is not part of the light receptor or photo diode. Light falling on these regions is collected by the junctions of this circuitry. This essentially is the reason for the low fill factor problem of active pixel sensors.

2. Proposed pixel structure

A method to raise the fill factor should manage to get all (or a large part) of the photo generated charge into the collection junction, instead of into the unrelated junctions. We have realised this by placing a small but effective electrostatic barrier between the photo sensitive volume and the unrelated junctions, which is absent between the photo sensitive volume and the useful junction (fig. 1).

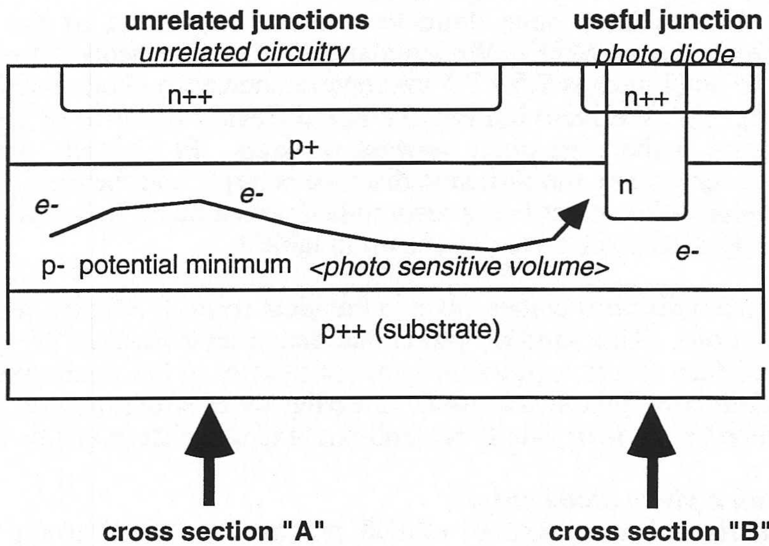

fig. 1: schematic cross section of pixel structure

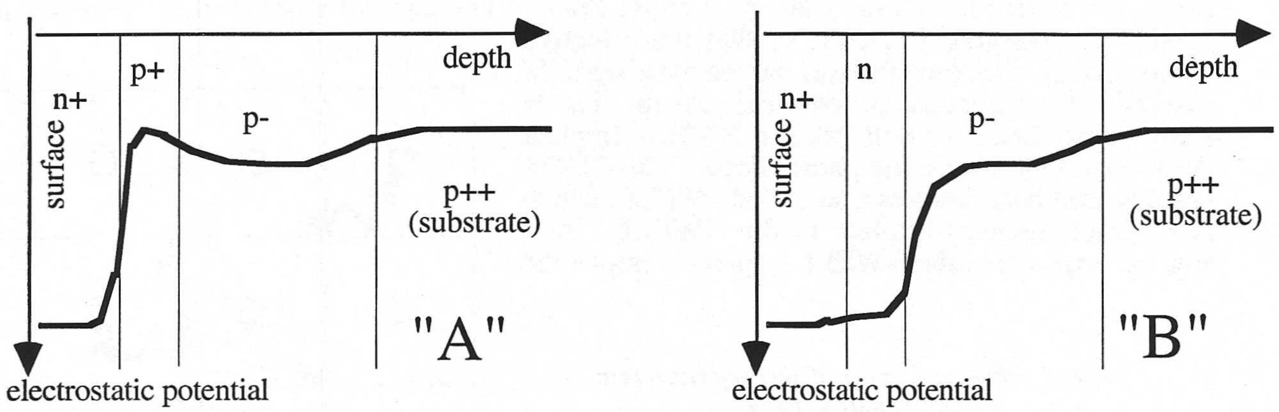

fig 2a : electrostatic potential versus depth for cross section "A"

fig 2b : electrostatic potential versus depth for cross section "B"

Figure 2 represents the electrostatic potential in two cross sections in the pixel: "A", underneath a non-collecting junction in a part which contains (unrelated) electronic circuitry; and "B", through the photo sensitive collecting junction. Both junction may be at the same potential, yet in case "A", electrons in the

p^- zone will not diffuse easily to the junction, as there is a small barrier in the p^+ area. In case "B", the electrons will see no barrier between the p^- area and the n^+ junction. It is likely that electrons in zone "A" will diffuse sidewards to the zone "B", and are collected there.

The introduction of the structure has two main effects:
1) the photo diodes collect photo charge from the whole pixel. The fill factor is limited by 3 things:

- light trapped inside the unrelated junctions themselves. This is certainly a limitation for short wavelength light, which has a low penetration depth.
- light reflected by interconnect metallisation.
- recombination. free electrons will not diffuse indefinitely, but recombine after some typical "recombination length". In the envisaged technology, this length turned out to be several times the pixel pitch.

2) the sharpness of the image.
In the case that a barrier is present between the substrate and the junctions, this will prevent an easy collection of charges by the photo diode junction. The free carriers will rather diffuse to neighbouring pixels and eventually be collected or recombined there, and cause thus an unsharp image.

3. Evaluation of the pixel structure

- ***Simulation of the diffusion of charge carriers***

Monte-carlo-simulations have been done to evaluate the effect of the sideward diffusion on the modulation transfer function (MTF). We simulated the "random walk" of electrons that are generated in a pixel matrix. The pixel pitch is 7.5 x 7.5 micrometer, and each pixel contains a deep collecting junction of various size (fig. 3). We recorded the average diffusion distance of the electron. Electrons are in worst case generated at the edge point between 4 pixels. In a classic structure, where the barrier p^+ implant is present everywhere, the diffusion distance is large, and the electrons diffuse over several pixel distances before being collected or being recombined with a hole. In the structure with the extra implant, the electrons are collected much faster, as shown in table 1.

The resulting diffusion distance comes close to the ideal result (3.75 µm: when each electron is collected in the nearest junction). This kind of pixels has thus a near-ideal MTF. It has also a near 100% fill factor, where all surface that is exposed to light contributes to the light collection. The substrate charge will flow to the collecting junction in total; in earlier pixel structures, parts of the generated charge is collected by unrelated circuits or simply recombines, and this charge is thus lost.

- ***Experiments on a photo diode array***

In one test we fabricated in a standard CMOS process two small arrays of photo diodes, which are representative for a pixel array, and similar to the subject of the above simulation. In the first (A), the junction are "normal" source-drain-like shallow n-junctions in the p-substrate. The junctions measure 3x3 µm, the pixel pitch is 7.5 µm. A central row of pixel is exposed to the light, neighbouring rows of pixels are covered from the light by a metal shield. The parallel outputs of rows of pixels are taken outside the integrated circuit, so that the effective photo current of a row of pixels can be measured. In case (B), the structure is identical, except that in every photo diode, a small 2x2 µm NWELL implant ("dot") is made inside the photo diode. The CMOS process used here features a so-called PWELL, which is a complementary implant to the NWELL. Any area not exposed to the NWELL implant is implanted

table 1 : diffusion distance of minority carriers in the structure of fig. 4

size of collecting junction	diffusion distance in x (σ_x)
none	15.5 µm
1 µm	6.1 µm
2 µm	4.5 µm

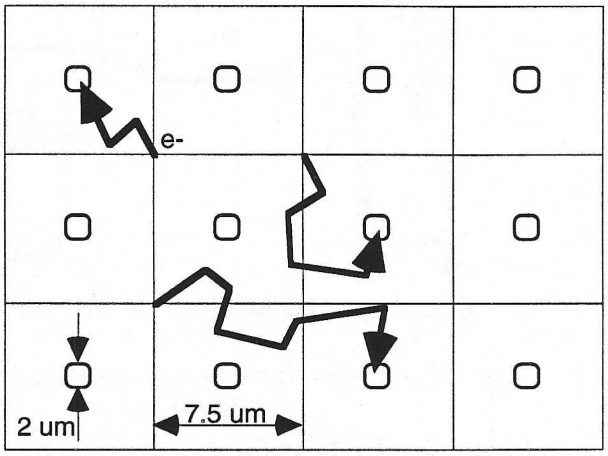

fig 3 : model for simulations on the diffusion of charges

with a p-type dopant, to enhance the p-concentration close to the surface. The effect is a small potential barrier as in fig. 1.
In the ideal pixel array, the exposed row of pixels should detect all photo current, and the covered rows should deliver zero current. The fact that this is not the case is mainly due to sidewards diffusion of charges and to a lesser extent to optical diffraction.
The results are summarised in figure 4, for both cases A (classic, shallow junctions) and B (junctions with extra NWELL dot).

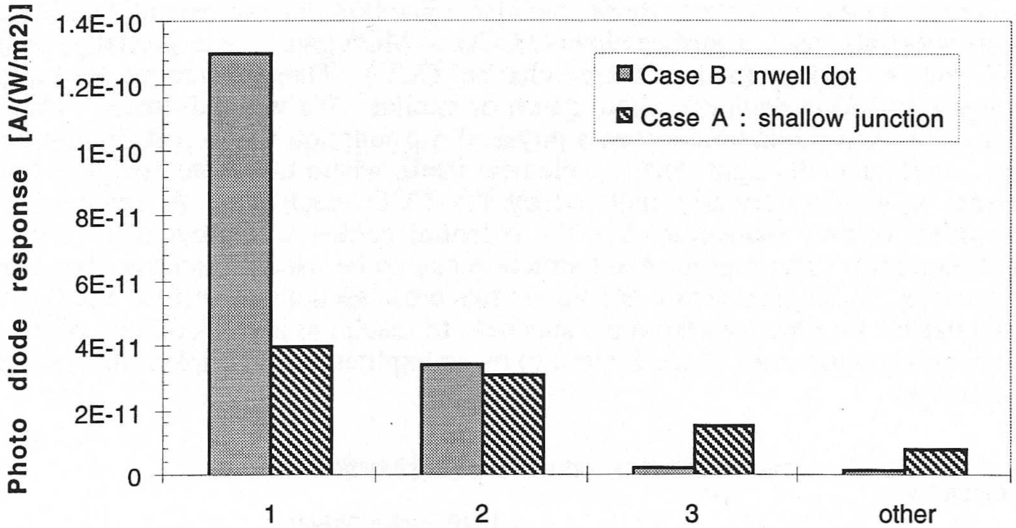

fig 4 : Photo current/light intensity measured on a test structure. Results obtained with illumination with a white lamp.

In the above results, "1" is the current collected by the exposed pixels, "2" by the (covered) neighbour, "3" by the neighbour thereafter, and "other" it the sum of the current collected by 4 successive neighbours thereafter.
The change of behaviour by the effect of the NWELL dots is undeniable, and it proves the principle. Not only does the central exposed pixel row collect relatively more photo current, but also the absolute level of the total current is much higher, which indicated that structure (B) collects charges which are otherwise lost by recombination in structure (A).
The pixels used in this experiment did not contain "unrelated" circuits, and are only relevant for passive pixels.

- ***Experiments on active pixels.***

Similar experiments on various types of active pixels showed even a more prominent difference. As test vehicle we used the 3 transistor pixels as in ref. [1]. Adding a small dot of NWELL inside the photo diode increased the collected current dramatically, with a factor 5 to 10, for light of 650 nm. The increase of the collected current can only be attributed to the described effect. Considering that the pixel is designed with a 15 % fill factor (area of the exposed photo diode only), then this factor indicates that the fill factor could be close to 100% now. Of course this conclusion is too simple as the increase of the collected current is also partly due to the reduction of the recombination in the substrate.

- ***Noise***

The capacitance of the collecting junction is considerably smaller than the capacitance of a junction that would cover the full pixel surface, yet they have effectively the same collecting surface.
One of the main noise sources in image sensors is the so-called kTC-noise. This noise is proportional to the square root of the capacitance of the junction node. In order to obtain a pixel with a low noise charge, one must design low capacitance photo diodes. Yet, for a given capacitance per unit area, the lowest noise diode has also the smallest area, and thus a low light collecting area. The present method allows to make photo diodes which have a small junctions and small junction capacitances, yet a large collecting volume. [Note that the idea of a large collection volume and a small collecting junction is not new, the novelty is a method to extend the collecting volume beneath parts of circuits that have diodes (and are potentially collecting junctions themselves).]

- ***Standard technology***

The effect can be obtained even in standard CMOS technology. For the fabrication of sub-micron CMOS foundries have introduced the "twin well" as shown in fig. 1. Other processes may have similar structures but call them differently: anti-punch-through implant, blanket implants, Vth-adjust implant etc. This and similar structures have been introduced in order to allow shorter channel transistors in the CMOS process, but this is not the issue here.

4. On the implementation in a CCD or CCD-like structure

The photoreceptor can be a photo diode, but also a junction that consists of a depletion layer or inversion layer to its substrate (as in a surface channel CCD or MOS gate), or a (partially) depleted buried channel to its substrate or surface (as in a buried channel CCD). These structures are typically used in CCDs, CIDs (charge injection devices), photo gates, or similar. We will call them "virtual junctions", as they have in fact the same functionality as a physical n-p junction while collecting photo charges. A CCD electrode can thus be the light sensitive element itself, where the photo charge is collected in a potential pocket that is electrostatically induced by the CCD electrode. A potential barrier between the photosensitive volume (substrate) and the potential pocket will prevent the collection of charges by unrelated junctions. The present pixel structure can so be used to enhance the charge collection of the virtual junction. In the next figure are shown two cross sections of surface channel CCD-like structures, where the barrier for electrons from the substrate to reach the inversion layer of the CCD is suppressed: a) by an opening (omission) of the P-well, b) by an explicit n-well implant that pierces or lowers the said potential barrier.

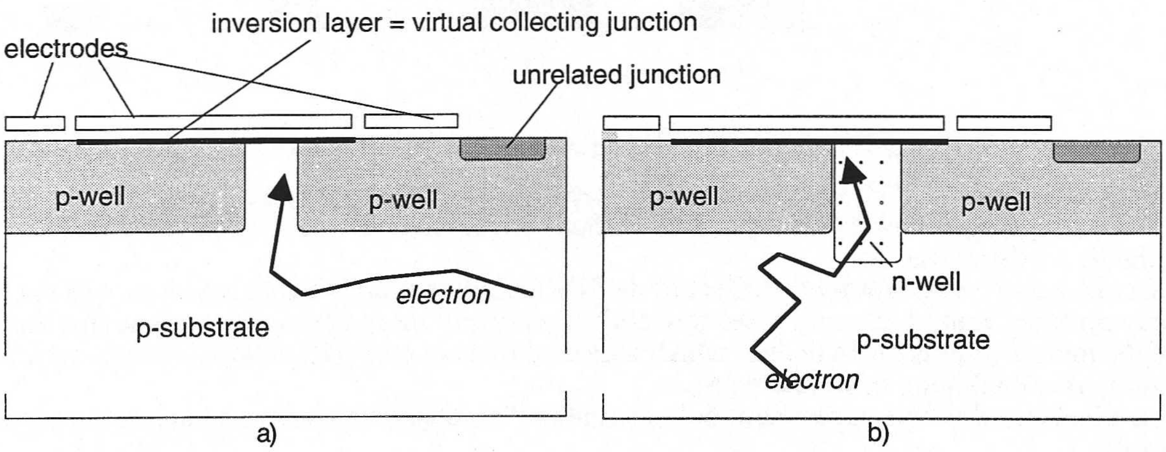

fig. 5 : implementation in a CCD-like structure; (a) opening in the p-well, (b) n-well dot

5. Conclusions

Advantages of the proposed pixel structure are :
-photo charge of light falling on area that is not covered by the photo diode junction is collected by the photo diode, even if this area is covered by circuitry including junctions that can collect charges too. The pixels structure has a near complete (100%) fill factor, except for those parts that are covered by opaque material as metal interconnections. Also charge generated *inside* junctions of unrelated circuitry is lost for detection. As these junctions are shallow, this effect causes only a minor lowering of the sensitivity and only for short wavelengths.
- better MTF performance of the image sensor. The diffusion distance of the generated charges in the substrate decreases, leading to a higher sharpness of the image.
- a higher absolute photo current. In twin-well CMOS processes, a part of the generated charges recombines before they reach a shallow photo diode junction in the well.
- lower noise : pixels have a small collecting junction and junction capacitance, yielding low kTC noise.

6. References

[1] N. Ricquier, B. Dierickx, "Pixel structure with logarithmic response for intelligent and flexible imager architectures", ESSDERC '92; published in Microelectronics Engineering vol.19, p.631, 1992