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Shared pixels for CMOS image sensor arrays

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Shared-pixel architectures for CMOS image sensors are being pursued to achieve high sensitivity and good dynamic range.[1] The promise of a shared pixel is that it can provide the noise performance of a pinned photodiode while requiring fewer components, fewer nodes, fewer bus lines, and fewer technology-driven overhead areas per pixel than for a pixel in which components are not shared (Fig 1). With less of the pixel taken up with circuitry, the optical fill factor increases. Having the sense node shared between multiple pixels results in more charge handling capacity without impinging on optical fill factor. This is particularly important since scaling predictions[2] have been derailed as the pixel array technology has been held at 3.3 V and specialized FETs are required to reset the photodiode.

The sharing of pixels also provides opportunities for combining the charge between pixels and adding shared functionality.[3]

There are a variety of opportunities to institute sharing. Pixel layouts can be mirrored to share contacts, vias, busses, and signal lines (Fig 2). FETs can be shared, as in the source follower (Fig 3).[4] Charge can be transferred or combined (Fig 4).[5] Circuits, such as comparators or ADCs or bit memory, can be shared to enable increased functionality within the array without requiring the overhead in every pixel (Fig 5). Sharing can be carried out in various patterns, including 2×1,[4] 4×1,[6] and 2×2,[7].

An example of sharing is a 2×2 layout of pixels with pinned photodiodes mirrored to share the sense node and circuitry (Fig 6). Each pixel in the subarray has a photodiode and transfer gate, but all of the other components are shared along the axis of symmetry. This means that each pixel only requires ½ of a sense node with contact, ½ of a reset FET, ½ of an active FET, ½ of a select FET, ½ of a reset bus, ½ of a select bus, ½ of a V_{dd} bus, and ½ of a signal bus. The pixels are differentiated by the clocking of individual transfer gates. Operation involves resetting the sense node, reading the reference level, transferring the charge with the respective transfer gate, and reading out the signal level. This allows true CDS operation, which removes reset noise. This can be extended to larger arrays of pixels, such as 4×1 and 2×2, further improving the optical fraction, but it adds complexity in wiring and further breaking of the symmetry to achieve this goal.

Sharing introduces a series of challenges that must be overcome because the design can no longer rely on all pixels being identical to guarantee matching in pixel performance. Mirroring turns asymmetric features in the photodiode design into response variations between pixels, leading to hue shifts (Fig 7). Mismatch is introduced if mirroring is used, even if the layout is symmetric, because a misalignment orthogonal to the symmetry axis can result, and will have opposite effects, on the layouts (Fig 8) introducing a gain variation. For higher levels of sharing, mismatch is introduced because the environments around the photodiodes are no longer identical as a result of the differences in the adjacently located circuit component (Fig 9). The differences are both optical – affecting photoresponse – and electrical – affecting fixed-pattern noise and signal output, and they can affect offset or gain with the modulo of the sharing.

Sharing allows the tailoring of sense node capacitance. For pinned photodiode pixels, the sense node capacity increases with sharing, as diffusions are linked in series and interconnect capacitance is added (Fig 10). This occurs while the optical fill factor is increased. However, the increase in capacitance also decreases conversion gain, resulting in more severe requirements on circuit noise. There is an optimum amount of sharing related to responsivity and dynamic range for each design.

Sharing means that defects and variations from the sense node now are shared in the

performance of all of the pixels sharing it. The result is that defects in the sense node become multi-pixel defects, and fixed pattern noise from the source-follower now is present at a lower spatial frequency. Each is worse from an image science standpoint.

The shared sense node is used for each pixel in the subarray. As such, it must be isolated from smear, from charge or from capacitive coupling, and from the pixels not being read, a requirement beyond that of individual small pixels (Fig 11).

The result is that the shared pixel has great potential to provide improved performance, but loses the inherent matching that is achieved in an array of identical pixels. The success of this approach depends upon defeating the mismatch with design and process engineering.

[1]*Guidash, R.M.*, US Patents 6,107,655, 6,160,281, 6,466,266 & 6,657,665.
[2]*Wong, H-S.*, IEEE Trans. Electron Devices, 43, 1996, 2131-2142.
[3]*Yang, D.X.D.*, et.al., IEEE Journal of Solid-State Circuits, 34, 1999, 1821-1834.
[4]*Rhodes, H., et al.*, Microelectronics and Electron Devices, 2004 IEEE Workshop on, 2004, 7–18.
[5]*Sugawara, M., et al.*, Digest of Technical Papers. 41st ISSCC., 16-18 Feb. 1994, 228–229.
[6]*Takahashi, H., et al.*, IEEE Journal of Solid-State Circuits, 39, 2004, 2417-2425.
[7]*Mori, M., et al.*, IEEE Journal of Solid-State Circuits, 39, 2004, 2426-2430.

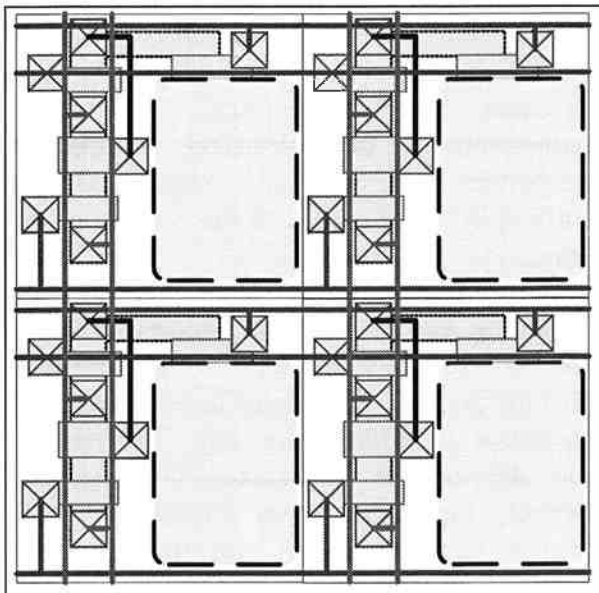

Figure 1. 2 × 2 array of pixels without sharing: 4 FETs and 5 busses per pixel.

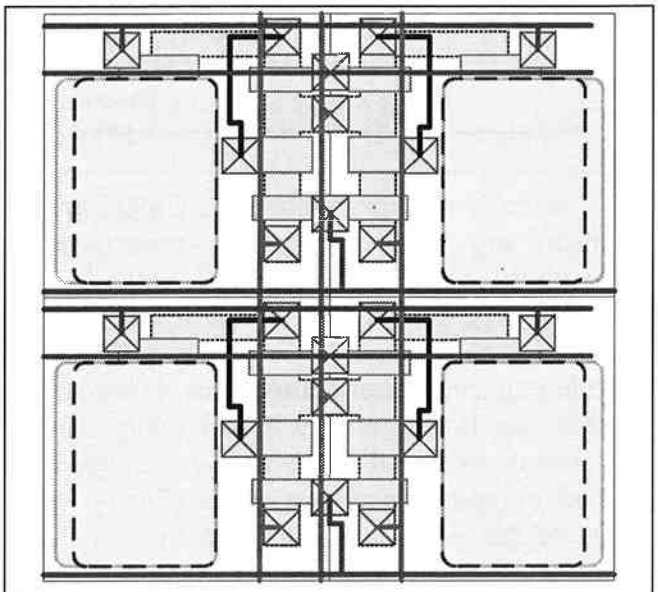

Figure 2. 2 × 2 array of pixels demonstrating shared contacts, diffusions & busses: 4 FETs and 3.5 busses per pixel.

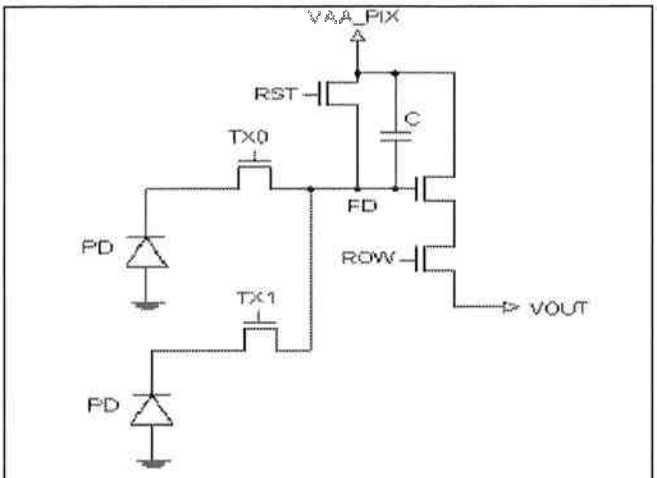

Figure 3. Pixel schematic for a shared source follower.[4]

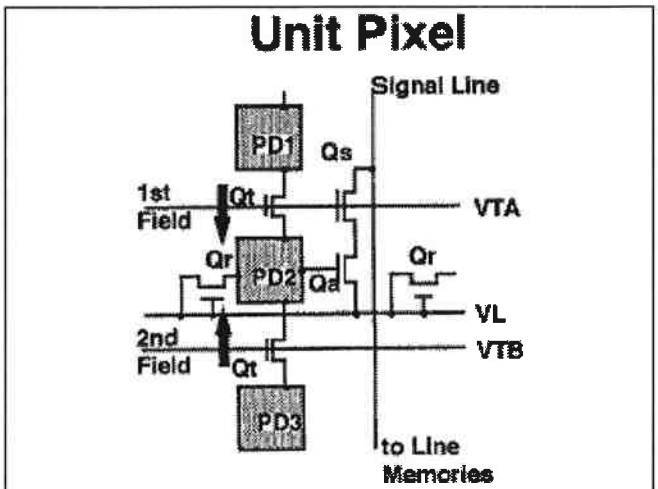

Figure 4. Pixel with interline operation through charge transfer.[5]

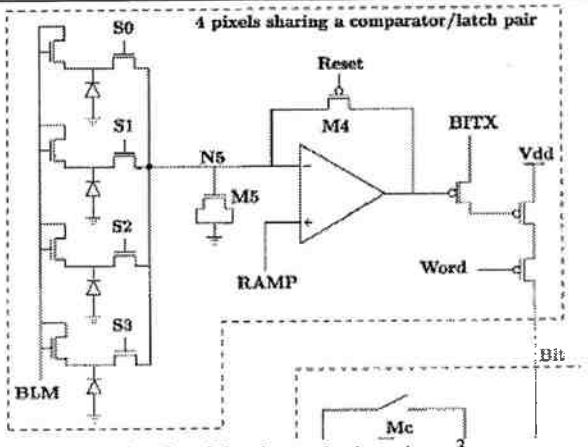

Figure 5. Pixel with shared circuitry.[3]

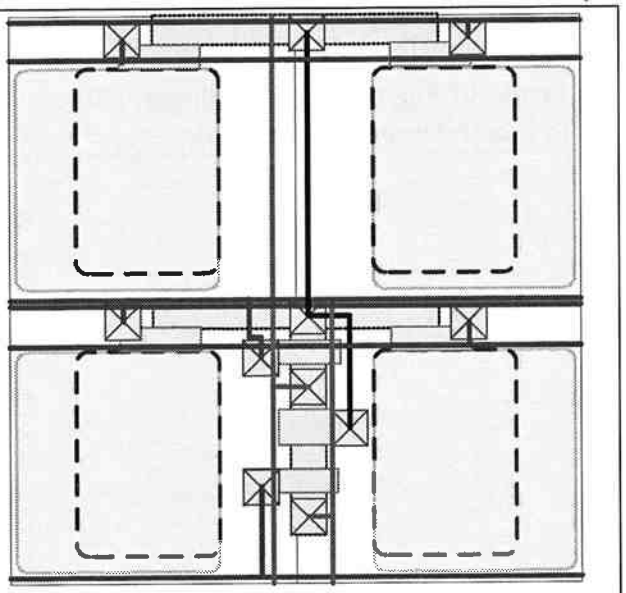
Figure 6. 2 × 2 array of pixels with shared source-follower: 1.75 FETs and 4 busses per pixel (n.b., this could be improved by moving circuits from between two photodiodes to the center of 4 × 4 arrays).

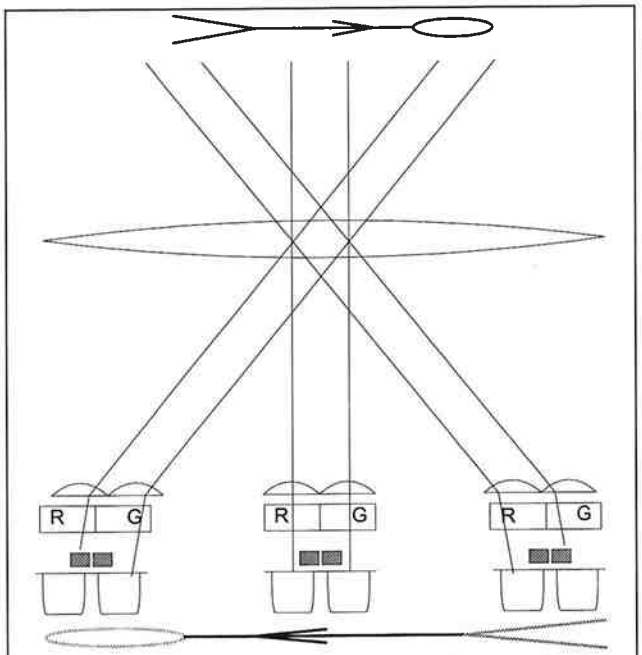

Figure 7. Asymmetry in mirrored layout leads to hue shift: TG gate on blocks red and green light from opposite ends of image so person will have greenish head and reddish feet.

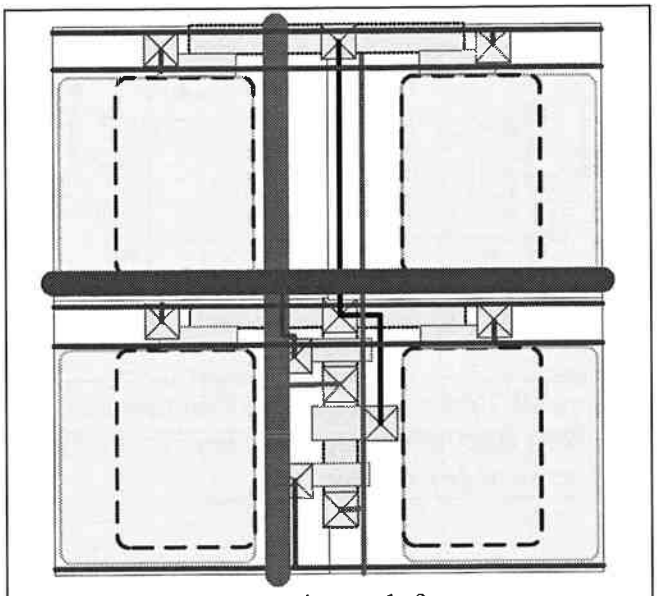
Figure 8. Response mismatch from misalignment in layout in Fig 6: response of upper right photodiode decreases.

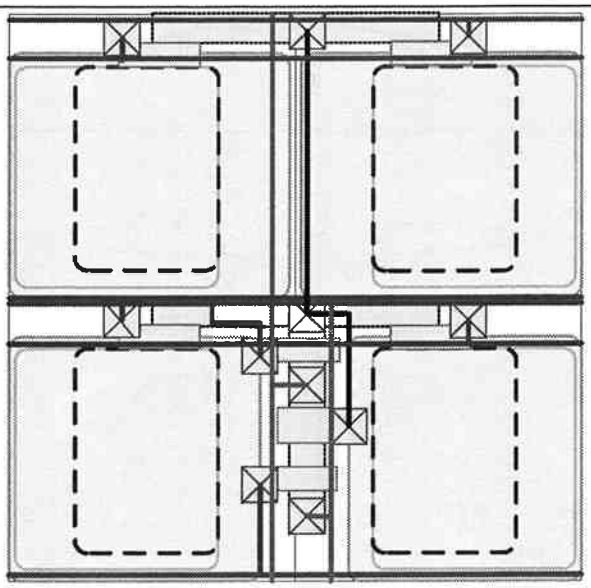

Figure 9. Electrical mismatch due to electrical differences in layout in Fig 6: shading shows optically active area of each photodiode.

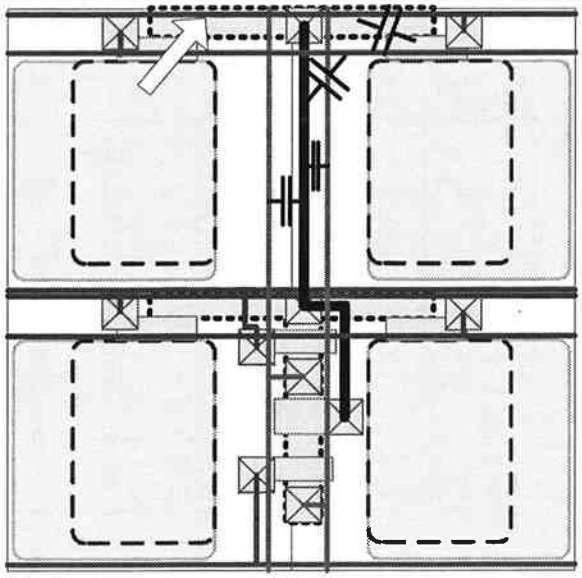

Figure 11. Cross-talk issues within 2×2 array in layout of Fig. 6: charge spillover; gate coupling; interconnect coupling.

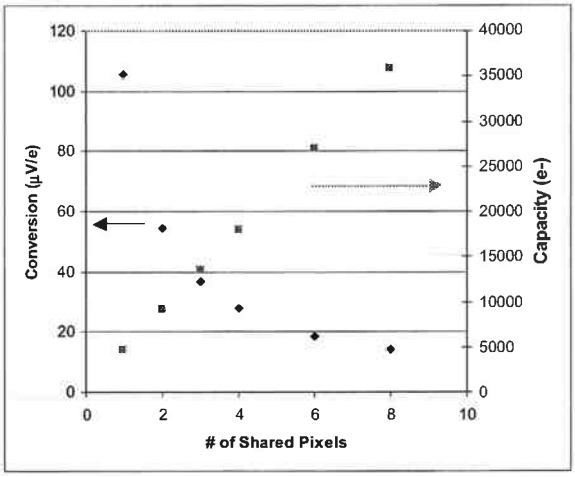

Figure 10. Performance as function of number of pixels sharing a sense node: conversion gain and sense node capacity.