A novel colour sensitive CMOS detector

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PRESENTATION OUTLINE
1. Colour Imaging Devices
2. TFD working principle and simulations
3. CMOS TFD experimental results
Colour Imaging basics

scene reconstruction +
colour detection =
colour imaging

• A **spatial sampling** photo-device (for instance a matrix of pixels) allows to get a black and white image of the captured scene

• To detect the colour each pixel must produce at least **three different functions** $f_i(\lambda)$ of the radiation wavelength to describe the 3D colour space
CFA patterns

• Colour Filter Arrays patterns

  – Possibility of sharp photoresponses
  – Bayer RGGB, CMYY
  – RGBE

  – Need for micro-filters deposition
  – Consistent light loss (60%)
  – Colour reconstruction leads to artefacts and errors
Multilayer Silicon sensors

• 3 colours Foveon®
  – Use of stacked junctions to simulate multi-layer films
  – Reduced light loss (no filter)
  – Higher colour fidelity
  – No more than 3 colours in triple well CMOS
  – Junctions depths depends on the chosen technology
The Transverse Field Detector (TFD)*

BASIC WORKING PRINCIPLE

- Carriers collection is performed through diagonal paths inside the semiconductor bulk
- Diagonal paths are generated by means of transverse electric fields
- Transverse field components are generated by surface contacts
Vertical sampling of light

• Contact #0 samples light from the surface until a limited depth, $f_0(\lambda)$

• Contact #1 samples light from the surface until a greater depth, $f_1(\lambda)$

• ...

• Contact #n samples light from the rest of the depleted region, $f_n(\lambda)$

• By means of the comparison of the different contacts charge, light distribution vs. depth can be reconstructed from which colour is determined!!
Device level: pn junction TFD

- The simplest implementation in a completely standard CMOS technology
- No change in the technology process flow is need for this solution
- As it is, the simplest solution does not work: it needs several improvements

Very shallow N+ implants:
- Generation of the transverse field configuration
- Low blue light absorption

Low-doped P-type epitaxial layer of sufficient thickness W:
- A few μm depletion region for electrons drift
- Collection of absorbed red light

A detailed analysis of this region

Part 2: TFD working principle and simulations
N⁺ isolation (1): insertion of P⁺

- **The Epi-layer does not provide isolation** between different N⁺ contacts… A huge leakage current flows when a voltage is set between contiguous N⁺

- **Is the insertion of shallow P-type regions** between N⁺ effective in providing isolation? Yes, but…
**N⁺ isolation (2): insertion of STI**

- In CMOS technologies, N⁺ and P⁺ dopings are generally very high (above $10^{20}$ cm⁻³).

- Contiguous N⁺/P⁺ regions constitute a tunnel diode with very low (few mV) on voltage.

- To avoid these undesired effects, Shallow Trench Isolation (STI) can be used for contiguous highly doped region isolation.
N⁺ isolation (3): experimental data

#0 dark current (#1 at the same bias voltage as #0)

#0 and #1 current exchange with #1 at 2.9 V and #0 sweeping

#0 Dark Current [pA]

#0 Reverse Voltage [V]

#0, #1 Current [pA]

High current exchange

Low current exchange for ΔV₀,₁ < 1.25 V

P⁺ contact always at 0 V
3 colours TFD device design

- Insertion of external N well allows to lower the outer voltage (V#2 ~ V#1) and to better isolate pixels.

- Total 3 colours pixel size is ~ 5 µm (4 colours 5.8 µm).

- Following ISE-TCAD simulations performed at these biasing values: V#0 = 1.0 V, V#1 = 2.1 V, V#2 = 2.3 V, V_EPI = 0 V.
Charge collection inside the TFD

• The Electric Field Streamlines schematically represent electrons drift paths inside the depleted region.
• A Monte-Carlo simulation for diffusion describes electrons diffusion paths in undepleted region.

Part 2: TFD working principle and simulations.

ELECTRIC FIELD STREAMLINES
ELECTRONS EQUI-CONCENTRATION CURVES
AND QUASI-FERMI GRADIENT

#0 #1 #2

4 μm epitaxial layer

#0 = 1.0 V
#1 = 2.1 V
#2 = 2.3 V
Vepi_p = 0 V

#0 #1 #2 #1
TFD Energy Band graph

- The resulting energy band graph with contacts increasingly biased from the center to the border

- \( V_{#0} = 1.0 \) V
- \( V_{#1} = 2.1 \) V
- \( V_{#2} = 2.3 \) V
- \( V_{\text{epi}_p} = 0 \) V

Part 2: TFD working principle and simulations
90 nm CMOS Technology TFD

TEST STRUCTURE: ARRAY OF 34 PIXEL STRIPS READ TOGETHER
- A 3-colour structure (results analyzed in the following slides)
  - A 4-colour structure (shown below)

NO FILL FACTOR OPTIMIZATION SO FAR (~ foreseen FF for smaller structures is > 60%)
A charge pump and a current mirror are designed once for the whole matrix (shadowed in blue).

Each pixel includes a single transistor charge amplifier ($M_3$), a current generator ($M_2$), a follower ($M_4$), a reset transistor ($M_R$), a select transistor (not shown) and a capacitance ($C_F$).
Technology Quantum Efficiency

- The technology used for this first realization of the device has alternated layers of different dielectrics where metals are not drawn.

- It is expected to result in strong wavelength selective reflectivity, as shown in the simulation below.

Quantum efficiency measured from a simple test diode.

<table>
<thead>
<tr>
<th>Incident Wave (90°)</th>
<th>Reflectivity [%]</th>
<th>Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.55</td>
<td>450</td>
</tr>
<tr>
<td>d₁=600 nm</td>
<td>0.35</td>
<td>500</td>
</tr>
<tr>
<td>d₂=1100 nm</td>
<td>0.30</td>
<td>550</td>
</tr>
<tr>
<td>d₃=578 nm</td>
<td>0.25</td>
<td>600</td>
</tr>
<tr>
<td>d₄=578 nm</td>
<td>0.20</td>
<td>650</td>
</tr>
<tr>
<td>d₅=578 nm</td>
<td>0.15</td>
<td>700</td>
</tr>
<tr>
<td>d₆=578 nm</td>
<td>0.10</td>
<td>750</td>
</tr>
<tr>
<td>d₇=578 nm</td>
<td>0.05</td>
<td>800</td>
</tr>
</tbody>
</table>

Part 3: CMOS
TFD design and experimental results.

Quantum efficiency measured from a simple test diode.

- Solutions:
  - Choose a technology without alternated dielectric layers.
  - Try to avoid dielectric deposition over the sensitive area.
Experimental Colour Results

- **Photoresponses** of the three different contacts biased at $V_{#0} = 1.45$ V, $V_{#1} = V_{#2} = 2.90$ V

- They can be considered as the **Equivalent Colour Filters** of this CMOS 90 nm TFD

- Though the presence of responsivity holes TFD performances remain good
Qualitative Colour Analysis

• A qualitative and quantitative instrument to verify colour representation is the *Macbeth Colour Checker (MCC)*

• It provides a set of known reference colours which can be used as a setup and adjustment standard in film and video calibration

• In the picture a simulation (through the ISET software) of the *acquisition through the TFD experimental colour filters* of the *MCC* is depicted
Quantitative Colour Analysis

- The 24 colours acquired through the TFD Colour Filters are represented (circles) in the CIExy diagram and on the CIELAB diagram.

- The lines starting from each circle lead to the original Macbeth Colour Checker point.

- Good colour agreement: mean MCC colour error in CIELAB space is $\Delta E_{ab} = 2.57$ ($< 3$, a good result for photography)
Final remarks

• A novel CMOS device has been developed
  – Isolation between N⁺ implants on low-doped epitaxial layer has been proved, through the insertion of combined P⁺ implants and shallow trenches (STI) between N⁺ implants

• Its primary application is colour detection
  – Major advantages: reduced light loss, no need for filters, higher colour fidelity, lower post processing, CMOS standard compatibility
  – Colour detection capabilities have been demonstrated
  – A compatible APS electronics has been demonstrated (with a foreseen Fill Factor > 60%)

• In the future...
  – Different ways to obtain small-area capacitance will be investigated, in order to keep a higher pixel fill factor with scaled dimensions
  – Four colours pixels (extended gamut), already designed, will be tested