QE of front side and back side thinned CMOS Image Sensors between 100 and 400nm

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Presentation Outline

- Types of thinning to increase sensitivity
- Theory behind the need of an AR coating
- Obtained QE of various thinning types
- VUV measurements
- Take Home Message
Device Selection and Definitions

- All devices tested have nearly identical geometrical and operational parameters. Devices are processed at 3 different foundries/processes, in 110 and 180nm CIS nodes with various process options related to BSI, FST, ARC (anti-reflective coating) and wafer starting material.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>FSI</td>
<td>Classic frontside illuminated</td>
</tr>
<tr>
<td>FFST</td>
<td>Fully frontside thinned down to Silicon, apart from thin layer of SiO2</td>
</tr>
<tr>
<td>PFST</td>
<td>Partially frontside thinned: passivation removed, about half the SiO2 remaining</td>
</tr>
<tr>
<td>BSI</td>
<td>Backside illuminated, various ARC options, various epi-thickness and resistivity options</td>
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</tbody>
</table>
Types of Thinning

- Classic frontside illuminated
- FFST
- PFST
- Backside thinned Backside illuminated

Passivation SiN
SiO₂

Handle wafer (carrier wafer)
ARC
Fully FST SEM cross section (device “d”)
2nd Fully FST example (device “BASTION”)
BSI example SEM cross-section (device “R”)

Carrier Wafer

4µm EPI

AR Coating

Seal ring

Backside bond pad
Some Theory

- Silicon has high refractive index.
- Without Ar coating, 30-40% reflection.
- For UV, difficult to find CMOS compatible transparent materials.
Anti reflection coating (ARC)

- Maximal QE is determined by reflection at air-Si interface
  \[ n_{Si} \approx 4 \Rightarrow \text{huge reflection} \]
- Adding a coating can reduce the reflection
- Single layer
  \[ \text{At a fixed wavelength, perpendicular reflection can be removed by a simple single layer coating} \]
  \[ n_{ARC} = \sqrt{n_1 \times n_2} \]
  \[ d_{ARC} = \frac{\lambda}{4 \times n_{ARC}} \]
  \[ \Rightarrow \text{Still reflection at other wavelengths, other angles} \]
- Multiple layers
  \[ \Rightarrow \text{Reflection can be minimized across a range of wavelengths and angles} \]
  \[ \Rightarrow \text{Better performance if layers with different refractive indices (n1 < n < n2) are available} \]
QE of standard FSI
**BSI versus FSI: QE**

- ~90% peak QE @ 540nm
- No fringes in UV and visible
- 80%+ peak QE if no metals
- Interference in SiN and SiO2 layers
- "etaloning" (interference in Si-layer)

Maximum at 270nm
- $\rightarrow = \frac{540\text{nm}}{2}$
- $\rightarrow 2 (3, 4\ldots) \text{ electrons per photon beyond 3.6eV}$

Significantly enhanced UV and blue sensitivity

- Classic FSI
  - BSI with ARC max
  - ~540nm
Fully thinned: likely becomes best in the VUV (not measured)
Partially thinned: VUV behavior not tested

Fully thinned: poor QE! high reflection due to large jump in index of refraction
VUV measurements

- 200-1100nm done at Caeleste
- 100-200nm (VUV) at PTB in Berlin
  - Mandatory to do testing in Vacuum.
- UV beam can cause secondary emission which will influence QE results. Shielding required.
VuV measurements - Setup

Caeleste QE test Structures
3 bondwires

PEEK holder with pin hole above the pixel area
Test Setup at PTB
VuV Measurements Results

- Thickness of AR coating has a significant impact on the QE performance.
- Thickness of AR coating = 160nm
- Future measurements planned with thinner AR stack and other AR compositions which are more transparent to UV.
VUV QE is poor: Nature and thickness of ARC not suitable

Gap due to different DUT

Multiple maxima: means ARC is much thicker than λ/4

NIR response proportional to Si thickness
All cases combined

Quantum Efficiency vs Wavelength (nm)

- partially frontside thinned
- BSI thin epi
- BSI thick epi
- BSI thick epi
- BSI 400nm ARC
- classic FSI
- standard
- fully frontside thinned
- BSI 400nm ARC VuV

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Take home messages

- Largest UV sensitivity killer: SiN passivation. BSI or FST are solutions.
- If you want absolutely no interference fringes: fully FST
- If you do not want interference fringes in the UV ➔ green: BSI
- Partial FST yields decent QEs 200-400nm, yet suffers from interference fringes
- Chemical nature and thickness of ARC and Si impacts UV QE
- QE peaks are seen at fractions of ARC wavelength optimum
Questions

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UV peak at 250nm?

- One high energy photon/particle generates a number of e-h pairs
- QE can actually be higher than 100%
- Generation time of e-h pairs no longer random
- Formula of photon shot noise as square root of e-h pairs no longer valid
- Noise will be higher than sqrt(N), excess noise due to non-Poisson distribution
- Peak not very useful