Dark Current Limiting Mechanisms in CMOS Image Sensors

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Introduction to Dark Current

Definition:

Dark current is the signal from a typical pixel that is not due to photons

Corollary:

Photo-carrier collection tends toward equilibrium
Dark current caused by thermal processes does the same
Dark current is a charge-domain offset in dark frames & in image frames

• Dark current is physical charge
• Dark current in current technology is not understood
• Understanding is needed to drive improvement
The present state & mystery [1]

Synthetic dark image appears grainy

Surface plot shows combination of “grainy” gray & of “snow” spikes

- Dark current is what happens in every pixel
- Defects happen only in some pixels – not the subject of this talk
The present state & mystery [2]

1974:
- Room temperature dark current of 2 nA/cm²
- Temperature dependence is SRH \((E_g/2)\)

2015:
- Room temperature dark current of 0.4 pA/cm² ⇒ 5000x improvement
- Temperature dependence is bandgap \((E_g)\)

Canon Inc. ⇒ 20 pA/cm² 60°C

• 5000x improvement in Dark Current;
• Shift in temperature dependence indicates shift in mechanism

CCD Workshop, Edinburgh, UK

EXPERIMENTAL AND CALCULATED CURVES OF DARK CURRENT VS. TEMPERATURE. THE EXPERIMENTAL DATA WAS TAKEN WITH A UNIT EXHIBITING AN AVERAGE DARK CURRENT OF 2 nA/cm² AT ROOM TEMPERATURE. THE TWO ORDINATES ON THE LEFT GIVE THE DARK OUTPUT AND THE CORRESPONDING DARK CHARGE PER PIXEL. THE ORDINATE ON THE RIGHT GIVES THE CALCULATED DARK CURRENT DENSITY.
The present state & mystery [3]

- Dark current data for a selection of world-class CIS foundries:
- Dark current has progressed with nominal 10x scaling per technology node
- Dark current in a technology seems best characterized “per pixel area”

- Commercial applications have & are pushing development as constant improvement
- At some point there is a limit: defect-free silicon limited or device-limited
- Neither is understood

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I want to acknowledge Nobu Terenishi’s talks also exploring root cause of “diffusion” dark current

• Many possibilities exist for dark current in the pixel

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### Pixel: Dark current sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Dependence</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallics</td>
<td>Photodiode depletion region</td>
<td>“$E_g/2$” temperature dependence (~10C doubling); Photodiode depletion area &amp; volume</td>
<td>Reduced by bulk gettering, use of screen oxides, cleaning &amp; implant contamination control</td>
</tr>
<tr>
<td>Interface states</td>
<td>TX-gate-edge depletion region</td>
<td>“$E_g/2$” temperature dependence (~10C doubling); TX gate width dependence</td>
<td>Should be isolated from photodiode by bulk barrier</td>
</tr>
<tr>
<td>Substrate diffusion current</td>
<td>Bulk silicon (depleted &amp; undepleted)</td>
<td>“$E_g$” temperature dependence (~6C doubling); Pixel area dependence; Presence of un-depleted substrate</td>
<td>Minority carrier diffusion; Should be reduced by BSI thinning</td>
</tr>
<tr>
<td>Pinning layer diffusion current</td>
<td>Photodiode pinning layer</td>
<td>“$E_g$” temperature dependence (~6C doubling); Pixel area dependence</td>
<td>Sensitive to dielectric-induced stress</td>
</tr>
<tr>
<td>STI diffusion current</td>
<td>STI edge</td>
<td>“$E_g$” temperature dependence (~6C doubling); STI length; STI depth</td>
<td>Sensitive to STI corner stress; Impact of STI engineering &amp; depth has reduced</td>
</tr>
<tr>
<td>Back surface diffusion current</td>
<td>Back interface for thinned device</td>
<td>“$E_g$” or “$E_g/2$” temperature dependence; Pixel area dependence</td>
<td>Mitigated by accumulation in present BSI</td>
</tr>
<tr>
<td>Contact diffusion current</td>
<td>Contact</td>
<td>“$E_g$” temperature dependence (~6C doubling)</td>
<td>Diffusion through substrate from contact</td>
</tr>
<tr>
<td>Gate injection</td>
<td>TX edge</td>
<td>Weak temperature dependence; Gate voltage dependence</td>
<td>Should be isolated from photodiode by bulk barrier</td>
</tr>
<tr>
<td>Gate-induced diode leakage</td>
<td>TX edge</td>
<td>Weak temperature dependence; Non-linear TX gate voltage dependence</td>
<td>Due to high fields; Isolated from photodiode by bulk barrier</td>
</tr>
<tr>
<td>Spill back dark current</td>
<td>TX edge</td>
<td>“$E_g$” or “$E_g/2$” temperature dependence; TX gate width dependence</td>
<td>Should be isolated from photodiode by bulk barrier</td>
</tr>
<tr>
<td>Dopants</td>
<td>Bulk silicon</td>
<td>“$E_g$” temperature dependence</td>
<td>SRH with shallow traps</td>
</tr>
<tr>
<td>Auger / Impact ionization</td>
<td>Bulk silicon</td>
<td>“$E_g$” temperature dependence</td>
<td>Requires valence band momentum transfer</td>
</tr>
</tbody>
</table>

- More possibilities other than contamination & interface states exist for dark current
Dark Current Temperature Dependence

- TCAD can generate a prediction for defect-free silicon with $\sim E_g$ temperature dependence
- $E_g$ temperature dependence can result from various mechanisms
  - Front or back surface generation & diffusion
  - SRH for traps near the band edge
  - SRH for dopants

3-d simulation of pixel dark current mechanisms. $E_t$ is the SRH trap energy relative to mid-gap. $E_a$ is the activation energy from the slope of the curve.

Ref. 1) H. Rhodes et al, “The Mass Production of Second Generation 65 nm BSI CMOS Image Sensors”, 2011 IISW, Hokkaido, Japan

Ref. 2) E. Smith, “Silicon Image Sensor Technology”, 2012 ISCA, Tokyo, Japan

Ref. 3) M. Kodama et al, “The Development of High-Performance BSI CMOS Image Sensors”, 2013 IISW, Tokyo, Japan
Characterization: probing the pixel

• Temperature dependence
  - Dramatic due to exponential dependence of Boltzmann equation
  - Leads to use of ‘doubling temperature’ as metric:
    - \( \frac{E_g}{2} \sim 11 \text{ C/doubling} \)
    - \( E_g \sim 6 \text{ C/doubling} \)

• Voltage dependence
  - Biasing shapes the depletion region
    - Changes the volume
    - Creates inversion layers
    - Changes the dopants
    - Moves barriers

• Device operation is a window into pixel dynamics
Dark Current Spectroscopy (DCS)

Impact in the Photon Counting World:

- Reduced dark current is critical for photon counting imagery
- The *dark current changes from looking like background noise to looking like “false positive” signal*
- Dark current will be a random phenomenon quantized in space & time

Progression of dark current in the pixel

Dark current quantization means that in the extreme-low dark current required for photon counting most pixels most the time will have no dark current
2-d DCS

- From dark image offset
- From dark image offset & dark image noise

- Interface states
- Substitutional defect
- Substitutional defect

- Many more possibilities exist for dark current
Past progress & present mystery

Past progress:

• Initially uniform dark current was dominated by interface states; these were eliminated by use of inversion & pinning layers: CCD & CIS pinned photodiodes

• Snow-like dark current addressed by using DCS as a tool to relegate metallics to be only “bright pixels” through contamination control & gettering

• Dark current temperature dependence shifted from ~11 C/doubling to ~6 C/doubling

Present conundrum:

• Manufacturing improvements aimed at contamination does not address ~6 C/doubling

• Categorizing ~6 C/doubling as “diffusion current” does not provide an “actionable” root cause
  - Dark current diffusion is backwards from p-n junction diffusion (e- flow is from p-to-n instead of n-to-p)
  - Question of whether “diffusion” in image sensor without recombination

• Root cause is needed to have actionable improvement
Limits of dark current in silicon [1]

Simplistic model for deep-depleted photodiode

a. Model is for deep-depletion photodiode, undepleted pinning layer & undepleted substrate
b. $E_g = 1.12 \text{eV}$
c. Lifetime is limited by Auger process:
   a. electron promoted into conduction band
   b. hole created in valence band
   c. electron or hole that conserves momentum
d. Generation lifetime equals equilibrium recombination lifetime: $\tau_{1/2} = 2.5 \cdot 10^{-3}\text{ s}$
e. No recombination occurs because electrons generated are swept away due to electric fields
f. Charge generation depends on $\Delta n$, the concentration difference from equilibrium

- Simple model based on Auger process looks at “pinning layer + depleted PD + undepleted”

Calculations carried out for nominal $T = 27\text{C}$

Limits of dark current in silicon [2]

Simplistic model for depleted volumes in photodiode

1. Available electrons are the valence band density of states: \( N_V = 3.1 \cdot 10^{19} \text{ cm}^{-3} \)
2. Conduction band electron concentration given by Boltzmann equation:
   \[ n = N_V \exp\left(-\frac{E_g}{kT}\right) \]
   where \( kT = 0.025 \text{ eV} \)
3. In equilibrium the recombination has exponential decay:
   \( \tau_{1/2} = 2.5 \cdot 10^{-3} \text{ s} \)
4. Generation process in all cases equals recombination in equilibrium characterized by the lifetime due to very small acceptor density:
   \[ G = -R = n/\tau_{1/2} \]

\[ G = \frac{N_V \exp\left(-E_g/kT\right)}{\tau_{1/2}} = 450 \text{ e}^-/\text{cm}^3 \cdot \text{s} = 7 \cdot 10^{-5} \text{ pA/cm}^3 \]

\[ G_{FSI}^{dd} (1.5 \mu m) = 9 \cdot 10^{-9} \text{ pA/cm}^2 \]
\[ G_{BSI}^{dd} (2.5 \mu m) = 1.5 \cdot 10^{-8} \text{ pA/cm}^2 \]

• Conclusion: Negligible dark current from depleted volumes

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Limits of dark current in silicon [3]

Simplistic model for undepleted substrate

1. Equilibrium concentration \( n = n_i^2 / N_A \) where \( n_i = 1.0 \cdot 10^{10} \text{ cm}^{-3} \)
2. Removing equilibrium constraint leads to exponential-decay recombination which is doping dependent: \( \tau_{1/2} \) from Figure 1
3. Generation process equals recombination in equilibrium characterized by the lifetime as acceptor density becoming very small: \( G = -R = n / \tau_{1/2} = n_i^2 / (N_A \cdot \tau_{1/2}) \)
4. Pinning layer is doped \( 3 \times 10^{18} \text{ cm}^{-3} \) with 0.1 \( \mu \text{m} \) depth: \( \tau_{1/2} = 10^{-6} \text{ s} \)
5. Collection volume for FSI is doped \( 1 \times 10^{15} \text{ cm}^{-3} \) with 6.5 \( \mu \text{m} \) depth: \( \tau_{1/2} = 2 \times 10^{-4} \text{ s} \)
6. Collection volume for BSI is effectively zero

\[
G^{\text{pin}} = (1.0 \cdot 10^{10} \text{ cm}^{-3})^2 / (2 \cdot 10^{18} \text{ cm}^{-3} \cdot 10^{-6} \text{ s}) = 3.5 \cdot 10^7 \text{ cm}^{-3} \cdot \text{s}^{-1} = 6 \text{ pA/cm}^2
\]

\[
G_{(0.1 \mu \text{m})}^{\text{pin}} = 6 \cdot 10^{-5} \text{ pA/cm}^2
\]

Calculations carried out for nominal \( T = 27 \text{C} \)

\[
G^{\text{collect}} = (1.0 \cdot 10^{10} \text{ cm}^{-3})^2 / (1 \cdot 10^{15} \text{ cm}^{-3} \cdot 10^{-4} \text{ s}) = 1.4 \cdot 10^9 \text{ cm}^{-3} \cdot \text{s}^{-1} = 2 \cdot 10^2 \text{ pA/cm}^3
\]

\[
G_{(6.5 \mu \text{m})}^{\text{FSI}} = 1.4 \cdot 10^{-1} \text{ pA/cm}^2
\]

\[
G_{(0 \mu \text{m})}^{\text{BSI}} = 0 \text{ pA/cm}^2
\]

• Conclusion: FSI undepleted substrate is dominant dark current

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Limits of dark current in silicon [4]

**Discussion**

- Image sensors have not reached the limits of dark current possible in "perfect" silicon, so process improvements are still important to reach the fundamental limit.
- FSI is approaching these limits due to the generation in the undepleted collection volume.
- BSI could also approach this limit if it introduces thicker silicon enabled by better pixel-to-pixel isolation.
- Process improvements that increase the depletion volume should lower the fundamental limits without trading off spectral response.

**Dark current generation rate (27C)**

\[
G_{FSI}^{dd} = G_{FSI}^{dd}(1.5 \, \mu m) + G_{FSI}^{pin}(0.1 \, \mu m) + G_{FSI}^{collect}(6.5 \, \mu m)
\]

\[
= 9 \cdot 10^{-9} \frac{pA}{cm^2} + 6 \cdot 10^{-5} \frac{pA}{cm^2} + 1.4 \cdot 10^{-1} \frac{pA}{cm^2}
\]

\[
= 1.4 \cdot 10^{-1} \frac{pA}{cm^2}
\]

\[
G_{BSI}^{dd} = G_{BSI}^{dd}(2.5 \, \mu m) + G_{BSI}^{pin}(0.1 \, \mu m) + G_{BSI}^{collect}(0 \, \mu m)
\]

\[
= 1.5 \cdot 10^{-8} \frac{pA}{cm^2} + 6 \cdot 10^{-5} \frac{pA}{cm^2} + 0 \frac{pA}{cm^2}
\]

\[
= 6 \cdot 10^{-5} \frac{pA}{cm^2}
\]

Calculations carried out for nominal T = 27C

• Dark current limit for simple model
Looking into a crystal ball darkly

• Conjectures:
  - Commercial pressures will continue to push to reduce dark current
  - General view that improvement is natural fallout from advancing technology nodes
  - Improvement would be helped by identifying root cause of the dominant defect(s)
  - Understanding the root cause provides opportunity for design-driven improvement
  - Data is needed for actionable understanding
  - There will be a point where silicon rather than defects becomes the limitation ⇒ only design-driven improvements will be possible

• Dark current reduction is actionable
Illumination

• SRH theory has provided a means to understand & eliminate a predominant source of dark current

• Dark current has gone from “gray” background to quantized snow and back to “gray” background. It is about to again be quantized, *this time in space & in time*

• There is no root cause to understand the present dark current

• There is a need for data & analysis

• It is unclear when dark current will hit the limit of pure silicon where process improvements will no longer help.

• When there is an identified root cause then there is the possibility for improvement through design

• Understanding of dark current root cause and limits is needed