Recent Progresses of Visible Light Image Sensors

February 23, 2018

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University of Hyogo / Shizuoka University
Contents

1. Basics of Visible Light Image Sensors
2. Dark Current and Blemish
3. Pinned Photodiode (PPD)

Recent Progresses
4. Photon Counting Image Sensor
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6. Near InfraRed (NIR)
7. ToF (Time of Flight)
8. Polarization Image Sensor
9. Monocular 3D Image Sensor

10. Queen Elizabeth Prize for Engineering
What is Image Sensors?

- Semiconductor device, which converts light image to electric signal.
- Used in cameras.

Examples of applications

- Smartphone
- Movie
- Automobile
- Endoscope
- Iris verification
- Security

Image Sensor

- DSC
- Image sensor
- Pixel array

Pixel cross-section

- Light
- Microlens
- Color filter
- Photodiode

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- IS sales amount has grown by camera phone.
- IS spreads into various applications,
- "Others" includes scientific, industrial, ...

(Source: TSR)
Pixel Structure

Cross-section of frontside illumination type CMOS image sensor pixel

- microlens (ML)
- Color filter (CF)
- Amplifier (SF)
- Transfer gate (TG)
- Detective capacitance (Floating diffusion (FD))
Based on (Piet De Moor (IMEC))

Sensitivity Expansion to Invisible

Inner Shell Excitation

Large depletion is needed.

Small surface dead layer is needed.

Visible light

X-ray

Absorption Length (μm)

0.01

0.1

1.0

10

100

1000

10,000

Photon Energy (eV)

10

100

1000

1000

Near UV

Near IR
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Classification of Dark Current and Blemish

Average: Dark current
- Dark current shot noise
- Black level shift by temperature

Dark current FPN (Dark current pixel-by-pixel fluctuation)

Micro white blemish (Mid-range)

White blemishes (Large-range)

Very large level blemish by radiation damage
Metal Contamination (1)

- Metals, especially transition metals, form mid-gap levels, which become GR centers.
- Generate dark current based on Shockley–Read–Hall (SRH) process

\[
U = \sigma_{th} N_t \frac{pn - n_i^2}{n + p + 2n_i \cosh \left( \frac{E_t - E_i}{kT} \right)}
\]

Assuming the cross sections, \( \sigma_n = \sigma_p = \sigma \)

\( N_t \): GR center (trap) density

- Assuming depletion condition, then, \( n, p = 0 \), and \( E_t = E_i \) because \( U \) becomes the largest;

\[
U = -\frac{\sigma_{th} n_i N_t}{2} \quad \text{(Unit : 1/cm}^3 \text{s})
\]

- One GR center generates \( U = -\frac{\sigma_{th} n_i}{2} \), (Unit : 1/s)

\( U \): Recombination Rate
(Sze: “Semiconductor Devices” Chap. 1 Eq.(59))

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"Dark Current Spectroscopy" identifies metals and estimates concentrations.

It can measure very small amounts of metal contamination.

(D. McGrath et al. (TI); “Counting of Deep-Level Traps Using a Charge-Coupled Devices”)
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PPD (Pinned PD) Structure and Advantages

1. Grounded P⁺ pinning layer prevents interface to be depleted, and stabilizes PD electrically.
   - Low dark current
   - Large saturation
   - High blue sensitivity

2. Complete electron transfer
   - No image lag,
   - No transfer noise

Shallow P⁺ pinning layer (Low energy implantation) ⇒ Good electron transfer

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Dark Current Reduction by PPD

- Theoretical dark current reduction ratio using Shockley–Read–Hall Process:

\[
\frac{|U(\text{Not depleted})|}{|U(\text{Depleted})|} \leq \frac{\sigma v_{th} N_t n_i / 2}{\sigma v_{th} N_t n_i^2 / p} = \frac{p}{2n_i} \sim 10^{-7}
\]

Assuming hole density \((p)\) at the P+ pinning layer is \(10^{17} \, \text{h}^+ \, \text{cm}^{-3}\)

- Actual dark current reduction ratio:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme</td>
<td>CCD</td>
<td>FSI CMOS</td>
<td></td>
</tr>
<tr>
<td>Pixel size</td>
<td>23 x13.5</td>
<td>1.12 x 1.12</td>
<td>μm</td>
</tr>
<tr>
<td>Dark current</td>
<td>1,300</td>
<td>5.6</td>
<td>e⁻/s/μm² at 60℃</td>
</tr>
</tbody>
</table>

Still big reduction! ©2018 N. Teranishi
Example of Dark Current Reduction by PPD

If Dark current is reduced, dark current FPN, and dark current shot noise are also reduced.

Dark current FPN is suppressed, then, picture quality is much improved.
Saturation is Increased by PPD

Saturation becomes 12 times larger by PPD.
- PN junction area is increased.
- Acceptor density at pinning layer $\gg$ Donor density at storage.

Saturation by simulation

$12.5\text{ times}$

1984 B. C. Burkey et al. (Kodak)
Shrinkage has been carried out steadily.

- Lens volume and weight become 1/1000 when pixel size becomes 1/100, assuming that F-number, view angle and pixel number are constant.

- Mass production year

- 50% shrinkage in 3.5 years

- 24 years

- 1/100

- Minimum Pixel Area (um²)

- Mass Production Year

- CCD

- CMOS
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Photon Counting Image Sensor

**SPAD**
(Single photon avalanche diode)

- QVGA SPAD, 20 fps, room temperature
- High avalanche gain makes following circuit noise negligible.
- Large dark count. Small fill factor

(N. Dutton et al., VLSI Symposium 2014)

**4-Tr CMOS + High conversion gain + CMS (Correlated multiple sampling)**

- In 2015, several organization reported low noise < 0.3 e- rms.
- DEPFET (Max Plank)

(MW. Seo, S. Kawahito et al., IEEE EDL 2015)
Photon Counting (2)

(a) Original object (USAF test chart)

(b) Image by the RG-less CIS ($0.27e^{-}_{rms}$)

(c) Image by a conventional low-noise CIS ($0.44e^{-}_{rms}$)

(Seo, Kawahito et al, IEEE EDL, Dec. 2015)

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Motivation of stack image sensors
- Non-silicon material for sensor part
- Finer process technology for logic part
- Smaller footprint
- More flexibility of wiring
- Isolation between analog and digital circuits

Approach
- Bump bonding (In, solder Au, etc.)
- SOI
- Wafer-to-wafer oxide bonding + TSV
- Wafer-to-wafer hybrid bonding
Stack (2). Wafer-to-Wafer Oxide Bonding

Wafer-to-wafer oxide bonding + TSV(Through silicon via) at peripheral

- Smaller chip size → Smaller camera, lower cost
- Optimal processes for both sensor and logic
- More functions can be integrated.

Suitable for large volume applications
Stack (4). Wafer-to-Wafer Hybrid Direct Bonding

- Oxide bonding + TSV (Through silicon via) Interconnections are limited at only peripheral.

- Hybrid bonding Interconnection can be located at pixel array also.

- Cu2Cu optimized CMP
  - Gap height (a.u.)
  - < 150 °C
  - BEOL CMP

- Post-bond annealing
  - Y. Kagawa et al. (Sony), IEDM 2016

- 2 um pitch interconnection
  - E. Beyne (IMEC), 2018

K. Shiraishi et al. (Toshiba), ISSCC 2016

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NIR --- Motivation

1. To cover shortage of visible light and to increase sensitivity
   eg. Most illuminations have NIR.
   Night glow
   • Security use

2. Invisible for mankind and animal.
   • Gesture interface, ToF,
   • Animal observation at night

3. Eye safe laser (1.4–2.6um)
   • Longer than Si cutoff wavelength

4. Specific wavelength for each application
   • Window to living organisms
   • Fluorescent protein
   • Hemoglobin (Hb)
   • Bill validator (NIR and UV inks are used.)

5. Smaller sunlight background
Nightglow (Airglow)

- Emission in the upper atmosphere
  - Photoionization by the sun
  - Luminescence by cosmic ray
  - Chemiluminescence
- Light intensity at near IR is larger than that of visible light

<table>
<thead>
<tr>
<th>Wavelength ($\lambda$)</th>
<th>Photons (/cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4-0.7 $\mu$m (visible)</td>
<td>$7 \times 10^8$</td>
</tr>
<tr>
<td>0.4-1.0 $\mu$m (Si)</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>0.4-1.4 $\mu$m</td>
<td>$2.5 \times 10^{10}$</td>
</tr>
<tr>
<td>0.4-2.0 $\mu$m</td>
<td>$1 \times 10^{11}$</td>
</tr>
</tbody>
</table>

Intensity of night glow

http://en.wikipedia.org/wiki/Nightglow

Night glow from ISS

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1.4 – 2.6 μm wavelength light hardly reaches retina.

Application: Night vision, range finder, obstacle detection

Note: Silicon cannot detect 1.4 – 2.6 μm wavelength light.
Window to Living Organisms

- NIR, 700~900 (1400) nm, has a good transmittance of human body.
- It can pass through even 30 cm thick human body.

Specific wavelengths
- Hemoglobin (Hb):
  Oxygen density in vein
- Myoglobin:
  Oxygen density in cardiac muscle and skeleton muscle
- Cytochrome c oxidase (COX)
- Melanin

Application
- Vein authentication
- Optical topography
- Fluorescent protein

Absorptance of hemoglobin and water

https://www.an.shimadzu.co.jp/bio/nirs/nirs2.htm
NIR Fluorescence Imager (ICG Fluorescence)

- Portable intraoperative diagnosis
- Both excitation light and fluorescence light are inside the widow of living organisms.

ICG: Indocyanine-green

Excitation light (760 nm) → Fluorescence light (830 nm) → ICG

Visible light image → NIR fluorescence image

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ToF, for example, uses active illumination or modulated illumination.
Longer wavelength at NIR, the sunlight background becomes smaller, and SN ratio will be improved.
Absorption of NIR and X-ray in Silicon

- Large depletion layer is needed to detect NIR or X-ray. For example, 900 nm wavelength NIR (equivalent with 5.4 keV X-ray) is absorbed half by 15 um silicon.
  
  ref: 3 um silicon for 700 nm
NIR QE Increase (1), Pyramid Surface for Diffraction

- Pyramid Surface, which enhances diffraction.
- DTI (deep trench isolation) between pixels to suppress crosstalk

Increase effective sensor thickness and increase NIR QE.

Infrared light

Pyramid surface ofr diffraction

Wavelength [nm]

(2017IEDM Oshiyama (Sony))
Black Silicon

- Black silicon is formed on illuminated surface by femtosecond laser
- As well as NIR QE is much improved, the cutoff wavelength is enlarged beyond 1.2 μm.

Pulse Number dependence (50 μm square)

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Ge Image Sensor for NIR

(B. Ackland et al. 2009)

Figure 2 - Germanium selective growth

Figure 3 - Germanium diode embedded in CMOS

Figure 4 - Pixel circuit

Figure 13 - Moonless night image
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ToF (Time of Flight) Mechanism

Modulated light source

ToF setup

ToF image sensor

Intensity image

Distance image by ToF
(Kawahito Lab., Shizuoka University)

Intensity vs. Time

Distance = $\frac{1}{2} c \Delta T$  \hspace{1cm} (c: light velocity)

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http://www.idl.rie.shizuoka.ac.jp/study/project/tof/index_e.html
ToF Applications

- **Gesture input**: game, medical, digital signage, automobile
- **Range finder, 3D measurement**: automobile, dental, robot

Game
(EETimes Japan, 2011)

Digital signage

Dental
(C. Niclass, ISSCC 2013)
ToF Challenges (Multi-Pass Errors)

- To resolve the multi-pass errors is challenge at ToF.

(a) Normal

(b) Reflector

(c) Semi-Transparent

(d) Corner
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Optical Rotation

Metal grid polarizer
(Tokuda 2011 IISW)

Stress image (Plastic lens)
https://www.4dtechnology.com/

Antireflection
R. Muller
ISEurope2017

Output

10^3
10^2
10^1
10^0

0 45 90 135 180
Polarization angle (degree)

43.7

Extinction ratio = 43.7
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Monocular 3D Image Sensor

Monocular 3D is required instead of binocular 3D
- Compact,
- No precise assembling is needed.

(S. Koyama et al. @ Panasonic, ISSCC 2013)
New world of image sensors

Human sees photos and videos.

Computer vision (Computers see photos)

New Functions

[Images of various sensors and applications]

Range image
(Kawahito, Shizuoka University)

Fluorescence lifetime image

Driving assistance
(Subaru)

Face recognition
(NEC)

Gesture input

Barcode

Robot
(SoftBank)

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Purpose: The world’s most prestigious engineering prize, to celebrate world-changing innovations in engineering.

Citation: The creation of digital imaging sensors.

Winners:
- Eric Fossum: CMOS image sensor
- George Smith: CCD (Charge-Coupled Device)
- Nobukazu Teranishi: Pinned photodiode (PPD)
- Michael Tompsett: CCD image sensor
The Master of the Household
has received Her Majesty’s command to invite

Professor Nobukazu Teranishi
to a Reception to be given at Buckingham Palace for
The Queen Elizabeth Prize for Engineering 2017
in the presence of
H.R.H. The Prince of Wales
on Wednesday, 6th December, 2017 at 12.40 p.m.

A reply is requested to:
The Master of the Household
Buckingham Palace, London SW1A 1AA
Email: master.household@royal.gov.uk

Guests are asked to arrive between 12.15 and 12.30 p.m.

Dress: Lounge Suit / Day Dress

Reception at Guildhall hosted by the Lord Mayor of London

http://www.guildhall.cityoflondon.gov.uk/gallery
From left, Prince Charles, Eric Fossum, Michael Tompsett, Nobukazu Teranishi (Absent: George Smith)
Impression

- Proud and happy
  The best award for engineers

- Lucky
  There are so many important and beneficial technologies.

- Acknowledgement
  To family, teachers, seniors, colleagues, and everybody

- Step-up
  I would like to grow up as a person of the Prize.

- Education for engineers
  Good engineers are needed to evolve industries.
  So, I would like to introduce respectable engineers to young generation, and help them to learn technologies.

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Anyone can take a photo anywhere, anytime!

Thank you!
Pixel Shrinkage — Crosstalk —

Crosstalk effect:
- Color mixture, degradation of chromatic S/N.
- Degradation of resolution

① Angled incident light

② Multi-reflection, Diffraction

③ Charge diffusion

~3 um

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**Pixel Shrinkage — DTI (Deep Trench Isolation) —**

- BSI is used for small pixel to reduce crosstalk and increase sensitivity.
- DTI suppress both optical cross talk and charge diffusion cross talk.

**B–DTI (Back–side DTI)**
- DTI is formed from backside.
- Metal is buried in DTI.
- Sufficient cross talk reduction
  (Y. Kitamura et al. (Toshiba), IEDM, 2012)

**F–DTI (Front–side DTI)**
- DTI is formed from front side.
- Poly–silicon is buried in DTI.
- Better DTI interface
  (JC Ahn et al. (Samsung), ISSCC, 2014)
Dark Current Possible Causes

Large electric field at TG edge
Large electric field at P⁺ /N junction
PD interface GR center

TG interface GR center
FD dark current
RG off-leak

Charge flow from the outside
STI interface GR center
Diffusion current
Depleted region GR center

- Pixels should be carefully designed by using precise ion implantations.
- Implantations occasionally bring metals and damages into silicon.
Causes of Image Lag in PPDs (1)

(A) Small electric field

(B) Barrier at the PD edge

(C) Pocket at the TG edge

(D) Pump back when the signal is large

(E) Traps at the TG interface

On the next slide.
(E) Traps at the TG interface

If the electron transfer path touches the interface, some electrons are captured by traps.

- Some of them are detrapped in the following frames, causing lag.
- Some of them are annihilated, causing non-linearity.

- The signal electron annihilation exhibits this kind of non-linearity.
- A buried transfer path is needed to suppress these phenomena.
Pixel Shrinkage Trend

- Shrinkage speed becomes slower recently.
- In 2017, 0.9 um pixel began to be mass produced.

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Stack (3). Pixel–DRAM–Logic Oxide Bonding

19.3 Mpixel

- Wafer bond
- Middle wafer thinning
- TSV and wire formation

1 Gbit

- Wafer bond
- Top wafer thinning
- TSV formation

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(WikiChip Fuse, 2018/02/3)
On-chip Optics Functions

(1) Light collecting
   Microlens
   Lightpipe
   BSI (Back Side Illumination)

(2) Color filtering
   Color filter
   Vertical color separation

(3) New specific functions
   Polarization image sensor
   Phase detection autofocus
   Computational photography

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RGB–IR Image Sensor

- RGB–IR image sensor is proposed to obtain IR image and RGB image simultaneously.
- Double bandpass filter in stead of conventional IR-cut filter is used to detect NIR.
- Color reproducitvity is not sufficient.