EDET DH80k – Characterization of a DePFET based sensors for TEM Direct Electron Imaging

VCI2019 - The 15th Vienna Conference on Instrumentation
19/02/2019

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Motivation and Introduction

DePFET Structure and Measurement Setup

Optimization of Operation Parameters and Response Function

Summary and Outlook
Motivation for the project

Stroboscopic imaging provides insights to the dynamics of processes:

• short, discrete illumination periods with high intensity
• decouples exposure time, image contrast and motion blur
• pulse intensity defines the image contrast
• frequency of illumination defines time resolution
• pulse duration defines impact of motion blur
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Challenges of stroboscopic imaging in TEM world:

• real space imaging → high granularity
• high intensity → high dynamic range
• direct electron detection → thin substrate
• high pulse frequency → high framerate
• “grey scale” image → no data reduction possible
Introduction to the camera system and its challenges

Camera system:

- focal plane area (FPA) consists of 4 individual and independent modules ("tiles"), each capable of stand-alone operation
- small sensitivity gap between tiles (1.2 mm)
- All Silicon Module (ASM)
- readout in rolling shutter mode, 100 ns/row, 4 rows in parallel
- maximum framerate of 80 kHz or 12.8 µs/frame
- front end electronics (FEE) buffers bursts (movies) with 100 frames
- maximum burst rate 100 Hz

Data rate:

- 8 bit digitization resolution:
  - tile module data rate of ~3 GB/s
  - total data rate of ~12 GB/s
- data reduction difficult if not impossible

sensor array (30.7 x 30.7) mm²

array of drain current digitizer (DCDE) ASICs

array of digital movie chip (DMC) ASICs

bondpads for DCD/DMC data & supplies

JTAG bias contacts switcher bank test pads

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Introduction to the camera system and its challenges

Sensor array

- 1 MPixel for the complete FPA
- 512 x 512 pixels per tile
- (60 x 60) μm² pixel size

Dynamic range of pixels:

- single primary e⁻ sensitivity
- capable of storing the signal from 100 primary e⁻ at 300 keV (~800k signal e⁻)

Spatial resolution improvements:

- reduce e⁻ multiple scattering
  - thin sensitive detector substrate (50 μm and 30 μm)
- reduce e⁻ back scattering
  - no support layer
  - highly effective beam dump
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The DePFET structure and its positive sides

Depleted p-channel Field Efect Transistor on high resistive n-doped bulk

• integrated 1st stage amplification ($g_q$)
• charge storage capability
  • readout on demand
  • rolling shutter mode
• small capacitance and low noise
• high quantum efficiency and fill factor
• fully depleted bulk
  • optionally thinned
• front- or back-side illumination possible
• easily scalable
• adjustable dynamic range
• signal compression
  • achieved by overflow charge storage regions with different $g_q$
The DePFET structure and its operation principle

Two states of operation:

- **OFF state:**
  - idle state, no power dissipation, but collecting signal charge

- **ON state:**
  - transistor current depending on signal charge in internal gate
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![Graph showing DePFET operation](image)
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The DePFET structure and its operation principle

INITIAL STATE VS. FILLED STATE

INITIAL DePFET RESPONSE IS LINEAR CALIBRATION WITH A KNOWN RADIOACTIVE SOURCE
The EDET DePFET structure and its operation principle

INTERNAL GATE is under the GATE
1st OVERFLOW REGION is around the SOURCE
2nd OVERFLOW REGION is under the SOURCE

Response curve $V_{ds} = -5\,\text{V}$

Drain current [mA] vs. Collected charge [$10^6\,\text{electrons}$]
Measurement setup

Design concept: MODULARITY
Measurement setup

Design concept: MODULARITY

Operating principle
Measurement setup

Design concept: MODULARITY
Measurement setup

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operating principle

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Measurement setup

Design concept: **MODULARITY**

**Operating principle**
Single PIXle setup

actual setup

Design concept:

MODULARITY
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Measurements – operation window
on depleted 50 μm thick EDET structures

Clear Gate and Clear low voltage influence

- back-emission of e⁻ from clear contact,
- inversion (parasitic channel under the Clear Gate), and
- charge loss to clear contact.

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**W09 F07**

- Thickness: 50 μm
- Gate L: 5.0 μm
- Gate W: 27.2 μm
- Drain: -5.0 V
- Source: 0.0 V
- Gate Off: 5.0 V
- Gate On: -2.17 V
- Clear low: sweep
- Clear high: 17.0 V
- Clear Gate: sweep
- Depletion: -35.0 V
- Bulk: 10.0 V
- Drift: -5.0 V
- Guard: -5.0 V

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**NO EXTERNAL ILLUMINATION; OBSERVING ONLY THE INITIAL STATE**

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Overlay (red box) of an identical measurement done with the smaller version of the final camera setup.
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LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO \( \sim 10 \times 55 \text{Fe K}_{\alpha} \)

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LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X ^{55}Fe Kα
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![Graph showing Clear Gate low sweep and other voltages](image)

LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO \(~10^5\)\(^{55}\)Fe K\(_{\alpha}\)

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LED FLATFIELD ILLUMINATION (FFIL); 1 INJECTION CORRESPONDS TO ~10X $^{55}$Fe K$_\alpha$

1.8M SIGNAL $e^-$

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Measurements – incomplete clear on depleted 50 μm thick EDET structures

Clear high voltage and clear pulse length ($t_c$) influence

- efficiency of complete charge removal from internal gate and overflow regions.

Slow switching stage of SwitcherS ASIC limits $t_c > 70$ ns. Final camera setup $t_c \sim 20$ ns achieved with SwitcherB ASIC.

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- **Clear high**: sweep
- **Clear Gate**: -0.5 V
- **Depletion**: -35.0 V
- **Bulk**: 10.0 V
- **Drift**: -5.0 V
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**FFIL; SMALL SIGNAL CHARGE ~2.5X $^{55}$Fe $K_{α}$; HARDEST TO REMOVE**

4k SIGNAL \( e^- \)

METHOD I.

- $g_e = 293 \text{ pA} / \text{e}^-, \ 1 \text{ mV} \approx 137 \text{ e}^-$
- $q_{\text{max}} = 27 \text{ mV}$

METHOD II.

- $g_e = 293 \text{ pA} / \text{e}^-, \ 1 \text{ mV} \approx 137 \text{ e}^-$
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<td>-5.0 V</td>
</tr>
<tr>
<td>Guard</td>
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**FFIL; Almost Full Internal Gate**

$g_{inj} = 293 \text{ pA/e}^-$, $1 \text{ mV} \approx 137 \text{ e}^-$

$\theta_{inj, \text{ max}} \approx 244 \text{ mV}$

40k SIGNAL $e^-$

**FFIL; Filling the Overflow Regions**

$g_{inj} = 293 \text{ pA/e}^-$, $1 \text{ mV} \approx 137 \text{ e}^-$

$\theta_{inj, \text{ max}} = 403 \text{ mV}$

**METHOD I.**

**METHOD II.**

90k SIGNAL $e^-$

19/02/2019
Measurements – incomplete clear on depleted 50 μm thick EDET structures

Clear high voltage and clear pulse length ($t_c$) influence

- efficiency of complete charge removal from internal gate and overflow regions.

Slow switching stage of SwitcherS ASIC limits $t_c > 70$ ns. Final camera setup $t_c \sim 20$ ns achieved with SwitcherB ASIC.

W09 F07

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<tr>
<td>Clear high sweep</td>
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Measurements – charge collection on depleted 50 μm thick EDET structures

Depletion and Drift voltage influence

- integrated 1st stage amplification ($g_q$),
- charge loss to Clear, and
- charge loss to Drift region.

W09 F07

Thickness 50 μm
Gate L 5.0 μm
Gate W 27.2 μm

Drain -5.0 V
Source 0.0 V
Gate Off 5.0 V
Gate On -2.17 V
Clear low 1.0 V
Clear high 18.0 V
Clear Gate -0.5 V
Depletion sweep
Bulk 10.0 V
Drift sweep
Guard -5.0 V

4.5k SIGNAL $e^-$
Measurements – charge collection
on depleted 50 μm thick EDET structures

Depletion and Drift voltage influence
• integrated 1st stage amplification ($g_q$),
• charge loss to Clear, and
• charge loss to Drift region.

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Drain      -5.0 V
Source     0.0 V
Gate Off   5.0 V
Gate On    -2.17 V
Clear low  1.0 V
Clear high 18.0 V
Clear Gate -0.5 V
Depletion  sweep
Bulk       10.0 V
Drift      sweep
Guard      -5.0 V
Measurements – charge collection
on depleted 50 μm thick EDET structures

Depletion and Drift voltage influence

• integrated 1st stage amplification ($g_q$),
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Operational point also depends on the drift and the depletion current due to problematic heat dissipation in thin devices.
Measurements – charge collection on depleted 50 μm thick EDET structures

Depletion and Drift voltage influence

• integrated 1st stage amplification ($g_0$),
• charge loss to Clear, and
• charge loss to Drift region.

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Drain -5.0 V
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Gate Off 5.0 V
Gate On  -2.17 V
Clear low 1.0 V
Clear high 18.0 V
Clear Gate -0.5 V
Depletion sweep
Bulk  10.0 V
Drift sweep
Guard  -5.0 V

FFIL; SMALL SIGNAL CHARGE ~2.8x $^{55}$Fe Kα

OPERATIONAL POINT ALSO DEPENDS ON THE DRIFT AND THE DEPLETION CURRENT DUE TO PROBLEMATIC HEAT DISSIPATION IN THIN DEVICES.
Measurements – noise v integration time

on depleted 50 μm thick EDET structures

Integration time (t_int) influences
• the overall noise performance of the system.

Noise dominated by Leakage Current and Common Mode Noise.

W09 F07

Thickness 50 μm
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Drain -5.0 V
Source 0.0 V
Gate Off 5.0 V
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Clear low 1.0 V
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Clear Gate -0.5 V
Depletion -21.0 V
Bulk 10.0 V
Drift -5.0 V
Guard -5.0 V

55Fe RADIOACTIVE SOURCE ILLUMINATION

NOISE: 12.7 e−
FWHM: 186 eV
Measurements – noise v integration time on depleted 50 μm thick EDET structures

Integration time \((t_{int})\) influences
• the overall noise performance of the system.

Noise dominated by Leakage Current and Common Mode Noise.

\(55\text{Fe RADIOACTIVE SOURCE ILLUMINATION}\)

\[ g(x) = Ae^{-\frac{(x-x_0)^2}{2\sigma^2}} \]

\(g_{\text{ch}} = 290 \text{ pA} / \text{e^-} \)

\(\text{FWHM: } 163 \text{ eV} \)

\[
\begin{array}{|c|c|c|c|}
\hline
A & \mu & \sigma \\
\hline
4.75 \times 10^3 & 0.80 \times 10^3 & 3.88 \times 10^{-2} \\
2.26 \times 10^3 & 5.89 \times 10^3 & 6.93 \times 10^{-2} \\
\hline
\end{array}
\]

\(W09\text{ F07}\)

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Measurements – noise v integration time

Integration time ($t_{int}$) influences
• the overall noise performance of the system.

Noise dominated by Leakage Current and Common Mode Noise.
Response function – Calibration of depleted 50 μm thick EDET structures

Procedure:

• insertion of fixed amount of charge by $^{55}\text{Fe}$ radioactive source at optimized operation voltages

• extraction of the primary $g_q$

• explore the full dynamic range with calibrated LED pulses and leakage current

$W09\ F07$

Thickess 50 μm
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$\text{55Fe RADIOACTIVE SOURCE ILLUMINATION}$

$s_F = 291 \ \text{pA/e}^-$

$\text{y(x)} = Ae^{-(x-\mu)^2/2\sigma^2}$

$\text{Ch4: } t_{\text{int}} = 3200 \text{ ns}$

$\text{noise fit}$

$\text{noise fit area}$

$\text{K_a fit}$

$\text{K_a fit area}$

NOISE: $10.3 \ \text{e}^-$

FWHM: 168 eV

$g_q = 291 \ \text{pA/e}^- \ (1 \pm 0.014)$
Response function – Dynamic range
of depleted 50 µm thick EDET structures

Procedure:

• insertion of fixed amount of charge by $^{55}\text{Fe}$ radioactive source
  at optimized operation voltages

• extraction of the primary $g_q$

• explore the full dynamic range with calibrated LED pulses and
  leakage current

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PRIMARY $g_q = 291 \text{pA/e}^- (1 \pm 0.003)$
SECONDARY $g_q = 70 \text{pA/e}^- (1 \pm 0.10)$
LEAKAGE $I_L = 0.57 \text{e}/\mu\text{s}(1 \pm 0.05)$
Summary and outlook for the project

DePFETs
• extremely versatile detectors
• established in spectroscopy
• paving their way in the tracking applications

EDET project
• pilot production successfully finished, fabrication of the main batch has been resumed
• pilot devices showing expected results
  • signal compression
  • dynamic range of >800k signal e⁻
  • operation window big enough to operate the large area devices
• commissioning of the first tile modules with FEE without movie storage (Belle II DHP ASICs) in 2Q2019
• FEE with movie storage (DMC ASIC) currently under evaluation at MPG HLL
• commissioning of the first fully EDET tiles in late 4Q2019
THANK YOU FOR YOUR ATTENTION!
Backup slides
### Common mode noise

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### 55Fe RADIOACTIVE SOURCE ILLUMINATION

**WITHOUT CMC**

![Graph](image1)

**WITH CMC**

![Graph](image2)

m19 px4, $t_{exp} = 100$ μs  
m20 px4, $t_{exp} = 50$ μs  
m21 px4, $t_{exp} = 30$ μs
Common mode noise

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55Fe RADIOACTIVE SOURCE ILLUMINATION

WITHOUT CMC

WITH CMC

20 % CHANGE IN $\sigma_{\text{noise}}$
Radiation hardness

Radiation causes positive charge buildup in Oxide:

- homogeneous radiation – compensated by gate voltage shifts
- inhomogeneous radiation – could cause problems