R&D on Counting Pixel Chips

Yunpeng Lu
Outline

• Motivation
• Fundamental Issues
• Current Mirror & Amp-Sha-Disc
• Nested-Wells & DSOL
• Summary
Motivation(1)

• Shielding is a key issue in SOI Pixel Technology, and Counting Pixel is an effective measure to study it.
  – Necessity of shielding was recognized and understood by F. X. Pengg
  – Integrating pixel works fine with BPW suppressing back gate effect (Why no charge injection observed? Slow slew rate/ Cancelled by integration?)
  – But in counting pixel, charge injection messed up the counting results.

Shielding-well proposed by F. X. Pengg in his dissertation “Monolithic Silicon Pixel Detectors in SOI Technology”

Good concept but not implemented successfully.

Figure(2.11a): The n+-p-n- structure of shield and well in the high resistivity substrate, cut.
Motivation(2)

- Counting Pixel is getting more and more popular in synchrotron radiation application.
- Particularly interested in the area detector proposed by Prof. Kishimoto.
  - 30 um$^2$ pixel size
  - 1k frames/s
  - 14 bit counter
  - Low energy X-ray 2~4 keV

Very compact pixel circuit and good S/N required!
Fundamental Issues

• On-chip circuit
  – Amp-Sha-Disc system
  – Counter and register in pixel

• Shielding
  – Nested-wells
  – Double SOI

• Leakage current
  – Low temperature would mitigate it

• Radiation damage
  – Should be fine if back-illuminated by low energy X-ray
Review of CPIXTEG2 results

- Amp-Sha-Disc system
- Counter and Register
- Bias and Aobuf
- Current Source variation
- Shielding between analog and sense node
- Response of Light stimulus
- Shielding between counter and sense node not reported

測定実施TEGR一覧

<table>
<thead>
<tr>
<th>N基板用及び[N.P]基板共用TEGR</th>
<th>P基板用TEGR</th>
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<tr>
<td><strong>TEG種別</strong></td>
<td><strong>TEG種別</strong></td>
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<td>Pixel array</td>
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<tr>
<td>Preamp+Shaper+Discrim.</td>
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Continuing efforts of Nested-wells on CPIXTEG3

New nested-wells layout:
- Expand to full pixel
- More BNW contacts

CPIXTEG3
TEG04C_N
Findings though CPIXTEG2/3

- Low current source variation (double checked)
- Insufficient shielding efficiency if the sense node overlaps with Discriminator or Counter (measured on CPIXTEG3)
  - Shielding between shaper and sense node is good (double checked)
- A new chip CPIXTEG3b designed on basis of above findings.
The Krummenacher Scheme and current source

• The kummenacher scheme was adopted for Preamp and Shaper in cpixtcg2/3 design.
  – Baseline of output can be set by Vref, which is good for DC coupling to the next discrimination stage.
  – However, its operation relies on the exact ratio of $I_{\text{source}_h}$ and $I_{\text{source}_l}$.

• CPIXTEG3 Measurement
  • PMOS current increased dramatically!
    – $V_{\text{H_FB\_AMP\_N}}/V_{\text{L_FB\_AMP\_N}}=1.0\text{nA}/0.55\text{nA}$ (SPICE)
    – $V_{\text{H_FB\_AMP\_P}}/V_{\text{L_FB\_AMP\_P}}=0.53\text{nA}/1.1\text{nA}$ (SPICE)
- PREAMP is not supposed to work with \( VH\_FB\_AMP\_P/VL\_FB\_AMP\_P=3.14nA/1.95nA \) (0.53nA/1.1nA by SPICE).
  - Feedback current \( \sim (VL\_FB\_AMP\_P - VH\_FB\_AMP\_P) \)
- Some PREAMPs among the 13 TEG elements did fail to operate.
  - Others showed quite different falling edge, which implies different feedback current

350ns falling edge \( \sim 4.6nA \) feedback current
48.4us falling edge \( \sim 0.033nA \) feedback current
6.1us falling edge \( \sim 0.26nA \) feedback current
Constant Current Feedback

• Constant current feedback structure is less dependent on the precision of low current source.
  – Variation of current source only changes falling edge but the amplifier would still operate.
  – $V_{out}$ depends on the $V_{th}$ of input transistor, leakage current and DC operating point of feedback transistor.
  – DC coupling to discriminator is not a good choice any more.
Differential-pair discriminator

- DC coupled discriminator used in CPIXTEG2/3.
  - Differential pair with composite load (a diode-connected transistor and another one operated in linear region)
  - Hysteresis
  - DAC coded current to adjust the local threshold
Diode-biased-inverter discriminator

- Used in the PILATUS chip.
- AC coupling is compatible with Amp-Sha that adopted the constant current feedback.
- 120e- threshold dispersion without threshold trim reported, very attractive.
- Threshold voltages set by $V_{diode}$ according to $I_{th} = I_s(e^{V_D/V_T} - 1)$
Amp-Sha-Disc System designed for CPIXTEG3b

- Constant current feedback Preamp, 5fF feedback capacitor
- AC coupled to shaper, voltage gain of 6
- AC coupled diode-biased inverter discriminator, 4-bit local tuning
$I_{\text{threshold}} (I_0) = 40 \text{nA}, \text{ input charge} = 750 \text{e}^- \text{ to } 2000 \text{e}^-$
input charge = 1500e^-, I_{\text{threshold}} (I_0) = 40\text{nA} to 66\text{nA}
I_{threshold} = 25nA, Assuming V_{TLH} = 1.3V and V_{THL} = 0.5V for the following digital inverter;

Transition btw. 712.5e^- and 775e^-
<table>
<thead>
<tr>
<th>$I_{\text{threshold}}$</th>
<th>input charge (e⁻)</th>
<th>Transition charge (e⁻)</th>
<th>Average input charge (e⁻)</th>
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</thead>
<tbody>
<tr>
<td>25nA</td>
<td>625-812.5</td>
<td>712.5-775 (62.5)</td>
<td>743.75</td>
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<tr>
<td>75nA</td>
<td>1500-1687.5</td>
<td>1575-1662.5 (87.5)</td>
<td>1618.75</td>
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<tr>
<td>125nA</td>
<td>2375-2562.5</td>
<td>2437.5-2537.5 (100)</td>
<td>2487.5</td>
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<tr>
<td>150nA</td>
<td>2812.5-3000</td>
<td>2875-2975 (100)</td>
<td>2925</td>
</tr>
</tbody>
</table>

Average input charge (e⁻)

\[ y = 17.441x + 308.69 \]

$I_{\text{threshold}}$ adjustment range: 25-150nA

$I_{\text{threshold}}$ tuning step: 2-5nA

$I_{\text{threshold}}$ tuning DAC: 4 bits or 3 bits
Total Noise Spectrum @ shaper output

Primary noise source: NN1&PP1 of preamp around 2 MHz;
  NN1&PP1 of shaper at low frequency;

$$SUM = \text{NN1\_preamp} + \text{PP1\_preamp} + \text{NN1\_shaper} + \text{PP1\_shaper}$$

(Total – SUM) is mainly contributed by the Feed-back Tr. (P1) in shaper

$V^2/Hz$
- **Noise @ PREAMP Output**
  - $n_0 = 1.4\text{mV}$
  - equivalent to $70\ e^-$
- **Noise @ SHAPER Output**
  - $n_0 = 6.8\text{mV}$
  - equivalent to $57\ e^-$

Cd = 100fF;  
Cf = 5fF;  
Ccouple = 30fF  
Ifb_preamp = Ifb_shaper = 1nA;

ENC (e^-)

\[ y = 0.4089x + 14.856 \]

Leakage Current Noise not Included  
1/f noise and channel thermal noise included
First Test Results of CPIXTEG3b (1)

- Bias current measurement (VIO_BPW = 0.85V)
  - Discrepancy between I_{out} and I_{out\_pixel1,2,3} affected by VIO_BPW, but required different VIO_BPW to compensate NMOS and PMOS respectively.
  - Error on Ifb_shaper not understood.
  - Should be OK to operate the chip on the basis of measurement results.

<table>
<thead>
<tr>
<th>Current Source</th>
<th>I_{in} (nA)</th>
<th>Current Ratio</th>
<th>I_{out} (nA)</th>
<th>I_{out_pixel1} (nA)</th>
<th>I_{out_pixel2} (nA)</th>
<th>I_{out_pixel3} (nA)</th>
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<tr>
<td>Ifb_preamp</td>
<td>-10.5</td>
<td>10:1</td>
<td>-1</td>
<td>-0.49</td>
<td>-0.5</td>
<td>-0.47</td>
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<td>Ifb_shaper</td>
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<td>Iref_preamp</td>
<td>-3000</td>
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<td>-791</td>
<td>-726</td>
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<td>Iref_shaper</td>
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<td>8:1</td>
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</tbody>
</table>
First Test Results of CPIXTEG3b (2)

- Analog out of Preamp
  - $V_{\text{test}} = 80\text{mV}$, equivalent to 1900 e$^{-}$
First Test Results of CPIXTEG3b (3)

- Analog out of Shaper
  - $V_{\text{test}} = 80\text{mV}$, equivalent to $1900\text{ e}^-$
First Test Results of CPIXTEG3b (4)

- Analog out of Discriminator
  - $V_{test} = 80mV$, equivalent to $1900 \text{ e}^-$
First Test Results of CPIXTEG3b (5)

- S curve measurement
  - ENC ~ 27e⁻
Shielding Measurement on CPIXTEG3 (1)

1. Oscillation

2. Oscillation stopped after shaper disabled

3. Response to Charge Injection 300mV

Vtest = 300mV;
VL_AMP_N = 300mV;
Vdet = +5V

Pixel Layout
Shielding Measurement on CPIXTEG3 (2)

Vdet = +5V;
Adjust VL_AMP_N = 0.2V;
Vtest = 300mV;
Vthh = 1250mV;
Vthl = 800mV;
Glitches can be removed by disabling Disc. via DO_EN.
Shielding Measurement on CPIXTEG3 (3)

1. Charge Injection with Discr. working

Vtest = 600mV;
VL_AMP_N = 280mV;
Vdet = +5V

2. Charge injection with Discr. stopped
Shielding Measurement on CPIXTEG3 (4)

- Hit logic operation
- Counter operation

**Hit logic operation**

- X011_1111_1111_1111 → X100_0000_0000_0000
- X100_0000_0001_0111 → X100_0000_0001_1000
- X100_0000_0010_0111 → X100_0000_0010_1000

**Counter operation**

- 16 clks
- X111_1111_1111_1111 → X000_0000_0000_0000

**Diagram Details**

- **PREAMP**
- **SHAPER**
- **DO 14**
- **LO X**
First CPIXTEG3b delivered was fabricated on normal SOI wafer. No DSOI at all. Clear crosstalk seen.
Summary

• Shielding is a critical issue in counting pixel chips.
• A new Amp-Sha-Disc system works, which is less dependent on the precision of very low current source.
• Nested-Wells provided shielding between analog and sense node, but no sufficient for shielding digital part in the pixel.
• Small sense node and small pixel is being pursued.