MICroelectronic RHone AUvergne

A Charge-Sensitive Amplifier Associated with APD or PMT for Positron Emission Tomography Scanners

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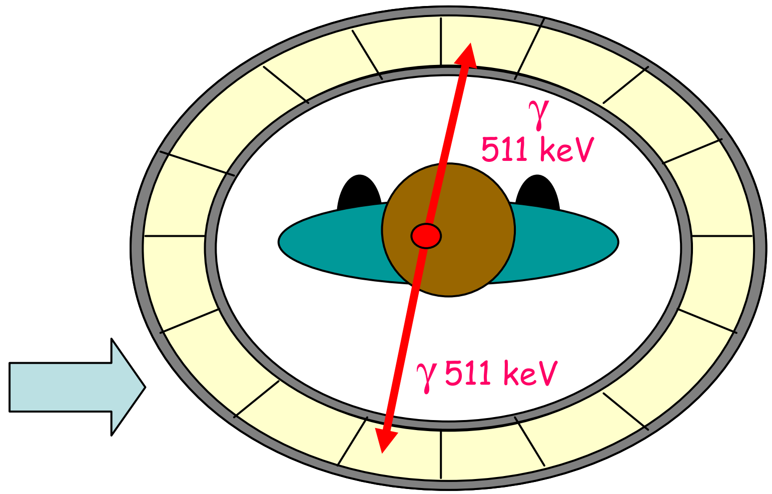
Outline

1. PET scanners and electronic architecture
2. Charge Sensitive Amplifier design
3. Noise considerations
4. Layout design
5. Test set up and measurements
6. Conclusion

1 : PET Scanners Concept

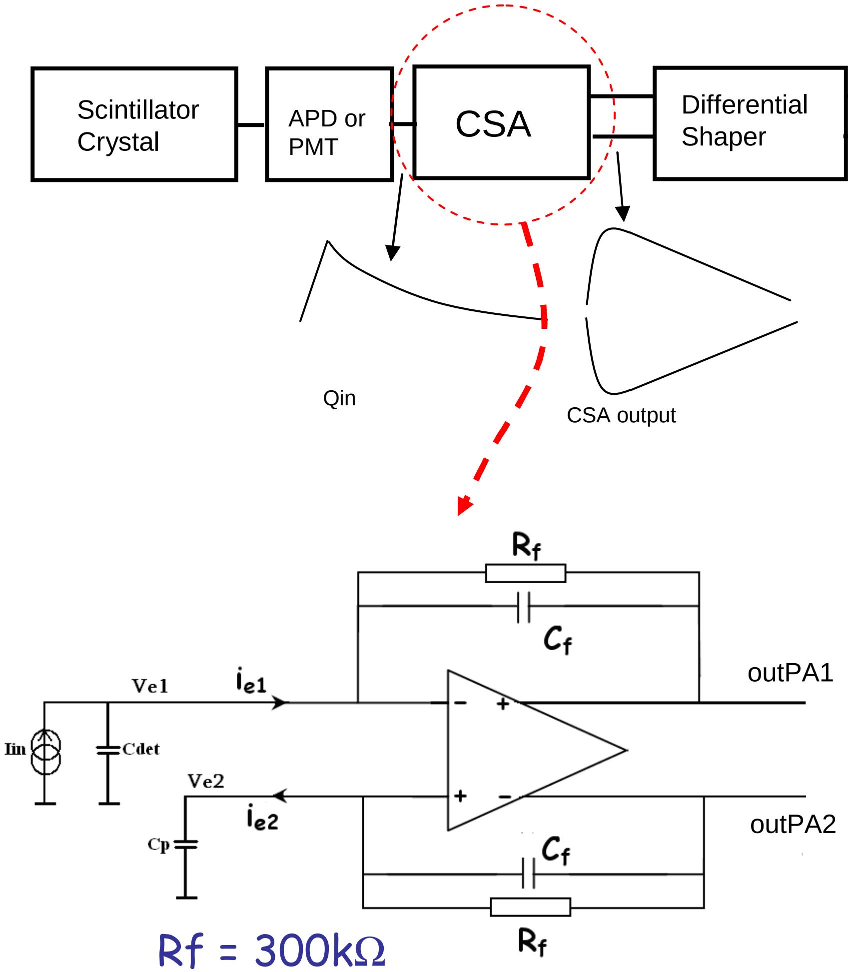
Sensitive instruments for biomedical imaging :
- Brain studies
- Cardiac imaging
- Cancer diagnosis and therapy

PET scanners operation :
- Detection in coincidence of 511 KeV Photon pair



Main ideas :
- o Use LHC (CERN) electronics concepts
- o Dead time reduction << 1ns
- o Spatial resolution ~ 1mm
- o Improvements of PET performances

1 : Electronic Architecture



Rf = 300kΩ
Cf = 1pF

<u>2 types of APD :</u>

- Hamamatsu G=200 Cd=80pF Qmax = 200fC
- RMD G=400 Cd=50pF Qmax = 500fC
- PM $G=10^5 > 10^6$ Cd=10pf Qmax=10pC

(not implemented in this design)

<u>Main difficulty :</u>

- High value of Cd
- Low Qmax

<u>Noise :</u>

- Shaper time constant = 20ns
- ENC = 3000 e- (With APD stimulus)

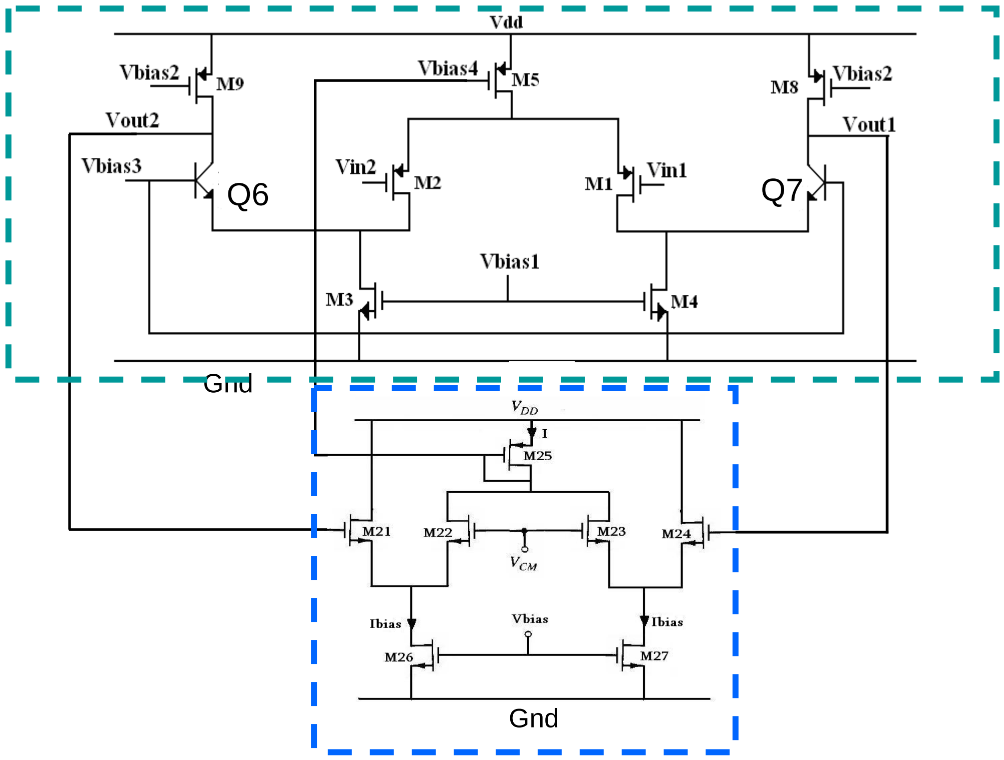
<u>Differential mode :</u>

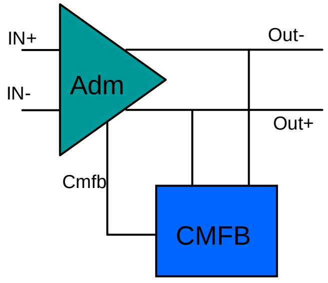
- ➢Shaper and ADC architecture
- ➢APD or PM

2 : Charge Sensitive Amplifier Design

CSA is made with a fully differential amplifier = Adm + CMFB

Technology : AMS 0.35µm BiCMOS SiGE S35D4M5
4 metal, 2 poly, high resistive poly



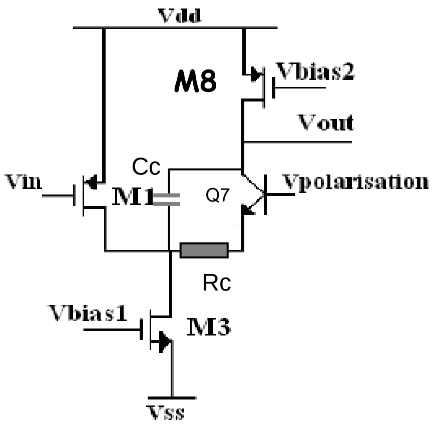


CMFB acts as :

- Control of common mode output voltage
- In single input mode : reduce residual voltage

2 : Charge Sensitive Amplifier Design

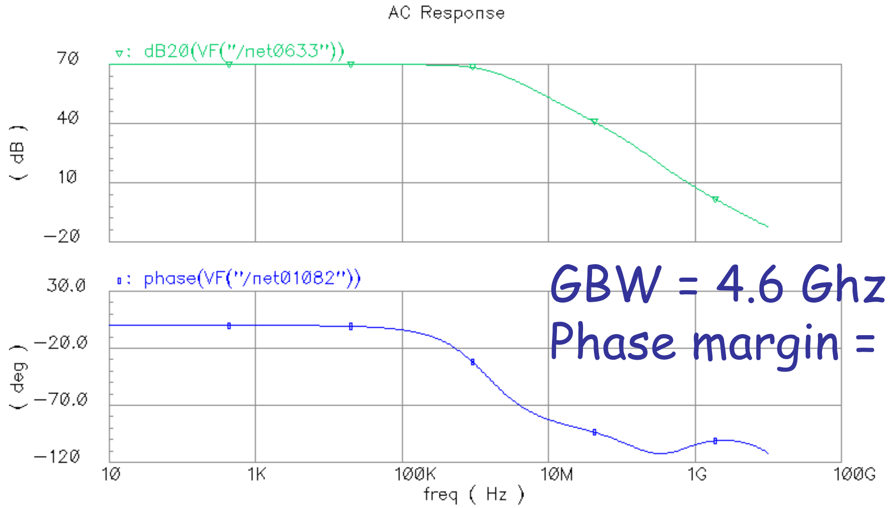
Half Adm part



$$A_0 \approx -\frac{g_{m1}}{g_{ds8}}$$

$$f_c = \frac{g_{ds8}}{2\pi C_{out}}$$

$$g_{ds1} \leq \frac{1}{R_c} \leq g_{m7}$$



GBW = 4.6 Ghz
Phase margin = 80 deg

CMFB part

$$p_{nd} = \frac{g_{m25}}{C_{gs5} + C_{gs25}}$$

Ids25/Ids5 ~ 1

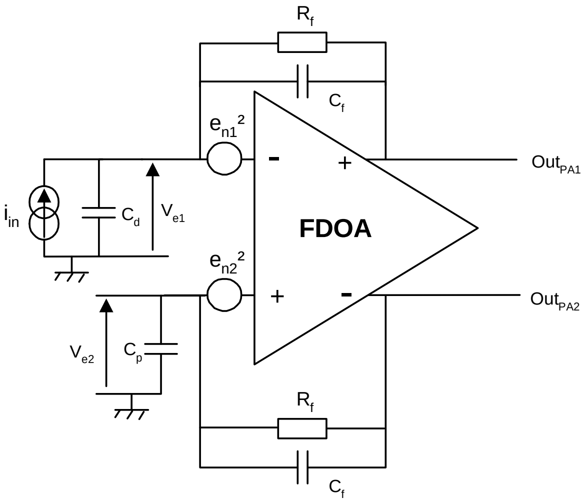
CSA input characteristics

$$\tau_{csa} = \frac{C_d}{2\pi \cdot GBW \cdot C_f} = C_d \cdot R_{in}$$

$$R_{in} = \frac{C_{out}}{g_{m1} \cdot C_f}$$

3 : Noise considerations

(Noise is a Key issue for this design)



$$S_n = \frac{8}{3}\frac{kT}{g_{m1}} + \frac{K_f}{C_{ox}^2 WLf}$$

Cf<<Cp and Cf<< Cd

$$\Delta V_{out}(\omega) = \frac{2A_{dm}\left[(v_1 - v_2) - V_{out,cm}(\beta_1 - \beta_2)\right]}{2 + A_{dm}(\beta_1 + \beta_2)}$$

$$\beta_1 = \frac{\frac{1}{j\omega C_p}}{\frac{1}{j\omega C_p} + \frac{R_f}{1 + j\omega R_f C_f}} \sim \frac{1 + j\omega C_f R_f}{1 + j\omega C_p R_f} \qquad \beta_2 = \frac{\frac{1}{j\omega C_d}}{\frac{1}{j\omega C_d} + \frac{R_f}{1 + j\omega R_f C_f}} \sim \frac{1 + j\omega C_f R_f}{1 + j\omega C_d R_f}$$

$$H_n(\omega) \approx \frac{\Delta Vout}{V_{1,2}} \approx \frac{2}{\beta_1 + \beta_2} \approx \frac{2}{\frac{1 + j\omega C_f R_f}{1 + j\omega C_d R_f} + \frac{1 + j\omega C_f R_f}{1 + j\omega C_p R_f}} \approx \frac{2}{C_f\left(\frac{1}{C_d} + \frac{1}{C_p}\right)} \approx \frac{2C_d}{C_f}$$

Noise Gain $\quad H_n(\omega) \approx \frac{C_d}{C_f}$

$$v^2{}_{noise} \approx \int_0^\infty 2S_n \left|H_n(f)\right|^2 \frac{G^2 (2\pi f \tau_s)^2}{\left[1 + (2\pi f \tau_s)^2\right]^2} df \approx \frac{G^2}{\tau_s}\left(\frac{2}{C_f\left(\frac{1}{C_d} + \frac{1}{C_p}\right)}\right)^2 \frac{2kT}{3g_{m1}} \approx \frac{G^2}{\tau_s}\left(\frac{2C_d}{C_f}\right)^2 \frac{2kT}{3g_{m1}}$$

3 : Noise considerations

$$V_{out,shaper}(\tau_s) = 2 \cdot \frac{qG}{e.C_f}$$

In differential mode

$$ENC \approx \frac{eC_d}{q}\sqrt{\frac{2kT}{3\tau_s g_{m1}}}$$

Serial noise only

$$ENC \approx \frac{eC_d}{q}\sqrt{\frac{kT}{\tau_s}\left(\frac{2}{3g_{m1}} + r_{poly}\right)}$$

Including access gate serial resistor r_{poly}

PMOS input Optimization :

- Increase Gm (100 mA/V @ Id 10 mA and w/l =5000/0.35)
- Minimize WL to minimize Cgs input transistor capacitance

- Minimize in layout access gate serial resistor

3 : Noise considerations

Differential output

$$ENC \approx \frac{eC_d}{q}\sqrt{\frac{2kT}{3\tau_s g_{m1}}}$$

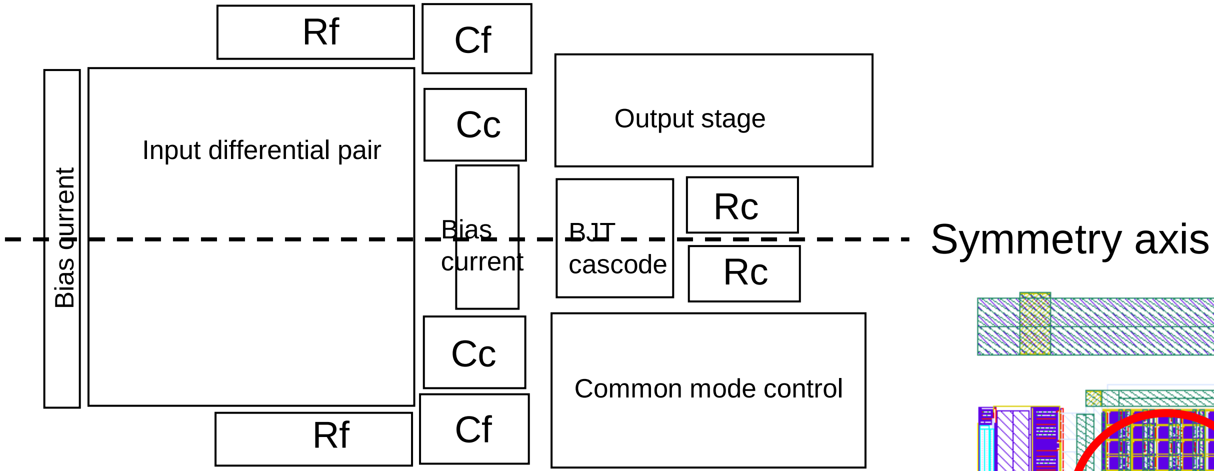
Single ended output

$$ENC \approx \frac{eC_d}{q}\sqrt{\frac{kT}{3\tau_s g_{m1}}}$$

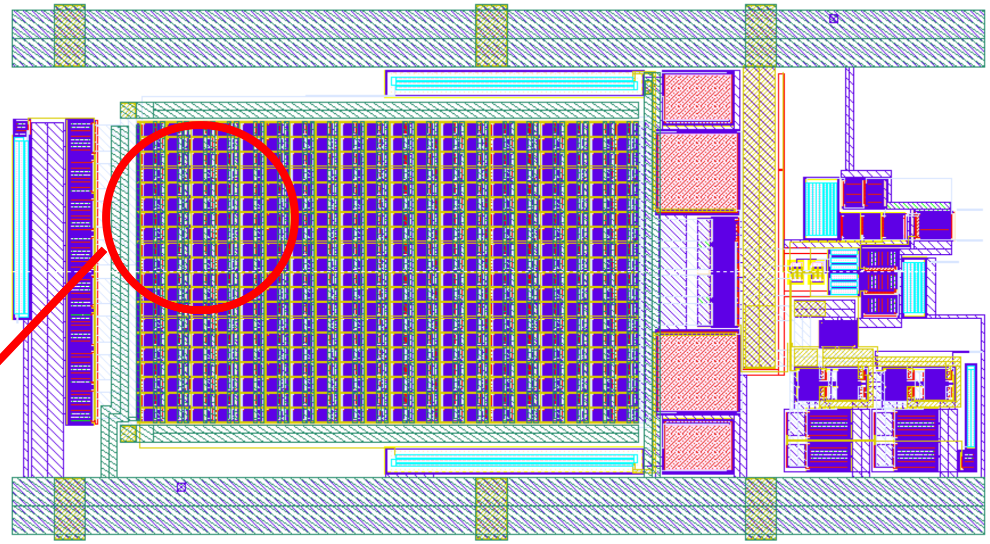
$$*\sqrt{2}$$

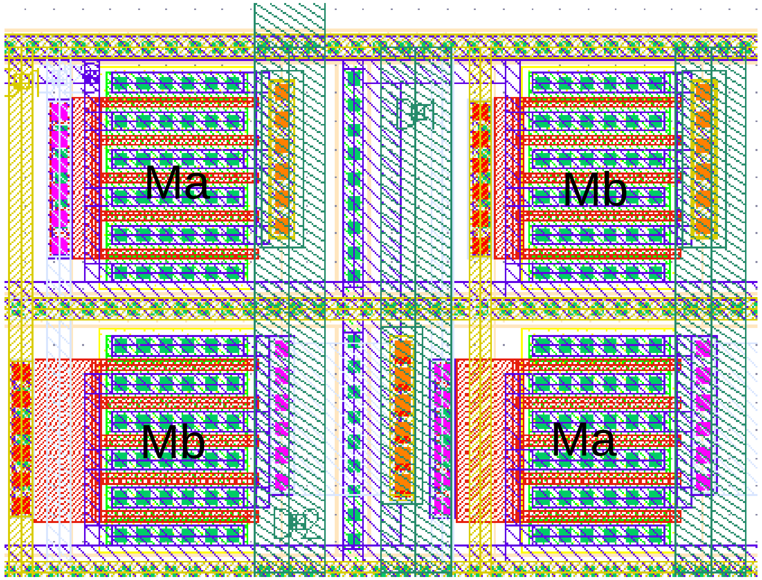
- *ENC increase by a factor sqrt(2)*
- Adaptation to either PMT or APD
- Less sensitive to coupling (common mode)

4 : Layout Design



Core cell layout





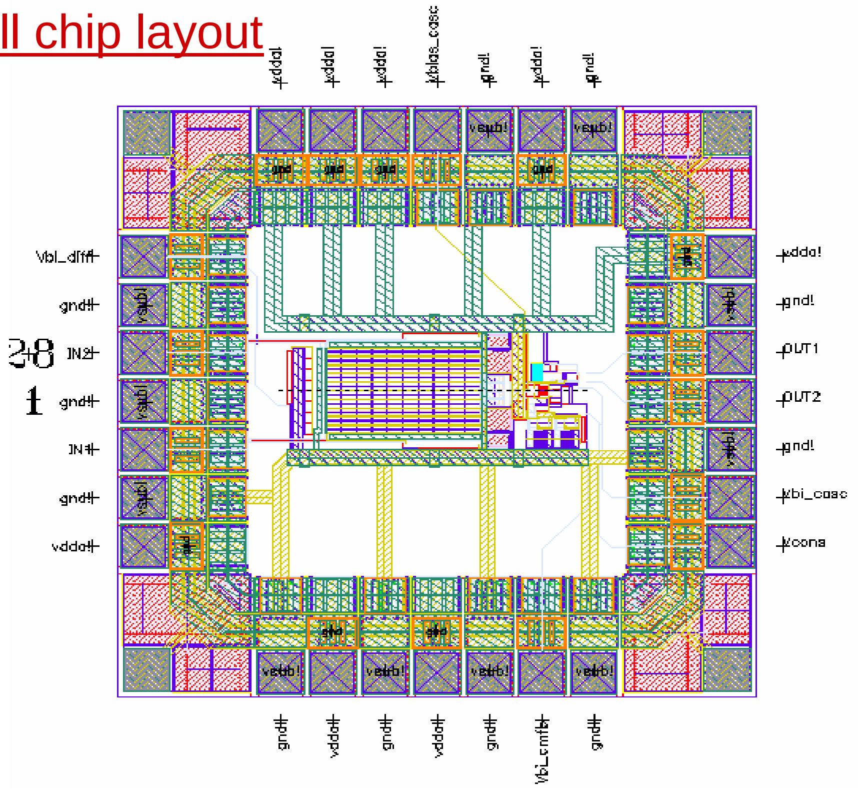
10*10 common centroid
structure for input differential pair

Special thanks to E. Bechetoille for his help

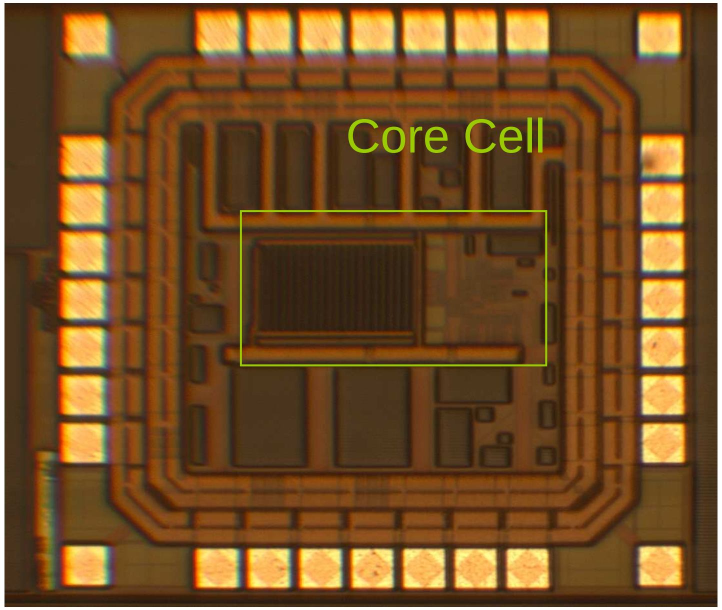
4 : Layout Design

- Chip was submitted in MPW in November 2008 through CMP
- Return in February 2009 and fully tested
- 28 pins JLCC ceramic package

Full chip layout

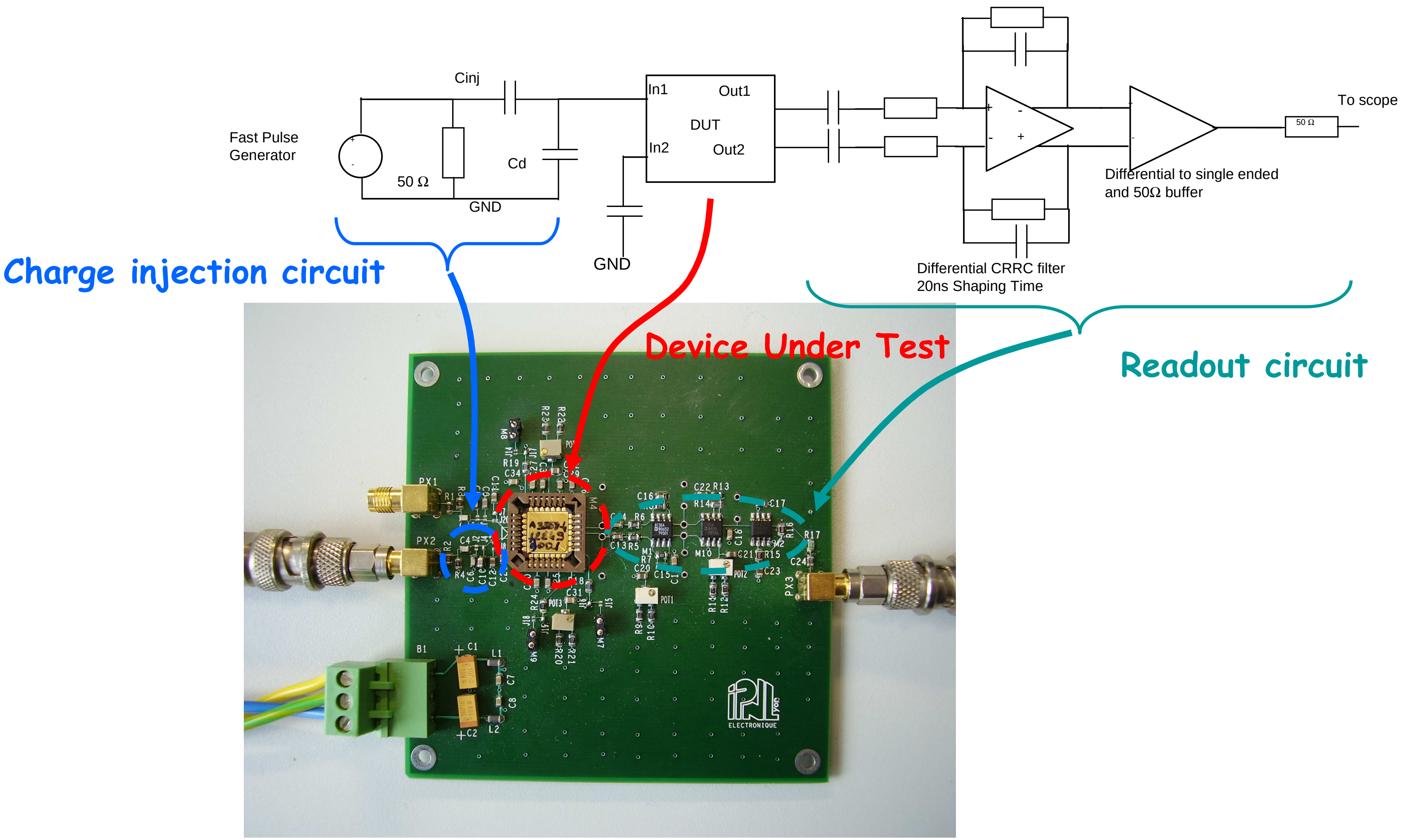


Photography



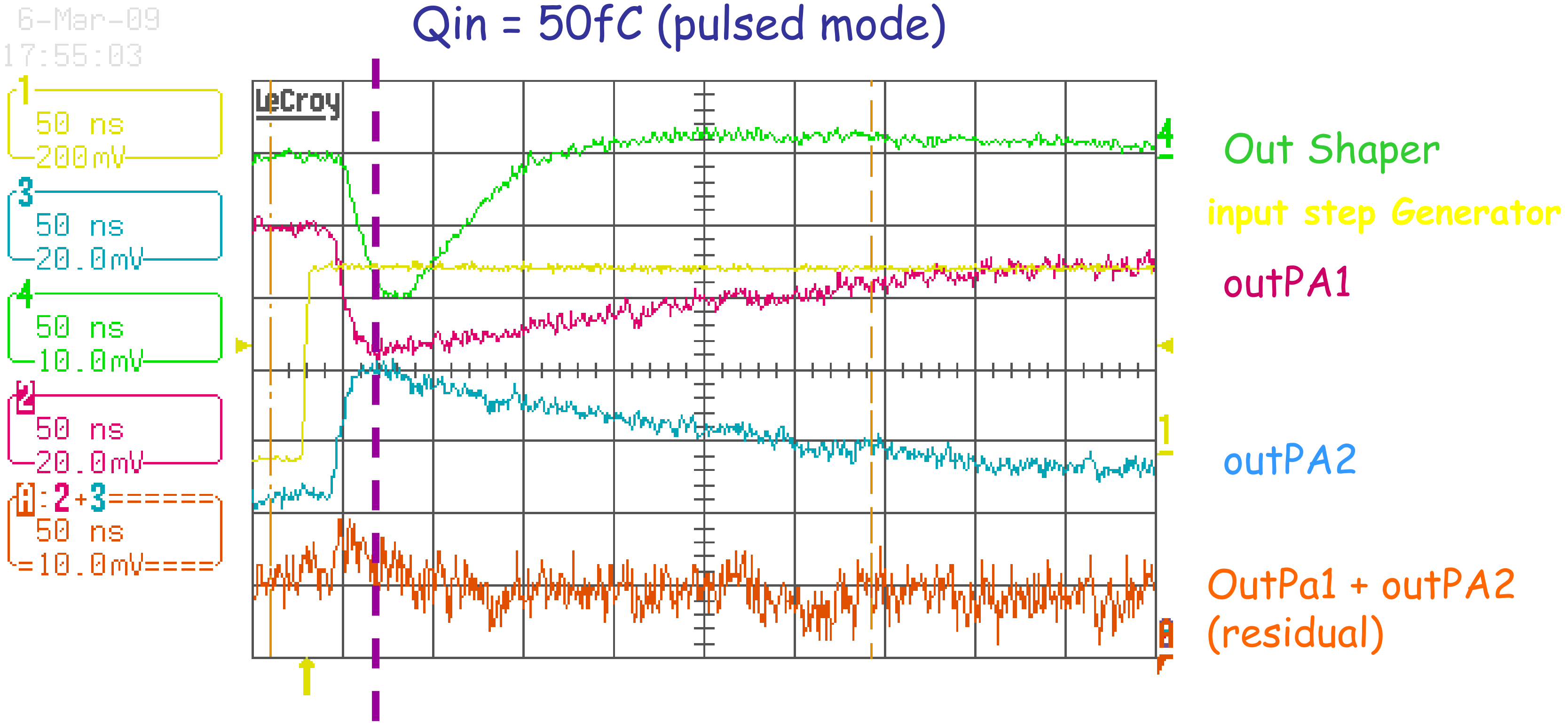
Core cell area = 0.2 mm2

5 : Test setup


Cinj
Fast Pulse Generator
50 Ω
Cd
GND
In1
Out1
DUT
In2
Out2
GND
Differential CRRC filter
20ns Shaping Time
Differential to single ended and 50Ω buffer
50 Ω
To scope
Charge injection circuit
Device Under Test
Readout circuit

5 : Results

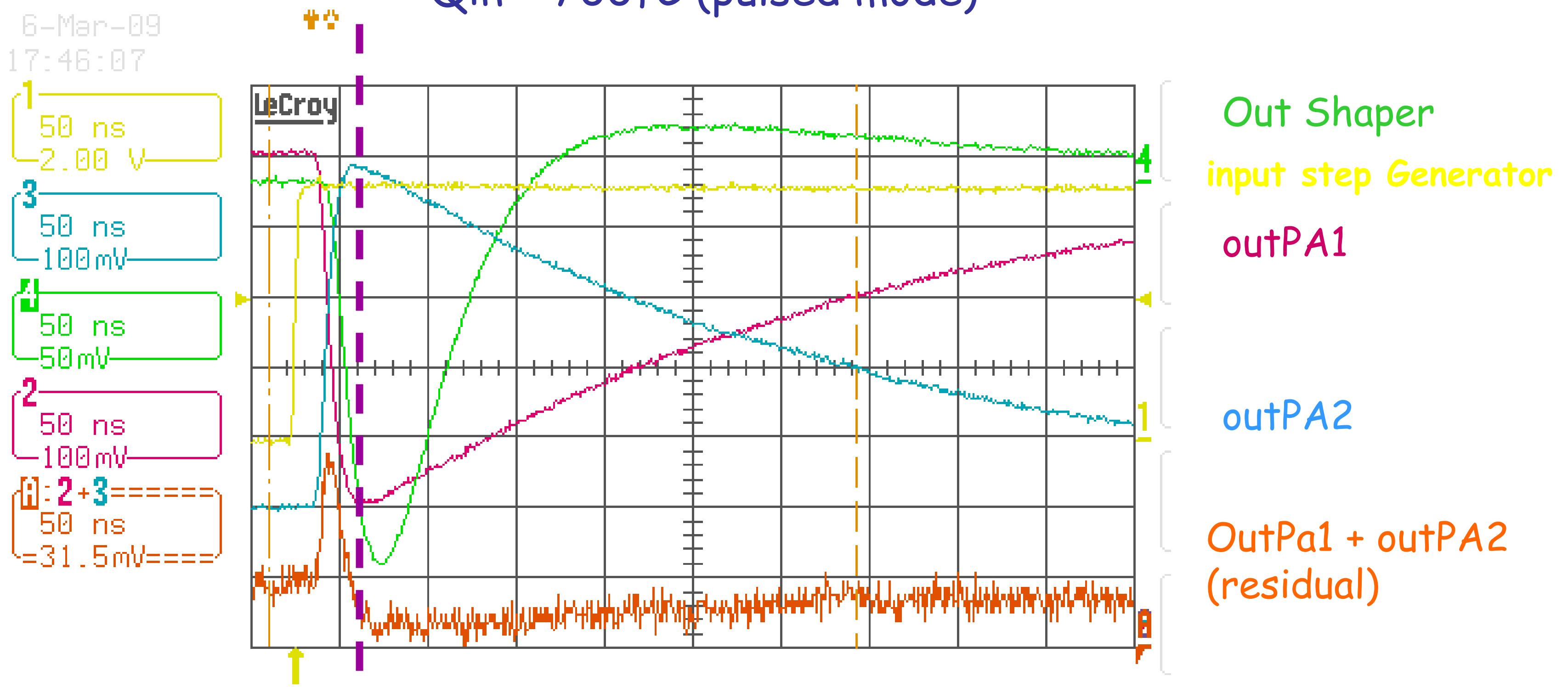
Qin = 50fC (pulsed mode)



Differential output voltage = 80 mV
Peaking Time = 25 ns (CSA)
Residual voltage = 8 mV
Conversion gain = 1.44 mV/fC

5 : Results

Qin = 700fC (pulsed mode)

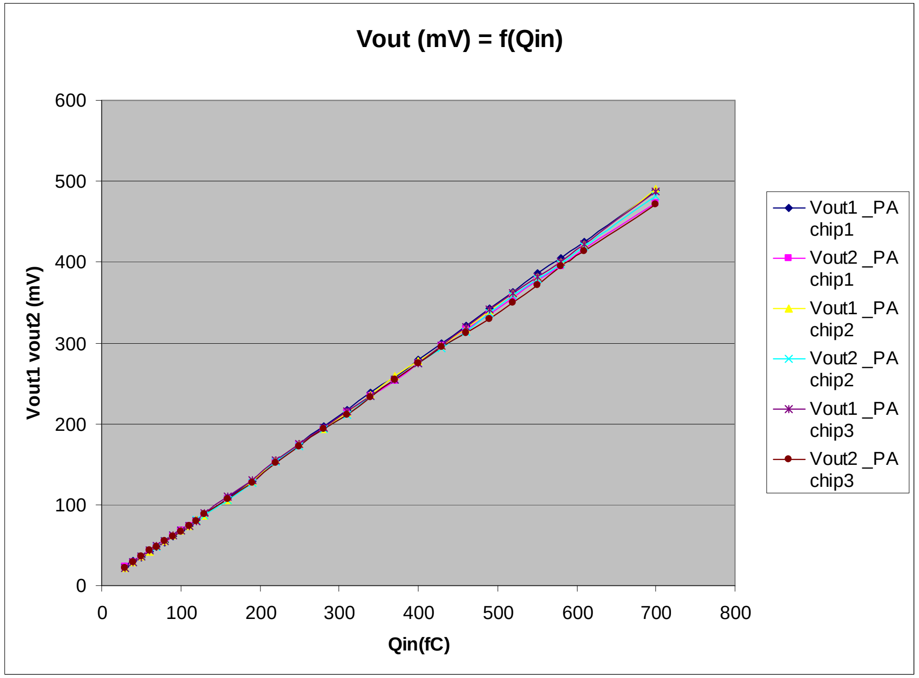


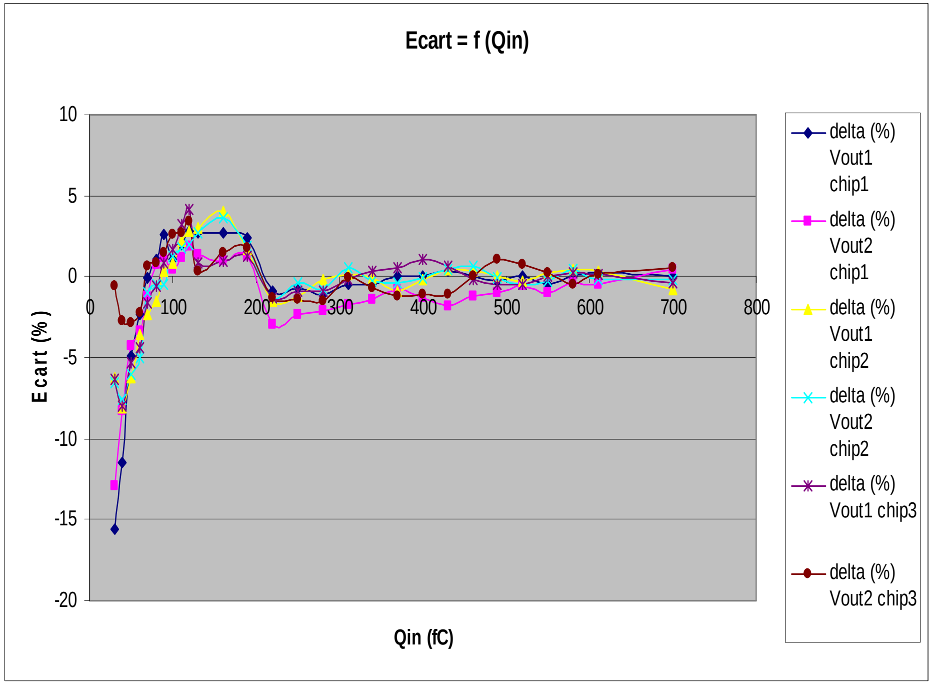
Differential output voltage = 980 mV
Peaking Time = 26 ns
Residual voltage = 50 mV
Conversion gain = 1.4 mV/fC

5 : Results

outPA1, outPA2, 3 chips fully tested from 50fC to 700fC in pulsed mode

Nonlinearity

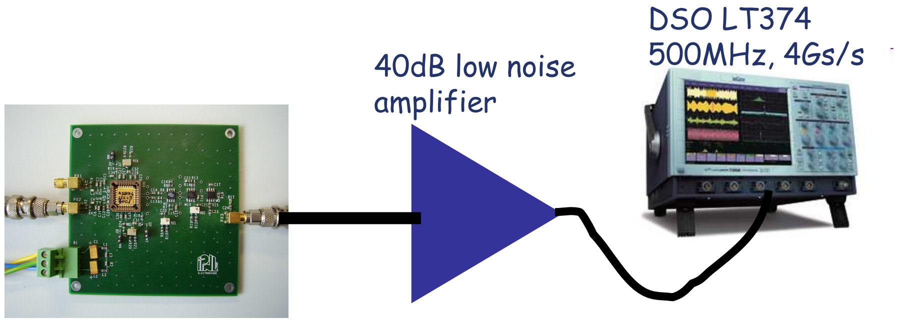




OutPA1,2 slope = 0.7 mV/fC
⇨ 1.4 mV/fC in differential mode

NL estimated by : (measure - linear fit)/measure
At low injection NL is dominated by instruments accuracy
NL is less than +-2% for Qin > 100fC

5 : Results



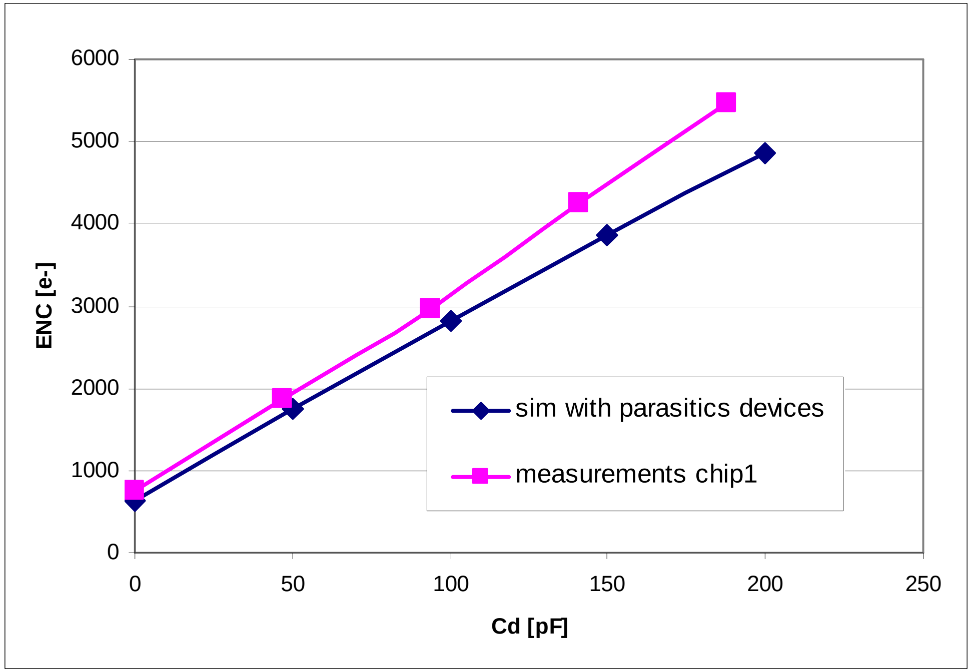
Noise Results :

ENC = 2000 e-

Cd = 50pF

Gconv : estimated with pulsed stimulus (~ 40 mV/fC)

Shaper time constant : 20ns



ENC_{meas} = 692 e- + 25 e-/pF

ENC_{sim} = 670 e- + 21 e-/pF

6 : Conclusion

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- Proceeding conference MIPRO (Croatia may 2009)
- Paper submitted in MIM-A

We designed a CSA in differential mode (APD, PM)
which is adapted to the post processing (differential shaper and ADC)

Results are (3 chips were measured) :

- ✓ Rise time 26ns for pulsed stimulus
- ✓ Rise time ~ 110ns for APD like stimulus
- ✓ Noise 2000 e- @ Cd=50pF, pulsed stimulus, 20ns shaper time constant
- ✓ Noise 3200 e- @ Cd=50pF, APD stimulus, 20ns shaper time constant
- ✓ Dynamic range 700fC
- ✓ Conversion gain 1.34mV/fC
- ✓ Area = 0.195 mm2 not including pad ring
- ✓ Power supply = 136 mW @ 3.5V