Prototype of the Front-end Circuit for the GOSSIP (Gas On Slimmed Silicon Pixel) Chip in 0.13 µm CMOS Technology.

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Abstract.

The new GOSSIP detector, capable to detect single electrons in gas, has certain advantages with respect silicon (pixel) detectors. It does not require a Si sensor; it has a very low detector parasitic capacitance and a zero bias current at the pixel input. These are attractive features to design a compact, low-noise and low-power integrated input circuit.

A prototype of the integrated circuit has been developed in 0.13 µm CMOS technology. It includes a few channels equipped with preamplifier, discriminator and the digital circuit to study the feasibility of the TDC-per-pixel concept.

The design demonstrates very low input referred noise (60e$^-$ RMS) in combination with a fast peaking time (40 ns) and an analog power dissipation as low as 2 µW per channel. Switching activity on the clock bus (up to 100 MHz) in the close vicinity of the pixel input pads does not cause noticeable extra noise.

I. Introduction

The GOSSIP (Gas On Slimmed Silicon Pixel) detector [1], depicted in Fig.1, consists of a CMOS pixel array with a grid foil, placed parallel at a distance of 50 µm. Recently the grid has been realised by means of wafer post-processing technology (Integrated Grid or InGrid) [2]. One mm above this grid a cathode foil is built. The cathode foil and the grid are put at -800V and -400V, respectively, and the pixel array surface is at ground potential. The volume between the cathode foil and the pixel array is filled with a suitable gas mixture.

When a fast charged particle crosses the drift gap, a track of electron-ion pairs will be created. Driven by the electric field the electrons will drift into the holes in the grid. In the gap between the grid and the (pixel) anode, an electron avalanche occurs with sufficient charge to activate an on-pixel integrated circuit [3]. The activated pixels will show the projection, on the array surface, of the track. From drift time measurements the polar angle of the track and its distance to the anode could be obtained [1].

The GOSSIP detector has advantages with respect to the now widely used Si vertex detectors. Instead of a silicon sensor it has a 1 mm layer of gas, reducing the material budget, and the radiation damage in the depletion layer of the silicon sensor is eliminated (the on-pixel circuit will be sufficiently radiation hard due to the intrinsic properties of the up-to-date deep-submicron CMOS technology).

The value of the parasitic capacitance at the input of the front-end circuit is determined by the area of the pixel pad and consequently could be as low as 5 - 30 fF. This feature enables us to design a low-noise (60 – 80 e$^-$ (RMS)) and at the same time very low power circuit (2 µW per pixel).

The low power aspect is of primary importance since cooling systems add material to the detector. We expect the GOSSIP chip to dissipate 100 mW/cm^2. In this work we have developed a prototype of the front-end circuit in 0.13 µm CMOS technology.

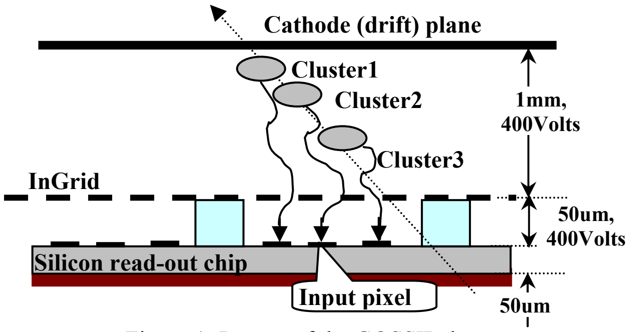

Figure 1: Layout of the GOSSIP detector.

II. Inputs and requirements for the design of the readout circuit

A. *Single electron efficiency*

Simulations show that 90 % efficiency of detecting single electrons can be reached at a gas gain of 4000 and a threshold of 400 electrons (see Fig.2). This sets a limit to the input-referred ENC.

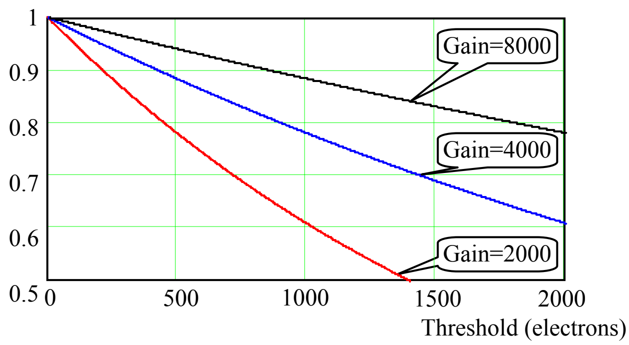

Figure 2: Single electron efficiency as a function of operating threshold.

B. Shape of the detector current signal

The detector current has an electron and an ion component. The drifting electrons cause a short current pulse, while the ion component is determined by the drifting ions crossing the gap between the anode and the grid (see Fig.3).

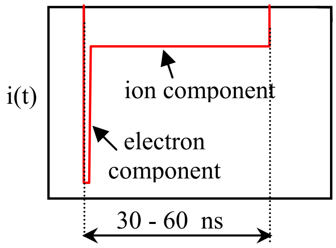

Figure 3: Schematic shape of the detector current [3].

C. Single electron drift time measurements.

Simulations have shown that a time resolution of 2 ns (RMS), corresponding to spatial resolution of 100 μm (RMS), seems feasible (see Fig.4).

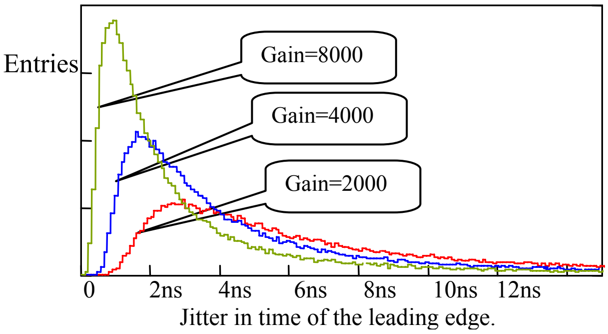

Figure 4: Simulations of the single electron drift time resolution at various gas gain factors.

In order to measure the drift time of each of the electrons on the track, each pixel must be equipped with an individual time-to-digital (TDC) converter.

D. Analog-digital crosstalk.

Data taking and readout will occur simultaneously and constantly. The high sensitive analog front-end circuit will operate in the close vicinity of the high speed switching gates. This requires to make every effort to keep the front-end away from the switching noise.

E. Power consumption.

A low power dissipation reduces the amount of material for a cooling system. We intend to limit the power dissipation to 2 μW per pixel (~ 100 mW per cm^2).

III. The prototype of the front-end circuit.

A. Parasitic capacitance at the input of the front-end circuit.

The detector source capacitance is an important input parameter for the front-end circuit design. It determines the optimum set of parameter values for speed, noise and power consumption. In the GOSSIP detector, the source capacitance consists of three components. These are the pad-to-InGrid capacitance ($C_{p\text{-}grid}$), the pad-to-pad capacitance ($C_{p\text{-}p}$) and the pad-to-substrate capacitance ($C_{p\text{-}sub}$) (see Fig.5).

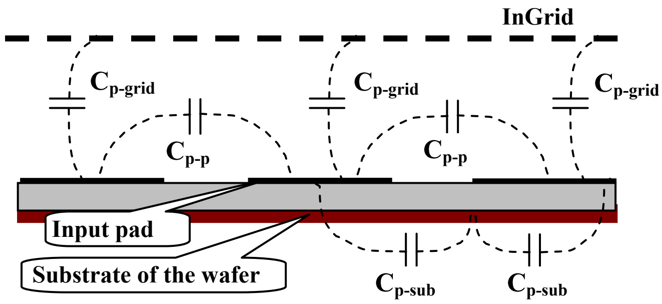

Figure 5: Parasitic capacitances associated with the input pad

The pad-to-substrate capacitance is dominant: it depends on the pad size and is large due to the very thin dielectric layer in the body of the chip. With no need for a (bump-bonded) silicon sensor, a very small size of the input pad is possible. As a result, a very low value of the source capacitance of around 10 fF can be reached (see Fig.6).

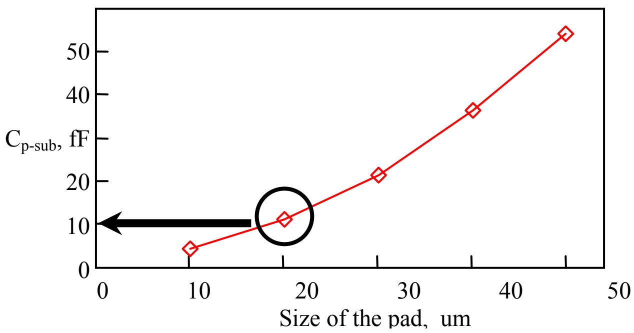

Figure 6: The pad-to-substrate capacitance as a function of the size of the pixel.

B. Gain in the charge-sensitive preamplifier.

Charge-to-voltage gain of the charge-sensitive preamplifier (see Fig.7) is inversely related to the feedback capacitance.

$$\text{Charge-to-voltage gain} \approx C_{fb}^{-1} \quad (1)$$

To get the highest gain we should decrease the feedback capacitance. However, its value must be larger than the parasitic capacitance value divided by the open loop gain factor as follows:

$$C_{fb} >> C_{par} / A \quad (2)$$

Since C_{par} is 10fF and A is around 100, we can consider a feedback capacitor with a value as low as 1fF.

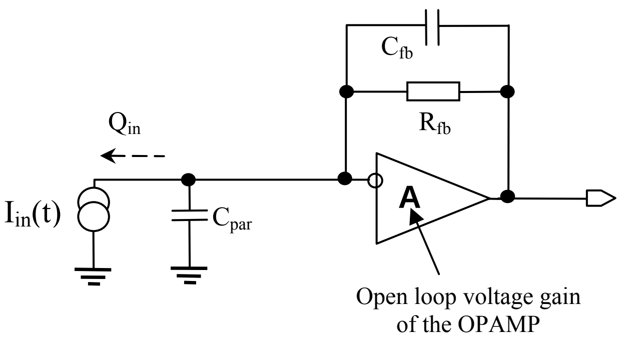

Figure 7: The charge-sensitive preamplifier.

In order to optimize the parasitic capacitance, a coaxial-like structure has been applied (see Fig.8). In this structure the feedback capacitance is formed by vertical plate capacitance. High precision in the capacitance is guaranteed due to accuracy of lithography and thickness of the metal layer. In addition, in this layout the high sensitive input is shielded and isolated.

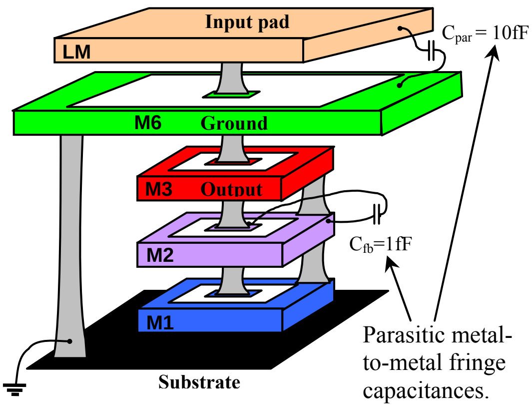

Figure 8: Layout of the input interconnection.

C. *Schematic of the preamplifier.*

The scheme proposed by Krummenacher [4] is a common way to implement a preamplifier for hybrid pixel detectors. The circuit compensates for the leakage current of the silicon sensor. It will, however, become unstable if the parasitic capacitance at the input is very low.

The GOSSIP detector has no leakage current. Krummenacher's scheme has been modified to improve the stability (see Fig.9). The current in the load of the differential pair M1-M2 has been kept fixed. As a result, the circuit has an intrinsically safe phase margin, even when the input parasitic capacitance approaches 10 fF.

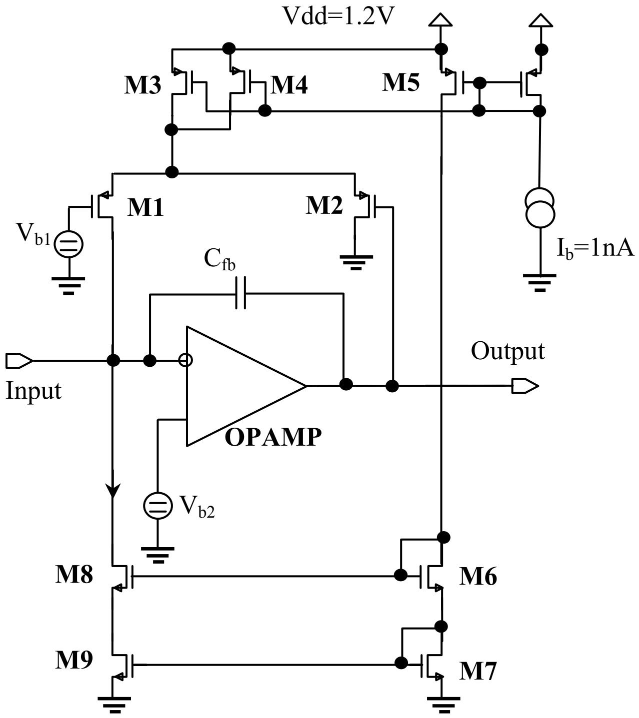

Figure 9: Schematic of the charge sensitive preamplifier.

DC feedback in the circuit allows for discharging of the feedback capacitor. The virtual resistor is a sum of inverse transconductances of transistors M1 and M2 and equals 80 MΩ. It also biases the input of the circuit so as to keep the voltage at the output equal to the reference voltage (V_{b1}). Because of use of differential stages and floating current sources the biasing is highly insensitive to temperature drift and power supply voltage instability. Statistical spread of the offset at the output is 20mV (RMS) corresponding to the input referred signal of 170 electrons.

The operational amplifier (see Fig.9) is formed by a cascode differential pair, loaded with a current mirror (see Fig.10). A voltage follower provides a low output impedance of the amplifier. The input-to-output small signal transfer function has a pole with time constant of 14 ns, and the opamp has a DC gain of 130. The circuit draws about 1.2 µA current from the 1.2 V power supply. The overall power consumption is 1.5 µW.

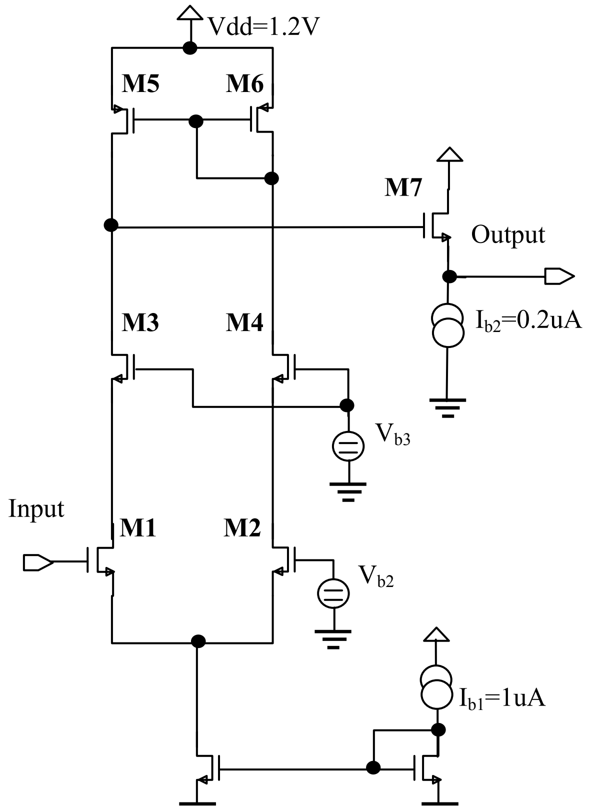

Figure 10: Schematic of the operational amplifier.

D. Objectives of the prototype.

In prototype, submitted on December 12, 2005, we intended to measure the most important characteristics of the front-end circuit such as stability, pulse response, noise and channel-to-channel spread. For this purpose a bare preamplifier with a voltage follower has been designed. We also built a complete front-end circuit including a CMOS comparator and a counter. With this, cross-talk between the sensitive analog inputs and the high speed switching CMOS blocks can be observed. A general view of the physical layout of the prototype is given in Figure 11.

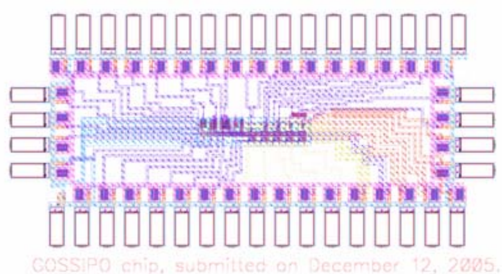

Fig.11. The prototype of the GOSSIP chip, submitted on December 12, 2005.

Substrate noise is likely to be the most significant cause of the analog-digital crosstalk. The local substrate potential fluctuates due to current flow, originated by the switching of the digital gates. The substrate fluctuations will affect the characteristics of the analog circuits. A very nice feature in the used 0.13 µm CMOS technology is the option to make a floating p-well separated from the substrate. In the p-well we can place analog N-type transistors and keep them away from the substrate noise (see Fig.12). Using this, the analog-digital crosstalk has been essentially eliminated.

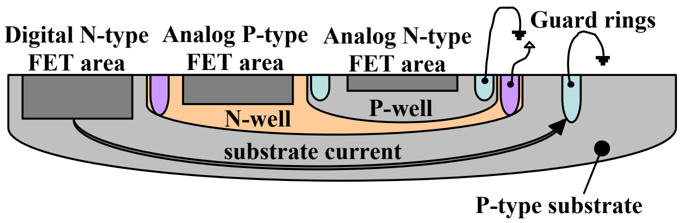

Figure 12: Triple well layout in the 0.13 µm CMOS technology.

E. Measurements & results

The measurements demonstrate that the preamplifier has a sufficient stability margin and an expected shape of the pulse response (see Fig.13). The equivalent input noise charge is 60 electrons (RMS), in agreement with simulations.

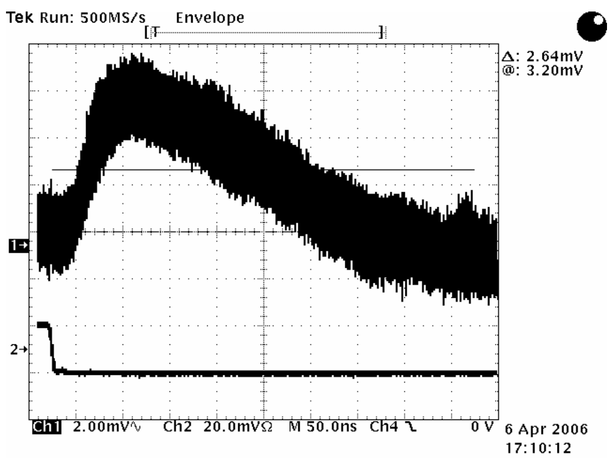

Figure 13: Delta-pulse response of the preamplifier. The input signal is 410 electrons.

The output response of the CMOS comparator of a delta-pulse at the input is given in Figure 14. No indication of after-pulsing or oscillation supports our expectation that the parasitic output-input crosstalk is very low.

The channel-to-channel spread of the threshold is 160 electrons (RMS). Also this result is consistent with simulation.

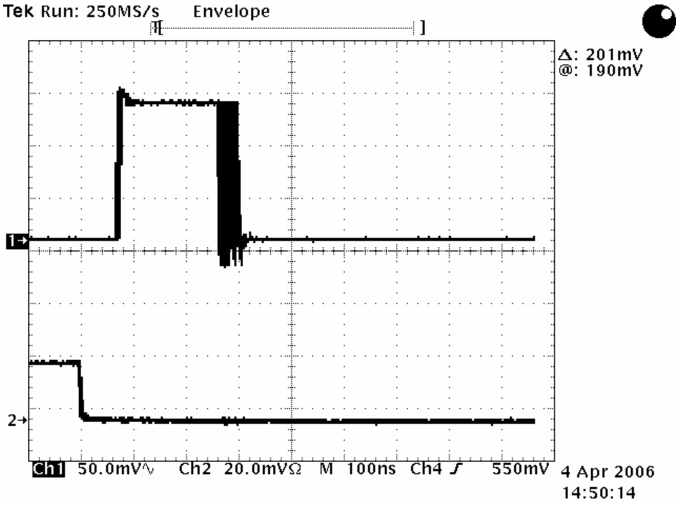

Figure 14: Delta-pulse response of the output of the CMOS comparator. Input signal is 410 electrons. Threshold is 300 electrons.

We also studied the analog-digital crosstalk by asserting a 100 MHz clock signal to the CMOS counter which is in the close vicinity of the high sensitive front-end. Even at very low threshold, no significant crosstalk to the input has been observed at the output of the comparator (see Fig.15).

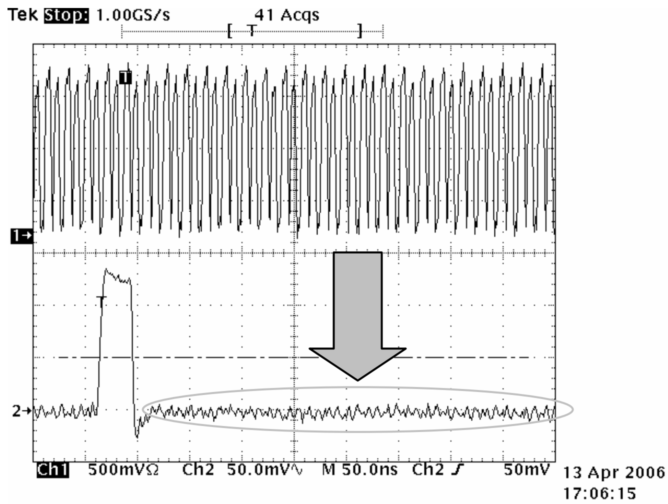

Figure 15 Output of the CMOS comparator along with the clock signal running at 100 MHz.

IV. Conclusions and plans.

The front-end readout circuit of the GOSSIP chip benefits from the low detector parasitic capacitance and the absence of any leakage current.

This first prototype demonstrates that a fast (40 ns peaking time), low-noise (ENC = 60e$^-$ (RMS)) and low-power (2 µW per channel) front-end circuit can be implemented in a 0.13 µm CMOS technology.

Owing to the triple well layout used in the prototype, the sensitive analog inputs are effectively isolated from the high speed switching gates.

A new prototype featuring a TDC-per-pixel concept will be submitted at the end of 2006.

V. Acknowledgements.

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VI. References.

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