Design and Characterization of Leakage Current Compensation Circuit for Semiconductor Detectors

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Introduction

The noise optimization of CMOS-based front-end electronics for semiconductor based detector readout consists of current and voltage noise minimization in the design of Charge Sensitive pre-Amplifier (CSA). However, the leakage current which is in the order of tens of nA contributes significant amount of noise which is detrimental in case of low noise application e.g. detector with PIN diode type configuration. The CSA with a capacitor and a resistor in feedback type of architecture would not block detector leakage current, produced by thermally generated electron-hole pairs within the depletion region. The fluctuations of the leakage current are the source of noise and higher leakage current can even cause saturation of CSA output.

The front-end signal processing for multichannel setup viz. CPDA, GMDA at VECC relies on the self-developed customized ASIC and has the advantage of introducing a leakage current compensation circuit (LCC) [1] with the CSA which is otherwise not available in the commercial preamplifiers. With this motivation, LCC has been designed using CMOS and integrated in the second version of GMDA ASIC. The detail design of the LCC has been described in this paper. The result obtained after simulation has been shown and explained.

Design of Leakage Current Compensation Circuit

In a typical detector system, the leakage current is limited to the bandwidth around 10 kHz and a circuit can be devised as shown in Fig. 1.

$$ENC_i^2=(F_i\tau)\left[4kT\left(\frac{1}{R_f}+\frac{1}{R_{bias}}\right)+2qI_{leakage}\right] \quad (1)$$

The sources of total noise in a charge amplifier are the combination of voltage (series) noise and

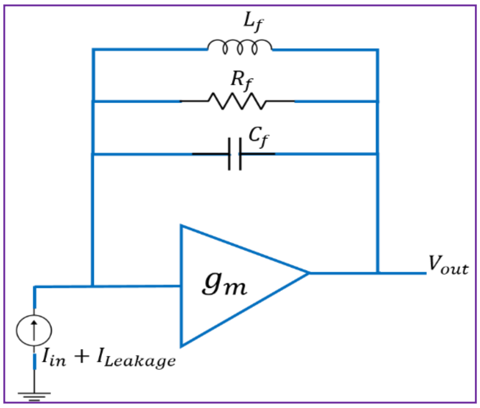

Fig. 1: Block Diagram of the LCC

current (parallel) noise. The voltage noise minimization has been done while designing the core transconductance amplifier (g_m). The current noise appears due to detector leakage current ($I_{leakage}$), feedback resistance (R_f) of the charge amplifier and detector bias resistance (R_{bias}) and this noise is proportional to the shaping time (τ) and inversely proportional to R_f and R_{bias} [2]. The contribution of this noise in terms of ENC as per [2] is given by Equation (1). F_i = 0.4 for the fifth order Gaussian shaper [2], k is the Boltzmann constant and T is the absolute temperature. A LCC can nullify the noise from leakage to increase resolution of the spectroscopy.

The transfer function of the CSA with LCC is shown in Equation (2)

$$\frac{V_{in}(s)}{I_{in}(s)} = \frac{1}{sC_f+\frac{1}{sL}+\frac{1}{R_f}} \quad (2)$$

For, C_f = 4.5pF, L=100H, the condition as per Equation (3) is satisfied to block any signal with frequency less than ~10 kHz which will essentially block the detector leakage current from the output path.

$$sC_f \ll \frac{1}{sL} \quad (3)$$

For stability of the circuit, two poles, as shown in Equation (4) & (5) of the transfer function presented in Equation (2) should satisfy the condition $p_2 \gg p_1$

$$p_1 \approx \frac{R_f}{L} \quad (4)$$

$$p_2 \approx \frac{1}{R_f C_f} \quad (5)$$

Therefore, a large inductance of the order of ~100H is required to keep $L \gg \frac{{R_f}^2}{C_f}$ which is not possible to be put inside monolithic chip. Hence a CMOS based equivalent circuit is designed (Fig. 2) which mimics the functionality of an inductor and feedback resistor with equivalent value as per Equation (6) & (7).

$$R_f = \frac{2}{g_{m_{MC}}} \quad (6)$$

$$L_f = \frac{2C_l}{g_{m_{MC}} g_{m_{MC_3}}} \quad (7)$$

where, g_m is the trans-conductance of the respective MOSFETs shown in Fig. 2.

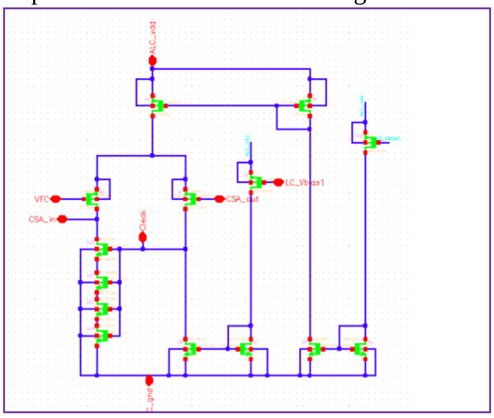

Fig. 2: CMOS implementation of LCC.

Results and Discussion

Fig. 3 shows the output of CSA without applying any leakage current compensation circuit. Here, CSA is given an input current pulse (in both positive and negative direction) at regular interval of time along with low frequency sinusoidal current pulse mimicking the leakage current.

It is clear from fig. 3 that the baseline of CSA output fluctuates and follows input leakage current signal, which leads to erroneous measurement of peak voltage for same input charge. This eventually affects the final energy resolution.

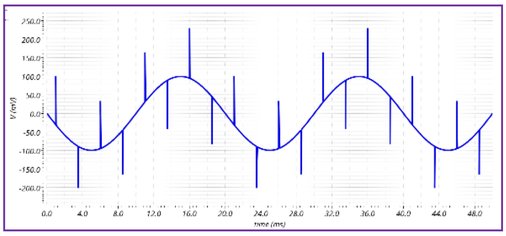

Fig. 3: CSA output without leakage current compensation circuit.

Fig. 4 shows output for the same input with leakage current and CSA circuit but with leakage current compensation applied.

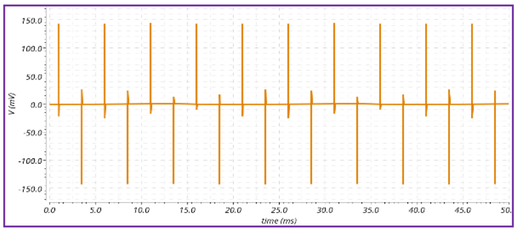

Fig. 4: CSA output without leakage current compensation circuit.

It is evident from fig. 4 that even with leakage current the peak output voltage of CSA does not vary at all for constant input charge when LCC is applied, resulting in a better energy resolution as expected.

Conclusion

The tested LCC design has been integrated in the second version of GMDA ASIC. Layout design, verification are completed. The final tape-out is being sent to the foundry for fabrication.

References

[1] Y. Hu, G. Deptuch, R. Turchetta and C. Guo, "A low-noise, low-power CMOS SOI readout front-end for silicon detector leakage current compensation with capability," in IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, vol. 48, no. 8, pp. 1022-1030, Aug. 2001, doi: 10.1109/81.940194.

[2] P. Grybos, "Front-end Electronics for Multichannel Semiconductor Detector Systems", 1st ed. Warsaw, Poland: WUT, 2010.