Pre-current amplifier based transimpedance amplifier for biosensors

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ABSTRACT

In this paper, we present current amplifier based transimpedance amplifier (TIA) for biosensor applications. Proposed design has low-noise, high Transimpedance gain that can be used for low current measurement applications. The current amplifier based TIA is implemented in order to resolve the fabrication issues related to high value feedback resistor. In this design, the input block to TIA is a low amplitude current amplifier. The designed amplifier is implemented in 90 nm complementary metal-oxide semiconductor (CMOS) technology. The design achieves transimpedance gain of 800 kΩ with a bandwidth of 5 kHz and input referred current noise is of 0.152 pA/$\sqrt{HZ}$ for an input of 41 nA bypassed from current amplifier with input of 200 pA.

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1. INTRODUCTION

In the field of biosensor and optical communication low current measurement is one of the important block as instrumentation system or readout circuit is concerned. For any biosensor or optical photonic readout circuit measuring low current and processing for further usage is one of the complex task. Apart from sensor field TIA can be used in the design of optoelectronics devices. In order to perform this step a sensitive and fast current measurement device is used i.e., transimpedance amplifier (TIA). Designing a TIA with constraints like low noise, low power and high transimpedance gain found to be complex. metal-oxide semiconductor (CMOS) TIA is preferred because of CMOS advantages with respect to scaling and performance parametrs. For implementation TIA two configurations called open and closed loop are followed. Open loop TIA uses common gate configuration for low input impedance and in this configuration noise is more. In the case of closed loop configuration feedback which includes shunt-shunt configuration is followed.

Usually in closed loop TIA feedback resistor is used for conversion of low current input from sensor or photodiode to equivalent voltage. In open loop configuration input referred noise is high because of this reason open loop TIAs are not suited for the design of front ends. For higher gain common source amplifier, cascade amplifier or a CMOS inverter are used.

TIA design procedure mainly involves design of amplifier with feedback resistor. The resistor plays a very important role in converting current to voltage. TIA topologies has been introduced and analyzed by authors with respect to design and topologies. Various TIA topologies have appeared in including various fields and also many domains which make the choice of the best TIA topology, but for a certain application is a challenging task. TIA topologies analyzed with respect to parameters like transimpedance gain, noise, power and even feedback resistor value. Different topologies are followed in order to design and analyze Transimpedance amplifier. There are different TIA topologies are designed and their characteristics are studied and compared [1]. TIA design challenge is measuring low current in the order of pA to nA. Many TIA design shown by Authors have closed loop with feedback high value resistor value. Feedback resistor design plays a very important role with respect to parameters like noise, transimpedance gain and Bandwidth. For noise reduction high value resistor is implemented in design but issues related to high value resistor is fabrication of resistor. To resolve the issue related to feed back resistor authors showed different fabrication techniques like using pseudo resistor, OTA in the feedback and also active feedback resistor [2]-[3].

Passive components can be used in the low current measurements in shunt or feedback configuration with respect to an active amplifier. For large current sensing Inductors also used for measurement but with biosensor inductors are not practically used. In this paper we propose new current amplifier based TIA where first stage of TIA is current amplifier and second stage we can employ differrent TIA topologies. Current amplifier is used to amplify current with amplitude from pA to nA. In the proposed design for feed back resistor fabrication more significance is given. For low input amplitude current to reduce feedback resistor value current amplifier is employed. Some authors presented pixel-level current readout circuit and new group-cluster architecture to address the circuit challenges in high-performance biosensor arrays**,** and also some authors presented current mirror based, switched capacitor based, resistive feedback TIA, OTA as feedback resistor in TIA feedback path [4]-[10]. The literature contains numerous examples of CMOS electrochemical current readout circuits for multi-channel measurement [11]-[15], including a recent review. Transimpedance gain is one of the parameter which specify the amplitude of current being measured with limitations [16]-[18] very few authors presented current amplifier based TIA that is efficient in reducing feedback resistance value. One of the technique current amplifiers with different transistor aspect ratio can be used as current amplifier but it is required to match size of transistor in order to mirror proper value of current. There some current amplifier design which doesn’t follow the aspect ratio [19]-[21] which is efficient design to overcome issues related to mismatch transistor size. Main aim of TIA design is to provide a optimized circuit with the requirement of bandwidth and also low input impedance. Along with required bandwidth and input impedance it’s also important to obtain high gain and low input noise. In order to get noise as low as possible different TIA topologies are initiated by many designers. TIA design involves current mirrors for biasing and also implementation of amplifiers [22]-[26]. In the bio sensing application TIA design is reffered to obtain required optimized parameters open loop configuration is not suited, so closed loop configuration with feedback path is used and also it provides better performance with respect to gain, bandwidth and noise [27]. This configuration also gives better stability to the system.

2. TRANSIMPEDANCE AMPLIFIER

Figure 1 shows simple shunt feedback of Transimpedance amplifier. As we can see resistor is used in the feedback path, which plays very important role in converting low amplitude current to voltage. Researchers developed different TIA topologies, one of the main challenges in designing TIA is the feedback resistor which is used to convert low amplitude current into voltage. As per the literature survey resistor value is in the range of Mega ohm to Giga ohm as it’s used to convert very low amplitude of nA to pA current to voltage. If the input current is in the range of PA to nA definitely feedback resistor range will be high in the range of GΩ, to fabricate this high value resistor in very-large-scale integration (VLSI) is difficult. Many authors shows even how to implement high value resistor using pseudo resistors and using operational transconductance amplifier (OTA) in feedback path. Reducing resistor value without compromising noise and gain with respect input is great challenge in TIA design and analysis.

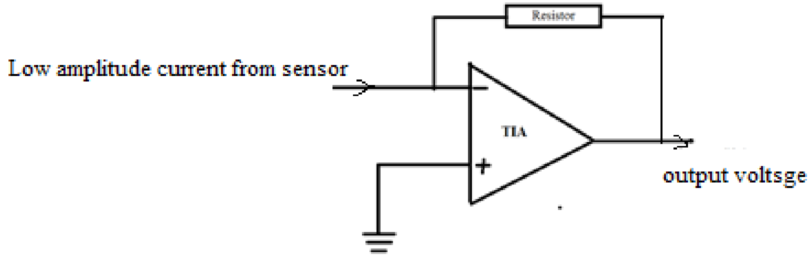

Figure 1. Block diagram of resistive feedback TIA

Very less authors showed design and analysis of current amplifier based TIA. Using current amplifier in the design of TIA feedback resistance value can be optimized. In this paper current amplifier based TIA is presented and analyzed. Same design can be used in different applications like sensor, communication, optoelectronics and also photonics field where data is in terms of light. Data which is coming from photodiode can be measured using TIA. Basic current amplifier is current mirror with different aspect ratio so that current input from different source like sensor or photodiode can be converted into voltage and also amplified. There are various current mirror designs are used in the design of voltage and current amplifiers. As TIA is mainly used in order to measure current from photodiode also high precision instrumentation systems that measure physical properties often include a TIA.

Figure 2 shows inverter cascade based TIA, it is extended version of Inverter based TIA. In this configuration two transistors are introduced positive-MOS (PM2) and negative-MOS (NM2). Because of these two transistors gain and gain bandwidth product (GBW) is enhanced. Gain of TIA is illustrated in (1) and (2). Gain dependence on gm of tranistor NM1 and PM1. Equation (3) illustrates ouput resistance.

$$A_{TIA} = -G_m * R_{out} \tag{1}$$

$$A_{TIA} = (g_{mNM1} + g_{mPM1})R_{out} \tag{2}$$

$$R_{out} = (g_{mNM2} + 1/r_{oPM2} + 1/r_{oPM2})r_{oNM1}r_{oNM2}||(g_{mPM2} + 1/r_{oPM1} + 1/r_{0PM2})r_{oPM1}r_{oPM2} \tag{3}$$

The noise current equation for above mentioned TIA is given in (4). Noise equation has 4 terms, first term describes the input noise contribution due to Rfb i.e., feedback resistor. Second term is due to transistors M_{NM1} and M_{PM1}.Third term and fourth term are contribution to M_{NM2} and M_{PM2} respectively.

$$I^2{}_{in} = 4K_BT[(G_m^2 + 2\pi f C_{pd})^2/(1 - G_mR_{fb})^2]R_{fb} + [(1 + 2\pi f C_{pd}Rfb)^2/(1 - G_mR_{fb})](g_{mNM}\gamma_{NM1} + g_{mPM1}\gamma_p) + [(1 + 2\pi f C_{pd}Rfb)^2/(1 - G_mR_{fb})(g_{mNM2} + 1/r_{oNM2})r_{oNM1}] + [(1 + 2\pi f C_{pd}Rfb)^2/(1 - G_mR_{fb})(g_{mNM2} + 1/r_{oNM2})r_{oNM1}] \tag{4}$$

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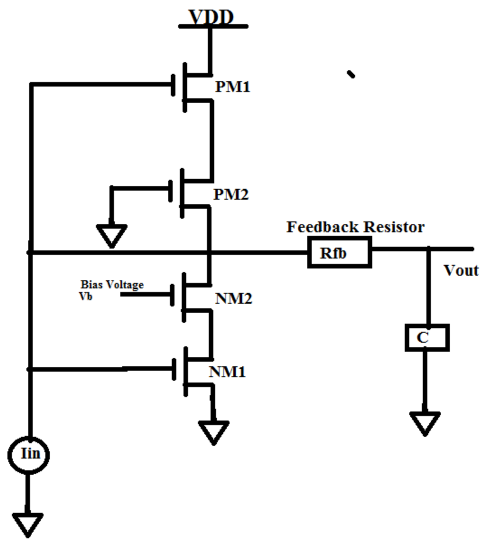

Figure 2. Inverter cascade based TIA

If we consider (4) and first term dominates at low frequencies then noise related to Rfb will be more. If we want to reduce noise at low frequencies that some biomedical application which handles low frequencies definitely Rfb must be low. If it is required to measure low current in the range of pA-nA definitely Rfb will in the range of GΩ. As the feedback resistor value increases noise also increases and also high value resistor implementation in VLSI is difficult. To overcome this difficulty and reduce the value of Rfb current amplifier based TIA is best suited as shown in Figure 3.

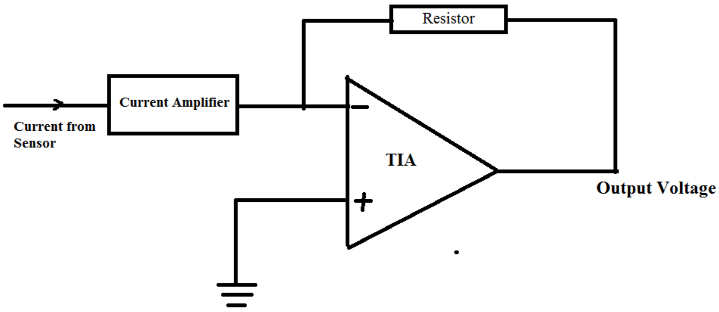

Figure 3. Current amplifier based TIA

Main reason behind using current amplifier based TIA is to amplify low amplitude current and applied to TIA in order to convert it to voltage. For the conversion of current to voltage using TIA feedback resistor is used. If input current amplitude is low definitely feedback resistance value will be in the range of MΩ to GΩ. As we know fabrication of high value resistance is difficult.

Figure 4 shows test bench diagram of current amplifier based TIA where first block is current amplifier and second block is Inverter cascade based TIA. If we apply low amplitude current directly to TIA if we measure feedback resistance value will be in terms MΩ if input current range in µA. So fabricating MΩ resistor in VLSI is difficult so if we pre amplify the current and convert it to voltage with feedback resistance value is less than MΩ.

As the feedback resistance value is decreasing definitely noise will be more as per (4). Using optimized noise reduction techniques design can be validated with low noise with low feedback resistance. Based on the Input current to the TIA noise calculation can be done. In the proposed TIA design slight increase in noise as it compared with existing one, using optimal fabrication techniques the KΩ feedback resistor can be fabricated for the input in the range of nA.

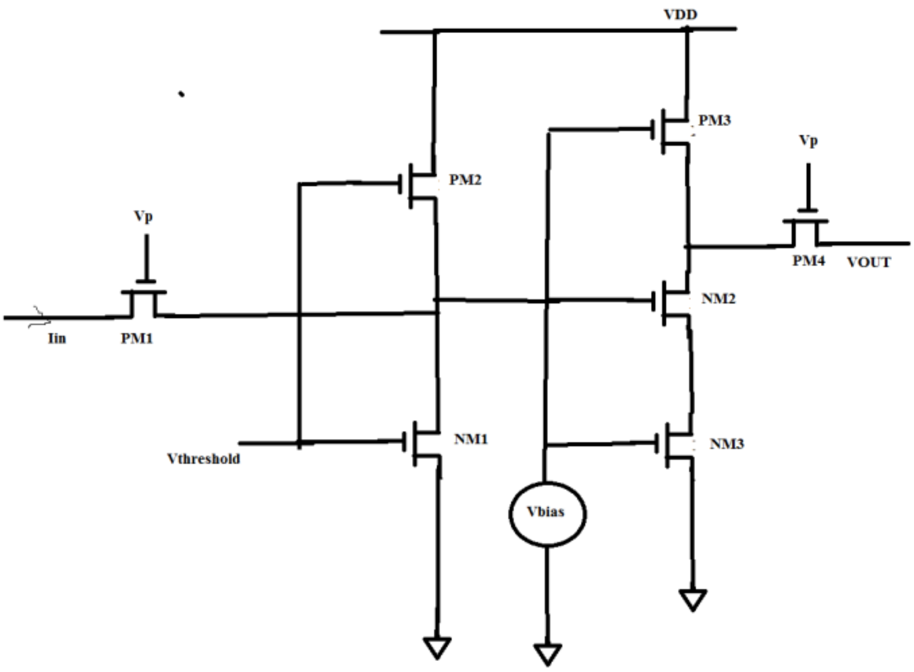

Figure 4. Schematic of low amplitude current amplifier

3. RESULTS AND DISCUSSION

Transimpedance amplifier is simulated in Cadence using 90 nm technology with different design parameters like input current, different feedback resistor values and also with current signal frequency. Figure 5 and Figure 6 shows transient analysis of current amplifier based TIA with 10 MΩ and 1 MΩ resistor. Input current applied is in the range of 200 pA and amplified using current amplifier with the output of 41 nA. Figure 7 show similar transient analysis of for Rfb values around 800 kΩ.

Figure 8 shows noise analysis of Transimpedance amplifier, for 200 pA input current with current amplifier as input stage to TIA noise value is optimal. Figure 9 shows schematic diagram of current amplifier based Transimpedance amplifier schematic. Table 1 depicts the comparison parameters of proposed design with existing one, if we analyze with respect to feedback resistor value, if we use current amplifier based TIA definitely resistor value is reduced but slight rise in noise as compared to other authors designs. As the input of TIA is in the range of nA after amplifying from current amplifier the required resistance value in kΩ range. From GΩ the resistor value is reduced from kΩ, its takes lower fabrication processing steps as compared to fabrication of high resistor value in the range of GΩ. This method definitely useful if we consider design with lower resistor value for low amplitude current conversion to voltage. Current amplifier based TIA is best suited for bio sensing application if we consider the fabrication process steps.

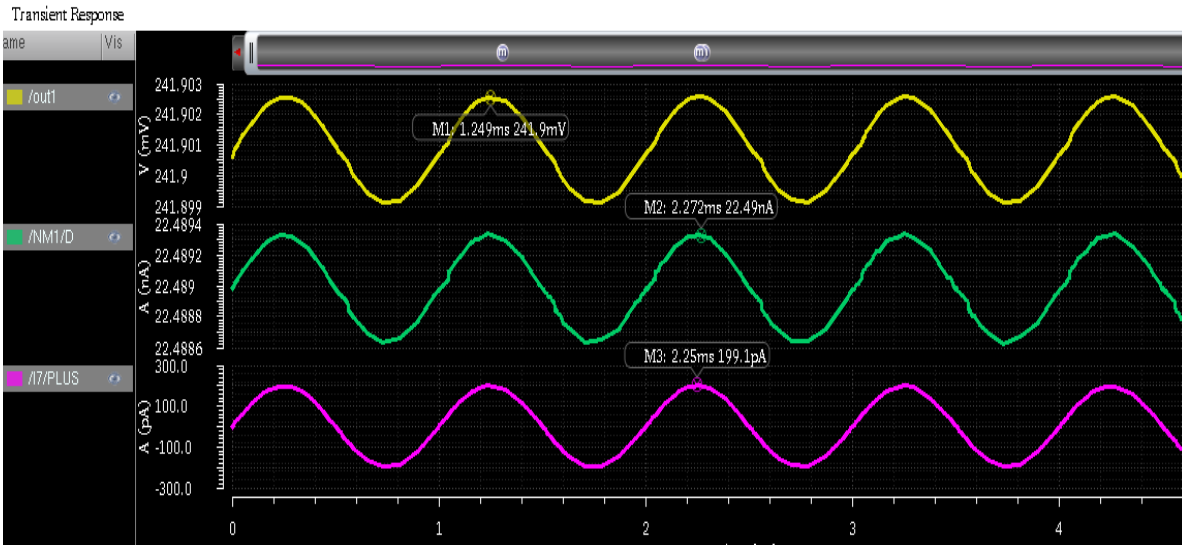

Figure 5. Transient analysis of TIA with Rfb of 10 MΩ

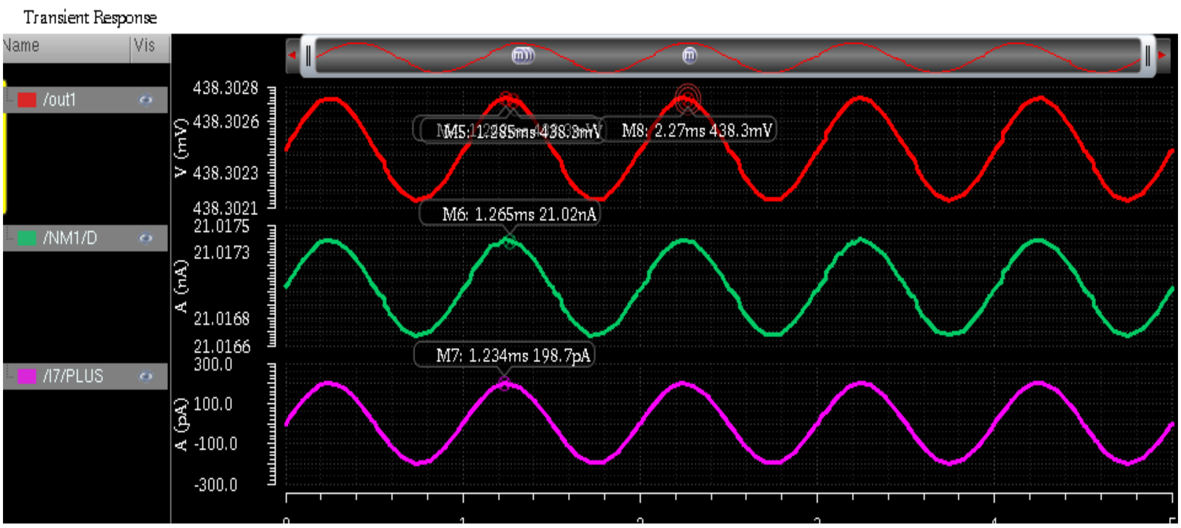

Figure 6. Transient analysis of TIA with Rfb of 1 MΩ

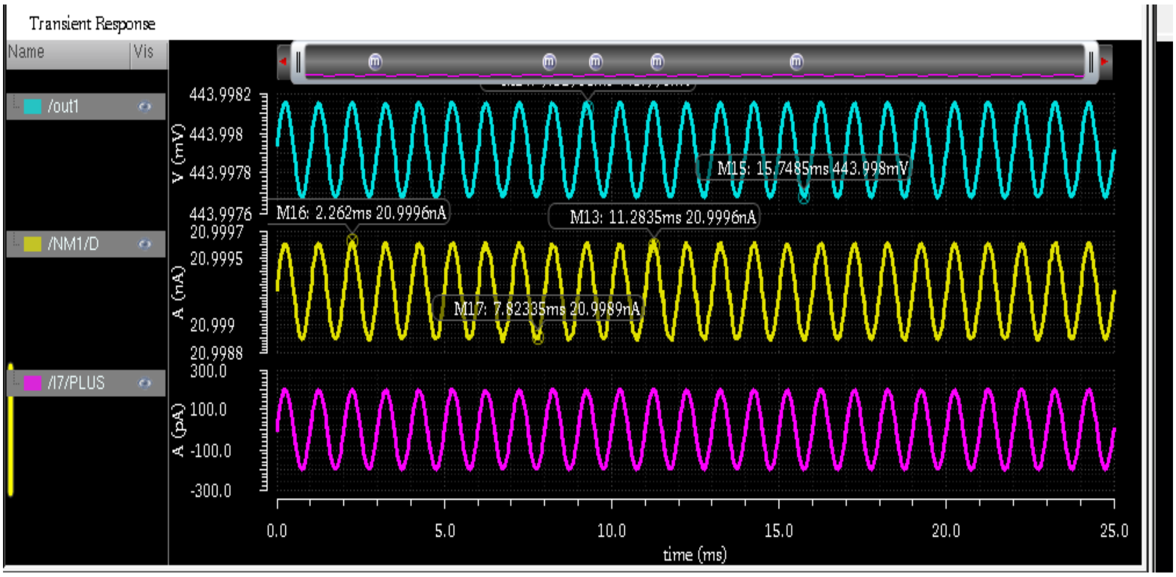

Figure 7. Transient analysis of TIA with Rfb of 800 kΩ

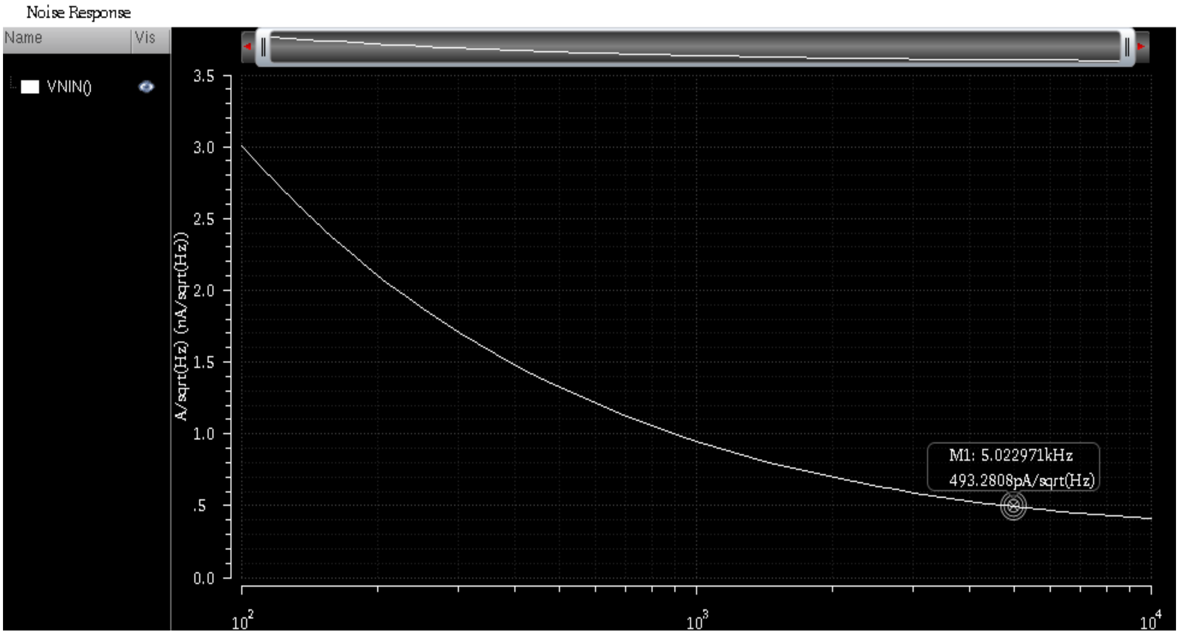

Figure 8. Input referred noise of current amplifier based TIA

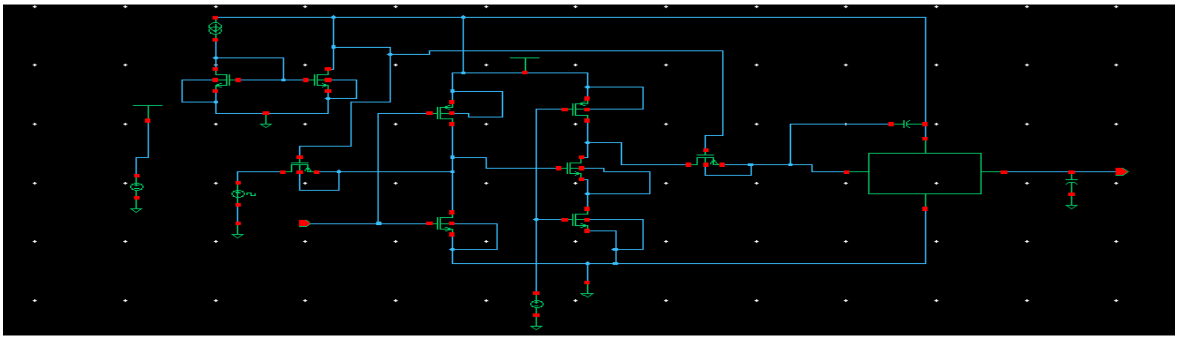

Figure 9. Schematic of current amplifier based TIA

Table 1. Comparison of design parameters

Sl.no.	Mulberry *et al.* [2]	Romanova and Barzdenas [3]	Li *et al.* [4]	Proposed TIA design (CA based INV CAS TIA)
Application technology	180 nm	180 nm	180 nm	90 nm
Input current	200 nA	150 nA	200 pA	200 pA
Current amplifier output	---	--	---	41 nA
Bandwidth	5 MHz	----	180 MHz	5 kHz
Transimpedance gain	6 MΩ	1 MΩ	1.72 GΩ	800K Ω
Supply voltage in V	1.2	1.2	1.4	1.2
Input referred noise	3.2 pA/$\sqrt{Hz}$	3.2 pA/$\sqrt{Hz}$	18 fA/$\sqrt{Hz}$	493 pA/$\sqrt{Hz}$

4. CONCLUSION

In this paper we implemented current amplifier based Transimpedance Amplifier for low current measurement Biosensor applications. Mainly in this paper feedback resistor value is considered as one of the important parameter for fabrication, so current amplifier based TIA is designed and achieved high transimpedance gain 800 kΩ with respect to amplified current from sensor with 1.2 V in 90 nm CMOS technology. Input referred current noise found to be 0.159 pA/$\sqrt{Hz}$ and bandwidth of 5 kHz.

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