A LOW-NOISE HIGH-PERFORMANCE INSTRUMENTATION AMPLIFIER BASED CNFET READOUT CIRCUIT FOR CARDIAC TROPONIN I DETECTION

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ABSTRACT

Detection of cardiac biomarker is crucial in diagnosis of acute myocardial infarction (AMI). According to National Centre for Biotechnology Information (NCBI) increase in Troponin protein beyond the limits in the blood is main cause for cardiac injury. Researchers have designed and implemented precise and accurate Troponin I detection sensors. Output of these sensors is too low to activate read out device for display. Therefore, too low output should be strengthened and further processed by signal conditioning circuit. This paper proposes design of first block Instrumentation amplifier of signal conditioning circuit using Carbon Nanotube Field Effect Transistors (CNFETs). Proposed instrumentation amplifier designed with CNFETs has very low noise and high performance of 108dB gain with a signal to noise ratio of 116dB. Sensor output is too low in the range of microvolts which is prone to low frequency noise. Proposed circuit reduces noise density to 0.4pV/√Hz.

Index Terms: CNFET, Instrumentation Amplifier, Cardiac Troponin I

I. INTRODUCTION

myocardial infarction (MI) is a leading cause of morbidity and mortality all over the world. MI leads to increase in elevated cardiac troponin I protein levels beyond its recommended levels in blood [1]. Acute myocardial infarction (AMI) is diagnosed by detecting the increased troponin I levels in blood [3]. Detection of this biomarker is carried out using available accurate biosensors, which has a limit of detection (LOD) of 0.03ng/ml to 5pg/ml [1-4]. This is converted to electrical signals of very low voltages or current. These electrical values are too low to be displayed on a read-out device. Therefore, obtained signal must be further amplified and processed to display. Reduction of Noise and amplification are main concern for biosensor signals as they are at low frequencies and have low magnitudes [5-7]. This paper proposes design of Instrumentation amplifier using CNFETs with a low-noise high-performance amplifier, which eliminates the flicker noise present in the signal. Frequency band considered from the cardiac troponin I detection sensor is 20Hz [8].

In this work, we designed the first block of signal conditioning circuit to amplify low output voltages of sensor and reduce noise of such low voltage bio signals. Instrumentation amplifier is designed using CNFETs of 10nm technology node [9], replacing MOSFETs.

Section II shows the significance of CNFETs over MOSFETs of this work. Section III shows the circuit description and derivation of gain of instrumentation amplifier. Section IV and V show the measurement results and conclusion.

II. CIRCUIT DESCRIPTION

I. CNFETs over MOSFET Technology

Demand for miniaturization has led to scaling of MOS devices. Later, practical scaling faced short channel effects such as DIBL (Drift Induced Barrier Length), Punch through, surface scattering, velocity saturation, Impact ionization. This problem of short-channel effects has started era for new geometrical devices, but none could compete with CNFETs. High mobility, ballistic transport, nano channel length, high trans-conductance, natural
ultra-thin body, efficient hole and electron transport properties, reasonable energy gap are characteristics of CNFETs which provide best solutions for the above pitfalls observed in MOSFET [9-10].

The fabrication process of CNFETs uses CVD (Chemical Vapour Deposition) method which is discussed in detail in Lorraine Rispal et al. [11]. In brief fabrication process is discussed in four steps. First step involves the highly doping of p-type silicon wafer used as back gate. Oxidation process is the second step, which deposits Nickle on Aluminium (catalyst layer). This provides a SWNT (Single-Wall Nano Tube) growth. Third step involves the annealing method followed by CVD. Finally, source and drain are structured using lift-off method. Process of CNT growth takes 10 minutes.

1. Device modelling

Ballistic transport of CNFETs lead to high drain current compared to MOSFETs. Ballistic transport means moment of electrons in ohmic free medium which reduces scattering of electrons. V-I characteristics of ballistic model of CNFETs is studied by Mostafa Fed way et al. [12]. The results obtained from above model has shown reduced running time of 23%.

Quasi ballistic transport: Scattering faced by electrons in a medium will be lessin quasi ballistic transport. Quasi-ballistic virtual-source model of CNFETs is reported in Chi-Shuen Lee et al. [13].

2. Device characterization

1. Drain current decreases with increase in gate oxide thickness both in ballistic and quasi-ballistic models. Research carried out by Nirjhor Tahmidur Rouf et al. [12]
2. The value of dielectric constant improves drain current even in non-ballistic model of CNTFET. [12]
3. Steep Voltage transfer characteristics curve is observed for CNTFETs with increasing diameter. [13]
4. For a given chirality MWCNT and SWCNT has same VTC curve.
5. Power consumption is reduced with reduction in chirality vector but delay increases.
6. Power delay product reduces (PDP) with chirality. It can be concluded that reduced chirality or diameter reduces energy dissipation.
7. PDP analysis is stable for high temperatures. CNTFETs have better tolerance for PVT (Process, voltage, Temperature) variations compared to MOSFET [14].

Recent study suggests that properties of CNTs and graphene is suitable for implementing accurate, reliable and high-speed biosensors. CNTs have a property to easily bind bio-compounds on their surfaces. This property can be utilised for many health monitoring applications.

3. Instrumentation Amplifier

Bio signals are at low frequencies which are susceptible to 1/f (flicker noise) [6]. To overcome this problem Instrumentation amplifiers with properties of suppressing common mode noise and amplification are used in biomedical applications. They are used where high sensitivity, high precision and high stability is required. This paper proposes such instrumentation amplifier to amplify the cardiac troponin sensor signals which are in the range of 1μV to 5μV. Circuit is designed using three, two stage op-amp with a gain of 51dB and phase margin of 60dB using CNFETs 10nm technology node. Instrumentation amplifier is configured as shown in the Fig. 1. It consists of three, two-stage op-amps with resistors connected to provide desired gain. With this circuit, gain can be set with a single resistor Rg. It consists of two input unity buffer stages with differential amplifier. Buffer stages provide proper impedance matching with high input impedance which minimizes loading effect at the sensor. It is balanced input and single output amplifier with high CMRR, high gain, low noise amplifier. Two buffer stages are used to connect one input as a reference signal and other is a sensor output.

From the Fig. 1, output voltage \( V_0 \) is derived from the two voltages \( V_A \) and \( V_B \)

\[
V_0 = \left( \frac{R_1}{R_2} \right) (V_A - V_B ) \tag{1}
\]
Considering ideal operational amplifier conditions with negative feedback, $I_g$ passes through $R_g$ as well as $R_3$. Therefore $I_g$ is given by equation 2 and $(V_A - V_B)$ in terms of $V_1$ and $V_2$ is given by equation 5, it is obtained by substituting equation 3 in equation 4. Rearranging equation 5 we get, equation 6.

Substituting equation 6 in equation 1, finally gain of instrumentation amplifier is obtained and given by equation 7. Gain of Instrumentation Amplifier is given by

$$\text{Gain} = \left(1 + \frac{2R_1}{R_g}\right) \left[\frac{R_3}{R_2}\right] = \frac{V_0}{(V_2 - V_1)}$$

Resistor $R_1$ is connected to buffer stages with gain resistor $R_g$, resistor $R_2$ is connected between buffer stages and output stage. The ratio of internal resistors, $R_2/R_1$, sets the unity gain in the first two Op-amp stages. Instrumentation amplifier provides high CMRR because of balanced signal.

Mathematically gain accuracy depends on resistor matching, which is obtained by many circuit techniques [11]. Design parameters of CNFET are given in Table 1. It is designed instrumentation amplifier using CNTFET 10nm technology node considered from primitive transistor models [12].
Fig. 2. Schematic of the two stage amplifier.

Instrumentation amplifier is designed using three, two stage op-amps. CNTFET schematic of op-amp is shown in Fig. 2 with a bias current of 10μA and compensation capacitance of 3pF.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate length ( L_g )</td>
<td>10nm</td>
</tr>
<tr>
<td>Device ( W )</td>
<td>1000nm</td>
</tr>
<tr>
<td>Gate oxide thickness ( t_{ox} )</td>
<td>3nm</td>
</tr>
<tr>
<td>Gate oxide dielectric constant ( K_{ox} )</td>
<td>23</td>
</tr>
<tr>
<td>CN diameter ( D )</td>
<td>1.2nm</td>
</tr>
<tr>
<td>CN spacing ( S )</td>
<td>1000nm</td>
</tr>
</tbody>
</table>

4. Noise analysis

This section briefly discusses about the noise sources in CNTFETs. It includes five noise sources.

**Thermal Noise of R\(_G\):** Random movement of electrons in the conductor causes voltage fluctuations, even the current is zero. The spectrum of thermal noise is proportional to temperature. Gate resistance produces thermal noise whose spectral density is given by

\[
S_{TH} = \frac{4KT}{R_G}
\]  

where \( K \) is Boltzmann’s constant, \( T \) is temperature, \( R_G \) is gate resistance.

Thermal noise of Rs and Rd:

Highly doped regions of drain and source has high resistance with thermal noise occurring at drain and source. \( R_d \) and \( R_s \) is similar to equation 1.

Channel Thermal noise:

Channel thermal noise is given by

\[
S_{ch} = 4KT\gamma g_{ds}
\]  

Where \( \gamma \) is termed as gamma noise factor, value varies from 2 to 3 in ballistic devices [15].

Shot noise:

In Ballistic and quasi ballistic devices such as CNFETs potential barrier is the main obstacle for the carrier flow rather than the scattering. Shot noise is the result of injection of charge carrier over the barrier. It is given by equation 10.

\[
S_{shot} = 2qI_dF
\]
Where \( q \) is the charge, \( I_d \) is the drain current, \( F \) denotes Fano factor which is in the range of 0.3 to 1 [16-17]. Input obtained at the sensor is a low frequency signal in the range of 10Hzs to 20 Hz. According to the analysis carried out, shot noise and flicker noise are dominant at low frequencies [18]. Therefore, shot noise and flicker noise is calculated theoretically. Considering values of equation 10, Fano factor value of 0.3 and 1, with drain current of 10uA, and charge, shot noise density obtained theoretically 0.4pV/√Hz.

**Flicker noise:**

In Carbon Nanotube devices, Flicker noise mainly depends on number of charge carriers \( N \). It is given by equation 11. From this equation, it is analyzed that flicker noise is inversely proportional to frequency. This work consists of design of Instrumentation amplifier with input signal operating at low frequencies in the range of 20Hz. amplifier designed with CNFETs with low frequencies are more prone to flicker noise.

\[
S_{\text{NI}} = \frac{A_H I_d^2}{f} = \left[ \frac{\alpha_H}{N} \right] I_d^2 \quad (11)
\]

Where \( A_H \) is the flicker noise amplitude given by the ratio of \( \alpha H \) and \( N \), \( \alpha H \) is the Hooge’s constant with most probable value of \( \sim 10^{-3} \). \( N \) number of carriers, \( I \) is the drain current and \( f \) is the frequency. From equation 11, as \( \alpha H \) is constant value with drain current and frequencies, flicker noise amplitude depends on number of carriers (\( N \)). \( N \) is calculated by equation 12, which depends on channel length of CNFET [19].

\[
N = \frac{(I L_d s)}{(V_{ds} \mu \epsilon)} \quad (12)
\]

Where \( I \) is the drain current, \( L_d s \) is channel length, \( V_{ds} \) is drain to source voltage, \( \mu \) is mobility of charge carriers, \( \epsilon \) is electron charge. By considering the optimal values of parameters theoretical calculation of number of charge carriers is obtained. Finally Flicker noise is calculated for Stanford CNFET 10nm technology node with the specifications provided is 0.1fV/√Hz.

A quantitative noise analysis is carried on CNFETs based on stanford CNFET model with 10nm technology node. By considering electrostatic and electromagnetic effects CNFET channels can be classified as 1. Uncorrelated channel (Pitch >20nm). 2. Correlated channel (pitch <20nm). Channel current is independent of their position for uncorrelated channel. All uncorrelated channels have similar properties. According to the specifications considered for Stanford CNFET model, pitch is 1000nm. Therefore noise analysis is considered for uncorrelated channel CNFETs. From Table. 1, as input signal is at low frequency band of 20Hz [8], flicker noise is dominant in CNFET [20-21]. Noise analysis is carried out by considering flicker noise density of CNFET which is given by equation 13 [22].

\[
i_n^2 = 2qI_dF \quad (13)
\]

Equation 13 gives flicker noise density, where \( q \) is charge, \( I_d \) is drain current of CNFET, \( F \) is Fano factor which is in the range of 0.3 to 1 [23]. Noise density is calculated for 20Hz signal frequency with Fano factor of 1.

### III. SIMULATION RESULTS

The ac response of proposed CNFET based IA is shown in Fig.3. From this, it may be noted the gain is 108dB. Fig. 4 shows the output-referred noise plot of the IA. The output-referred noise level is 79nA/√Hz.
Table 2 represents a comparison state of art of the proposed instrumentation amplifier (IA) design with some existing literature designs. The demanding design constraints taken into discussion for comparison the gain, CMRR, gain bandwidth, power dissipation, input referred voltage noise, output referred voltage noise for proposed design of IA and other literature. The comparison shows that effective increment in gain, CMRR and gain bandwidth product with moderate noise and power performance.

Proposed Circuit is compared with conventional different CMOS technology nodes. Specifications obtained from the proposed circuit is given in table 2. Output from Cardiac troponin sensor is applied as one of input of Instrumentation amplifier, with other input as reference signal. This circuit amplifies a signal range of 1μV to 5μV.

Noise is also reduced because of two reasons 1. Instrumentation amplifier reduces noise by reducing common mode noise signals.2. CNTFET contributes very less internal noise. Noise analysis is carried out for 1GHzs bandwidth, as the application is for low frequencies of 20Hzs, simulated output noise is 79nA/√Hz from Fig. 4. Ac analysis is carried for a frequency range of 1GHz. Required operation of frequency is very less, that is up to maximum of 20Hz, closed loop gain of 93dB is obtained as shown in Fig.5, differential gain obtained from the circuit is 108dB, with a phase margin of 60°.

As shown in Fig. 6, shows the common mode rejection ratio (CMRR) is the ratio of differential gain to common mode gain. Common mode gain is 7dB, which provides a total of 101dB CMRR.
This paper presents a low noise high performance instrumentation amplifier based CNFET readout circuit for cardiac troponin I with a gain of 108dB. Readout circuit is designed with CNFETs replacing MOSFETs, has reduced noise density to 0.4pV/√Hz, at a frequency range of 10Hz to 20Hz compared with different MOSFET instrumentation Amplifier circuits. This Instrumentation amplifier can find its applications in improving the strength of biomarkers with a very low output voltages ranging from μV to mV.

REFERENCES
