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DESIGN OF FEEDBACK CIRCUIT OF SCANNING TUNNELING MICROSCOPE USING CURRENT CONVEYOR

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ABSTRACT
A new Current Conveyor (CCII) based feedback circuit for use in scanning tunneling microscopy(STM) is proposed. The proposed circuit uses three CCIIs and five resistors. The feedback circuit is consist of pre-amplifier, amplifier and error detector. The pre-amplifier has a high bandwidth and good noise performance, which help in the improvement in the writing quality and speed of STM. The pre-amplifier associates a very high amplification factor (20µV/nA) to a sufficiently high bandwidth (126MHz). The feedback circuit has low input impedance, hence suitable for current signal. The CCII has been implemented using the 0.35µm CMOS technology. The PSPICE simulation agree well with the theoretical design.

Keywords: Feedback electronics for STM, Scanning Tunneling Microscope, CCII based STM Electronics.

I. INTRODUCTION

Scanning tunneling microscope (STM) invented by Binnig and Rohrer [1] enables us to image the surface of a sample and study their local electronic properties down to atomic scales. The STM is based on the concept of quantum tunneling. When a conducting tip is brought very near (few Å) to a metallic or a semiconductor surface, a bias voltage (10-1000mV) between the two can allow electrons to tunnel through the air between them resulting a tunnel current of the order of 1–20nA. Variations in tunnel current as the probe passes over the surface are translated into image. The feedback electronics, which controls the tunneling gap, maintains a constant tunneling current and hence adjust to a constant height of the tip of the STM from the surface under investigation with a feedback voltage applied to the piezoelectric height control mechanism [2-6]. The feedback Instrumentation essentially consists of a pre-amplifier, amplifier and a feedback loop. The performance of a scanning tunneling microscope depends, to a great extent, on the bandwidth and noise performance of the pre-amplifier [2,8,9,12,13]. Pre-amplifier converts the high impedance tunneling current to a low impedance voltage signal. Hence pre-amplifier has to fulfill several conditions including very low noise, high bandwidth, high(low) input impedance for input voltage(current) and low(high) output impedance for output voltage(current) [7,11]. Most commercial STMs use operational amplifier as an active element. The op-amps are operated in voltage mode and have limitations on their maximum frequency of operations due to lower slew rate and constant gain bandwidth product. The gain bandwidth product of most of the op-amps used in STMs is in the range of 1-2MHz . Hence, bandwidth of most commercial STM is limited to several tens of KHz [9]. The study of surface in sub µs time scale required different feedback electronics [12-13]. The current mode pre-amplifiers operated using current conveyors have some distinctive advantages over conventional voltage mode circuits such as wider signal bandwidth, greater linearity, wider dynamic range and low power consumption and hence useful for this kind of applications [14-17]. The proposed design for STM electronics is implemented with a pre-amplifier followed by an amplifier and a error detector employing plus type second generation current conveyor(CCII+). Pre-amplifier converts tunneling current to voltage to a wider bandwidth. The amplifier block amplifies the pre-amplifier output voltage to a level comparable to the reference voltage in the error detector. The error detector feeds back an optimum controlling voltage to the piezoelectric transducer of the STM tip after comparing the input voltage with a reference voltage. This feedback voltage (error voltage) controls the height of the tip from the scanning surface making the tip to move at constant height to scan the surface. The proposed circuit is found to be suitable for high bandwidth at high amplification and also has low input and output noise.

II. CIRCUIT DESIGN

Symbolic representation of a CCII+ structure is shown in the Fig.1. The port relationship of it may be characterized by

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix} \quad (1)$$

The CMOS structure of CCII+ is shown in Fig. 2. The proposed feedback circuit along with the Piezo system for STM is shown in the Fig. 3. It consists of three plus type second generation current conveyors (CCII+) and five resistors. The first CCII+ is used as a current to voltage convertor cum pre-amplifier and second CCII+ as an amplifier and the third one as an error detector. The tunneling current (I_{in}) is applied at the low input impedance terminal of pre-amplifier, hence the loading effect is almost eliminated.

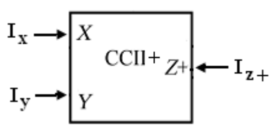

Figure 1. Block diagram of CCII+

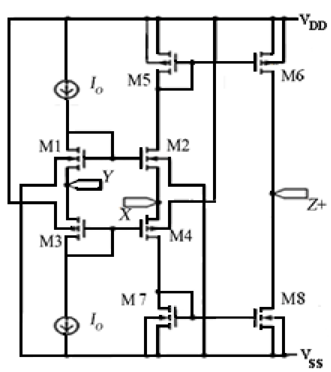

Figure 2. Internal structure of CCII+

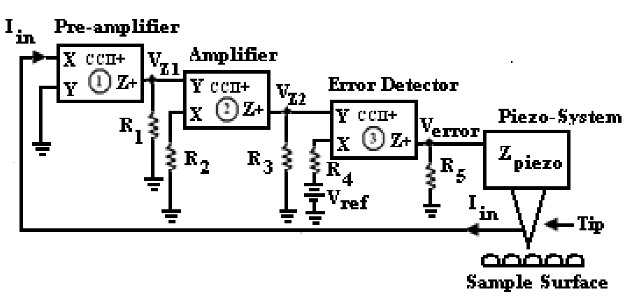

Figure 3. Proposed feedback Circuit along with Piezo - System

The routine analysis of the circuit of Fig. 1 yields the following expressions

$$V_{z1} = - \quad I_{in} R_1 \quad (1)$$

$$V_{z2} = - \quad I_{in} \left(\frac{R_1}{R_2}\right) R_3 \quad (2)$$

$$V_{error} = \left[-I_{in} \left(\frac{R_1}{R_2}\right) R_3 - V_{ref}\right] \frac{R_5}{R_4} \quad (3)$$

where, I_{in} is the current developed at the STM tip and V_{error} is the error voltage which is fed back to height control mechanism of STM tip.

III. EFFECT OF NON-IDEALITIES OF CURRENT CONVEYOR

The frequency performance of the proposed circuit may deviate from the ideal one due to non-idealities of current conveyors (CCII+s) [18,19]. The port relationships of current conveyor including non-idealities of CCIIs modify to [18]

$$V_x = \beta_i(s)V_y, \quad I_z = \alpha_i(s)I_x \quad \text{and} \quad I_y = 0, \quad (5)$$

where i = 1,2,3. β_i (s) and α_i (s) denote voltage and current transfer functions respectively, which can be molded as

$$\beta_i(s) = \frac{\beta_{oi}}{s+\omega_{\beta_i}} \quad \text{and} \quad \alpha_i(s) = \frac{\alpha_{oi}}{s+\omega_{\alpha i}} \quad (6)$$

The terms β_{oi} and α_{oi} represent low frequency values of β_i (s) and α_i (s) respectively; ω_{β_i} and ω_{α_i} are respectively pole frequencies of voltage and current transfer functions. Considering the error in the current and voltage transfer functions, the expression for the output of pre-amplifier, amplifier and error detector circuits modify to

$$V_{z1} = -\frac{\alpha_{oi}}{s+\omega_{\alpha i}} I_{in} R_1 \quad (7)$$

$$V_{z2} = -\frac{\alpha_{oi}}{s+\omega_{\alpha i}} \frac{\beta_{oi}}{s+\omega_{\beta_i}} I_{in} \left(\frac{R_1}{R_2}\right) R_3 \quad (8)$$

$$V_{error} = \frac{\alpha_{oi}}{s+\omega_{\alpha_i}} \left[-\frac{\alpha_{oi}}{s+\omega_{\alpha_i}} \left(\frac{\beta_{oi}}{s+\omega_{\beta_i}}\right)^2 I_{in} \left(\frac{R_1}{R_2}\right) R_3 - V_{ref}\right] \frac{R_5}{R_4} \quad (9)$$

The low frequency values of current (α_{oi}) and voltage transfers (β_{oi}) are found as 0.985 and 0.987 respectively which are very close to unity so their affect can be ignored. The expression (7) to (9) clearly indicate that the pole frequencies of current and voltage transfer functions of CCII+ affect the overall frequency response. The effect can however be ignored if the operating frequencies are chosen sufficiently smaller than current and voltage transfer pole frequencies of CCII+ which are simulated to be around 1.5GHz. As the bandwidth of the proposed circuit is 126MHz, the non-ideality effect may be ignored.

IV. RESULT AND DISCUSSION

To validate the theoretical design, the proposed circuit is simulated with SPICE using schematic of CCII+ as given in the Fig.2 and AMS 0.35µm CMOS technology with dimensions of transistors given in Table I and supply voltage of ±2.5 volts and bias current of 50µA. In most of the standard applications, the tunneling current of STM is within the range of several nA {1-20} nA. We are interested in wide bandwidth measurements of the tunneling current. PSPICE simulations of the frequency vs transimpedance and output voltage of the pre-amplifier is shown in Fig.4. The simulation result shows an improved 3dB bandwidth of 126MHz [8,9] and a transimpedance of 20kΩ. The output voltage of pre-amplifier is 20µV with 1nA input current and R_1= 20kΩ. However it is evident that the desired output voltage may be obtained by proper select of the value of R_1.To study the noise performance of the pre-amplifier, the input and output noise of the pre-amplifier are simulated as given in Fig. 5. It shows that the noise of the pre-amplifier is quite low upto about 126MHz [8]. To verify the proper working of the feedback electronics, the constant height of the STM tip from the sample surface has to be maintained which will give rise to a constant tunneling current. Let us consider the constant height is h and corresponding tunneling current is 10nA. If the height of the STM tip reduces while scanning, then current will increase from 10nA. The feedback electronics consequently should produce proportional negative error voltage to be applied to piezo system to bring the STM tip height back to constant height h and consequently the tunneling current to 10nA. Simulation has been carried out for resistance values of R_1= 20kΩ, R_2= 100kΩ, R_3= 200kΩ, R_4= 100kΩ, R_5= 100kΩ. Fig. 6 shows the ramp (rising and falling) tunneling current, the corresponding pre-amplifier output voltage(V_{z1}), amplifier output voltage (V_{z2}) and error voltage (V_{error}). It is observed that the error voltage is 0 (zero) when tunneling current is 10nA and increases negatively as the tunneling current increases. Similarly, the error voltage increases positively when tunnel current decrease from 10nA. Hence , it is evident that the error voltage (V_{error}) which is applied to the piezo system will bring back STM tip height to its constant value h and consequently tunnel current to 10nA. Fig.7 shows a 100MHz sinusoidal tunnel current applied to the input of pre-amplifier. The corresponding output voltages as shown in Fig.8 follow the same nature as that of Fig.6 and verifies theoretical design.

TABLE I: Aspect ratio of the transistors

Transistor	W(µm)/L(µm)
M_1-M_2	20/0.35
M_3-M_4	60/0.35
M_5-M_6	30/2
M_7 –M_8	10/2

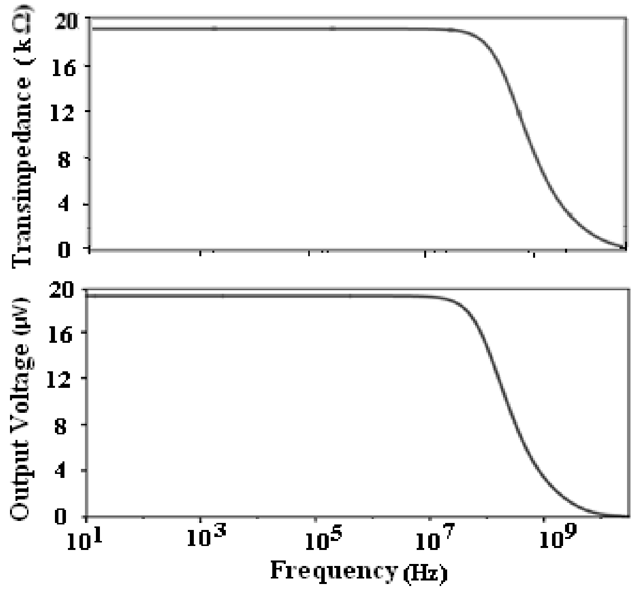

Figure. 4. Transimpedance and output voltage of the pre-amplifier with I_{in} =1nA and R_1= 20kΩ

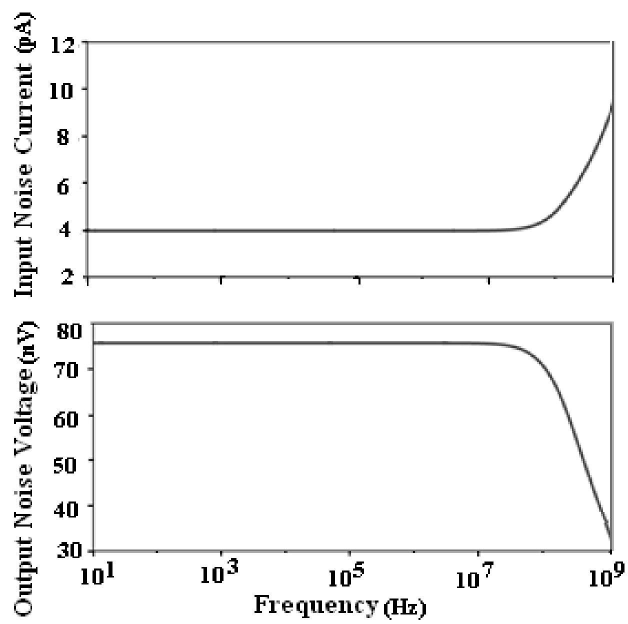

Figure 5. Input noise current and Output noise voltage of the pre-amplifier

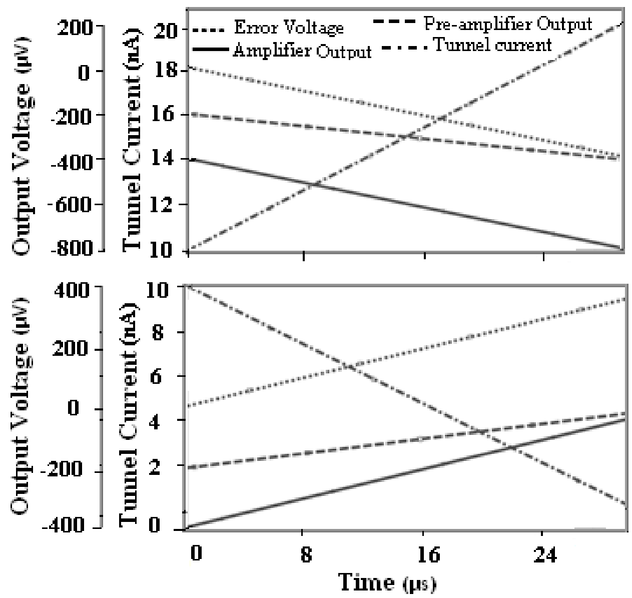

Figure 6. Input tunnel current and corresponding output voltage of pre-amplifier, amplifier and error detector

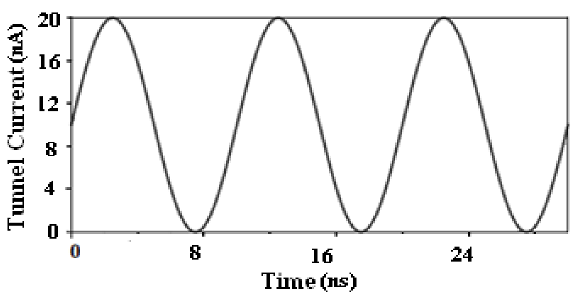

Figure 7. Sinusoidal input tunnel current

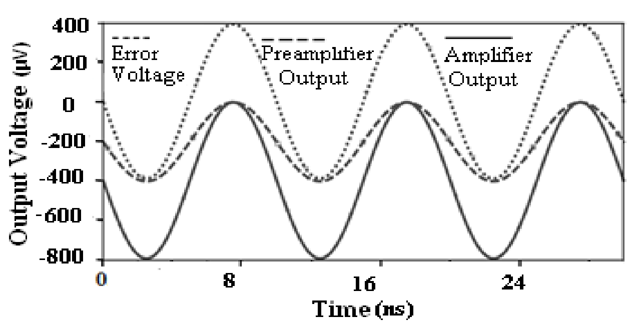

Figure 8. Output of pre-amplifier, amplifier and error detector

V. CONCLUSION

A Current conveyor based feedback circuit has been proposed for STM. The workability of the circuit is tested. The bandwidth of the pre-amplifier achieved is about 126MHz in comparison to 35MHz and 50MHz realized in [8,9]. However the bandwidth of pre-amplifier may further be enhanced by using different internal structure of CCII+ and different technology. The output of the feedback control system consisting of pre-amplifier, amplifier and error detector circuits is in conformity with the operation of STM. The non-linearity effect of CCII+ on the performance of the circuit has been discussed.

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