A low-noise and wide-band ac boosting current-to-voltage amplifier for scanning tunneling microscopy

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A compact, fast, and low-noise current-to-voltage amplifier is built for scanning tunneling microscopy. The amplifier consists of two amplification stages. The first stage performs low-noise transimpedance amplification by using a high performance FET operational amplifier together with a high-ohm feedback resistor of 1 G Ω and a parallel trimming capacitor. The ac boosting amplifier in the second stage recovers the higher frequency above the 3 dB cutoff of the first stage to extend the maximum bandwidth up to 100 kHz. This two-stage current-to-voltage amplifier shows a low current noise below sub-pA rms when tuned to have the bandwidth of around 1 kHz. It also guarantees stable frequency response in the presence of 1000 pF input capacitance. © 2005 American Institute of Physics. [DOI: 10.1063/1.1841873]

I. INTRODUCTION

In scanning tunneling microscopy (STM), the tunneling current between the tip and the sample contains all the essential informations. The tunneling current provides the basic topography of the sample surface for the determination of the atomic structure, and it gives the tunneling spectroscopy for the electronic structure. Since the magnitude of the tunneling current is very small in the range from below pA to nA, it should be amplified by the gain of 10^8-10^{10} (V/A) to be used in the electronic circuits of STM. Hence the high performance current-to-voltage converter (IVC) is the most important part in STM.

Two types of amplifiers, the electrometer^{1,2} and the inverting feedback,^{1,3} are generally used as the IVC. The former uses a shunt resistor to generate a voltage signal, which is amplified by the following instrumentation amplifier. The latter is more popular in many fields including the STM experiments, since it is convenient for the detection of a fast and low current signal due to wider bandwidth and lower noise. Moreover the inverting feedback IVC can be built easily using a commercial FET operational amplifier (op-amp) and a high-ohm feedback resistor as shown in Fig. 1(a). However, many incompatible requirements of the IVC such as high gain, low noise, wide bandwidth, low dc error, and small size are required for the STM applications. Ideally the inverting feedback IVC with a large feedback resistance above 1 G Ω can provide a proper dynamic range covering the tunneling current (pA-nA) and minimize the noise. However, the actual frequency response or bandwidth is generally limited below 1 kHz due to the parasitic capacitance (0.2-0.5 pF) across the feedback resistor,¹ since the transfer function of the IVC is practically the same as that of RC low-pass filter consisting of the feedback resistor and parasitic capacitance distributed over it. There are several methods to overcome the narrow bandwidth limitation of the inverting feedback IVC;^{1,3} cascade amplification, *T*-network, guard band, and capacitance compensation, etc. However, the cascade amplification and the T-network have poor noise performances in the measurement of small current, since these methods use small feedback resistors $(1-10 \text{ M}\Omega)$ at the first stage and then extend the bandwidth. As another category, the guard band [Fig. 1(b)] and the capacitance compensation [Fig. 1(c)] reduce the effective parasitic capacitance. The former requires a special resistor with three leads and a low parasitic capacitance. The latter entails careful circuit design due to the inhomogeneous distribution of the parasitic capacitance. Though both of them modestly recompense the bandwidth around 2–4 kHz, they have a drawback of exhibiting "ringing or oscillation" in the presence of a high input capacitance.⁴ Hence these IVCs do not provide stable performances for STM experiments where large input capacitance is inescapable.

In this article, we report the design and performance of an ac boosting IVC which satisfy simultaneously the various requirements for versatile STM experiments. Our IVC consists of simple two stage amplifications; the first stage has the characteristics of high stability and high gain of an inverting feedback IVC, and the second stage is an ac boosting amplifier to recover the higher frequency above the 3 dB cutoff of the first stage. The maximum bandwidth of the IVC can be extended up to 100 kHz. When the bandwidth is tuned to be around 1 kHz, the noise level is below sub-pA rms in the presence of 100 pF input capacitance.

II. NOISE AND FREQUENCY RESPONSE OF THE IVC

There are two kinds of noise in the IVC; interference noise picked up from outside the circuit and inherent noise arising within the circuit itself. The typical magnitude of the interference noise is not negligible and ranges from sub-pA to a few hundred pA.⁵ The interference noise can be reduced by taking precautions such as filtering, decoupling, shielding, low noise power supply, clean circuit board, and vibration free cabling. Apart from the interference noise, we have still the inherent noise arising from the amplifier itself and the feedback resistor.

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FIG. 1. (a) The circuit diagram of the inverting feedback IVC for modelling the tunneling current and input noise. (b) Guard band technique eliminates parasitic capacitance partly. (c) Capacitance compensation method corrects frequency response effectively but has some drawbacks.

The inherent noise characteristics of the IVC can be modeled by the combination of noise sources and the following noiseless amplifier with a feedback resistor. Figure 1(a) shows a typical circuit of the inverting feedback IVC with several noise sources. Since the noise components are generally random and uncorrelated, the total spectral noise density (TSND) from each contribution can be given by⁶

$$i_{\text{TSND}} = \sqrt{\left(\frac{e_n}{R_f}\right)^2 + i_n^2 + \frac{4KT}{R_f} + (2\pi C_{\text{in}}e_n)^2}$$
 (1)

in A/ $\sqrt{\text{Hz}}$, where R_f is the feedback resistance, e_n is the input voltage noise density of the op-amp, i_n denotes the op-amp's

input current noise density, and the input stray capacitance $C_{\rm in}$ includes all the contributions from input cable, connector, op-amp, etc. Equation (1) represents the best theoretical noise performance of the IVC with an ideal current source." Well-designed discrete op-amps^{4,8} or high performance commercial units have typically the input voltage noise density of several nV/\sqrt{Hz} and the input current noise density of sub-fA/ $\sqrt{\text{Hz}}$.⁹ Therefore if C_{in} is low enough, the TSND from the IVC itself can be reduced to the theoretical limit, Johnson noise, of the feedback resistor. However, it should be noted that the best noise performance described above does not guarantee the best performance of the IVC in STM experiments where fast scan or high input capacitance are inevitable. In these situations, the most significant noise comes from the coupling of the total input capacitance and input voltage noise in the form of $2\pi C_{in}e_n$ as shown in Eq. (1). Therefore, the strategy to keep both e_n and C_{in} as low as possible by using a proper op-amp¹⁰ and placing the IVC close to the current source is very important. In addition to the above noise sources, the offset voltage and the input bias current of the op-amp can be considered as dc noise sources that vary with time, temperature, etc. The full bandwidth noise of IVC should be calculated by integrating the TSND over the full bandwidth. Therefore the magnitude of the total full bandwidth current noise including both interference and inherent noise is higher than the calculated theoretical limit of Johnson noise.

Because the high-ohm resistance of around 1 G Ω is a good solution for the low noise and adequate dynamic range of the IVC, we need to check the bandwidth of the IVC in more detail. (i) If we assume the gain bandwidth product (GBP) of the op-amp to be infinite, the frequency response of the IVC is given by a transfer function similar to the simple low pass filter with 3 dB corner frequency of $1/(2\pi R_f C_p)$. If we use, for instance, a feedback resistor of 1 G Ω with the



FIG. 2. (a) The circuit diagram of twostage ac boosting IVC. (b) The PSPICE simulation of the ac boosting IVC. The gain of the composite amplifier starts to increase from the 3 dB cutoff frequency of the inverting feedback amplifier in the first stage.

parasitic capacitance of 0.2 pF, the bandwidth of the IVC will be limited below 800 Hz. (ii) Assuming that GBP of the op-amp is finite but sufficiently large, the transfer function of the IVC can be written in the form of two simple low pass filters in cascade¹¹

$$\frac{1}{T(s)} = (R_f C_p s + 1) \left(\frac{C_p + C_{\text{in}}}{C_p \cdot \text{GBP}} \cdot s + 1 \right).$$
(2)

The frequency response now has two corner frequencies. The first $1/(2\pi R_f C_p)$ is caused by the parasitic capacitance across the feedback resistor, the second higher cutoff frequency $(C_p + C_{in})/(2\pi C_p \cdot \text{GBP})$ comes from the finite GBP of the op-amp. To improve the frequency response of the IVC, one usually tries to reduce C_p . This reduction of C_p increases the first corner frequency but reduces the second one at the same time, usually by about the same factor. (iii) If we consider the extreme case where the two corner frequencies become comparable, the effect of input capacitance C_{in} on the input terminal should be introduced. In this case, the amplifier will behave like a damped harmonic oscillator and the approximation of Eq. (2) is no longer valid. When C_p is decreased down to the threshold, causing the crossover of the two corner frequencies, the bandwidth of the IVC does not increase further; instead the frequency response begins to show a peak, and the step response shows "ringing or oscillation."

To permit a large input capacitance up to several hundred pF for versatile STM applications, it is desirable to have an op-amp with GBP far above 10 MHz. Unfortunately, commercially available low noise, low input capacitance, and low input bias current FET op-amps⁹ have GBP below a few MHz. That means most of the op-amps are not adequate for low level and high speed current recording, since they do not guarantee the stable frequency response over the entire bandwidth. Therefore, it is rather better to keep C_p as high as possible in the first stage for both stable operation and small noise pick up, and then recover in the next stage the higher frequency region above the 3 dB cutoff frequency of $1/(2\pi R_f C_p)$.¹²

III. A LOW-NOISE AND WIDE BAND IVC: DESIGN AND PERFORMANCE

In the previous section, it is shown that a high-ohm feedback resistor above 1 G Ω and the large parasitic capacitance is more desirable for the proper dynamic range, low-noise, and stable operation of the IVC. The wide bandwidth without deteriorating the noise performance is the problem we have to solve in the design scheme.

The scheme of our IVC design is two-step serial amplification as shown in Fig. 2(a); the low-noise transimpedance amplification and the following ac boosting.

The first stage consists of a FET op-amp OPA111BM (Burr Brown) with a 1 G Ω feedback resistor and a parallel air trimming capacitor C_f (0.3–3 pF). The trimming capacitor is used to adjust the exact 3 dB frequency from which the second ac boost stage starts to increase the gain. We found that the capacitance C_f of around 1.3 pF ensures much lower noise gain and superior frequency response in the presence



FIG. 3. (a) Diagrams for the measurement of the risetime, and (b) for the measurement of the total input current noise. An oscilloscope is used to check unusual noise spike or line frequency pick up.

of large input capacitance. The op-amp's input lead, the trimming capacitor, and the feedback resistor should be soldered directly to the input connector via a whittled Teflon standoff and should not touch any surface to prevent the current leakage and the stray capacitance pickup from the PCB trace.

The second step, ac boosting amplifier, recovers high frequency signal which is damped down by the low pass transfer function of the first stage. For the ac boosting stage, we built a composite amplifier by using the dual op-amp OPA2111KP. Compared to a single op-amp, the composite amplifier has the advantages of large open loop gain for higher accuracy and phase compensation for small noise in the high frequency region.¹³ The ac boosting circuit amplifies only the ac component with the variable resistor R_4 to extend the bandwidth, excluding the dc component from amplification with the capacitor C_1 . By trimming C_f , C_1 , and R_4 , we can extend the bandwidth up to 100 kHz. Finally we select a desirable bandwidth and noise performance of the total IVC by installing a proper C_3 in the booster stage as in Fig. 2(a).

We used two 9 V batteries for the power supply, since they can be placed together with the IVC in an aluminum shielding box not to cause the ground loops and the 60 Hz line pickup.¹⁴

The PSPICE simulation¹² of the inverting feedback IVC in the first stage, the composite amplifier in the second stage, and the total IVC as the convolution of the two stages, is shown in Fig. 2(b).

To assess the performance of the IVC, we need a current source in the range of pA–nA. The current source can be implemented by a triangular waveform generator and a high quality ceramic capacitor. The derivative of triangular voltage wave (~190 mV_{p-p} and 100 Hz) across the shielded 15 pF capacitor produces a square wave current source with the magnitude of about 2 nA_{p-p}.¹⁵ The bandwidth of the IVC is generally estimated by measuring the rise time of the square wave current source to the IVC, we get an output of square waveform with the amplitude of ~2 V_{p-p}, whose risetime is directly related to the bandwidth as

Bandwidth =
$$0.35/risetime(10\% - 90\%)$$
. (3)

The risetime was measured by a digital oscilloscope, and the noise of the IVC was measured by an oscilloscope and



FIG. 4. The bandwidth of the IVC can be adjusted from 10 kHz to 1 kHz by changing the C_3 value in the boosting stage from 100 to 1500 pF.

true rms voltmeter. We see from Fig. 4 that the edge of the square response becomes blunter as we increase the value of C_3 from 100 to 1500 pF.

Table I summarizes the relations between bandwidth and noise performance of the ac boosting IVC for several values of C_3 .

The lower trace of Fig. 5 shows that the high frequency peaking of the capacitance compensation IVC [Fig. 1(c)] exhibits "ringing or oscillation" in the presence of 161 pF input capacitance (5 feet RG-58 coaxial cable). On the other hand, the upper trace of Fig. 5 shows very flat and stable frequency response of the ac boosting IVC with the same coaxial cable. Even at larger input capacitance over 1000 pF, the IVC shows good performance without any ringing or oscillation. The ac boosting IVC has the current noise below sub-pA rms and can detect a small tunneling current down to a few pA with the bandwidth of around 1 kHz in STM experiments. For the wideband requirement, it permits the bandwidth up to 100 kHz. Moreover, this compact amplifier can be placed very close to the current source of the STM so that it can minimize the unfavorable noise pickups and reduce the stray input capacitance.

TABLE I. The bandwidths of the ac boosting IVC tuned by different C_3 values, and the corresponding noise characteristics.

<i>C</i> ₃ (pF)	Bandwidth (kHz)	Noise (pA) ^a	Noise (pA) ^b
100	11.3	2.25	4.55
220	5.4	1.29	2.69
470	2.4	0.71	1.37
1000	1.2	0.47	0.73
1500	0.76	0.40	0.58

^arms values with the input open.

^brms values with the input capacitance of 100 pF.



FIG. 5. The upper trace is obtained from the ac boosting IVC and shows stable frequency response in the presence of 161 pF input capacitance, while the bottom trace shows "ringing effect" of the capacitance compensation method with the same input capacitance.

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- ¹⁰The input common mode plus difference capacitance of op-amp itself contributes to the total input capacitance C_{in} . The op-amp OPA111BM has 8 nV/ $\sqrt{\text{Hz}}$ input voltage noise and 4 pF input capacitance.
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- ¹⁵ High-ohm resistor does not represent a true current source for any IVC with feedback gain above 10⁷. The high-ohm resistors have intrinsic parasitic capacitance and will result in out-of-phase current, noise, and dc drift. The results will be totally erroneous on these gain settings. The voltage of triangular waveform and a capacitor should be used for correct results.