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Citation: Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena **35**, 033201 (2017); doi: 10.1116/1.4981017

View online: http://dx.doi.org/10.1116/1.4981017

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Circuit design considerations for current preamplifiers for scanning tunneling microscopy

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(Received 30 January 2017; accepted 3 April 2017; published 12 April 2017)

Current-to-voltage preamplifiers for scanning tunneling microscopy were tested side-by-side using a consistent testing protocol, to optimize performance and understand potential design trade-offs. Current-to-voltage gain and voltage noise density were measured as functions of frequency for two different circuit architectures: the feedback transimpedance amplifier and the current-shunt electrometer. The effect of specific component choices—of the integrated circuits, resistors, and capacitors—was also investigated. © *2017 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4981017]

I. INTRODUCTION

In the development of scanning tunneling microscopes (STMs), Binnig *et al.* showed that the distance between an atomically sharp metal tip and a conductive surface could be controlled at the subångström scale and that the resulting DC electron tunneling currents from 10^{-6} to 10^{-9} A and below could then be measured.[1] Modern STM imaging can require tunneling currents as low as 10^{-12} A. At these levels, minor deviations from the ideal behavior of the transistors (whether as discrete devices or within integrated circuits) used for measurements become significant, as do fundamental physical limitations such as thermal and statistical fluctuations of electron flow.

Best practice for minimizing the introduction of interference and noise is to amplify a signal near its source using a low-output-impedance device; in this case, this means placing a current-to-voltage preamplifier as close as is practical to the STM tunnel junction. STM preamplifiers typically have transimpedance gains of 10^9 V/A (1 GΩ) or higher. An ideal preamplifier would also be noise-free with a high slew-rate, so that the amplified signal would have the same noise and frequency spectrum as the original, although the higher the transimpedance gain, the more difficult these ideals are to approach.

Traditionally, the simple two-stage feedback transimpedance amplifier (TIA) shown in Fig. 1(a) has been the most widely used design for STM. Several examples of circuit implementation are in the literature, and manufacturers' specifications provide data to guide electronic component selection. Here, we explore a range of options for the operational amplifiers, resistors, and capacitors that make up the TIA by constructing multiple circuits and measuring each one with a consistent series of tests.

This series of tests is also used to compare the TIA design with current-to-voltage preamplifiers built with an alternate architecture: the shunt electrometer circuit [Fig. 1(c)], which has been used in several cases for low-current measurements in general and STM in particular. We relied particularly on the work of Chen *et al.*, who described the optimization of such an amplifier specifically for high-speed scanning.[2]

The goal of this paper is to gather together results scattered over 20 years of the instrumentation literature and to provide in one place a quantitative, side-by-side comparison of multiple different preamplifier circuits.

II. EXPERIMENT

Circuits were constructed using custom-built printed circuit boards (PCBs). In order to minimize current leakage, a polytetrafluoroethylene-dielectric BNC connector was used at the input of each device and the initial connection (to R_s or R_F) "air wired" between the BNC and the input pin of the integrated circuit (an operational amplifier in the transimpedance amplifier and an instrumentation amplifier in the shunt electrometer amplifier). The TIA feedback resistor was either an Ohmite Slim-Mox metal-oxide resistor or a standard thick-film resistor; no difference in performance was observed based on the resistor composition. All other resistors (including the electrometer shunt resistor) were standard 1%-precision metal-film resistors. Feedback capacitors were NP0 ceramics, while polymer film capacitors were used for low-pass filtering. In all the cases, power supply pins for each IC were bypassed to ground using 0.1 μF ceramic capacitors.

The preamplifier transimpedance gain was measured directly as a function of frequency, using a programmable sine-wave generator (AD9833, Analog Devices) at discrete frequencies between 20 Hz and 15 kHz. In order to measure noise levels, a 0.9 Hz square wave was used as a quasi-DC current source, and the frequency spectrum of the noise was obtained through the discrete-time Fourier transform. In both the cases, low-current test signals were generated by passing the output of a function generator through a capacitor. While a series resistor could also be used for this purpose, the high-value resistor necessary to produce picoampere-to-nanoampere currents will typically have an undesirable level of

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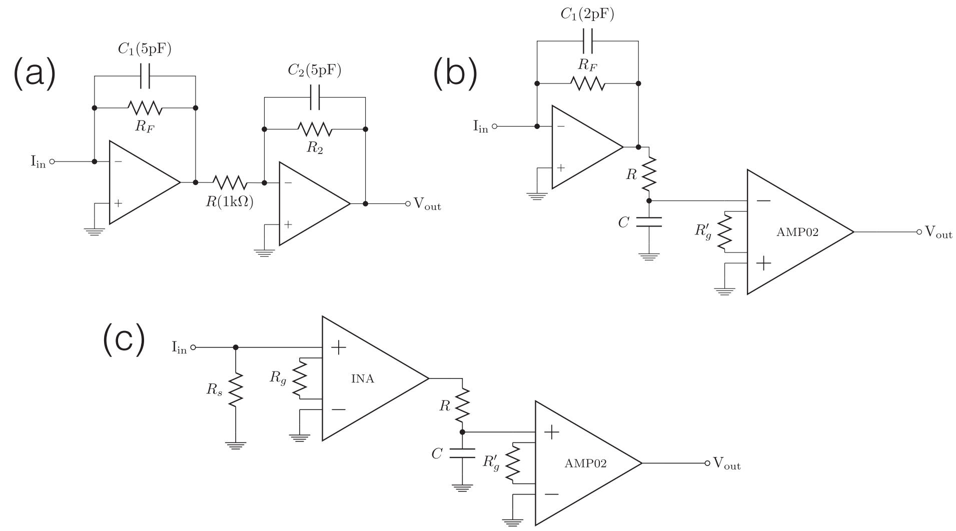

FIG. 1. (a) Simple two stage feedback transimpedance amplifier (TIA). (b) TIA with a low-pass filter and an instrumentation amplifier (Analog Devices AMP02) as the second stage. (c) Electrometer with an identical low-pass filter and an instrumentation amplifier second stage.

parasitic capacitance and/or inductance.[3,4] The 1.05 V AD9833 output was filtered, attenuated between 10 and 1000 times, and then passed through a 4 pF capacitor, producing sine-wave signals with amplitudes between 0.01 and 0.5 nA (depending on the frequency and attenuation). A 0.15 nA square wave was produced using a triangle-wave analog oscillator circuit based on a low-noise operational amplifier, also coupled through a 220 pF capacitor.

Signals were acquired using a 16-bit, 50 kS/s analog-to-digital converter (1608FS, Measurement Computing) with an input impedance of >100 MΩ, interfaced to a personal computer using MATLAB. This device also provided digital channels used for handshaking between MATLAB and the Arduino Uno controlling the AD9833, automating the acquisition of gain-versus-frequency curves.

A circuit schematic for the transimpedance amplifier is shown in Fig. 1(a). The following parameters were varied to determine their effect on performance:

(1) first-stage versus second-stage gain, that is, the values of R_F and R_2 shown in Fig. 1(a);
(2) the operational amplifier; a list of ICs used is given in Table I; and
(3) the composition of resistor R_F.

For the electrometer circuit shown in Fig. 1(c), the following parameters were varied:

(1) shunt resistance versus second-stage gain, that is, the values of R_s and R'_g shown in Fig. 1(c);
(2) first-stage versus second-stage gain, that is, the values of R_g and R'_g shown in Fig. 1(c); and
(3) the first-stage instrumentation amplifier; the two ICs used are listed in Table I.

For both the circuit designs, an overall transimpedance gain of 10^{10} V/A (10 GΩ) was used for all the tests.

It is important to note that for the TIA circuit, the capacitor C_1 was necessary to avoid oscillations and instability, and the value of C_1 required depended on the operational amplifier used as well as the value of R_F. While some op amps were stable with values as low as 1 pF, a value of 5 pF was used for all the TIA tests.

TABLE I. Specifications for operational amplifier and instrumentation amplifier ICs tested. All the values listed are reported as typical.

IC	Voltage noise at 1 kHz (nV/√Hz)	Current noise at 1 kHz (fA/√Hz)	Input impedance (Ω)	Input bias current (pA)
LT1169	6	1	10^{13}	4
TL072	18	NA	10^{12}	65
OPA2134	8	3	10^{13}	5
AD822	16	0.8	10^{13}	2
CA3260	NA	NA	10^{11}	2
INA116	28	0.1	10^{15}	0.003
INA111	10	0.8 (at 10 kHz)	10^{12}	2

III. RESULTS

Figure 2 shows the gain-versus-frequency and noise performance for the transimpedance amplifier design shown in Fig. 1(a); measurements were made using $R_F = 100$ MΩ and $R_F = 1$ GΩ. In general, the bandwidth of the circuit depends on the values of R_F and C_1 as well as the presence of other parasitic capacitances. The choice of IC makes relatively little difference, and the small differences observed between ICs would be expected anyway as a result of the component-to-component variation between capacitors. This is not the behavior seen in noise measurements, where there are clearly superior components (LT1169, AD822, and OPA2134) and inferior ones (TL072 and CA3260). The general behavior of the circuit is well known: a larger first-stage feedback resistor results in lower noise and lower bandwidth for a given overall transimpedance gain.

Figure 3 shows the electrometer's [Fig. 1(c) with the INA111 amplifier] dependence on shunt resistance versus

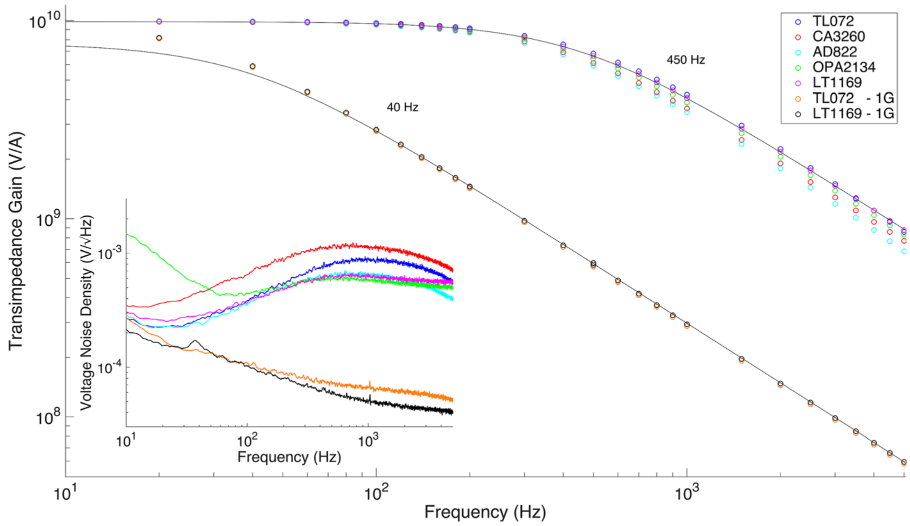

FIG. 2. (Color online) (Main panel) Transimpedance amplification gain as a function of frequency for R_F values of 100 MΩ (top) and 1 GΩ (bottom), with the total transimpedance gain held constant at 10^{10} V/A. Each color corresponds to a different amplifier IC. (Inset) Voltage noise density as a function of frequency. Fits are to the transfer function of a simple low-pass filter, a $A/\sqrt{1+(\omega/\omega_0)^2}$ functional form.

second-stage amplification. Similar to the TIA, the greater gain in the shunt stage results in both the lower noise and bandwidth. A first-stage amplification (selected using R_g) of $\times 100$ provided the optimal circuit performance; in particular, higher values reduced the electrometer's bandwidth without a corresponding decrease in noise (not shown). The electrometer performance was nearly identical whether using the INA111 or INA116 instrumentation amplifiers.

Figure 4 presents a direct comparison between the TIA and the electrometer. Here, the circuit shown in Fig. 1(b) is used for the TIA, making the second amplification stage identical to that of the electrometer [Fig. 1(c)]. The TIA is optimized to get the lowest noise and the highest bandwidth, using a LT1169 op amp with $R_F = 1$ GΩ and $C_1 = 2$ pF. The shunt resistor on the electrometer is then chosen to be 100 MΩ in order to match the bandwidth of the TIA as closely as possible. The data in Fig. 4 show that under these conditions, the overall noise performance of the electrometer is superior. Likewise, using a 10 MΩ shunt resistor in the electrometer produces noise levels comparable to the TIA with a faster time response.

With a 1 GΩ shunt resistor and $\times 100$ first- and second-stage gains, the electrometer can operate with a total transimpedance gain of 10^{13} V/A, resulting in sensitivity to subpicoampere signals, as shown in Fig. 5.

Several studies suggest that the inherently low bandwidth of the TIA can be compensated by "boosting" higher-frequency signals using capacitive coupling between the first and second amplifier stages.[3,5] We built and tested this circuit and found that while a 5–10 kHz bandwidth was indeed achievable, the resulting noise levels were

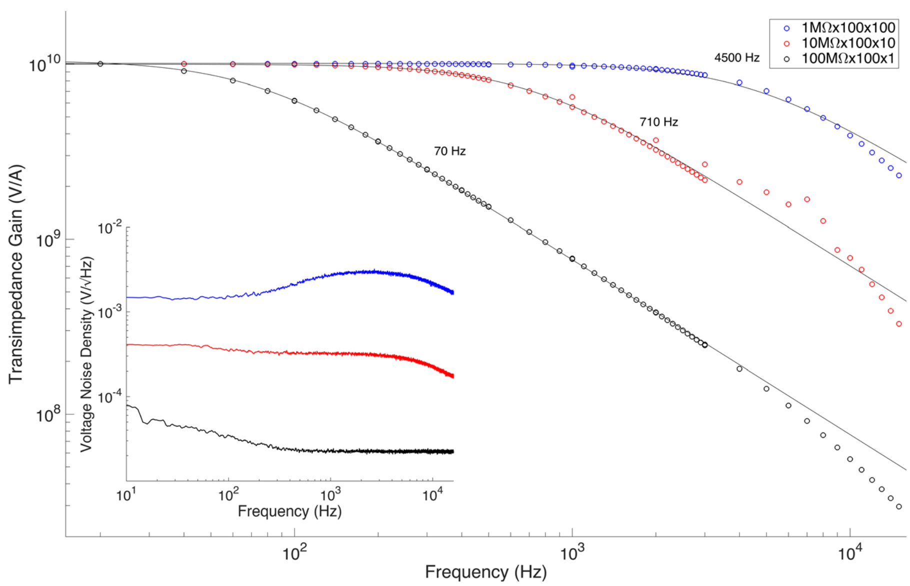

FIG. 3. (Color online) (Main panel) Transimpedance amplification gain as a function of frequency for the electrometer circuit using the INA111 instrumentation amplifier. Colors show different values of the shunt resistor R_s, again with a constant overall transimpedance gain of 10^{10} V/A. (Inset) Voltage noise density as a function of frequency. Fits are to a $A/\sqrt{1+(\omega/\omega_0)^2}$ functional form.

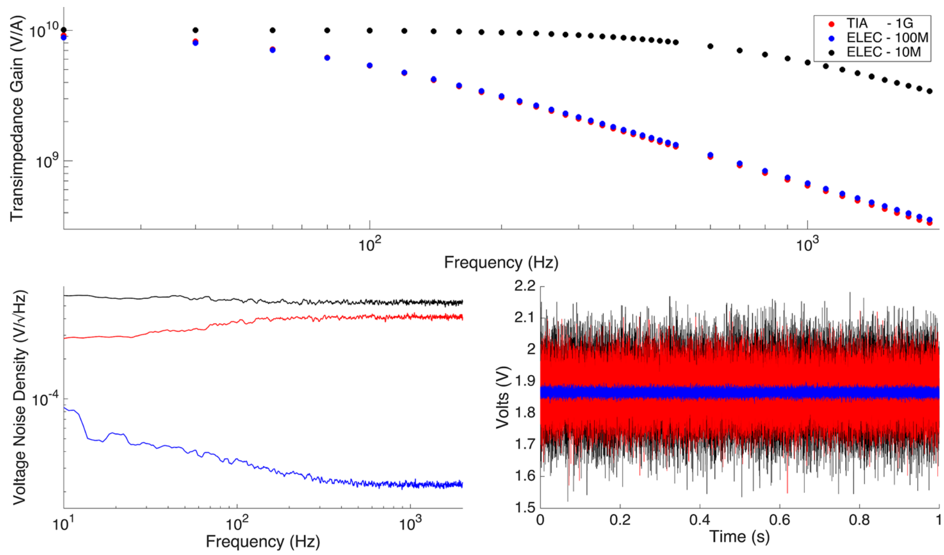

FIG. 4. (Color online) Comparison of a low-noise TIA (LT1169, $R_F = 1$ GΩ) with the electrometer circuit, showing gain vs frequency, voltage noise density vs frequency, and signal vs time. The TIA is shown in red while the electrometer is shown in black ($R_s = 10$ MΩ) and blue ($R_s = 100$ MΩ).

significantly higher than that could be achieved with an electrometer operating with an equal or higher bandwidth.

IV. DISCUSSION

When building the TIA style preamplifier, one can optimize the electronics by taking into account a few considerations. For the best performance, the LT1169 op-amp is recommended as it is very stable, has a low input bias current and a low input capacitance, and is moderately priced. The AD822 is another acceptable choice from a low-noise point of view. The TL072 amplifier, sometimes used because of its very low price, has higher noise and performs poorly (phase inversions and lock-up are not uncommon). The OPA2134 is a better budget pick.

The feedback capacitor C_1 is necessary to compensate for the nonideal behavior of the op-amp in the TIA circuit. Specifically, a parasitic capacitance to ground at the op-amp input combines with R_F to form a low-pass filter of the op-amp output. This results in the noise gain that increases with frequency, eventually leading to oscillations and instability of the circuit. Placing C_1 in parallel with R_F causes the gain to decrease with frequency, solving this problem at the price of reduced operational bandwidth. The optimum performance of the TIA requires choosing the smallest value of C_1 that will effectively stop oscillations. We found that this value depends on the op amp used; for example, the LT1169 required a 1 pF capacitor, while the CA3260 did not function without 5 pF. We expect that there would also be chip-to-chip or circuit-to-circuit variability and that best design would have C_1 chosen and tested for every circuit built.

It does not appear that undue care needs to be taken in choosing the feedback resistor, R_F. While manufacturers do advertise "low noise" resistors, a standard metal-oxide or

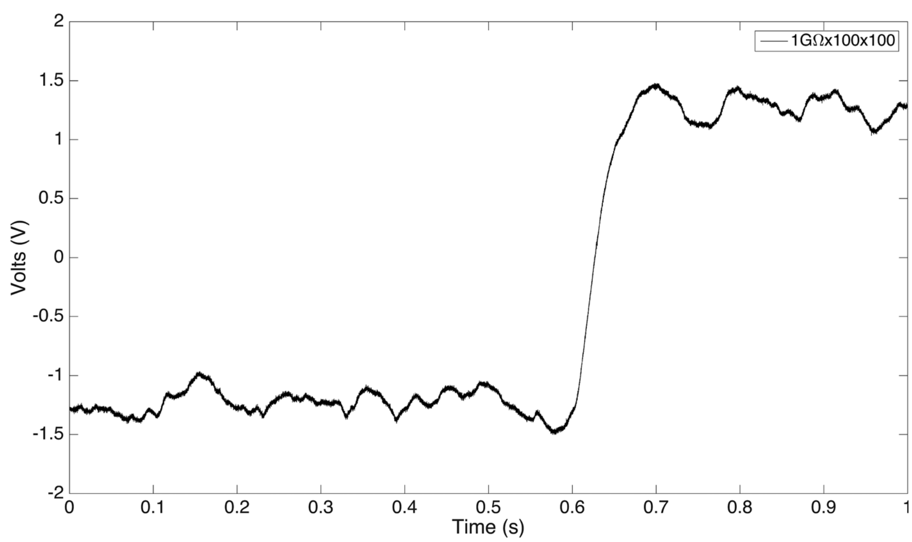

FIG. 5. Electrometer configured at 10^{13} V/A transimpedance, using a 1 GΩ shunt resistor and ×100 first- and second-stage gains. The signal is a 240 fA-amplitude square wave.

carbon-composition resistor seems to produce identical performance, at least under the conditions relevant for an STM preamplifier, that is, low current, low voltage, and low bandwidth. Presumably, this is because inherent noise sources (thermal and shot noise) dominate under these conditions.

When building an electrometer preamplifier, the INA111 can be chosen when relatively small-value (<1 MΩ) shunt resistors are used and the bandwidth is a priority. Otherwise, the INA116 is particularly well suited for STM applications as its input bias current of 3 fA is lower than that of all but a few operational amplifiers currently available. Both the chips provide input overvoltage protection, a feature typical for instrumentation amplifiers but rarer for operational amplifiers; for the INA116, this extends to ± 40 V.

A significant advantage of the electrometer circuit is that it operates free of oscillations over a wide range of current-to-voltage gains without the need for an external capacitor, and the result is more flexibility when it comes to making the trade-off between the bandwidth of the circuit and its noise. As is shown in Fig. 4, the electrometer can be adjusted to have a higher bandwidth at comparable noise levels to the TIA or lower noise at a comparable bandwidth. Unlike the electrometer, however, the TIA has noise that tends to drop off with lower frequency, and so there may be some operating regimes where it has superior performance.

While flexibility and stability are primary advantages of the electrometer, simplicity is an advantage of the TIA design: the circuit shown in Fig. 1(a) can be implemented using a single low-cost IC. More importantly, the TIA avoids a complication that affects the operation of the electrometer, where the shunt resistor allows the measurement point to float away from ground. As a result, while the bias voltage is well defined with the TIA measurement, it varies with the tunnel junction impedance for the electrometer. This is a small effect during a constant-current measurement in which the tunnel junction resistance is maintained much greater than the shunt resistance, but it is more problematic in constant-height and spectroscopic measurements.

For either the TIA or the electrometer design, good circuit construction techniques should be used. These include the use of electromagnetic shielding and a ground plane, bypassing all power supplies to ground and keeping signal traces clean and free of flux. Particular care must be taken with the low-current input to the circuit, which should be isolated from the PCB either by an air gap or by Teflon or other high-quality dielectrics.

ACKNOWLEDGMENT

Support for this work has been provided by the National Science Foundation (NSF CHE-1507213).

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