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CURRENT-TO-VOLTAGE AMPLIFIER WITH A
HIGH VOLTAGE ISOLATED INPUT

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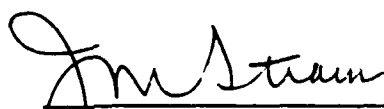
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The measurement of currents in the picoampere-to-nanoampere range that are collected on electrodes held at a few kilovolts above ground potential is a commonly encountered experimental problem. We confronted it while studying the long-term behavior of electron multipliers of the type used in cesium-beam atomic clocks. Measuring the first dynode conversion coefficient γ requires floating a picoammeter at high voltage. The input of commercially available instruments can be typically held at only about 100 V from case potential, thus preventing us from performing the measurement. One possible way around this difficulty would be to isolate the electrometer from the ac power line and to then float it at the first dynode potential. However, this procedure is somewhat risky for both experimenter and electrometer. Therefore, we have designed and built an instrument to measure safely small (pA-nA-range) currents collected on electrodes held at high voltages (a few kV). This instrument allows us to measure γ at the normal electron multiplier operating voltage, but, more generally, it is a low-cost, flexible replacement for a commercial electrometer in many applications, with the added advantage of the floating input.

The basic design philosophy for the instrument just discussed was determined by our requirements: it should accept a very low-current input, and provide a low-impedance voltage output and high-voltage isolation between its input and output stages. Figure 1 shows the circuit we designed to fulfill these requirements. The input stage is an operational amplifier connected in the classic current-to-voltage (transresistance) amplifier configuration,[1] followed by an amplifier stage whose gain can be adjusted by decade steps between 1 and 1000. The third stage is a unit-gain, optically coupled, isolation amplifier. The common reference ("signal common") for the first two stages and isolation amplifier input is isolated from ground and can be floated at high voltage; the output of the isolation amplifier is referenced to ground.

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[1]P. Horowitz and W. Hill, The Art of Electronics (Cambridge University, New York, 1980), p. 99.

GROUND

+15V

1 3 K

722

.01
3KV

BIAS

1 3 K

722

SIGNAL COMMON

.1 .1

.1 .1

.1 .1

.1 .1

1 K

500 K

IN

OPA 104

INA 101

3650

OUT

100M

1600

500 K

ZERO ADJ

10 K

4440 — 10^{-9}
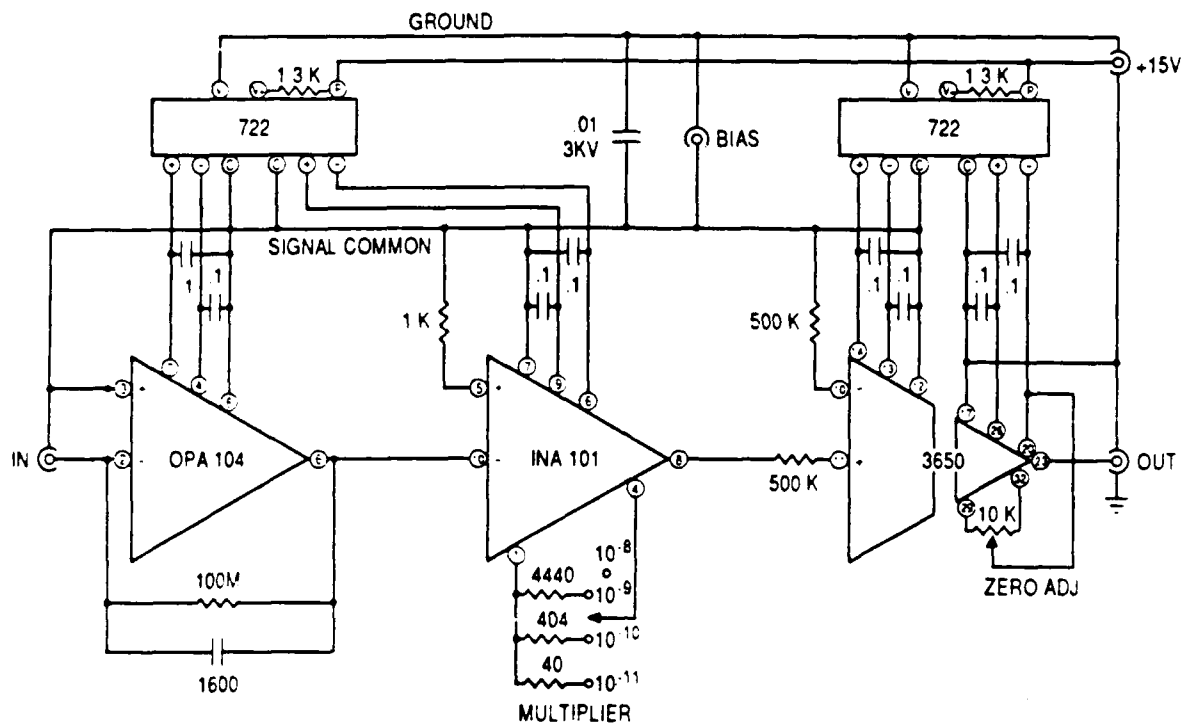404 — 10^{-10}
40 — 10^{-11}
10^{-8}

MULTIPLIER

Fig. 1. Transresistance Amplifier Circuit Diagram

For the first stage we needed a low-drift operational amplifier with the lowest possible bias current; we selected a FET input device made by Burr-Brown, the OPA104, with a maximum bias current of 75 fA. The 100 MΩ feedback resistor sets the sensitivity of the amplifier at 10^8 V/A. Since the maximum output voltage is 10 V, the maximum input current will be 0.1 μA. The open-loop gain for the OPA104 is about 4×10^5, making the amplifier input resistance about 250 Ω. The 1600 pF feedback capacitor provides a 1 Hz bandwidth. In order to minimize leakage currents, the OPA104 is mounted on a Teflon socket, the signal lead is connected directly to a Teflon standoff, and the case of the OPA104 is connected to signal common.

The second stage required a low-noise, low-drift, highly linear amplifier. We decided to use an instrumentation amplifier made by Burr-Brown, the INA101, connected to the OPA104 in an inverting configuration so that the combination of first and second stages provides a voltage output of the same polarity as the input current. The gain of this device is set by an external resistor; metal-oxide film 1% resistors (40, 404, and 4440 Ω) selected by a rotary switch provide gains of 1000, 100, and 10, respectively. A fourth open-circuit position in the switch provides a unit-gain setting. Combined with the 10^8 V/A sensitivity of the first stage, this arrangement provides 10^{-11}, 10^{-10}, 10^{-9}, and 10^{-8} A/V multipliers for the 0, ±10 V output of the INA101. Since the INA101 will float at the signal common potential, its case must be connected to signal common. Because the rotary switch which selects the gain resistor must be well isolated from ground, we mounted it on an acrylic plate, rather than directly on the instrument's metal case, and have ensured that the attached knob will not suffer electrical breakdown at the highest operating voltage.[2] In order to minimize leakage currents, the input signal connector was mounted on the same acrylic plate.[3]

The third stage provides electrical isolation between the instrument's input and output. We selected an optically coupled, linear isolation amplifier made by Burr-Brown, the 3650. The input-output isolation is ±2 kV. This device is set as a unit-gain amplifier by the matched pair of 500 kΩ, 1% metal-oxide film input resistors. The output is referenced to ground, and the output resistance is less than 2 kΩ. A 10 kΩ potentiometer on the output side of the 3650 provides the means to balance the instrument's overall zero-offset voltage.

The ±15 V supplies for the first, second, and input half of the third stages are referenced to signal common, so they must have at least 2 kV of

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[2]Attention should be paid to the presence of metal set screws in the knob.

[3]Since the connector's receptacle will float at the input bias voltage, it should be adequately shielded to protect t' ɔ operator.

isolation from ground. The output half of the third stage requires ±15V referenced to ground. The Burr-Brown 722 dual isolated dc/dc converter supplies two independent ±15 V bipolar output channels from a 15 V input. The two output channels are isolated from each other and from the input; the breakdown voltage is 8 kV. Our instrument requires two 722 modules. Both 15 V inputs are ground referenced. Three of the bipolar output channels are referenced to signal common, while the fourth is referenced to ground. Each one of the instrument's stages is powered by an independent ±15 V output channel.

The circuit is laid out on a printed circuit board[4]; signal common and ground are ac coupled by a high-voltage capacitor (0.01 μF, 3500 Vdc) and a SHV connector allows biasing the signal common up to ±2000 Vdc. The instrument fits inside a 7 in. × 5 in. × 2 in. RFI chassis box on which all necessary connectors and controls are mounted.[2]

Figure 2 shows the results of our linearity/calibration tests. In each case, the relationship between the instrument's output V_{out} and input current I_{in} is accurately represented by a linear expression, $V_{out} = T_R I_{in}$, T_R being the instrument's transresistance. The differences between expected and measured values of T_R are on the order of 3% and can be attributed to the 1% tolerances in the source resistor, the feedback resistor, and the INA101 and 3650 gain resistors, as well as the (unspecified) tolerances in the gain formulas for those two devices. The instrument's readings are internally (range-to-range) consistent to 0.5%. The 3% error in absolute current measurements is acceptable for many applications; if more accurate absolute measurements are required, the instrument can be calibrated. Figure 3 shows that the instrument's output is independent of the bias voltage applied between signal common and ground. The instrument's frequency response, defined as the ratio of ac to

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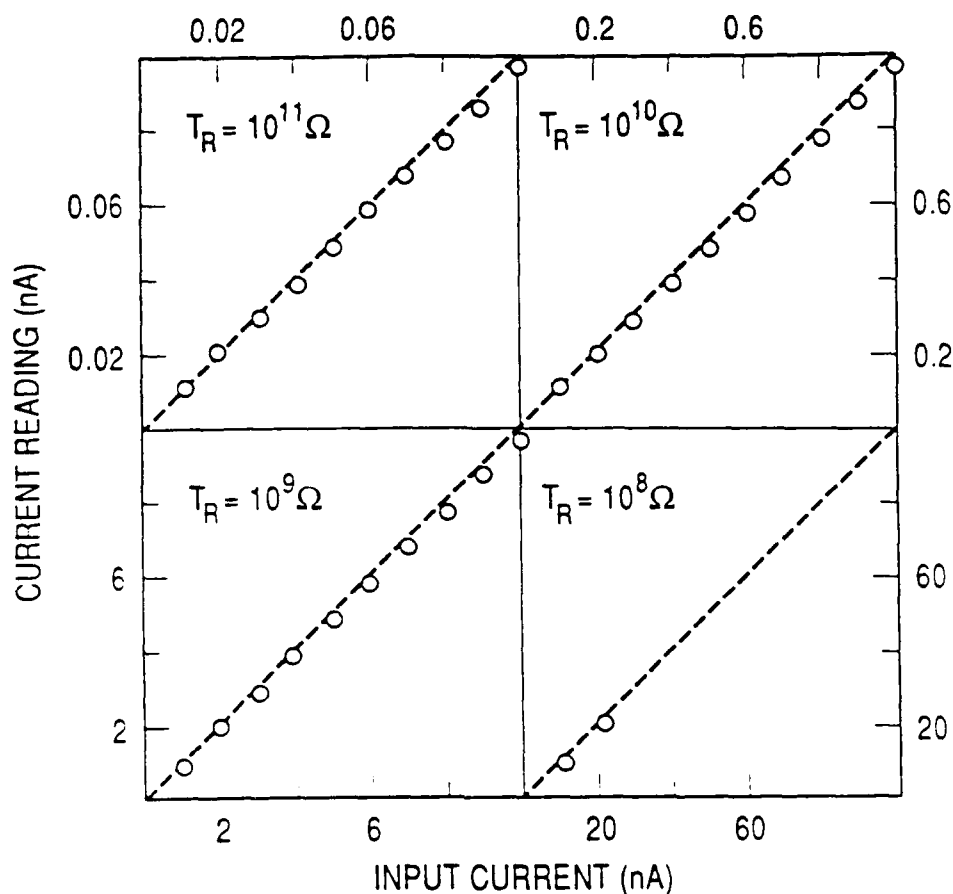[4]The printed-circuit board layout is available on request from the authors.

Fig. 2. Linearity/Calibration Tests. Current Reading = V_{out}/T_R. The nominal Transresistance for each range is indicated on the diagram. Dashed lines show nominal calibration.

dc transresistances, $T_R(f)/T_R(0)$, is consistent with the 1 Hz bandwidth defined by the feedback resistor and capacitor. Figure 4 shows the comparison of measurements of the anode current in an electron multiplier monitoring a cesium-ion beam by a commercial electrometer[5] and by the instrument we have designed. Both instruments were connected in series. It can be seen that the absolute current measurements are consistent with each other, the apparent noise level is similiar in both instruments, and there is no relative drift on either chart-recorder traces. The temperature drift of the ±10 V output of the instrument is 250 µV/°C in the 25-60°C temperature range.

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[5]We used a Keithley model 642 electrometer. Of course, our instrument does not match the full range of applicability of that electrometer.
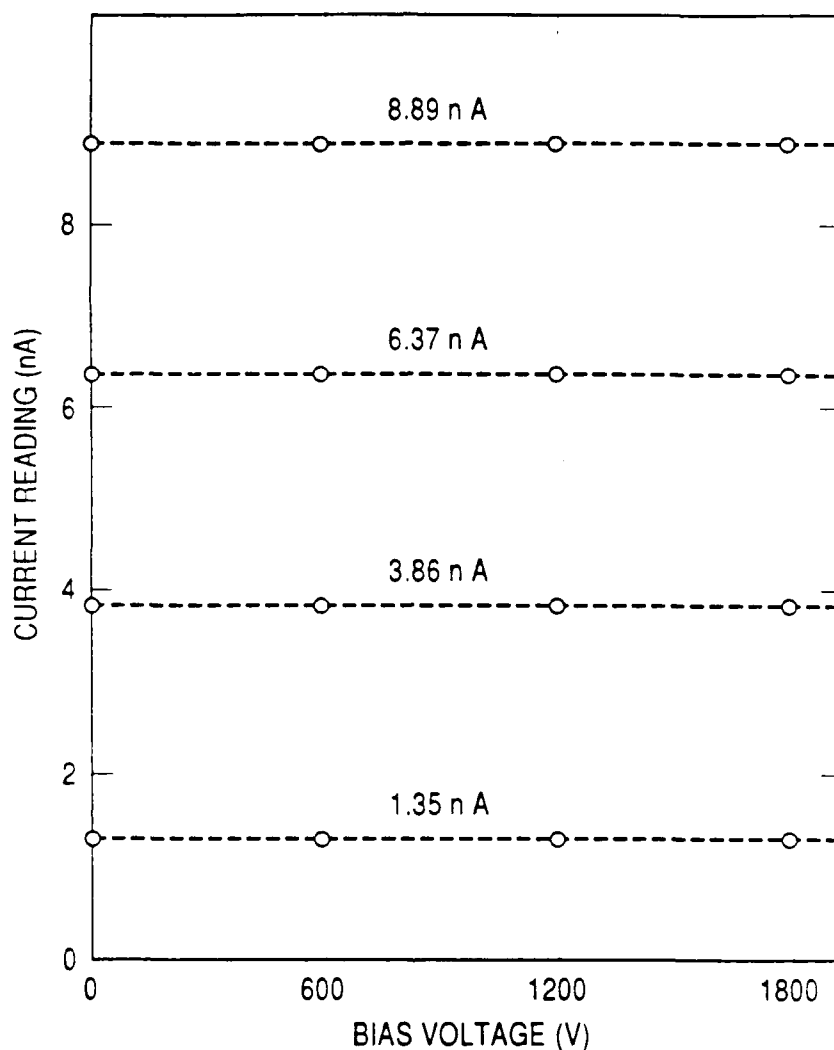
Fig. 3. Transresistance Amplifier Performance with a
Biased Input. Numbers on each side indicate
constant input current

Some of the instrument's specifications can be easily modified. The
input sensitivity can be altered by changing the feedback resistor; the
frequency response, by changing the feedback capacitor; and the output
voltage range, by changing the last stage gain resistors. The construction
cost of this instrument runs in the few-hundreds-of-dollars range, well
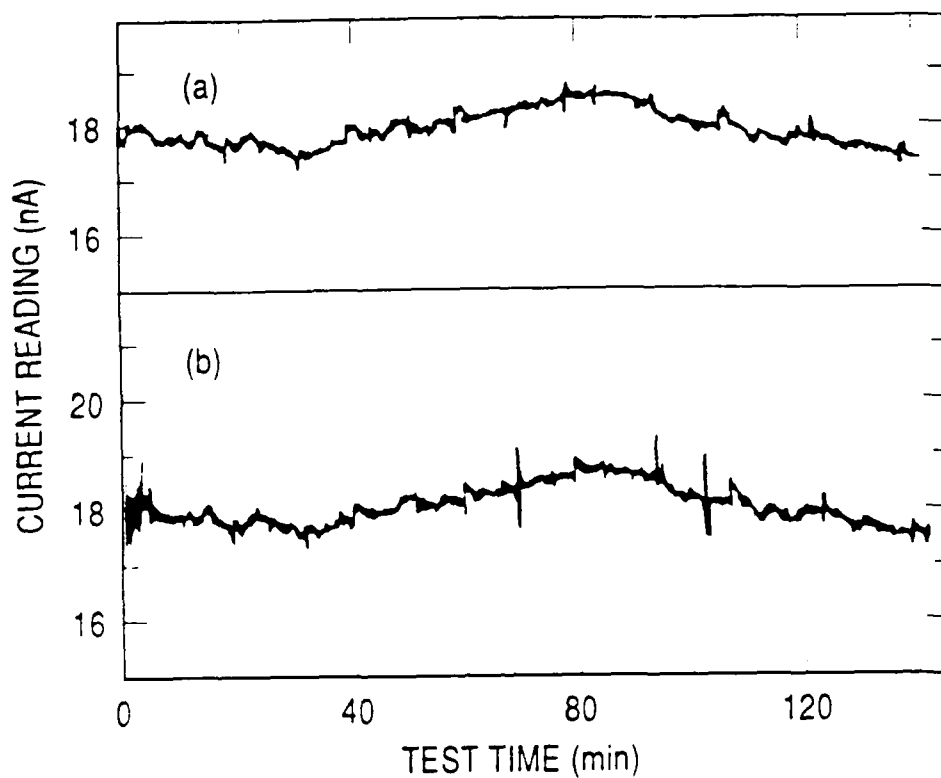below the cost of any commercially available electrometer.

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Fig. 4. Comparison Between the Performance of (a) the
Transresistance Amplifier and (b) a Commercial
Electrometer. The input current is the anode
current of an electron multiplier.

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