Build a Picoammeter, Start Experimenting (p.62) • Put a Multidimensional SBC to Work (p. 68)

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by Robert Lacoste

Picoammeter Design

If you occasionally work with low currents, you should have a picoammeter on your workbench. With some perseverance and a little know-how, you can build one in a couple of hours. But first you need a good understanding of current measurement and transimpedance amplifiers.

Welcome back to "The Darker Side." I think I got my first multimeter when I was 10 years old. Well, more precisely, I took my father's multimeter and played with it so long that we soon both considered it mine. The ohm-meter feature was particularly fascinating. I could put the two wires on anything and then check the galvanometer to see if it was behaving more or less as a conductive surface. Another interesting game involved taking a wire in each hand and tightening them between two fingers to get the lowest possible resistance.

I am a little older now, but I am still playing with resistance and current measurements, even though galvanometers have disappeared from our multimeters. As you may have noticed, energy saving is a hot topic, and we can now find integrated circuits with standby currents in the tens of nanoamps range or even lower. But measuring these currents is nearly impossible with a standard multimeter. For example, my trusted Fluke 189—which is a very high-end device—has a best-case resolution of 10 nA per count, which makes measurements under 40 or 50 nA unrealistic. To measure lower currents, a dedicated low-current piece of equipment is required—namely, a picoammeter. Usually, when you work with low currents, you don't need a top-range accuracy because there are plenty other error and noise sources. But a wide dynamic range is fundamental. Moreover, you'll probably use it only a few times per year, so a homemade solution makes sense.

This month, I'll begin by covering concepts relating to current measurement and transimpedance amplifiers. I will then describe how I prototyped a small low-cost picoammeter in a couple of hours with satisfactory results. Lastly, with memories from my childhood fresh in my mind, I'll show you how I've used it to measure high impedances.

Let's go. Switch on your soldering iron.

BASIC CURRENT MEASUREMENT

Imagine that you have a wire in which a small current is circulating—say, from pico-amperes to micro-amperes. How can you measure this current?

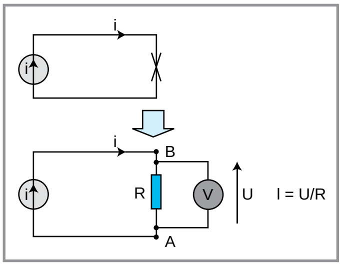

Figure 1—This is the basic current measurement method. Just open the circuit, insert a resistor, and measure the voltage across this resistor.

Some methods don't require you to open a circuit (e.g., like Hall effect sensors or current transformers), but they are usually not applicable to such low currents. You can also use a galvanometer, in which the current directly moves the indicator, but you also will be limited to reasonably high currents, micro-amperes or more. So, the most obvious and common solution is

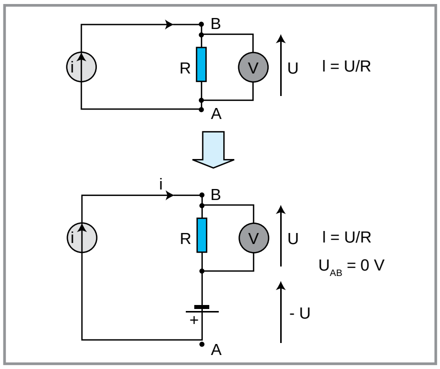

Figure 2—Unfortunately, the current moving through the circuit will be modified by the added serial voltage. The key idea is to add a counter-voltage to exactly nullify the voltage between points A and B.

to build a current-to-voltage converter followed by a high-impedance voltmeter. And the most basic current-to-voltage converter is simply a resistor (see Figure 1). Thanks to Ohm's law, the voltage across the resistor R will be V = R × I, so I = V/R. You know R because you chose the resistor. You measure V so you can calculate I.

But this approach has two drawbacks when measuring very low currents. One, you need to use a high-value resistance. For example, if you want to convert a 100-pA current into 10 mV, you need a 100-MΩ resistor. You then need to use a voltmeter with an input impedance far higher than 100 MΩ, which will be a challenge if even possible. The other problem is more insidious: low currents are often generated by low voltages. The additional measurement resistor adds a small voltage in series on the circuit—and, of course, it's identical to the voltage sent to the multimeter. Unfortunately, this added serial voltage may change the current actually circulating in the wire. Do you want a numerical example? Imagine that the 100-pA current source is generated by a 20-mV voltage in series with a 200-MΩ resistance. If you add a 100-MΩ measurement resistance, you will change the actual current by up to 33% because the current now will be:

$$I = \frac{U}{R} = \frac{20\ \text{mV}}{(100 + 200\ \text{M}\Omega)} = 67\ \text{pA}$$

How can you get a precise current measurement without interfering with the source? You need to avoid any added series voltage. More precisely, you will insert a measurement circuit in the current loop, but the voltage between the two measurement points must stay as close as possible to zero. The solution is simple but powerful: you can add to the circuit an anti-voltage source that's set to exactly compensate the voltage drop caused by the measuring resistor (see Figure 2). That way the voltage across the measuring device stays zero as the resistor drops and the voltage source cancel each other, so a precise current can be measured. The only difficulty is that this anti-voltage must be adjusted depending on the current: if the current is constant, you can trim it yourself. But if it is varying, you need some kind of control loop to automatically adjust it.

TRANSIMPEDANCE AMPLIFIERS

If you think "op-amp" when you read the words *control loop*, you're right. A transimpedance amplifier is the exact implementation of the anti-voltage current measurement idea. Look at Figure 3. The op-amp's two inputs are connected to the two ends of the measuring device. As you know, such an amplifier, when properly wired (with a negative feedback), changes the voltage on its output until the voltages on its two inputs are identical. By the way, this is partially wrong as the gain of the amplifier is not infinite. But let's consider it to be large enough. Op-amp details will require another article.

So, at equilibrium, the voltage between points A and B is zero, which is exactly what you are looking for to avoid any perturbation on the current

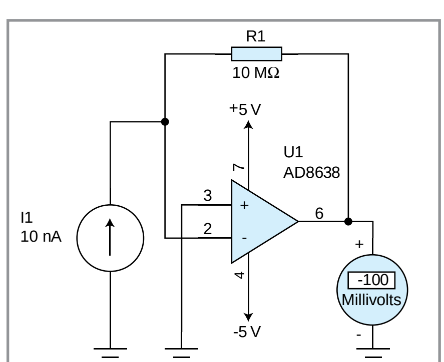

Figure 4—This is a simulation of a transimpedance amplifier done under VSM. The input current of 10 nA is translated into a –100-mV voltage thanks to the 10-MΩ feedback resistor.

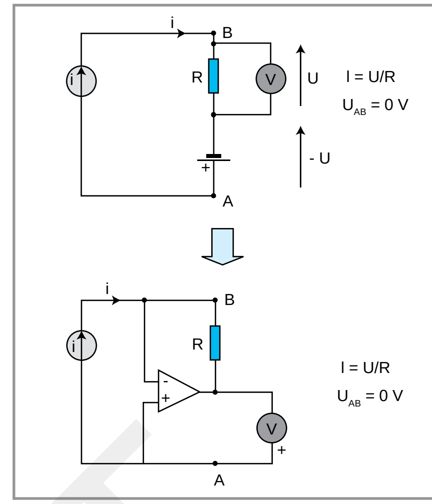

Figure 3—The transimpedance amplifier is a way to automatically adjust the counter voltage. An operational amplifier will set its output in order to have a nearly null voltage offset between its two inputs: U_{AB} = 0, which is exactly what we are looking for.

source. If you consider the amplifier to be perfect, no current is circulating through its inputs. Thus, the current I is entirely circulating in the resistor R and through the amplifier's output. As a result, the voltage at its output is (–R × I). This is a transimpedance amplifier: the current-to-voltage conversion ratio is identical to a simple resistor of R ohms, but with two key advantages: no added serial voltage and a low output impedance.

Of course, this presentation of transimpedance amplifiers was a little simplistic. Perfect op-amps are difficult to find, so you will have to select a device with reasonably low input offset voltages and high enough input impedance (meaning far higher than R). Usually, you will also need both positive and negative power supplies for the amplifier because its output will be below 0 V when the input current is positive.

Figure 4 depicts you a simulation of a transimpedance amplifier performed with Labcenter's VSM software. The virtual voltmeter shows you the simulator output voltage of the op-amp.

Transimpedance amplifiers are everywhere. In particular, I bet that you will find them in most photodiode-based designs, as such a light sensor generates low currents with low voltages. By the way, another advantage

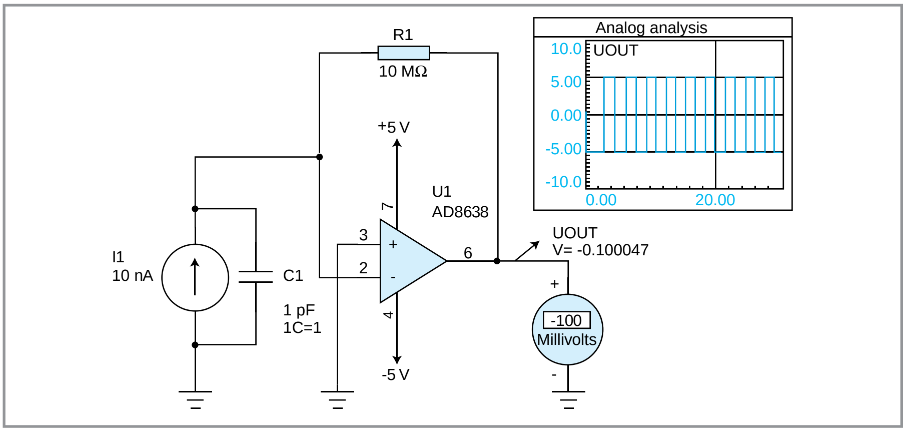

Figure 5—If you consider that the input source has a parasitic parallel capacitance, and if you don't damp the amplifier with a capacitor in parallel to the feedback resistor, then you will have unfortunately built an oscillator, as demonstrated here.

of the transimpedance amplifier over a simple series resistor is speed. Why? Imagine that you build an optical data transmission system with a photodiode providing a 100-nA current. No component is perfect, so this photodiode will also have a parasitic parallel capacitance, usually around 10 pF. Imagine that you measure this current with a simple high-value resistor—say, 100 kΩ—to get a 10-mV output. What will happen? The 10-pF capacitor and this 100-kΩ resistor will implement a low-pass filter with a time constant of RC = 1 µs, so the bit rate will need to stay quite low. There's no way go get significantly higher than 1 MBps. In comparison, with a transimpedance amplifier, the measuring resistor is not "visible" to the source, as the voltage at the measurement point stays at 0 V thanks to the amplifier, so the bit rate is limited only by the op-amp's bandwidth and parasitic components. Far better performance is possible, as proven by gigabits-per-second fiber links.

However, this source of parasitic capacitance induces another problem. It might transform your amplifier into an oscillator. The problem, which is simulated in Figure 5, will make your life a little more difficult when working on real-world applications. This is not the only kind of circuit where parasitic oscillations can occur, but it is always unpleasant. Fortunately, there's a solution: you can limit the bandwidth of the transimpedance amplifier by adding a parallel capacitor across the feedback resistor. Although this will slightly reduce the system's bandwidth, it will make it stable. Bob Pease provides a good explanation in his article, "What's All This Transimpedance Amplifier Stuff, Anyhow?" (*Electronic Design*, 2001). Basically, this additional capacitor should be proportional to the square root of the source capacitance and inversely proportional to the square root of the feedback resistor and gain bandwidth of the amplifier. Anyhow, you will not know the source of parasitic impedance in many applications, so you'll have to use the trial-and-error method: increase the feedback capacitor until you achieve stability, then increase it a little more, and then test it in all conditions. It should work.

BUILD A PICOAMMETER

You're now familiar with all the basic ideas associated with designing a low-cost picoammeter. Figure 6 is a full schematic diagram of my prototype**.** The design is quite simple, but I carefully selected the components. Starting from the two inputs, I included two protection diodes (D1 and D2), which limit input voltage to ±0.6 V to prevent overloading. Be really careful. These diodes can't be generic because their reverse current must remain far lower than the measuring range—100 pA in this instance. I used a pair of low-leakage NXP Semiconductors BAS416 diodes, which are rated at 3 pA. (Compare this value with the 25 nA of a standard 1N4148. Even at 20°C, it's nearly 10,000 times lower.) Then the transimpedance amplifier is built around an Analog Devices AD8638 op-amp, which was selected for its low offset (9 µV) and small bias current (7 pA is typical). The gain resistor is manually selected from 1 Ω to 10 MΩ with a manual rotary switch, and of course each resistor has its corresponding parallel capacitor to avoid oscillations. A second op-amp provides another 100× voltage gain, as well as offset compensation through a trimming resistor in

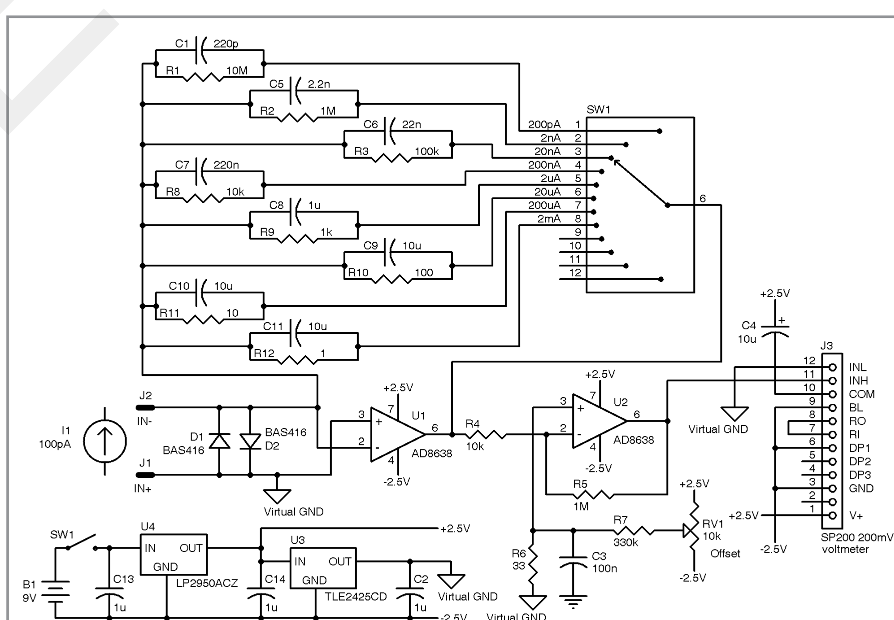

Figure 6—This is the full schematic of my small picoammeter. There are very few components except the rotary switch and its different feedback resistors and compensating capacitors.

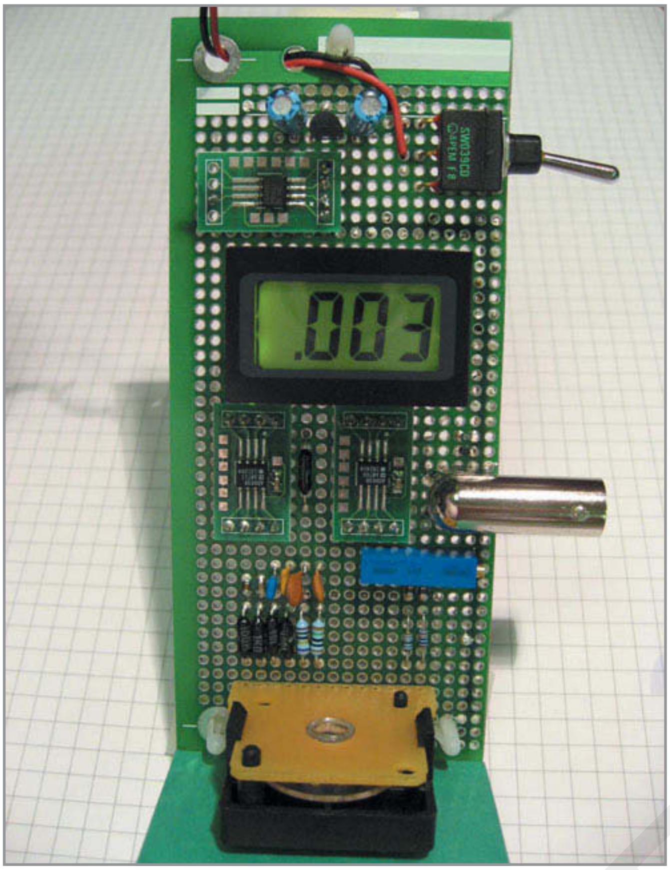

Photo 1—Even if this is usually not a good idea for such low-level signal designs, I built the ammeter on a standard prototyping board. Far better results could be achieved with a proper printed circuit board. I used precision resistors everywhere to avoid the need to calibrate the device.

order to get a 200-mV full-scale output.

For a display, I simply hooked up (at the output) a standard 3.5-digit voltmeter module (Lascar Electronics SP200), built around a MAX138 ADC. Just take care to use a meter with true differential inputs like this one.

Lastly, let's consider the power supply. I don't recommend using anything other than a battery for your picoammeter's power source. Any transformer will have huge parasitic currents in comparison to the pico-amperes you want to measure. I used a simple 9-V battery regulated by an LP2950 5-V regulator. A symmetrical power supply was needed, so I added a Texas Instruments TLE2425 virtual ground generator. This chip divides the power supply rail into two halves, so I could use its output as a virtual ground and the 0- and 5-V lines as a ±2.5-V power source.

Such a circuit must be assembled on a properly designed PCB to achieve good performance. In particular, a good ground plane should be used, as well as guards around the ultra-low-current inputs. Well, I tried to build it on a standard prototyping board (see Photo 1 and Photo 2). I expected disappointing results, but I was pleasantly surprised to be able to use it down to the 2-nA full-scale range. Honestly, the 200-pA range is currently useless because measurements are a little erratic, but it should be usable with a proper PCB. I had more difficulties with the high current ranges of 200 µA and 2 mA, which occasionally oscillate on my prototype. The feedback capacitors on these two ranges are definitively too small, but the difficulty would be to find low-leakage capacitors with high capacitance, more than 100 µF. Anyway, this is not a serious problem because my standard multimeter is working like a charm for reasonably high currents. I didn't spent a lot of time on this issue.

If you want to build this picoammeter, I'm sure you will be able to design a pretty PCB for it. Don't forget the ground plane, and remember to put it in a shielded enclosure for the best results. You can also easily replace the 3.5-digit voltmeter display with a microcontroller and a standard LCD. Doing so will enable you to add zillions of interesting features like software-based auto-zeroing (very helpful), averaging (helpful with noisy signals), or even automatic range selection through reed relays or something similar. Don't hesitate to share your design ideas with other *Circuit Cellar* readers!

Another interesting option would be to use a derivative form of the transimpedance amplifier, where the feedback resistor is replaced by a capacitor. This gives an integrator, with an integration time proportional to the input current. Dedicated chips like the IVC102 from Texas Instruments (e.g., Burr Brown) implement this concept and should be quite easy to interface with a microcontroller. And their 100-fA (yes, femtoampere) bias input current should result in impressive performances.

FIRST EXPERIMENT

Before closing, I want to describe my first experiment with my small picoammeter. I connected a 9-V battery in series with the ammeter input and built an ohmmeter, soldered a small two-pin 1-cm-wide header at the end of the wires, and pushed this homemade sensing probe on several surfaces to measure their resistance (see Photo 3). Neither a classic plastic bag nor an FR4 epoxy substrate gave measurable current, meaning lower than 10 pA. They are definitively good insulators. On the contrary, I was able to measure the resistances of a full range of other materials (see Table 1), even if nearly all the materials appeared as perfect insulators when tested with a classic multimeter. Measured values are very high, in

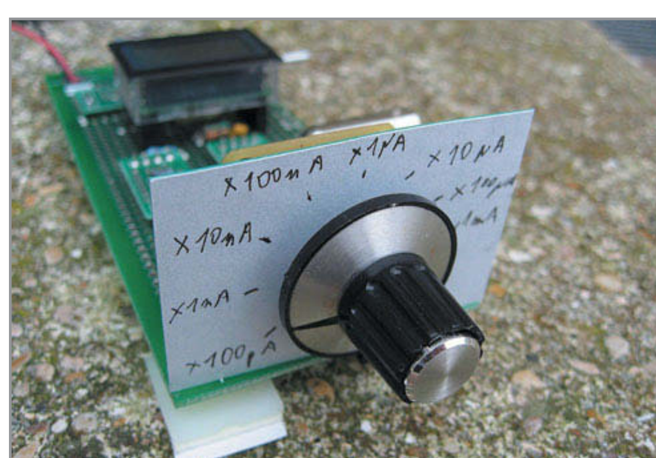

Photo 2—The legend of the range selector was, well, quickly done, but it is always impressive to see a "100-pA" range.

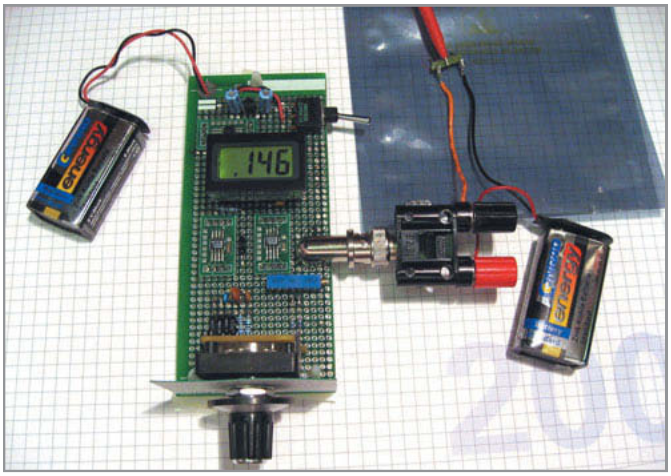

Photo 3—This is the setup I used for surface resistance measurements. A second 9-V battery is used to build an ohmmeter, and the test probe is made with a 1-cm-wide header and two test pins.

gigaohms, but this is not a surprise. Even good antistatic bags are specified for typical surface resistance of 10-GΩ per square. In fact, such bags have an inner layer with a far better conductivity, but this layer is wrapped between two

Material	Measured current	Equivalent resistance (between two electrodes 1 cm apart)
Classic plastic bag	Less than 10 pA	Greater than 900 GΩ
FR4 Epoxy substrate	Less than 10 pA	Greater than 900 GΩ
Antistatic foam (pink)	17 pA	530 GΩ
Antistatic bubble wrap (pink)	42 pA	210 GΩ
Dry paper	70 pA	130 GΩ
Antistatic bag (black)	250 pA	36 GΩ
Antistatic carpet	11 nA	820 MΩ

Table 1—Here I list the surface resistivity of different materials, as measured with a 9-V battery and two electrodes 1 cm from each other.

polymeric plastic layers that have a far higher resistance, just low enough to dissipate ESD charges.

So here we are. Was this journey into the world of low currents pleasant? I hope you are convinced that such a picoammeter should be on your workbench, especially because you can build one in a couple of hours. And, of course, I hope that you now have one more set of tools in your engineering toolbox: transimpedance amplifiers. ◾

Robert Lacoste lives near Paris, France. He has 20 years of experience working on embedded systems, analog designs, and wireless telecommunications. He has won prizes in more than 15 international design contests. In 2003, Robert started a consulting company, ALCIOM, to share his passion for innovative mixed-signal designs. You can reach him at rlacoste@alciom.com. Don't forget to write "Darker Side" in the subject line to bypass his spam filters.

PROJECT FILES

To download VSM project files, go to ftp://ftp.circuitcellar.com/pub/Circuit_Cellar/2010/237.

RESOURCES

Keithley Instruments, "Low Current Measurements," Application Note 100, www.keithley.com/data?asset=6169.

M. Pachchigar, "Design Considerations for a Transimpedance Amplifier," National Semiconductor, AN-1803, 2008, www.national.com/nationaledge/files/national_AN-1803.pdf.

B. Pease, "What's All This Transimpedance Amplifier Stuff, Anyhow (Part 1)?," *Electronic Design*, 2001, http://electronicdesign.com/Articles/Index.cfm?ArticleID=4346&pg=1.

SOURCES

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Analog Devices | www.analog.com

VSM Mixed-signal simulator
Labcenter Electronics | www.labcenter.co.uk

SP 200 3½ Digit voltmeter
Lascar Electronics | www.lascarelectronics.com

BAS416 Diode
NXP Semiconductors | www.nxp.com

IVC102 Amplifier and TLE2425 virtual ground
Texas Instruments | www.ti.com