

Counting Electrons: How to measure currents in the attoampere range

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THE tiny world of nanotechnology is making big waves in industry these days. Nanoscale materials hold promise for areas such as medicine, homeland security, defense, and many other industries. Researchers in R&D and development labs all over the globe are investigating the physical and electrical properties of nanoscale components as in single-electron transistor (SET) and quantum-dot research. With this reduction in physical size of the material under investigation come new problems; specifically, accurately measuring electrical parameters such as resistance, voltage, and current.

To keep pace, test and measurement instruments and techniques have had to adapt to the changing needs of researchers. Already, improvements in instrumentation make it fairly simple to measure currents in the low picoamperes ($1 \times 10^{-12} \text{A}$), and electrometers with current sensitivities of femtoamperes ($1 \times 10^{-15} \text{A}$) have been available for some time. Measuring currents in the range of ten attoamps and below, however, is a different matter. After all, one attoamp ($1 \times 10^{-18} \text{A}$) corresponds to just six electrons per second.

Typically, measuring such low currents has meant using expensive test equipment, upwards of \$100,000, and costly cryogenic current comparators. However, it is possible to measure *changes* in current as small as one attoamp at room temperature using commercially available test and measurement equipment. This article looks at a simple setup and technique for making repeatable and reliable measurements at the attoamp level.

Equipment required

Making current measurements in the at-

toamp range requires a device that can measure currents with a few tens of attoamps RMS noise in the range of 0.1 to 0.01Hz and, in the case of a demonstration setup, a current source with a resolution better than one attoamp. A category of instruments known in the industry as Source-Measure Units (SMUs) contain a precision voltage source, a precision current source, a voltmeter, and an ammeter. The Keithley Model 6430 Sub-femtoamp Remote SourceMeter instrument has an ultra-low noise current amplifier and provides these functions in a single instrument. *Figure 1* shows a typical SourceMeter instrument with the source block representing both the voltage source and current source capability. The V_{measure} circle represents the built-in voltmeter which gives feedback to the source block and can be used to control it. The I_{measure} circle represents the built-in ammeter, and it, too, can control the source block. Note also that the instrument can provide both V_{measure} and I_{measure} functions simultaneously.

A good SMU can source very small currents, and the 6430 SourceMeter instrument can source current with 50 attoamp resolution. But this experiment called for a source capable of repeatedly producing accurate ten attoamp currents. The voltage source within the Model 6430 was used to create a current source with this high resolution. To reduce the difficulty of working with extremely high value resistors, the voltage source was first divided down by a factor of ten, then applied across a two-teraohm resistor to the current measurement input. The result is ten attoamps of current flowing with 200 microvolts applied. The five microvolt digital resolution of the source yields a 0.25 attoamp current

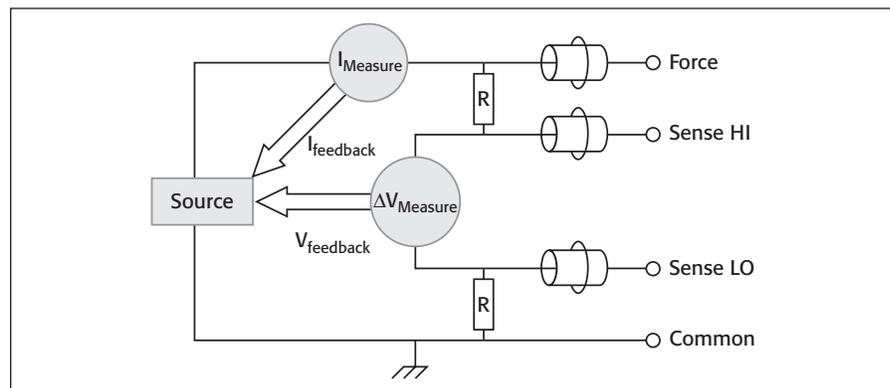


Figure 1. A source measure unit includes a precision voltage source and a precision current source (shown here as one block), a voltmeter, and an ammeter.

resolution. It is important to recognize that this is not a *true* current source – its output current will be very sensitive to the load. The reason why it still works for this application is that the load is going to be a nearly perfect ammeter – i.e. virtually a short circuit.

Making measurements with a few tens of attoamps RMS noise in the bandwidth of 0.1 to 0.01Hz required using a digital filter with a rise time of roughly five seconds. This meant that the standard deviation of 60 seconds worth of measured data didn't exceed 100 attoamps. A remote preamp on the Model 6430 reduced cable noise, giving us 30 attoamps of RMS noise.

Measurement procedure

The simplest way to make attoamp current measurements is to alternately measure a positive signal, then a negative signal of the same magnitude, and repeatedly take the difference. This method is still applicable even if there is no way to generate a negative signal by taking the difference between a positive signal and zero signal, although there is a factor of two noise penalty.

Because current sources in typical nanotechnology applications are functions of time rather than constants, we chose a current source that varies with time. In this case, the current took the form of a staircase function. The procedure involves taking a fixed number of readings at each step level for a total of N readings. The first of the series of readings taken with the positive source applied is averaged with the negative of the first in the series of readings taken with the negative source applied. In equation form, this is expressed as:

$$I_n = \frac{(I_n^+ - I_n^-)}{2}$$

The division by two comes about because the signal-to-noise ratio is the same in both signals, but there is twice the signal present

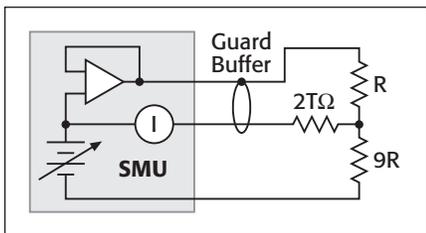


Figure 2. The schematic shows a basic measurement circuit.

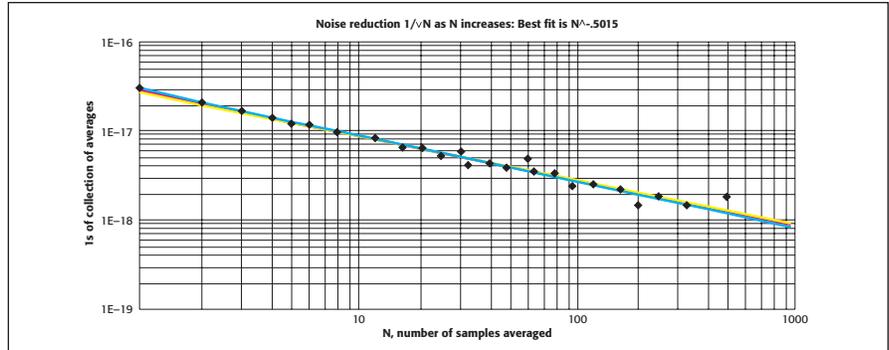


Figure 3. The graph depicts a plot estimating the uncertainty in the mean, which is $\pm 0.8aA$.

in the full plus-to-minus signal. For signals with no negative component, the equation is identical except there is no division by two. Doing this for each of the readings in the series yields a series of difference readings. The whole process is repeated several times and averaged. Each difference series is averaged point-by-point resulting in a single series of readings representing the current shape produced by the source.

Setting up the measurement

Choosing how fast to alternate between positive and negative sourcing requires some balancing. Faster alternations help minimize the effects of slow drifts in input current, and also reduce noise. But with teraohms of resistance in the source (which is typical for any source generating such small currents), the settling time is one to two seconds. If the source alternated every few seconds, most of the measurement would be of the source settling instead of the final DC value. One way to solve this is to let the source settle for ten percent of the time after each alternation and measure for 90 percent of the time—which meant a half-period of ten times the settling time, or about 20 seconds.

Using this mathematical technique, the valid points from the current shape (i.e. the last 90 percent) were averaged to produce the final measurement. Estimating the error in this mean value required using the statistics of uncorrelated noise. Instead of one final current shape averaged from many difference series, N current shapes are generated. Each of these yields a mean from its valid data points so the collection of mean values has a standard deviation. Because the means are uncorrelated, the final answer, the mean of the N means, has a one sigma uncertainty equal to the standard deviation of the col-

lection of means divided by the square root of N.

$$\sigma_x^- = \frac{\sigma_x}{\sqrt{N}}$$

This was verified by generating 1,000 current shapes and plotting the standard deviations of the collections for N=1000, 500, 250, ..., etc. As expected, the standard deviations of the collections dropped as the square root of the number of means in the collection.

Results

For the simplest case using a single current value and using 40 seconds for each source polarity, after one hour of measurement or 45 reversal pairs the uncertainty was about 2.6 attoamps. After 12 hours of averaging, the uncertainty fell to about 0.75 attoamps. After several such 12-hour runs, the collection of results had a standard deviation consistent with 0.75 attoamps.

A good way to estimate the time required to achieve these results on an arbitrary system with unknown external noise sources is to measure the noise of the system in the 0.1 to 0.01Hz bandwidth as described earlier. The test system with source on but constant measured 60 attoamps RMS in this bandwidth. If another system had 120 attoamps, it is reasonable to expect that each of the uncertainties achieved here could be done in approximately four times the amount of time.

Physical precautions

The largest contributor to low-frequency noise in this sort of test setup is temperature variation. Instrument offset currents vary with ambient temperature, in this case by less than 500 attoamps/°C. But even slow

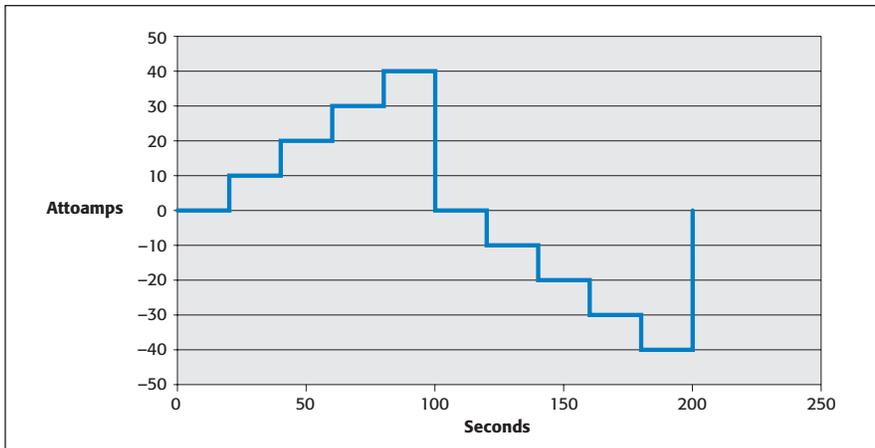


Figure 4. A graph of the staircase current waveform used in the experimental setup.

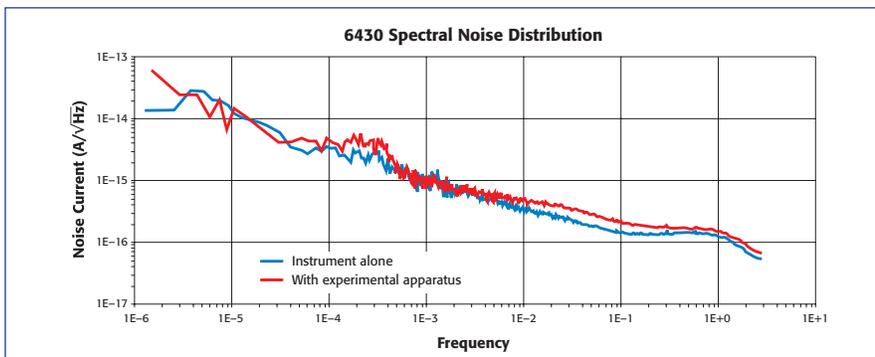


Figure 5. The noise spectrum of the experimental setup shows that noise decreases with increasing frequency.

temperature changes from a building's heating and cooling systems could cause large current changes. One way of avoiding this problem is to simply place a cardboard box over the low current amplifier and source fixture. Doing so nearly eliminates the problem. It is critically important that the low current amplifier have low power dissipation (in this case <math><1/3</math> watt) to avoid heat buildup in the enclosure.

Another concern is stray electrostatic fields. Housing the current-generating element (in this case the source's resistors) in an electrostatic shield that is grounded for safety eliminates this problem. It's also possible to improve the settling time of the source by placing the current-generating element in-

side an inner electrostatic shield driven by the guard buffer.

Time-varying input

Using a slow staircase input instead of a simple DC signal shows that a discernable signal can be retrieved from the noise. After every 90 measurements (about 18 seconds), the current source was incremented by 10 attoamps. Inverting the staircase generated the negative source period. The results are shown in *Figure 3*.

Considering each step as a separate measurement and using the estimates described earlier, the mean of each current step has a one-sigma uncertainty of 0.8 attoamps. The measurement took 84 hours, only slightly

longer than the equivalent of five 12-hour runs for five separate measurements. The extra time required to reduce the noise is expected. The longer alternation period allows offsets to drift more between the positive and negative measurements, so the residual noise is larger. This can also be described by noting that offset drift due to temperature change typically has a $1/f$ characteristic. That is, noise current is inversely proportional to frequency. So while the current reversal process still narrows the bandwidth to $1/(12 \text{ hours})$ (0.00002Hz) the lower alternation frequency of the staircase places the measurement higher on the $1/f$ curve.

Conclusions

Using the data analyses and filtering described here, a wide range of tradeoffs between measurement time and uncertainty can be obtained. In addition, if proper attention is given to relevant noise sources such as temperature and cabling, current measurements can be made well below the one femtoamp level. In fact, using commercially available test equipment, measurements with uncertainties of one attoampere and below are possible and indeed practical. **KEITHLEY**

About the Author

Adam Daire is a Product Line Manager for Keithley Instruments' Research and Education Group. Prior to that, he worked as a core technology scientist. Daire has a BS in Physics from Case Western Reserve University, and a Masters in Business Administration from Weatherhead School of Management.

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