Application Note

Measurement and Calibration Techniques for Ultra-low Current Measurement Systems

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ABSTRACT

Ultra-low current measurements require careful attention to hardware and materials that are many times inconsequential in a typical circuit and PCB design. The goal of this application note is to discuss the considerations for femtoampere level current accuracy measurements, and provide operational-amplifier based circuits that can be used for calibration of systems that require ultra-low current measurements.

This paper starts from an ideal condition measurement, followed by practical designs that satisfy performance and efficiency for calibration of low current measurements using a common circuit technique called a coulombmeter. Measuring low-level current at this level requires careful analysis and understanding of not only the I_B characteristic of the op amp but also the surrounding circuitry to achieve reliable and repeatable results. As a result, it delineates the handling techniques for extremely low-level currents such as tens of atto-Ampere in resolution. The document will push the boundary of low-level current measurement and its application.

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Trademarks

1 Introduction

Many systems require ultra-low current amplifiers connected directly to a sensor or probe to achieve the maximum possible measurement accuracy. For this case, precision operational amplifiers can offer the best possible design to buffer a front-end probe or measure ultra-low currents. Precision Operational Amplifiers are designed to perform as closely to an designed for amplifier as possible. One key element of designed for amplifiers is infinite input impedance. For standard CMOS op amps, I_B ranges from several pico-amperes (pA) to hundreds of pA. These current levels can be achieved without advanced design considerations. However, additional circuitry and design details are required to achieve the lowest I_B performance. For high performance devices, such as the new OPA928, the I_B can be less than 1fA, into atto-Ampere levels. The input impedance is high enough to support a variety of high-impedance sensors.

2 Architecture of Small Current Measurement

2.1 Coulombmeter

One of the methods of measuring a current is using a coulombmeter. A coulombmeter consists of a capacitor within a negative feedback loop. The current is determined by the change in charge on the capacitor over time.

In Coulomb's law, charge Q is determined by the known value of capacitance C and measured voltage V across the capacitor. See Equation 1.

$$Q = VC \tag{1}$$

where:

- C is the capacitance in farads of the integration capacitor
- V is the potential in volts across the integration capacitor
- Q is the charge in coulombs on the integration capacitor

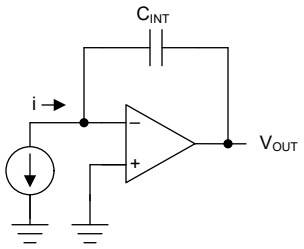

Figure 2-1. Basic Coulumbmeter Schematic

However, the flow of individual charges is not uniform due to noise and other random variables. One of the advantages of a coulombmeter is that the random flow for a certain time interval is averaged. The resolution of the measurement can be improved as longer integration times are allowed.

Current flow into the inverting terminal of the coulombmeter can create a voltage that is an integration function of the current versus time. Applying current flow into the inverting terminal of the amplifier and the circuit integrates the current over time. The op amp outputs voltage across the integration capacitor. Measuring the change in voltage over a specific time multiplied by capacitance gives current, measured in amperes.

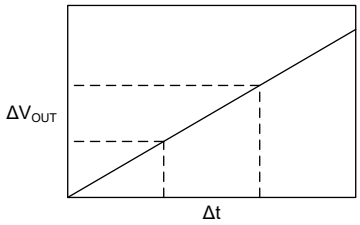

Figure 2-2. Change in Output Voltage versus Time

$$\frac{dV}{dt} \times C = I \quad (2)$$

Where:

- V is the voltage across the capacitor in volts
- t is the time in seconds
- C is the capacitance in Farads
- I is the current in Amperes

2.2 Using the Coulombmeter to Determine I_B

Even if the feedback terminal has no connection to the current source, there is a small current flow from the non-ideal input terminal of the op amp. The small current flow into or out from the input terminals is called input bias current (I_B). I_B is important to understand because it contributes to error in a system, and many times needs to be calibrated out for application circuits.

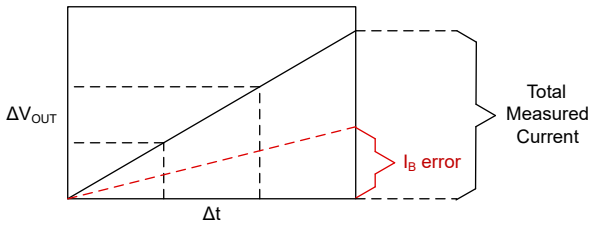

Figure 2-3. Components of Measured Current

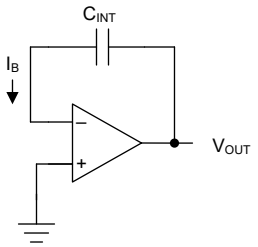

Figure 2-4. Model of Input Bias Current Integration

When not using the external current source, the feedback capacitor and integration capacitor (C_{INT}), integrates the charge of I_B alone. This architecture is commonly called the self-integration circuit. The sign of the current is determined by the direction of the bias current at the input terminal. A positive sign means the current is flowing into the op amp. A negative sign indicates input bias current flows out from the terminal.

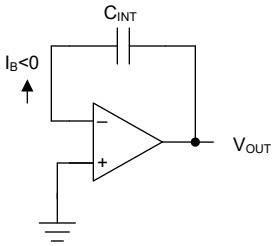

Figure 2-5. Model of input Bias Current Integration for Negative I_B

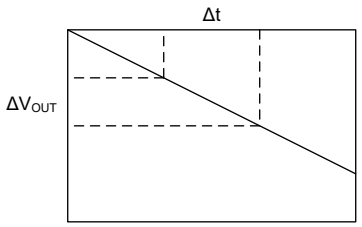

Figure 2-6. Negative Slope of Vout Versus Time Indicates $I_B < 0$

The magnitude of the input bias current varies depending on the process technology, the design of the op-amp, and the operating conditions, such as supply voltage, common-mode voltage, and temperature. For most CMOS op-amps, the input bias current is in the range of picoamperes. However, some precision op-amps designed for low I_B have input bias currents measured in atto-Amperes.

One of the alternative solutions is called the Ammeter. The circuit is simply an amplifier configured with a large feedback resistor. The challenge for the ammeter circuit is the need for extremely high resistance to measure low levels (for example, femtoamperes or fA) of current. When it comes to low I_B measurement, it is not practical to use multiple resistors such as 1TΩ in series to measure sub-femtoampere. The primary disadvantages are large thermal noise and thermal EMF that needs to be calibrated out.

For this reason, the budget-wise coulombmeter is the most practical approach, opposed to a high-resistance ohmmeter or ammeter that uses large feedback resistor. For the Ammeter, large resistors (>1 TΩ) can cost >$1000 to measure 1 [femtoampere] with a multimeter reading of 1mV. Additionally, the thermal noise is almost 100mV for a 1TΩ resistor, so the resolution is poor unless it is averaged for a long period of time. The large feedback resistor can also require a feedback capacitor to stabilize the amplifier. This results in time constants of a few seconds if the input terminal has capacitance of a few pF, and can take tens of seconds to settle.

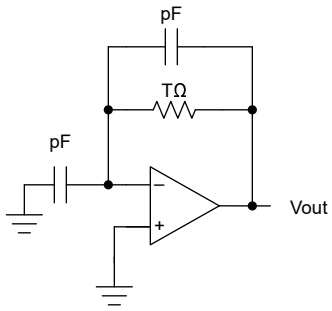

Figure 2-7. Ammeter with a Large Feedback Resistor

For the coulombmeter, a capacitor that is tens of pF can be purchased for less than $1. Charges on the 33pF capacitor to measure 1fA with a voltage change on the multimeter of 1mV over 33sec.

Coulomb meter

I = dV/dt x F

1fA = 1mV / 33sec x 33pF

Settling time: tens of seconds

Cost of a 33pF capacitor is < $1

Ammeter

I = V / R

1fA = 1mV / 1TΩ

Settling time: tens of seconds

Cost of a 1TΩ resistor > $1000

With that, a coulombmeter is more practical for very small current measurements over a long integration time.

Table 2-1. Comparison of the Coulombmeter and Ammeter

	Coulombmeter	Ammeter
Thermal noise	Undetectable	Large
Speed	Long integration time	Long data averaging time
Parts cost	Capacitor <$1	Resistor >$1000

2.3 Leakage of Integration Capacitor

One important performance parameter of the capacitor is the insulation performance. The insulation resistance of a capacitor can be basically modeled as a resistance between the two terminals of the capacitor. The resistance of the integration capacitor needs to be determined to calibrate the measurement. High insulation is one of the first requirements for ultra-low bias current measurements. Therefore, selecting high-insulation material is of primary importance.

Every material has the volume resistivity. Generally, a resistivity is measured one minute after the voltage is applied across the specimen at room temperature. However, due to internal charges with large parasitic resistance, more than one minute is needed to be an equilibrium condition for some materials. The specimen has both surface resistivity and internal resistivity. Some material are more sensitive to surface condition such as humidity and cleanliness.

Polypropylene capacitors have high resistivity and satisfactory high resistance for ultra-low bias current measurements. To understand the parasitic resistance, or *Insulation resistance*, vendors use a parameter represented by an Ohms-Farad product Ω·F as a unit. For example, a minimum spec of 10,000Ω·F (at 20°C 100Vdc) is extracted as

$10{,}000\Omega \cdot F / 1\mu F = 10 \times 10^{9}\Omega$

If we can extrapolate the curve for smaller capacitance, such as 100pF, we expect

$10{,}000\Omega \cdot F / 100pF = 0.1 \times 10^{15}\Omega$

The number indicates that the leakage current is 10aA or less in the condition of the voltage across the capacitor is 1mV. The next section can give us data on smaller capacitance and voltage, which is not described in the data sheet of the capacitor.

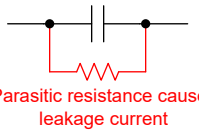

Figure 2-8. Capacitor has Leakage Across the Terminals

3 Benchmarking

3.1 Point to Point Wiring

The following test configuration was built to examine how much resolution of I_B can be obtained under the designed for measurement condition. As shown in Figure 3-1, a point-to-point wired self-integration circuit consists of a minimum number of parts, such as a decoupling capacitor and an integration capacitor. The only major leakage path is the integration capacitor. As air is one of the most insulated materials, we rely on it to obtain benchmark data.

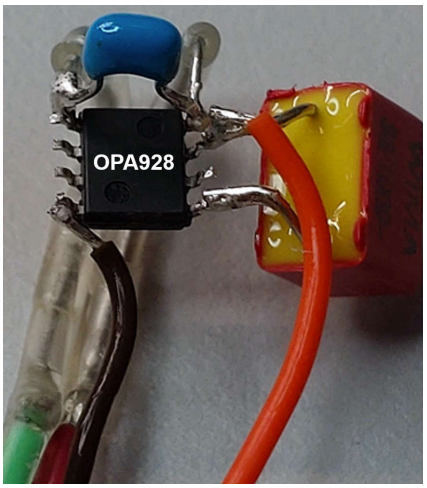

Figure 3-1. OPA928 SOIC Point-to-Point Wiring

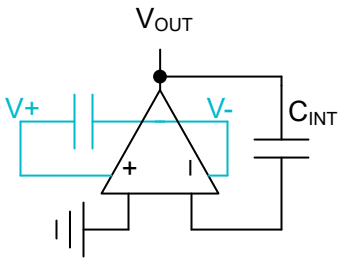

Figure 3-2. Schematic of the Point-to-Point Wiring

As seen in the previous section, the input bias current model is a DC flow into the capacitor. Therefore, the voltage change across the capacitor over time indicates the amount of I_B. When multiplied by the capacitance, the result is current in Ampere.

$$I_B(A) = dV/dt(V/sec) \times C(F) \quad (3)$$

The data acquisition rate is 6SPS for 100 samples and calculates a slope of Vout over time, dV/dt. Multiply by the integration capacitor 31.7pF, and I_B is plotted as shown below. The average number is 0.387fA to 0.397fA for the entire measurement of three days.

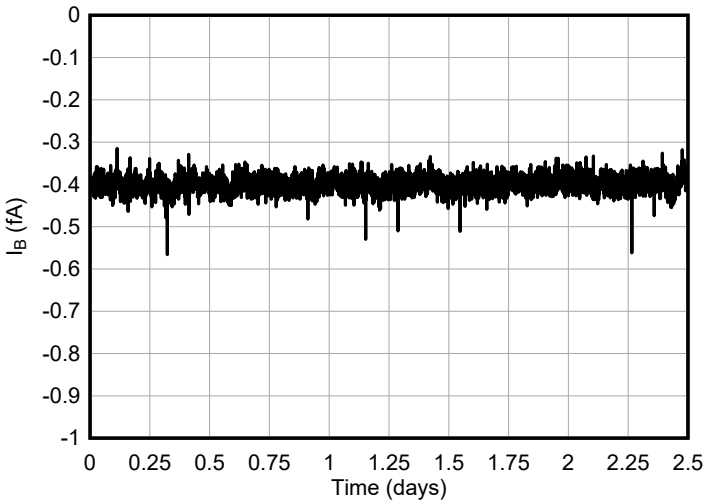

Figure 3-3. Course Measurement of I_B Over Time With Point-to-Point Wiring

As mentioned previously, one of the advantages of the coulomb meter is that the meter averages the current flow over time; the longer the integration time, lower the noise and higher measurement resolution.

Looking at the data plotted versus time can help understanding what inaccuracies can occur in the coulombmeter circuit. The measurement shown in Figure 3-4 shows the effects of the initial condition on the circuit. Each data point is a localized derivative, with the graph starting at –0.8V. The derivative of the curve changes in the first few hours. The data starts at 395aA and eventually goes up to 400aA.

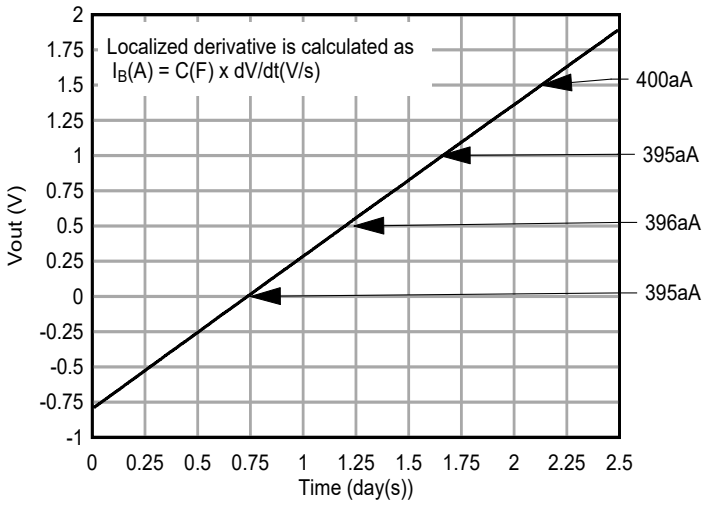

Figure 3-4. Fine Measurement of I_B Over Time With Point-to-Point Wiring

The fitting curve of measured current versus voltage (voltage across the capacitor) provides resistance of the integration capacitor in 649PΩ. The lowest amount of leakage occurs when the output voltage crosses zero volts because the voltage across the capacitor is close to zero. The current measured at the curve crossing zero volts indicates the least leakage across the capacitor, and the value is 395aA. Benchmarking data provides I_B data with a resolution of tens of atto-Amperes.

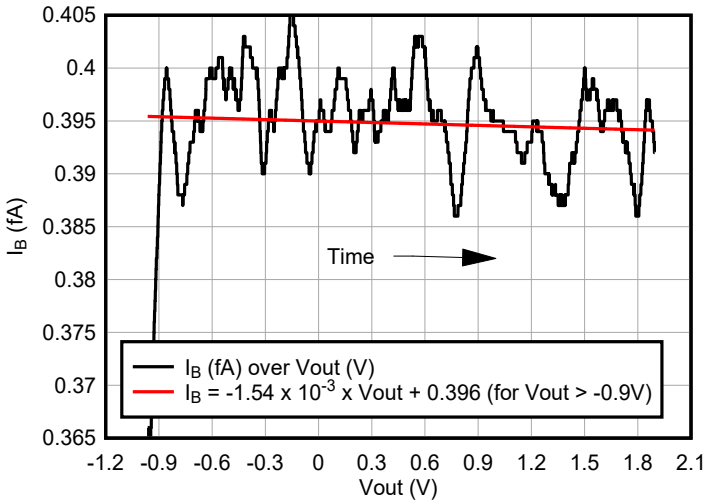

Figure 3-5. Course I_B Over Vout With Point-to-Point Wiring

Benchmarking data provides I_B data with a resolution of tens of atto-Amperes.

3.2 Shielding

Due to the high impedance of a modern amplifier, the circuit has an ultra-high impedance node, and the circuit is sensitive to the movement of the person or an object near the instrument that creates unwanted electrical coupling.

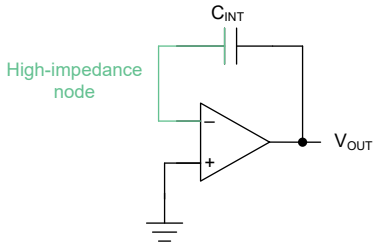

Figure 3-6. Coulombmeter With the High Impedance Node in Green

In addition, AC fields, such as the mains line, also influences high-impedance node. When the high-impedance node couples with mains lines with a parasitic capacitance of 1fF, the resulting error current can be 42pA.

$$I = V / Z = 110V \times 2 \times \pi \times 60Hz \times 1fF = 42pA \quad (4)$$

Figure 3-7. Aluminum Box for Shielding High-Impedance Node From EMI

An aluminum box shields the high-impedance node from electronic field coupling. Depending on the type of radiation, different material is selected. For inductive coupling, higher permeability material is required.

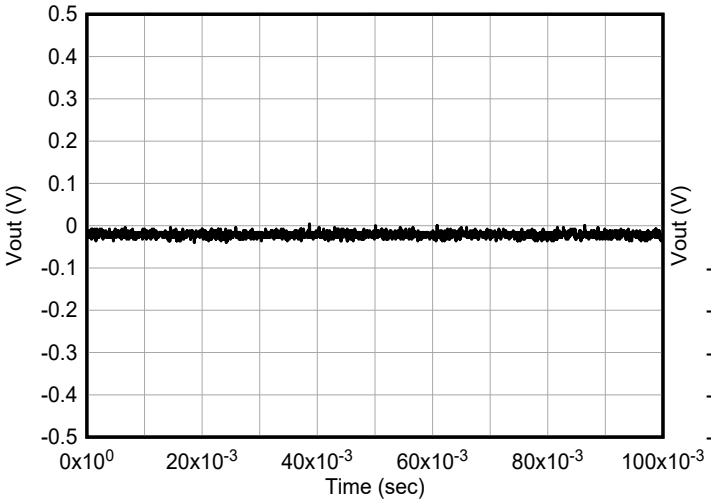

Figure 3-8. Vout With a Shield

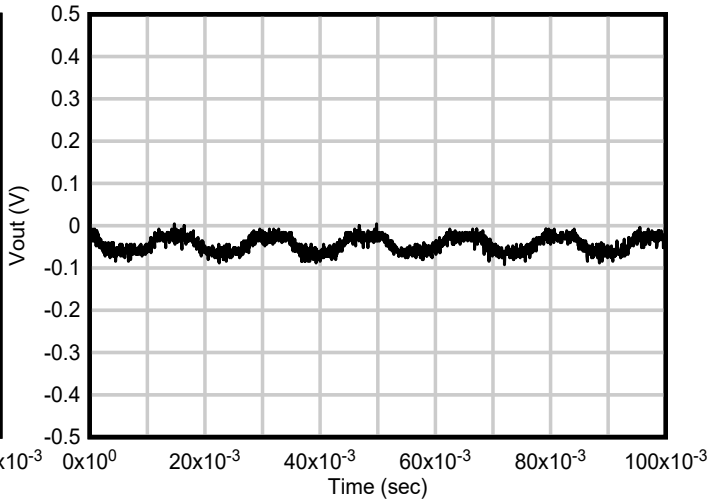

Figure 3-9. Vout Without Shield

3.3 PCB Cleaning

The hardware cleanliness significantly affects the measurements. Although not all of the parts on the board have to be cleaned, contamination on the sensitive components result in leakage of bias current, resulting in measurement error.

Though there are traditional cleaning methods, such as brushes or sprays, ultrasonic cleaning is highly effective for cleaning electric components. Ultrasonic cleaning is optimized for removing contaminants and flux from complex geometries and small dimension boards.

The ultrasonic cleaning process uses a tank filled with a solution such as de-ionized (DI) water. Once the components are immersed in the solution, transducers generate high-frequency sound waves that create tiny bubbles. The energy of the micro-burst dislodges and removes flux and other unwanted residuals on the surface of the component.

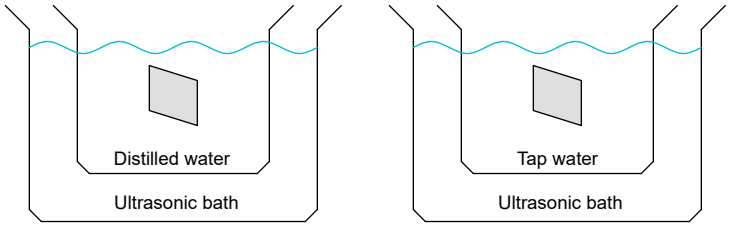

Figure 3-10. Comparison Between DI Water Versus Tap Water

The power of the bubbles is strong enough to erode typical aluminum foil. The energy of micro-burst is reduced in the tap water. As shown in the pictures, aluminum foil in the tap water has less erosion than that of the de-ionized water. This is because tap water has more particles that reduce the energy of micro-burst.

Figure 3-11. Aluminum Foil Before Ultrasonic

Figure 3-12. Aluminum Foil After Ultrasonic With De-ionized Water

Figure 3-13. Aluminum Foil After Ultrasonic With Tap Water

The duration of the ultrasonic cleaning process depends on the cleanness of the board. Typically, cleaning cycles can range from several minutes to ten minutes at warm temperatures. Some components are more sensitive and can be damaged, such as MLCC capacitors, and care need to be taken to not leave these components in the cleaning process beyond the maximum recommendations.

After the cleaning cycle is complete, the components are rinsed with clean DI water to remove any residual cleaning solution. The components are then carefully dried, either through air drying or by using specialized drying equipment such as an oven with dry air to remove moisture. The temperature depends on the components, though, ultra-low current measurement requires 125°C for several hours.

3.4 Temperature Stability

Temperature stability is required for the circuit, or the offset voltage drift over temperature is added as error to the output voltage. This phenomenon can appear even when the temperature in the room is changed by a few degrees; The graph indicates steep voltage change periodically that sync with the air conditioner is on. Not only I_B drift but also input offset voltage (Vos) drift of the op amp appears as a dent of the output voltage. The circuit needs to be in the oven to maintain temperature during the measurement.

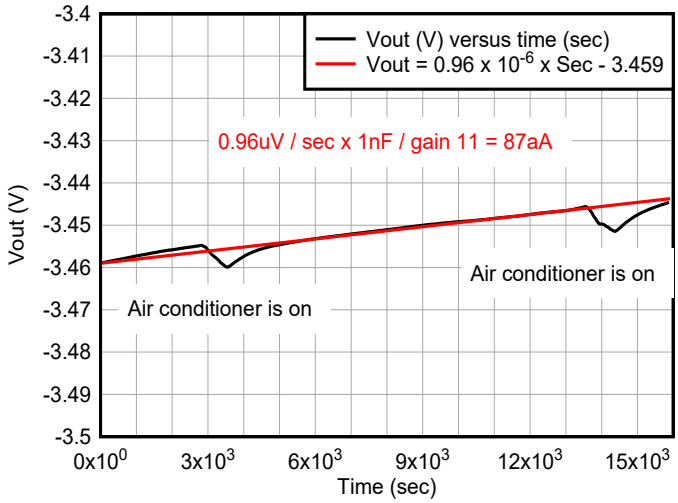

Figure 3-14. Vout Over Time in the Condition of Room Temperature

4 Calibration Using a Coulombmeter for Application Circuits

Previous sections described the limits and precautions of the measurement. To realize a full design, the coulombmeter circuit deploys:

- A polypropylene capacitor for an integrator that resistance was measured as tens of PΩ at the room temperature.
- Double layer metal shielding to prevent coupling electric field to the high-impedance node.
- Point-to-point wiring for high-impedance nodes.
- Cleanliness.

Figure 4-1 shows an example of a PCB that can allow for both standard surface-mount devices, along with point-to-point wiring. The layout specifically around the input high-impedance nodes of the circuit has milled slots with point-to-point wiring; see below.

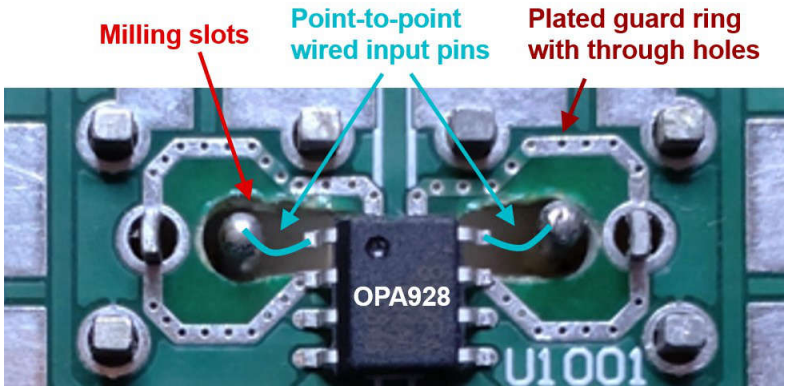

Figure 4-1. OPA928 Calibration Board Layout for the High-Impedance Node

4.1 Calibration of Common Application Circuits

Input bias current can impact several types of applications, see the following examples.

4.2 Calibration of Inverting Input

The first case occurs when the high impedance node is connected to the inverting input terminal. These typical cases are leakage current measurements (or insulation resistance), a trans-impedance amplifier, and piezoelectric element amplifier.

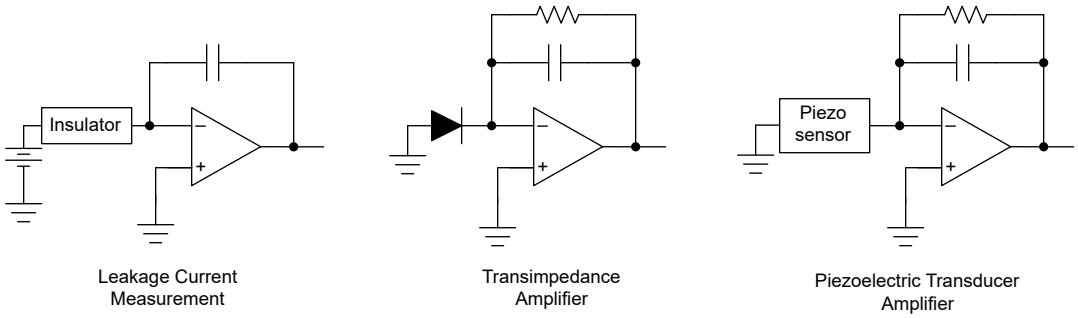

Figure 4-2. Application Circuits for High-impedance Inverting Input Terminal

As shown in the drawing, disconnect the sensor and transform the circuit into a feedback loop with a buffer amplifier with gain. Short the non-inverting input pin to the ground.

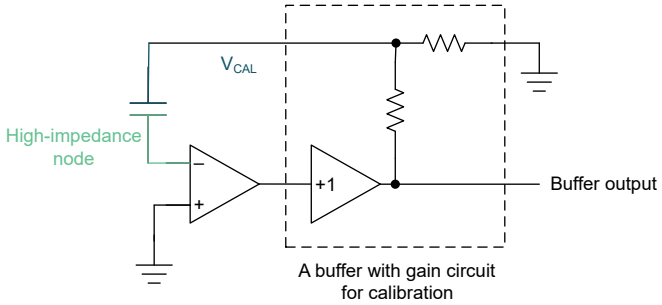

Figure 4-3. Configuration for Inverting Input Terminal Calibration

Insert an integration capacitor between the inverting input and Vcal. So that the circuit is in the calibration mode.

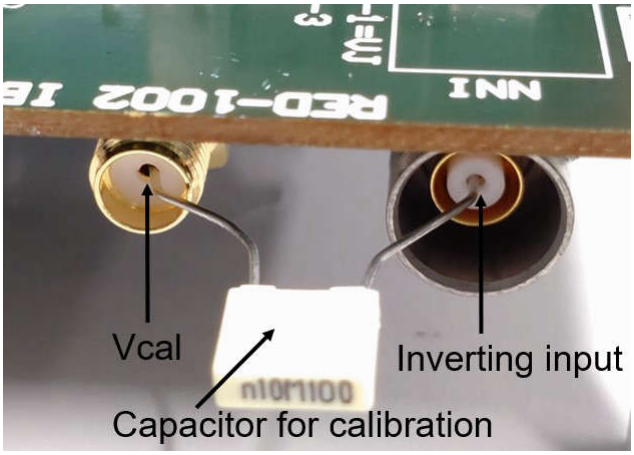

Figure 4-4. Inverting Input Terminal Calibration Using a Coulombmeter

4.3 Calibration of Non-Inverting Input

Convert application circuits into the calibration mode

The second case is for the high-impedance node, which is the non-inverting input terminal of the op-amp, such as high-impedance sensor application.

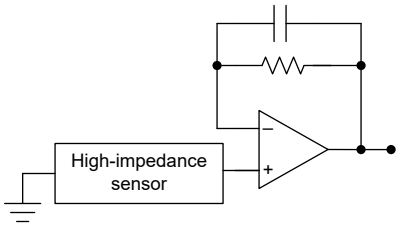

Figure 4-5. Application Circuits for High-Impedance Non-Inverting Input Terminal

As shown in the drawing, disconnect the sensor and transform the circuit into a feedback loop with a buffer amplifier with gain. Short the inverting input to the ground.

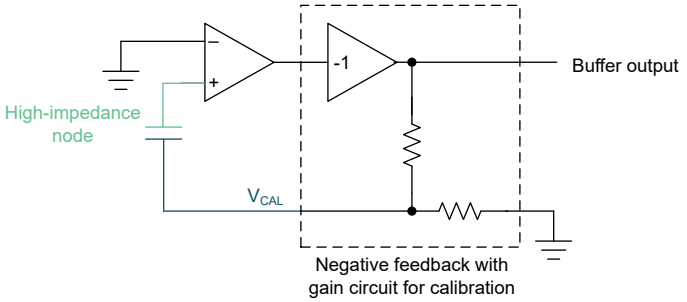

Figure 4-6. Configuration for Non-Inverting Input Terminal Calibration

Insert an integration capacitor between the non-inverting input and Vcal. So that the circuit is in the calibration mode.

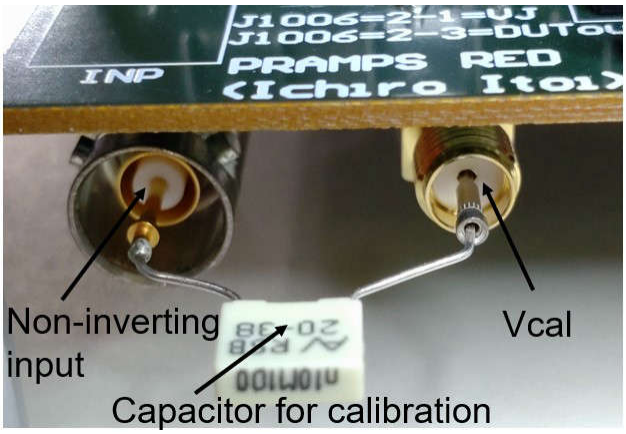

Figure 4-7. Non-Inverting Input Terminal Calibration Using a Coulombmeter

4.4 Determine Resistance of the Capacitor Using Zero-Cross Method

As mentioned previously, an integration capacitor can have leakage current flowing through the parasitic resistance between the plates. Since this path is resistive, the leakage current is proportional to the voltage delta between the terminals. The schematic shows a model of capacitor leakage. Vcal bias determines the direction of the leakage current because the input terminal is always zero volts; technically, little away from zero volts due to the input offset voltage of the op amp. There are four types of combinations depending on the sign of I_B and the sign of Vcal.

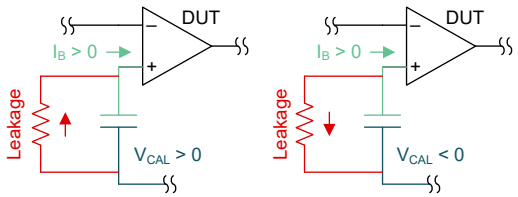

Figure 4-8. Capacitor Leakage Model for Positive I_B

For positive I_B, if the junction voltage, Vcal, is negative (lower than the input terminal bias), the high-impedance node reduces charge faster than the original I_B due to the leakage across the capacitor. Also, if the junction voltage, Vcal, is positive, the leakage cancels out I_B. Therefore, measured dV/dt can be smaller as Vcal is increased.

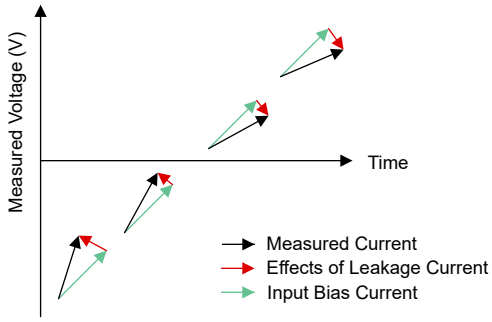

Figure 4-9. Capacitor Leakage Changes Vcal Over Time (Positive I_B)

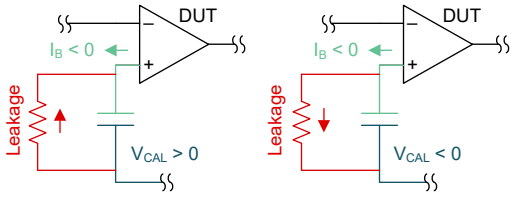

Figure 4-10. Capacitor Leakage Model for Negative I_B

The opposite is true for negative I_B. If the junction voltage, Vcal, is positive (higher than the input terminal bias), the high-impedance node accumulates charge faster than the actual I_B due to the leakage across the capacitor. also, when the junction voltage, Vcal, is negative, the leakage cancels out I_B. Therefore, measured dV/dt can be smaller as Vcal is lower.

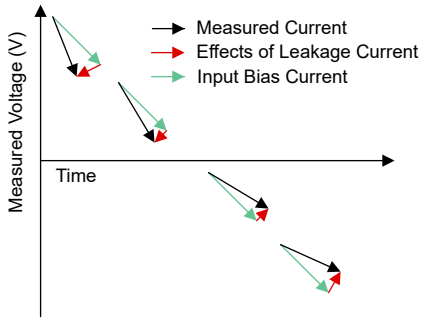

Figure 4-11. Capacitor Leakage Changes Vcal Over Time (Negative I_B)

We can estimate the error of measured I_B compared to the actual I_B by using the resistivity of the integration capacitor as 250PΩ determined in Section 2.

If a measured slope of voltage across the 100pF capacitor is 1uV/sec, Vcal is 1V, I_B is calculated as

$1 \times 10^{-6} \times 100 \times 10^{-12}$ = 100aA (without calibration)

$1 \times 10^{-6} \times 100 \times 10^{-12} + 1 / 250 \times 10^{-15}$ = 104aA (with calibration)

Focusing on the point that minimizes the leak across the capacitor can give us a method to determine I_B more accurately. As the integrator accumulates charges, the voltage across the integration capacitor crosses zero volts. We can take a derivative at this point and obtain the least leakage condition to determine I_B. For positive I_B, Vcal needs to start from negative. For negative I_B, Vcal needs to start from positive so that we can see the capacitor voltage crosses zero volts.

Suppose if the resistance follows the Ohm's row, leakage of the capacitor is proportional to Vcal.

Drawing below models zero-cross method for positive I_B, two parameters are used – leakage and I_B over Vcal.

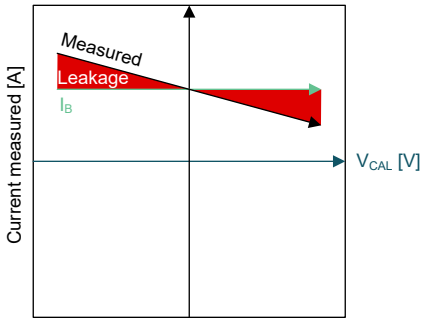

Figure 4-12. Model of the Zero-Cross Method for Positive I_B

Drawing below models zero-cross method for or negative I_B, two parameters are used – leakage and I_B over Vcal.

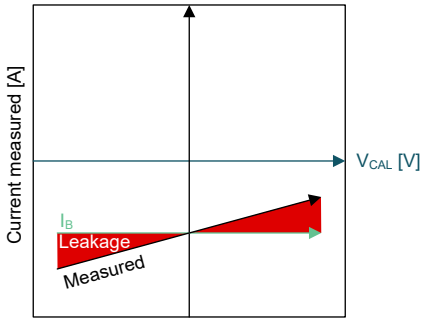

Figure 4-13. Model of the Zero-Cross Method for Negative I_B

For example, Vcal is measured over time, as shown in the graph below. The voltage across the capacitor starts from -400mV. As the integration goes by, the voltage crosses zero. The derivative of the curve when Vcal crosses zero volts gives 312aA. The dV/dt x C, when the voltage crosses zero, is the lowest leakage current achievable. Please note that Vcal is the voltage across the integration capacitor. Measuring I_B in the condition is considered as the lowest leakage on the integration capacitor, Zero-cross method.

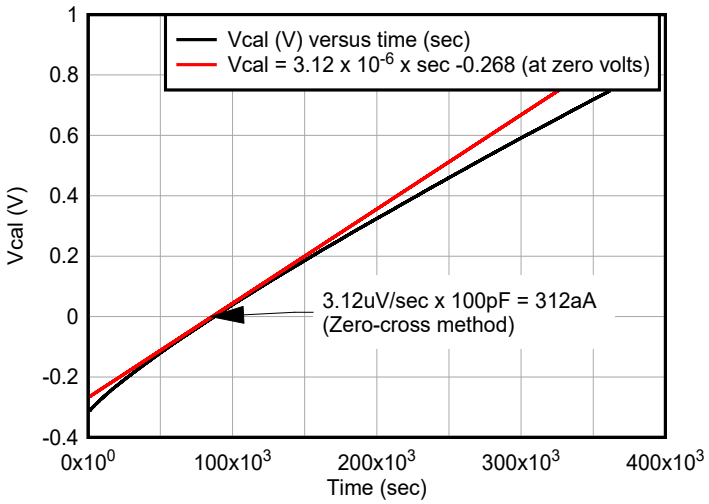

Figure 4-14. Zero-Cross Method Provides the Least Leakage Condition to Read I_B

4.5 Dielectric Absorption and Relaxation

Capacitors are made of dielectric material with permittivity and dielectric loss. Permittivity and dielectric loss depend on frequency and temperature. In this case, frequency is super low, and temperature is stable.

A polypropylene capacitor was chosen for an integrator because of the high resistivity. Most polymer is a dielectric material. Dielectric material polarizes by the external electric field. There are several models of the polarizations that are electron cloud, ion of the atom and ion, and dipole orientation.

In this case, permittivity is increased as the movement of dipoles that follow the direction of the external electric field until aligning the orientation.

Dielectric relaxation is explained as a procedure of mechanical orientation. During the procedure of orientation, dipoles have resistance from the molecules around them, and orientation takes time to complete.

For a high-frequency electric field environment, the dipole cannot follow the change of the electric field as it is faster than the orientation process. Also, for low-frequency electric fields, dipole follows the change in the electric field without delay.

The electronic model of a capacitor with dielectric absorption is shown below. The model consists of multiple RC time constants in parallel. Due to parasitic capacitors and resistors with a very long time constant, the capacitor behaves as if the capacitor memorized the previous voltage.

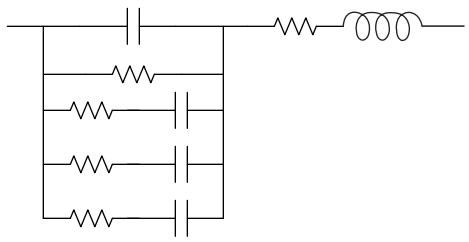

Figure 4-15. Parasitic Model of a Capacitor

Dielectric absorption is standardized by IEC / EN 60384-1. According to the procedure of measurement, charge a capacitor at DC voltage for sixty minutes, followed by discharge for ten seconds. Then measure the voltage recovery for fifteen minutes, which indicates dielectric absorption voltage. The percentage of the voltage before and after is the level of the absorption. Polypropylene film capacitor has dielectric absorption of 0.05 to 0.1%.

Measuring ultra-low currents in the femtoampere range requires enough time for dielectric absorption and relaxation.

Figure 4-16 shows multiple cycles of integration measurements with a varying start voltage.

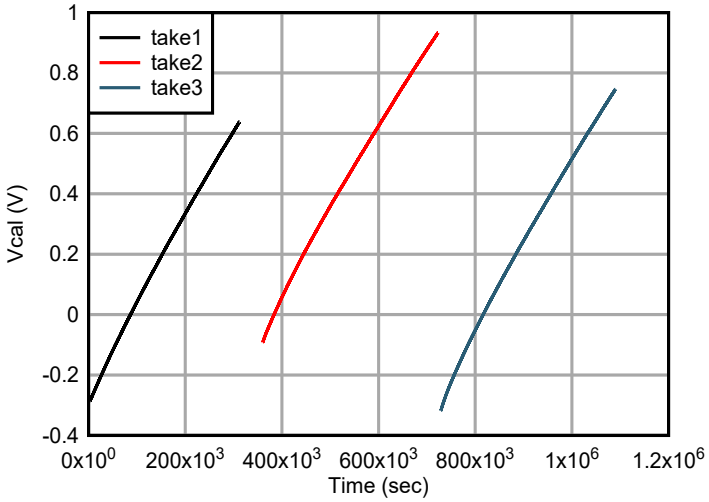

Figure 4-16. Vcal Over Time With Zero-Cross Method for Multiple Measurements

Using the data in Figure 4-17 to calculate I_B, we can see that the initial I_B measurements vary significantly from the settled measurements. This effect is an additional error from the I_B starts from different points and gradually aligns together as time goes by, which is Vcal goes up in this case. Though the relaxation process lasts long, we suppose the dielectric absorption was almost negligible at Vcal = 0.4V as the curves are aligned. With that, the

slope of I_B versus Vcal for Vcal is from 0.4V to 0.6V, indicating resistance. From the slope, the resistance is more likely as 16.2 x $10^{15}\Omega$.

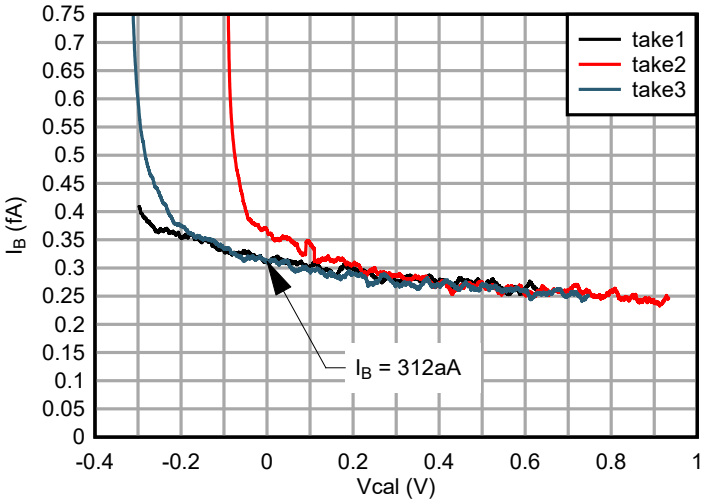

Figure 4-17. I_B Over Time With Zero-Cross Method for Multiple Measurements

At this point, we have only three parameters to consider. These are dielectric absorption, capacitor resistance, and I_B as shown in the drawing.

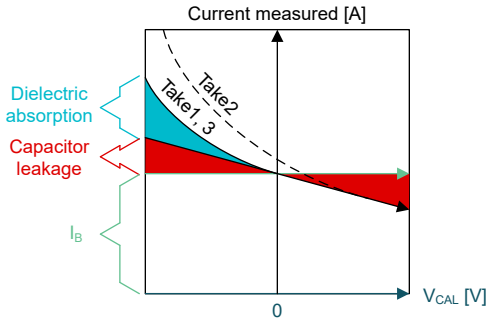

Figure 4-18. Model of the Three Parameters in the Measured Area

Estimate an error for the measured slope depending on what Vcal we took derivative. A calibration uses the resistance 16.2PΩ to provides 6aA leakage when the voltage across the capacitor is 100mV.

For example, if we measure the slope of the buffer (gain 10x) output is 10uV/sec, and Vcal is 1V which is the voltage across the integration capacitor of 100 [pF], I_B is calculated as

10 x 10^{-6} / 10 x 100 x 10^{-12} = 100aA (without calibration)

10 x 10^{-6} / 10 x 100 x 10^{-12} + 0.1 / 16.2 x 10^{-15} = 106aA (with calibration).

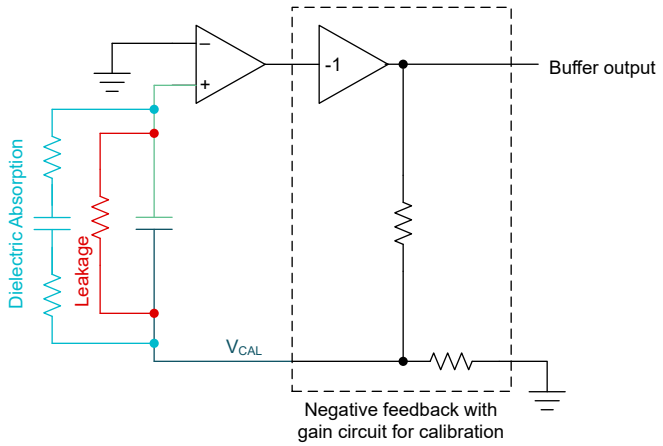

Figure 4-19. Configuration of Non-Inverting Input Terminal Calibration With Leakage and Dielectric Absorption

We can add or subtract leakage current to or from the measured number depending on the signs of Vcal and I_B.

4.6 Calibration at 85°C

I_B typically can have a logarithmic relationship relative to temperature. This means that as the temperature increases, the I_B can be significantly higher. For this reason, highly accurate systems can need to calibrate I_B across temperatures. Following is a summary of the steps necessary to achieve ultra-low current calibration. Each step is then described in detail.

- Transform the circuit into calibration mode.
- Monitor the output voltage over time.
- Find a point where the output voltage crosses zero volts.
- Calculate current using the derivative of the output over time multiplied by the capacitance.
- Plot I_B versus output voltage to determine at what voltage the dielectric relaxation has settled. Make sure the zero-cross point is away from dielectric relaxation.
- Apply a temperature coefficient of the capacitor for calculation.

In the example, the output voltage (buffer with a gain of ten) moved from +1.0V to -3.4V.

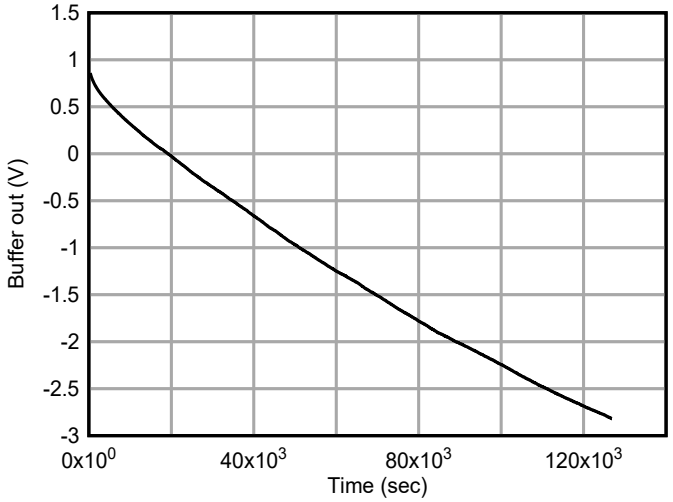

Figure 4-20. Calibration at 85C With Zero-Cross Method (Buffer Out Over Time)

The curve crosses zero volts, and a derivative at the point shows -33.7µV/sec. Assuming the number is the smallest leakage current condition across the capacitor, I_B is calculated as -33.7µV/sec / 10.1 gain x 108.6pF x (1-200 x 10^{-6} x (85-20)) = -357.6aA. The calculation includes the temperature coefficient of the capacitor of -200ppm/°C.

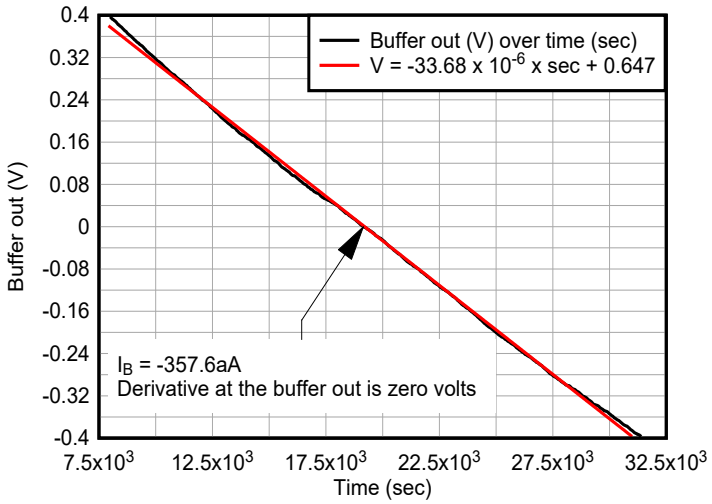

Figure 4-21. Calibration at 85C with zero-cross method (buffer out over time) zoom

Next, make sure the zero-cross point is away from dielectric relaxation. Calculate the derivative of output voltage over time. The plot of current over output voltage settles at around output voltage closes zero volts. This indicates dielectric relaxation settles at around the output of zero volts. A fitting curve shows -50.5aA/V. The resistance of the integration capacitor is calculated as 1 / (-50.5aA/V) / 10.1 (gain) = 1.96PΩ. The intercept of the fitting curve indicates I_B is -354.8aA.

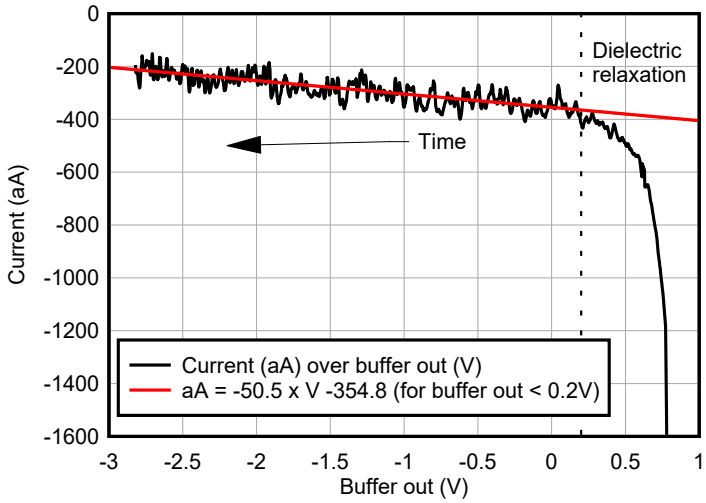

Figure 4-22. Calibration at 85C with zero-cross method (current over buffer out)

Comparing the number between the intercept of the fitting curve (-354.8aA) and the zero-cross method (-357.6aA) gives a delta of 2.8aA. With that, I_B is most likely between -354.8aA to -357.6aA at 85°C.

4.7 Calibration at 25C

Figure 4-23 shows an example of the measurement at 25°C. Although most of the procedure is the same as for 85°C, the example shows the output voltage did not cross zero volts. In this case, one additional step is needed. To remove the effects of the leakage in the parasitic resistance of the capacitor, the parasitic resistance must be calculated.

- Transform the circuit into calibration mode.
- Monitor the output voltage over time.
- Find a point where the output voltage is away from dielectric relaxation.
- Calculate the parasitic resistance of the integration capacitor.
- Calculate current using the derivative of the output over time multiplied by the capacitance.
- Apply the leakage current using the resistance oc the capacitor.

- Make sure the point to calculate derivative is away from dielectric relaxation.
- Apply a temperature coefficient of the capacitor for calculation.

In the example, the output voltage (buffer with a gain of ten) moved from 0.05V to 1.3V. As the curve does not cross zero volts, we need to take a leakage current into account. Leakage across the capacitor is proportional to the voltage across the capacitor multiplied by the resistance of the capacitor.

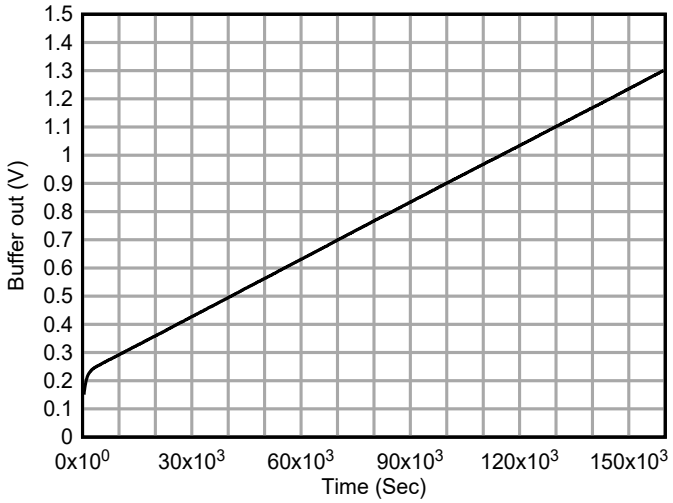

Figure 4-23. Calibration at 25C (Buffer Out Over Time)

Plot current over the output voltage. The curve indicates dielectric relaxation settles at around output voltage 0.3V. The fitting curve shows -0.93aA/V. The resistance of the integration capacitor is calculated as 1 / (-0.93aA/V) / 10.1 (gain) = 106PΩ at 25°C. The intercept of the fitting curve indicates I_B is 79aA. In this example, the resistance of the capacitor is used as the output voltage does not cross zero.

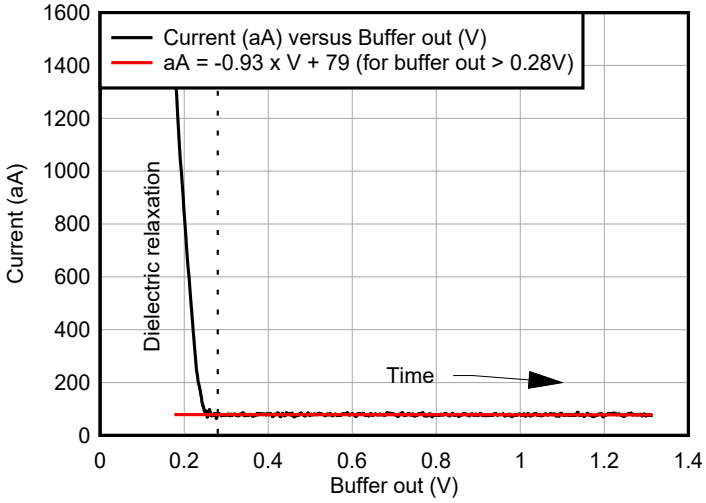

Figure 4-24. Calibration at 25C (Current Over Buffer Out)

Go back to the original curve of output voltage over time. Zoom in the area where dielectric relaxation was settled. For example, take a derivative between 0.263V to 0.273V, dV/dt, to obtain a slope that is 6.73µV/sec. Apply the parasitic resistance of the capacitor of 106PΩ, on 0.268V / 10.1(gain) to obtain leakage of 0.25aA. I_B is calculated as 6.73µV/sec / 10.1 x 117.4pF x (1-0.0002 x (25-20)) + 0.25 = 78.4aA. The calculation includes the temperature coefficient of the capacitor of -200ppm/°C.

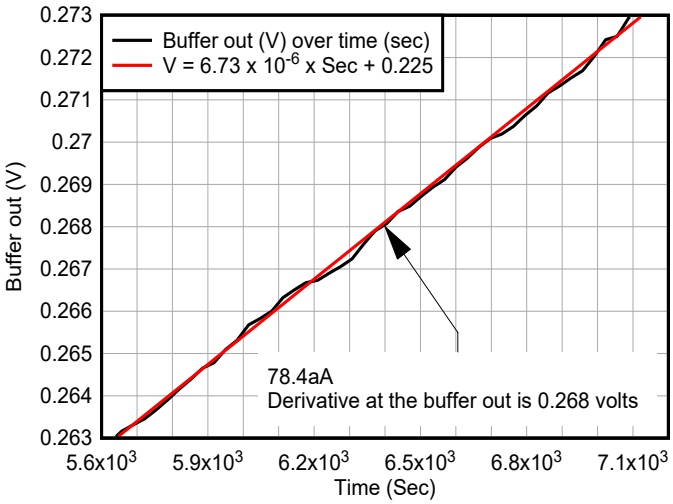

Figure 4-25. Calibration at 25C (Buffer Out Over Time) Zoom

Comparing the number between the intercept of the fitting curve (79aA) and (78.4aA) gives a delta of 0.6aA. With that, I_B is most likely between 79aA to 78.4aA at 25°C.

5 Summary

As a result, we obtained calibration data for the coulombmeter at 85°C and 25°C. At the same time, we obtained resistance of the capacitor at 85°C and at 25°C as 19.8PΩ and 106PΩ, respectively. The number can be used for the application circuit as the same capacitor can be used for the application.

We also obtained dielectric absorption time for 85C and at 25°C as 300 minute and 90 minute, respectively.

Table 5-1. Result of the Calibration at two Different Temperatures

	Unit	85°C	25°C
Bias current of the coulombmeter	Atto-Ampere	-354.8 to -357.6	78.4 to 79
Resistance of the integration capacitor	Peta Ω	19.8	106
Dielectric absorption time	min	300	90

This document demonstrates the calibration of low current measurement in tens of atto-Ampere in resolution.

6 References

- WIMA FKP 2*Polypropylene (PP) Film/Foil Capacitors for Pulse Applications in PCM 5 mm. Capacitances from 33 pF to 0.033 µF. Rated Voltages from 63 VDC to 1000 VDC*.
- KEMET, *RSB, 5 mm Lead Spacing, 50 – 630 VDC (Automotive Grade)*.

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