μA-level current measurement

Short introduction

I wanted to measure currents of several hundred microamperes and decided to find a way to do it. In simple terms I used an operational amplifier setup as a non-inverting amplifier to amplify the voltage drop of a resistive shunt.

Theory

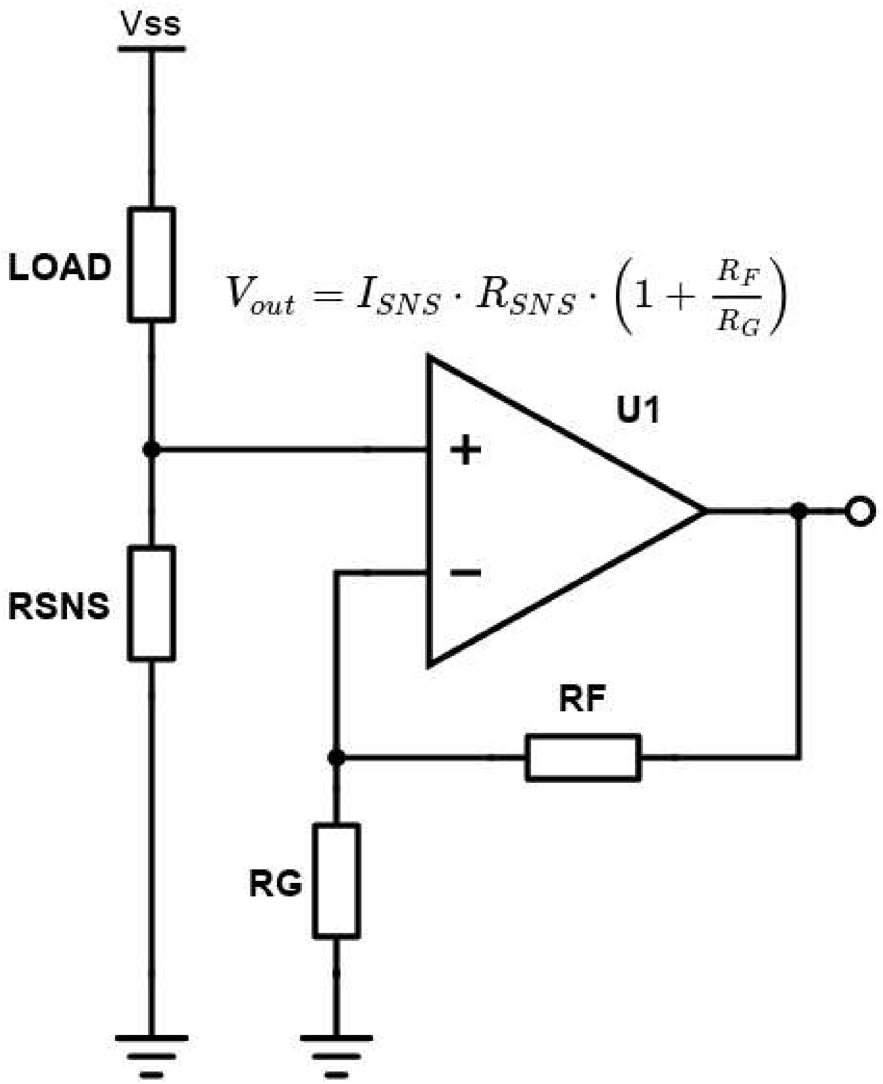
Current measurement methods can be separated into two distinct categories: invasive and non-invasive.

The invasive way is to either use an ammeter or a resistive shunt to take measurements of the current flow.

A resistive shunt is any low-resistance, tight-tolerance, high-wattage resistor that is invasively introduced in a circuit between two nodes with the stated intent of measuring current values. The shunt drops a proportional voltage, also known as burden voltage, the voltage divide by resistance gives us the current flowing between the two nodes.

A major concern ragarding shunt choice is the maximum burden voltage experienced by the shunt, as this voltage drop can sometimes negatively affect the functioning of the circuit. A simple example: For a current of 100 μA a 1 Ω shunt will drop 0.1 μV, but for 1 A the same resistor will drop 1V / 1W, enough to kick a transistor out of saturation.

The basic amplifier configuration used to amplify the voltage readout is presented below:



Low-side current sense amplifier

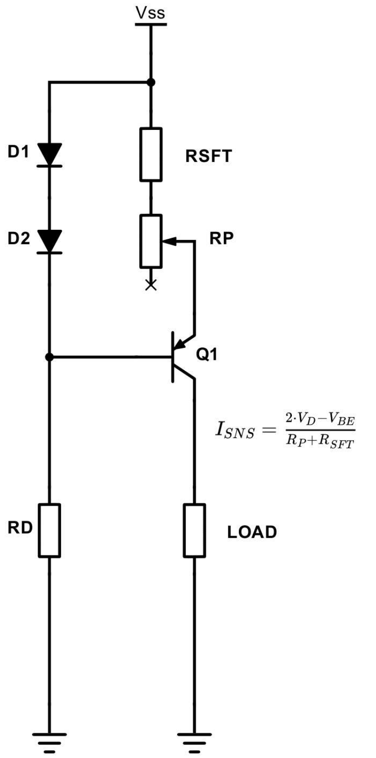
I should note that the circuit presented above does not account for input offset voltage or input bias current. I just wanted a quick and dirty solution to better understand the subject.

Practical implementation

The physical circuit consists of two distinct components:

- a variable constant current source
- current sense amplifier

The variable CCS is a generic PNP-based source, which is depicted below:

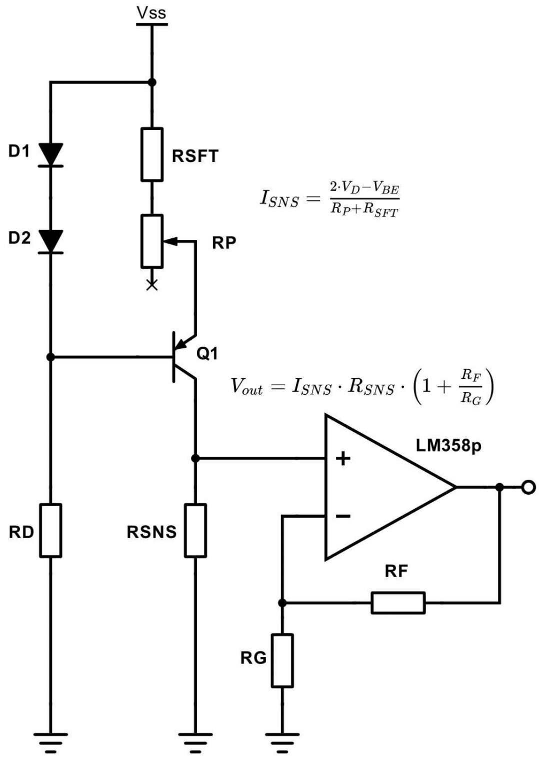


Variable PNP-based Constant Current Source

In my implementation of the circuit the current setting resistor is replaced by a 500mW potentiometer and a "safety" resistor. The safety resistor R_{SFT} is a 22 Ω, 250mW resistor that sets the maximum allowable current through the PNP transistor. R_D is used to bias the two diodes.

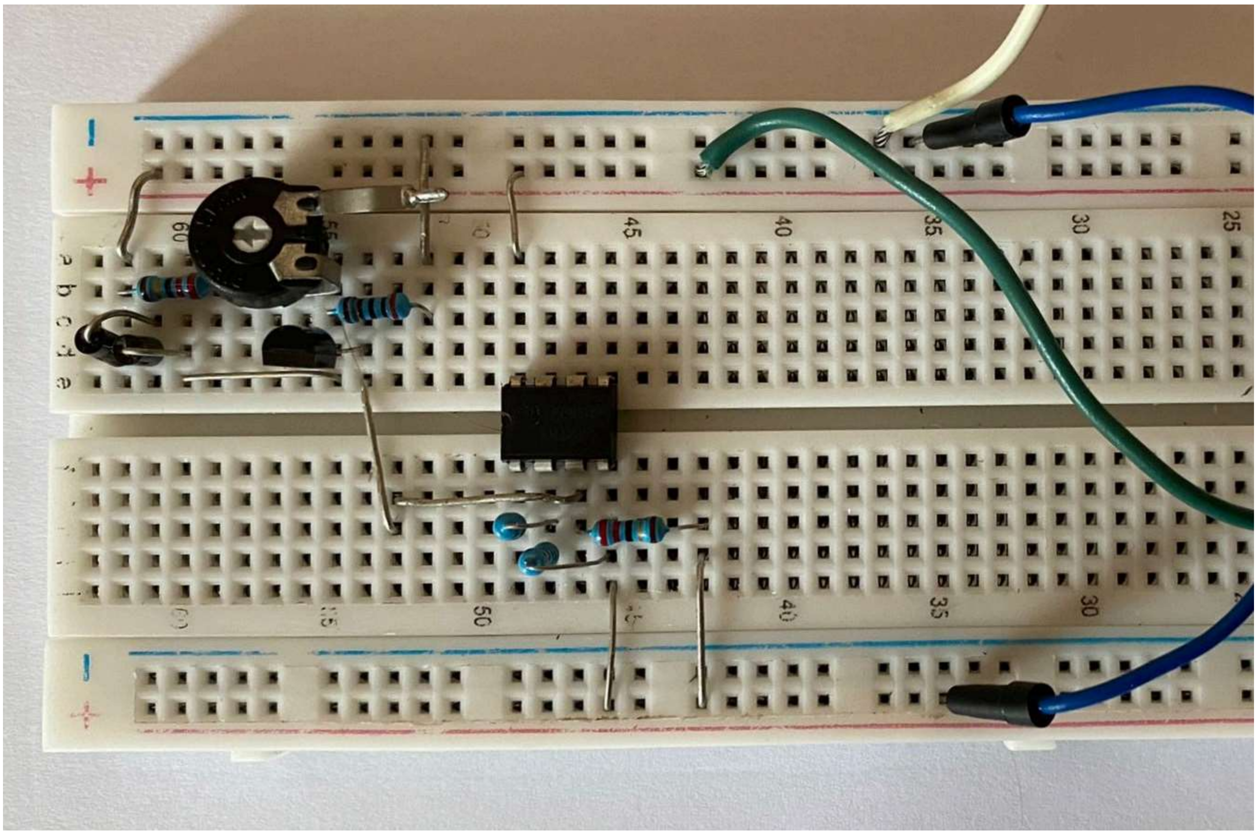
The output current of the CCS, given that operating conditions are met, is $I_{SNS} = \frac{2 \cdot V_D - V_{BE}}{R_P + R_{SFT}}$, which for comparable V_D and V_{EB} can be reduced to a simpler form: $I_{SNS} = \frac{V_D}{R_P + R_{SFT}}$

The final circuit's schematics look like this:



The complete circuit schematics

And this is how the circuit look like built up on a breadboard:



Breadboard version

The maximum possible gain of the operational amplifier LM358p is about 100,000. My opamp's feedback network is constructed such that the gain is about 22,000 to 23,000. The error caused by the input offset voltage will be quite big, but experimentally the results were better than I expected.

The Results

After cycling the CCS from 100 μA to 400 μA the results presented below were obtained:

Current [A]	Output Voltage [V]
9.49E-05	0.1633
9.90E-05	0.2537
1.02E-04	0.3169
1.06E-04	0.4086
1.16E-04	0.6265
1.31E-04	0.9557
1.42E-04	1.2105
1.60E-04	1.5938

Current [A]	Output Voltage [V]
1.78E-04	1.9912
1.94E-04	2.355
2.88E-04	4.424
3.02E-04	4.732
3.24E-04	5.211
3.47E-04	5.721
3.81E-04	6.455
4.28E-04	7.328
4.67E-04	7.351
5.19E-04	7.349
5.35E-04	7.251
5.94E-04	7.347
6.72E-04	7.349

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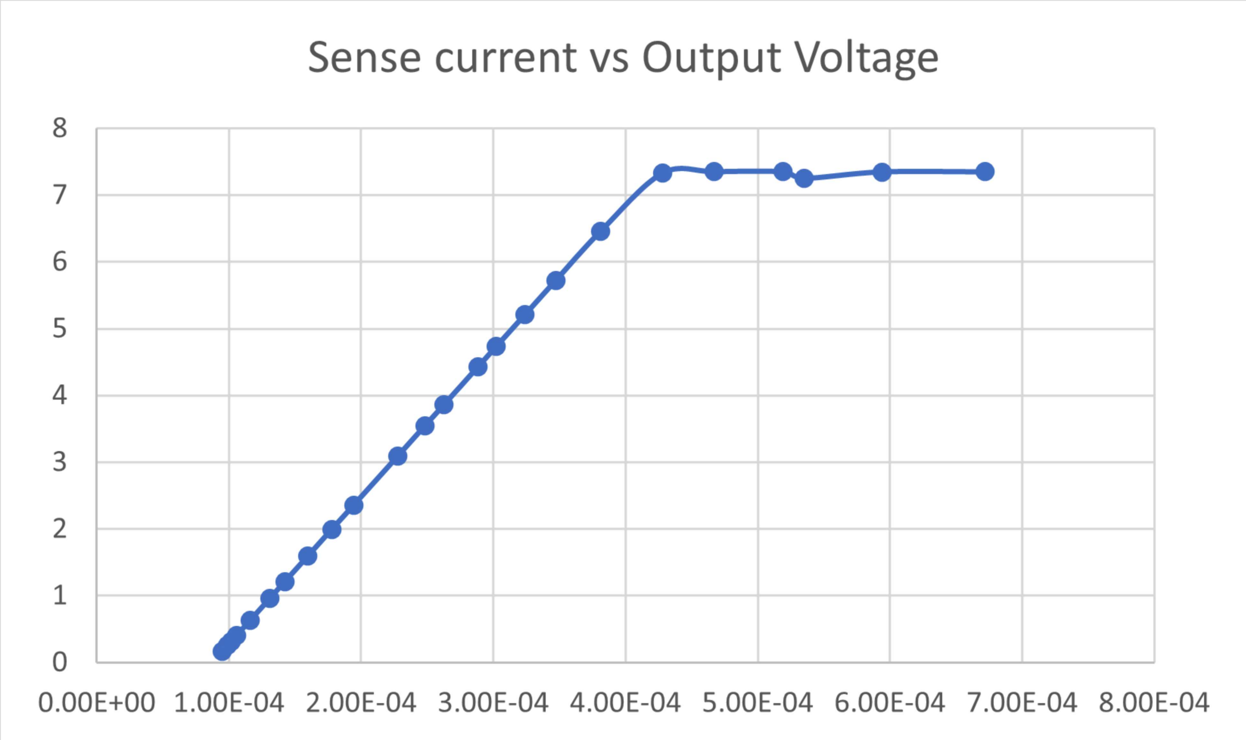
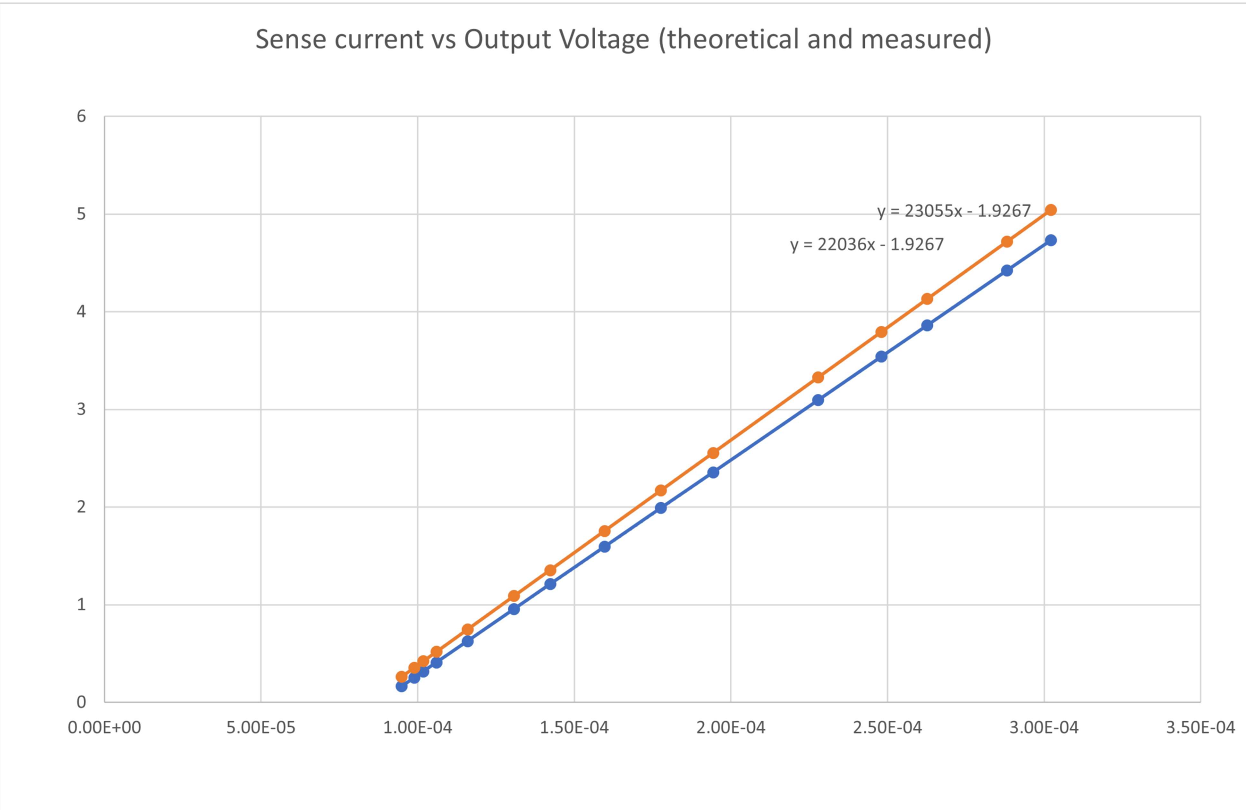
Preview Code Blame Raw

Above 400 microamperes the resulting theoretical output voltage is more than 80% of the supply rail voltage and so the operational amplifier saturates. AFter the op amp becomes saturated no more meaningful measurements cand be made, as it can be ascertained from the IV characteristic below.



Current vs Output Voltage Characteristic

The impact of the offset voltage becomes clearer as we increase the current.



Current vs Output Voltage (Theoretical and Measured)

In the chart above the orange line depicts $V_{out(theo)} = I_{SNS} \cdot Gain$, while the blue line depicts the real measured values of the output voltage. The difference between the two curves is because of the offset voltage.

To mitigate the effect of the offset voltage we either use a separate and complex compensation circuit, or we account for the observed error when writing the data acquisition programs for a microcontroller.

Conclusions

I've learned that sensing current in the microampere realm is certainly possible with some tweaking and ignorance of measurement errors.

The offset voltage problem can probably be solved by means of software adjusts in a microcontroller.

For usual applications the currents will be anywhere between 1mA and 1A, so the op amp gain shouldn't be as big as for microampere-level measurements

Resources

- https://e2e.ti.com/blogs_/b/analogwire/posts/how-to-lay-out-a-pcb-for-high-performance-low-side-current-sensing-designs
- https://www.analog.com/media/en/training-seminars/tutorials/MT-037.pdf