

# Circuits Lab 4

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3.3.13

## Experiment 1

Our first experiment compared transistors on the same MAT14 transistor array. For each npn transistor, we tied the collector to the +5V power rail and grounded the emitter. We swept the base voltage from .25V to .65V to characterize the transistor. One way of measuring how well matched transistors are is to measure  $\beta$  and  $I_s$ . To do this, we calculated the collector current using KCL:

$$I_e = I_b + I_c$$

We then calculated  $\beta$ :

$$\beta = \frac{I_b}{I_c}$$

To calculate  $I_s$ , we used the following relationship:

$$I_c = I_s e^{\frac{V_{be}}{V_t}}$$

Where  $V_{be}$  is the base-emitter voltage that we sourced with the SMU. The results of our calculation are summarized in the table below.

$\beta$	$I_s$
875.52	$2.01 * 10^{-13}$
875.64	$2.07 * 10^{-13}$
877.97	$2.10 * 10^{-13}$
875.66	$2.07 * 10^{-13}$

Beta is very consistent across the four transistors. We calculated the standard deviation of  $\beta$  to be 1.18, which is about .1%. The standard deviation of  $I_s$  is  $3.78 * 10^{-15}$ , which is about 3.6%. These deviation values suggest that the transistors in the MAT14 transistor array are very well matched. To further investigate  $\beta$  across all 4 resistors, we plotted  $\beta$  as a function of base voltage in figure 1. The plot shows that  $\beta$  is well matched across all operation regions of the transistors.

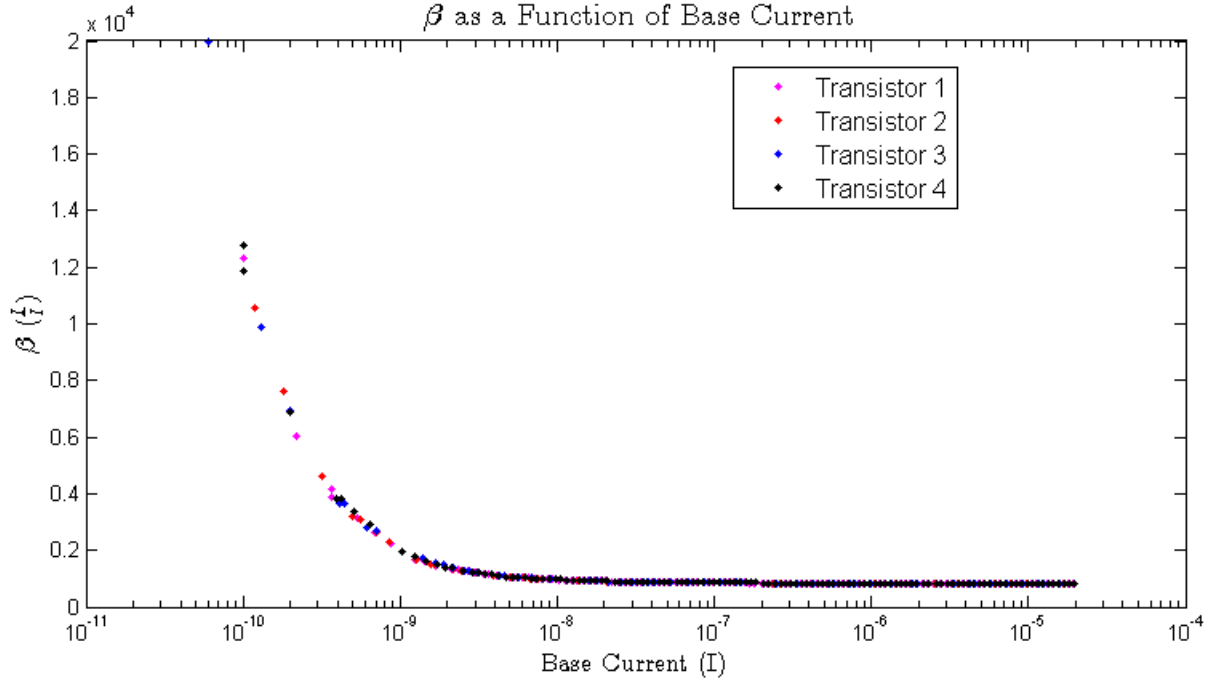


Figure 1:  $\beta$  as a function of  $V_{be}$  across all 4 devices.

Next, we wanted to investigate the similarity of currents between the devices. Figure 2 shows the base and collector currents for all 4 transistors on the same plot. The currents are almost identical.

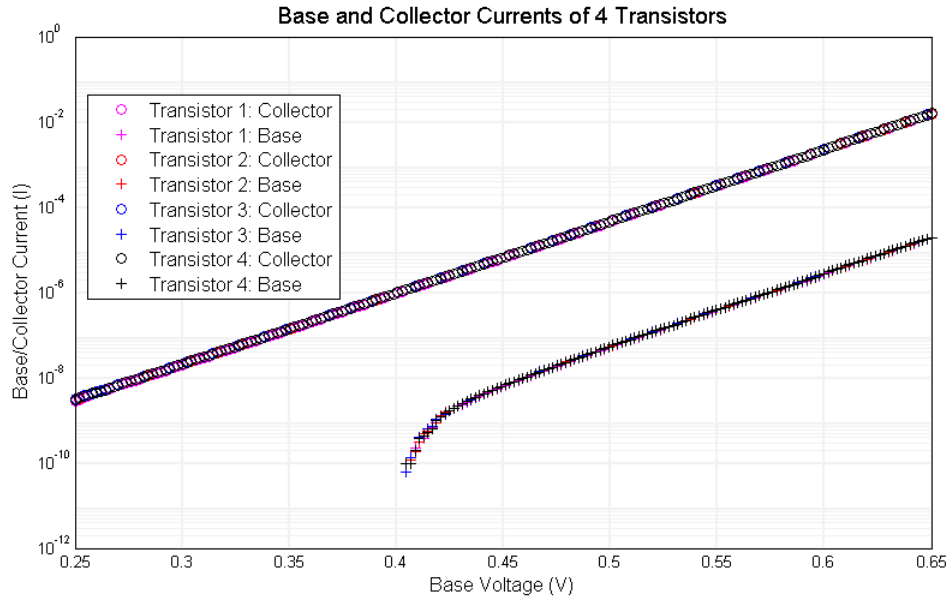


Figure 2: The base and collector currents of all 4 transistors in response to a base voltage sweep.

The similarity of the transistors' currents is better illustrated in figure 3. This plot shows the percentage difference of each transistor's collector current from the mean value. The collector currents are within a 2%

tolerance of the mean.

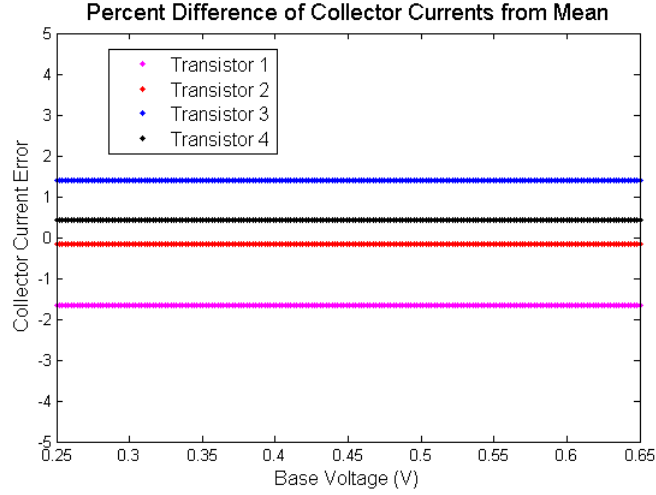


Figure 3: The percent error between each transistor's collector current and the mean value.

This experiment confirms that the transistors on the MAT14 are relatively very similar. This allows us to carry on with our experiments under the assumption that all 4 transistors are well matched.

## Experiment 2

In experiment 2, we analyzed the first translinear circuit, shown in Figure 4.

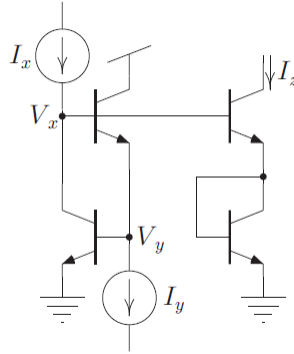


Figure 4: Translinear circuit 1.

### Configuration 1: Sweeping $I_x$

For our first configuration of the first circuit, we held the current  $I_y$  constant using a current sink that we made using the circuit shown in Figure 5. We sourced  $I_x$  using the SMU and measured the current  $I_z$  with the SMU as well.

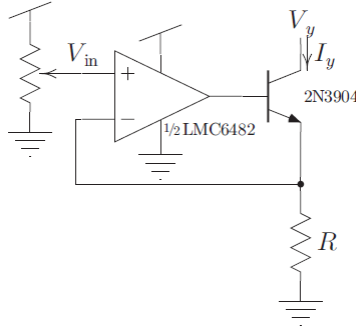


Figure 5: Our current sink.

### The Current Sink

We held that current sink constant by choosing our  $V_{in}$  and our  $R$  values such that we could produce a wide range of currents. We knew from our prelab that the voltage at the base of the bottom-left transistor,  $V_y$ , will be approximately .6 V in forward-active mode. Since the voltage will wiggle around .6 V, we needed the sink collector voltage, held at  $V_{in}$  by the op-amp, to be underneath that by at least  $V_{CEsat} \approx 200mV$ , so we chose a voltage that was well underneath it, .1 V.

We generated .1 V at  $V_{in}$  by using a voltage divider with resistor values 200 Ohms and 10k Ohms. Since our voltage source was 5 V, our resulting voltage at  $V_{in}$  was .1 V.

We used that voltage to generate a current through the current sink. To generate 10 uA, by Ohm's law, we needed a resistor with resistance 10k  $\Omega$ ; for 100 uA, 1k  $\Omega$ ; for 1 mA, 100  $\Omega$ .

### Measurement

We held  $I_y$  constant and used the SMU to sweep  $I_x$  over several orders of magnitude of current. We did this for three values of  $I_y$  that scaled three orders of magnitude.

From our prelab, we expect that this translinear circuit obeys the equation  $I_x I_y = I_z^2$ . As a result, when we hold  $I_y$  constant, we expect  $I_z = \sqrt{I_x I_y}$ .

Our experiment result, and our theoretical expectation, are shown in Figure 6.

## Translinear Circuit 1, Sweeping $I_x$

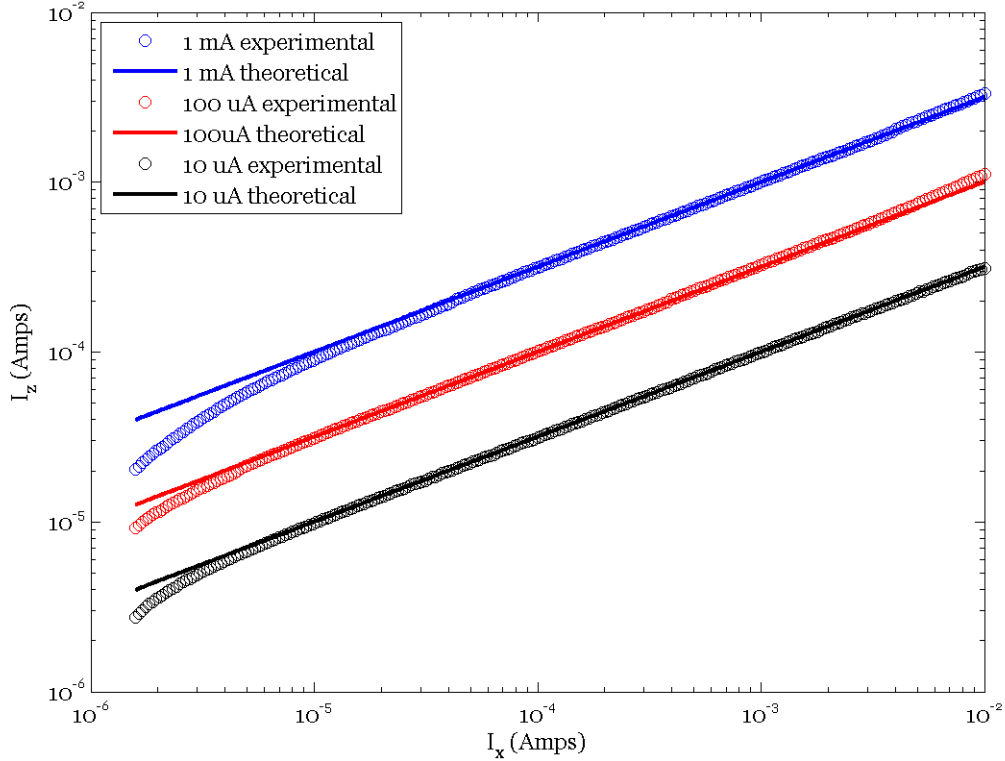


Figure 6: Translinear circuit 1, holding  $I_y$  at the values shown in the legend.

### Error Analysis

In general, this circuit behaves as we would expect from our analysis. For many decades, we see the expected line. However, in the low-current regions, we see that the current deviates from that line. This could be the SMU, but I believe a SMU issue would look noisy, and this looks smooth. Our current sink might not be in forward-active mode, but we chose our voltages such that we can almost guarantee forward-active mode, so I believe it is not that. A feasible explanation is that this is the small-signal Early effect, which makes the transistor linear, rather than exponential, in the small signal region - which would appear logarithmic on a loglog plot, which is similar to what we see here. As the current increases, this becomes negligible.

### Configuration 2

Next, we took the same circuit from before and replaced the current sink with one channel of the SMU, such that we could sweep  $I_y$ , and held  $I_x$  constant with a current source that we built. Our current source is shown in Figure 7.

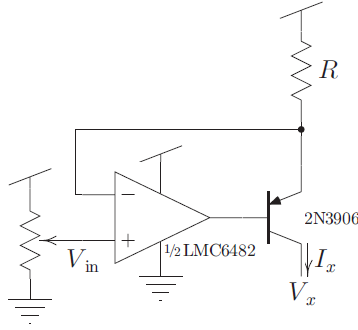


Figure 7: Our current source.

## The Current Source

We chose appropriate values of  $V_{in}$  and  $R$  such that we could sweep our  $I_y$  over several orders of magnitude, as in configuration 1.

For our voltage divider, we used a  $2\text{k}\Omega$  and a  $3\text{k}\Omega$  resistor to generate a voltage divider ratio of .4, and an output voltage of 3 Volts.

From the prelab, we know that our output current is  $\frac{5-V_{in}}{R}$ . To generate 1  $\mu\text{A}$ , we used a  $2\text{M}\Omega$  resistor; for 10  $\mu\text{A}$ , 200  $\text{k}\Omega$ ; for 100  $\mu\text{A}$ , 20  $\text{k}\Omega$ .

## Measurement

Again, we expected, from the prelab, that  $I_z = \sqrt{I_x I_y}$ . Our results are shown in Figure 8.

## Translinear Circuit 1, Sweeping $I_y$

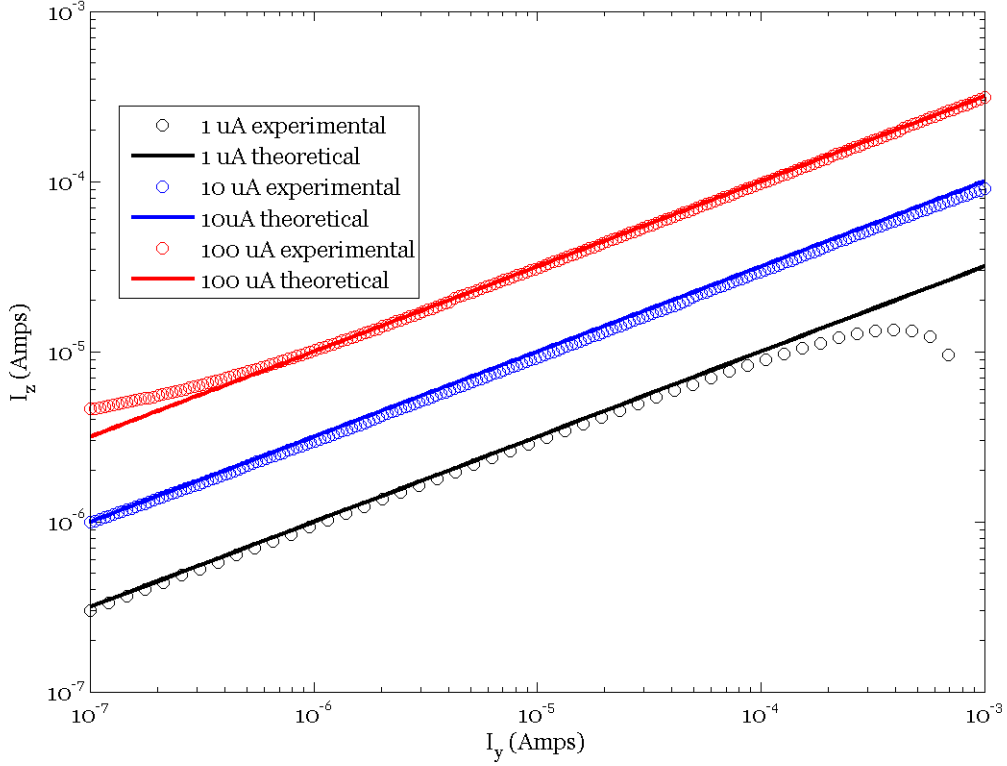


Figure 8: Translinear circuit 1, holding  $I_x$  at the values shown in the legend.

### Error Analysis

This circuit behaved well for almost all  $I_x$  for all except one transistor. However, with a high  $I_y$  we found that our circuit produced a very strange  $I_z$  at high current. We think we might have actually damaged a transistor during that measurement, possibly from pushing too much current through, because we were unable to take another measurement with a higher data rate without the output current becoming completely unstable.

### Translinear Circuit 2

We then repeated the experiments with a slightly different circuit, shown in Figure 9.

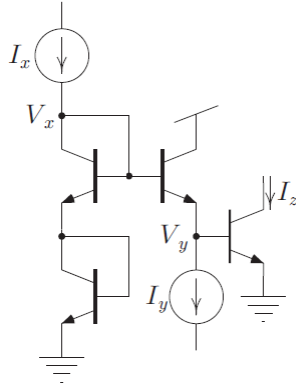


Figure 9: Translinear circuit 2.

As we did before, we used one channel of the SMU to sweep one of the currents in the circuit while holding the other current constant using current source or sink we built.

## Configuration 1

In the first configuration, we held  $I_y$  constant with our hand-built current sink and swept  $I_x$  with the SMU.

### The Current Sink

This current sink was almost identical from the current sink we used in Translinear Circuit 1, but we desired a slightly different range of currents to make the transistors behave over three decades. We used the same voltage divider to generate .1 V, but used a 200 k $\Omega$  resistor to generate 500 nA; for 5 uA, 20 k $\Omega$ ; for 50 uA, 2 k $\Omega$ .

### Measurement

From the prelab, we expect this circuit to follow  $I_x^2 = I_z I_y$ . As a result, holding  $I_y$  constant should yield  $I_z = \frac{I_x^2}{I_y}$ , which means that  $I_z$  will increase linearly on a log-log scale as we sweep  $I_x$ . Our results are in Figure 10.



## Translinear Circuit 2, Sweeping $I_x$

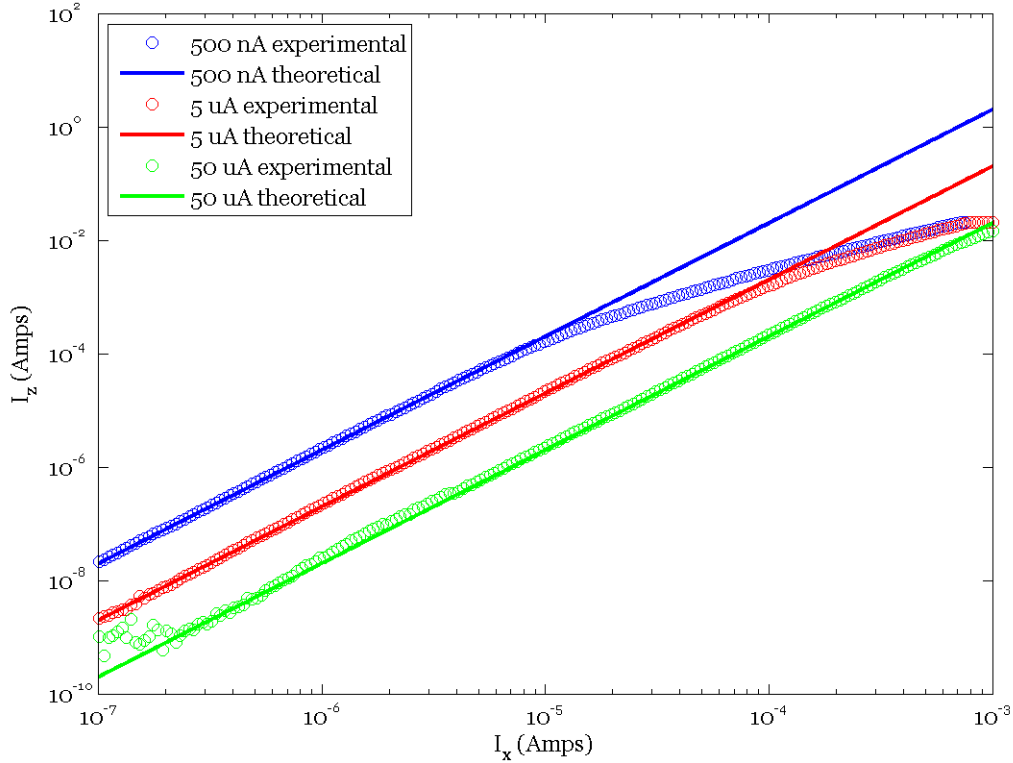


Figure 10: Translinear circuit 2, holding  $I_y$  at the values shown in the legend.

We swept over a high dynamic range (five orders of magnitude) and found that the data matched the theoretical expectation very well for the majority of the range of our input current values.

### Error Analysis

We found that decreasing  $I_y$  caused the current to increase more slowly as we increased  $I_x$ , and that this effect seems to depend, on first glance, on  $I_y$ . There are many possible explanations for this error. We could chalk it up to the SMU, however the SMU would most likely create ugly, noisy data (like in the small-current region of the 50 uA measurement, which is almost certainly a SMU issue). This error is continuous and smooth, so is probably a circuit characteristic.

Another explanation is that our chosen current sink voltage is too low, and thus the current sink is not pulling enough current, however our choice of voltage should have protected us from any possible voltage that this circuit could produce.

Another explanation is a compounding Early effect. This would involve some or all of the transistors having an Early effect that adds up, causing the translinear property to hold a little less well. This might be reasonable.

However, we can get a deeper understanding by looking critically at the data itself. Though it seems that the effect is  $I_y$  dependent, on closer inspection, all of the data appears to flatten into a particular line when it intersects that line. It turns out that that line has slope 1, as seen in Figure 11.

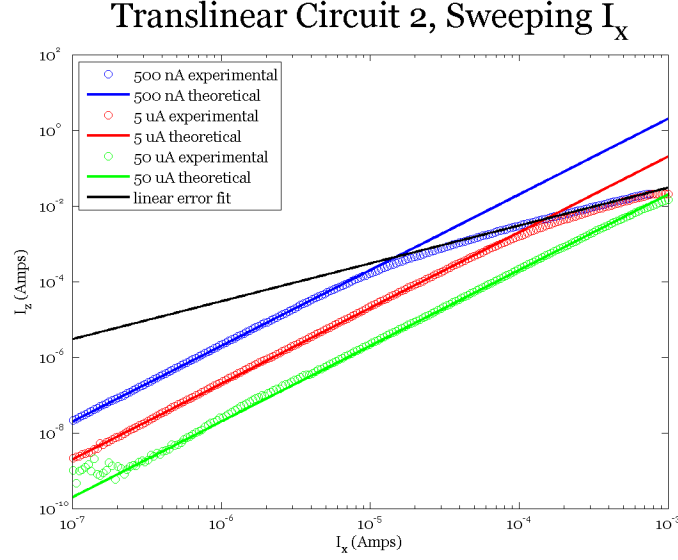


Figure 11: Translinear circuit 2, with a best-fit line plotted on the error region.

In the log-log plot, this best-fit line has a slope of 1, meaning that is just a shifted version of  $I_x$ . This means that the output current,  $I_z$ , no longer has a squared relationship with  $I_x$  but rather a linear one. This is interesting, but still confusing. It may be that our transistors are not perfectly matched and have trouble squaring the current after the output needs to be higher than the input.

## Configuration 2

We then switched our circuit around such that our current source was holding  $I_x$  constant and the SMU swept  $I_y$  over a high dynamic range. Again, we expect  $I_z = \frac{I_x^2}{I_y}$ , which means that  $I_z$  should decrease linearly on a log-log scale as we sweep  $I_y$ .

## The Current Source

We used a similar current source to the one that we used in Translinear Circuit 1. However, we swept over a slightly tighter dynamic range (about one and a half orders of magnitude). To generate 22 uA, we used a 90 k $\Omega$  resistor; for 10 uA, 200 k $\Omega$ ; and for 100 uA, 20 k $\Omega$ .

## Measurement

Our results can be seen in Figure 12.

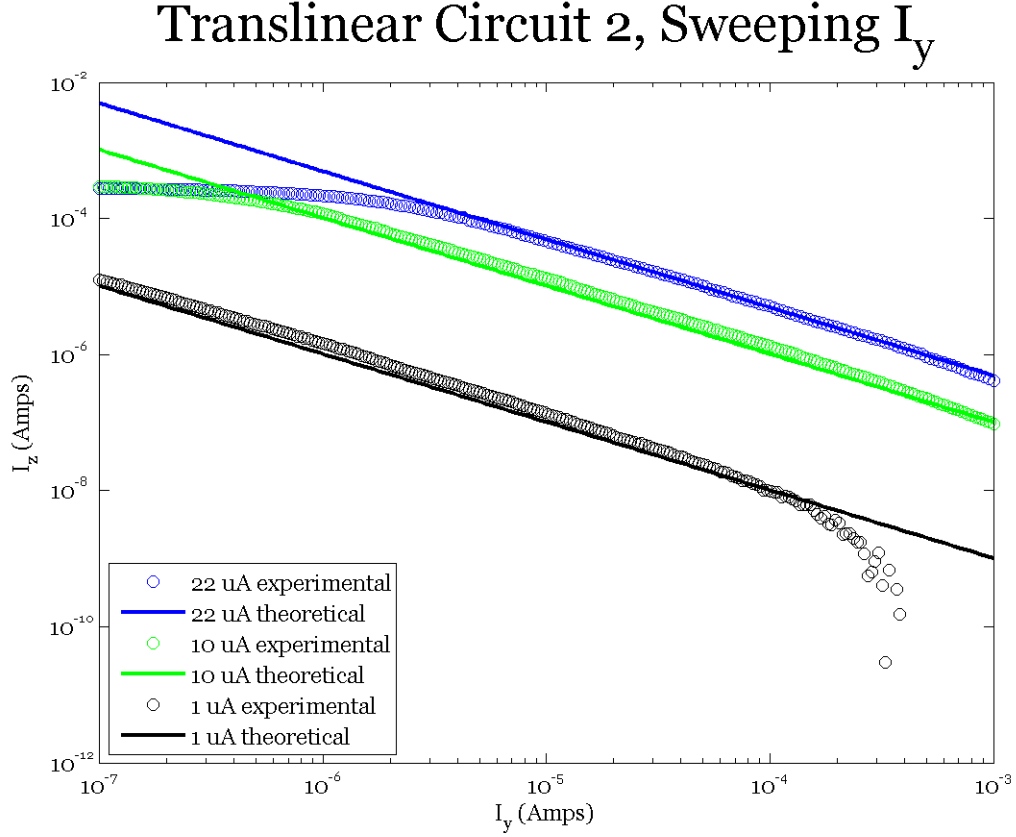


Figure 12: Translinear circuit 2, holding  $I_x$  at the values shown in the legend.

### Error Analysis

This was our worst-behaved configuration. We found that if we increased  $I_x$  above 20 uA,  $I_z$  was dominated by the non-linear region we discussed at length in configuration 1. If we decreased  $I_x$  to less than 100 uA, we found that  $I_z$  was very noisy for large input values, which we believe is SMU noise: the measured currents are very low, in the tens of nanoamps, and this is difficult to measure. As a result, we only measured  $I_y$  for  $I_x$  at values of 22 uA, 10 uA, and 100 uA because these produced a reasonable response over a reasonable range of currents.