

Summary

Lab 11 measured the DC resistance of eight copper traces (5, 10, 20 and 100 mil wide, 1 in and 2 in long) four ways: a sheet resistance estimate, a 2-wire DMM measurement, a 2-wire measurement with the leads nulled, and a 4-wire measurement at 1 A. The 2-wire readings were dominated by about $180\text{ m}\Omega$ of lead and contact resistance, so they were 2 to 40 times the real trace resistance. Nulling the leads helped, but the leftover contact resistance (up to about $85\text{ m}\Omega$) was still as large as the narrow traces themselves. The 4-wire method removed the leads and contacts from the measurement entirely. For the 5, 10 and 20 mil traces the 4-wire results were consistently 16 % below the $0.5\text{ m}\Omega/\text{sq}$ estimate, which corresponds to a measured sheet resistance of $0.41\text{ m}\Omega/\text{sq}$ and a copper thickness of about 1.6 mil. Lab 12 forced increasing current through the 5 mil trace. It became noticeably warm at 1.4 A, hot to the touch at 3 A, and began to smoke at 5 A. The IPC-2221 limit for this trace is about 1 A for a 40°C rise, so IPC is conservative for a short, heat sunk trace, and I would keep a 5 mil, 1 oz trace at or below 1 A.

1 Test Board and Plan

1.1 The test board

The test board (Figure 1a) is the bottom half of the assembly practice board: a two layer board with four test lines on each side of a wide central bus bar. The left lines are 2 in long and the right lines are 1 in long, with widths of 5, 10, 20 and 100 mil. Each line runs from a 2 pin header at the board edge into the 700 mil wide center bus, which has its own header at the bottom. Every measurement in both labs is therefore from an edge header, through the line, into the bus, and out the bus header. I confirmed this connectivity with the DMM continuity mode before measuring. Nine 2 pin headers were soldered on (Figure 1b) so the high current clips do not melt the mini grabbers. (The silkscreen labels all four right side lines “100 mils, 1in Long”; the widths can be seen from the copper.)

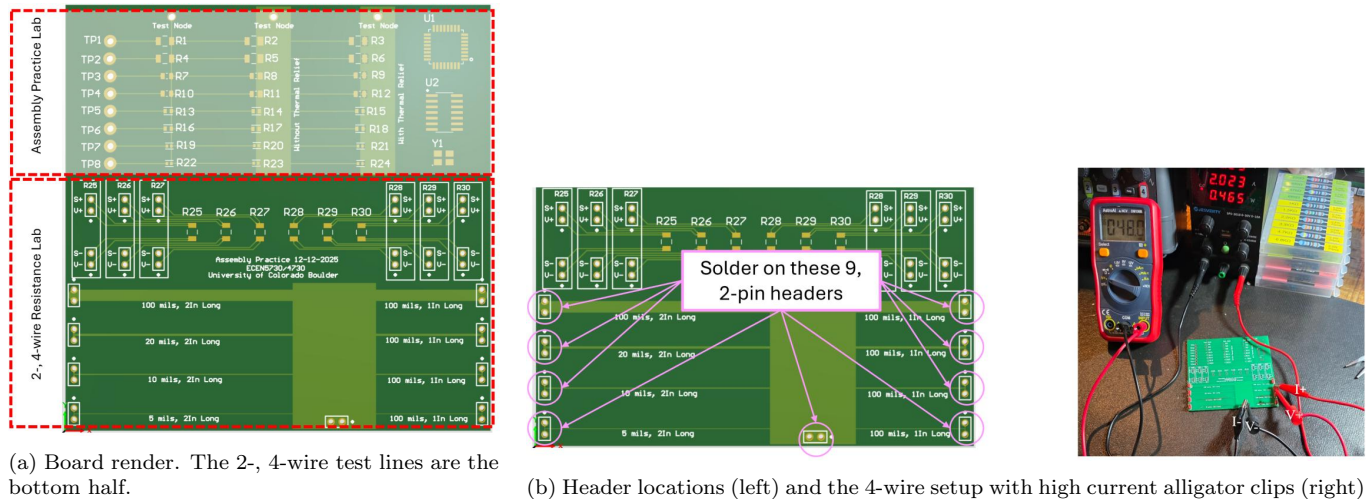


Figure 1: The trace resistance test board and measurement setup (images from the lab manual).

1.2 What a successful lab looks like

Following Rule #9, I wrote down what I expected before measuring:

- E1. Each line's resistance is (number of squares) $\times$ (sheet resistance), with about $0.5\text{ m}\Omega/\text{sq}$ for 1 oz copper.
- E2. The 2 in line is twice the 1 in line of the same width, and halving the width doubles the resistance.
- E3. A 2-wire DMM reading includes the leads and contacts (on the order of $0.1\text{ }\Omega$ to $0.2\text{ }\Omega$), so it will read high for every line.

- E4. A 4-wire reading at 1 A agrees with the estimate, because no current flows in the voltage sense leads.
- E5. In Lab 12 the 5 mil trace gets warm near the IPC-2221 current for a 10 °C to 20 °C rise, and fails at a current several times larger.

2 Lab 11: Trace Resistance

2.1 Exp 2: Estimating resistance by counting squares

1 oz copper is 1.37 mil (35 μm) thick. With $\rho_{Cu} = 1.72 \mu\Omega \cdot \text{cm}$ the sheet resistance is

$$R_{sq} = \frac{\rho}{t} = \frac{1.72 \times 10^{-8} \Omega \cdot \text{m}}{35 \times 10^{-6} \text{ m}} \approx 0.5 \text{ m}\Omega/\text{sq}.$$

A trace of length L and width w has L/w squares, so a 1 in (1000 mil) long, 5 mil wide line has 200 squares and $200 \times 0.5 \text{ m}\Omega = 100 \text{ m}\Omega$. Table 1 lists every line.

Length	Width	Squares	R_{sq}	Estimate
1 in	5 mil	200	0.5 m Ω	100 m Ω
	10 mil	100	0.5 m Ω	50 m Ω
	20 mil	50	0.5 m Ω	25 m Ω
	100 mil	10	0.5 m Ω	5 m Ω
2 in	5 mil	400	0.5 m Ω	200 m Ω
	10 mil	200	0.5 m Ω	100 m Ω
	20 mil	100	0.5 m Ω	50 m Ω
	100 mil	20	0.5 m Ω	10 m Ω

Table 1: Resistance estimates made before any measurement.

The center bus is in series with every line. In the worst case about 1.5 in of the 700 mil wide bus is in the path, which is about 2 squares or 1 m Ω . That is negligible for every line except possibly the 100 mil lines.

2.2 Exp 3: 2-wire measurement, with and without null

Figure 2 shows the 2-wire connection: the bench DMM forces a small test current through its own leads and the trace and measures the voltage at its own terminals. Everything in series is included: the two leads, the two probe to header contacts, the headers, and the trace.

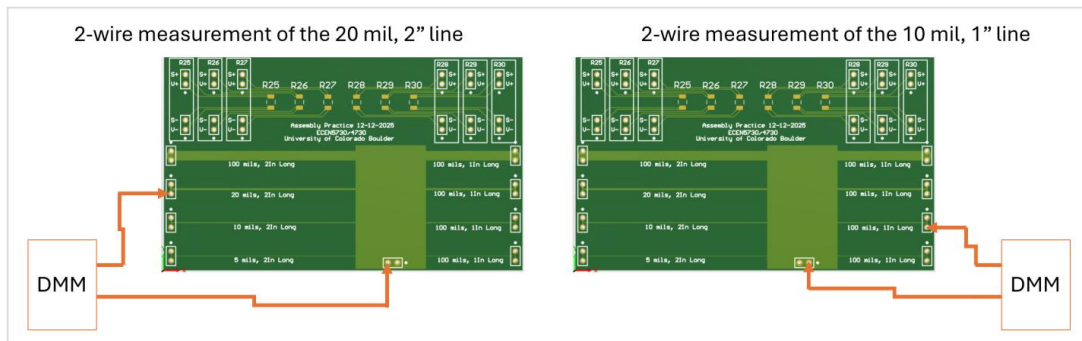


Figure 2: 2-wire measurement path from an edge header to the bus header (image from the lab manual).

Without nulling, every line read 180 m Ω to 400 m Ω (Table 2). The 100 mil, 1 in line read 220 m Ω even though it should be about 5 m Ω , and the 100 mil, 2 in line read lower than the 1 in one. The readings do not follow the expected trends at all. Subtracting the 4-wire value from each reading gives the series offset: 154 m Ω to 235 m Ω , average 182 m Ω . This matches the roughly 0.15 Ω of the test leads plus a few tens of m Ω of contact resistance.

Shorting the leads together and pressing Null removes the lead resistance. The nulled readings moved much closer to the estimates, and the 20 mil lines (50 m Ω for both lengths) and the 10 mil, 2 in line (100 m Ω) agree with the 4-wire values to within 20 m Ω . The rest are still off by 4 m Ω to 85 m Ω : the 100 mil, 1 in line read 70 m Ω , eight times its 4-wire value. The null only removes the lead resistance at the moment the leads were shorted. The contact resistance

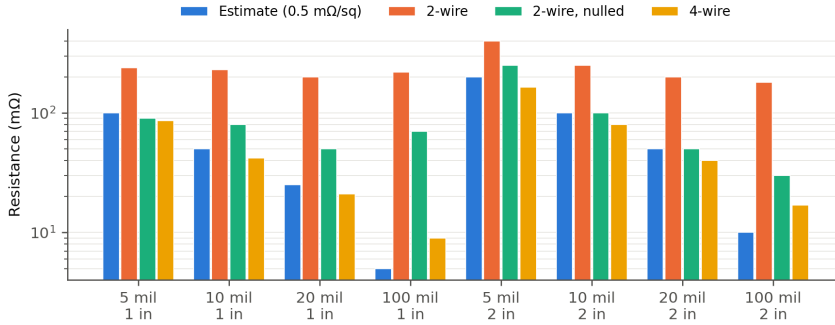
between the probe tips and the header pins changes each time the probes are placed, depending on pressure, angle and oxide, and it is tens of $\text{m}\Omega$. The DMM's resolution on its lowest range is also about $10\text{ m}\Omega$. Both of these are the same size as the traces being measured, so 2-wire is not usable for resistances under about $100\text{ m}\Omega$, even nulled.

2.3 Exp 4: 4-wire measurement

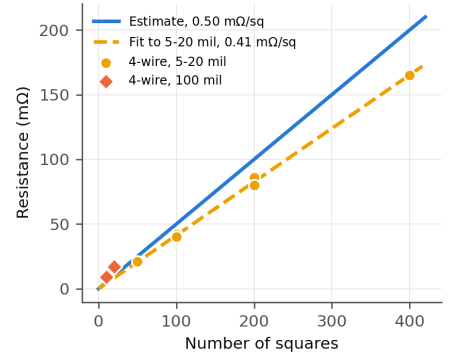
For the 4-wire measurement the power supply, in constant current mode, forced 1 A from the edge header, through the line and the bus, and out the bus header using the high current clips. A separate pair of leads from the AstroAI DMM measured the voltage at the second pin of the same two headers. Because the DMM input draws essentially no current, there is no voltage drop in the sense leads or their contacts, and the measured voltage is only the drop across the copper between the two sense points. With $I = 1\text{ A}$, the voltage in mV reads directly as resistance in $\text{m}\Omega$.

			2-wire (bench DMM)		4-wire		
Length	Width	Estimate	Not nulled	Nulled	V	I	$R = V/I$
Equipment cost		Free	\$1000	\$1000	AstroAI DMM	\$22 + supply	\$2400
1 in	5 mil	100 mΩ	240 mΩ	90 mΩ	86 mV	1 A	86 mΩ
	10 mil	50 mΩ	230 mΩ	80 mΩ	42 mV	1 A	42 mΩ
	20 mil	25 mΩ	200 mΩ	50 mΩ	21 mV	1 A	21 mΩ
	100 mil	5 mΩ	220 mΩ	70 mΩ	9 mV	1 A	9 mΩ
2 in	5 mil	200 mΩ	400 mΩ	250 mΩ	165 mV	1 A	165 mΩ
	10 mil	100 mΩ	250 mΩ	100 mΩ	80 mV	1 A	80 mΩ
	20 mil	50 mΩ	200 mΩ	50 mΩ	40 mV	1 A	40 mΩ
	100 mil	10 mΩ	180 mΩ	30 mΩ	17 mV	1 A	17 mΩ

Table 2: All Lab 11 results. The \$22 DMM in a 4-wire setup is far more accurate here than the \$1000 bench DMM in a 2-wire setup.



(a) All four methods for each line (log scale).



(b) 4-wire resistance vs. squares.

Figure 3: Lab 11 results. The 2-wire bars are nearly flat across lines because the lead and contact resistance dominates; the 4-wire bars follow the estimate.

The 4-wire results follow every expected trend (Figure 3a): halving the width doubles the resistance, and the 2 in lines are 1.89 to 1.92 times the 1 in lines at all four widths. Figure 3b plots resistance against the number of squares. The 5, 10 and 20 mil lines all fall on a straight line through zero.

2.4 Interpreting the results

The narrow lines are 16 % below the estimate. The 4-wire to estimate ratio is 0.86, 0.84, 0.84 for the 1 in lines and 0.82, 0.80, 0.80 for the 2 in lines. A least squares fit through the six narrow lines gives

$$R_{sq, meas} = 0.41\text{ m}\Omega/\text{sq} \Rightarrow t = \frac{\rho}{R_{sq}} = \frac{1.72 \times 10^{-8}\text{ }\Omega \cdot \text{m}}{0.41 \times 10^{-3}\text{ }\Omega} \approx 42\text{ }\mu\text{m} = 1.6\text{ mil.}$$

The ratio is the same for 5, 10 and 20 mil. If the error came from the etched width (for example, every trace etched 1 mil wider than drawn) the 5 mil line would be off by 20 % and the 20 mil line by only 5 %. A constant ratio instead

points to a property shared by all the lines, which is the copper thickness. On a two layer board the outer layers are plated up during via plating, so a nominal 1 oz layer finishing at about 1.6 mil is reasonable. The 2 in to 1 in ratio of 1.9 rather than 2.0 is also the same at every width, so it is most likely the drawn lengths (where each line meets the pad and the bus) rather than contact resistance, which would not scale with $1/w$.

The 100 mil lines are about 1.8 times the estimate. They measured $9\text{ m}\Omega$ and $17\text{ m}\Omega$ against estimates of $5\text{ m}\Omega$ and $10\text{ m}\Omega$. Part of this is resolution: the AstroAI reads 9 mV with 1 mV resolution, an uncertainty of $\pm 11\%$. The center bus adds up to about $1\text{ m}\Omega$, and the current spreading from the narrow header pad into a 100 mil line adds a little more. These are only important when the trace itself is a few $\text{m}\Omega$. The excess still grows with length (about $4\text{ m}\Omega$ on the 1 in line and $8\text{ m}\Omega$ on the 2 in line), so it is not fully explained by fixed contact or pad resistance. Measuring the actual copper width under a microscope and moving the sense clips onto the ends of the copper itself would be the next step to resolve it.

Which method to use.

- **Most accurate:** 4-wire. It is the only method whose result follows the expected geometry for every line.
- **Most cost effective:** the estimate. It is free, takes seconds, and is within 20 % for any trace narrower than about 20 mil. That is accurate enough for nearly every design decision (IR drop, power loss, current sense layout).
- **When the estimate is not enough:** very low resistances (wide traces, planes, busbars) where pads, vias and spreading matter, and any time the copper thickness is uncertain.
- **2-wire:** only for resistances well above about $1\text{ }\Omega$, where $0.2\text{ }\Omega$ of leads and contacts is small.

3 Lab 12: Blowing Up Traces

3.1 Exp 1: IPC-2221 estimate

Before applying any current, I estimated the maximum current with the IPC-2221 external layer formula, which is the default model in the Saturn PCB Toolkit:

$$I = 0.048 \Delta T^{0.44} A^{0.725},$$

with I in amps, ΔT in $^{\circ}\text{C}$ and the cross section A in mil^2 . For 1 oz copper $A = w \times 1.378\text{ mil}$.

Width	A (mil^2)	$\Delta T = 10^{\circ}\text{C}$	$\Delta T = 20^{\circ}\text{C}$	$\Delta T = 40^{\circ}\text{C}$
5 mil	6.9	0.54 A	0.73 A	0.99 A
6 mil	8.3	0.61 A	0.83 A	1.13 A
10 mil	13.8	0.89 A	1.20 A	1.63 A
20 mil	27.6	1.46 A	1.99 A	2.69 A

Table 3: IPC-2221 maximum current for 1 oz external traces.

From Table 3 I expected the 5 mil trace to feel warm (a rise of roughly 15°C to 20°C) somewhere around 0.7 A, and to pass the 40°C rise limit near 1 A.

3.2 Exp 2: Setup

The setup is the same 4-wire connection used in Lab 11 (Figure 1b). The supply was set to constant current mode with a 1 A limit and the voltage set point a few volts, enough for the supply to stay in constant current mode. The current flows from the supply through the high current clip, the edge header, the 5 mil line, the 700 mil bus, the bus header, and back. The current is the same everywhere in this series path, but the current density is not: the 5 mil line has by far the smallest cross section, so nearly all of the I^2R heating happens there. The DMM sense leads on the second header pins measured the voltage across the line throughout, so the line resistance could be watched while it heated. With safety glasses on, I raised the current set point in steps, touching the trace between steps, and shut the supply off as soon as the trace began to smoke.

Observation	Current	Power per inch ($I^2 R'$, 25 °C)	IPC-2221 ΔT at this current
Noticeably warm	1.4 A	0.17 W/in	about 90 °C
Hot to the touch	3 A	0.77 W/in	about 500 °C
Smoking	5 A	2.2 W/in	over 1000 °C

Table 4: 5 mil trace under constant current. $R' = 86 \text{ m}\Omega/\text{in}$ is the room temperature 4-wire value from Lab 11. The last column inverts the IPC-2221 formula; values this far outside its range only show how conservative it is.

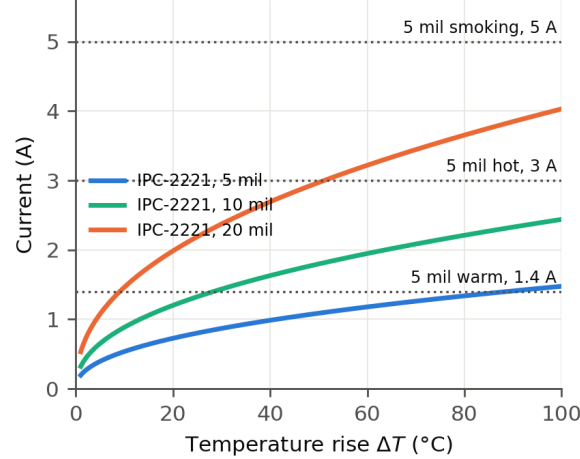


Figure 4: IPC-2221 current vs. temperature rise for 1 oz traces, with the three observed currents for the 5 mil trace. All three are above the IPC curve for any rise up to 100 °C.

3.3 Results

The 5 mil trace was noticeably warm at 1.4 A, hot to the touch at 3 A, and began to smoke at 5 A (Table 4). Power per unit length is used because it does not depend on which length of line was tested: the heat generated in each inch of line is $I^2 R'$, and each inch loses heat to the board and air at about the same rate.

The trace survives far more current than IPC-2221 predicts. IPC-2221 says a 5 mil line reaches a 40 °C rise at 1 A. A 40 °C rise (about 65 °C) would feel hot, but the trace only felt warm at 1.4 A and did not feel hot until 3 A, roughly three times the IPC current (Figure 4). There are three reasons:

1. IPC-2221 is based on decades old data for long, isolated traces and is intentionally conservative.
2. This line is short and both of its ends are attached to large thermal masses (the header, the alligator clip and cable at one end, the 700 mil bus and its header at the other). Much of the heat flows out the ends instead of into the FR4. The newer IPC-2152 standard accounts for this kind of heat spreading and allows more current.
3. The copper is about 1.6 mil thick (Lab 11), not 1.37 mil, so the line has about 16 % less resistance and heating than assumed.

Rising voltage at constant current and thermal runaway. In constant current mode the supply holds I fixed, so any change in the voltage across the line is a change in its resistance. Copper's TCR is about 0.4 %/°C, so a 40 °C rise increases the resistance by about 16 %, and a 250 °C rise (where the solder mask and FR4 begin to decompose and smoke) roughly doubles it. This is a positive feedback loop: hotter copper has higher resistance, so at the same current it dissipates more power, which makes it hotter still. At 5 A the dissipation is at least 2.2 W/in at room temperature and around 4 W/in once the resistance has doubled, which is more than the line can conduct away, so the temperature runs away until the board smokes.

3.4 Recommended maximum current

I would stay at the IPC-2221 40 °C values even though the test trace tolerated more (Table 5). At 1 A the 5 mil trace was not even warm to the touch, which leaves margin for a real board where the trace may be long, far from any heat sink, next to other hot parts, or in a hot enclosure. That margin is a factor of 5 below the smoking point and a factor

Width (1 oz, outer layer)	IPC-2221, $\Delta T = 40^\circ\text{C}$	Measured	Recommended max
5 mil	0.99 A	warm 1.4 A, hot 3 A, smoke 5 A	1 A
10 mil	1.63 A	not tested	1.5 A

Table 5: Recommended maximum continuous current per trace.

of 3 below hot. The 10 mil recommendation is based on the same IPC margin; the measured behavior of the 5 mil line suggests it would also survive well above its IPC value.

4 Analysis

4.1 What worked and what I will keep doing

- **Estimating before measuring.** Having the square counting estimate written down first made it obvious that the 2-wire readings were wrong (220 m Ω for a 5 m Ω line) instead of accepting them.
- **4-wire for anything under an ohm.** A \$22 DMM in a 4-wire setup gave better results than a \$1000 bench DMM in a 2-wire setup. The quality of the measurement setup mattered more than the cost of the instrument.
- **Constant current mode with a low limit.** Setting the supply to 1 A before connecting, then raising it slowly, kept the test controlled until the trace failed.
- **Looking for patterns across all the data.** The constant 16 % offset at every width is what pointed to copper thickness rather than etching or contact resistance.

4.2 Takeaways for future boards

1. Use $R = (L/w) \times 0.5 \text{ m}\Omega/\text{sq}$ for 1 oz copper. It is within 20 % of the measured value, and the real board was slightly better than the estimate.
2. Never trust a 2-wire reading under about 1 Ω . Lead and contact resistance add about 0.2 Ω , and nulling does not remove the contact variation.
3. Design for the IPC-2221 40 $^\circ\text{C}$ current (about 1 A for a 5 mil trace and 1.6 A for a 10 mil trace in 1 oz copper). It is conservative, and the extra margin against thermal runaway is worth it.
4. On boards with high current paths, add Kelvin sense pads so the trace resistance and the current can be measured with the 4-wire method.