Frequency Response Properties of the Silicon Vertex Detector for BaBar

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Contents

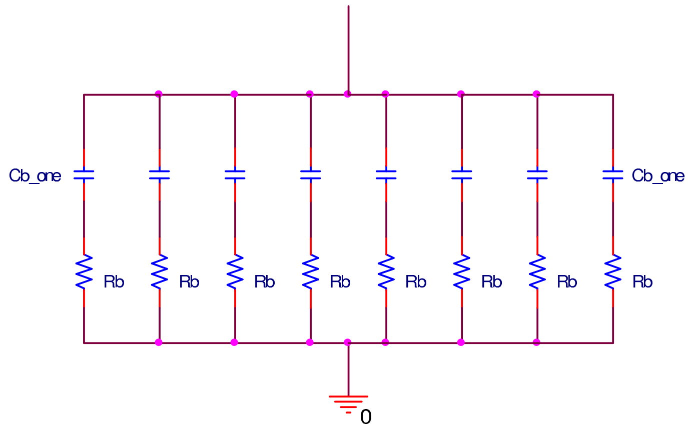

Figure 1: The capacitances and resistances to the backplane, which can be simplified to a single resistance and capacitance

1 Introduction

We attempt to model the frequency response of the silicon vertex detector for BaBar with a network of capacitors and resistors using PSPICE and compare to measurements. Specifically we measure the impedances and phases of a 1B3 part which is a Layer 1 backward part. The important capacitances and resistances are the capacitances between the AC metal strip and the implant C_{AC}, the bias resistance R_b, the bulk capacitance from one strip to a single strip on the backplane C_{b_one}, and the interstrip capacitance between implants C_{is}. In addition, each strip also sees an effective resistance to ground after going through C_{b_one} to the backplane. If n is the number of strips, then each strip sees n C_{b_one} capacitors and n R_b resistors in series (see Fig. 1). The equivalent circuit for this is a single capacitor with value nC_{b_one} in series with a resistor with value R_b/n. From now on, we will define $C_b \equiv nC_{b\_one}$ while still referring to the resistance as R_b/n.

We study the frequency response of the detector with an LCR probe between the AC metal strip and the implant for frequencies between about 10 Hz and 1 MHz with an amplitude of 1V for the input frequency. For actual measurements, there are many parasitic elements between the probe and the detectors, such as those of the relay boards. We will see that the data does not agree very well with the SPICE simulations, although there are some ways of compensating for the parasitic elements.

The values we use for the detector are

$$\begin{array}{rcc} C_{AC} & = & 24 \text{ pF/cm for the n-side} \\ C_{AC} & = & 46 \text{ pF/cm for the p-side} \\ R_b & = & 5 \text{ M}\Omega \\ Cb & = & 0.17 \text{ pF/cm} \\ C_{is} & = & 1.05 \text{ pF/cm} \\ n & = & 798 \text{ total strips on two wafers} \end{array} \tag{1}$$

Each wafer is 4 cm by 4 cm and there are two wafers placed side by side. On the p-side, there are n strips on each wafer running along the short side. On the n-side, the strips run along the long side and so there are n strips on each wafer that are linked by AC metal strips that are connected between wafers. Both sides still end up seeing C_b and Rb/n to the backplane assuming that the interaction between strips on different wafers is negligible. So on each side, we multiply by 4cm to get the total values. The values we get for the p-side are

$$\begin{array}{rcc} C_{AC} & = & 184 \text{ pF} \\ R_b & = & 5 \text{ M}\Omega \\ Cb & = & 0.68 \text{ pF} \\ C_{is} & = & 4.2 \text{ pF} \end{array} \tag{2}$$

while the values for the n-side are

$$\begin{array}{rcc} C_{AC} & = & 96 \text{ pF} \\ R_b & = & 5 \text{ M}\Omega \\ Cb & = & 0.68 \text{ pF} \\ C_{is} & = & 4.2 \text{ pF} \end{array} \tag{3}$$

2 p-side of the Detector

The p-side is simpler so we will look at models for that side first. The simplest model ignores C_{is}, which effectively ignores adjacent strips. This simple model is shown in Fig. 2. The R_{big} resistor represents the leakage to the other side of the detector. However, it is really there because SPICE gives an error if it's not there for some unknown reason.

The frequency response of the simple circuit given by SPICE is plotted with the measured data of strip 120 on the p-side of the 1B3 part with full bias voltage of 40V as shown Fig. 3. The simulation does not match well

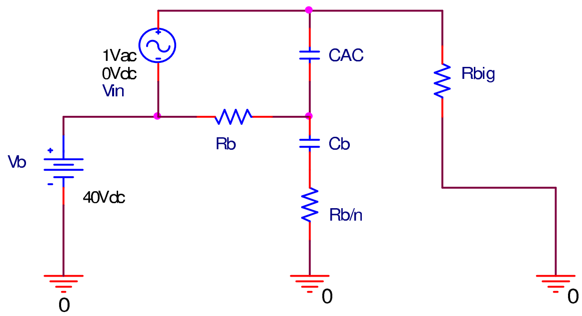

Figure 2: Simple model ignoring adjacent strips

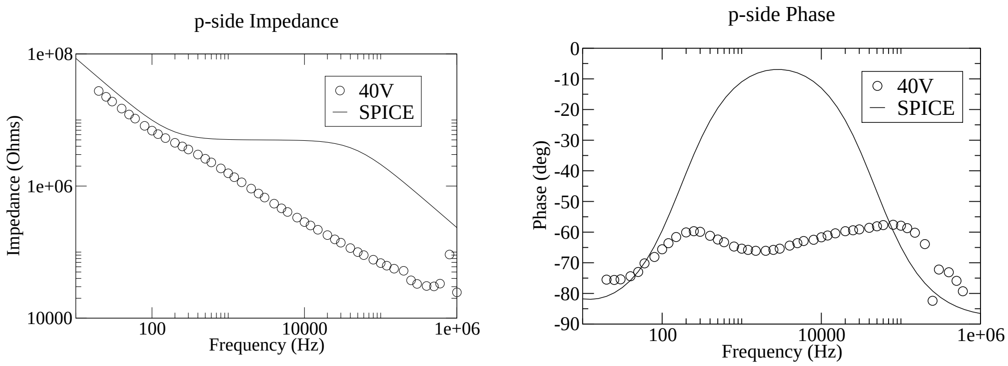

Figure 3: Simulation of the simple model vs. measurements on a normal strip

with the data. However, we can see the important features of the model. The initial downward slope is due to C_{AC}. When the magnitude of the impedance of C_{AC} given by $|1/\omega C_{AC}|$ equals R_b, the bias resistor begins to dominate and we see the flat region. When R_b equals $|1/\omega C_b|$, then the impedance starts to turn downwards again. At very high frequencies beyond 1 MHz and off the plot, we see another flat region where R_b/n dominates. A few things to note about the plot are that there is some sort of interference, perhaps a radio station, at 800kHz and 250kHz and possibly the regions around those frequencies.

At this point, there are two things that we can do. The first is to assume that the parasitic elements due to the probe station is in parallel with the model and try to extract the data that is just the detector. The assumption that the parasitics are in parallel with the detector is a bad one at higher frequencies when the interstrip capacitances come into effect and we no longer have a parallel model. The second thing to try is to model the raw data by adding parasitic elements to the simple SPICE model that we have. Of course none of this has taken into account the adjacent strips yet.

First, we will take a look at modeling the raw data by adding extra elements into the original simple model. We put a capacitor in series with an element consisting of a resistor in parallel with a series RC (see Fig. 4). The values of C_1, C_2, R_1, and R_2 are arbitrary and chosen to fit the data (see Fig. 5). It is not known at this point whether this model is meaningful in any way, and it fails at high frequencies. The values for the

$$\begin{aligned} C_1 &= 90 \text{ pF} \\ C_2 &= 50 \text{ pF} \\ R_1 &= 250 \text{ k}\Omega \\ R_2 &= 60 \text{ k}\Omega \end{aligned} \tag{4}$$

Other values can fit the phase data better at frequencies around 1MHz, but fit the impedance worse. For example the values

$$\begin{aligned} C_1 &= 90 \text{ pF} \\ C_2 &= 20 \text{ pF} \\ R_1 &= 110 \text{ k}\Omega \\ R_2 &= 5 \text{ k}\Omega \end{aligned} \tag{5}$$

are plotted as well in Fig. 6. Also of note is that R_b/n and C_b can be removed with little change in the plot. The parasitic element dominates over the coupling to the backplane.

Now we take a look at a circuit that only includes the parasitic part (see Fig. 7). This SPICE model is compared with the data of a plucked strip 108 on the p-side of the 1B3 part at 40V bias (see Fig. 8 and 9). From this, we can see if the model of the parasitic elements matches the data on a plucked strip. The first plot is for the first set of values for C_1, C_2, R_1, and R_2 and the second plot is for the second set of values listed above.

The second thing to try is to assume that the parasitic element is in parallel with what is being measured. Let Z_T be the total impedance of a normal strip. If we measure the impedance Z_p of a strip that is plucked between the upilex and the wafers, then we can subtract out the effect of Z_p, the parasitics due to the probe and possibly the upilex. What we are then left with is Z_s, the impedance of the silicon detector. The extraction process

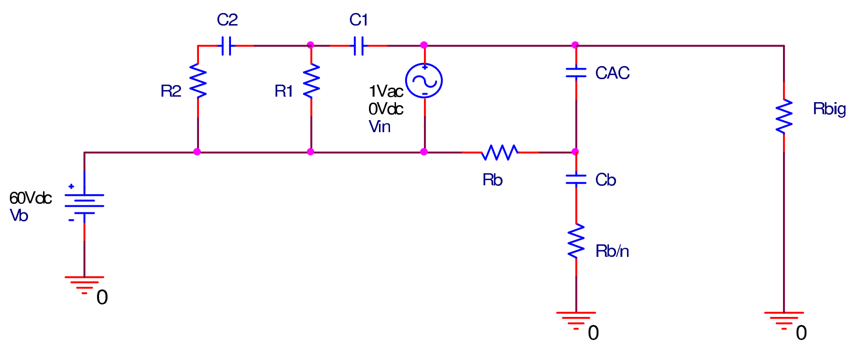

Figure 4: Model of one strip with additional parasitics

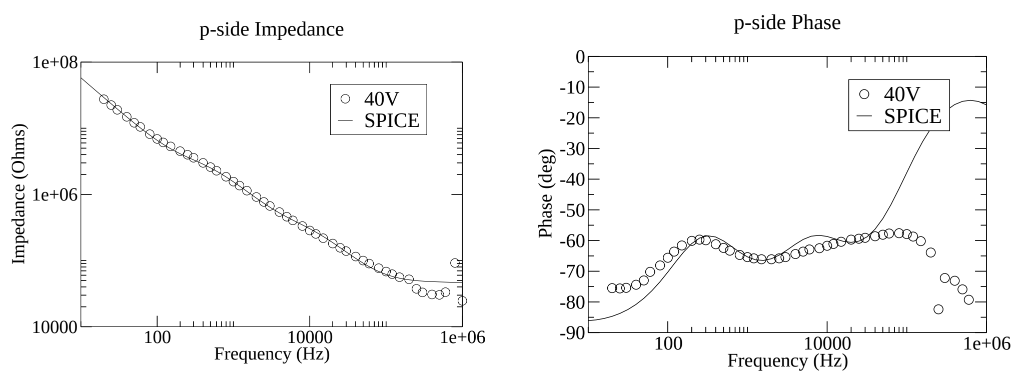

Figure 5: Simulation of a model with parasitic elements vs. measurements of a normal strip

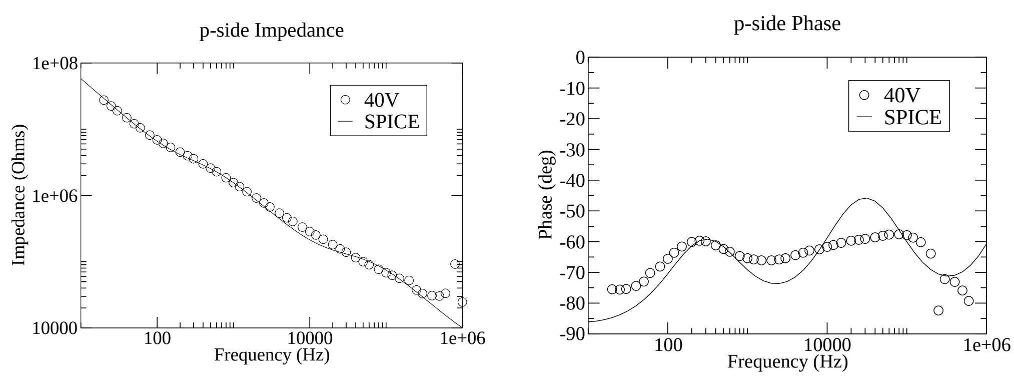

Figure 6: Simulation of a model with parasitic elements vs. measurements of a normal strip

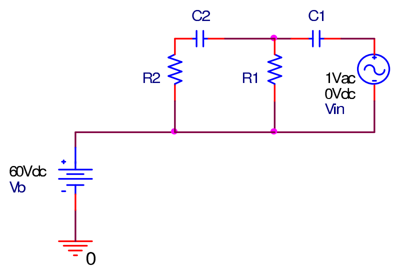

Figure 7: A plucked strip should only see this part of the circuit

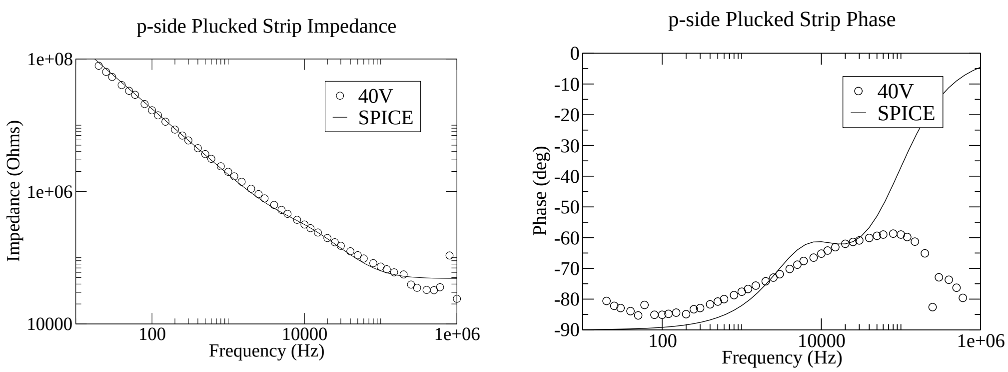

Figure 8: Simulation of the parasitic model vs. measurements of a plucked strip

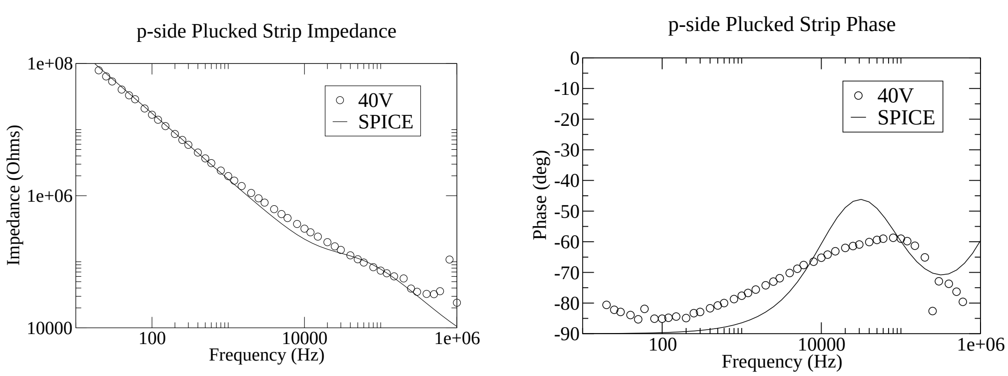

Figure 9: Simulation of the parasitic model vs. measurements of a plucked strip

works as follows. The total impedance is given by

$$\frac{1}{Z_T} = \frac{1}{Z_p} + \frac{1}{Z_s} \tag{6}$$

Let us define the following

$$\begin{aligned} Z_T &= |Z_T|\ e^{i\phi_T} && (7)\\ Z_p &= |Z_p|\ e^{i\phi_p} && (8)\\ Z_s &= |Z_s|\ e^{i\phi_s} && (9) \end{aligned}$$

so that

$$\frac{1}{|Z_s|} = \frac{1}{|Z_T|}\ e^{i(\phi_s-\phi_T)} - \frac{1}{|Z_p|}\ e^{i(\phi_s-\phi_p)} \tag{10}$$

Now we equate the real and imaginary parts to get

$$\frac{|Z_T|}{|Z_u|} = \frac{\sin\phi_s - \phi_T}{\sin\phi_s - \phi_p} \tag{11}$$

and

$$|Z_s| = \frac{1}{\frac{1}{|Z_T|}\ e^{i(\phi_s-\phi_T)} - \frac{1}{|Z_p|}\ e^{i(\phi_s-\phi_p)}} \tag{12}$$

The first equation, we can solve numerically for ϕ_s with Mathematica or Excel and plug into the second equation.

Now we can attempt to plot the data given by SPICE for the simple model (see Fig. 2), against this newly extracted data. The plots are shown in Fig. 10. We can see that at low frequencies, the extraction process works well. However, when the neighboring strips become important and C_{is} comes into play, we get a deviation from the model.

To go even further, we can add the neighboring strips into the model, as well as break up the strip itself into a series of capacitors and resistors. We put in the interstrip capacitances and in addition, we put in an implant resistance R_{impl}, which has a value of about 54 kΩ/cm which gives about $R_{impl} = 220k\Omega$, and a upilex interstrip capacitance C_u which is about 0.5 pF/cm giving a value of about 3pF.

At this point, we need to get into the details of how the probe works. The probe has 256 pins. 252 of them are all connected together and float. Of the four remaining, one is the test strip and the other three are floating. The

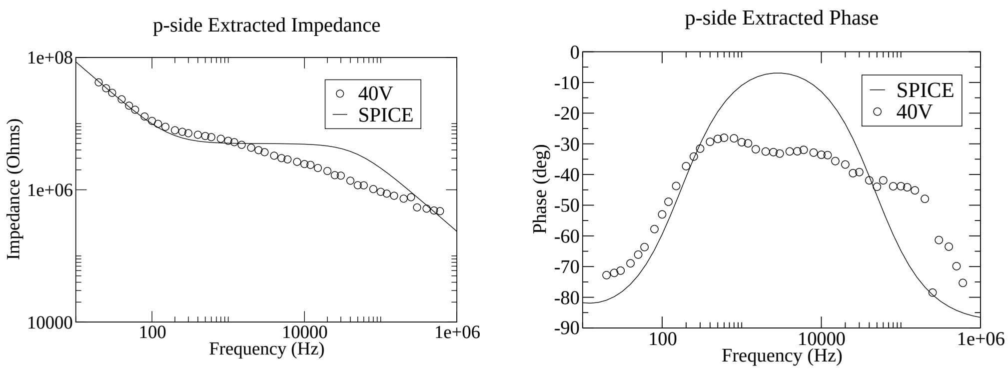

Figure 10: Simulation of the simple model vs. extracted data

test strip is always next to one floating strip on one side and two floating strips on the other side.

The only way to get anything close to the measured data is to include the parasitic elements shown previously in Fig. 7. We find that the impedance and phase no longer change after adding about 48 neighboring strips. We also find no change after dividing the strip up into four segments, each with their own interstrip and AC coupling capacitances. In this model, we have to alter the values that we used previously for C_1, C_2, R_1, and R_2 to get a good fit of the data. Also, a different value of C_u was used other than 3pF. This might have to do with the fact that there is also an interstrip capacitance between upilex strips that are 2 apart in addition to the nearest neighbor interstrip capacitance. Additionally, the value of R_{big} is important at very low frequencies. R_{big} actually represents the leakage to the backplane and to get a better fit around 50 Hz, we set that value as well. The values used to produce the plot in Fig. 11 are

$$\begin{aligned} C_1 &= 80 \text{ pF} \\ C_2 &= 30 \text{ pF} \\ R_1 &= 350 \text{ k}\Omega \\ R_2 &= 160 \text{ k}\Omega \\ C_u &= 10 \text{ pF} \\ R_{big} &= 150 \text{ M}\Omega \end{aligned} \tag{13}$$

Another parameter that we can vary is the bias voltage V_b. As the bias voltage drops, the capacitance to the backplane should increase as the charge carriers get closer to each other and the depletion region shrinks. The capac-

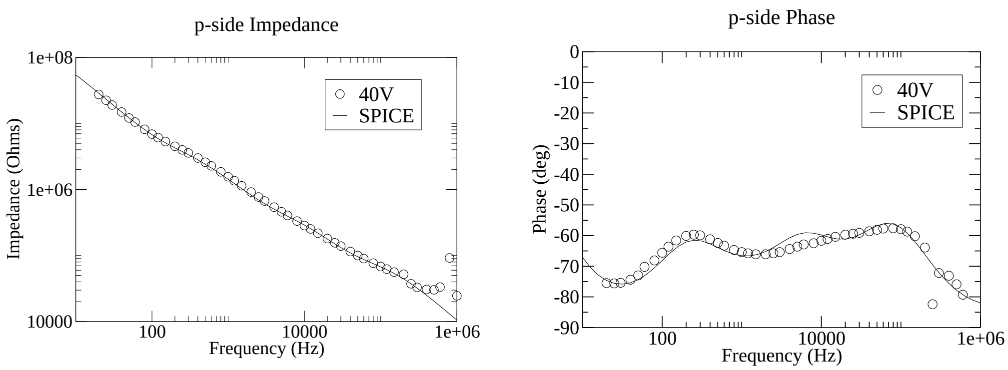

Figure 11: Simulation of a complicated network model vs. data

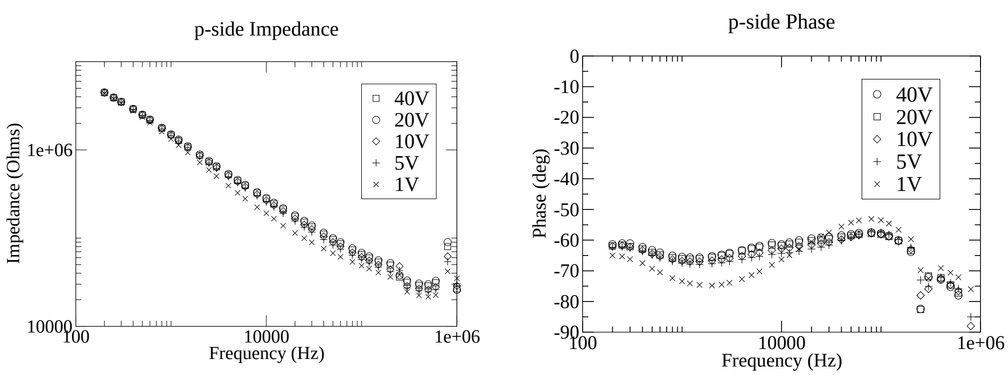

Figure 12: Impedance and phase for various bias voltages

itance C_b should be proportional to $\frac{1}{\sqrt{V_b}}$. The question is if this effect can be seen, and if we can quantitatively extract the value of C_b by taking measurements. One thing to be careful of is the amplitude of the input frequency. If it is comparable to the bias voltage, then we could see unwanted effects. So for this data, the bias voltage was at 100 mV. Because of noise, we begin taking data at 200 Hz rather than 20 Hz. We expect that C_b affects only higher frequencies and so this shouldn't be a problem. Fig. 12 is a plot of the impedance and phase at various bias voltages. We can see that there is some dependence on V_b for lower bias voltages. Now we pick fixed frequencies of 1kHz, 10kHz, and 100kHz and vary V_b (see Fig. 13). If C_b dominates at a certain frequency, then $|Z| \sim \frac{1}{\omega C_b}$. So if we plot $|Z|^2$ vs V_b, we should get a straight line since $C_b \propto \frac{1}{\sqrt{V_b}}$, or equivalently, $V_b \propto \frac{1}{C_b^2}$. The plots are shown in Fig. 14. There is a region for each of the plots where the behavior is somewhat linear. It is not know yet if this effect is completely due to C_b or if other capacitances such as C_{is} are also somehow varying and changing these values.

3 n-side of the Detector

We now switch to the n-side of the detector. Many of the measurements at a bias voltage of 40V are very similar to those of the p-side. This may be an indication that the parasitic elements in the probe dominate over anything we are trying to see in the detector itself. The n-side is different in several ways from the p-side. There are two wafers whose strips run along the length of the detector, compared to the p-side where the strips run along the width of the detector. The AC metal strips above are connected together and while each strip still has its own bias resistor. This means that when we measure the impedance between the AC metal and the bias line, we measure twice the C_{AC} since there are two strips connected together. In addition, we also see two R_b in parallel and so the resistance appears to be half that of the bias resistance. We show some data for an n-side strip 252 at 1V input amplitude and full bias of 40V along with the data from the p-side for comparison in Fig. 15. From the plots, it can be seen that the most difference is found at low frequencies where the value of the bias resistance is effectively halved compared to the p-side. The value for C_{AC} is about 96 pF for n-side, however, the probe at low frequencies effectively see twice that amount so that the effective value is 192pF which is about the same as C_{AC} on the p-side.

We can do the same type of modeling for the n-side with a network of resistors and capacitors. If we assume that the parasitics are the same, meaning that we keep the values that we used for the p-side,

$$\begin{aligned} C_1 &= 80 \text{ pF} \\ C_2 &= 30 \text{ pF} \\ R_1 &= 350 \text{ k}\Omega \\ R_2 &= 160 \text{ k}\Omega \\ C_u &= 10 \text{ pF} \\ R_{big} &= 150 \text{ M}\Omega \end{aligned} \tag{14}$$

we get somewhat good agreement as show in Fig. 16. By altering some of the values shown above, we can get better agreement as shown in Fig. 17

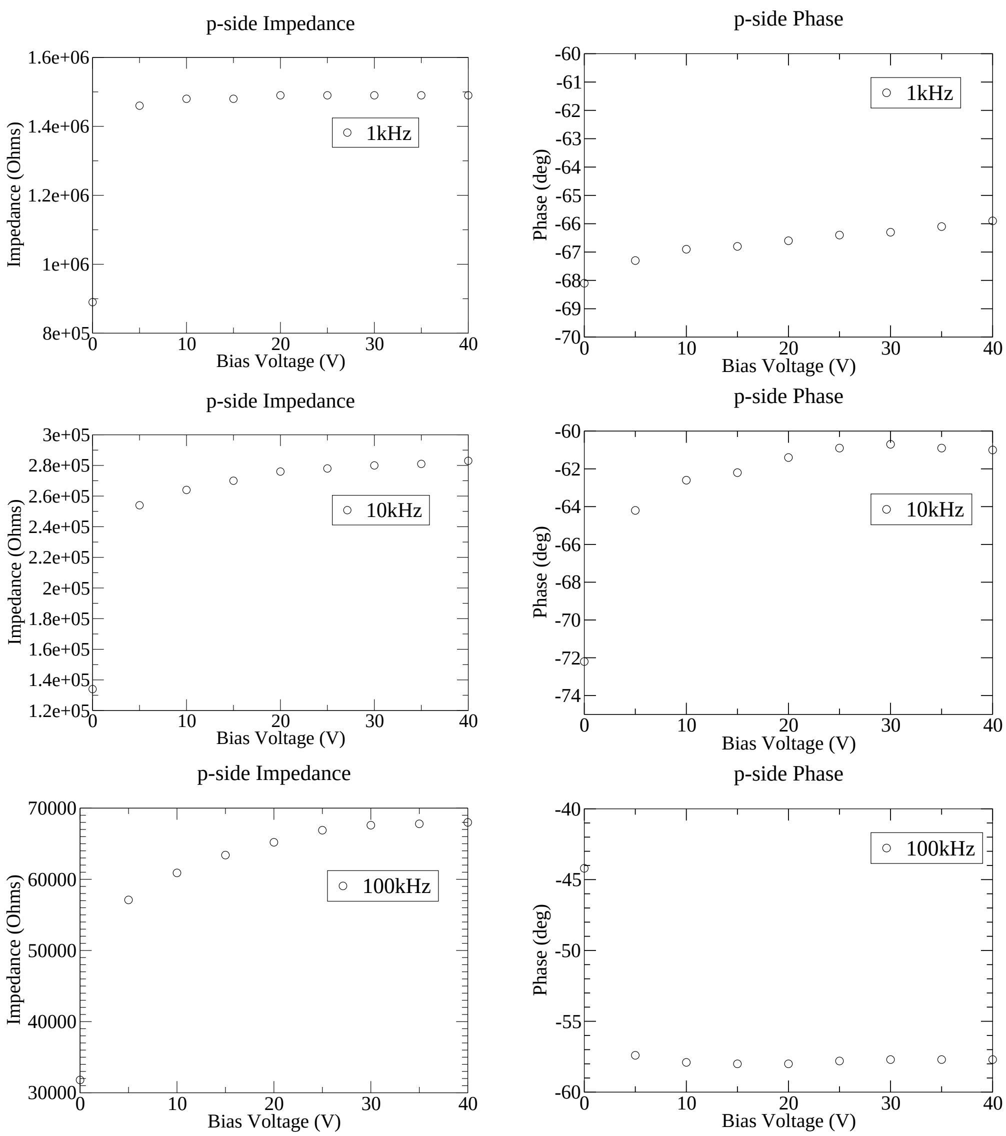

Figure 13: Bias voltage sw for various frequencies

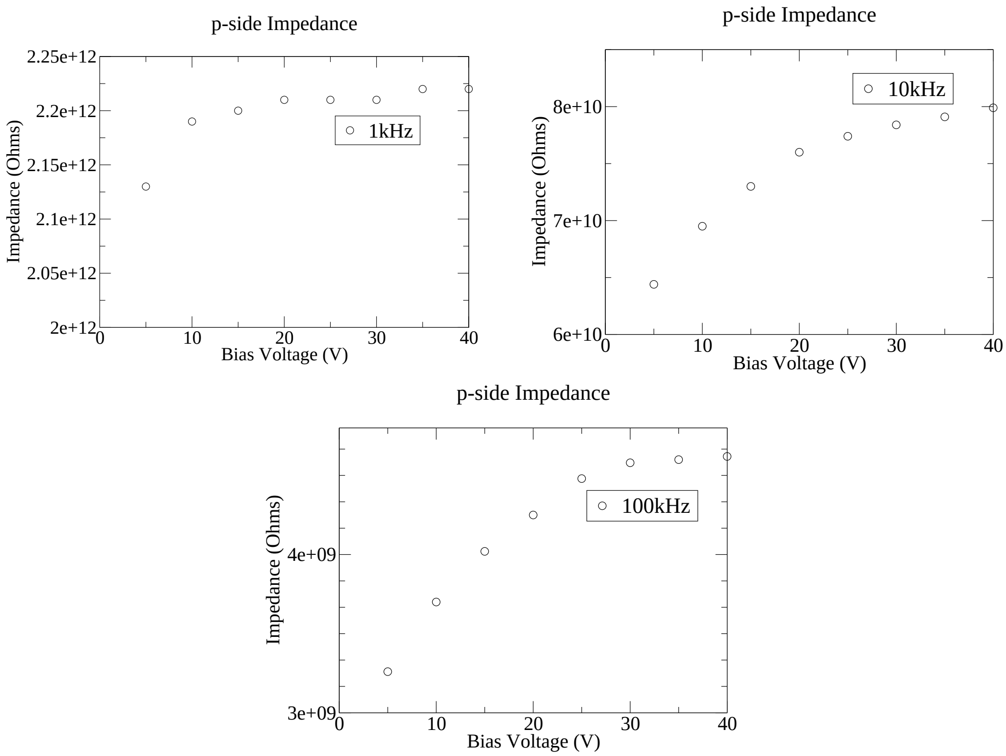

Figure 14: Plots of $|Z|^2$ for various frequencies

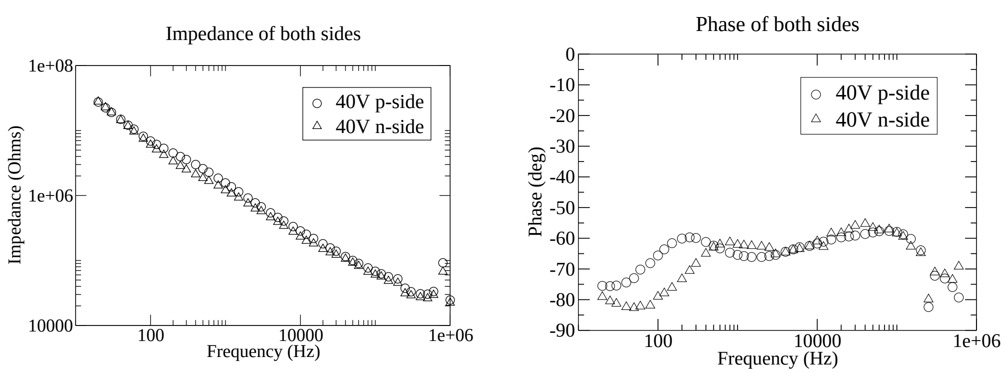

Figure 15: Impedance and phase measurements for both sides

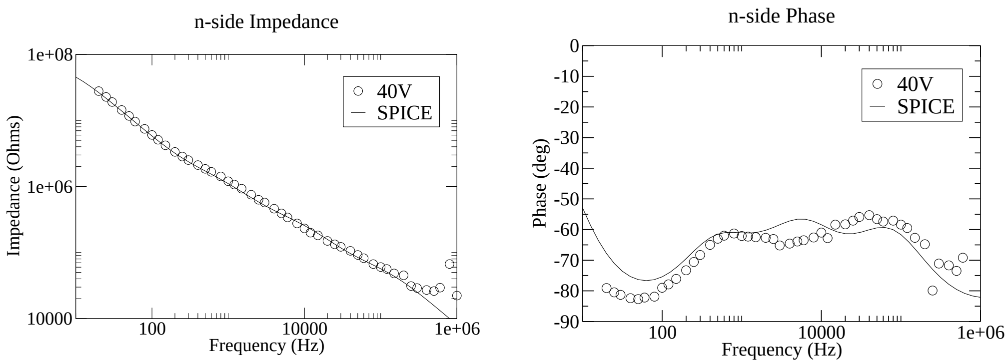

Figure 16: Simulation of a complicated network model vs. data

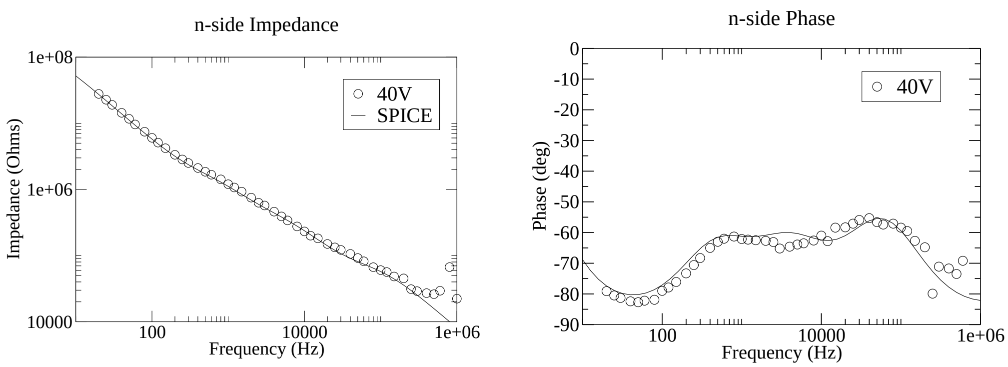

Figure 17: Simulation of a complicated network model vs. data

using the values

$$\begin{aligned} C_1 &= 80 \text{ pF} \\ C_2 &= 50 \text{ pF} \\ R_1 &= 250 \text{ k}\Omega \\ R_2 &= 160 \text{ k}\Omega \\ C_u &= 10 \text{ pF} \\ R_{big} &= 300 \text{ M}\Omega \end{aligned} \tag{15}$$

Another distinction between the n-side and the p-side is that the n-side has p-doped p-stops between the strips to prevent them from shorting together. The p-stops only work when the detector is fully depleted, which happens at around 30V. So as we vary the bias voltage on the n-side, the strips start shorting together and so we should see effectively more and more resistors in parallel. So the effective value of R_b should drop and we can see

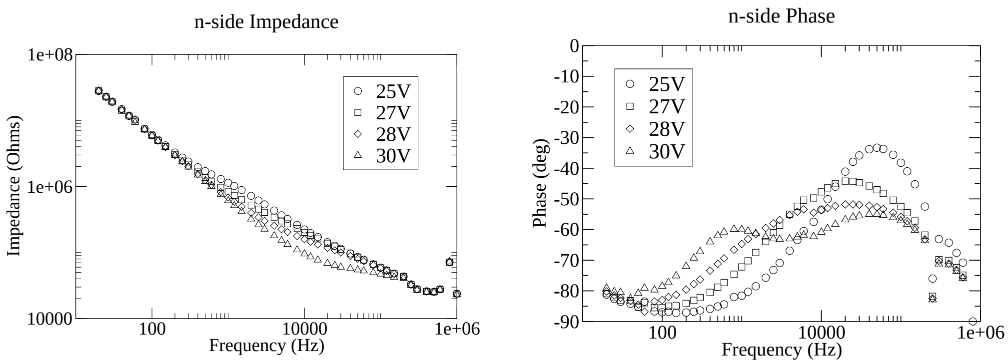

Figure 18: Impedance and phase at various bias voltages

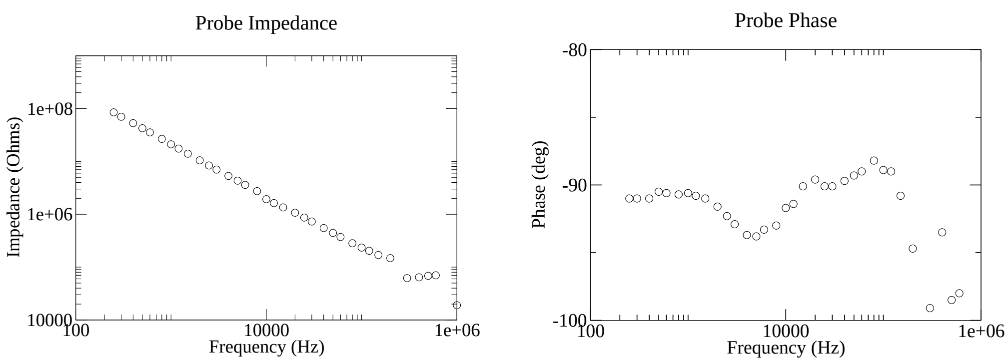

Figure 19: Impedance and phase of the probe by itself

this clearly from the plots shown in Fig. 18.

4 The Probe Station and Other Effects

To try and learn more about the parasitics, we can measure the probe by itself without any connection to the upilex. The results are shown in Fig. 19. The impedance and phase indicate mainly those of a pure capacitance since the magnitude of the impedance goes like $\frac{1}{\omega}$ and the phase is around -90 degrees which is a pure capacitance $\frac{1}{i\omega C}$. The value of the capacitance is about 7 pF.

This can be compared to a measurement with a part that is unbonded from the upilex to the silicon. Unfortunately, we did not have any Layer 1 Backward parts, but we measured a Layer 3 Backward part on the n-side.

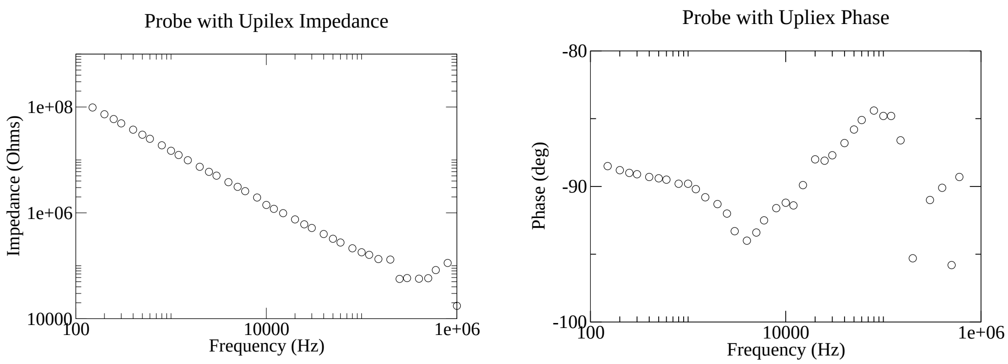

Figure 20: Impedance and phase of the probe on an unbonded upilex part

The p-side had already been bonded. The data for the unbonded part is shown in Fig. 20. It is also almost purely capacitive with a value of about 10 pF.

Appendix

The files that the raw data are stored in are called `n-side_raw_data.xls` and `p-side_raw_data.xls`. The data extracted using the parallel model are stored in `n-side_extracted_data.xls` and `p-side_extracted_data.xls`. The data on the probe station by itself with no detector is in the file `no_detector.xls`. The data on the layer 3 backwards n-side upilex with no bonds to the wafers are in the file `unbonded_upilex.xls`. The schematics for the network used for the SPICE model are shown as well for both the p-side and the n-side.

p-side

Below are the schematics for the model on the p-side.

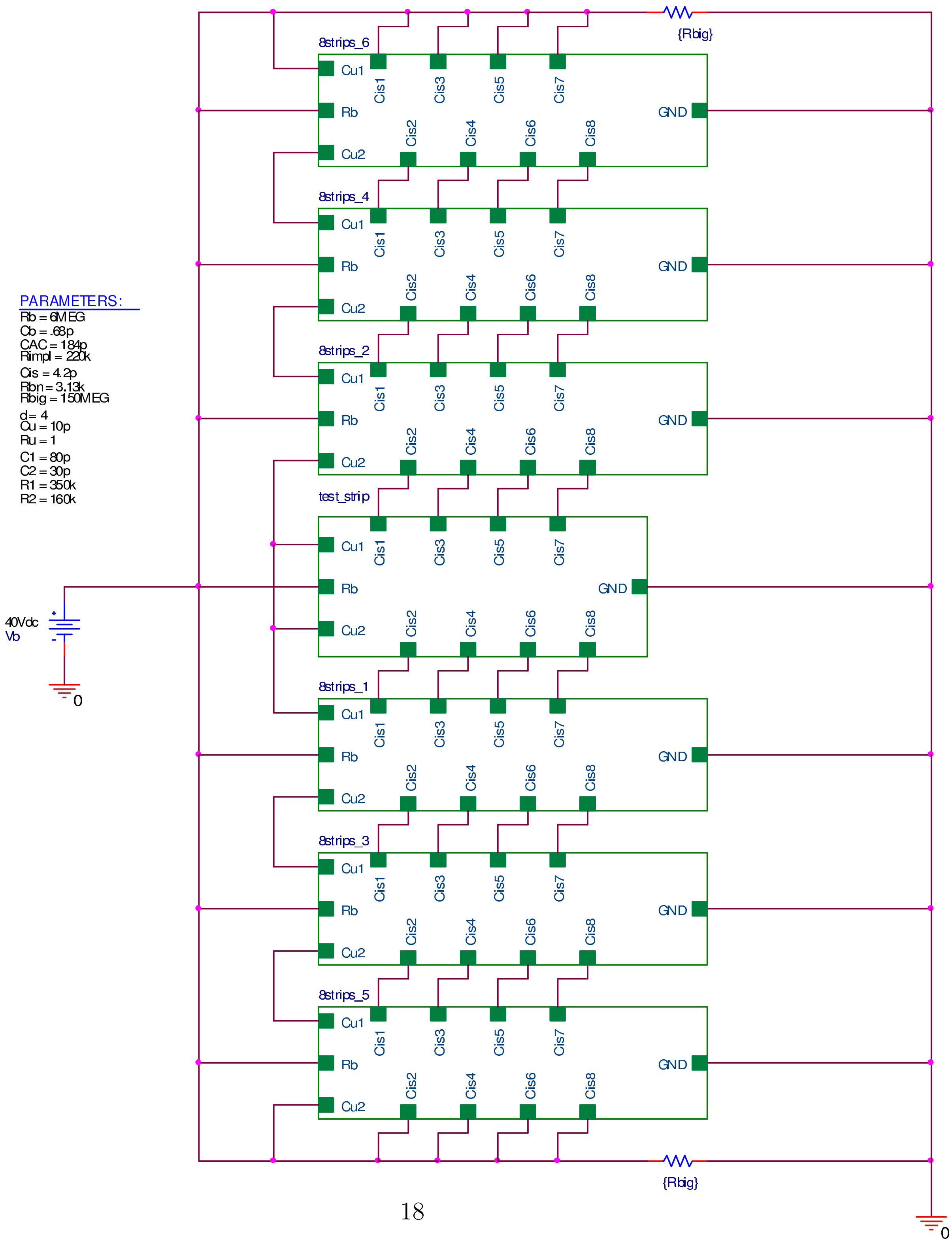

Figure 21: Top level with values of parameters

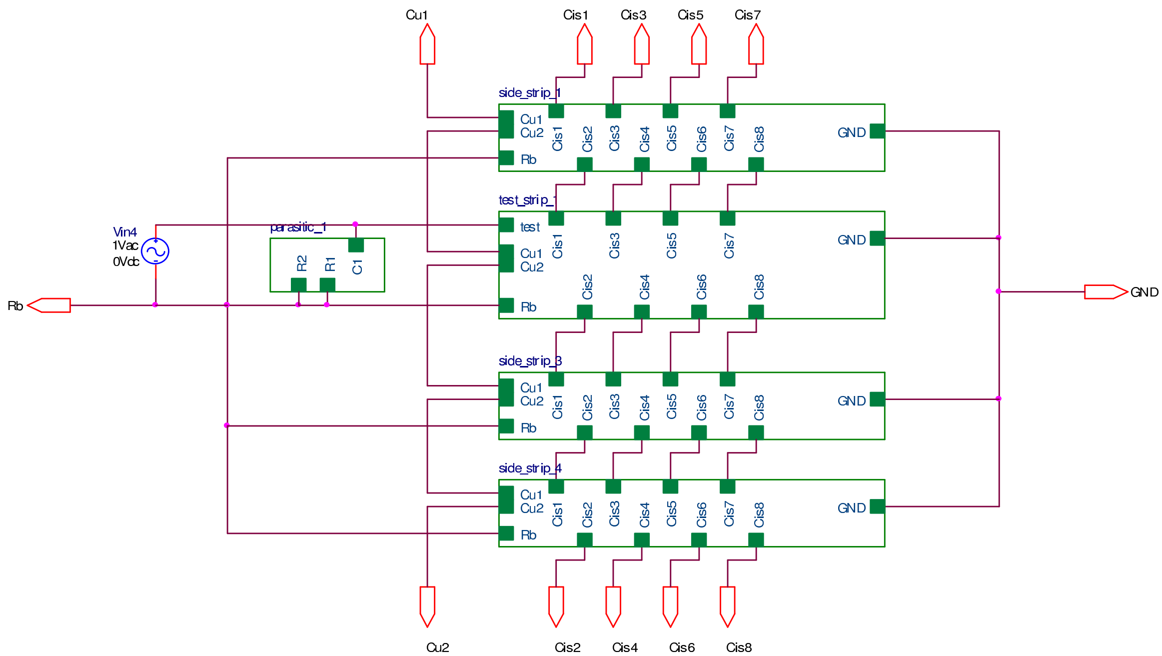

Figure 22: The test strip and strips around it

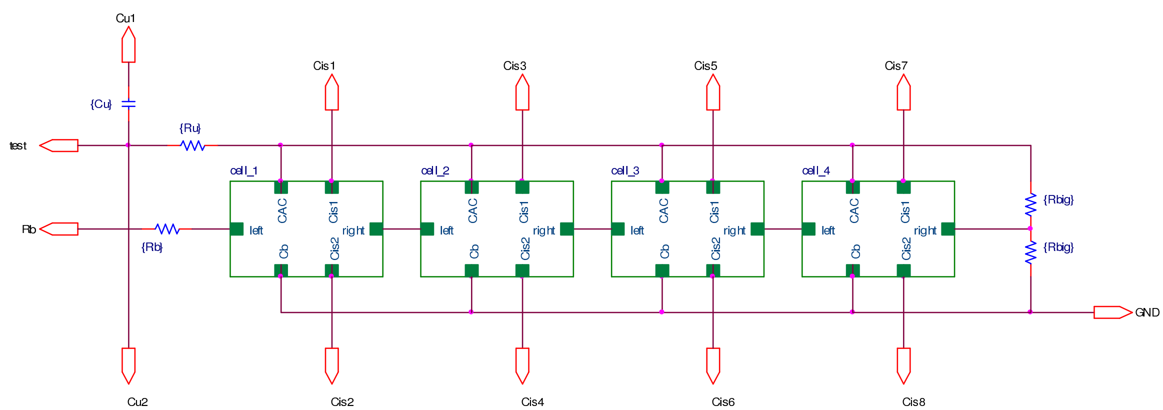

Figure 23: The test strip

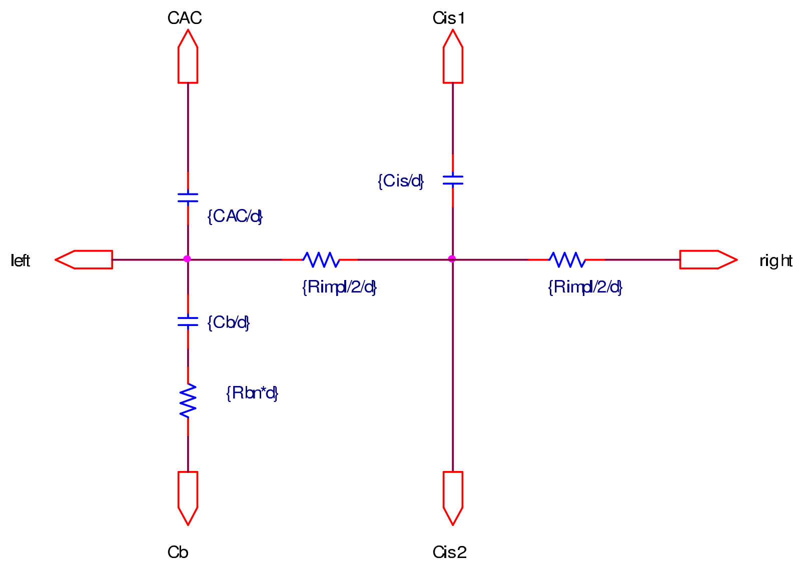

Figure 24: One division of a strip

n-side

Below are the schematics for the model on the n-side.

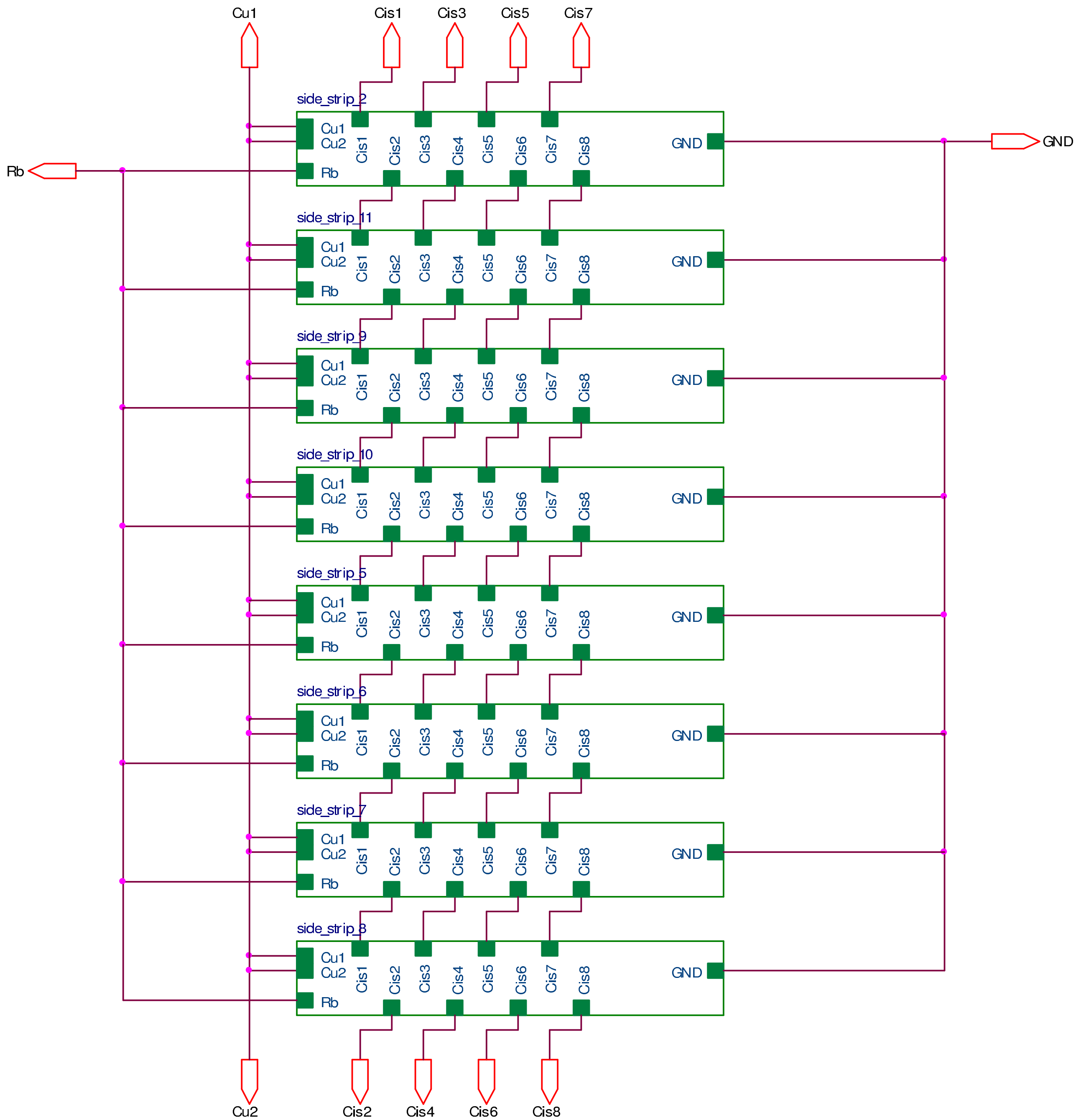

Figure 25: A block of 8 neighboring strips

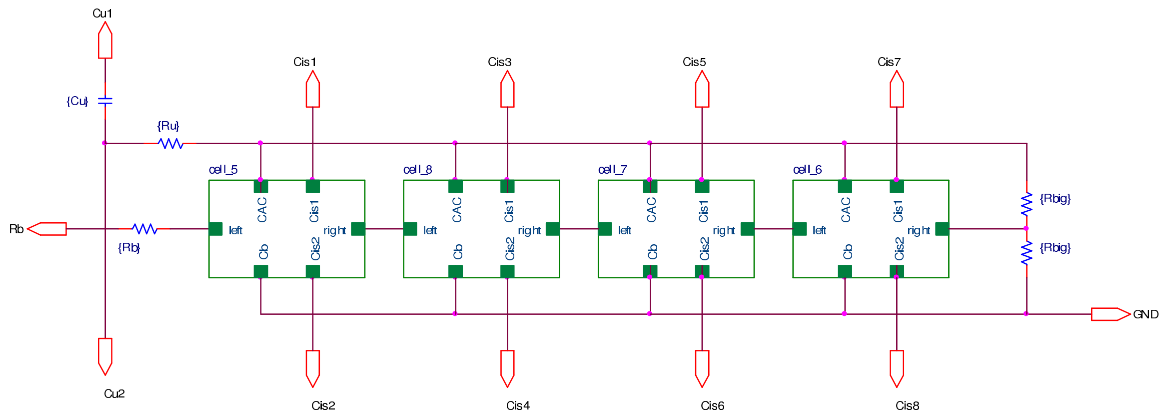

Figure 26: A neighbor strip

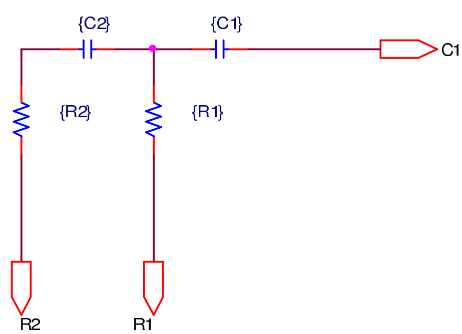

Figure 27: Parasitic elements

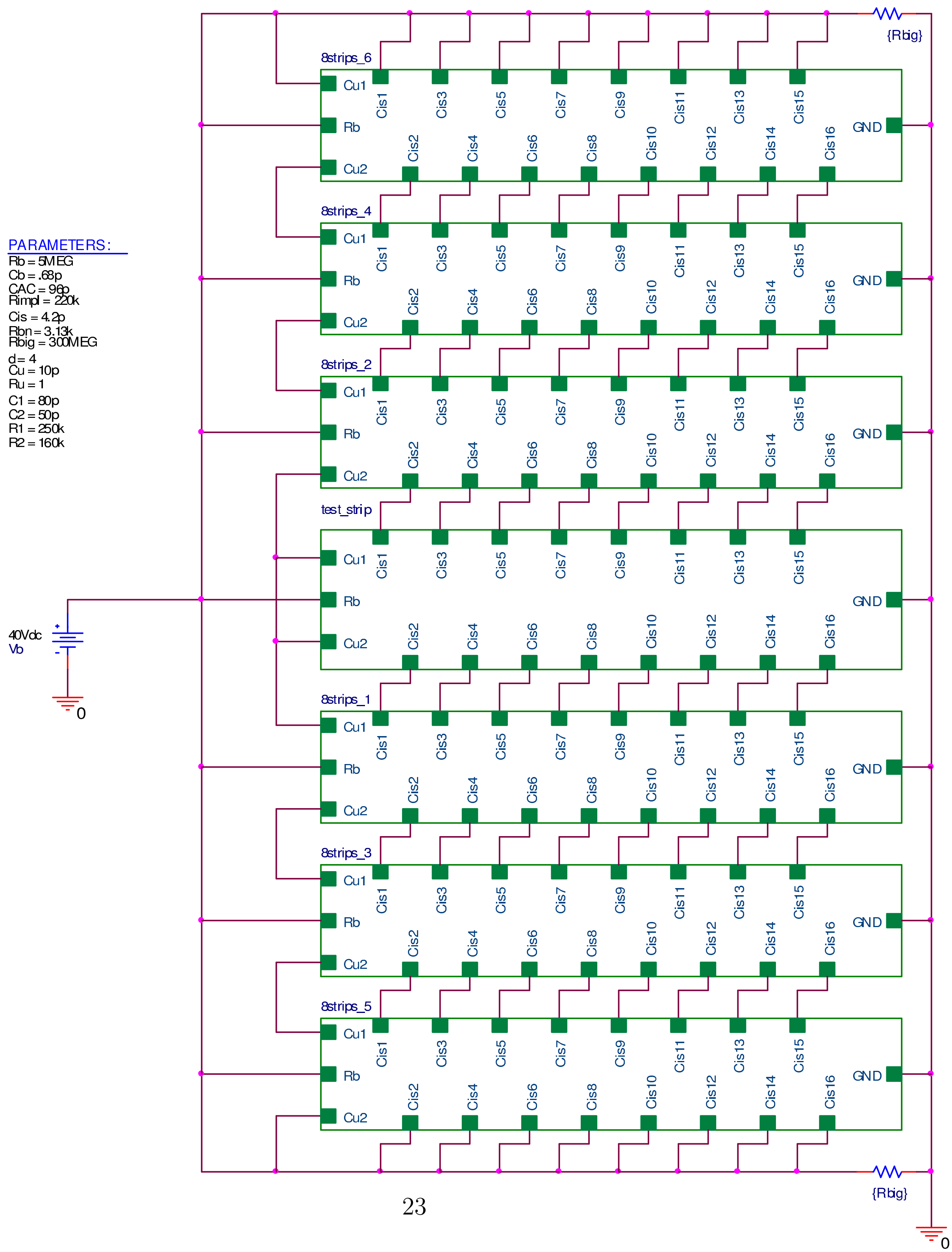

Figure 28: Top level with values of parameters

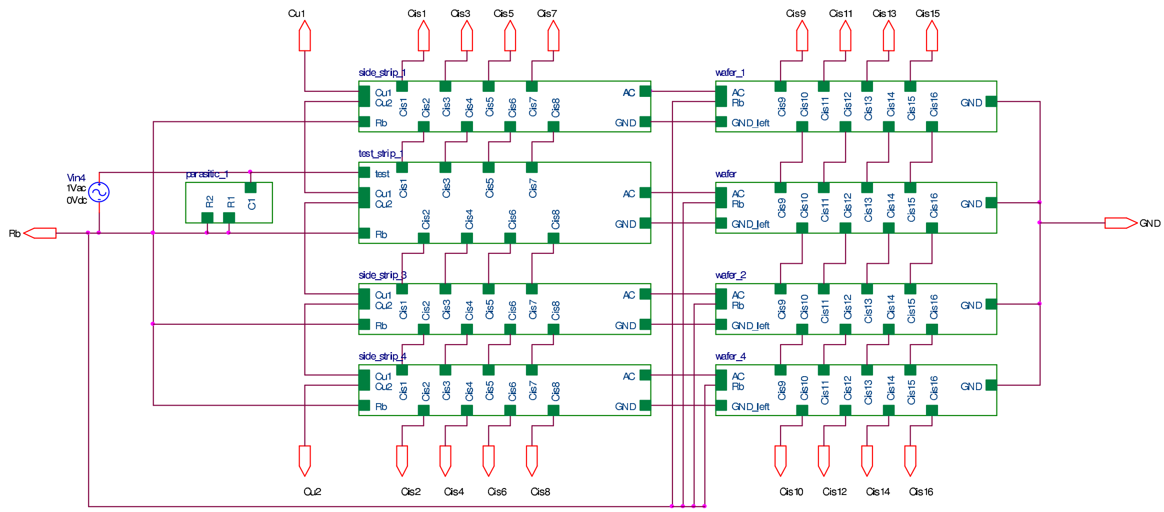

Figure 29: The test strip and strips around it

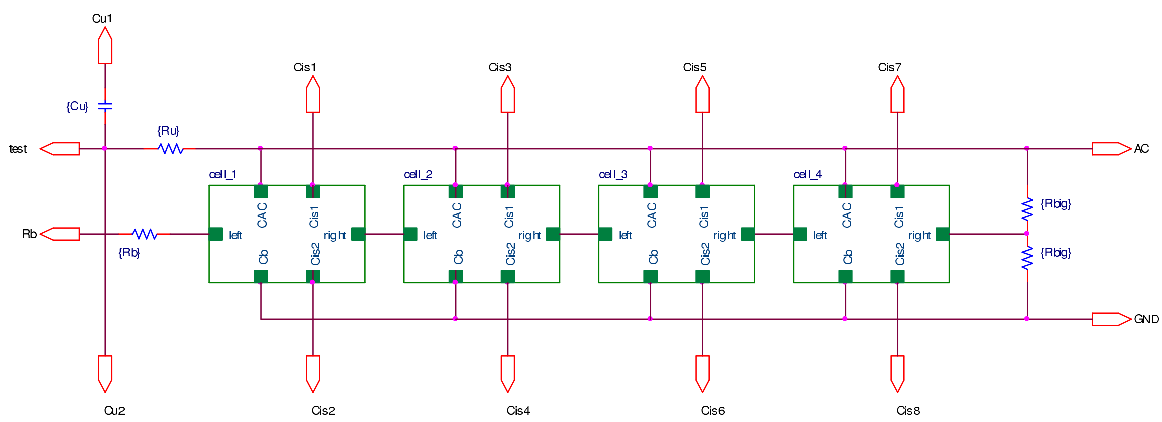

Figure 30: The test strip

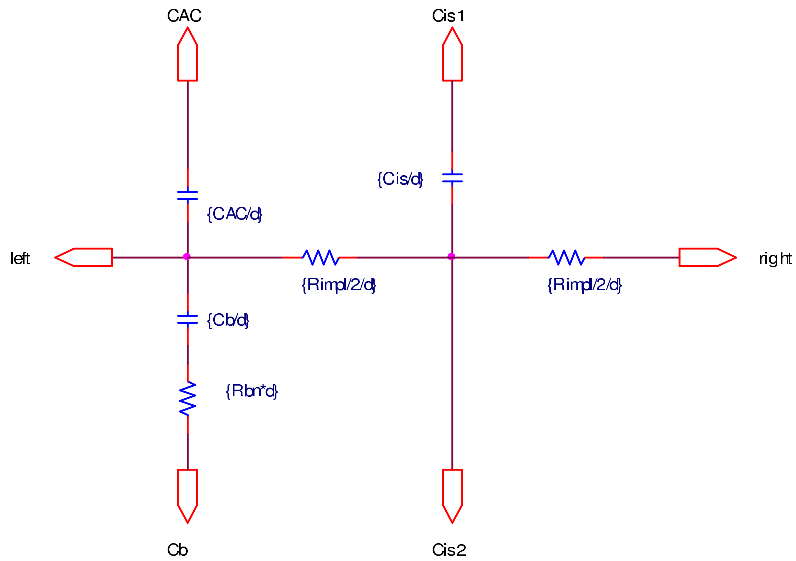

Figure 31: One division of a strip

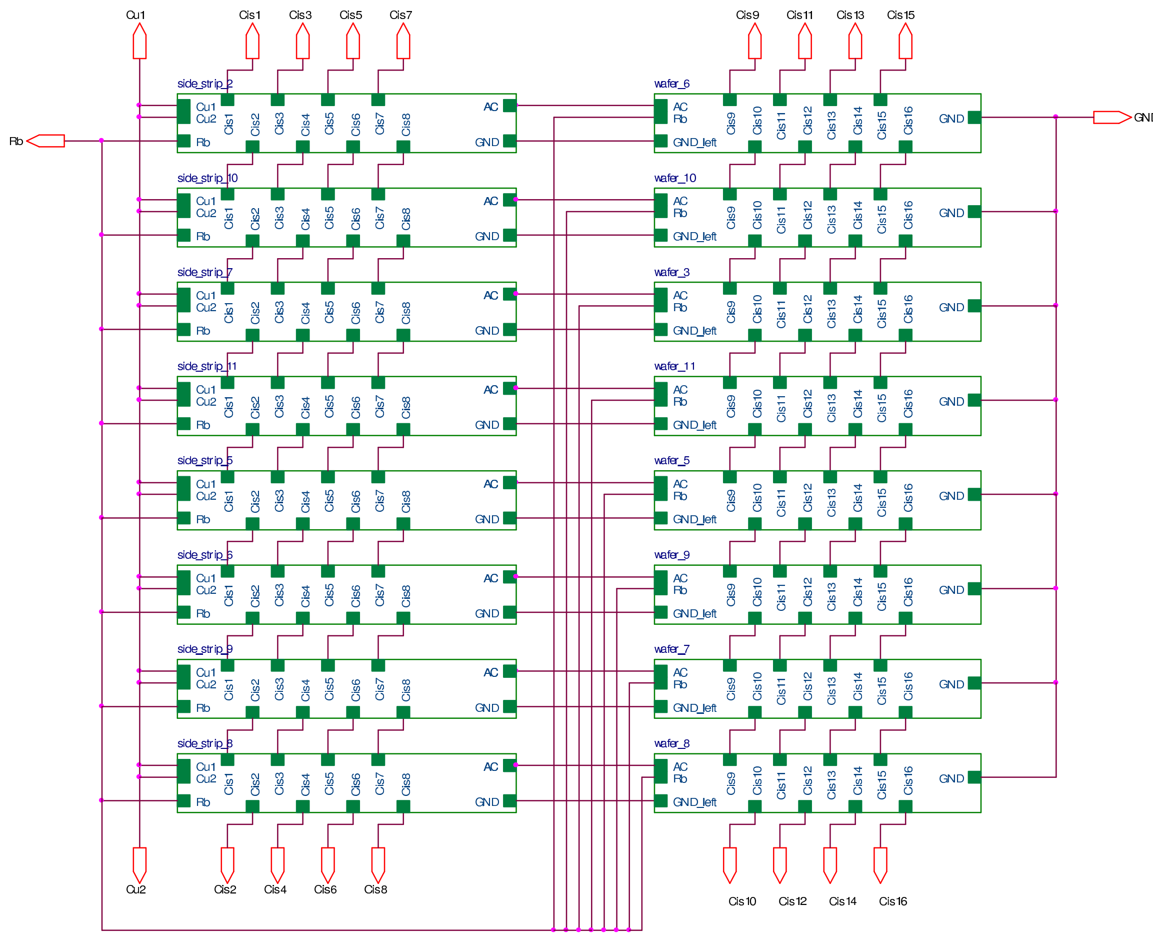

Figure 32: A block of 8 neighboring strips

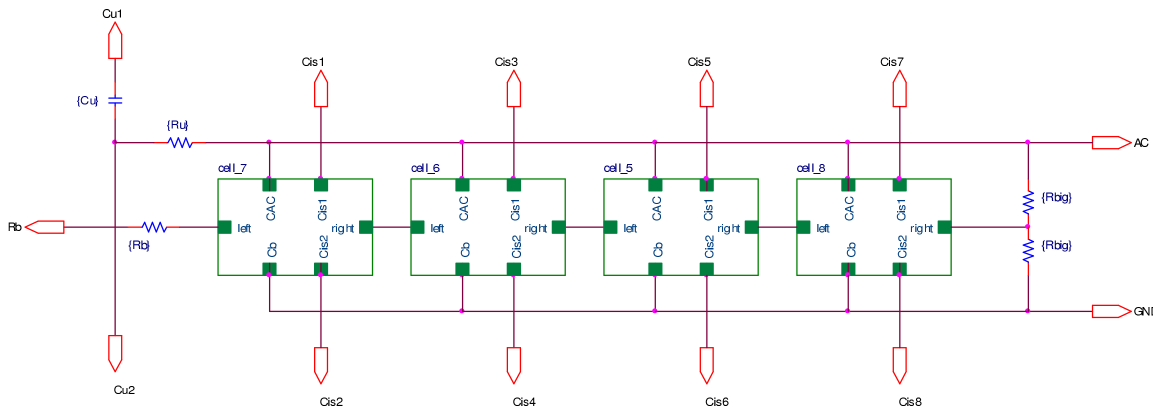

Figure 33: A neighbor strip

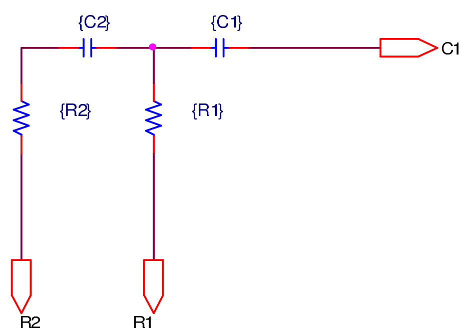

Figure 34: Parasitic elements