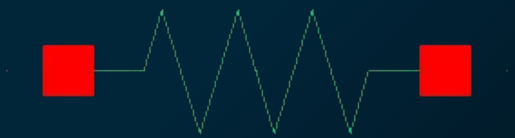
High Resolution Digitally Trimmable Resistor



Presented by: Alek Benson, Clark Reimers, Pierce Nablo, Oluwatosin Oyenekan

Overview

- **Intro**
- Initial Research
- Proposed Approaches
- Testing
- Evaluation & Comparisons
- Conclusion

Intro - Project Statement

Our goal is to design a high resolution digitally trimmable resistor. It should be capable of adjusting its resistance value by ±1%, and should be re-trimmable infinitely many times. The trim steps should be binary weighted.

Intro - Requirements

The requirements of this project are the following:

- Resistance value can be adjusted to ±1% via binary weighting
- Designed in TSMC .18μ process
- Size should be comparable to current resistor solutions
- Temperature dependencies minimized

Intro - Assumptions/Limitations

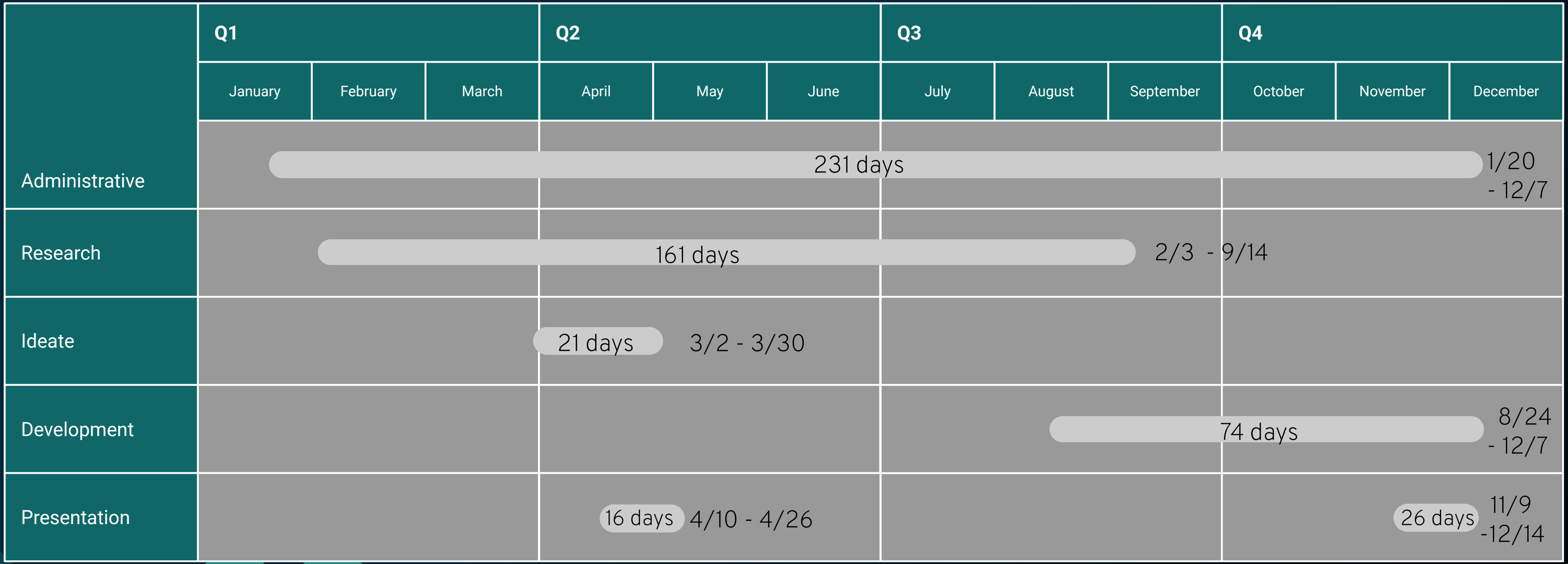
Assumptions

- Process variations exist
- Inherent gradient effects exist
- Operating environment is controlled
- Power consumption should be minimized
- Area should be minimized

Limitations

- Non-ideal switch technology
- Software capabilities
- Simulation errors
- TSMC process available to ISU

Intro - Timeline



Intro - Project Milestones

- Understand TCR
- Make reference design
- Simulate and Evaluate Reference Designs
- Scale-up Proposed Design
- Simulate and Evaluate Proposed Designs
- Repeat
- Select Final Design

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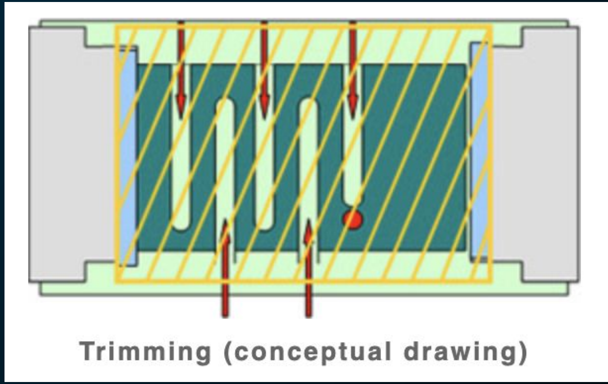
Initial Research - Trimming Methods

Currently trimming resistors in IC is done with various methods.

- Laser Trimming
- Anti-Fuse Trim
- Magnetic Tunnel Junction Element
- On-Chip Heater
- Digital Trimming
  - Series Resistor Structure
  - Parallel Resistor Structure

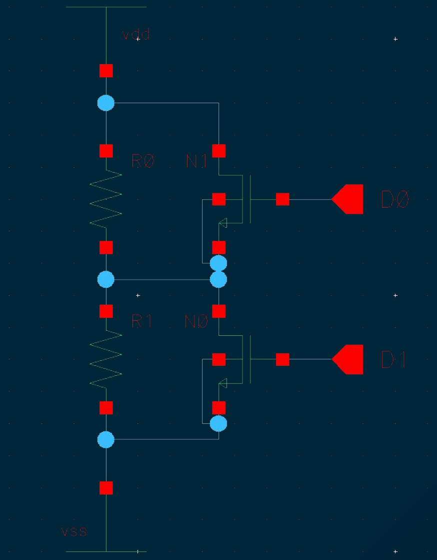
Laser Trim:



https://www.susumu.co.jp/usa/tech/know_how_05.php

Initial Research - Series Design

Series Structure:

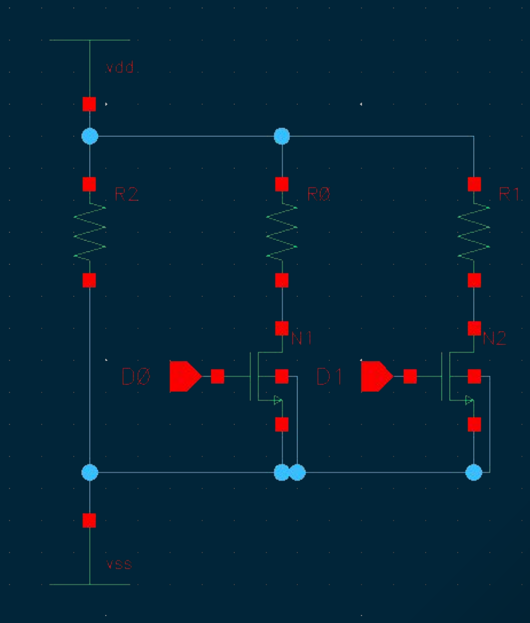


Shortcomings:

- All current is driven through the mosfets.
- Highly temperature dependent
- Resistor and mosfets have different temperature coefficients which don’t cancel out in voltage divider equation.

Initial Research - Parallel Designs

Parallel Design:



Shortcomings:

- Resistor area grows dramatically
- Area of total circuit is to large for practical applications.

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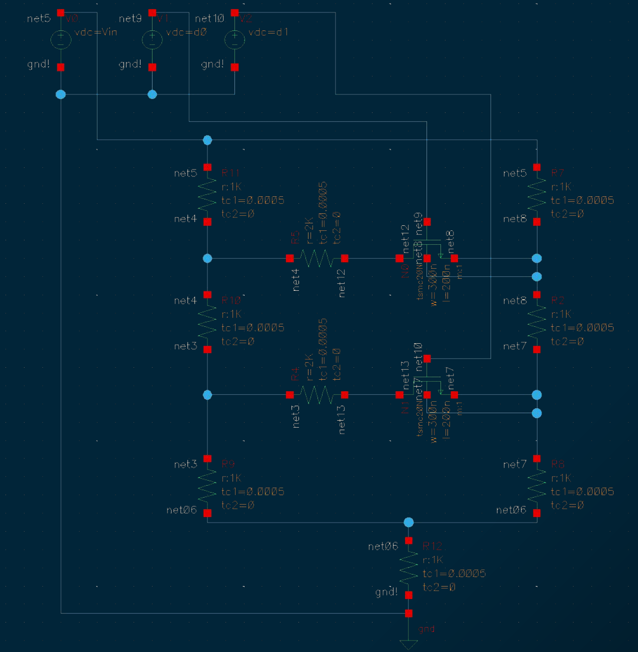
Proposed Approaches - Ladder Design

Ladder Structure:

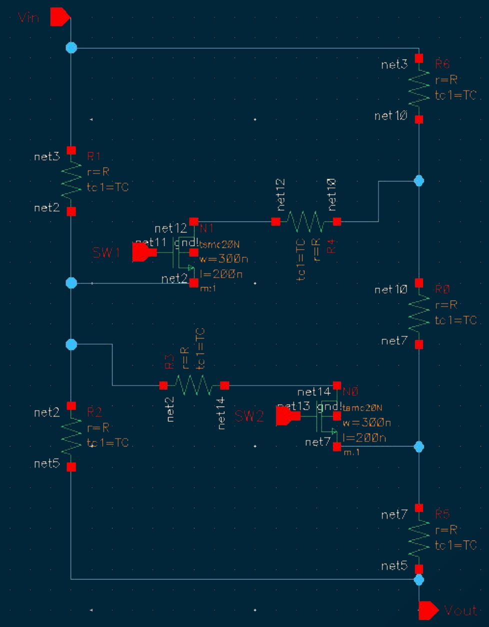


Theory:

- Minimize current flowing through the switches to prevent large TCR fluctuations
- Difficult to calibrate a binary trim.

Proposed Approaches - Truss Designs

Truss Structure:



Theory:

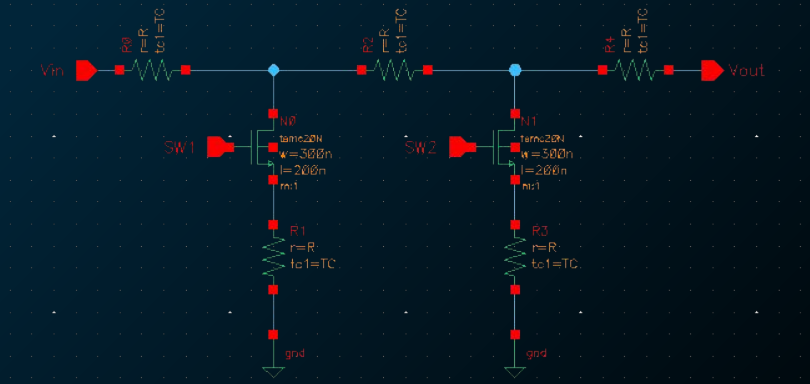
- Adapted from the ladder structure
- Keeps the idea of driving current through resistors only.
- Reconfigures how the trimming rungs are organized.

Proposed Approaches - Voltage Divider

Theory:

- Modified from the previous structure after poor performance
- Divided voltage in half every stage
- Naturally a binary trim

Voltage Divider Structure:



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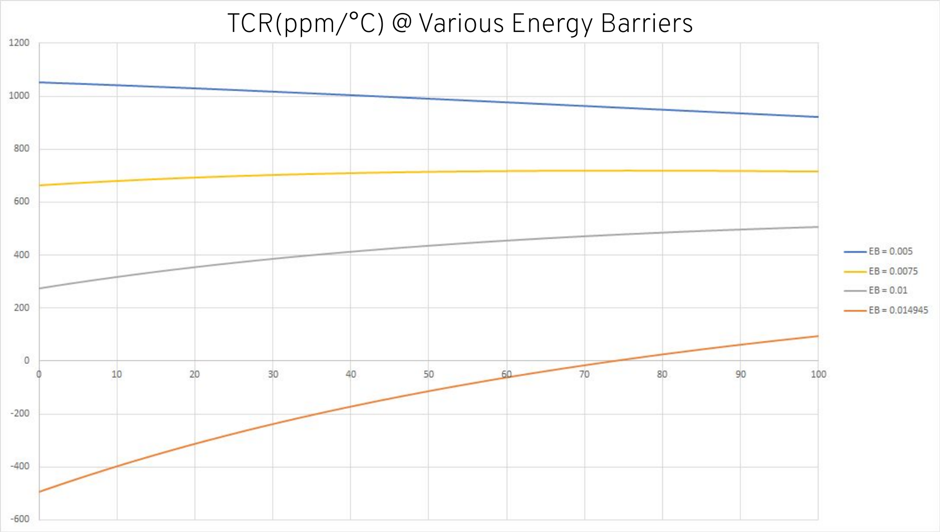
Testing - Resistor TCR

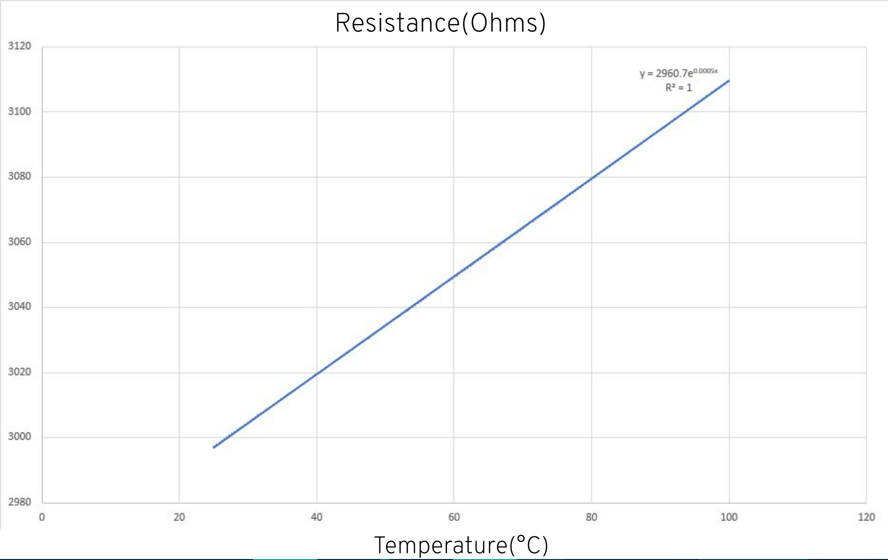
Energy Barrier is a function of grain size and carrier concentration.

$$TCR = \left(\frac{1}{R}\frac{dR}{dT}\right)\Bigg|_{op.\ temp} \bullet 10^{6}\ ppm/^{\circ}C$$

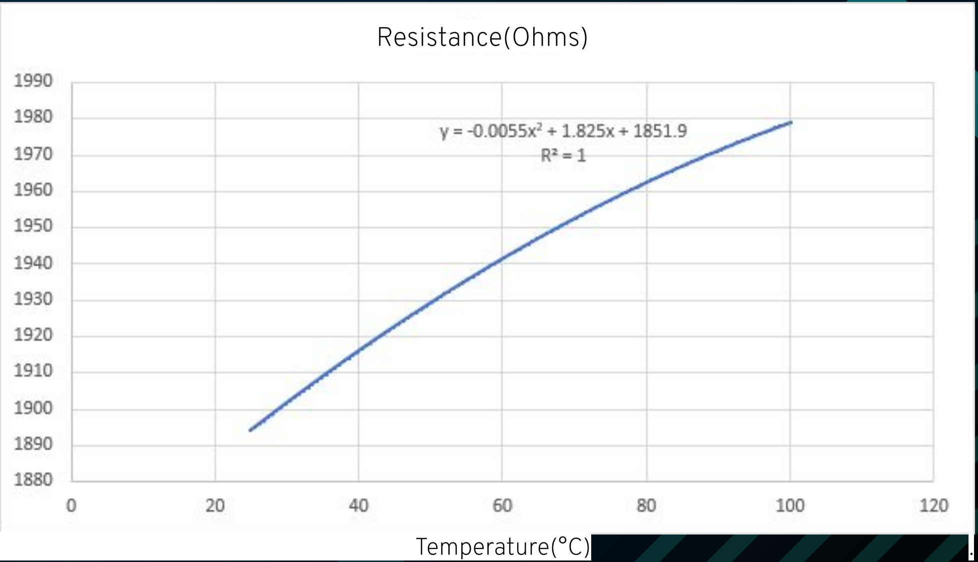


Testing - Series Structure

Switches - OFF

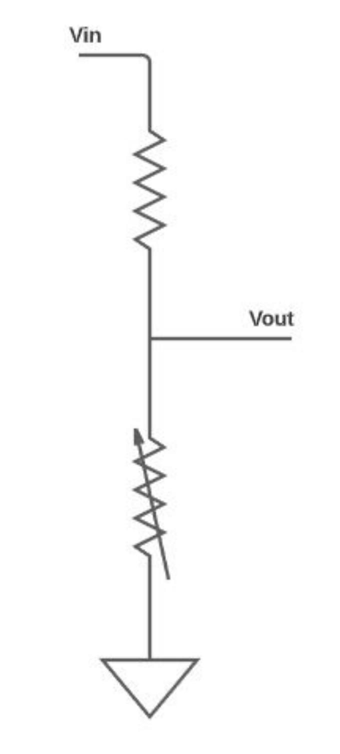


Switches - ON



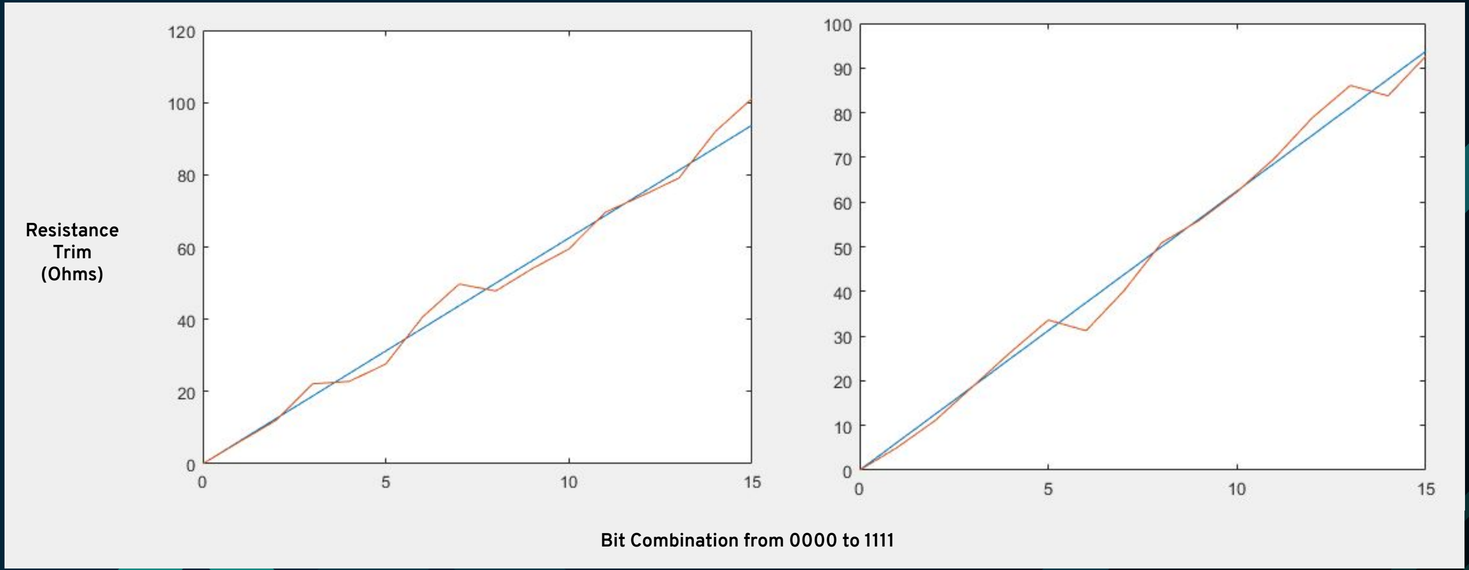
Calculated using resistor components with a TCR of 500 ppm/°C

Testing - Temperature Coefficient of Voltage



- Effectively a ratio of resistor TCRs
- Abbreviated as TCV
- Ideal value of 0

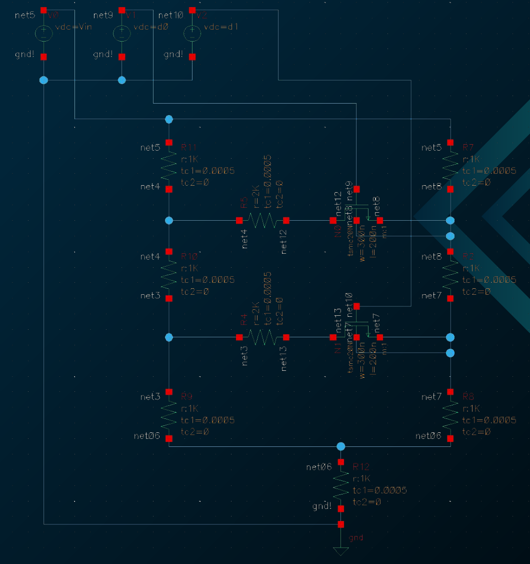
Testing - Trimming Stability

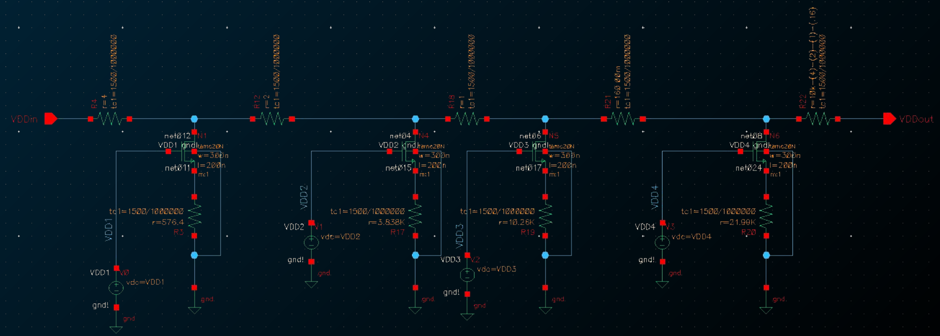


Testing - Overview

Run	Level	Left Res (Ohms)	Switch size W (n)	Switch size L (n)	Trim Res (Ohms)	Right Res (Ohms)	State	Temp	V	I	Resistance	Trim
	1					9,000	OFF OFF	27.00	0.49999999990	0.00005000000	10,000.00	0.00
	2	10,000	30,000	200	4,100		OFF OFF	28.00	0.49999999989	0.00004992511	10,015.00	
	3					2,000	ON OFF	27.00	0.50063564996	0.00005006356	9,974.61	25.39
	4	10,000	30,000	200	4,100		ON OFF	28.00	0.50063526020	0.00004998854	9,989.58	
1	5					9,000	OFF ON	27.00	0.50126428966	0.00005012643	9,949.56	50.44
	6						OFF ON	28.00	0.50126281038	0.00005005120	9,964.54	
	7						ON ON	27.00	0.50188352344	0.00005018835	9,924.94	75.06
	8						ON ON	28.00	0.50188172228	0.00005011300	9,939.90	

Performance TCR	Performance TCV	Performance % Trim	Total Trim Res Switch Res	Total Trim Res Total	Equivalent Switch Resistance. (all gates on) Width (n)	Vs (v)	Length (n)
1500.0001	0.0000	0.00%			0		
			4.76	4,104.76	300	0.751237	1615.716853
1501.5614	-0.7785	0.25%			0		
			4.76	4,104.76	300	0.730814	1624.519166
1505.9261	-2.9511	0.50%			0		
					0		
1507.2156	-3.5888	0.75%			0		
					0		





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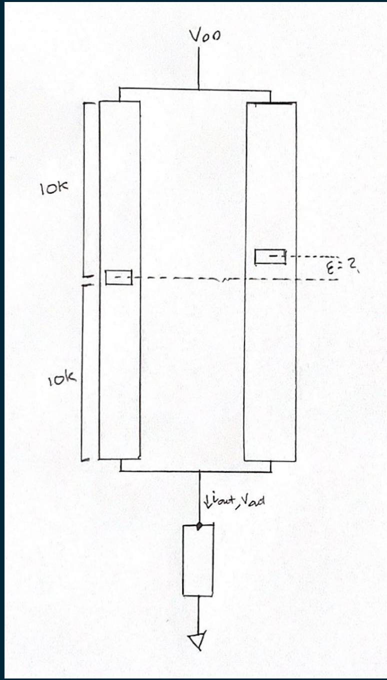
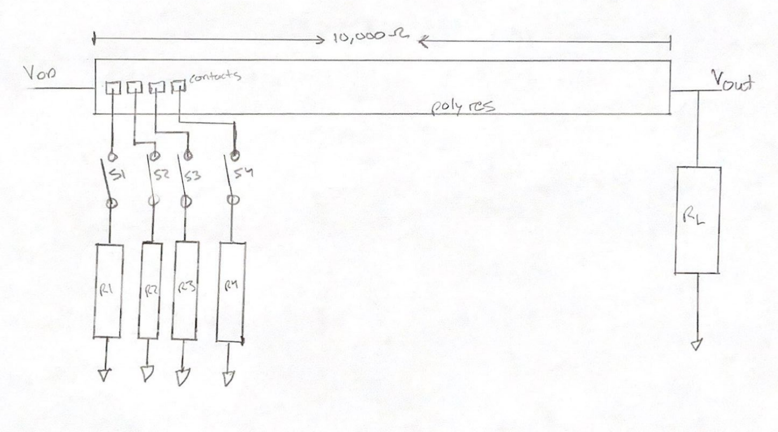
Code

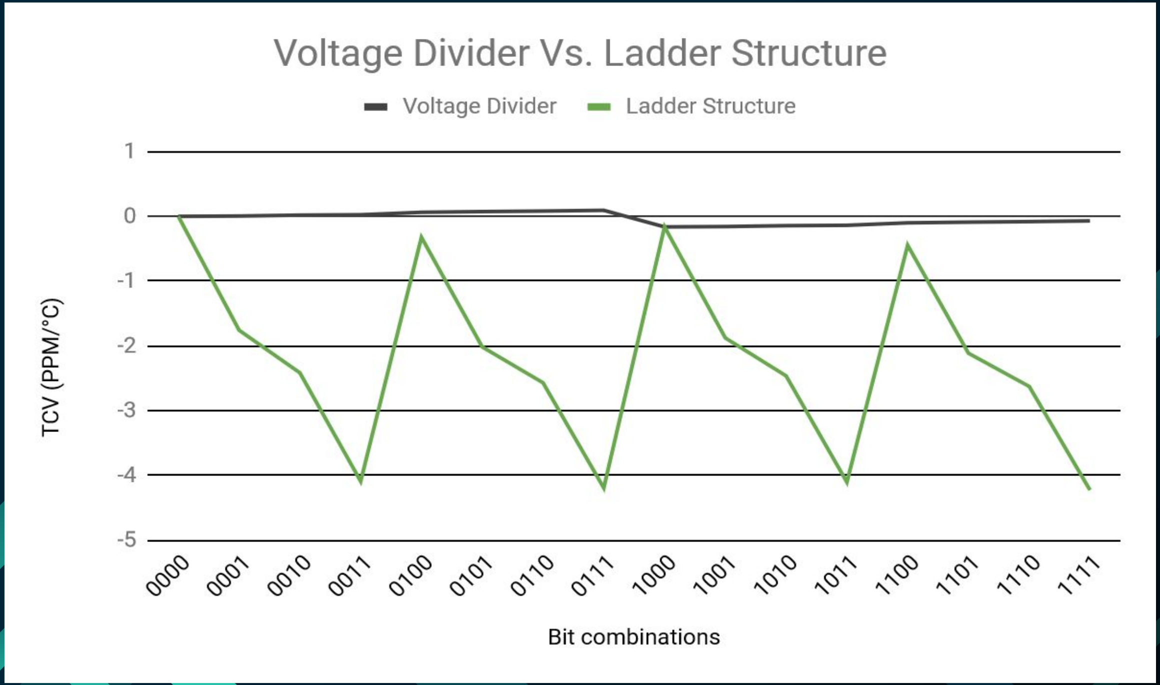
A big challenge with both the Ladder Structure and the Voltage Divider is calibrating the trimming. To do this we made some matlab code to perform the system of equations calculations





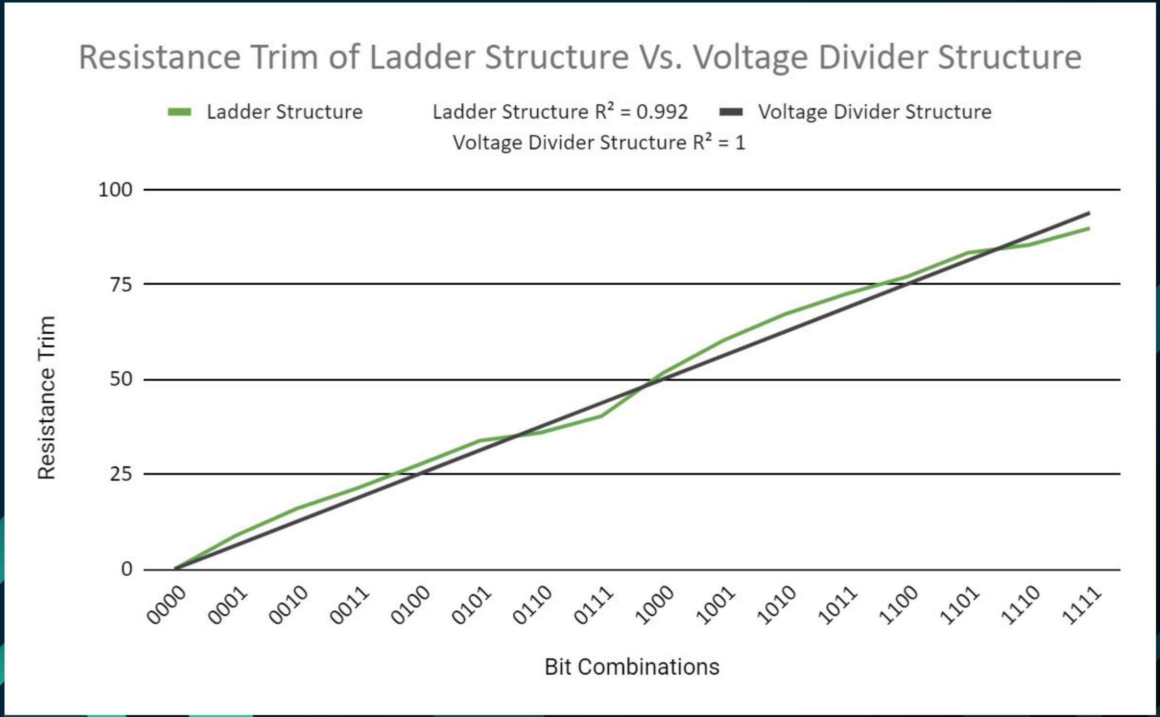
Evaluations and Comparisons

Temperature Comparisons



Evaluations and Comparisons

Trimming Precision and Accuracy



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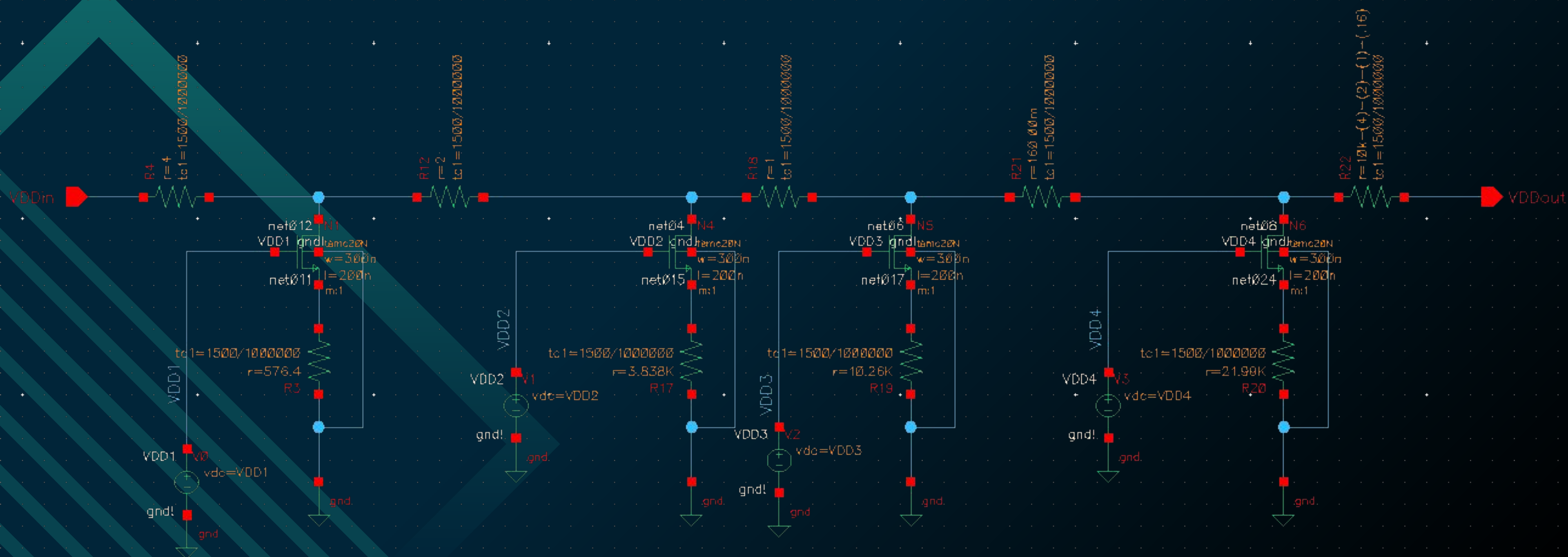
Conclusion - Final Design

The voltage divider is our final design because it satisfies the requirements of the project.

Voltage Divider Structure:

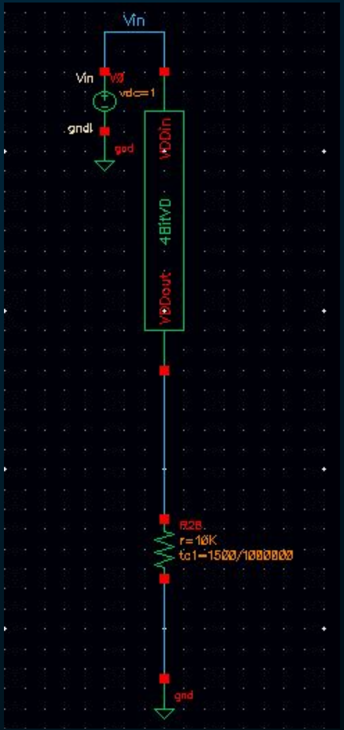


Conclusion - Demo

TCV values at each bit combo

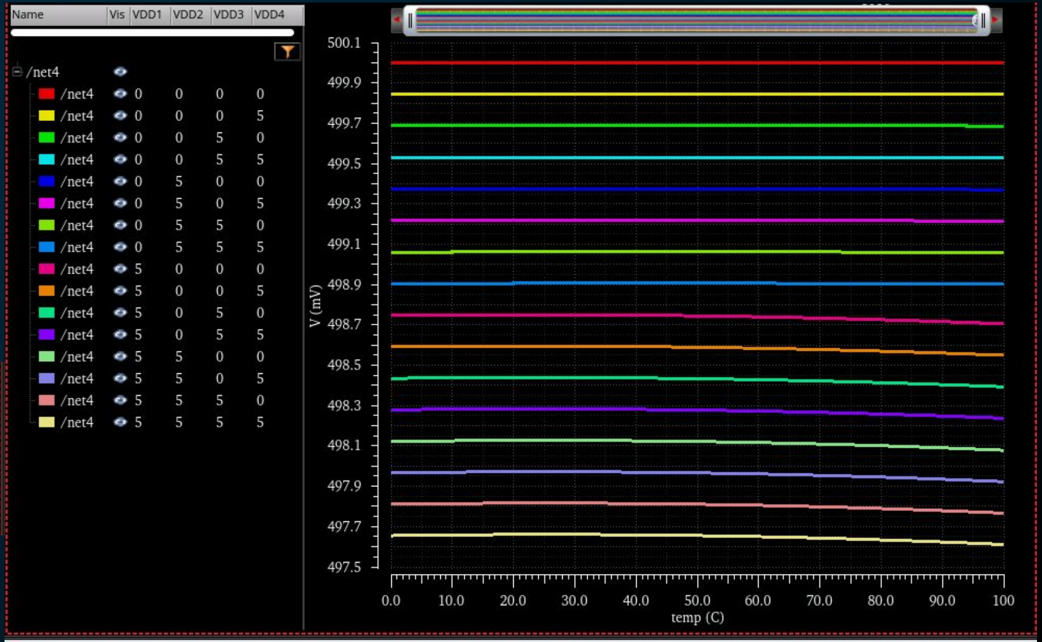
Bit combos	TCV
0000	-0.000002776
0001	0.005190602
0010	0.019135387
0011	0.024775990
0100	0.062854667
0101	0.073474643
0110	0.081841379
0111	0.092922495
1000	-0.162639859
1001	-0.157448289
1010	-0.143553029
1011	-0.137916192
1100	-0.100015642
1101	-0.089324100
1110	-0.081079560
1111	-0.069921784

Voltage Output Testbench



Conclusion - Demo

Uniform spacing as expected is observed with only minor drops in voltage of a 100 ℃ range. This test shows that the voltage divider circuit is a good alternative to the ladder structure.



Conclusion - Lessons learned & Future work

Lessons Learned:

- We should have used equation solvers like MATLAB at the beginning to help save time
- Make sure the circuits are built correctly before making conclusions on the simulation results.

Future work:

- Higher-Bit level resistor structures (8-bit)
- Using different process technology/switch components
- Work on reducing TCV even further

This concludes our senior design presentation

A big thanks to professor Geiger for all of his advising throughout senior design.

Thanks for listening!

Conclusion - Questions