Electronic Devices & Circuits I 2EI4
Project 2

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1. Ideal Switches & Switch Non-Idealities

Ideal Switch Properties	Non-Ideality	Quantization Methods
When the switch is in the off state, the current flow is 0A and the resistance is infinite. The switch then behaves like an open circuit.	A non-ideal switch has a finite resistance. The current across the switch is not 0A, also known as leakage current.	To quantify the non-ideality, the magnitude of the leakage current can be determined by using a multimeter at set voltages and resistances while the switch is in its off state.
When the switch is in the on state, the voltage drop is 0V. This implies that V_1 is equal to V_2 when measuring the voltage drop across an ideal switch, behaving like a short-circuited wire. This implies that the switch has zero resistance.	A non-ideal switch has a voltage drop that is not 0V when it is in the on state due to Ohm's law. The switch will also experience some resistance, which is not zero in a non-ideal switch as well.	To quantify the voltage drop across a switch, its magnitude can be determined by using a multimeter or devices such as AD2. The voltage drop across the switch can be calculated by measuring its resistance at a set current with a multimeter and using the Ohm's law equation, V = IR.
The switch can instantaneously transition between on and off states. This means that the delay time switching between the on and off states is zero.	A non-ideal switch does not have a time delay of zero and cannot instantaneously transition between on and off states. There is a limit in the switching speeds due to finite times between each state.	To quantify the delay time in switching states, an oscilloscope can be used to determine the average time it takes to transition between states. This can be implemented by measuring the average voltages at its on and off state and the time it takes the switch to transition from the average off state voltage to the average on state voltage. A rate can be determined by dividing the change in voltage by time.
The power of the switch is zero, meaning that that there is no power dissipation during its on, off and transition states.	A non-ideal switch experiences some power dissipation in its on and off state. In an ideal switch, the current is zero in its off state, whereas it is non-zero in a non-ideal switch, meaning that some power is lost. There is also a non-zero resistance in the on state of a switch, indicating that there is some loss of power as well. Additionally, some power may be used when transitioning the switch between the on and off states.	The power dissipation can be quantified using a multimeter to determine its current, power and resistance at different states. During its off state, P = IR^2 can be used where I is the leakage current. During its on state, P = V^2/R can be used where V is the voltage drop across the switch.

2. Test Plan

Non-Ideality	Quantitative Methods			
	$V_{control}$	V_{supply}	V_1	Measurements and Calculations
When the switch is ON, the resistance should be zero. A non-ideal switch has a non-ideal resistance value when switch is ON.	5V	5V	5V	Due to the non-ideality of the switch, there is some resistance when the switch is in its ON state. The voltage drop across the switch can be determined and the percent error can be calculated with the ideal voltage drop of zero.
When the switch is OFF, the current should be zero. A non-ideal switch has a non-ideal current value when switch is OFF.	0V	5V	5V	Due to the non-ideality of the switch, the current is non-zero when the switch if off. To calculate the leakage current with Ohm's law, the voltage and the resistance can be measured. $I_{leak} = 5 – V / R$. The percent error can then be determined with $I_{ideal} = 0$ and I_{leak}.
The range of V_1 and V_2 should be limitless, meaning the switch should be able to use any voltage. A non-ideal switch has $V_{min} < V_1$ and $V_2 < V_{max}$.	--	--	--	The maximum, V_{max}, and minimum, V_{min}, voltage can be determined based on the voltage ratings of the components used to design the switch. $V_{max} = V_{switch, max}$ $V_{min} = V_{switch, min}$
The switch should be bidirectional. The non-ideality is that the switch will have the same resistance value when $V_1 < V_2$ and $V_1 > V_2$.	5V	5V	$V_1 = 5V$ & $V_2 = 0V$, $V_1 = 5V$ & $V_2 = 0V$	The switch must be tested for its bidirectionality, which can be determined by swapping V_1 and V_2 and observing if the switch continues to function as intended. The forward current and the reverse current can be determined with a resistor by measuring the voltage drop and Ohm's law. $I_{forward/reverse} = V_{drop}/R$ The reverse conductivity can then be determined by taking the minimum and maximum values of the voltages, where $k = \min(I_{forward}, I_{reverse}) / \max(I_{forward}, I_{reverse})$ and the reverse conductivity (%) = 100 * k.

3. Switch Type I

i. Circuit Schematic

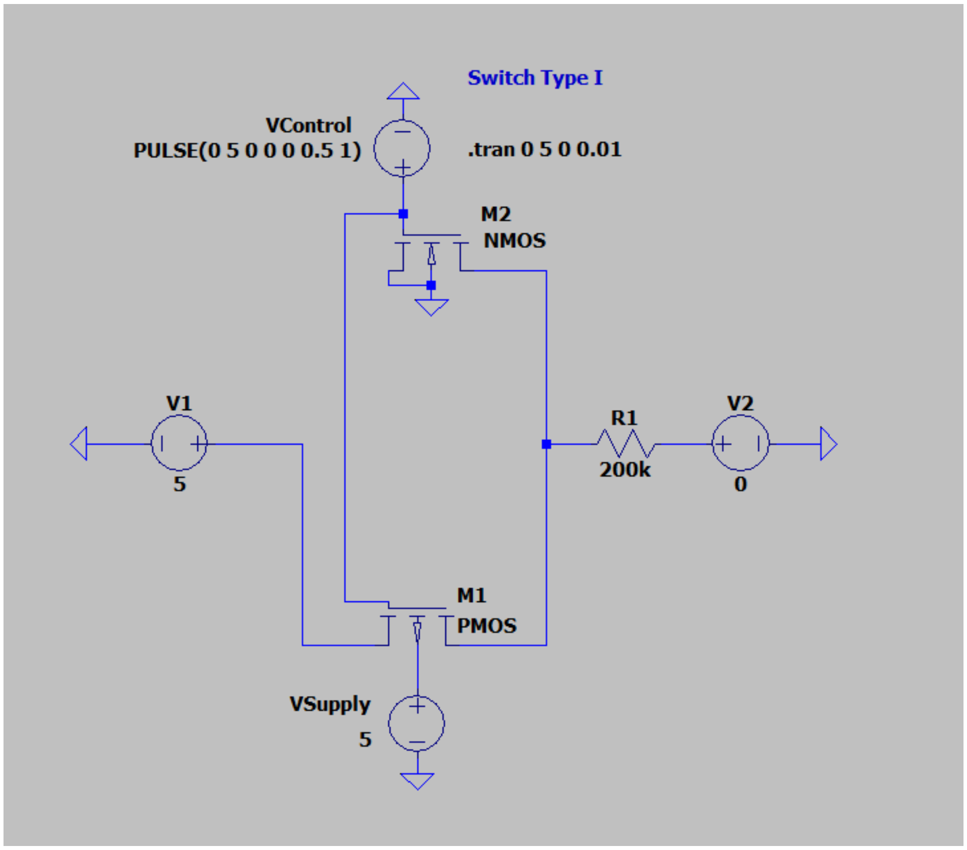

Figure 1. Circuit Schematic of Switch Type I

ii. Measurement Procedure

LTSpice Simulation

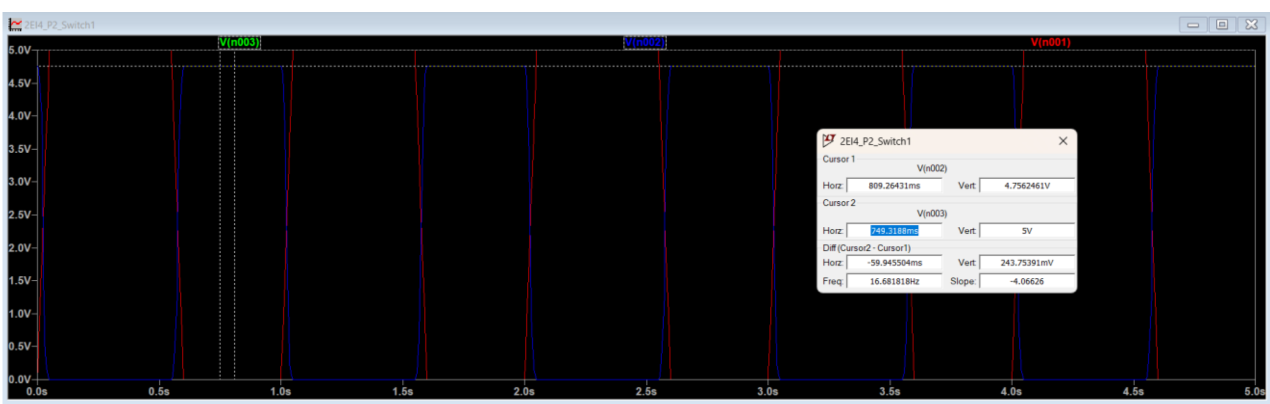

Figure 2. Simulation Results, where V_{red} = $V_{control}$, V_{green} = V_1, and V_{blue} = V_2

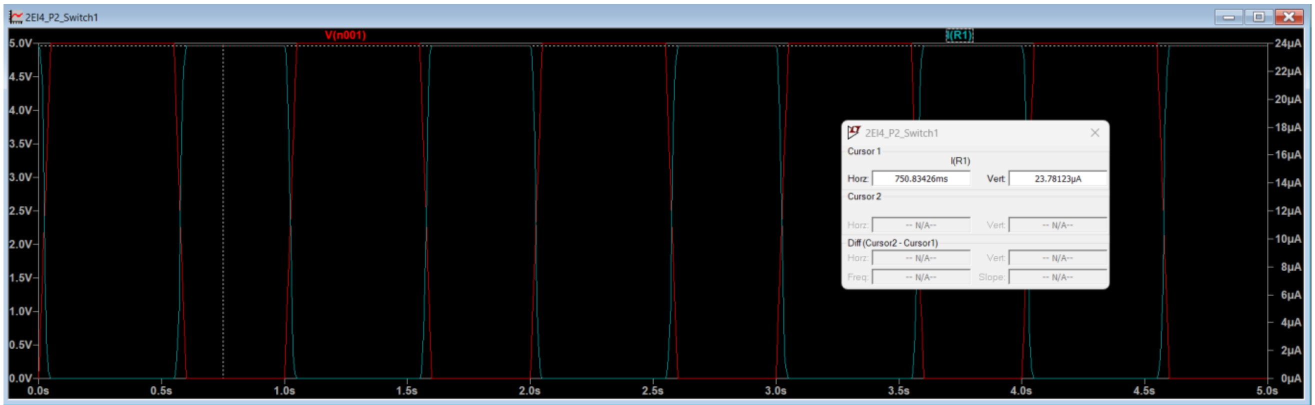

Figure 3. Simulation Results, where $V_{red} = V_{control}$ and $I_{blue} = I_{resistor}$

Switch Implementation

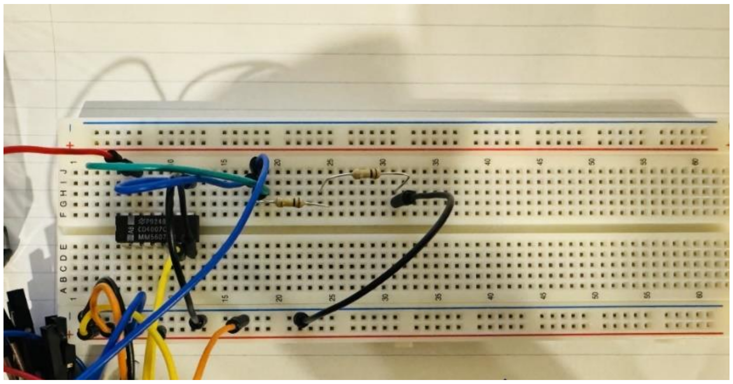

Figure 4. Physical Circuit for Type I Switch

Non-Ideality	Measurements	Quantization
When the switch is ON, the resistance should be zero. A non-ideal switch has a non-ideal resistance value when switch is ON.	V_1 = 5.0645V V_2 = 4.9973V V_{drop} = 0.0672V R = 200kΩ $V_{measured}$ = 2.4367V $I_{measured}$ = 25.315 uA $R_{switch} = V_{measured}/I_{measured}$ = 9.63kΩ	Therefore, the V_{drop}, measured = 0.0672V and an R_{switch} = 9.63kΩ, quantifying the non-ideality in the resistance during the switch's ON state.
When the switch is OFF, the current should be zero. A non-ideal switch has a non-ideal current value when switch is OFF.	V_1 = 5.0645V V_2 = 4.9973V $V_{drop} = V_1 – V_2$ = 0.0672V R = 200kΩ Ileak = Vdrop/R = 3.36 mA	Therefore, the leakage current is 3.36 mA, demonstrating the non-ideality in the switch during its OFF state.
The range of V_1 and V_2 should be limitless, meaning the switch should be able to use any voltage. A non-ideal switch has $V_{min} < V_1$ and $V_2 < V_{max}$.	$V_{DS,\ maximum}$ = 20V V_{bulk} = 5V	Based on the datasheet, the maximum voltage is 5V.
The switch should be bidirectional. The non-ideality is that the switch will have the same resistance value when $V_1 < V_2$ and $V_1 > V_2$.	$V_{forward}$ = 2.4939V $V_{reverse}$ = 2.3210V R = 200kΩ $I_{forward}$ = 0.0125 mA $I_{reverse}$ = 0.0116 mA k = 0.928	Therefore, the switch is bidirectional with non-idealities. The reverse conductivity is 92.8% and the percent difference in the forward and reverse voltages is 7.18%.

	reverse conductivity = 92.8%	

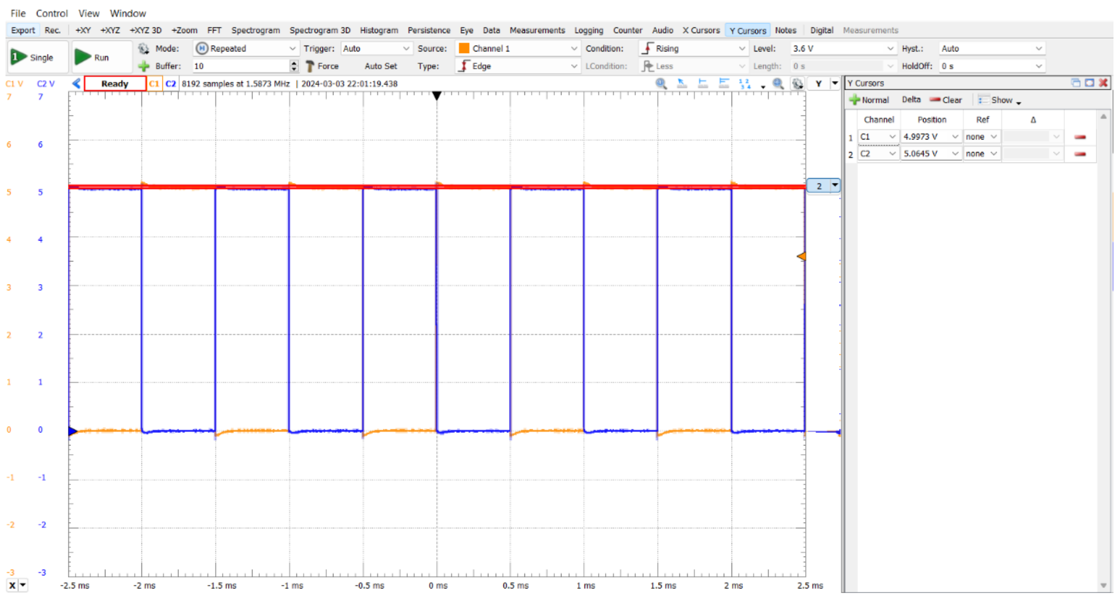

Figure 5. AD2 Results with $V_{control}$ and V_2

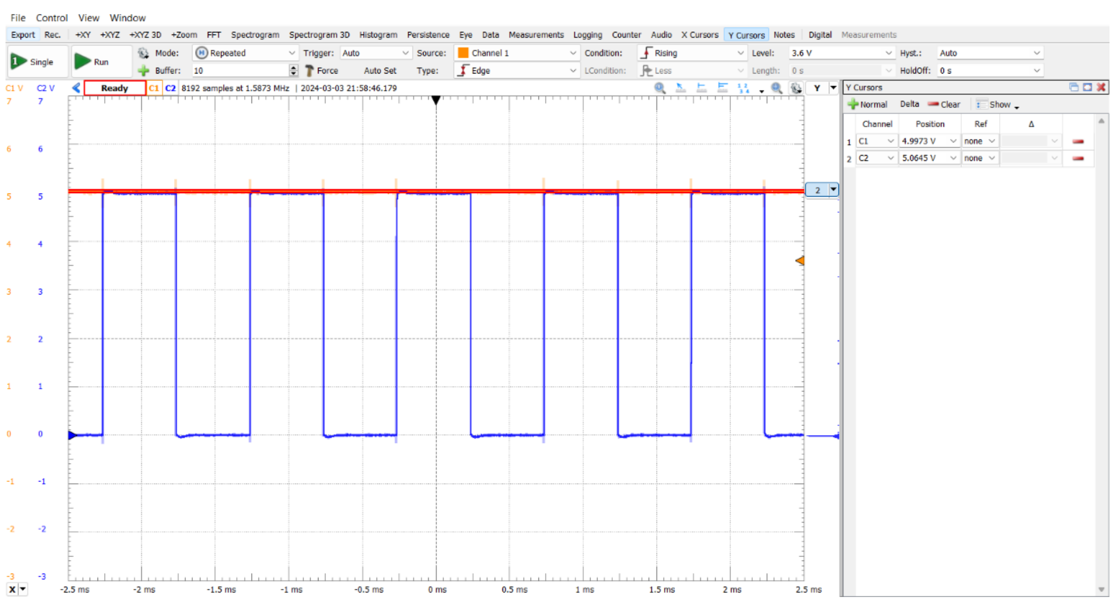

Figure 6. AD2 Results with V_1 (C1) and V_2 (C2)

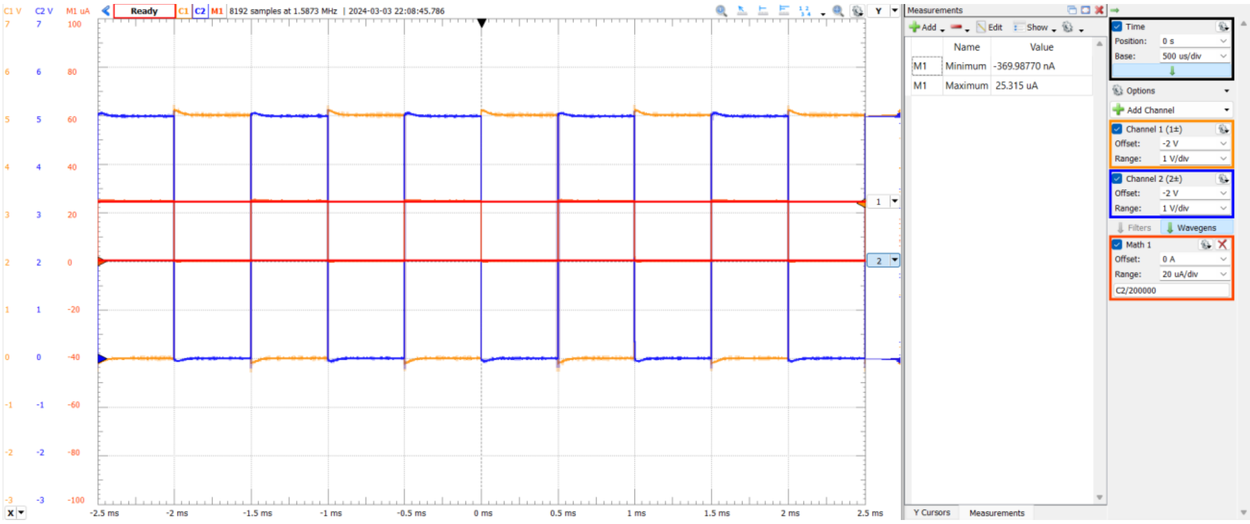

Figure 7. AD2 Results with Current Across Resistor

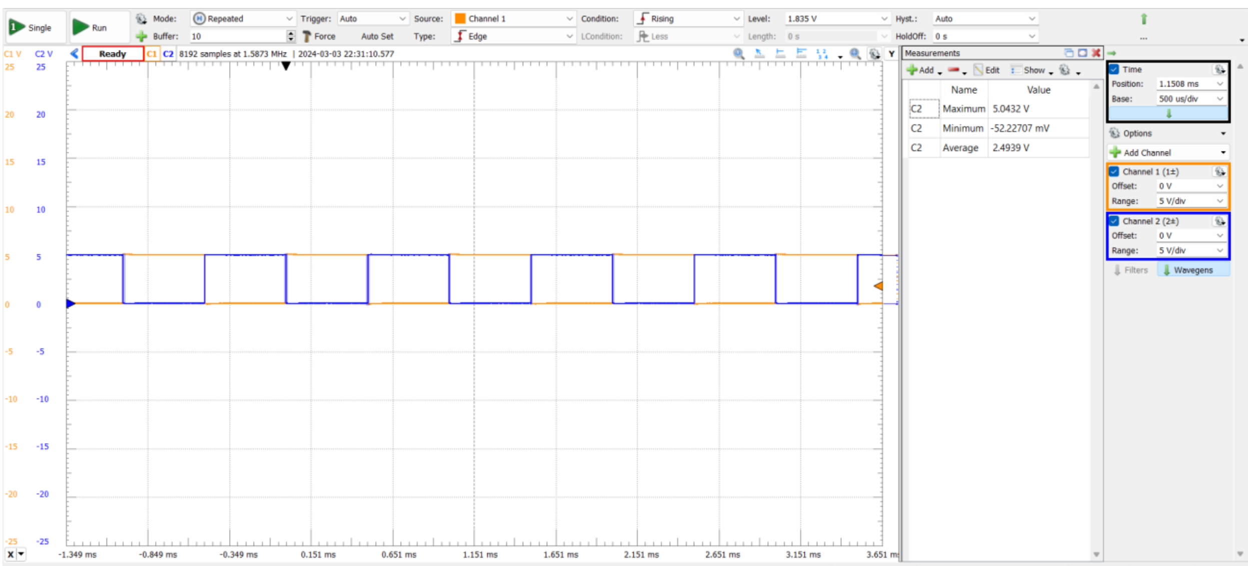

Figure 8. AD2 Results with Forward Voltage

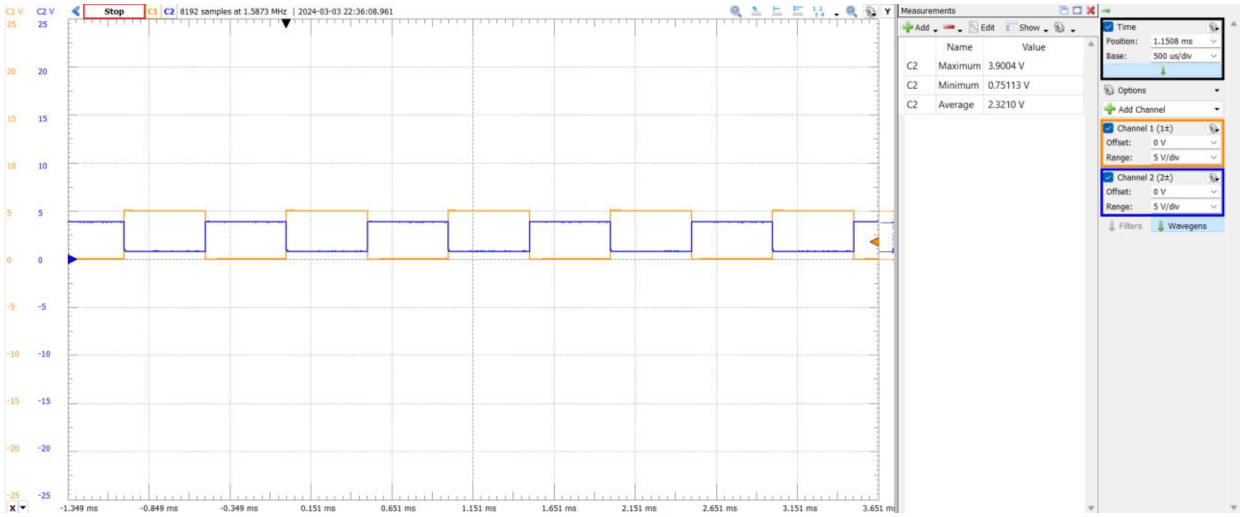

Figure 9. AD2 Results with Reverse Voltage

iii. Results

Based on the measurements, the results illustrate the non-idealities in the type I switch. In an ideal switch, the resistance should be zero during the switch's ON state, but in the physical switch, the resistance was non-zero, amounting to 9.63kΩ. Due to the usage of the N-channel and P-channel MOSFETs and its internal properties, the voltage drop across the drain and the source are non-zero. During the OFF state, the current across an ideal switch should be zero, whereas there is some leakage current in a non-ideal switch. According to the measurements of the physical switch, the leakage current was calculated to be 3.36 mA, proving its non-ideality. This is also likely due to the properties of the MOSFETs which require a certain amount of current to function even in its OFF state. Furthermore, the switches bidirectionality was verified by swapping the voltage sources, where the forward and reverse voltages should be identical in an ideal switch. In the physical implementation, however, there was a percent difference of 7.18% between the two voltages. This result is expected as MOSFETs are less efficient when it is reversed as demonstrated by the reverse conductivity of 92.8% because it switches the flow of current between the source and drain.

iv. Design Trade-offs

Several design factors were considered during the type I switch design with a primary focus on simplicity and efficiency. The design with a N-channel and P-channel MOSFETs on a single IC with two resistors offers a simple, practical switch while remaining cost-efficient, despite the small leakage current of 3.36 mA and ON resistance. While more complex circuits with NOT gates and more MOSFETs may offer improved performance, the selected design optimally balances simplicity, functionality, and economic advantages.

4. Switch Type II

i. Circuit Schematic

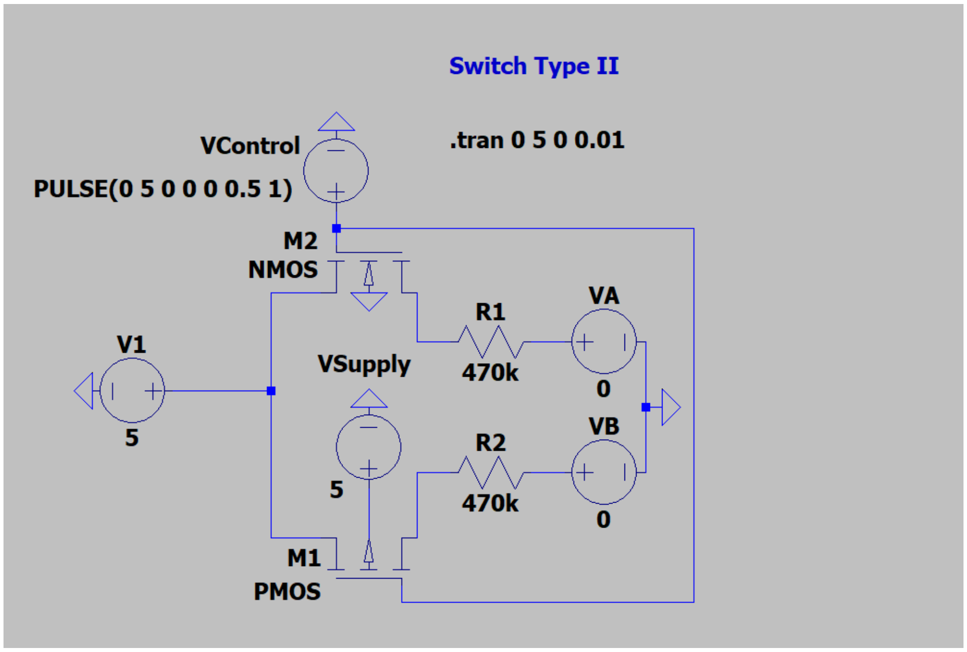

Figure 10. Circuit Schematic of Type II Switch

ii. Measurement Procedure

LTSpice Simulation

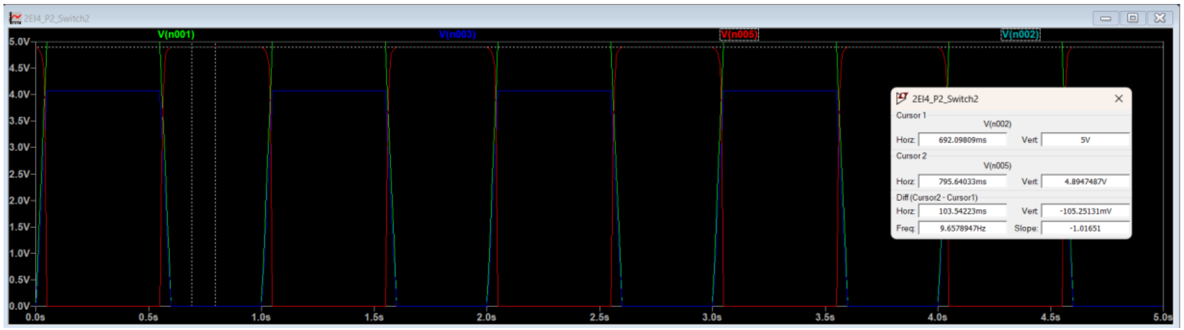

Figure 11. Simulation Results for VA and VB

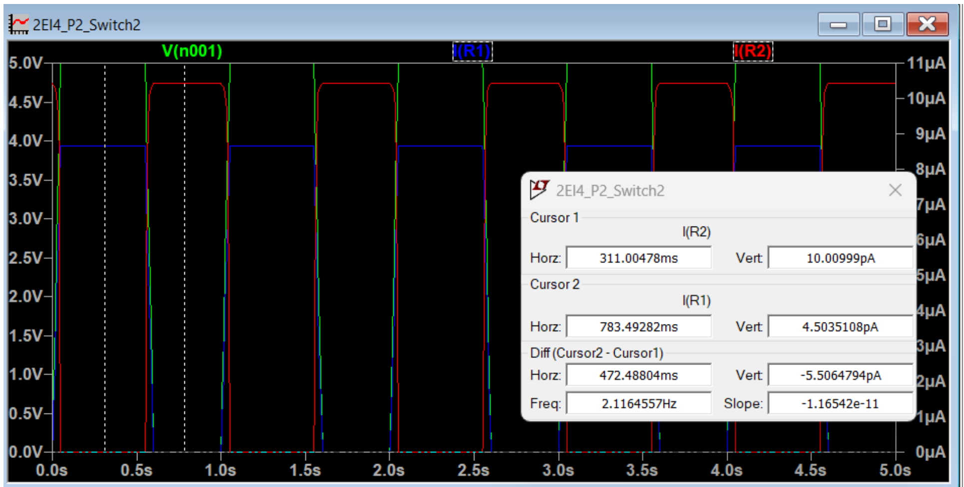

Figure 12. Simulation Results for Resistor Currents

Switch Implementation

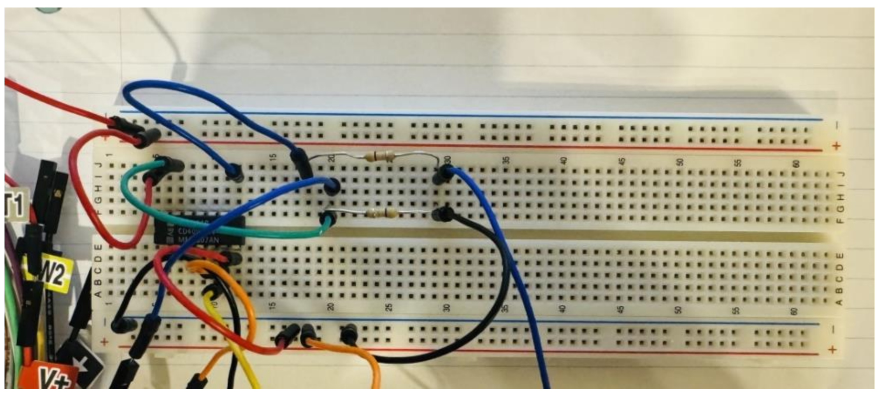

Figure 13. Physical Circuit for Type II Switch

Non-Ideality	Measurements	Quantization
When the switch is ON, the resistance should be zero. A non-ideal switch has a non-ideal resistance value when switch is ON.	$R_1 = R_2 = 470k\Omega$ $V_A = 2.5148V$ $V_B = 2.0098V$ $I_A = 8.6989$ uA $I_B = 10.746$ uA $R_{switch, A} = V_A/I_A = 289.09k\Omega$ $R_{switch, B} = V_B/I_B = 187.02k\Omega$	Therefore, the $R_{switch, A}$ = $289.09k\Omega$ and $R_{switch, B}$ = $187.02k\Omega$, quantifying the non-ideality in the resistance during the switch's ON state.
When the switch is OFF, the current should be zero. A non-ideal switch has a non-ideal current value when switch is OFF.	$V_{N,1} = 5.0470V$ $V_{N,2} = 4.0810V$ $V_{N, drop} = V_1 – V_2 = 0.966V$ $V_{P,1} = 5.0508V$ $V_{P,2} = 4.0885V$ $V_{P, drop} = V_1 – V_2 = 0.9623V$ $R = 470k\Omega$ $I_{N, leak} = V_{drop} /R = 0.0021$ mA $I_{P, leak} = V_{drop} /R = 0.0020$ mA	Therefore, the leakage current is 0.0021 mA and 0.0020 mA, demonstrating the non-ideality in the switch during its OFF state.
The range of V_1 and V_2 should be limitless, meaning the switch should be able to use any voltage. A non-ideal switch has $V_{min} < V_1$ and $V_2 < V_{max}$.	$V_{DS, maximum} = 20V$ $V_{bulk} = 5V$	Based on the datasheet, the maximum voltage is 5V.
The switch should be bidirectional. The non-ideality is that the switch will have the same resistance value when $V_1 < V_2$ and $V_1 > V_2$.	$V_{forward, A} = 4.1182V$ $V_{reverse, A} = 4.1145V$ $V_{forward, B} = 5.0847V$ $V_{reverse, B} = 5.0357V$ $R = 470k\Omega$ $I_{forward, A} = 0.00876$ mA $I_{reverse, A} = 0.00875$ mA $I_{forward, B} = 0.0108$ mA $I_{reverse, B} = 0.0107$ mA $k_A = 0.998$ reverse conductivity$_{, N}$ = 99.8% $k_B = 0.991$ reverse conductivity$_{, P}$ = 99.1%	Therefore, the switch is bidirectional with non-idealities. The reverse conductivity is 99.8% for N-channel MOSFETs and the percent difference in the forward and reverse voltages is 0.09%. The reverse conductivity is 99.1% for P-channel MOSFETs and the percent difference in the forward and reverse voltages is 0.97%.

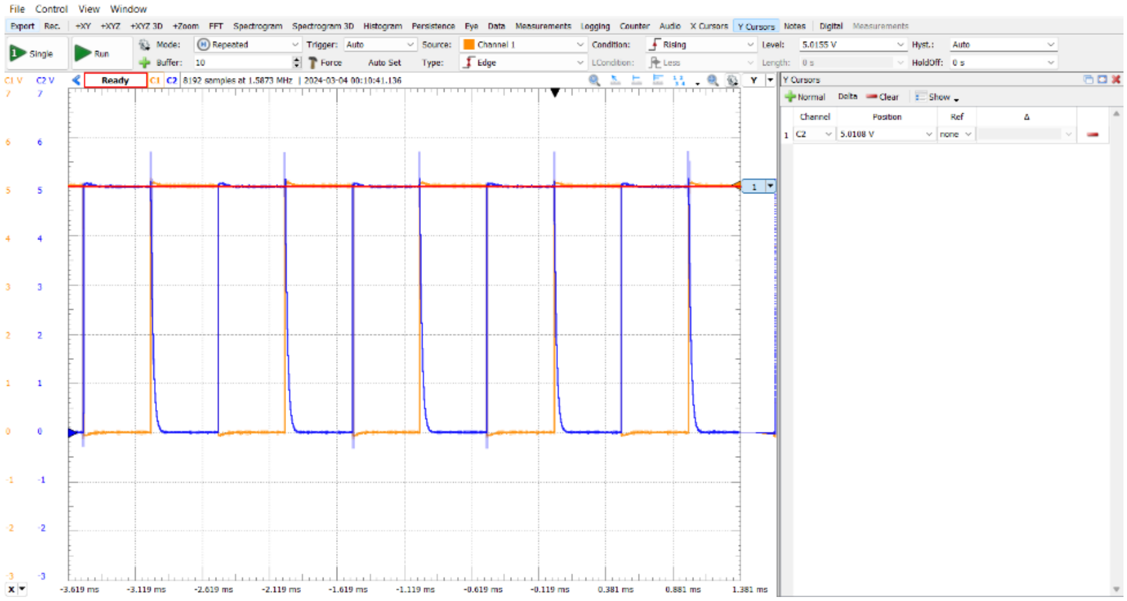

Figure 14. AD2 Results of Vcontrol (C1) and VA (C2), where VA = V1 ≈ 5V when Vcontrol = 0V

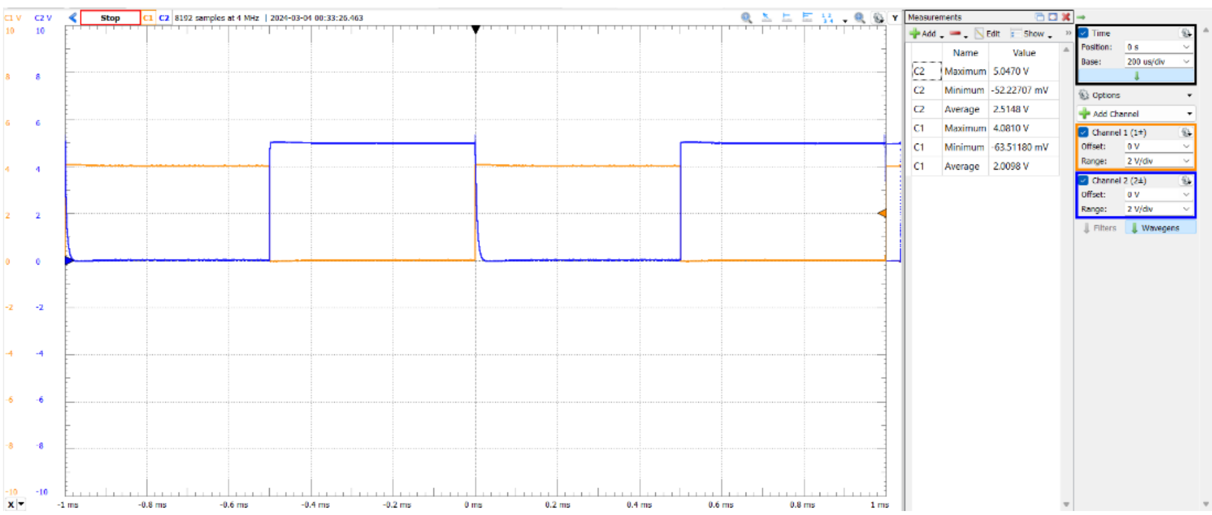

Figure 15, AD2 Results of VA (C1) and VB (C2) where VA = V1 ≈ 5V when Vcontrol = 0V and VB = V1 ≈ 5V

when Vcontrol = +5V

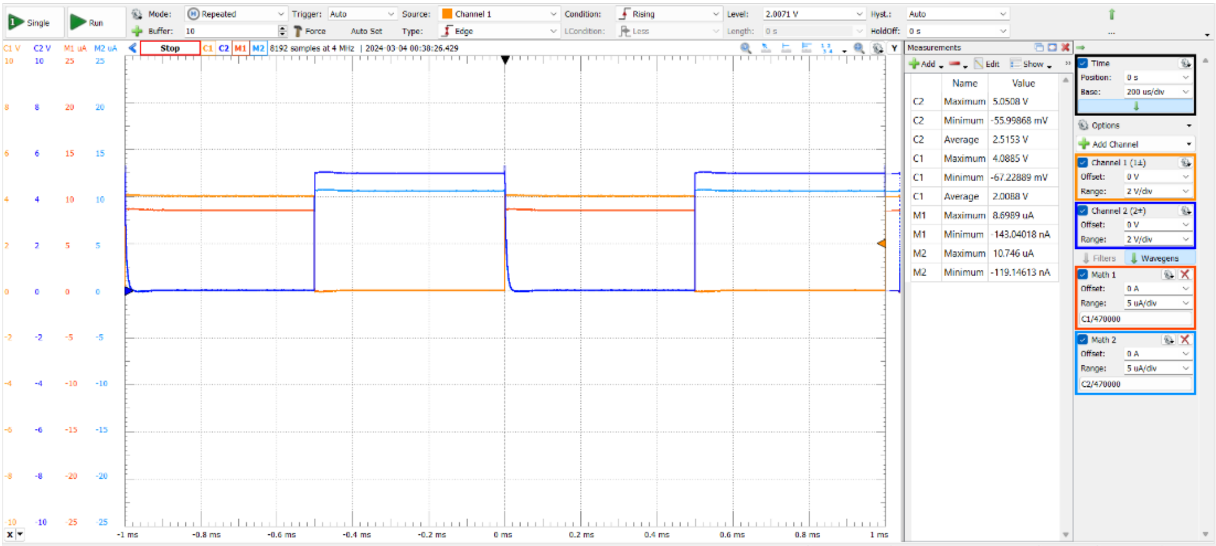

Figure 16. AD2 Results for the Currents

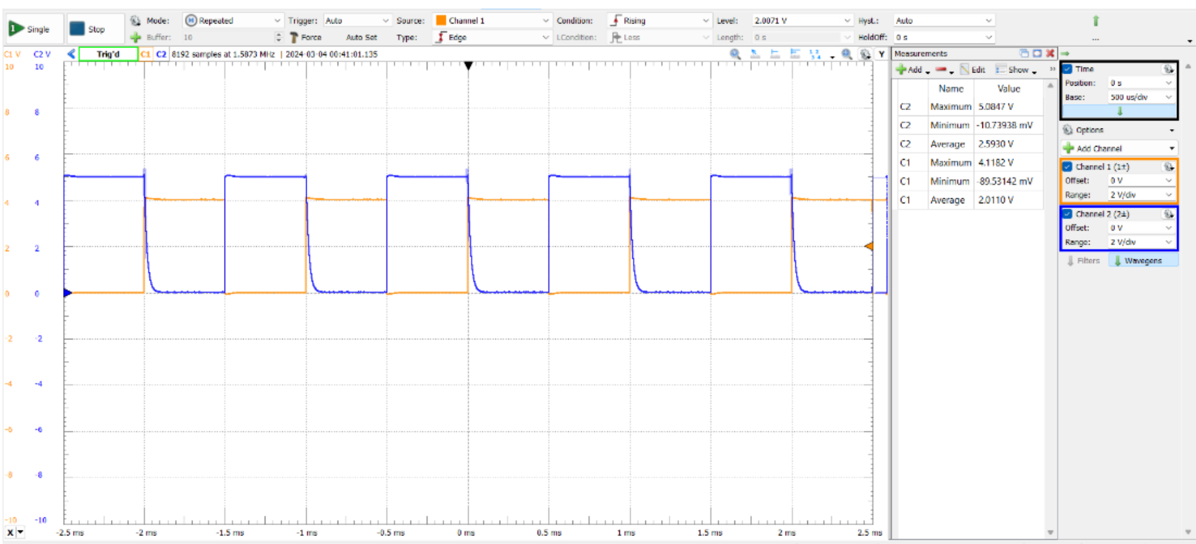

Figure 17. Forward Voltages for VA and VB

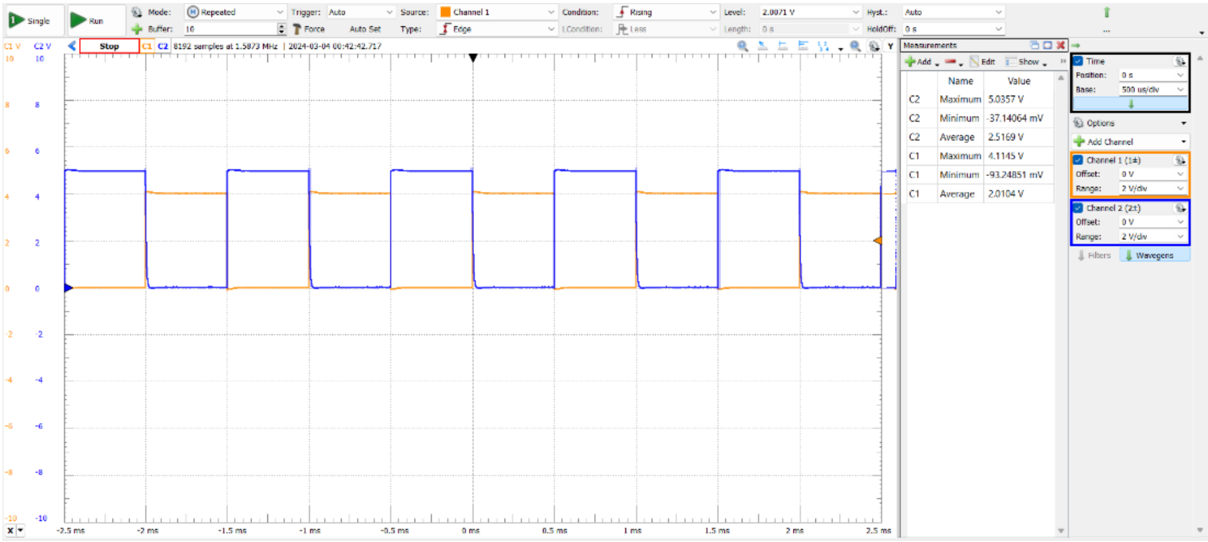

Figure 18. Reverse Voltages of VA and VB

iii. Results

According to the measurements, the switch exhibits the non-idealities in its properties. Compared to the theoretical resistance of zero during the switch's ON state, the physical switch has a $R_{switch, N}$ = 289.09kΩ and $R_{switch, P}$ = 187.02kΩ, quantifying the non-ideality in the resistance. This behaviour is likely due to the properties of the MOSFETs that were used in the design and internal resistance of the components. The current in an ideal switch should be zero during its OFF state, but due to the non-idealities in the physical switch there was some leakage current, amounting to the leakage current is 0.0021 mA and 0.0020 mA, which are nearly negligible. Additionally, the switches bidirectionality was verified by switching the voltage sources and reversing the current direction, like switch type I. In the physical implementation, there was a percent difference of 0.09% difference between the forward and reverse voltages in the N-channel MOSFETs. Similarly, there was a percent difference of 0.97% in the P-channel MOSFETs. While there are differences, the percentage is nearly negligible in both MOSFETS. This behaviour is likely due to the decrease in efficiency when it is reversed as demonstrated by the reverse conductivity of 99.8% and 99.1% because it switches the flow of current between the source and drain.

iv. Design Trade-offs

Several design considerations were made in the implementation of the type II switch with an emphasis on simplicity and functionality. In the design, two MOSFETS, one P-channel and one N-channel, and two resistors are used, providing a simple switch with efficient reverse conductivity and minimal leakage current, achieving a strong performance. While a more complex design with more MOSFETs may have reduced the resistance during the switch's ON state, the chosen design optimized the balance between simplicity, efficiency, and cost benefits.

References

[1] O. A. Ahmed, “Power Semiconductor Devices,” *University of Technology, Electrical Engineering Department*. [Online]. Available: https://odayahmeduot.files.wordpress.com /2015/11/lecture-02.pdf . [Accessed February 17, 2024].

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[3] “CD4007CN Datasheet (PDF) – Fairchild Semiconductor,” *AllDatasheet*. Available: https://pdf1.alldatasheet.com/datasheet-pdf/view/50834/FAIRCHILD/CD4007CN.html. [Accessed March 2, 2024].