Design Project 2

Voltage Controlled Switches

ELECENG 2EI4

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Ideal Switches:

An ideal switch is an electrical component that is used to control the flow of current in a circuit. It operates in two separate states, ON (closed) and OFF (open). In the ON state, the switch acts as a short circuit, allowing current to flow through with zero resistance with no voltage drop. In the OFF state, it behaves as an open circuit, providing infinite resistance to block current flow completely. To consider a switch to be ideal, it must meet several requirements. It should always act as a short circuit when in the ON state with zero resistance, ensuring that there is no voltage drop. It must also always act as an open circuit when in the OFF state with infinite resistance, preventing current leakage. Furthermore, the switch must maintain zero resistance regardless of the applied voltage, ensuring 100% efficiency with no power dissipation or heat generation. Finally. The current in the switch must be bidirectional, allowing it to operate within any voltage range.

Non-Ideal Switches:

A non-ideal switch is a more realistic concept and differs from the ideal switch due to physical constraints and unpredictable behaviour, leading to limitations in efficiency and underperform. Unlike an ideal switch, a real switch has a nonzero resistance when in the ON state, resulting in voltage drops and power dissipation. Furthermore, when in the OFF state, the switch does not achieve infinite resistance, causing small current leaks, leading to power loss and unexpected circuit behavior. Additionally, non-ideal switches have slight delays between states as well as specific voltage and current ratings. If they were to go beyond them, it may result in damage or unpredictable circuit behaviour. These limitations cause switching inefficiencies which can lead to potential overheating. Since real switches cannot achieve infinite resistance when off, some leaked current will always be present. Considering the practical constraints is key when designing circuits as the performance and reliability of real switches vary based on materials, design, and application.

Test Plan:

To verify the characteristics and behaviour of a non-ideal real switch, a simplified set of tests was created and will be used to analyze the switch's performance in both the ON and OFF states. The tests will focus mainly on resistance, leakage current, and bidirectionality. Measurements will be taken using the built-in multimeter, wave generator, and oscilloscope on the AD3.

Test Objectives:

1. Measure Resistance and Voltage Drop in ON State
    - Apply a constant 5V DC across the switch
    - Measure the voltage drop across the terminals using a multimeter
    - Calculate the ON state resistance using Ohm's Law by measuring the current

2. Measure Leakage Current in the OFF State
    - Apply 5V DC across the switch while it is open
    - Measure the leaked current flowing through the switch using an ammeter
3. Test Bidirectionality
    - Repeat the ON state resistance measurement with reversed switch terminals.
    - Compare resistance values to confirm if the switch behaves identically in both directions.
4. Verify Voltage Limitations
    - Slowly increase the applied voltage from 1V to 5V in 1V steps while monitoring switch performance
    - Identify any voltage threshold where the switch behavior changes unexpectedly

Switch 1:

Schematic Diagram:

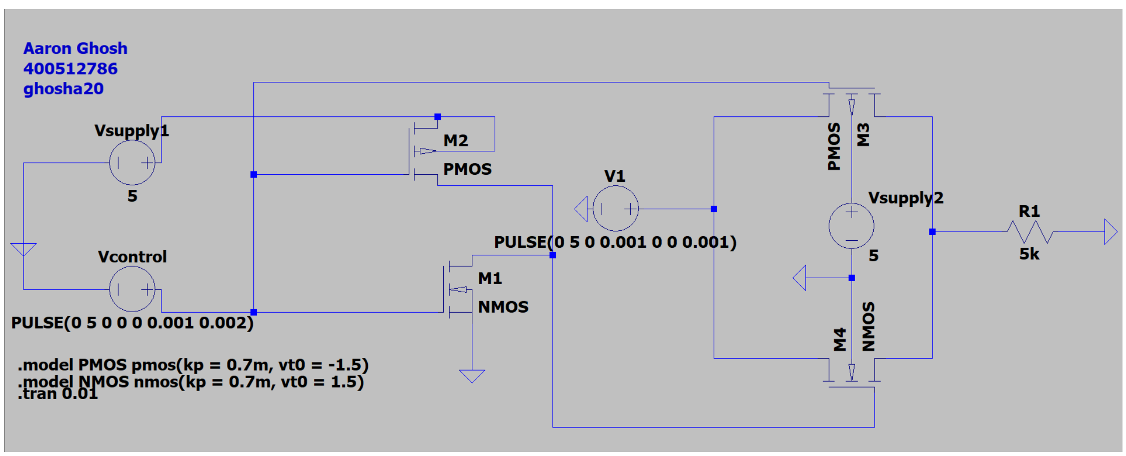

Figure 1: Schematic Diagram for Switch 1

Simulation:

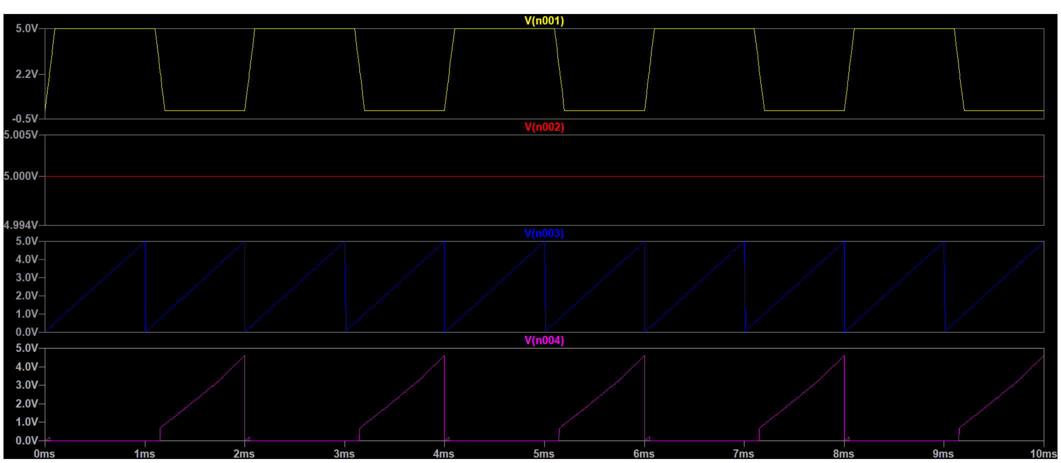

Figure 2: Simulation for Switch 1

Physical Circuit:

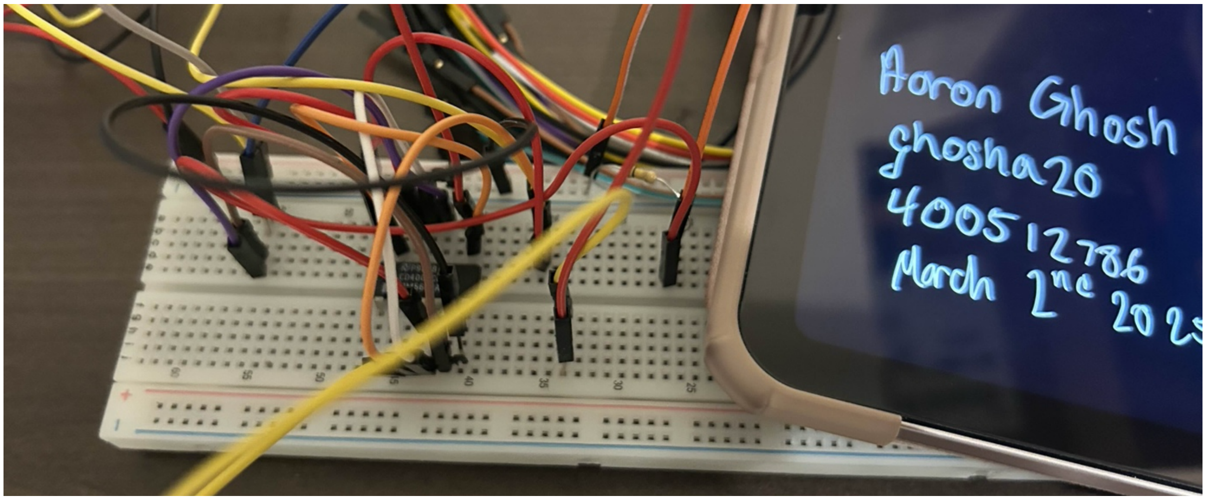

Figure 3: Physical circuit for Switch 1

Measurements:

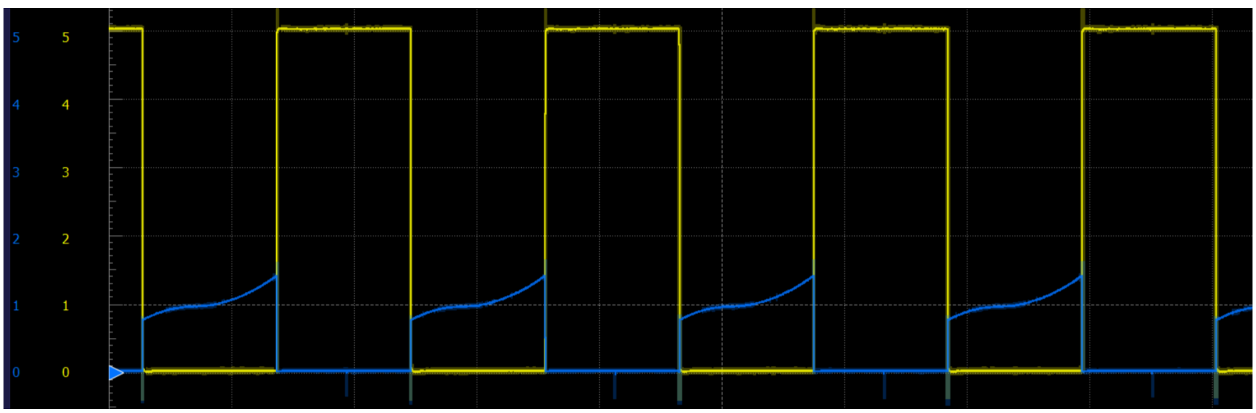

Figure 4: AD3 waveforms for Switch 1 (10KΩ)

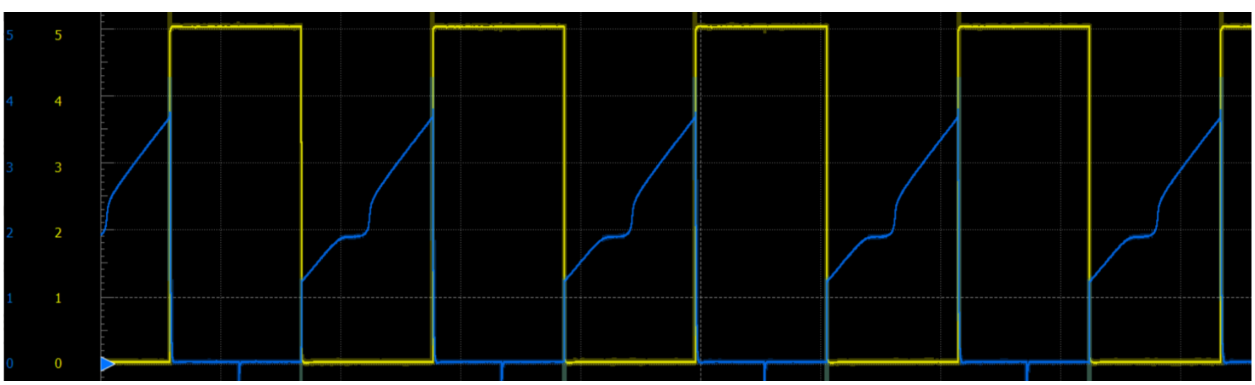

Figure 5: AD3 waveforms for Switch 1 (100KΩ)

Resistance	I_{on} (mA)	R_{on} (Ω)	I_{off} (mA)	R_{off} (Ω)
10KΩ	0.4534	487	0.048	916
100KΩ	0.04921	345	0.0052	9232345

Table 1: Tested current and resistor values

Resistance	V_1 (V)	$V_{2\ on}$ (V)	$V_{2\ off}$ (V)	$V_{drop\ on}$ (V)	$V_{drop\ off}$ (V)
10KΩ	5.03	4.77	0.05	0.28	4.95
100KΩ	5.04	5.02	0.04	0.02	4.96

Table 2: Tested voltage and resistor values

The bidirectionality test results were as expected and did not have any abnormal behaviour as the value of R_{on} remained the same when reversing the flow of current.

Theoretical Explanation:

The test results for switch 1 were reasonable and fell within the expected range. The resistance in the ON state was much lower than in the OFF state, this aligns with ideal switch behavior as when the switch is open, it showed extremely high resistance values, indicating that only a small amount of current leaked, behaving like an ideal switch.

Throughout testing, it was confirmed that the switch is bidirectional. This makes sense as MOSFETs are built symmetrically, allowing current to flow in either direction without any issue. If set up correctly the bulk terminal will allow this property based on the MOSFET's type. Furthermore, the switch performed as intended across the input voltage ranges, with the exception of a small inconsistency between 1.5V and 2.5V. This happened because the MOSFETs entered saturation mode. The nMOS handled voltages from 0-3V, while the pMOS took over from 3-5V, and the transition between them caused minor distortion.

Design Trade-offs:

The first switch can be designed in multiple ways, however, the design selected was chosen as it uses a minimal number of components, thus being cost-effective and less complex. This design includes two power sources, a n-type MOSFET, a p-type MOSFET, and a resistor. By minimizing the total amount of components, it helps to reduce noise in the circuit. This improves the accuracy of measurements by preserving signal characteristics and minimizing inconsistencies. However, this design includes some limitations. One constraint is the limited variety of components available from the course kit, restricting the number of potential designs. Furthermore, the AD3 had its own set of limitations as it was tasked for supplying the voltage for the circuit. This limited the switch design to be within a 0 - 5V range. A larger range would allow for more flexibility and functionality.

Another major decision was deciding to use a MOSFET over a BJT. To make this decision, several factors were taken into consideration such as power efficiency, power loss, and switching performance. In the end, we chose to move forward with the MOSFET as it consumes less power and operates more efficiently compared to the BJT. Moreover, MOSFETs are typically more thermally stable which helps minimize switching losses.

Switch 2:

Schematic Diagram:

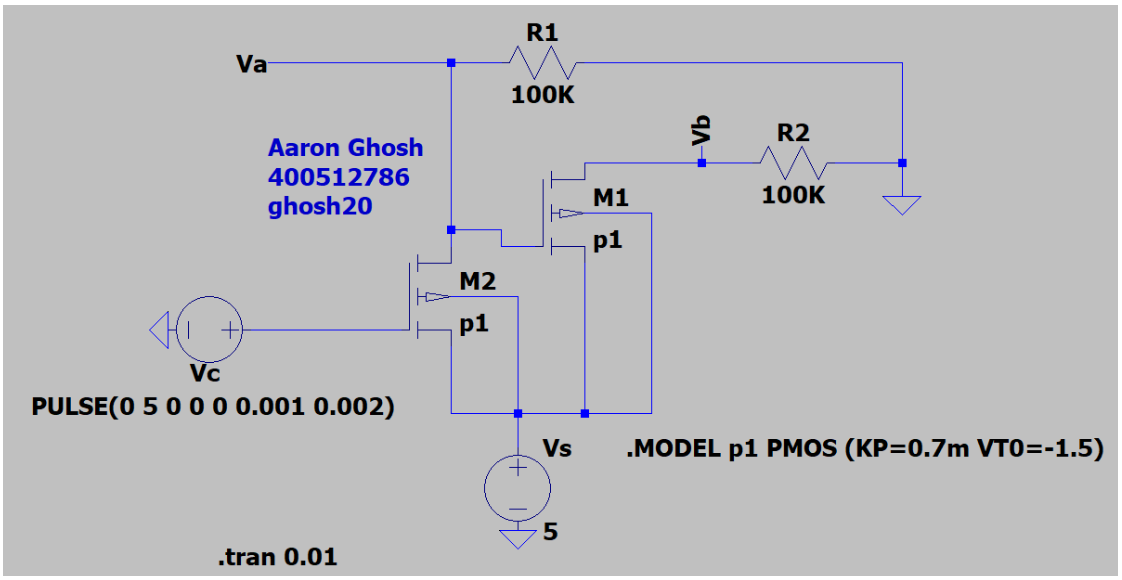

Figure 6: Schematic for Switch 2

Simulation:

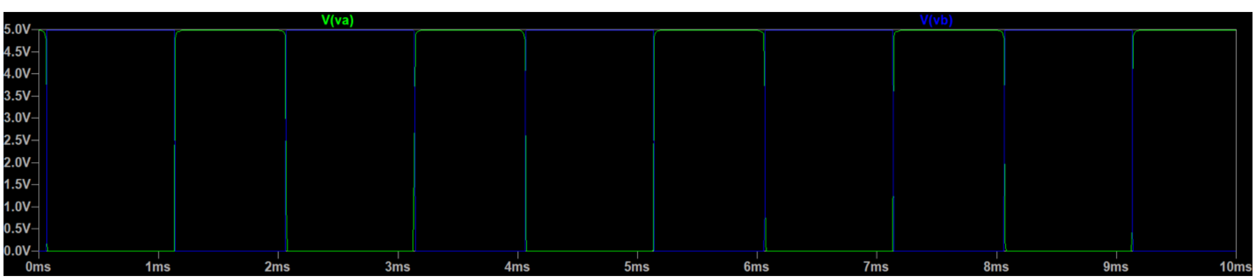

Figure 7: Simulation for Switch 2

Physical Circuit:

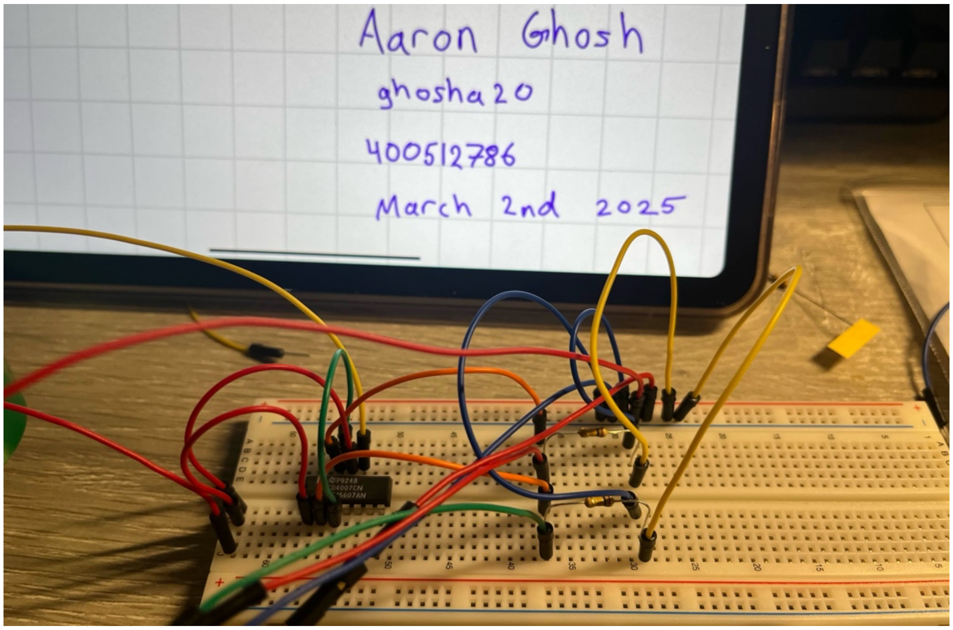

Figure 8: Physical circuit for Switch 2

Measurements:

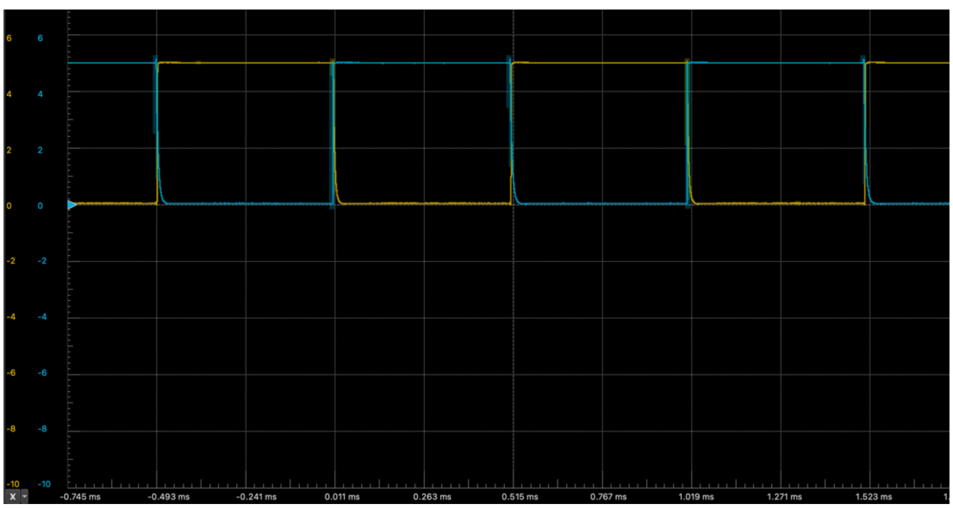

Figure 9: AD3 waveforms for Switch 2

Resistance	$I1_{on}$ (mA)	$R1_{on}$ (Ω)	$I1_{on}$ (mA)	$R2_{on}$ (Ω)	I_{off} (mA)	R_{off} (Ω)
10KΩ	0.4741	568	0.048	703	0.0039	1.124M
100KΩ	0.05022	412	0.0052	387	0.00061	11.987M

Table 3: Tested current and resistor values

Resistance	V_1 (V)	$V_{2\ on}$ (V)	$V_{2\ off}$ (V)	$V_{drop\ on}$ (V)	$V_{drop\ off}$ (V)
10KΩ	5.01	4.72	0.03	0.32	4.93
100KΩ	5.03	5.04	0.01	0.02	4.97

Table 4: Tested voltage and resistor values

Just like switch 1, in switch 2, the bidirectional characteristic behaved as expected. It operated normally and did not have any weird characteristics when the terminal was switched. The value of R_{on}, remained very similar, proving that current can flow in both.

Theoretical Explanation:

Whenever $V_{CONTROL} = 0V$ it will set $V_{SG} = 5V$, which is greater than the threshold voltage ($V_T = 1.5V$). This causes MOSFET 1 to set it in linear mode. Moreover, since MOSFET 2's gate is tied to V_A which is also V_{D1} whereas $V_{G2} = 5V$. The source gate voltage is $0V < -V_T$, setting MOSFET 2 into cutoff mode where $V_B = 0V$. Similarly, when $V_{CONTROL} = 5V$, $V_{SG} = 0V$ for MOSFET 1, setting it in the off mode. As a result, no current flows through MOSFET 1, making $V_A = 0V$ and forcing V_{G2} to 0V. This makes $V_{SG2} = 5V$, activating MOSFET 2 in linear mode.

Design Trade-offs:

Just like switch 1, the design for switch 2 prioritizes efficiency and full utilization of the supply voltage range. However, this design introduces additional complexity, which can slightly increase costs. However, despite this, the choice of using a MOSFET design over a BJT design offers numerous advantages. MOSFETs have lower power consumption, higher output resistance, and superior thermal stability when compared to BJTs. However, one drawback to this design is that it would not be ideal to mass produce as BJTs are usually cheaper than MOSFETS, making this design not cost efficient as a switch. However, in the scope of our project, cost was not a factor to decide between the two devices as we had access to both and must prioritize efficiency and performance, making it the clear choice.

References:

[1] A. S. Sedra, K. C. Smith, T. C. Carusone, and V. Gaudet, Microelectronic Circuits, 8th ed. New York, NY, USA: Oxford Univ. Press, 2019.

[2] "Project 2", Avenue to Learn, February 25, 2025

[3] Diotec Semiconductor AG, 1N4148, 1N4150, 1N4151, 1N4448 Small Signal Switching Diodes Data Sheet, Aug. 2017. [Online]. Available: http://www.diotec.com/.