Royal Military College of Canada
Department of Electrical and Computer Engineering
EEE455/7 Electrical and Computer Engineering Design Project

DID-07 - Detailed Design Document

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Chapter 1

Introduction

This document is the detailed design document for the Class-D Audio Amplifier project. The purpose of this project is to take an analog signal and amplify it using pulse-width modulation techniques and new GaN transistor technologies. This chapter will cover some background information as well as the scope and aim of this project. Chapter 2 will cover the design of the project, highlighting the changes made to the original design, as well as problems that were prevalent within the design, with the solutions that were applied to address them. Chapter 3 will discuss the general assembly process of the amplifier and issues that were encountered. Chapter 4 will go over the testing methodologies and the results from these tests. Chapter 5 will explain the results and how they relate to the requirements set out at the start of this project. Finally, chapter 6 will wrap up the document and leave the reader with some final thoughts.

1.1 Document purpose

The purpose of this document is as follows:

1. To provide any overall changes or deviations from the original design in terms of the Statement of Requirement (SOR), the Preliminary Design Specification (PDS), and the Schedule Update;
2. to present a detailed discussion on the design of the class D amplifier;
3. to provide all design artefacts such as schematics, figures, layout drawings, and source code;
4. to present the final results of testing phase; and
5. to provide a summary of the degree of success of the amplifier design.

1.2 Background

1.2.1 Amplifiers

An audio amplifier's class, whether it be A, AB, or D, refers to the amount of time, per cycle, that the output transistors are conducting. For example, when presenting a class-A amplifier with a sine wave, the output transistor follows the input for the entire 360 degrees of the cycle. This has the desirable characteristic creating a near-perfect, or analogous, copy of the input signal at the output. For this reason, a class-A amplifier is deemed to be a linear device. A class-AB amplifier operates as a class-A amplifier at low power, while operating in class-B only in high-output scenarios. Class-B requires one pair of transistors, each conducting only for half of the input sine wave. In this way, each transistor is only conducting for half the time, when it is called upon. This has the effect of increased efficiency at the cost of distortion caused by the crossover region between the pair of semiconductors [1].

A class-D amplifier is a non-linear switching device that sends several short pulses, which are then correlated together to closely recreate the original input signal. Class-D amplifiers are used in everyday technologies such as cellphones and home theatre systems. These amplifiers have become increasingly popular, due to their high efficiency and relatively low cost. When compared to other classes of amplifiers, such as class A or AB, class-D amplifiers have the advantage in terms of efficiency, as the transistors only operate in a fully-on or off state. Theoretically, this would indicate that the only losses of efficiency for class-D would be in the transistor's internal resistance, and the heat dissipated by the transistor, while is switching on and off several times per second.

The technique used to decide for how long the transistors are on or off is called pulse-width modulation (PWM), although other techniques such as pulse-density modulation (PDM) are sometimes used. In the case of a PDM amplifier, the frequency of the output pulse stream must be at least 64 times faster than the sampling frequency of the input signal. For example, a high-resolution audio signal that is sampled at 192 kHz requires the output transistors to switch at 12.288 MHz. At such high frequencies, switching losses become a considerable source of inefficiency in a class-D amplifier, and may put into question the choice of a non-linear amplifier altogether if the efficiency dips into the range of a more traditional linear design.

While commercial offerings of high power PDM class-D amplifiers have yet to appear, the modulation techniques they employ do appear in other audio applications. Sony and Philips Electronics use a technology called Direct Stream Digital (DSD) in their successor to the compact disk, the Super Audio CD (SACD). In contrast to the average CD which uses 16-bit words sampled at 44.1 kHz to encode the voltage levels of the audio waveform, DSD uses a 1-bit signal which is sampled at 2.8224MHz and then further processed by the SACD player [2]. Noise shaping techniques are used to prevent any unwanted noise from appearing in the audible frequency spectrum.

1.2.2 Printed Circuit Boards

Most of today's electronics are built on printed circuit boards (PCB). The cheapest and most popular PCBs are 2-layer boards, meaning they have one conductor layer, a dielectric, and another layer of conductor material. PCBs can be manufactured with more layers if desired, with the option of four and sometimes six layers. Having more layers is often beneficial because it allows the designer to have a dedicated ground plane layer, as well as more signal layers to increase routing options, but this comes at a significant financial cost. The link between layers is called a via. Vias are holes drilled into the board with plating on the outside of the hole to make the electrical connection between layers. Vias are key to effectively using all layers and therefore to minimize the surface area of the board.

Usually, the conductor material used is copper, but more sensitive or high precision circuits may require better conductors such as gold or platinum, although both of these options are substantially more expensive. The thickness of the conductor is usually given in ounces per square foot, with the most popular option being 1 oz/ft^2 (1.4 mils or 0.03556 mm), however some designs call for 2 oz/ft^2. The coating on top of the conductor is called the solder mask. They come in a variety of colours, but the most popular option is green. Solder mask is a permanent protective coating for the conductor traces and also prevents solder from bridging between pads [3]. To facilitate assembly, there is often an additional layer on top of the solder mask called the overlay or silkscreen layer. The overlay is composed of writing to identify where parts go (called designators), part outlines, and a direction indicator for polarized components, diodes, or integrated circuits (IC). The overlay is normally a high contrast colour compared to the solder mask colour. On green solder masked boards, a white overlay is used.

The process by which components are electrically connected is called routing. This creates a "line" between two or more components, called a trace, to connect their pads (where they are soldered onto the board) into the same net. The width of each route is determined by the current that will flow through it, the maximum temperature rise allowed, the trace length, and the conductor thickness. The typical rule of thumb is the higher the current, the wider the trace. A popular baseline for trace width is 10 mils (0.254 mm) for low current circuits.

1.3 Aim

The aim of this project, as stated in the Statement of Requirements, is to design and build a class-D amplifier with low THD+N, high efficiency, and appropriate output power characteristics, to be applied in a home setting [4].

1.4 Scope

The scope of this project is to design and build a class-D amplifier that can function in the real world. This includes but is not limited to:

1. Circuit schematic design;

2. Printed circuit board design; and

3. Assembly and testing.

This will verify and validate the use of GaN technology in audio devices.

Chapter 2

Design

This chapter will discuss the main design considerations for this project as well as present the final design to be manufactured and assembled. Both of these topics will be covered in the coming chapters.

The following sections address the design of each module, part selection considerations, as well as the PCB design. How all of the modules connect to each other can be seen in Appendix A, in which the full schematic is shown.

2.1 Major Design Changes

The project underwent several major iterations:

1. The signal processing stage uses digital pulse-density modulation generated with a micro-controller. The higher switching frequency of the PDM implementation that was proposed would have meant less filtering needed at the output. This was discarded because of the complexity and lack of documentation of PDM;

2. The signal processing stage uses DSD straight from the output of the ADC. This was discarded because of the complexity and lack of documentation on DSD. The lack of documentation made us unsure of the circuit that was built and because of the lack of a transfer function for this non-linear DSD signal, a feedback network was too complex to design for our knowledge base. The higher switching frequency of DSD would have meant less filtering needed at the output;

3. The signal processing stage uses PWM through the use of a purpose-built Class-D audio IC that has a built-in comparator and triangle-wave generator running at frequencies up to 800kHz. The chosen PWM IC already has a time-proven circuit with included feedback. The lower switching frequency of PWM as compared to PDM and DSD will affect the output filter. This was the option that was chosen because of the simplicity of PWM audio compared to other modulation techniques as well as it being well-documented. The time constraint that was imposed upon this project was also a deciding factor.

2.2 Schematic

This section talks about each module–Input, PWM, GaNFET, Output, Protection, and Power–and how they connect to each other to make a class-D amplifier.

2.2.1 Input Module

The input module is comprised of three mains parts: the input select switches, the volume control circuit, and the microcontroller.

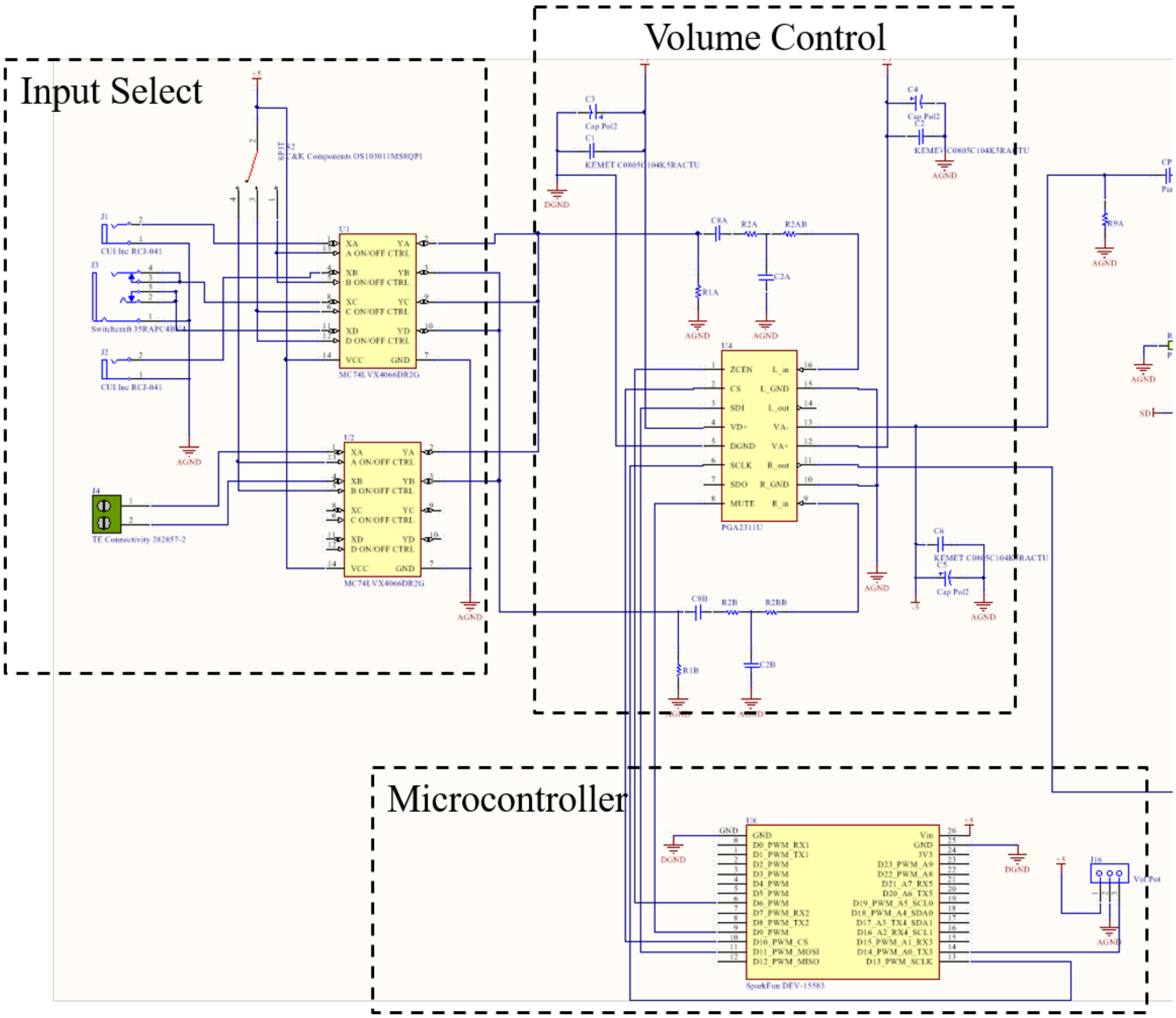

Figure 2.1: Annotated Input Module Schematic

The input select sub-module consists of all four input connectors (2x RCA connectors, a 1/8" jack, and a separate screw terminal for a Bluetooth module or other input), and switches. The main slide switch and the quad switch ICs control which input is fed to the amplifier. The switch ICs are needed because for each output of the slide switch, two signals need to be turned on or off.

Each channel is then fed to the input of the PGA2311 stereo volume control IC through an input filter, which will be described in section 2.4 of this document. The volume control IC requires a serial interface to control it.

The microcontroller interfaces with the volume control IC with code written in C described in section 2.3 and a linear potentiometer. Once the signal leaves the volume control IC, it goes into the PWM and signal processing part of the circuit.

2.2.2 PWM Module

The PWM module consists of the Infineon IRS2092 IC and its accompanying circuitry.

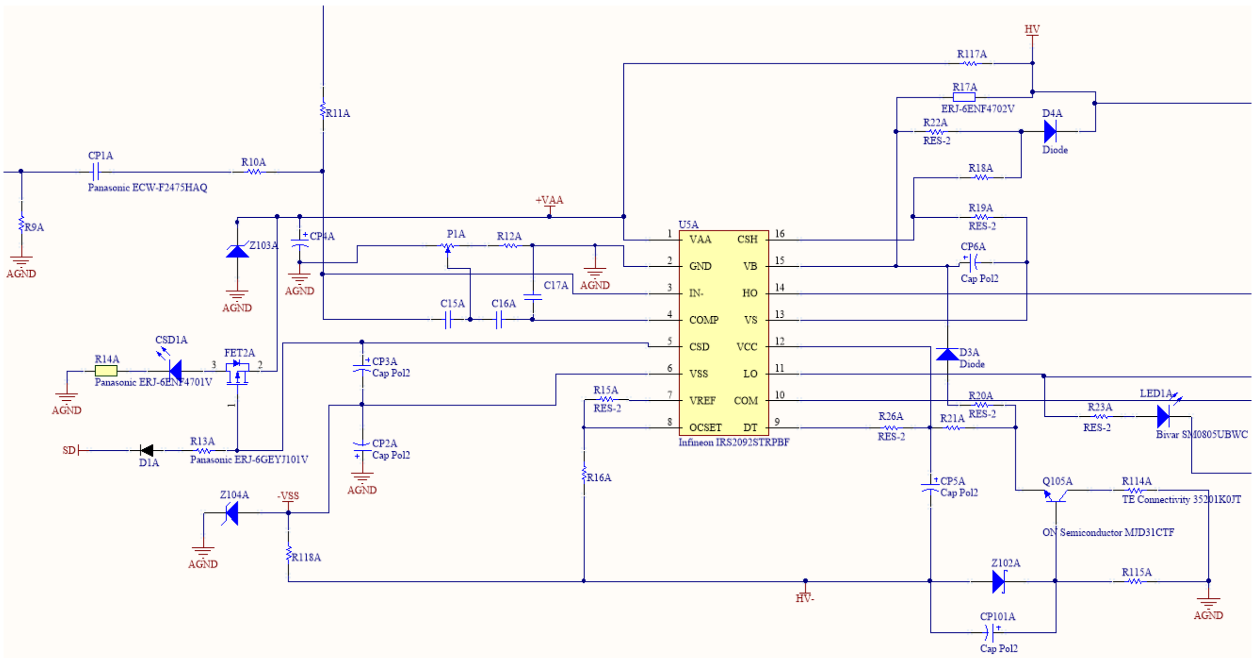

Figure 2.2: Single Channel PWM Module Schematic

In figure 2.2, the output of the Input Module comes in on the left, the wire going up is the feedback from the GaNFETs, and all wires going out the right-hand side go to the gate driver or the GaNFETs. When designing this module, both the circuits from the IRS2092 datasheet [5] and from the GaNFET Evaluation Board [6] were considered. Additionally, to optimize the IC for this use-case, several component values needed to be picked.

Particularly, to get the PWM switching frequency that was desired, two components need to be carefully picked.

Table 2.1: PWM Switching Frequency Values

PWM Switching Frequency Values		
Target Self-Oscillation Frequency (kHz)	C1=C2 (nF)	R1 (Ω)
500	2.2	200
450	2.2	165
400	2.2	141

Target Self-Oscillation Frequency (kHz)	C1=C2 (nF)	R1 (Ω)
350	2.2	124
300	2.2	115
250	2.2	102
200	4.7	41.2
150	10	20.0
100	10	14.0
70	22	4.42

Table 2.1, reconstructed from the IRS2092 Application Note, shows which values are needed to achieve different switching frequencies [7]. To allow for maximum flexibility in the design, a potentiometer was used instead of a resistor to be able to vary the switching frequency if the need arose. The IRS2092 has a maximum switching frequency of 800 kHz, and the aim is to be able to use the full range of the IC while still producing quality audio [5]. The higher the PWM switching frequency, the need for filtering close to the audio-band decreases.

A second case in which values needed to be chosen was when deciding how much dead-time the IC was to have. Dead-time can be described as the time between high states in different parts of a circuit [8]. Particularly, in a half-bridge configuration, too little dead-time can cause shoot-through which would destroy the circuit, while too much dead-time results in more Total Harmonic Distortion (THD), something that is to be avoided in audio circuits [9].

Table 2.2: Dead-Time Selection Parameters

Dead-Time Selection Parameters			
Dead-Time Mode	R1 (kΩ)	R2 (kΩ)	DT/SD Voltage
DT1	<10	Open	Vcc
DT2	5.6	4.7	0.46 × Vcc
DT3	8.2	3.3	0.29 × Vcc
DT4	Open	<10	COM

Table 2.2, reconstructed from the IRS2092 Application Note, shows which values are required to get different dead-time modes [7]. To ensure no shoot-through, the dead-time needs to be greater than the turn-off time of the transistor. There is no information on the transistor that is used in this design, the GaN Systems GS61004B, but the similar GaN Systems GaN E-HEMT GS66508T has a turn-off time of 4.5 ns. The minimum dead-time mode (DT1 from table 2.2) for the IRS2092 is 25 ns and this is the dead-time mode that was chosen for this design.

2.2.3 GaNFET Module

The GaNFET module only consists of two main parts: the gate drivers and the transistors. The gate driver used in this are the Texas Instruments LM5113. The gate drivers and why they are needed is elaborated upon in section 2.5. The second part of this module are the two transistors set in a half-bridge topology with DC decoupling capacitors on each rail.

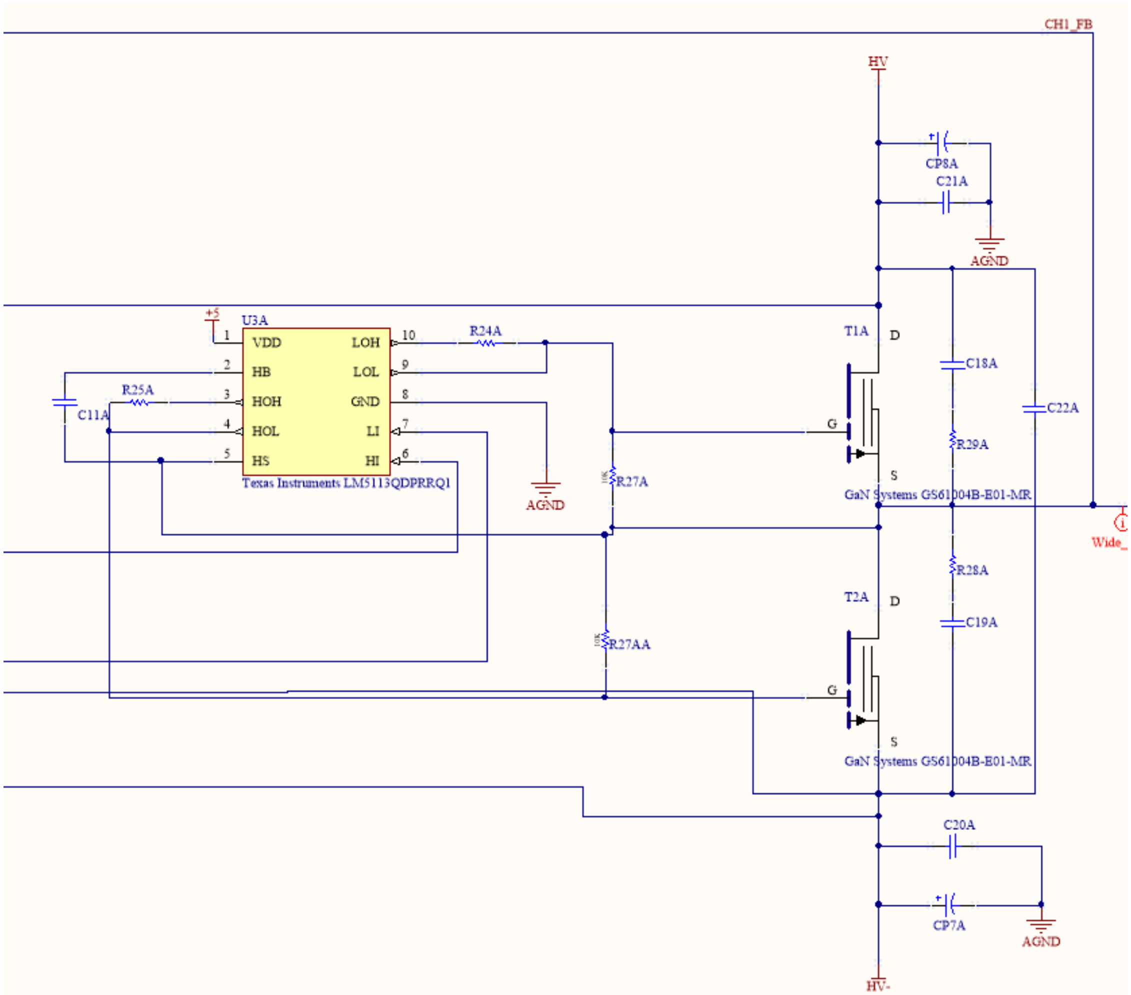

Figure 2.3: Single Channel Gate Driver and GaN E-HEMTs

Figure 2.3 shows one channel of the GaNFET module schematic as well as the feedback that goes back to the PWM module, as seen in figure 2.2. The capacitors in parallel with the transistors and the half-bridge help decrease DC voltage offset going through to the output.

2.2.4 Output Module

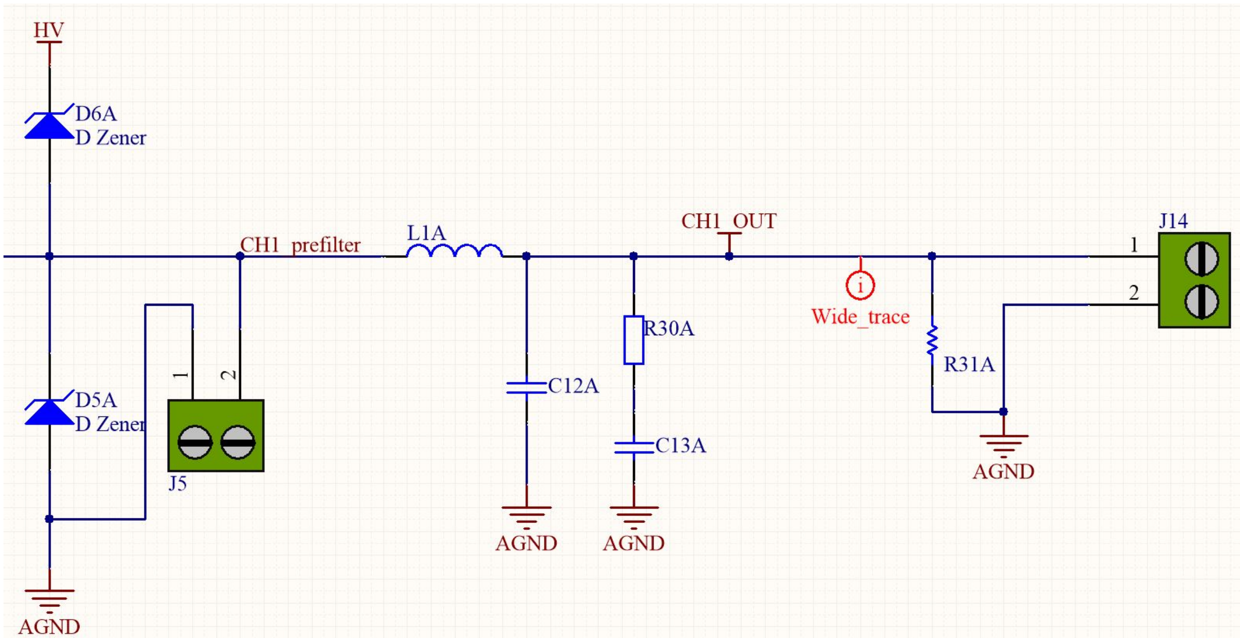

Figure 2.4: Single Channel Output Module

As figure 2.4 shows, the output module is comprised of clamping diodes, the output filter, and screw terminal outputs.

The clamping diodes act as a protection against a rise in voltage on the output rail towards the transistors when the inductor discharges [10]. Normally, a clamping circuit consists of a diode, a capacitor, and a resistor and is used as an AC level shifter, but for the simple protection needed in this case, the capacitor and resistor were not used.

The output filter limits the range of frequencies allowed through to the output and is discussed further in section 2.4.

This module has two screw terminal outputs per channel: one for the pre-filter output and one for the post-filter output. This was done to allow us to see the waveform that comes out of the GaNFET module and for further testing of the signal through the filter as well as to correctly analyze the filter and ensure it meets the specifications and simulation results.

2.2.5 Protection Circuit

The protection circuit for this design was taken mostly from the IRAUDAMP7S reference design protection circuit, adapted for the needs and specifications of this design [11]. This protection circuit provides over-voltage protection (OVP), under-voltage protection (UVP), speaker DC-voltage protection (DCP), and over-temperature protection (OTP) if needed. Over-current protection for the circuit is provided by the IRS2092 IC, expanded upon in section 2.5.

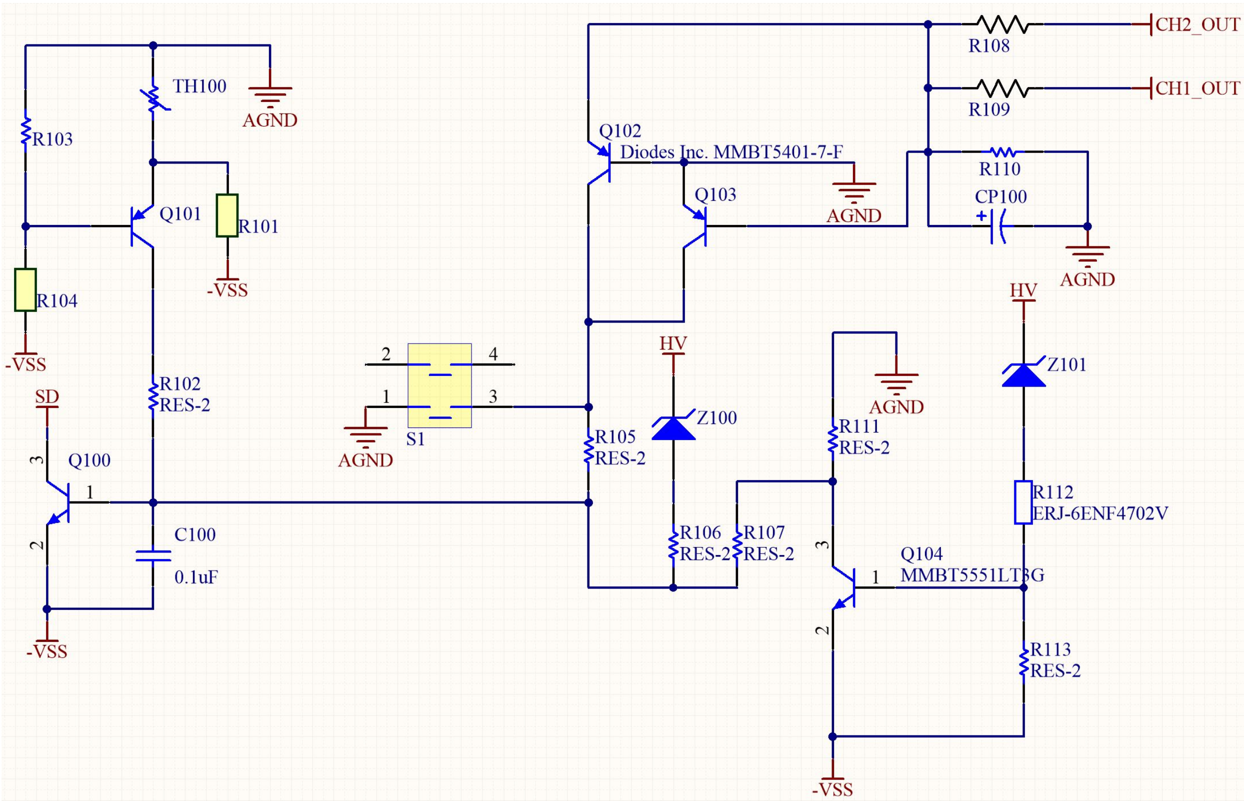

Figure 2.5: Protection Circuit

OVP in this circuit shuts down the amplifier if the the voltage between the high voltage (HV) bus and AGND exceeds 68 V. This limit is set by the Zener diode Z100 in figure 2.5. This protects the amplifier from excessively high voltages on the HV bus, either coming from the power supply or due to bus pumping.

UVP in this circuit shuts down the amplifier if the the voltage between HV and AGND goes below 39 V. This limit is set by the Zener diode Z101 in figure 2.5. This protects the output from noise coming from unstable PWM generation during power up or power down.

DCP protects the speakers from DC current. DC current detection detects irregular DC offset and turns PWM off. If this abnormal condition is caused by one the transistors being short-circuited or being stuck in the ON state, the power supply needs to be cut off to protect the speakers. DCP is triggered when the output DC offset is greater than ± 4 V.

In this design, OTP is not required, since the GaNFETs used are thermally efficient. However, in a conventional MOSFET-based design, this NTC resistor (commonly known as a thermistor) would be attached to the heatsink connected to the MOSFETs, shutting the amplifier down if the temperature rose above a predetermined value. The thermistor was kept in this design to offer the possibility of adding one should the need arise.

S1 in figure 2.5 is used as an additional ON-OFF switch in the circuit. The OFF position forces the amplifier to stay in shutdown mode, pulling the CSD pin on the IRS2092 down, keeping the transistors off.

2.2.6 Power Circuit

The power circuit was mostly taken from the GaN Systems Evaluation Board [6]. The 5V rail assumes that the input will be regulated and safe for all the electronics on-board.

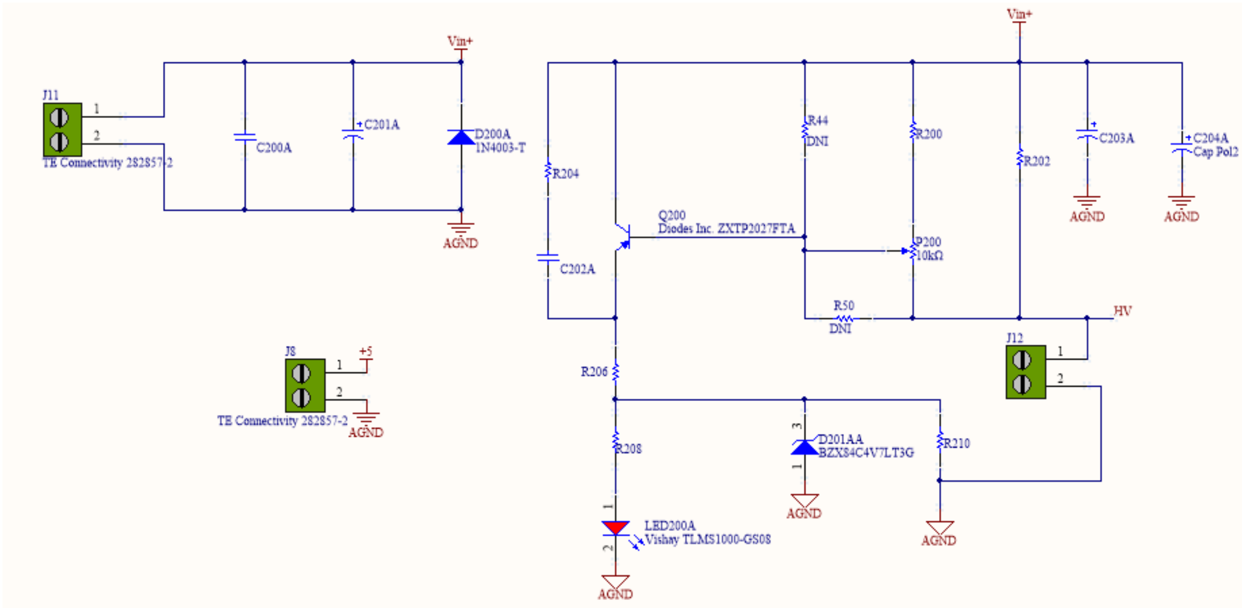

Figure 2.6: Power Input Circuit

As for the high-voltage rail, it has four decoupling capacitors (C200A, C201A, C203A, C204A) to reduce ESR and remove AC voltage as well as a diode (D200A) to protect the circuit against accidental polarity reversal at the input up to 1 A. The rest of the circuit seen in figure 2.6 acts as an over-current detection circuit, with the LED as the indicator for this condition. There is an additional screw terminal at the output of this circuit to measure the voltage going to the GaNFET module.

2.3 Coding

2.3.1 Volume Control

The first part of the code required by the design was for the volume control of the amplifier. This was done by using the Teensy 4.0 Development Board micro-controller coupled with the Arduino integrated development environment (IDE). The Teensy will receive a voltage signal from a user-controlled potentiometer, which it then translates into a command for the volume controller IC (the PGA2311). The Teensy will send this command to the PGA2311 in an serially encoded 16 bit word. The PGA2311 will interpret the 16 bit word and adjust its gain, thus adjusting the overall volume to a level chosen by the user. The range in analog values the potentiometer sent back to the Teensy ranges from 0 to 5 volts. From there, the micro-controller uses a 10 bit ADC, giving a range from 0 to 1023. The range of values the PGA2311 expects are two 8-bit bytes (one for the right channel and one for the left), which, in decimal representation, is equivalent to a range of 0 to 255. Since the range of readings from the potentiometer were a factor of 2^{10}, and the PGA2311 expected values that were a factor of 2^8, the following equation was used to determine the resolution of the volume control:

$$Resolution_{VolumeControl} = \frac{Range_{Potentiometer}}{Range_{PGA2311}} \tag{2.1}$$

Using equation 2.1, the resolution of the volume control was limited to four times smaller than the maximum potentiometer resolution. Although this was the most accurate resolution between the two devices, given the quality of the potentiometer, the readings were not as accurate, as there were increments as precise as one unit, all the way up to increments of seventeen units for the potentiometer readings. After the reading from the potentiometer was scaled down for the PGA2311, the following equation was used to find the gain produced by the PGA2311:

$$Gain(dB) = 31.5 - 0.5(255 - N) \tag{2.2}$$

The range of values for N in equation 2.2 are from 1 to 255, which are the values that the PGA2311 can accept in bytes in terms of volume, with N=0 representing the mute condition [12]. Once the potentiometer reading is ready to be sent, the data is sent to the PGA2311 through the Serial Peripheral Interface (SPI) communications interface. Since the PGA2311 reads data on a rising edge, the clock polarity (CPOL) and clock phase (CPHA) were both set to one, and the speed of the microprocessor was reduced to 6.25 MHz, which is the max frequency at which the PGA2311 can be operated[12].

2.3.2 Liquid Crystal Display

The second part of the code was for the Liquid Crystal Display (LCD). The purpose of the LCD is to have visual representation for the user to have an idea of the current volume level of the amplifier. There are two components to the LCD: the gain level, shown on the first row in decibels (dB), and a visual aid for the user, shown on the second row. Since the display being used is only capable of storing up to eight unique characters, the resolution for the visual representation was adjusted as such. This was done using an equation similar to equation 2.1. Once the resolution for the volume bar was decided, the data for the visuals was sent to the LCD through Inter-Integrated Circuit (I2C) serial computer bus communications.

In order for the micro-controller to communicate to the LCD through I2C, the address at which the LCD will read from for the I2C had to be determined. This was done using a simple address program called i2cscanner [13]. Once the address was found, the visuals required on the display were sent, which included the volume bar visuals for the user. The amount of bars in association with the gain which the PGA2311 would have was determined through the volume bar resolution, and implemented through a series of conditional statements. The LCD refresh rate was set to 200 ms to achieve the best balance between the precision of the data being displayed and the overall viewing experience of the user.

2.4 Filtering

Two major components of the design of this amplifier are the input and output filters. The purpose of these is to reject any unwanted signals from the audio source and prevent unwanted noise or radio-frequency signals from being passed on to the loudspeakers. Multisim was used to verify the behaviour of the filters using both the AC sweep function as well as the interactive simulation. The interactive simulation was crucial in determining behaviour and the heat dissipated by each component in steady-state.

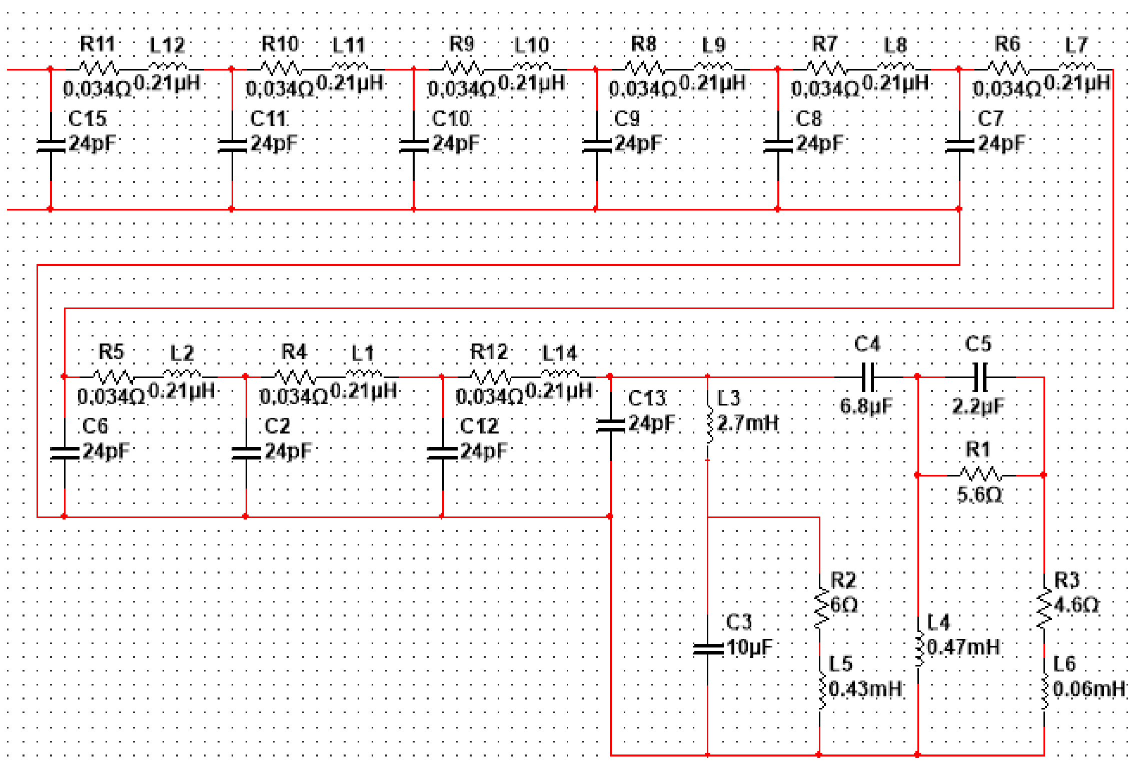

Figure 2.7: 3 Meter Speaker Cable and 2-way SEAS loudspeaker Model

In order to ensure the filter design would remain stable under normal conditions, the design was tested both unloaded and with 3 meters of speaker cable attached to a two-way loudspeaker with passive crossover designed by SEAS [14, 15].

2.4.1 Input Filter

The input filter's main purpose is to filter out any signal content around the oscillation frequency of the output low-pass filter, which is mostly comprised of an LC circuit. The input filter must also prevent the transmission of DC signals, as these would be amplified at the output of the amplifier and would quickly destroy delicate loudspeaker voice coils. Selection of the DC-blocking capacitor must be done carefully, as a poor quality component here will have a direct impact on signal integrity. For this reason, a polyester film type manufactured by Wima was chosen [16].

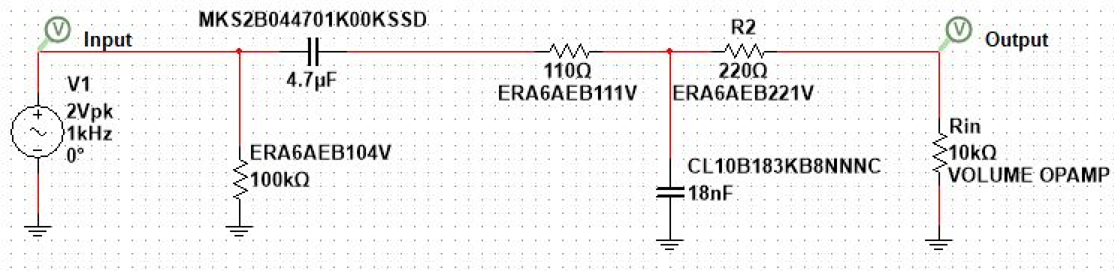

Figure 2.8: Input Filter Schematic

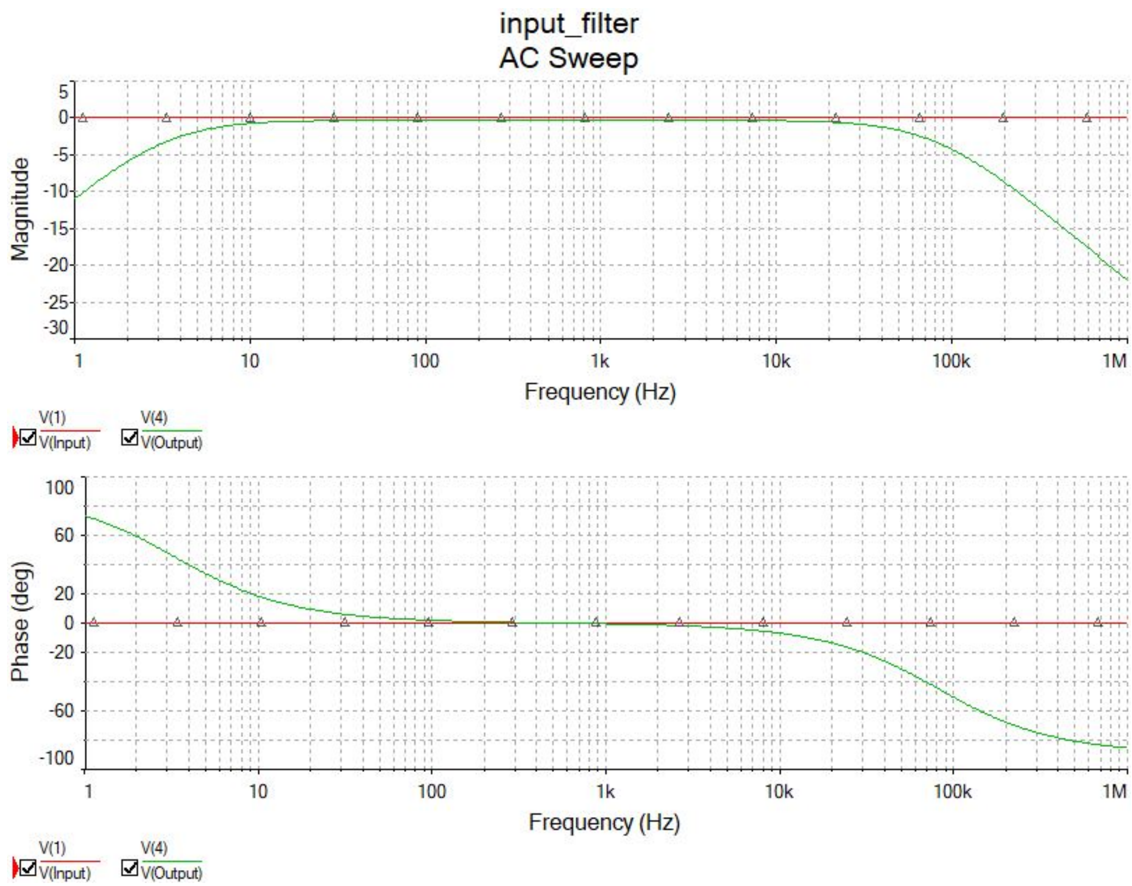

Figure 2.9: Input Filter AC Sweep

The result is a band-pass RC filter with 3dB attenuation at 3 Hz and 80 kHz and 0.3 dB attenuation in the pass-band, with a phase advance of 9° at 20 Hz and a delay of 13° at 20 kHz.

2.4.2 Output Filter

The output filter, also known as a reconstruction filter, must transform the high frequency square wave seen at the output of the transistors into the audio signal to be presented to the loudspeakers. That audio signal is the envelope that is left once the high frequency square wave is sent through a low-pass filter. In order to do this, an RC filter like the one used on the input would not be practical, so an inductor in series with the signal followed by a capacitor would be employed instead. The value of the inductor and capacitor influence the resonant frequency of the system, which can be tuned to a frequency far below the normal switching frequency of the output FETs. This mitigates the risk of having the output filter resonate and self-destruct due to excess energy being repeatedly exchanged between the inductor and the capacitor.

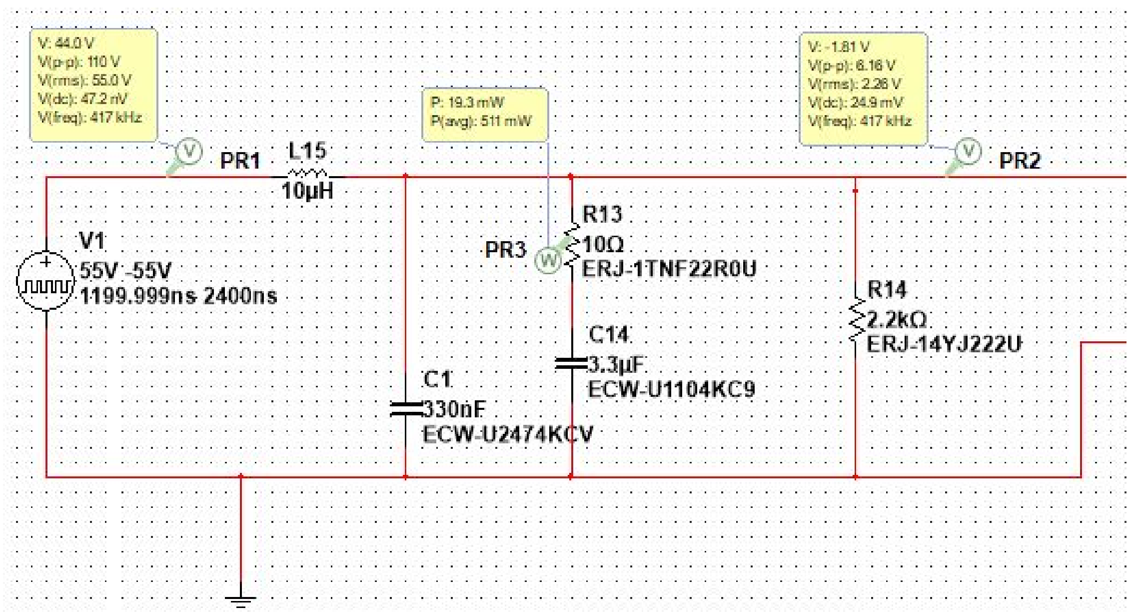

Figure 2.10: Output Filter Schematic

An impedance compensation circuit, also known as a Zobel network, composed of a capacitor and resistor, was included to soften the resonant peak caused by the LC filter. Initially, values for R and C were selected to achieve critical damping, resulting in over 40 W of heat being dissipated by the resistor at idle, which was unacceptable for both efficiency and practical reasons. The resistance value was therefore increased until the power being dissipated by the resistor was below one watt, which made finding a suitable surface mount resistor at a reasonable cost possible. An additional RLC series circuit could be added in parallel with the load to further reduce resonance, but this would double the amount of inductors in the circuit, increasing cost. The steady-state values for voltage at the output and power dissipated by the resistor are shown in figure 2.10.

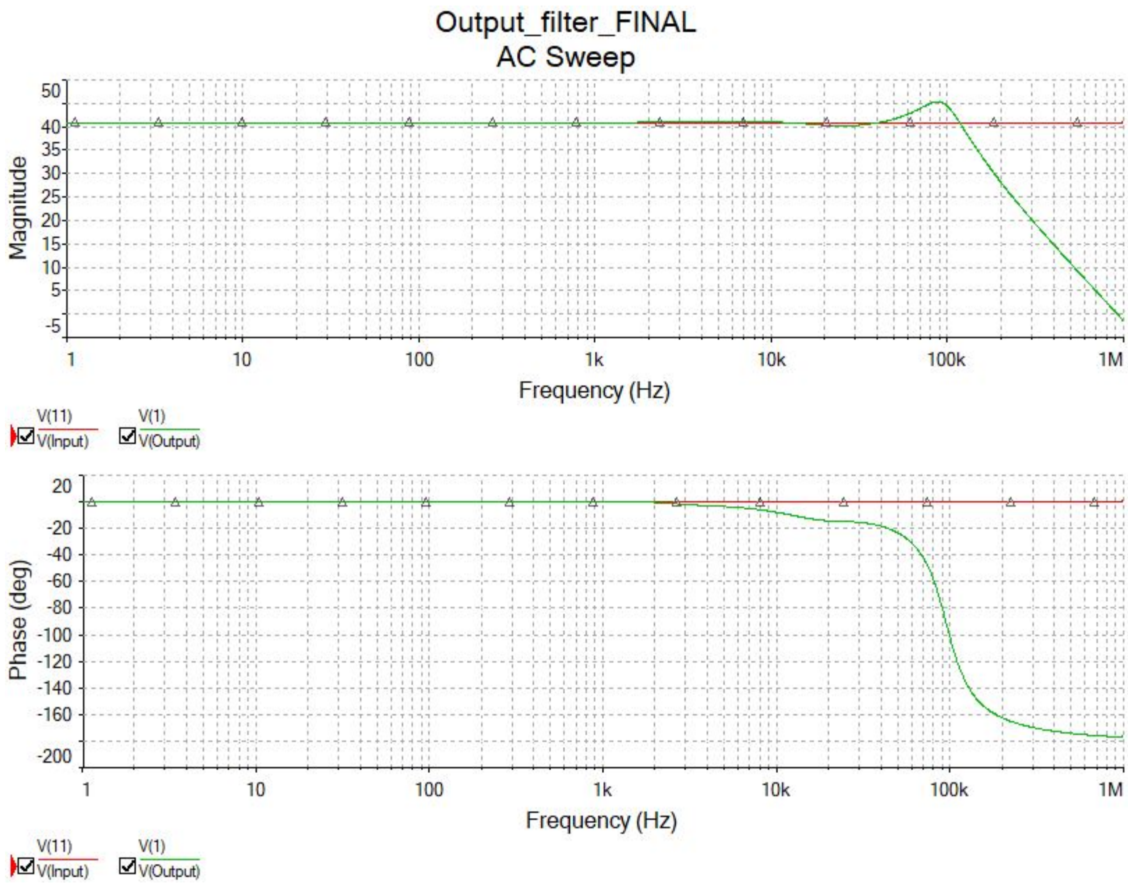

Figure 2.11: Output Filter AC Sweep

The 3 dB down point of the output filter is at 132 kHz and the resonant peak is +4 dB between 84 kHz and 92 kHz, with a maximum phase delay of 14° within the audible range.

2.5 Part Selection

Several different components and materials were required to design the amplifier. Even amongst the common circuit components such as resistors, inductors, and capacitors, the material and power rating of each component had to be considered, depending on whether they were on the signal path or not. Another factor that influenced the part selection was the design of the board.

In the initial design, a 4-layer PCB was intended to be built. With a 4-layer PCB, the space on the board was a factor of cost, as it would have been more expensive to have a bigger board. When compared to a two layered PCB configuration, the cost per area of a four layered PCB was much greater than the cost per area of a two layered PCB.

Considering this, the design had to take into account the size of the components, to take up less space on the PCB. This is why the majority of the parts selected were surface-mount components, as opposed to bigger through-hole components.

2.5.1 Basic Components

In terms of materials and power ratings for each basic component(resistors, capacitors, inductors), the main deciding factors were whether the component itself was on the signal path or not, as well as the price.

Materials such as film were considered for the resistor selection, due to the availability of thin and thick film surface mount resistors that were of high quality. For the capacitors on the signal path, film was decided to be the primary material, due to the fact that when compared to aluminium electrolytic capacitors, film capacitors resulted in less signal degradation, and therefore were used for the signal path capacitors of the design. The rest of the capacitors were aluminum electrolytic, or ceramic, due to the cost effectiveness, and the fact that they were not a part of the signal path.

For the inductors, there were only two that were required on the signal path, and there were two types that were available for the design: air core, and shielded iron core. The advantage of air core inductors were their linearity at high frequencies, due to the fact that there is no iron core to become saturated. The disadvantage with air core is that the magnetic fields that the inductor creates may negatively affect the rest of the circuit. As for iron core, the size of the inductors allowed for a smaller footprint on the PCB. The core is also shielded, which prevents the magnetic fields from affecting the circuit. Taking these factors into consideration, the shielded iron core inductor was chosen for the design, due to their form factor, as well as its shielding capabilities.

2.5.2 Transistor Selection

The transistor selected for the half-bridge configuration is the GaN Systems GS61004B Gallium Nitride Enhancement-mode High Electron Mobility Transistor (GaN E-HEMT). A E-HEMT is a type of FET. This transistor was chosen over its EPC-branded twin because of the size of the pads. Both have pins that are inaccessible with a soldering iron, but GaN Systems has its own propriety GaNFET GaNPX package as opposed to the ball-grid array (BGA) package that the EPC ones come in. The GaNPX package for the GS61004B is 4.6x4.4 mm^2 and has no thermal pad.

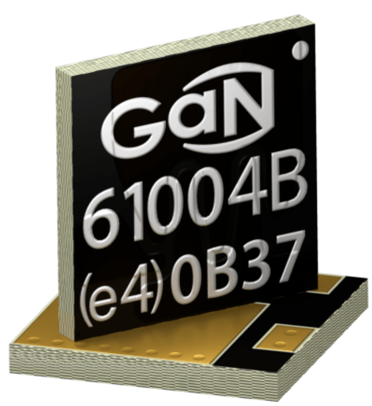

Figure 2.12: GaN Systems GS61004B GaN E-HEMT

The GS61004B has a gate drive of 0-6 V, and this design uses a gate voltage of 5 V. Using 5 V instead of 6 V as a gate voltage does diminish transistor efficiency, but reduced circuit complexity since there was already a 5 V rail in the system. This was considered as an adequate trade-off of efficiency for complexity.

In addition, this transistor is suitable for up to 100 V drain-source voltage, allowing a higher voltage power supply to be used. This is beneficial because it allows the amplifier to produce more power without creating distortion.

The low input capacitance of a GaNFET as compared to a MOSFET allows the GaNFET to have a much higher switching frequency. In the case of the GS61004B, the maximum switching frequency is approximately 10 MHz. GaNFETs are also much more efficient than MOSFETs because of their stronger electric-field [17]. MOSFETs typically have an intrinsic reverse current path with gate off property, typically called a body diode. GaNFETs do not have a body diode, but can conduct in reverse with V_{GS} off. Therefore, GaN devices do not need an anti-parallel diode [18].

2.5.3 Integrated Circuit Components

For the Integrated Circuit(ICs) components, the deciding factor was the functionality required of the amplifier in its various stages. For example, the IRS2092 is the IC that was considered to be the most important IC, as it had the most capabilities incorporated into one chip. Inside this IC, there is a self-oscillating triangle wave generator capable of operating at up to 800 kHz, a comparator, output error correction, and an assortment of protection circuits [5].

The IRS2092 also provides over-current protection (OCP) to the circuit with the OCSET and CSH pins of the IC. Setting the resistance of the OCSET pin to 7.5 kΩ limited the low-side current to 30 A, and setting the CSH pin resistance to 9.1 kΩ limited the high-side current to 29 A. More information about the choice of these resistances and their effect on OCP can be found on page 24 of the IRAUDAMP7s Reference Design manual [11].

Other ICs that were used were the Teensy 4.0 micro-controller Arduino clone, as well as the PGA2311 stereo audio volume control. The micro-controller and the PGA2311 use a serial connection to adjust the volume of the audio signal within the input stage [12]. In the initial design, the Teensy was supposed to comprise the signal processing stage of the amplifier, but it has since been re-purposed as part of the volume control circuit, due to design changes. The coding of the Teensy to interface with the volume control IC was discussed in section 2.3.

Finally, two Texas Instruments LM5113 serve as gate drivers for each channel's high and low side GaNFETs. They are designed specifically for use with Gallium Nitride field effect transistors and are controlled by the gate drivers already included in the IRS2092. The supplemental drivers were included because the gates on GaNFETs behave differently to traditional MOSFETs, which may have resulted in unpredictable behaviour. Furthermore, the added propagation delay acts to stabilize the feedback network that was originally designed to use slower silicon-based transistors, since the transistors used in this circuit are designed to switch at a faster rate [19].

2.6 Printed Circuit Board

This section will discuss the general layout topology, the module separation in the layout, the key auto-routing parameters, and the grounding techniques used to build the printed circuit board. The design of the PCB was greatly affected by the manufacturer used. Because of factors out of our control, low-cost PCBs from China were no longer available, and North America-based companies proved too costly for our budget. Therefore, the board was manufactured in-house on double-sided copper-clad board. This greatly influenced the design and will be discussed further in the following subsections.

2.6.1 Layout Topology

Originally, the PCB was going to be printed on a 4-layer board, with two signal layers, a ground plane, and a layer for the voltage rails. A two layer board was used instead, and this significantly influenced the PCB layout and routing options between components. Using a two layer board instead of a 4-layer board significantly increased the routing complexity and number of vias needed. As such, the top layer was prioritized for use by through-hole components, components that dissipated more heat, and tall SMT components. The bottom layer was used for ground planes and SMT components. DC decoupling capacitors were placed as close to the main component of each module as possible [20].

Component placement is an important consideration in printed circuit board design as it determines overall maximum performance. Therefore, it is important to group common-purpose components together and to isolate these groups from one another. In addition to common-purpose group isolation, it is important to isolate noise sensitive circuitry from noise generating circuitry.

In this design, the main noise sensitive part of the circuit lies in the feedback network connected to the input of the IRS2092. The main noise generating parts of this design are the PWM switching circuitry and the gate driver circuitry. To avoid injecting this noise into the system, it is crucial to place the noise sensitive circuitry far from the noise generating circuitry [21].

2.6.2 Grounding Techniques

Grounding in mixed-signal circuit boards is a difficult topic to tackle. Since the clock frequency of the digital components in this design is at 600 MHz, ensuring that there is a good ground is critical in reducing noise. Separating digital and analog signal components has the added benefit of reducing EMI and crosstalk between the two types of signals [22].

Each module has its own section and its own ground on the board. All of these grounds are then connected at one point one the board, at what is called a "star ground".

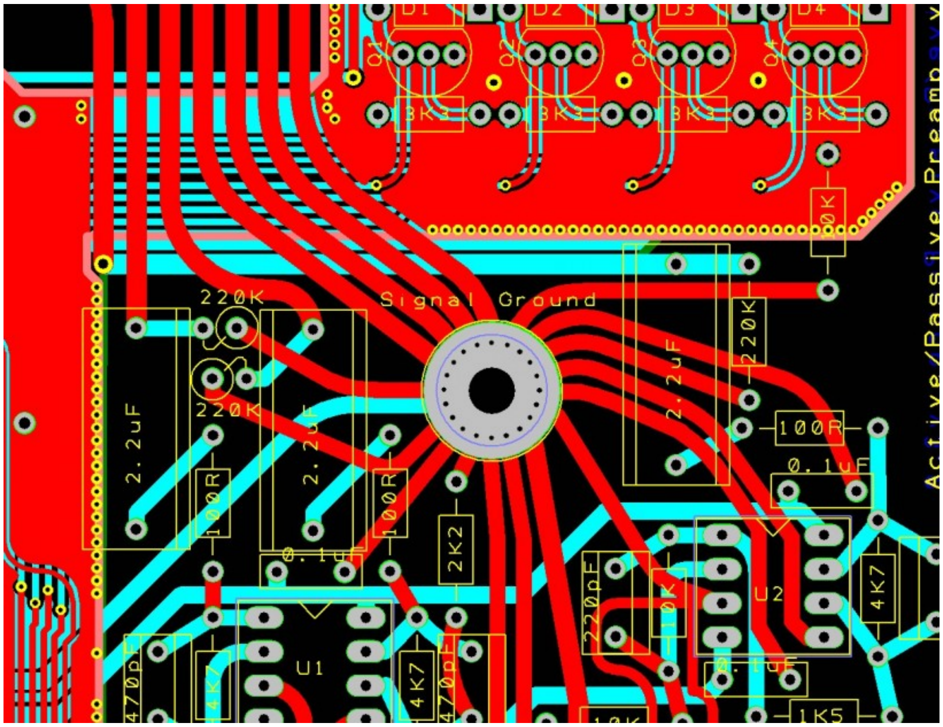

Figure 2.13: Star Ground Example [23]

Figure 2.13 presents an example of a star ground in a relatively simple circuit. Another technique is to group all common grounds together and then route them together to a star ground. The second technique is the one used in this design. Each of the digital, input analog, and output analog grounds were used separately first, and were then routed to the star ground point in the center of the board. When planning the grounds on the PCB, the guidelines from Autodesk's Eagle software were followed [24].

2.6.3 Auto-Route Tuning

Because of the number of components and the complexity of the circuit, the auto-routing feature of CircuitMaker was used extensively. Several rules were created for the circuit and routing to meet the specifications:

- The routing strategy used for the auto-routing was the default 2-layer strategy versus the multi-layer or via minimizing strategies;
- Clearance between vias, through-hole pads and adjacent polygon fills was increased from 0.15 mm to 1 mm. Via diameters were set to 2 mm instead of 1 mm and via hole size was also set to 1.5 mm compared to the default 0.6 mm. This was done to allow for space to solder wires inside vias;
- Small pitch components were used, such as the T.I. gate driver that only comes in a 10-pin WSON package, that has a 0.8 mm pitch. 0.8 mm pitch in a 10-pin WSON package means a spacing of less than 0.3 mm between pads [25]. For these components

to be used in the circuit without breaking the default 0.3 mm clearance rule, a 0.12 mm clearance exception was used for the nets associated to these gate-drivers;

- High current nets such as the two output channels were set to be wider than the typical trace. Using the Digikey PCB trace width calculator based on IPC-2221 PCB design standards, the width for these nets was set to 2.76 mm [26]; and
- All other nets were set to have 0.254 mm (10 mils) traces.

The auto-routing capability was useful in making most of the connections between components, but there were significant adjustments to be made. These were done manually using the interactive routing tool.

2.6.4 End-Product

After milling the first variation of the PCB design, it was noted that long thin traces of 0.254 mm (10 mils) would often get destroyed by the mill, and trying to fix the broken traces would have caused significant delays in the assembly process. The solution was to make all the traces bigger: all nets other than the high current nets were set to 1 mm trace widths for ease of manufacturing and where needed, smaller traces were used.

Using wider traces made the routing process around smaller components considerably more complex and created the need for several more vias.

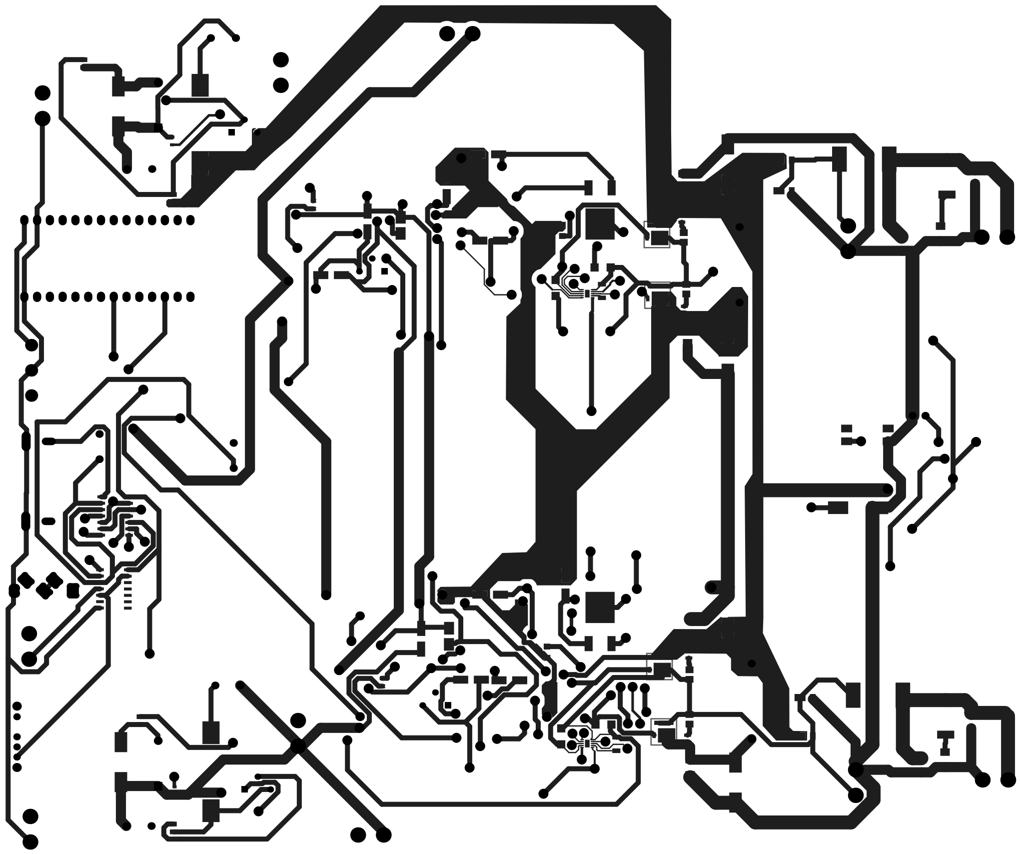

Figure 2.14: Top Copper Layer

Figure 2.14 shows the simulated top copper layer of the PCB without silkscreen overlays. The two polygon fills that span the entire width of the board are for the two high voltage rails. These fills provide a wider, non-conventional trace and allow more current to flow in those traces. On the left side of the board, there are the all of the input connectors and switches as well as the volume control IC and the Teensy micro-controller. The two gate driver circuits as well as the four GaNFETs are near the center of the board. On the right side of the board, in the output module, the two output channel traces are 2.76 mm or 2 mm wide. The protection circuit appears between the two output filters and connectors in the output module.

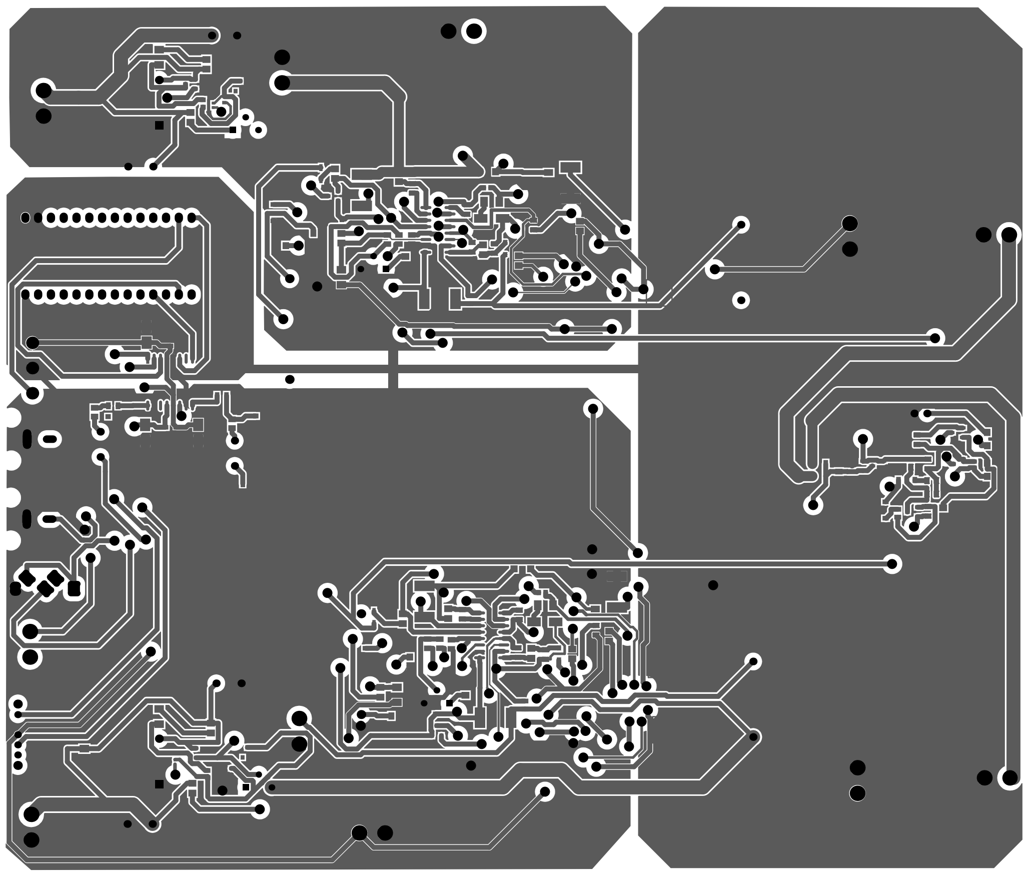

Figure 2.15: Bottom Copper Layer

Figure 2.15 shows the simulated bottom copper layer of the PCB, without silkscreen overlays. The four polygon fills are all the ground planes from left to right: the smaller digital ground, the two input analog grounds, and the output analog ground. Near the center of the board, there are the two PWM ICs and their accompanying components. This was placed on the underside of the board since there is no temperature limitation to this part of the circuit, to provide more routing options, and to save space on the top layer of the board. Just right of the center of the board, there are several components from the protection circuit.

Chapter 3

Assembly

3.1 Manufacturing Process

Due to unforeseen circumstances, the PCB could not be manufactured at the typical prototyping manufacturers from China such as JLCPCB or 7PCB. Other, North American manufacturers such as OSHPark would have exceeded the budget for the size of the board that was designed. Consequently, the board was manufactured in-house using a high-precision CNC mill. Manufacturing the PCB in-house created several limitations:

1. No solder mask, meaning that copper traces and fills are exposed to oxidation, gloves are now a requirement to avoid touching the copper with bare hands. This also presents a further danger to people working on the board and the user were they to touch it while in operation;

2. No silkscreen, making the assembly process slightly more complicated. A reference sheet will need to be used to identify the proper pads for each component;

3. Vias have to be soldered by hand rather than plated by machine. Several options to do this were considered. To be discussed in section 3.2;

4. Not as aesthetically pleasing, it does not look as professional.

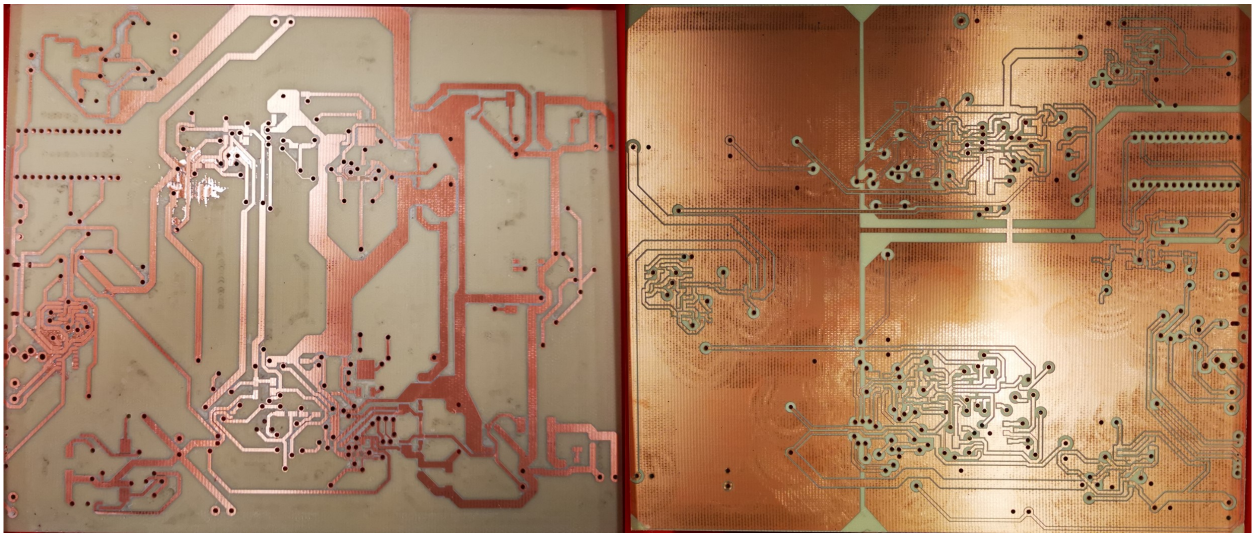

Figure 3.1: Fabricated PCB Pre-Assembly

Figure 3.1 shows the top and bottom copper layer of the PCB after having been milled. The mill did leave some copper in places where there should not have been any, and the extra copper was removed with an assortment of picks, files, and an Exacto knife. This quickly became tedious, therefore a Dremel tool with a small sanding tip was used.

3.2 Soldering

3.2.1 Wave One

The first wave of parts that was soldered to the board was the protection circuit and the two PWM modules. These three sub-circuits are made of approximately 76 parts in total. For assembly, a small amount of solder paste was applied to each pad, and the correct part was placed upon its respective pads. Once all three sub-circuits were completely populated, the board was put in an oven to reflow the solder paste. The solder paste used was a Sn63 Pb37 alloy with a melting temperature of approximately 183°C.

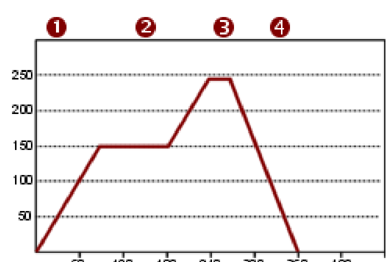

Figure 3.2: Standard Reflow Soldering Profile [27]

Standard reflow soldering profiles following the heating profile seen in figure 3.2, but due to a lack of an accurate reflow oven, a different, non-conventional heating profile was used.

The heating profile used for the assembly of the first three sub-circuits was pre-heating the oven to approximately 230°C then leaving the board in the oven for 3 minutes.

The result was a near-perfect solder job, with no short-circuits between nets and only slight movement of components on their pads that was easily fixed by re-heating with a soldering iron.

3.2.2 Wave Two

The second wave of parts that we soldered to the board were the volume control circuit and both of the high voltage rail circuits. Again, solder paste was applied to all necessary pads and the parts were placed upon them. This time, to avoid reheating all components in the oven, a hot air rework station was used to solder the components in place. The rework station was set to 400°C with the fan on its lowest setting. The end of the pen was held perpendicular to the board approximately 2-3" above the board. The pen was held in place above the desired component until the solder paste melted and flowed to the correct pad. Parts sliding away because of the hot air was something to be careful of.

The end result for these three sub-circuits was good, with only three short-circuits out of 66 connections made. The short-circuits were fixed by removing excess solder with a solder wick and iron, then reheating the solder with the rework station to clear the dielectric of solder.

All that was left to solder on the bottom side of the board were the ICs and the parts that had vias underneath them.

3.2.3 Vias

A few different options were discussed to solder all the vias on the board:

1. Use copper rivets with no solder. This option was discarded because there was no affordable option for a 1.5 mm hole size;

2. Use copper eyelets with solder. This option was discarded because we could not find eyelets with a hole size of 1.5 mm with a rim size of 2 mm or less;

3. Use a bare copper wire with solder. This option was discarded because the bare copper took too long to heat up to a temperature high enough that the solder adhered to it; and

4. Use tinned copper wire with solder. This was chosen option because it heated up fast enough that the solder adhered to it and formed nice solder joints. It was also chosen because it was the only option left.

Each via was hand soldered individually with care taken to avoid short-circuits. Once all vias were soldered, a final short-circuit check was made. All vias that happened to be beneath components were ground down using a Dremel tool to ensure that the vias did not touch the components.

3.2.4 Wave Three

The third and final wave of components were the all of the ICs, remaining through-hole components, and the connectors. These were all hand-soldered using a soldering iron and Sn63 Pb37 solder. The ICs were all tested for short-circuits between pads, and the through-hole components were all tested for continuity on both sides of the board. The continuity check was necessary because the holes were not plated, meaning the solder could not flow freely between both sides of the board.

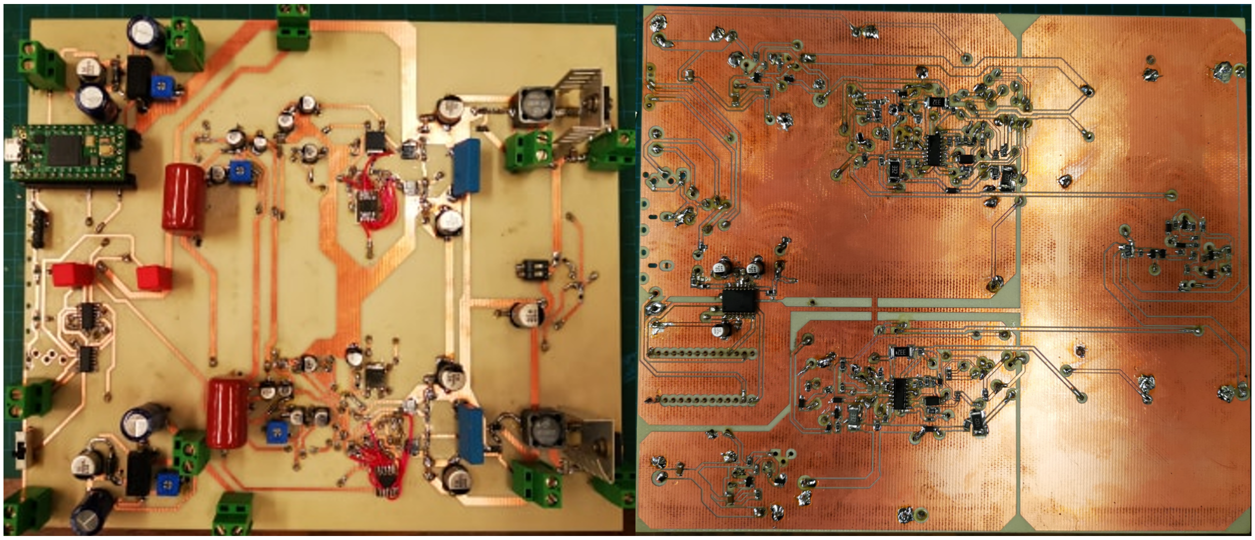

Figure 3.3: Top and Bottom View after Assembly

Figure 3.3 shows the top and bottom view of the assembled board. The only parts missing at this point are the components external to the amplifier itself such as the power supplies, the volume control and display, and RCA jacks. The next phase of development for this project was the testing cycle.

Chapter 4

Testing

4.1 Code Testing

The testing for the two modules that were programmed was conducted in different ways. For the volume control module, a logic analyzer was used to inspect the output waveforms from the SPI pins on the micro-controller. This was compared to the values that were printed on the serial monitor of the Arduino IDE. The serial monitor was operating at a baud rate of 9600 bps.

The LCD was tested incrementally, verifying that the resulting display matched with what was required. The following was the result of the coding for the LCD:

Figure 4.1: LCD output

As seen in figure 4.1, the first row successfully displayed the volume in dB, with 0dB being the reference input signal. The second row had an interactive visual representation for the volume level, displayed in bars.

For the volume control tests, the generated SPI waveforms were analyzed with a logic analyzer and compared to those printed on a serial monitor. The results are as shown in the next two figures:

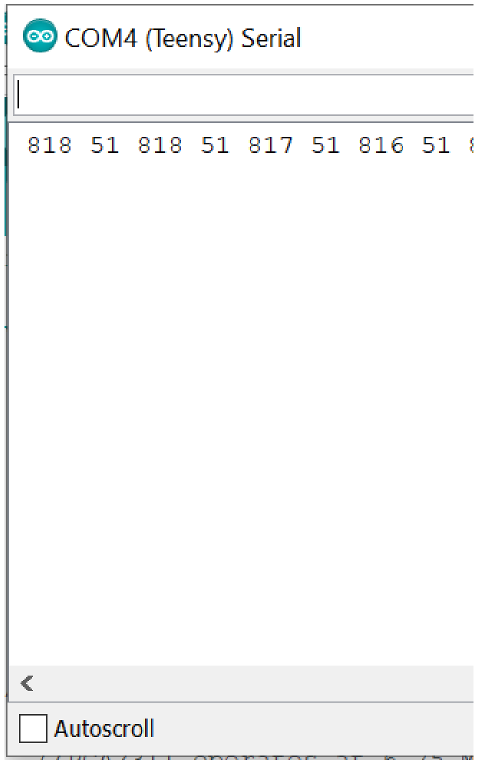

Figure 4.2: Output to Serial Monitor at a Baud Rate of 9600

In figure 4.2, the first value that is printed is the reading from the potentiometer, while the second is the decimal number that will be sent as an encoded byte to the PGA2311, through SPI.

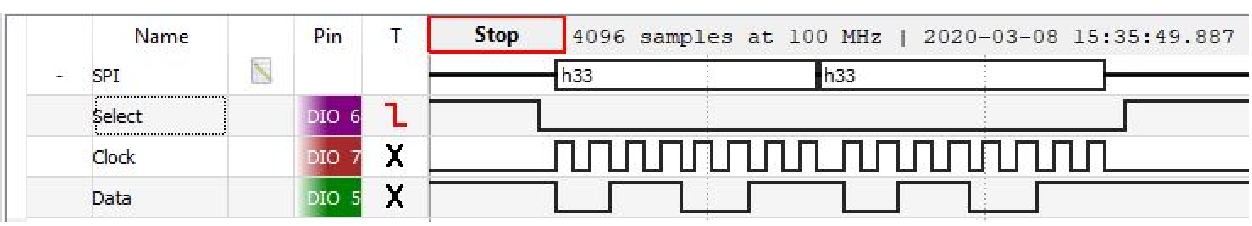

Figure 4.3: Logic Analyzer Readings from the SPI Pins of the Micro-controller

As seen in figure 4.3, the message that was received was the hexidecimal value of 33, which matches the second value of figure 4.2, since 33 in hexidecimal is 51 in the decimal number system. This proves that the SPI communication from the micro-controller works as expected.

4.2 Power Supply

A suitable power supply was required before testing the amplifier with an actual load (ie. power resistors and speakers) could commence. Initially, a switch-mode power supply was tested in order to determine if it was suitable for the amplifier. However, a problem that came with the power supply was the 1.04 kV voltage spike that occurred on start up, as seen in figure 4.4 below.

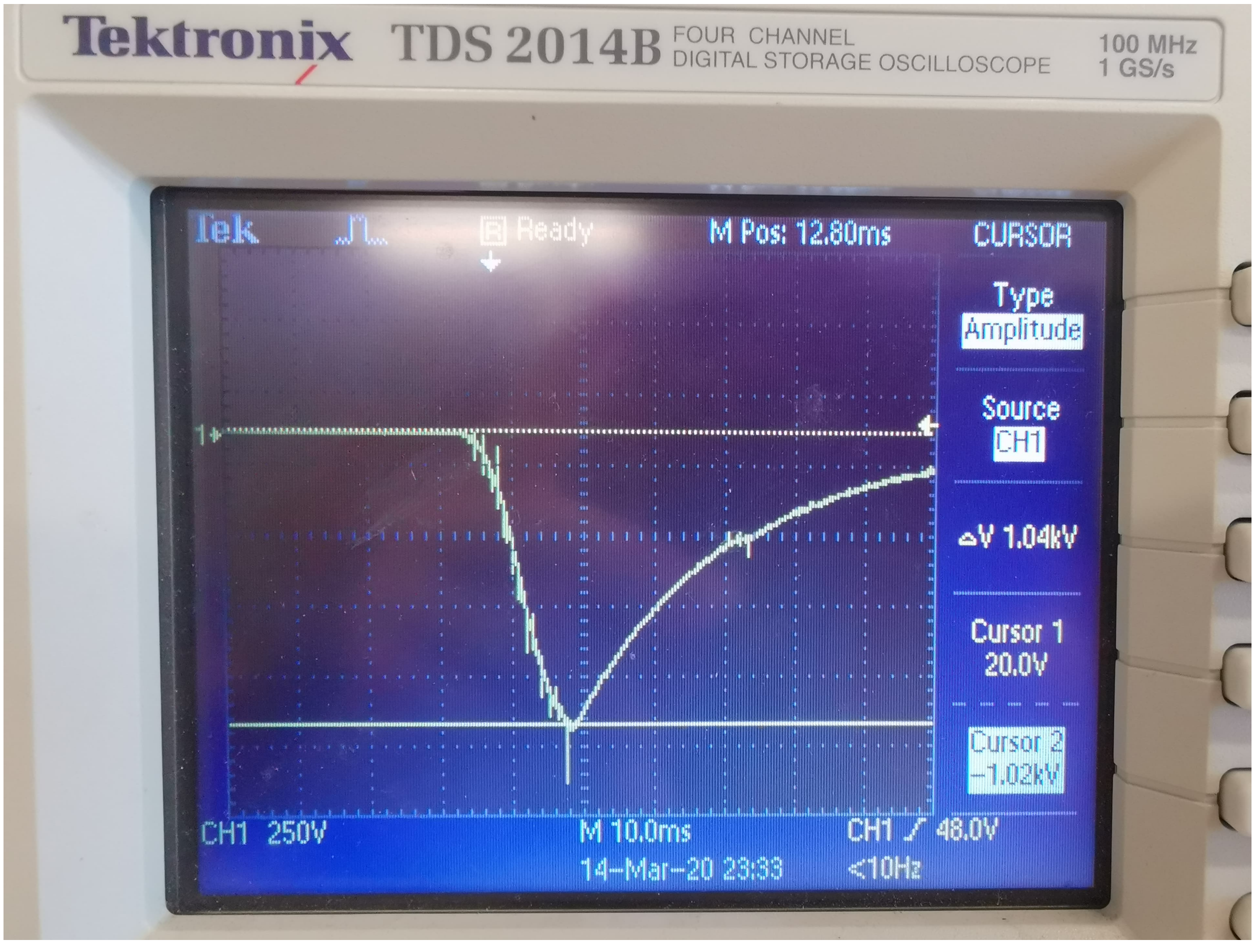

Figure 4.4: Voltage Reading from Switch Mode Power Supply

In an attempt to rectify this to avoid potential damage to the amplifier, capacitors were used to diminish the spike. Unfortunately, the capacitors only ended up prolonging the duration of the spike with no significant decrease in the voltage spike level. Consequently, another power supply had to be used.

In order to ensure the integrity and safety of the amplifier, a linear power supply was tested for compatibility with the amplifier. The linear power supply had a voltage spike of 600V. This was considered an improvement compared to the switch-mode power supply, and thus the risk was accepted.

Although the linear power supply was chosen to power the amplifier, there was an initial problem that needed to be addressed. When the power supply was tested with a pre-built amplifier (the IRAUDAMP7S), there was significant bus pumping occurring between the power supply and the amplifier. Bus pumping is the phenomena where the energy from the inductors of the LC filters is returned back to the supply [28]. This is because the amplifier uses a half-bridge topology, and the energy flow is bi-directional [29]. This phenomena occurred when the IRAUDAMP7S was operating at lower frequencies (below 100 Hz, i.e. bass). If too much energy is returned to the power supply, it could over load it, posing a risk to the user.

In order to rectify the bus pumping phenomena, two 4000 μF capacitors were put in parallel with each other for each channel (totalling four capacitors). By putting the two capacitors in parallel, the capacitance and the equivalent series resistance was halved. These two conditions allow the capacitors to be more reactive to transients from the amplifier.

4.3 PCB Testing

The testing of the PCB was be divided into four phases: checking for short-circuits, low voltage testing, high voltage testing, and testing with music.

For the first phase of testing, the PCB was tested for short circuits using a digital multimeter. This was done throughout the assembly process and a final time before the next phase of testing. Any shorts that were detected were fixed by re-soldering the faulty connection to the correct specifications of the design.

4.3.1 Low Voltage

The purpose of the low voltage testing is to confirm the functionality of all the individual components while using a sample waveform in order to verify if the signal indeed made it through each and every component of the amplifier. This is where the most amount of problems were expected to occur.

It was noted that there were several deficiencies that were presented in the PCB, in the form of short circuits. This was noticed when the output waveform was the same as the input waveform. This behaviour showed that the integrated circuits interfacing with the input signal had no effect and were therefore not functioning. Unfortunately, due to the design of the PCB and the time constraints on the project, most, but not all the short circuits were found and rectified. This meant that testing for low voltage could not continue beyond this point.

4.3.2 High Voltage

The high voltage portion of the circuit is designed to provide a stable high power source to be controlled by the output transistors and sent to the output filters. A short or a weak trace in this section would result in blown power supply fuses in the best case and burnt traces and exploding capacitors in the worst case.

The end result of our testing was neither of these outcomes, as we were unable to feed any voltage into the negative voltage rail without the circuit looking like a short circuit to the power supply. This behaviour opposed the multimeter reading, which showed an open circuit at the input terminals. All diodes were checked and several components were removed, bypassed and sometimes replaced with no change in the circuits' behaviour. Another, more powerful 50V/22A power supply was used in a final effort to discover the source of the intermittent short circuit, but this offered no additional information.

The circuit would not allow current to enter through the terminals while simultaneously causing the power supply to behave as if its terminals were shorted together. Thus, testing ended with only one high voltage rail achieving the target voltage, while the other remained unused. Because of the half-bridge topology of the amplifier, having only one out of the two voltage rails results in no observable behaviour by the entire high voltage portion of the PCB.

Chapter 5

Discussion

This chapter will look at the testing results and determine whether they meet the requirement criterion or not. The system limitations, scope re-examination, potential future developments, and lessons learned will also be discussed in this chapter.

5.1 Requirements Review

Table 5.1: Requirements Review

Requirements Review			
Index	Requirement	Result	Notes
FR-01	Accept an analog line-level unbalanced audio signal	Achieved	
FR-02	Accept signals ranging from 10Hz to 192kHz	Achieved	
FR-03	Produce a triangle wave of at least 1MHz	Partial	Did not achieve 1 MHz PDM, but 800 kHz PWM was achieved
FR-04	Have two separate channels for stereo audio	Achieved	
FR-05	Use a discrete power supply	Achieved	
FR-06	Provide complete isolation between the user and the high voltage circuitry	Failed	No casing was made
FR-07	Variable power supply capability	Achieved	High voltage rails could accept 39-68V
FR-08	Accept wireless audio input	Partial	Terminals to accept a Bluetooth input were included in the circuit
FR-09	Modular Design	Achieved	
PR-01	Efficiency	N/A	
PR-02	Total Harmonic Distortion	N/A	

Index	Requirement	Result	Notes
PR-03	Frequency Response	N/A	
PR-04	Signal Output	N/A	
IR-01	Power Control	Partial	Switch to control PWM generation but it does not turn off entire board
IR-02	Volume Control	Achieved	
IR-03	Connections	Achieved	
IR-04	Cool Factor	Partial	No VU meters were installed on the casing, but an LCD was installed with visual volume indicators
SimR-01	Speaker Load	Achieved	Speakers simulated using a speaker model and tested with power resistors
SimR-02	Microprocessor Code	Partial	PDM was not achieved, but volume control was coded.
ImpR-01	PCB Circuit Implementation	Achieved	
SchR-05	Detailed Design	Achieved	

Unfortunately, due to the state of the amplifier during the testing stage, none of the Performance Requirements set out during the initial statement of requirements could be met. This is because of the problems highlighted in section 4.3.1 and 4.3.2, as well as time restraints and the lack of resources available.

5.2 System Limitations

Although the design process was adequate, the lack of experience when it came to trace routing on the PCB caused issues that could not be resolved in time. Also, having the amplifier manufactured by a CNC mill caused some difficulties, particularly with the fact that it was too expensive to produce multiple copies, which limited the amount of design iterations that could be made.

5.3 Scope Re-Examination

The initial scope of this project included PDM signal processing as one of the main features of this amplifier [1]. Considering the lack of research and work that has been done on this topic so far, it was decided that this was out of reach for our knowledge and skill level. To fix this, the design was changed to a PWM scheme, as outlined in section 2.1. Other than this, the scope was ambitious yet achievable. The circuit and PCB design went well, although there is room for improvement. The assembly of the board was straightforward, but the hand-soldering of vias made the assembly process considerably more labour-intensive.

5.4 Potential Future Developments

This amplifier could benefit from further development and design changes. Below, some of the potential changes and developments are listed.

- Getting the board re-manufactured and getting solder mask and an overlay added to the board, with an additional solder paste stencil to help in the assembly. This would make the assembly easier and allow vias to be smaller since they would get plated in the manufacturing process.
- Adding gate resistors $R_{G(ON)}$ and $R_{G(OFF)}$ between the gate drivers and the GaNFETs would allow the designer to control the miller effect, achieve the optimal performance, and ensure drive stability [30].
- Modifying the PCB layout to bring the gate driver even closer to the transistors and lowering L_G and L_{CS} by using wider traces to reduce the likelihood of gate ringing. In addition, more care could be taken in respecting the best layout practices for the GaNFETs and gate drivers, as explained in the GaNFET Application Note from GaN Systems [30].
- Removing the over-current detection circuit seen in subsection 2.2.6 would decrease overall system complexity and cost. Since OCP is handled by the IRS2092, this circuit is redundant and could be removed.
- Changing the gate driver footprint to the correct footprint would improve signal integrity and overall circuit robustness around that part of the circuit.
- Adjusting the traces from the volume control IC to the DC coupling capacitor. During testing, it was discovered that the post-volume control signal line was connected to the -5 V rail instead of the signal output of the volume control IC. This was rectified by using wires, but a more robust solution would be to change the traces and re-manufacture the board.
- For the volume control, an Infrared (IR) sensor could be implemented with a remote, in order for the user to control the volume of the amplifier without having to be physically in front of it. Also, the potentiometer could be exchanged for a rotary encoder, so that amount of gain does not depend on the absolute position of the volume knob, but rather on the amount of rotation the user provides. In doing so, a secondary control source could be implemented, such as a remote.
- A bluetooth module could be implemented through the micro-controller, with the Teensy receiving the signal through the bluetooth module, which would then be processed by the Teensy.

5.5 Lessons Learned

This section will look into things that the project team ran into that they would not repeat, or do differently.

This project relied heavily upon CircuitMaker to create the schematics and printed circuit board for the design. While CircuitMaker does offer several useful features such as being free, direct access to Octopart(a price comparison and BOM creation tool), potential for collaboration, and online storage, there are some drawbacks. One of these is that configuration of the outputs is difficult to find and modify. Another is that CircuitMaker only stores the project documents online, and is therefore inaccessible with no internet connection. In addition, the file outputs from CircuitMaker are limited to be opened by Altium programs. If this project were to be restarted, Altium Designer(Paid) or other free options such as KiCad or DesignSpark PCB, would be considered.

A minor challenge that occured during assembly was that the footprint for the gate driver used in manufacturing the board was not the correct footprint. This means that the gate driver had to be installed on its own breakout board and wires had to be soldered from the breakout board to the main board. This goes to show that one should look at the dimensions of the footprint to ensure it is correct.

A roadblock that was encountered during testing was that one of the channels was accidentally connected to the -5 V rail, as explained in section 5.4. To avoid this, more care could have been taken in the final schematic verification. This shows the importance of looking over each other's work.

In industry, it is rare that engineers use the auto-route feature of circuit design software because of signal integrity issues, EMI concerns, and most efficient routing. Therefore, with proper guidance from experienced PCB designers, the amplifier could be greatly improved upon in terms of reliability and durability.

Chapter 6

Conclusion

The objective of this project was to design and build a class-D audio amplifier. A class-D amplifier is a complex system that involves many different modules to work, all of which were developed and built over the past seven months. This document described the design of all these modules as well as the assembly process that the PCB went through. This document also described the tests that were run on the amplifier and discussed the results of these tests to ensure that it met the requirements set out at the beginning of this project.

This project was a learning experience for all members involved and goes to show what a group of fourth year undergraduate engineering students can do with minimal guidance. Although the class-D amplifier is not new terrain, the use of GaNFETs in audio equipment is relatively new to the market and this project shows that it is a viable alternative to MOSFETs. With the improvements outlined in section 5.4, the amplifier designed for this project could be good enough for consumer audio and eventually get to market.

The EEE455/7 course was an important learning experience regarding the life cycle and development of small-scale engineering projects. Although there was a lack of subject-matter expertise in the RMC ECE department in the field of PCB design, the internet proved more than useful.

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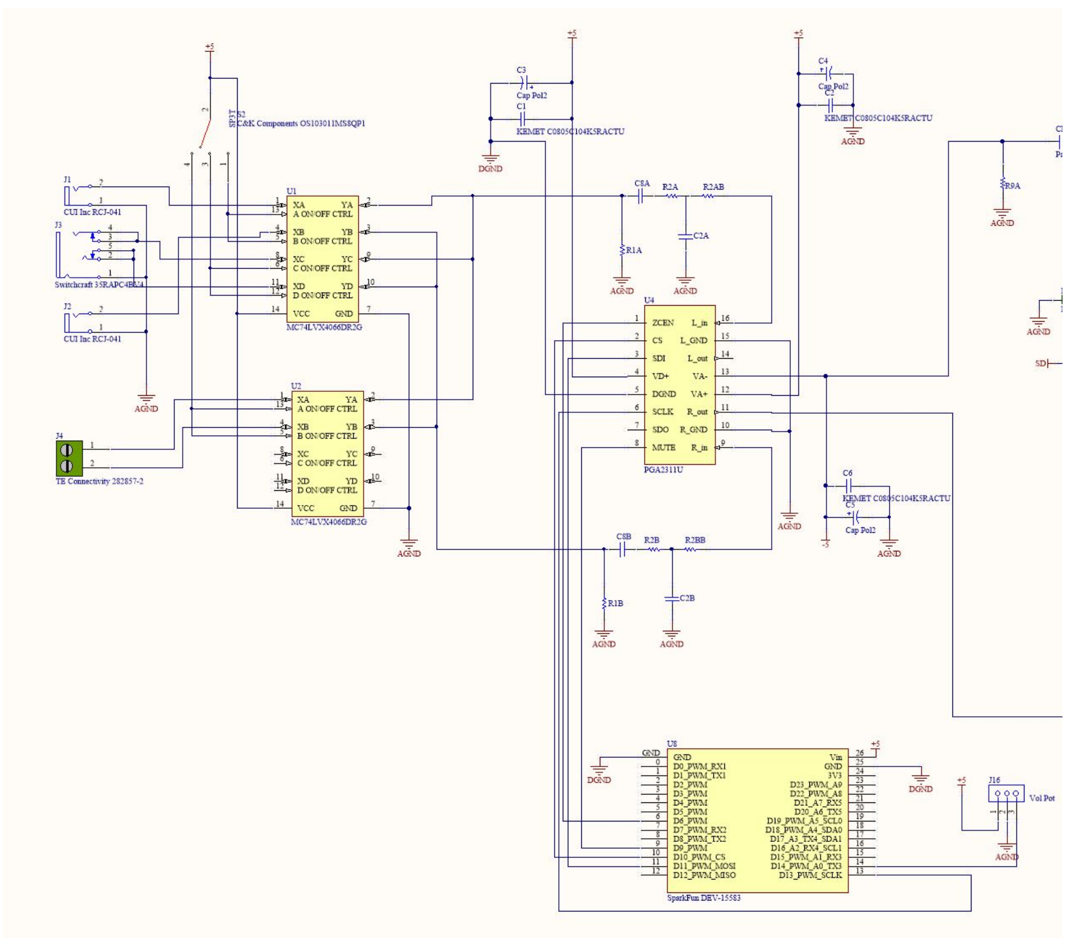
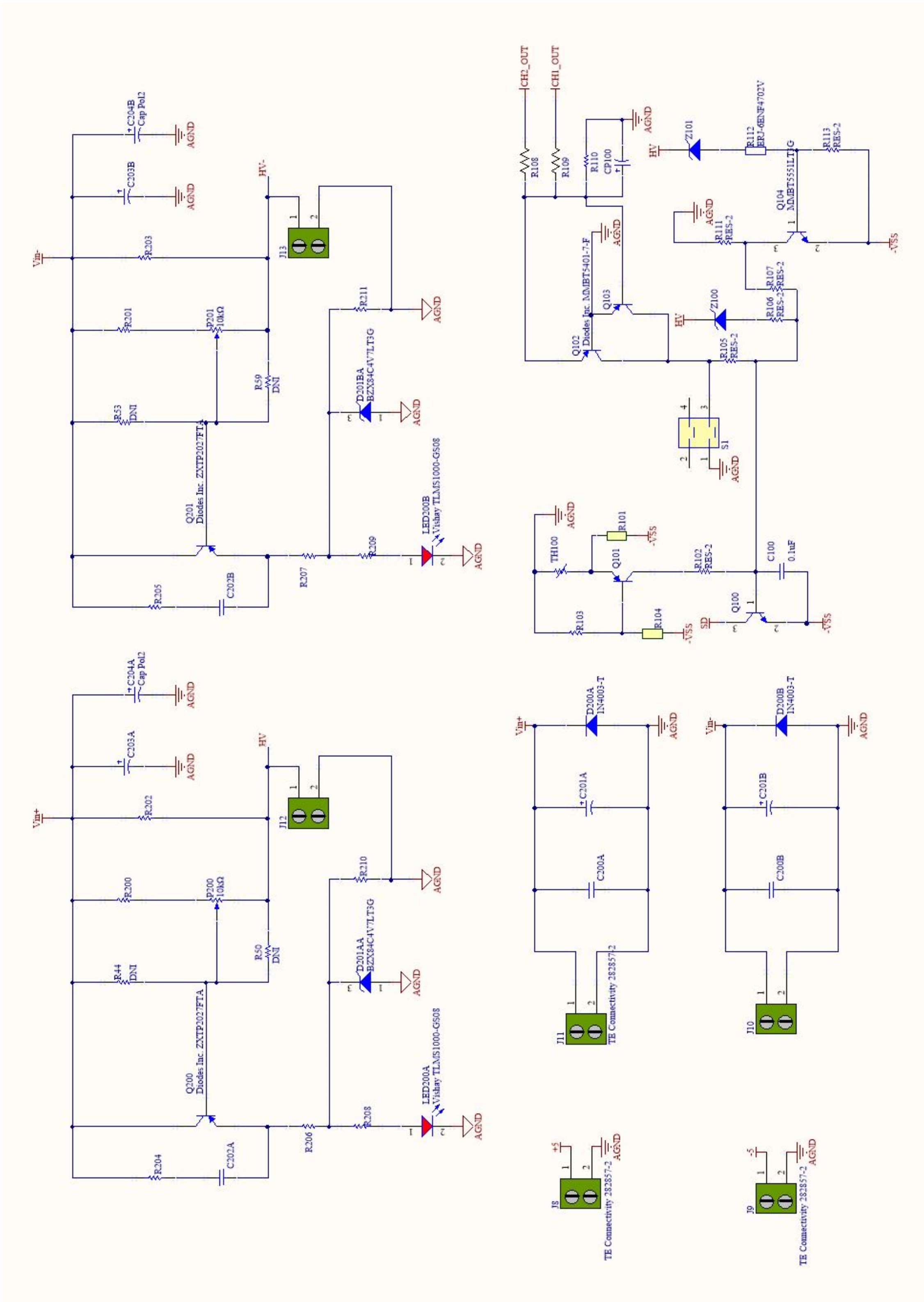
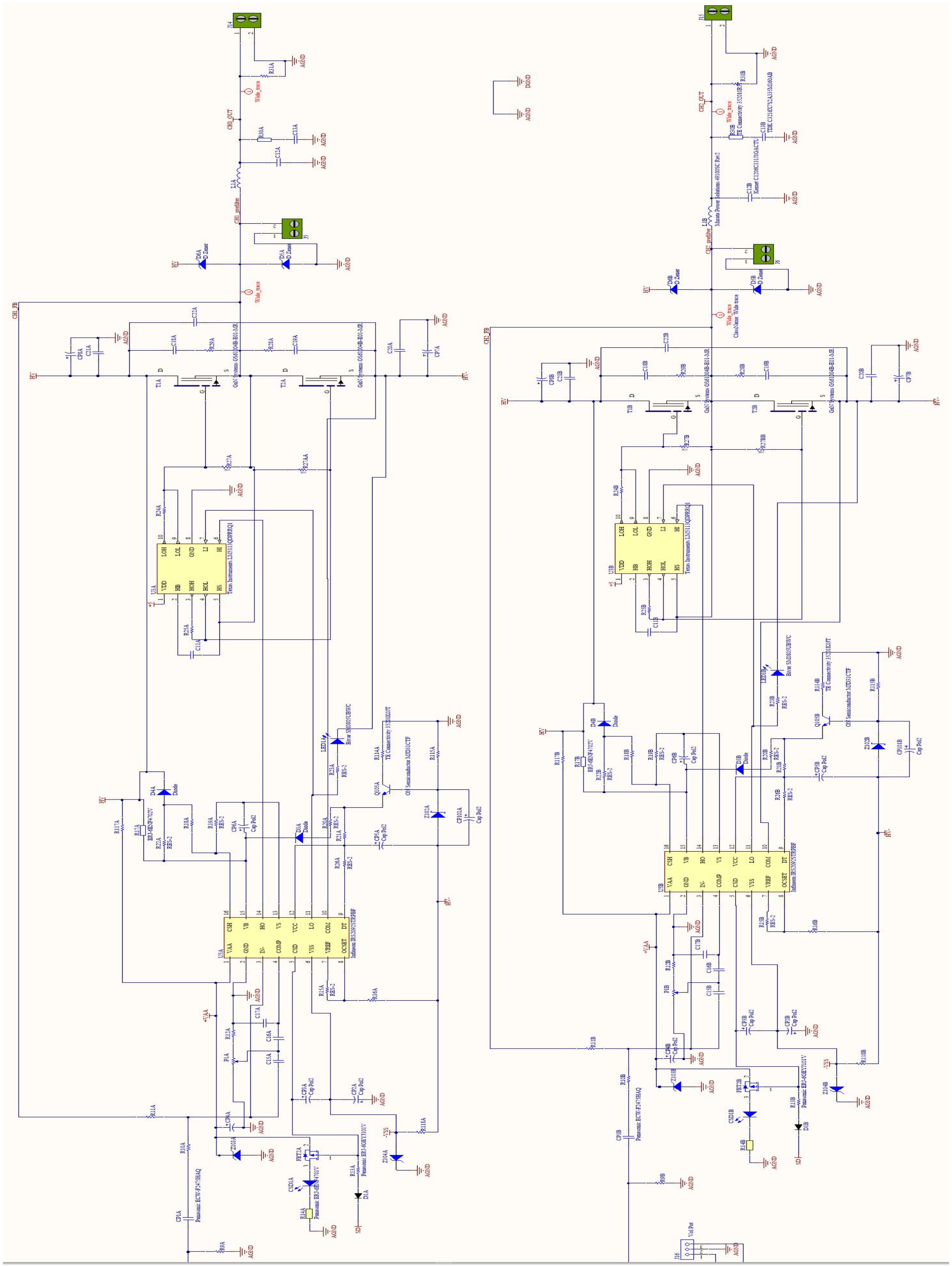
Appendix A

Schematics





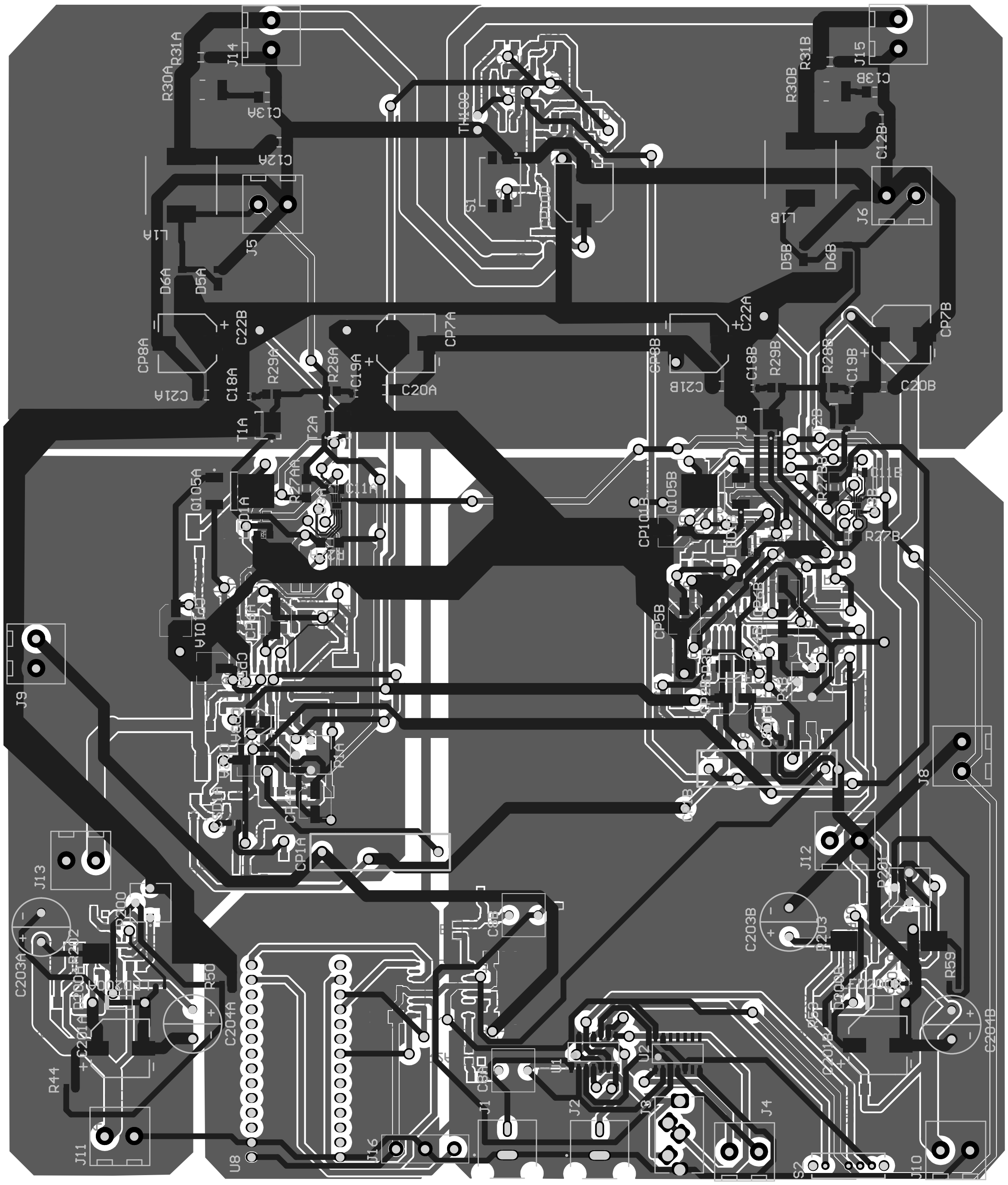
Vin+
Vin-
HV
HV-
C204A
C204B
Cap Pol2
C203A
C203B
AGND
R202
R203
R200
R201
P200
P201
10kΩ
R44
R53
R50
R59
DNI
J12
J13
Q200
Q201
Diodes Inc. ZXTP2027FTA
R210
R211
D201AA
D201BA
BZX84C4V7LT3G
LED200A
LED200B
Vishay TLMS1000-GS08
R204
R205
C202A
C202B
R206
R207
R208
R209
CH2_OUT
CH1_OUT
R108
R109
R110
CP100
Q102
Q103
Diodes Inc. MMBT5401-7-F
Z100
Z101
R112
ERJ-6ENF4702V
R113
RES-2
Q104
MMBT5551LT1G
R111
R106
R107
R105
S1
TH100
R101
-VSS
Q101
R102
C100
0.1uF
R103
R104
Q100
SD
D200A
D200B
1N4003-T
C201A
C201B
C200A
C200B
J11
J10
TE Connectivity 282857-2
J8
J9
+5
-5



Appendix B

PCB Composite Layout

This appendix features the PCB layout as seen from the top with all layers visible: top, overlays, mechanical, bottom. The black traces are on the top layer, and the gray traces and fills are on the bottom layer.



Appendix C

Bill of Materials

The following bill of materials includes only the parts ordered. It does not include the copper clad board from which the PCB was milled nor any of the equipment used during the assembly process.

BOM			
Qty	Manufacturer	MPN	Description
3	KEMET	C0805C104K5RACTU	Cap, Ceramic, 0.1 uF, 10% Tol, 0805
5	Panasonic	EEEFK1V100UR	Cap; Alum Elec; 10 uF; Tol 20%; SMT; 4x5.8
2	WIMA	MKS2B044701K00KSSD	Cap Film 4.7uF 50V 10% Radial 5mm
2	KEMET	C1206C104J1RACTU	Ceramic Cap MLCC - SMT 100volts 0.1uF 5%
2	KEMET	C1206C331J1GACTU	Ceramic Cap MLCC - SMT 100volts 330pF 5%
2	TDK	C3216X7S2A335M160AB	1206 3.3 uF 100 V 20% SMT Ceramic Cap
6	TDK	C2012C0G2E102J085AA	0805 1 nF 250 V 5% SMT Ceramic Cap
4	Murata	GCM21A7U2E151JX01D	CAP CER 150PF 250V 5% 0805
6	KEMET	C1206C104K1RACTU	Ceramic Cap MLCC - SMT 100volts 0.1uF 10%
2	EPCOS	B32652A4104J	Cap Film 0.1uF 400V 5% (18 X 5 X 10.5mm) Radial
1	Vishay	VJ0603Y104JXQCW1BC	Ceramic Cap MLCC - SMT 0603 0.1uF 10volts 5%
6	Panasonic	EEE2AA100UP	Cap Alum Elec, 10uf, 100v, 20%
2	KEMET	C1206C473K1RACTU	Cap Ceramic 0.047uF 100V X7R 10% SMD 1206
4	Panasonic	ECA-2AM101B	Cap Alum 100uF 100V 20% Radial 5mm
2	Panasonic	ECW-F2475JA	Cap Film 4.7uF 250V 3% Radial 20mm
1	Panasonic	EEEFK1A331P	Cap Alum Elec 330uF 10 Volt 20% (8 X 10.2mm) SMD 600mA
2	Lumex	SML-LX0603IW-TR	Red 0603 1.6 x 0.8 mm 160deg Diffused 14 mcd 2V Mount LED
2	Diodes Inc.	1N4148WS-7-F	DIODE SWITCHING 75V 0.15A SOD323
2	ON Semiconductor	MURA120T3G	Diode Rectifier MURA120T3G A=1 V=200
2	MCC	BAV19WS-TP	Diode Switching 120V 0.2A 2-Pin SOD-323
4	Diodes Inc.	DFLS2100-7	Diode Schottky 100V 2A 2-Pin
2	Diodes Inc.	1N4003-T	1.0 A Rectifier, 15 pF, 200 V,
2	ON Semiconductor	BZX84C4V7LT3G	Zener Voltage Reg, 225 mW, 3-Pin SOT-23, Pb-Fre
2	Diodes Inc.	BS250FTA	Trans MOSFET P-CH 45V 0.09A 3-Pin SOT-23
11	TE Connectivity	282857-2	2 Position 5.08 mm Pitch 30-12 AWG Terminal Block
2	Murata Power Solutions	49100SC	Ind Power Shielded Bobbin Core 10uH 20% 10KHz 43Q-Factor 5.1A T/R
2	Bivar	SM0805UBWC	LED Blue 468nm 2-Pin 0805
2	Vishay	TLMS1000-GS08	LED; SMD; 0603; red; 1.8-4mcd; 1.6x0.8x0.6mm; 80deg; 1.82.6V; 2mA
2	Bourns	3362P-1-202LF	Potentiometer 500mW
2	Bourns	3362P-1-103LF	Square Trimpot(R) , 10 KOhm, 300 V
2	ON Semiconductor	MMBT5551LT3G	High Voltage Transistor, NPN Silicon, 3-Pin SOT-23
3	Diodes Inc.	MMBT5401-7-F	Transistor, Bipolar, Pnp, -150V, -600Ma, SOT-23p;
2	Diodes Inc.	ZXTP2027FTA	ZXTP2027F Series 60 V 4 A PNP SMT- SOT-23
2	Panasonic	ERA-6AEB104V	Res Thin Film 0805 100K Ohm 0.1% 0.125W
2	Susumu	RG2012P-111-B-T5	RES SMD 110 OHM 0.1% 1/8W 0805
2	Panasonic	ERA-6AEB2212V	Res, Thin Film, 22.1 kohm, 125 mW, 0.1%
3	Panasonic	ERJ-6GEYJ104V	Thick Film Resistors - SMD 0805 100Kohms 5% Tol
2	Panasonic	ERJ-6ENF3001V	Thick Film Resistors - SMD 0805 3Kohms 1% Tol

Qty	Manufacturer	MPN	Description
4	Panasonic	ERJ-6GEYJ101V	Thick Film Resistors - SMD 0805 100ohms 5% Tol
4	Panasonic	ERJ-6ENF4701V	Res Thick Film 0805 4.7K Ohm 1% 0.125W
16	Panasonic	ERJ-6ENF1002V	RESISTOR,SMT,0805,10K OHM, 1%
2	Panasonic	ERJ-6ENF7501V	Thick Film Resistors 0805 7.5Kohms 1% Tol
3	Panasonic	ERJ-6ENF4702V	Res Thick Film 0805 47K Ohm 1% 0.125W
2	Panasonic	ERJ-6ENF9091V	Thick Film Resistors - SMD 0805 9.09Kohms 1% Tol
2	Panasonic	ERJ8RQF4R7V	Thick Film Resistors - SMD 1206 4.7ohms 1% Tol
2	Panasonic	ERJ-PA3F10R0V	Res Thick Film 0603 10 Ohm 1% 0.25W
8	Panasonic	ERJ-6ENF10R0V	Thick Film Resistors - SMD 0805 10.0ohms 1% Tol
4	Panasonic	ERJ-8GEYJ103V	Res Thick Film 1206 10K Ohm 5% 0.25W
2	Panasonic	ERJ-8GEYJ222V	Thick Film Resistors - SMD 1206 2.2Kohms 5%
4	Susumu	RL1220S-R22-F	RES SMD 0.22 OHM 1% 1/3W 0805
1	Panasonic	ERJ-6ENF7150V	Thick Film Resistors - SMD 0805 715ohms 1% Tol
2	Panasonic	ERJ-8GEYJ104V	Thick Film Resistors - SMD 100K OHM 5%
2	TE Connectivity	35201K0JT	Res Thick Film 2512 1K Ohm 5% 1W
2	Yageo	AC1206FR-0715KL	AC Series 1206 15 kO tol1% 0.25 W
2	Panasonic	ERJ-6GEYJ272V	Thick Film Resistors - SMD 0805 2.7Kohms 5% Tol
2	TE Connectivity	SMW5R22JT	Metal Film Resistor 0.22 ohm, 5 W, - 5%
2	Panasonic	ERJ-6GEYJ220V	Thick Film Resistors - SMD 0805 22ohms 5% Tol
2	Panasonic	ERJ-3GEYJ103V	Res Thick Film 0603 10K Ohm 5% 1/10W
2	Panasonic	ERJ-2GEJ182X	Thick Film Resistors - SMD 0402 1.8Kohms 5% Tol
2	Panasonic	ERJ-3GEYJ332V	Thick Film Resistors - SMD 0603 3.3Kohms 5% Tol
1	TE Connectivity	1825058-1	Switch DIP SPST 2 Raised Slide 0.1A 24VDC
1	C&K Components	OS103011MS8QP1	SP3T On-On-On Right Angle THT Slide Switch
4	GaN Systems	GS61004B-E01-MR	GaN Systems GS61004B-E01-MR
2	ON Semiconductor	MC74LVX4066DR2G	Quad Analog Switch, 2 to 6 V
2	Texas Instruments	LM5113QDPRRQ1	Driver 5A 2-OUT High/Low Side Full Brdg/Half Brdg Inv/Non-Inv 10-Pin WSON
1	Texas Instruments	PGA2311U	5V Stereo Audio Vol Ctrl 16-SOIC
2	Infineon	IRS2092STRPBF	High Performance Class D Audio Amp driver; 16-SOIC
1	Nexperia	BZT52H-C68,115	68 V 375 mW Single Zener Diode - SOD-123F
1	Diodes Inc.	BZT52C39-7-F	500 mW 39 V 10 mA Zener Diode - SOD-123
2	ON Semiconductor	MMSZ4702T1G	500mW 10mA 15V Zener Voltage Reg - SOD-123
4	MCC	BZT52C5V6-TP	BZT52C Series 500 mW 5.6 V Zener - SOD-123

Appendix D

Code

```
//------------------------------------------------------------------------
//Title: Volume_Ctrl.ino
//Authors: Sang Bin Park, William Carrier, Zach Poirier
//Date Created: 25 FEB 20
//Last Edit: 10 MAR 20
//
//Description: Arduino program for the Teensy4.0 microcontroller board
//             to control the volume on the PGA2311, as well as indicate
//             the gain in dB on a LCD screen for the user to see.
//------------------------------------------------------------------------

#include <stdlib.h>
#include <SPI.h>
#include<Wire.h>
#include<LiquidCrystal_I2C.h>

LiquidCrystal_I2C lcd(0x27,16,2);

//SPI variables
int potPin = 14;
int CS = 10;
int ZCEN = 6;
int MOSIpin = 11;
int val = 0;
int vol_out;
int speed_MAX = 6250000;

float Gain = 0;

byte data = 0;

byte vol_block1[8] = {B00000,B00000,B00000,B00000,B00000,B00000,B00000,B11111};
byte vol_block2[8] = {B00000,B00000,B00000,B00000,B00000,B00000,B11111,B11111};
byte vol_block3[8] = {B00000,B00000,B00000,B00000,B00000,B11111,B11111,B11111};
byte vol_block4[8] = {B00000,B00000,B00000,B00000,B11111,B11111,B11111,B11111};
byte vol_block5[8] = {B00000,B00000,B00000,B11111,B11111,B11111,B11111,B11111};
byte vol_block6[8] = {B00000,B00000,B11111,B11111,B11111,B11111,B11111,B11111};
byte vol_block7[8] = {B00000,B11111, B11111,B11111,B11111,B11111,B11111,B11111};
byte vol_block8[8] = {B11111,B11111,B11111,B11111,B11111,B11111,B11111,B11111};

void setup() {
  //intializing the pins for SPI
  pinMode(CS, OUTPUT);
  pinMode(ZCEN, OUTPUT);
  pinMode(MOSIpin, OUTPUT);

  pinMode(19, OUTPUT);
  pinMode(18, OUTPUT);
```

```
  digitalWrite(ZCEN, HIGH); //sets the ZCEN pin to HIGH, which enables
                            //zero-crossing noise detection

  //initialization for the LCD screen
  lcd.init();
  lcd.backlight();

  //Create new characters for volume bar
  lcd.createChar(0,vol_block1);
  lcd.createChar(1,vol_block2);
  lcd.createChar(2,vol_block3);
  lcd.createChar(3,vol_block4);
  lcd.createChar(4,vol_block5);
  lcd.createChar(5,vol_block6);
  lcd.createChar(6,vol_block7);
  lcd.createChar(7,vol_block8);
  SPI.begin();
}

void loop() {
  val = analogRead(potPin);
  data = volume_conv(val);
  send_volume(data);
  write_LCD(data);
  delay(200);
}

//-------------------------------------------------------------------------
//Function: volume_conv
//Input(s): an integer x
//Output(s): a byte vol_out
//
//Description: Scales down the reading from the potentiometer, and prepares
//             the result as a byte for the PGA2311 to read. Also, it
//             calculates the gain that the PGA2311 will be producing.
//-------------------------------------------------------------------------

byte volume_conv(int x){
  float temp = x/4;
  floor(temp);
  byte vol_out = abs(255 - temp);
  Gain = 31.5 - 0.5*(255-vol_out); //calculates gain in dB
  return vol_out;
}

//-------------------------------------------------------------------------
//Function: send_volume
//Input(s): a byte data
//Output(s): nil
//
//Description: Prepares the byte it receives to transmit to the PGA2311
//             through SPI. Completes the transaction within the function,
//             and sends the input byte twice for the left channel and
//             right channel.
//-------------------------------------------------------------------------

void send_volume(byte data){
//PGA2311 operates at 6.25 MHz, with MSB, and CPOL and CPHA equals 1
  SPI.beginTransaction(SPISettings(speed_MAX,MSBFIRST,SPI_MODE3));
  digitalWrite(CS, LOW);
  SPI.transfer(data);
  SPI.transfer(data);
  digitalWrite(CS, HIGH);
  SPI.endTransaction();
}

//-------------------------------------------------------------------------
```

```
//Function: write_LCD
//Input(s): byte vol
//Output(s): nil
//
//Description: Takes in the byte that was given, scales it down for the
//             eight volume bars, and prints the required amount of
//             volume bars compared to the gain sent to the PGA2311. Also
//             included is a mute functionality when the gain = -96.
//---------------------------------------------------------------------

void write_LCD(byte vol){
  float cond = abs(vol/32);
  int CursorPosn = 0;
  if (cond <= 1){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 0;
  }if(1 < cond && cond <= 2){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 1;
  }if(2 < cond && cond <= 3){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 2;
  }if(3 < cond && cond <= 4){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 3;
  }if(4 < cond && cond <= 5){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 4;
  }if(5 < cond && cond <= 6){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 5;
  }if(6 < cond && cond <= 7){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 6;
  }if(7 < cond && cond <=8){
    lcd.clear();
    lcd.setCursor(0,0);
    lcd.print(String("Volume:␣") + String(Gain,1) + String("dB"));
    CursorPosn = 7;
  }if(Gain == -96){
    CursorPosn = 8;
  }

  for (int i = 0;i <= CursorPosn;i++){
    if (CursorPosn == 8){
      lcd.clear();
      lcd.setCursor(0,0);
      lcd.print("Muted");
      break;
    }
    lcd.setCursor(5+i,1);
    lcd.write(byte(i));
  }
}
```