ECE445

Senior Design Laboratory

Design Document

Four Point Probe

By

Dorian Tricaud

Ming-Yan Hsiao

Simon Danthinne

Project Proposal for ECE 445, Senior Design, Fall 2024

TA: Dongming Liu

04 October 2024

Project No. 24

Abstract

This proposal is an extension of our project proposal; in this writing, we analyze in depth the measurement subsystem and power supply subsystem, for our project requires precision to discern sheet resistance voltage change on a small portion of a wafer. Based on our tolerance analysis, we design an elaborate measurement system involving a stable(+- 1% error) 200mA DC current, a high precision reading ADC (24 bits with 0.9V reference), a 50 V/V inverting negative feedback op-amp, a stable power supply system using a buck converter to efficiently convert 5 V to 3.3V DC for general power needs with an linear dropout regulator to provide a stable voltage for sensitive components, a concise microcontroller, a liquid crystal display, and buttons in our schematic design. After the circuit design, we designate the verifications of whether our circuit designs meet the requirements. Lastly, we ensure our project abides by ethics protocols and is without safety concerns.

Contents

1. Introduction

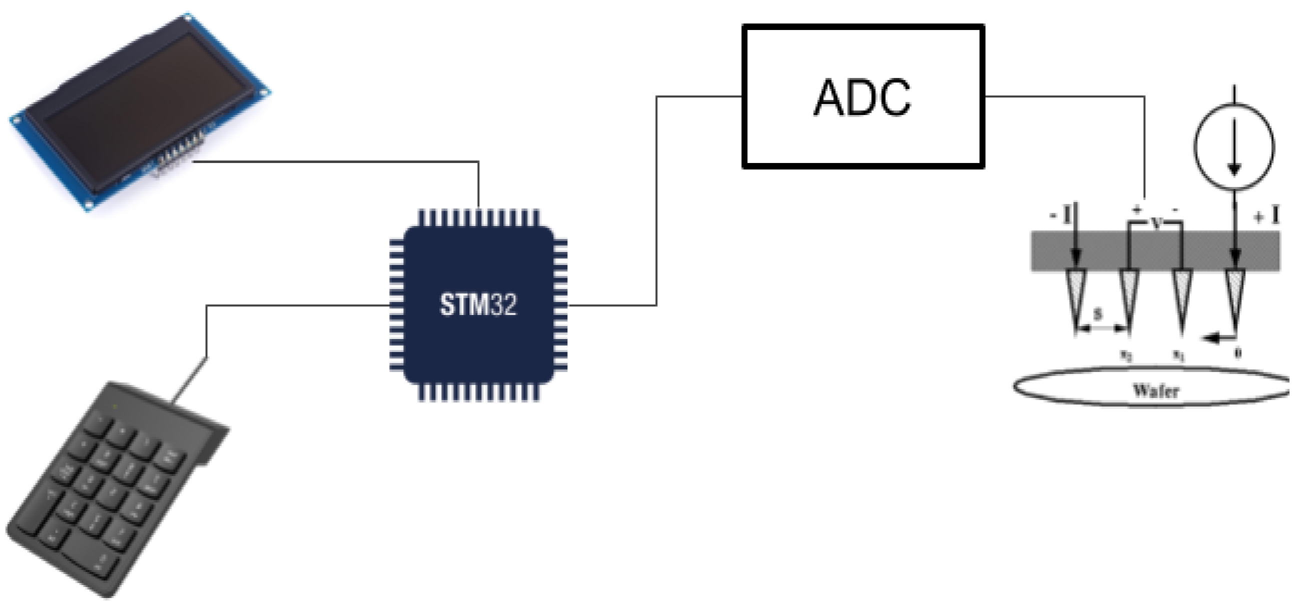
1.1 Problem

In the manufacturing process of semiconductor wafers, numerous pieces of test equipment are essential to verify that each manufacturing step has been correctly executed. This requirement significantly raises the cost barrier for entering semiconductor manufacturing, making it challenging for students and hobbyists to gain practical experience. To address this issue, we propose developing an all-in-one four-point probe setup. This device will enable users to measure the surface resistivity of a wafer, a critical parameter that can provide insights into various properties of the wafer, such as its doping level. By offering a more accessible and cost-effective solution, we aim to lower the entry barriers and facilitate hands-on learning and experimentation in semiconductor manufacturing.

1.2 Solution

Our design will use an off-the-shelf four point probe head for the precision manufacturing tolerances which will be used for contact with the wafer. This wafer contact solution will then be connected to a current source precisely controlled by an IC as well as an ADC to measure the voltage. For user interface, we will have an array of buttons for user input as well as an LCD screen to provide measurement readout and parameter setup regarding wafer information. This will allow us to make better approximations for the wafer based on size and doping type.

1.3 Visual Aid



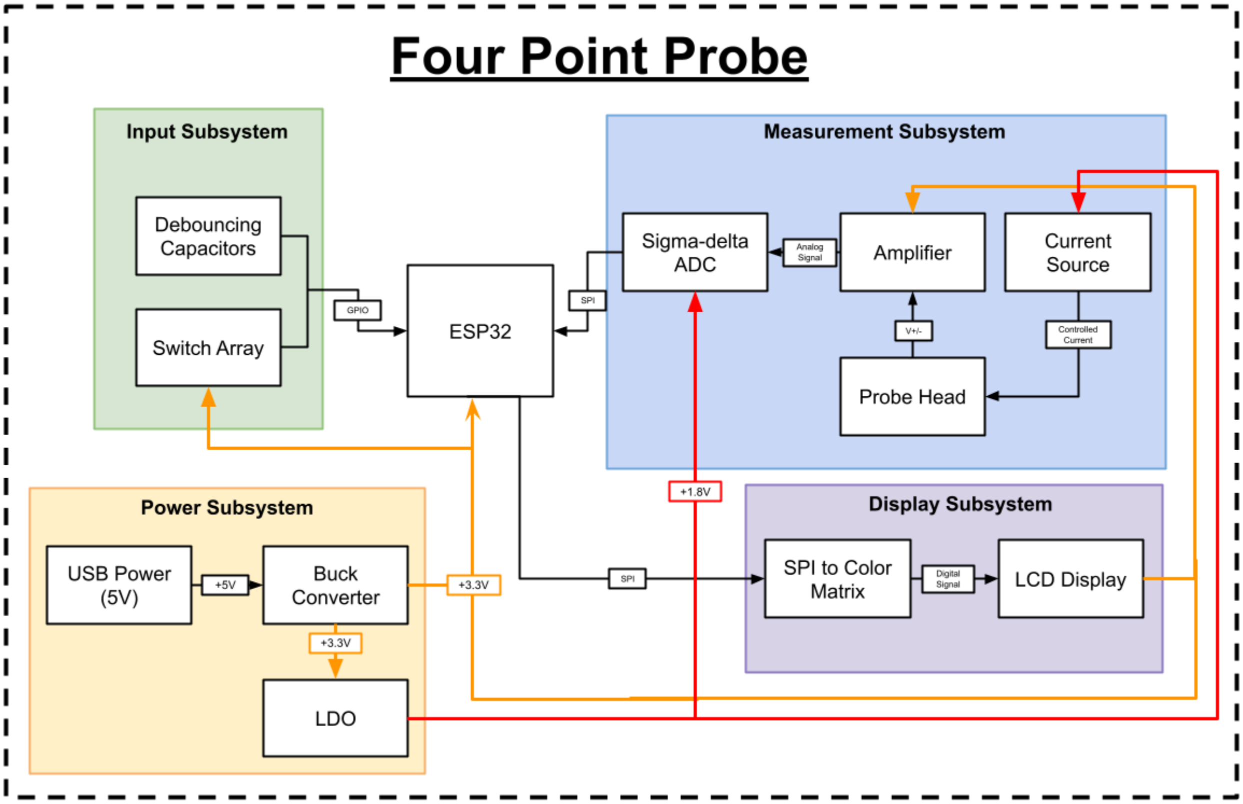
1.4 High-level Requirements

Setting up standards to determine our success, we aim to achieve the following requirements::

1. The measurement precision should lie in the range of ±50 milliVolt, the measurement converted to ADC scale.
2. The probe should be able to measure sheet resistance under 5 different shapes of wafers (1 to 5 inches diameter) with the assistance of user input.
1. The display system should be able to refresh every 100ms for the output display and show the measured sheet resistance as well as the estimated doping profile.

2. Design

2.1 Block Diagram

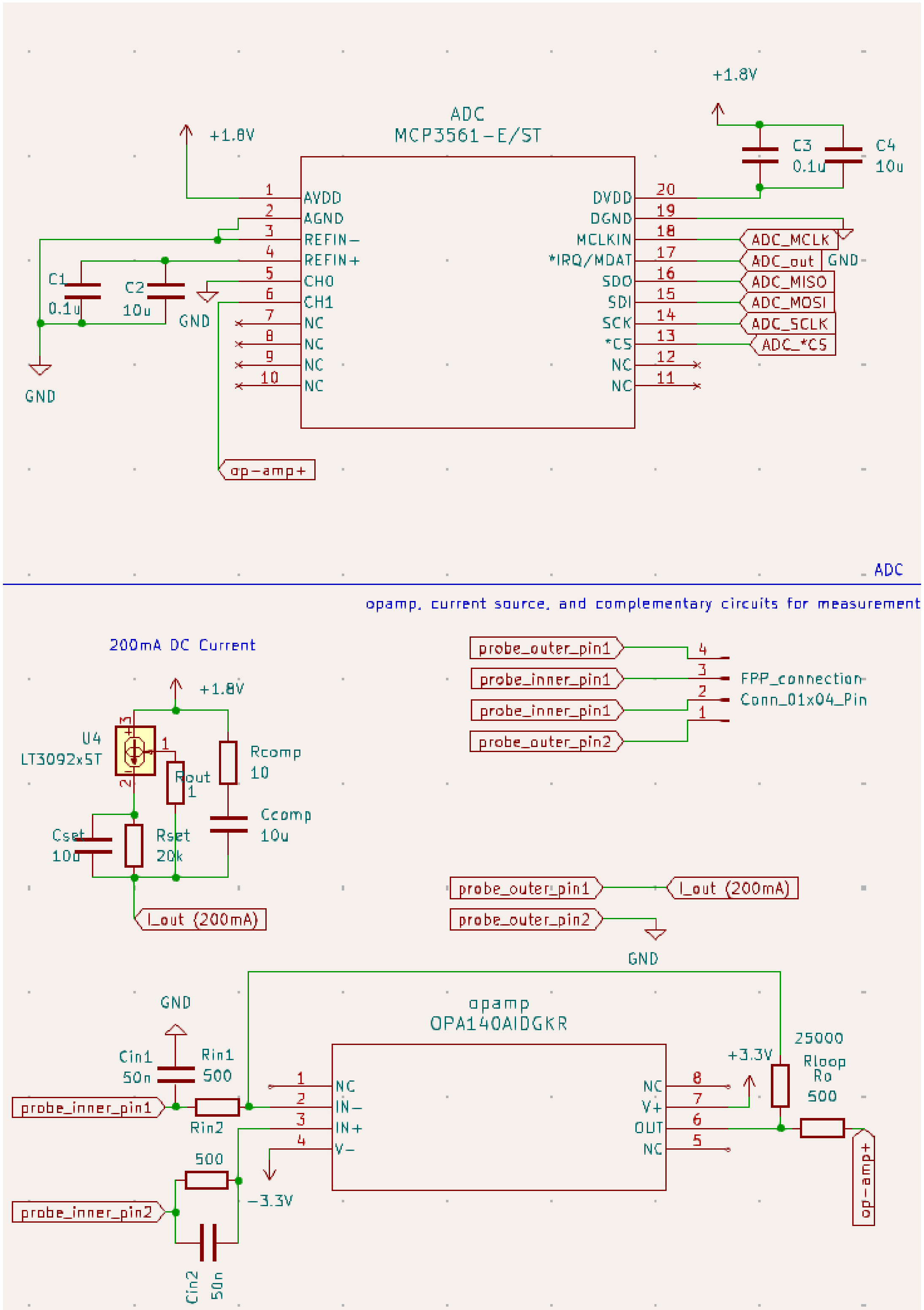


2.2 Subsystem Overview

2.2.1 Measurement Subsystem

We utilize a four-point probe head (HPS2523)[5] with 2mm diameter gold tips to measure the sheet resistance of the silicon wafer. A DC constant current source (LT3092)[2] will be employed to force 200mA through the two outer tips, while a 24-bit ADC (MCP3561RT-E/ST)[6] will measure the voltage across the two inner tips, with expected measurements in the millivolt range and current operation lasting several milliseconds. Additionally, we plan to use the switching feature of the DC current source to transiently sweep (~10ns range) the outer tips to measure capacitances between them, which will help determine the dopants present. To accurately measure the low voltages, we will amplify the signal using an JFET op-amp (OPA140AIDGKR)[3] to ensure it falls within the ADC's specifications. Using these measurements, we can apply formulas with corrections for real-world factors to calculate the sheet resistance and other parameters of the wafer.

Schematic for Measurement Subsystem:



200mA current source is derived by having LT3092-ST connected to 3 sets of resistors and capacitors. The derivation ought to be as formula below:

$$V_{max} = (V_{in} - V_{out})_{max}; V_{out,min} = R_{eq,min} * 200mA = 0.01V; R_{comp} = \frac{V_{max}}{200mV/R_1/0.9} \approx 10\Omega$$

The 10u capacitor used on the whole component to have less noise while the circuit is still stable under millisecond operations. Similar amounts of capacitances are decoupled across V_{ref} and $V_{dd,digital}$ of the ADC which are also recommended by the datasheet for stabilization.

For the op-amp design we chose to use an inverting setup due to its noise reduction capabilities. Our minimum voltage difference was set to 4 mV, which we wished to amplify up to 200 mV. This resulted in a gain of 50 V/V for the amplifier. Using the inverting op-amp circuit design, this requires two resistors: R_1 and R_2=50R_1. When choosing resistors for the op-amp, we wanted a large value to reduce output current requirements while still managing the op-amp input bias current. After a few trials, we calculated that a R_1=500 ohm resistor would result in about 1% output voltage error which is well within our tolerances. We coupled our inputs with a 50nF capacitor to slightly reduce the input noise while also balancing the charge time for changing inputs. Lastly, the datasheet recommends adding a 500 Ohm resistor to the output of the op-amp to achieve load isolation.

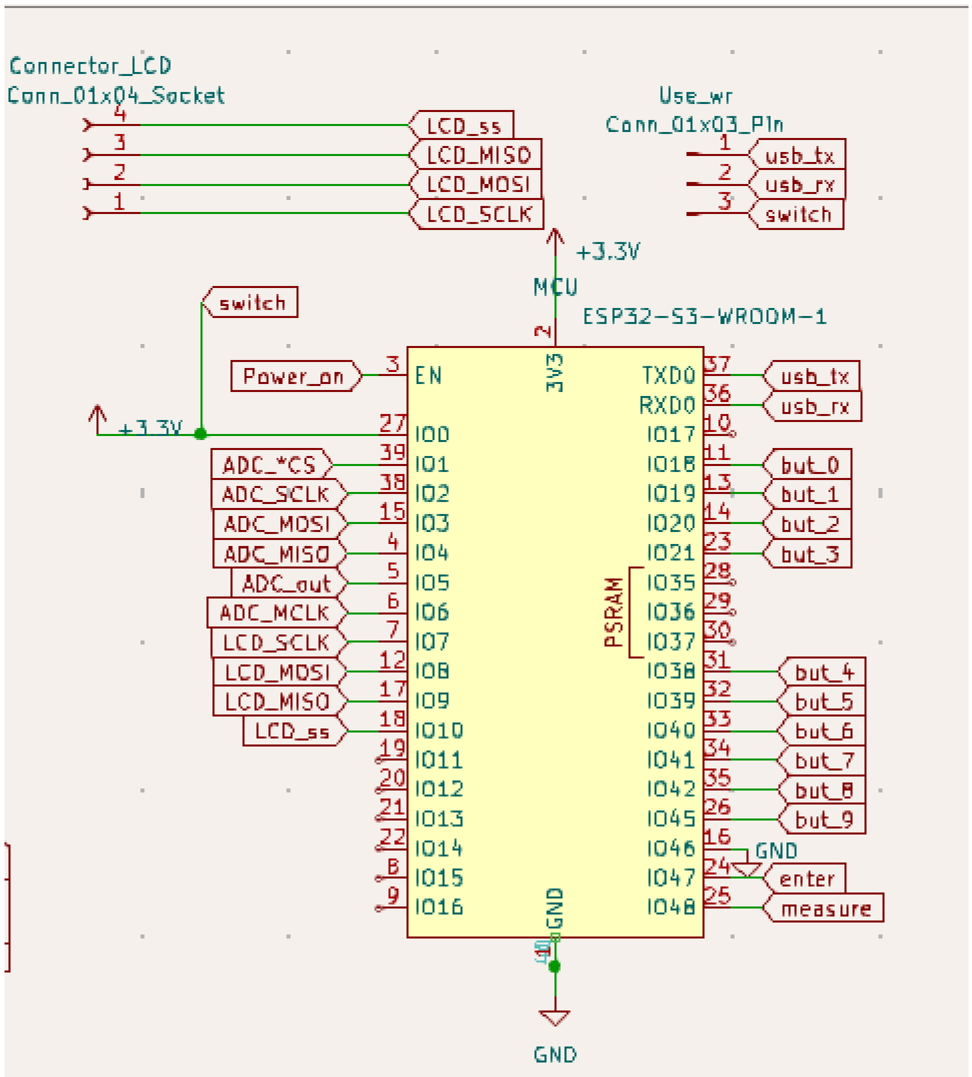
2.2.2 User Input Subsystem

To enable users to interact effectively with the measurement system, we will implement an array of buttons that offer various functions such as calibration, measurement setup, and measurement polling. This interface will let users configure the measurement system to ensure that the approximations are suitable for the specific properties of the wafer. The button interface will provide users with the ability to initiate calibration routines to ensure accuracy and reliability, and set up measurements by defining parameters like type, range, and size tailored to the wafer's characteristics. Additionally, users can poll measurements to start, stop, and monitor ongoing measurements, allowing for real-time adjustments and data collection. The interface also allows users to make approximations regarding other wafer properties so the user can quickly find out more information on their wafer. This comprehensive button interface will make the measurement system user-friendly and adaptable, ensuring precise and efficient measurements tailored to the specific needs of each wafer. As we can see in the subsystem next page, 12 button labels will be assigned to sockets (connecting to 1kΩ and 1uF for 1ms debouncing) for PCB connection to the actual interface, and their signals will be sent to MCU with functions of typing 0 to 9 and entering values, and initiating measurement.

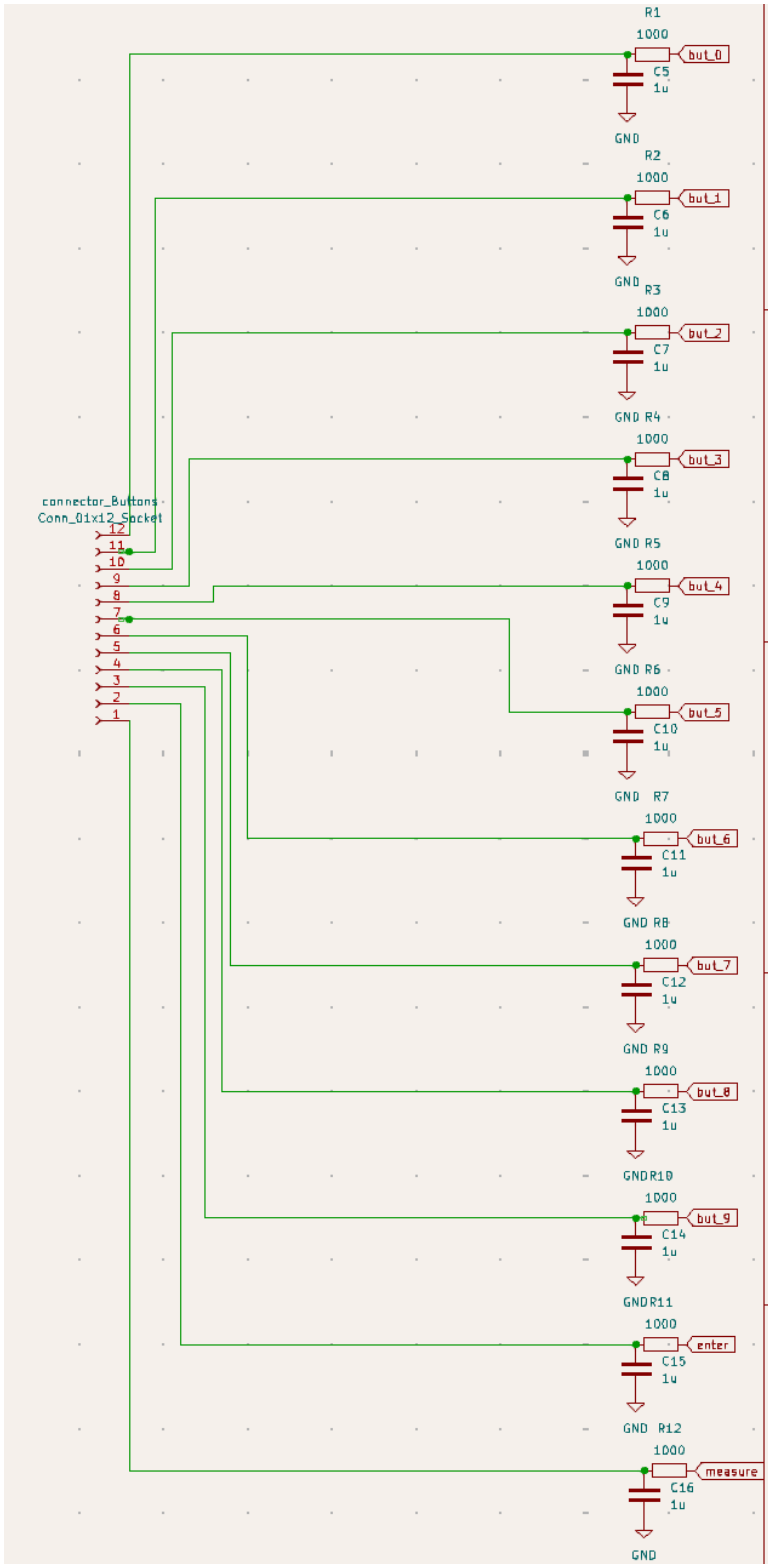
2.2.3 Display Subsystem

To provide output to users, we will utilize a monochrome 2.4 inch 128x64 OLED LCD display driven over SPI from the MCU[4]. This display will not only present data clearly but also serve as an interface for users to interact with the device. The monochrome LCD will be instrumental in displaying measurement results, system status, and other relevant information in a straightforward and easy-to-read format. Additionally, it will facilitate user interaction by providing visual feedback during calibration, measurement setup, and polling processes. This ensures that users can efficiently navigate and operate the device, making the overall experience intuitive and user-friendly. We will use SPI for routing MCU commands to the LCD Display, and we will use socket connection for non-PCB interface. MCU will be flashed externally, we have switch, usb_tx, and usb_rx pins connecting to external device which will pull low IO0 (switch) to indicate USB/UART writing, and usb_tx and usb_rx will be used to transmit data.

Schematic for MCU and Display Subsystems:

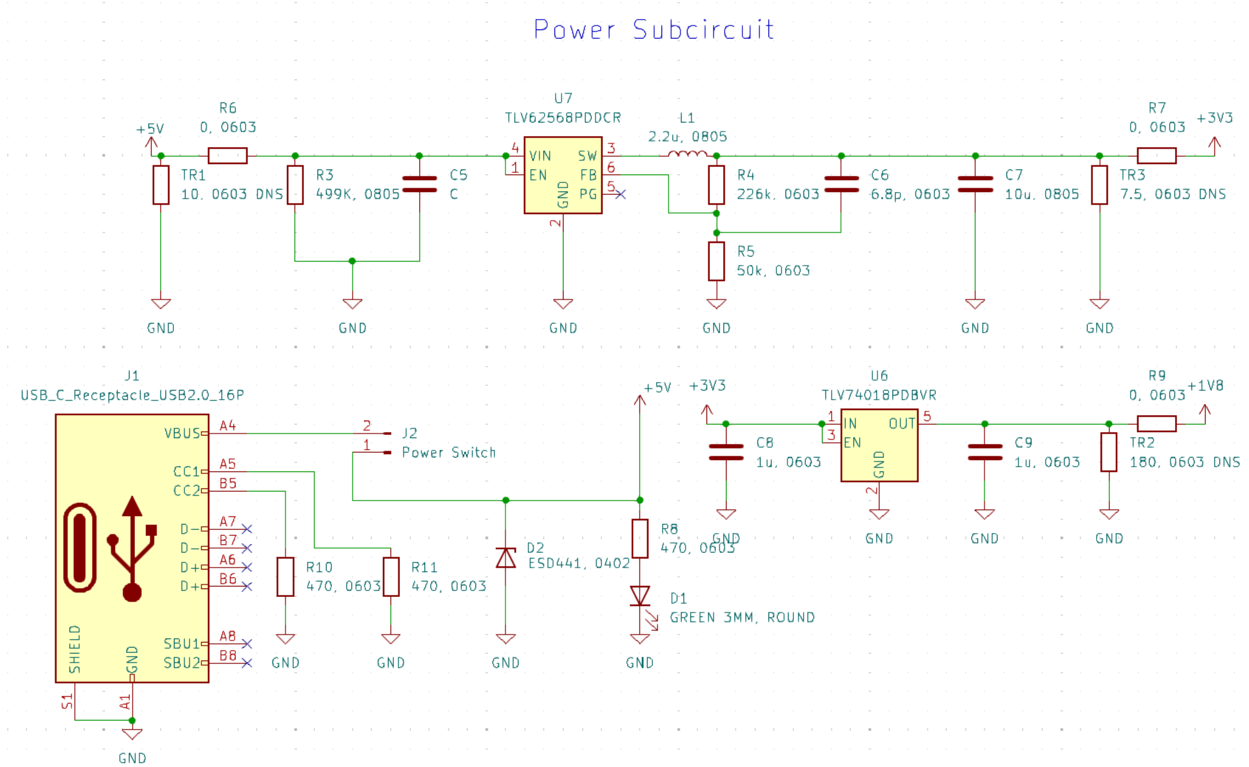


Schematic for User Input Subsystem:



2.2.4 Power Regulation Subsystem

To ensure that all components receive power within their specified requirements, we will employ a buck converter due to its high efficiency. This converter will step down the 5V input power to the 3.3V required by the components. By using a buck converter, we can efficiently manage power distribution, minimizing energy loss and ensuring stable operation of the system. This approach not only optimizes power usage but also enhances the overall reliability and performance of the device by providing a consistent and appropriate voltage to all components.



2.3 Subsystem Requirements

2.3.1 Measurement Subsystem Requirements

1. The current source (LT3092) should produce a +-1% 200mA constant current.
2. The ADC (MCP3561RT-E/ST) should at least detect a 40 millivolt range voltage change.
3. The probe head (HPS2523) should have tips separated 2 +-0.1 mm uniformly.

2.3.2 User Input Subsystem Requirements

1. Buttons can be used to select wafer parameters.
2. The buttons must be properly debounced and not result in multiple registered presses for a single button press.

2.3.3 Display Subsystem Requirements

1. The LCD display must be able to display measurements and calculated results legibly.
2. The display should refresh every time a measurement is taken.
3. It must be able to show the setup parameters currently being used.
4. The display must be able to refresh every 100 ms for the output display.

2.3.4 Power Regulation Subsystem Requirements

1. The system must be able to negotiate at least 5 ± 0.4V 500mA power over USB.
2. The system must be able to provide a 1.8 ± 0.1 V supply up to 50 mA.
3. The system must be able to provide a 3.3 ± 0.2 V supply up to 450 mA.

2.3.5 Requirements and Verification Table

Measurement Subsystem	
Amplifier Requirements	**Verifications**
1) For DC input range 4 mV to 40mV maintains a gain of between 45 V/V to 55 V/V. 2) For AC input up to 15 kHz maintain a minimum gain of 40 V/V.	1) 1Apply DC Voltage Difference of 4 mV, 15 mV, 30 mV, 40 mV to inputs of the amplifier and measure the DC output voltage. Calculate the corresponding gain. 2) Apply sinusoidal waveform at 1 Hz, 1 kHz, 10 kHz, 15 kHz to inputs of the amplifier and measure the resulting sinusoidal output. Calculate the corresponding gain
Current Source Requirements	**Verifications**
1) Current Source should provide a constant 190-210 mA current for a 20-50 millisecond measurement period.	1) Apply a square waveform of 1.8V to turn on the current source for 20, 35, 50 milliseconds. Have the current source feed into a 5 ohm resistor, and measure the voltage across the resistor. Verify that the voltage across the resistor is between 0.95 V and 1.05 V during the expected measurement period.
ADC Requirements	**Verifications**
1) Properly converts detected analog voltages between 25 - 100 mV to corresponding digital signal within ± 10 mV.	1) Apply DC Voltage of 25, 40, 60, 80, 100 mV to analog input and observe digital signal output. Verify digital signal output is within 10 mV of actual applied DC Voltage.
Probe Head Requirements	**Verficiations**

1) Probe head tips should have 2mm separation, with a precision of 0.1 mm.	1) Use a high precision caliper to measure the probe tip spacing.

User Input Subsystem	
Button Requirements	**Verifications**
1) The buttons must be properly debounced such that multiple button presses are not registered for a single button press. 2) Each individual button press is read as a change from logic HIGH to logic LOW by the microcontroller.	1) Apply a jumpy-input signal with 3 bounces separated by 50 us and verify that the output does not jump from logic low (0.25 V) back to logic high (0.75 V). 2) Apply a rectangle input signal and verify that the output returns to logic low (0.25) within 1 second.

Display Subsystem	
LCD Requirements	**Verifications**
1) The LCD display must be able to legibly display each measurement and calculated wafer parameters. 2) The display should update within 100 ms of user input.	1) Apply input signals corresponding to various doping concentrations (10^{19}, $2x10^{20}$, $6x10^{20}$) and verify proper legible display. 2) Use a camera to record the LCD display at 60 frames per second and measure the time difference between the button being pressed (oscilloscope) and the display changing.

Power Subsystem	
USB Requirements	**Verifications**
1) The circuit must be able to maintain 5±0.4 V with current draw up to 500 mA. 2) The buck converter must be able to output 3.3±0.2 V for up to 450 mA current draw. 3) The linear regulator must be able to provide 1.8±0.1 V output for up to 50 mA.	1) Desolder the 0 ohm resistor connecting the +5V supply to the voltage converters. Solder a 10 Ω (±5%) resistor in the TR1 resistor location. Connect the subsystem to power and turn it on. Measure the voltage across the resistor and ensure that is is between 4.6 - 5.4 V 2) Desolder the 0 ohm resistor connecting

	the +3.3 V supply to other devices. Solder a 7.5 Ω (±5%) resistor in the TR3 resistor location. Connect the subsystem to power and turn it on. Measure the voltage across the resistor and ensure that it is between 3.1 - 3.5 V. 3) Desolder the 0 ohm resistor connecting the +1.8 V supply to other devices. Solder a 180 Ω (±5%) resistor in the TR2 resistor location. Connect the subsystem to power and turn it on. Measure the voltage across the resistor and ensure that it is above 1.7 - 1.9 V.

2.4 Tolerance Analysis

2.4.1 Tolerance Analysis of the Measurement Subsystem

The imperative aspect of our design is the measurement subsystem since we want to reduce cost while maintaining decent precision. Thus, we need to perform tolerance analysis on the measurement subsystem. The most important two variables are ΔV(voltage change across inner tips) and R_{eq}(total equivalent resistance of the wafer cross-section), where e ΔV is for ADC detection and precision while R_{eq} checks for noise tolerance analysis. Notations of the calculation: I is the constant current passing through outer tips; ρ_s is the sheet resistance which normally lies between [100, 500] mΩ; and L/W is the 3*space between two tips over space between two tips (noting that tip is not a point).

$$\Delta V = I * \frac{\rho_s}{4.53} \approx 4.415mV \; , \frac{L}{W} = [2,4] \; , R_{eq} = \frac{L}{W} * \rho_s \approx 200mOhms$$

As we can see ΔV falls within our ADC selection (24 bits), but we will still use an op-amp to amplify the signal for avoiding exceeding slew rate (0.27 mV/ms) of the ADC since the DC current sweeping time will be 1ms. Looking at the table below, if we carefully design our PCB, the worst case scenario R_{eq} is still an order of magnitude higher than the wiring resistance of the PCB; we will also calibrate our probe heads to have minimum copper wire whose wire is around 0.1 Ω/m.

Table 1. PC Board Trace Resistance

WEIGHT (oz)	10mil WIDTH	20mil WIDTH
1	54.3	27.1
2	27.1	13.6

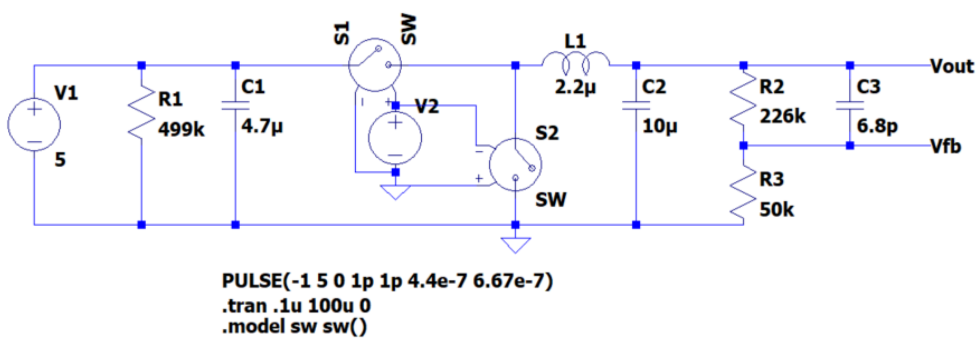
Trace resistance is measured in mΩ/in

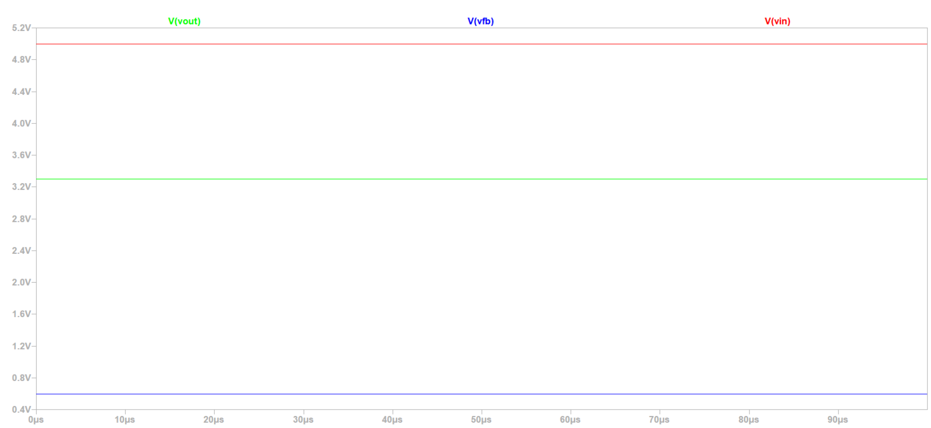
Table of PC Board Trace Resistance [2]

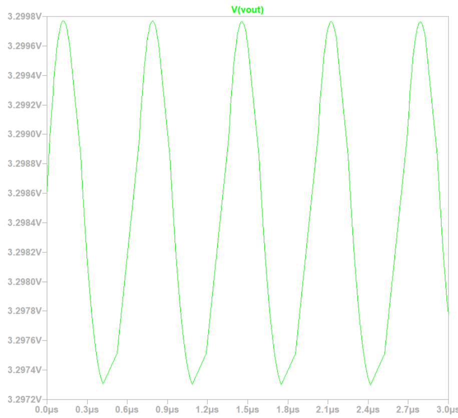
Various signal noise (wire resistance) is rather fixed and our R_{eq} is more significant than thermal noise and other sources of noise, we can use the amplifier circuit to offset it. Lastly, the constant current source should have be switchable while having +- 1% error rate to make our design more feasible since we may also adjust it to fit the "offset," since the measurement has linear relationship with delta V/I and we may alter the reading of delta V (ADC) corresponding to our amplifier/compensation design.

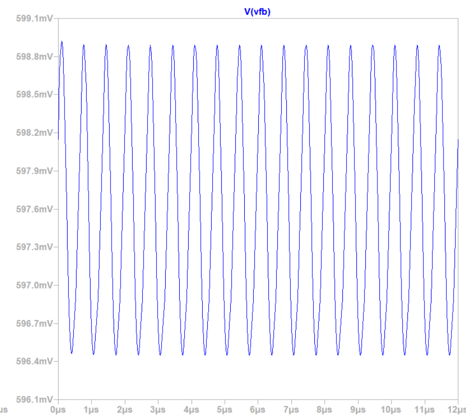
2.4.2 Tolerance Analysis of the Power Subsystem

It is imperative that the power subsystem meets the requirements of all of the other subsystems of this project. It needs to be able to provide current at specific voltages with ripple specifications. Alongside this, we must try to create the most efficient system possible to reduce power dissipated by the system. To make this possible, we chose to utilize a buck converter over an LDO for the first voltage step-down because of its theoretical 100% efficiency. Despite this positive quality of the buck converter, the drawback for this circuit is that we have an output ripple in our voltage. To double check that the buck switch that we chose is reasonable and that the passives chosen alongside it will provide the desired output we simulated the circuit in LTSpice.









This analysis revealed that our output voltage would have an average of $<v_{out}>$ = 3.299 V with a total ripple of Δv_{out} = 2.45 mV staying well within our specifications required by the other subsystems. In addition to this, our simulation revealed that the feedback voltage for our buck switch had an average of $<v_{fb}>$ = 0.598 V with a total ripple of Δv_{fb} = 2.43 mV staying well within the recommended range of (0.588, 0.612) V specified by the datasheet.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Parts and Materials

MPN	Description	Unit Price	Minimum Quantity	Ordering Quantity for 5 Boards (rounded up)	Minimum Price	Total Price
TLV62568PDDCR	IC REG BUCK ADJ 1A SOT23	0.22	1	10	0.22	2.2
RC0805FR-07499KL	RES 499K OHM 1% 1/8W 0805	0.025	1	10	0.025	0.25
RC0603FR-07226KL	RES 226K OHM 1% 1/10W 0603	0.014	1	10	0.014	0.14
RT0603BRD0750KL	RES 50K OHM 0.1% 1/10W 0603	0.104	1	10	0.104	1.04
CL10C6R8CB8NNNC	CAP CER 6.8PF 50V C0G/NP0 0603	0.04	1	10	0.04	0.4
CL21A106KOQNNNE	CAP CER 10UF 16V X5R 0805	0.07	5	30	0.35	2.1
WLFM201209M2R2PC	INDUCTOR FIXED 2.2UH 0805	0.063	1	10	0.063	0.63
TLV74018PDBVR	IC REG LINEAR 1.8V 300MA SOT23-5	0.059	1	10	0.059	0.59
CC0603KRX7R7BB105	CAP CER 1UF 16V X7R 0603	0.66	14	70	9.24	46.2
RC0603JR-070RL	RES 0 OHM JUMPER 1/10W 0603	0.015	4	20	0.06	0.3
ERA-6AEB4990V	499 Ohms ±0.1% 0.125W, 1/8W Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200 Thin	$0.10	3	20	$0.30	$1.98

	Film					
ERA-6AEB2491V	2.49 kOhms ±0.1% 0.125W, 1/8W Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200 Thin Film	$0.10	1	10	$0.10	$0.99
C0603C473K5RAC7867	CAP CER 0.047UF 50V X7R 0603	$0.02	2	10	$0.05	$0.24
RC0603FR-077R5L	RES 7.5 OHM 1% 1/10W 0603	0.029	1	10	0.029	0.29
CRGCQ0603F180R	RES 180 OHM 1% 1/10W 0603	0.023	1	10	0.023	0.23
2169900003	CONN RCP USB2.0 TYP C 24P SMD RA	0.63	1	7	0.63	4.41
RC0603JR-07470RL	RES 470 OHM 5% 1/10W 0603	0.017	1	10	0.017	0.17
151031VS06000	LED GREEN DIFFUSED 3MM ROUND T/H	0.16	1	10	0.16	1.6
ERJ-3EKF2002V	RES SMD 20K OHM 1% 1/10W 0603	0.1	1	10	0.1	1
RMCF0603FT10R0	RES 10 OHM 1% 1/10W 0603	0.015	2	10	0.03	0.15
RC0603FR-071RL	RES 1 OHM 1% 1/10W 0603	0.1	1	10	0.1	1
CC0603KRX7R7BB104	0.1 µF ±10% 16V Ceramic Capacitor X7R 0603 (1608 Metric)	$0.04	2	10	$0.08	$0.42
RC0603FR-071KL	1 kOhms ±1% 0.1W, 1/10W Chip Resistor 0603 (1608 Metric)	$0.02	12	60	$0.23	$1.14

	Moisture Resistant Thick Film					
M50-3140445	CONN RCPT 4POS 0.05 GOLD SMD	0.92	1	5	0.92	4.6
PPTC121LFBN-RC	CONN HDR 12POS 0.1 TIN PCB	0.79	1	5	0.79	3.95
ESP32-S3-WROOM-1	MCU, RF TXRX MOD BT WIFIU.FL SMD	2.95	1	5	2.95	14.75
LT3092EST#TRPBF	DC200mA,IC CURRENT SOURCE 1% SOT223-3	6.87	1	5	6.87	34.35
OPA140AIDGKR	IC OPAMP JFET 1 CIRCUIT 8VSSOP	4.23	1	5	4.23	21.15
MCP3561-E/ST	IC ADC 24BIT SIGMA-DELTA 20TSSOP	3.48	1	5	3.48	17.4
RC0603FR-075K1L	RES 5.1K OHM 1% 1/10W 0603	0.019	2	10	0.038	0.19
ESD441DPLR	TVS DIODE 5.5VWM 7.6VC 2-X2SON	0.18	1	10	0.18	1.8
HPS58003	2mm FPP Gold Tips	70	1	1	70	70
Total:					101.478	235.66

3.1.2 Estimated Hours of Development

Category	Estimated Hours (Hrs)		
	Ming-Yan	Dorian	Simon
Circuit Design	15	15	10
PCB Layout and Components Checks	15	15	20
Prototyping Measurement System	20	10	10

Modifying op-amps/ noise offset Design	10	20	10
LCD, Buttons, Flashing system Developments	15	15	15
Four-point Theory and Correction Factors Optimization	10	10	10
Soldering and Debug	10	10	20
Documentation and Logistics	30	30	30
Total Hours	140	140	140

The estimated hourly rate is $30 per hour for UIUC BS ECE recent graduates.

3.1.3 Total Estimated Cost

Category	Estimated Cost
Materials and Parts (5 rounds of PCB orders)	$235.66
Total Labor Cost	$12600
Total Estimated Cost	$12835.66

3.2 Schedule

Week	Task	Individuals
9/30	Design Documentation, Schematic Update/Review	Group
10/07	Design Review, Schematic Review, Breadboard Test on ADC and op-amp with resistor emulation according to the tolerance analysis	Dorian, Ming-Yan
10/14	Review on OP-AMP design, Optimization on Noise, ADC and MCU Development	Dorian, Simon
10/21	Test on Four-Point Probe Head, Final Breadboard Prototype, 1st PCB Order	Group
10/28	LCD Development, Measurement Development, Probe Calibration, and Routing Development	Simon, Ming-Yan

11/4	Routing dev. UI/UX optimization, correction factor experiments, outer shell 3D print	Group
11/11	Correction factor development (measurement optimization), 2nd order of PCB	Group
11/18	Mock demo, Debug, Review, Report and Documentation	Group
11/25	Fall break	
12/02	Final Demo, Mock Presentation	Group
12/09	Final Presentation, Final Report	Group

4. Ethics and Safety

As electrical engineers, we are compelled to uphold ethical standards as we perform our work. We understand that technology has an impact on the livelihood of individuals worldwide. For this project and course, we will follow all parts of the IEEE code of ethics. We have chosen to list a few ethical standards below which we believe to be most applicable to our work:

1. **"To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data, and to credit properly the contributions of others;" [1]**

   Part of this ethical standard is built into the format of the course, where we meet and present our work to TAs and professors, gaining feedback to use in redesigns. Our lab notebooks will be used to detail any errors and difficulties encountered within the design process, followed up by the corrective measures. Any outside information or help will be properly cited and recognized.

2. **"To treat all persons fairly and with respect, to not engage in harassment or discrimination, and to avoid injuring others." [1]**

   This project is a collaborative effort between team members and the community. Whenever interacting with other people one should treat everyone fairly and respectfully. Harassment and discrimination is unacceptable in a professional setting, and any such form will be reported to the necessary parties should it occur. Safety is an important part of work, with everyone accountable for the safety of each other. During the project we will be sure to follow safety rules and guidelines to ensure nobody gets injured.

3. **"to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;" [1]**

   As students we are always learning more about technology, browsing resources to gain more knowledge. We plan to consult various four-point probe research articles and relevant semiconductor textbooks. For the software used, namely KiCad and Spice, we plan to follow tutorials and documentation to ensure proper handling. We have all already completed our soldering and CAD training, and we will continue improving our skills.

Concerning the safety protocols and applicable regulations for this project:

1. All electrical components not requiring external input will be enclosed in an electrically insulated case to prevent any short circuits and limit exposures of potential bodily harm.
2. To prevent any physical harm incurred by the sharp four point probe, we will fix it to the case with the probe points facing inwards.
3. While assembling our project, we will follow all soldering safety guidelines to ensure an injury-free working environment.

4. Throughout the electronic testing phase of our device, we will implement stringent safety protocols to ensure the well-being of all personnel involved. This includes adhering to industry-standard safety guidelines, using appropriate protective equipment, and conducting thorough risk assessments prior to testing.

References

[1] IEEE. “IEEE Code of Ethics.” June 2020, [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 09/19/2024).

[2] Analog Devices, “200mA 2-Terminal Programmable Current Source,” LT3092 datasheet, 2009 [Revised Aug. 2020].

[3] Texas Instruments, “OPAx140 High-Precision, Low-Noise, Rail-to-Rail Output, 11MHz, JFET Op Amps,” OPA140 datasheet, June 2010 [Revised Mar. 2023].

[4] STMicroelectronics, “Arm Cortex -M33 32-bit MCU +TrustZone + FPU, 375 DMIPS 250 MHz, 2-Mbyte flash, 640-Kbyte RAM, math accelerators,” STM32H562 datasheet, Revised May. 2024.

[5] HELPASS, “D M F K D Z T S Y,”(“镀膜方块电阻测试仪”) HPS2523 datasheet, Revised Aug. 2022.

[6] Microchip, “Two/Four/Eight-Channel, 153.6 ksps, Low Noise 24-Bit Delta-Sigma ADCs with Internal Voltage Reference,” MCP3561 datasheet, Revised 2021.

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