Four Point Probe

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Abstract

This proposal is an extension of our RFA; in this writing, we introduce why our four point probe may be better than state-of-art probe and highlight the specifications to meet as a successful project. We further elaborate on the feasibility of the project through multiple detailed subsystem design and essential tolerance analysis. Lastly, we ensure our project abide by ethics protocols and is without safety concerns.

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1. Introduction

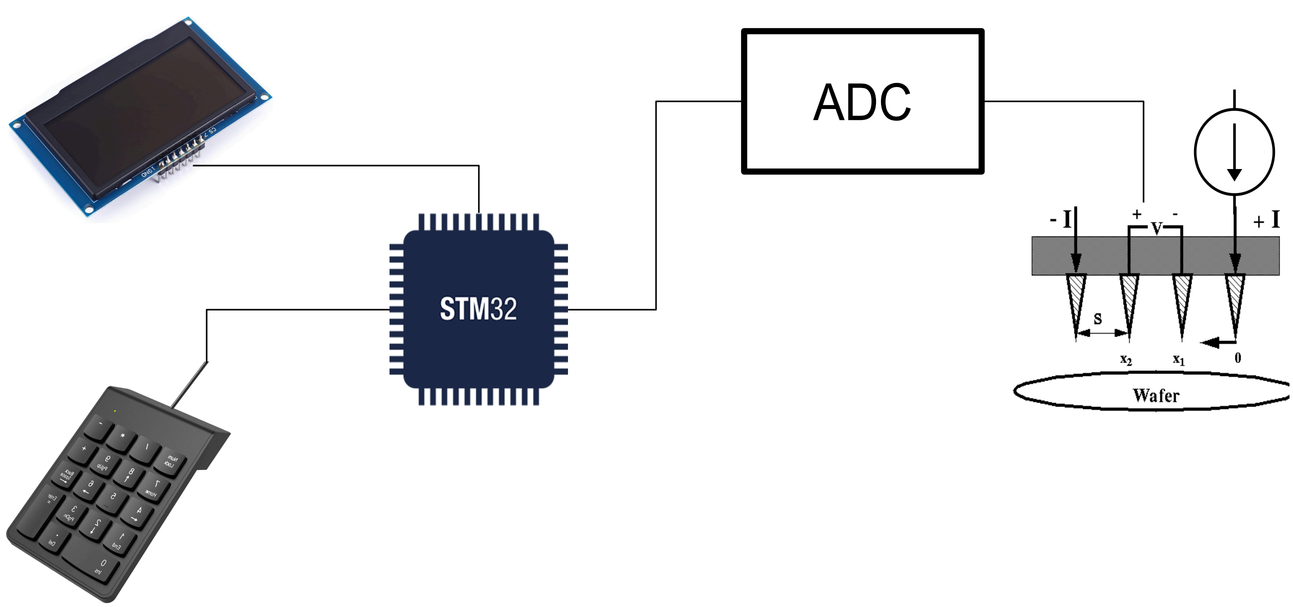
1.1 Problem

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



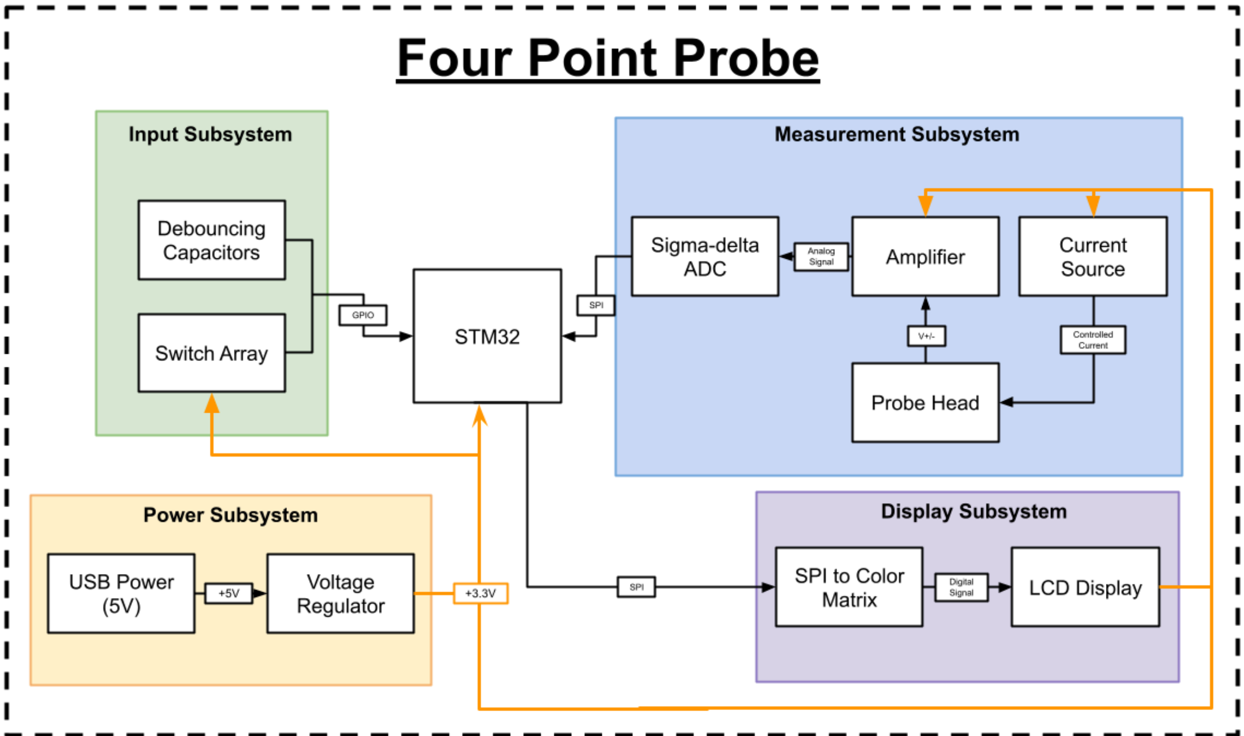
1.4 High-level Requirements

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.
3. 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 will 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.

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.

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(ESP32-S3-wroom-1). 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.

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 DC source (LT3092) should operate at 5V to 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 2mm 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 5V 500mA power over USB.
2. The system must be able to provide a 1.8 ± 0.05 V supply up to 1 mA.
3. The system must be able to provide a 3.3 ± 0.05 V supply up to 500 mA.

2.4 Tolerance Analysis

The imperative aspect of our design is the measurement subsystem since we want to cost down 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 and 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 lie 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. Seeing 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 head 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]

Such noise (wire resistance) is rather fixed and our R_{eq} is more significant than thermal noise and other background 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.

3. 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] Espressif Systems, “ESP32-S3-wroom-1, ESP32-S3-wroom-1u Datasheet,” ESP32-S3-wroom-1 datasheet, Revised 2023.

[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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