

DIEAGNOSIS

By

Josh Hartman

Pham The Minh

Megan Zeng

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TA: Yushi Zhou

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1. Introduction

1.1 Problem

In ECE 444, wafers are inspected under a microscope after fabrication steps to make sure the process was completed correctly. Since a wafer can contain dozens of dies and hundreds of devices, it is not practical to inspect every device after every fabrication step. Instead, only a small number of locations are usually inspected, and the rest of the wafer is assumed to be similar.

This can make it difficult to determine why a device fails after fabrication. For example, a problem with photoresist removal, etching, or deposition may affect a region of the wafer without being noticed during manual inspection. If the problem is only discovered during electrical testing, it can be difficult to determine which fabrication step caused it.

A missed fabrication problem can also affect later processing steps. In ECE 444, for example, wafers are sometimes moved between processes where contamination from an earlier step can affect subsequent fabrication. Photoresist removal is particularly important before furnace processing because leftover photoresist will contaminate the furnace and ruin the wafer. This makes it useful to know not only whether a wafer has a problem, but also where the problem is located before continuing with the fabrication process.

1.2 Solution

An automated inspection system could scan a much larger portion of the wafer after each fabrication step and identify regions that differ from the expected surface condition. This would provide additional information about where a fabrication problem may have occurred without requiring manual inspection of the entire wafer.

The proposed system will use a laser and photodiode to measure the optical response of different locations on the wafer. The wafer will be mounted on a moving X-Y stage while the laser and photodiode remain fixed to achieve a raster scan. The photodiode measurements will be collected by a microcontroller along with the corresponding X-Y positions. The measurements will then be sent to a computer, where they will be compared against a baseline measurement from an ideal wafer and displayed as a two-dimensional map. The system will be enclosed to reduce ambient lighting.

The intended use of the system is to place a wafer into the inspection system after a fabrication step and automatically scan the wafer before continuing to the next step. For example, after photoresist removal, the system could scan the wafer to identify regions that have an optical response different from the expected wafer surface before the wafer is placed into a furnace. The system would not determine the exact cause of a defect, but it could identify where on the wafer further inspection is needed. This could allow users to inspect specific regions instead of relying only on a small number of manually selected locations.

1.3 Visual Aid

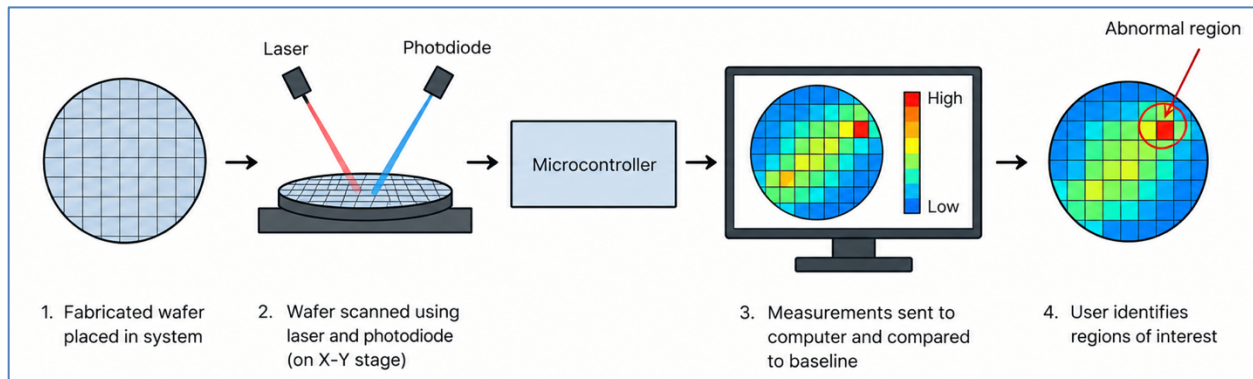


Figure 1: Diagram of the Proposed System Flow

1.4 High-Level Requirements List

Optical Measurement Repeatability and Anomaly Detection. The system should produce repeatable optical measurements at a fixed wafer location under identical operating conditions, with consecutive measurements varying by no more than 10% from the mean of the measurements. The system should detect and distinguish between two wafer surface conditions with a substantial optical response difference (photoresist, dust, large scratches), demonstrating that the system can identify meaningful surface abnormalities rather than only measure random variations.

Wafer Positioning and Spatial Mapping. The system should automatically position a 4-inch wafer across an X-Y raster scan with a positioning discrepancy of no more than ± 1 mm. This requirement may be reduced (e.g., ± 0.5 mm or ± 0.2 mm) as we test our stepper motors. We have chosen ± 1 mm as a conservative guess for now. The stage should return the wafer to a designated home position after a complete scan. The system should record the X-Y coordinates associated with each optical measurement and generate a two-dimensional map of the scanned region on a computer, allowing each detected optical anomaly to be associated with its corresponding physical location on the wafer. The difference in the position of the physical wafer and what is recorded on the computer should not differ by more than ± 1 mm. This requirement may be reduced similar to the one mentioned earlier in this paragraph.

Ambient Light Isolation. With the system enclosure installed, the photodiode measurement should remain stable despite changes in ambient lighting conditions. When exposed to ambient light levels ranging from 100 to 1000 lux, the measured photodiode signal should vary by no more than 5% relative to the measurement obtained under the baseline lighting condition. This requirement ensures that the optical measurements are primarily determined by the wafer surface and inspection system rather than external lighting.

2 Design

2.1 Block Diagram

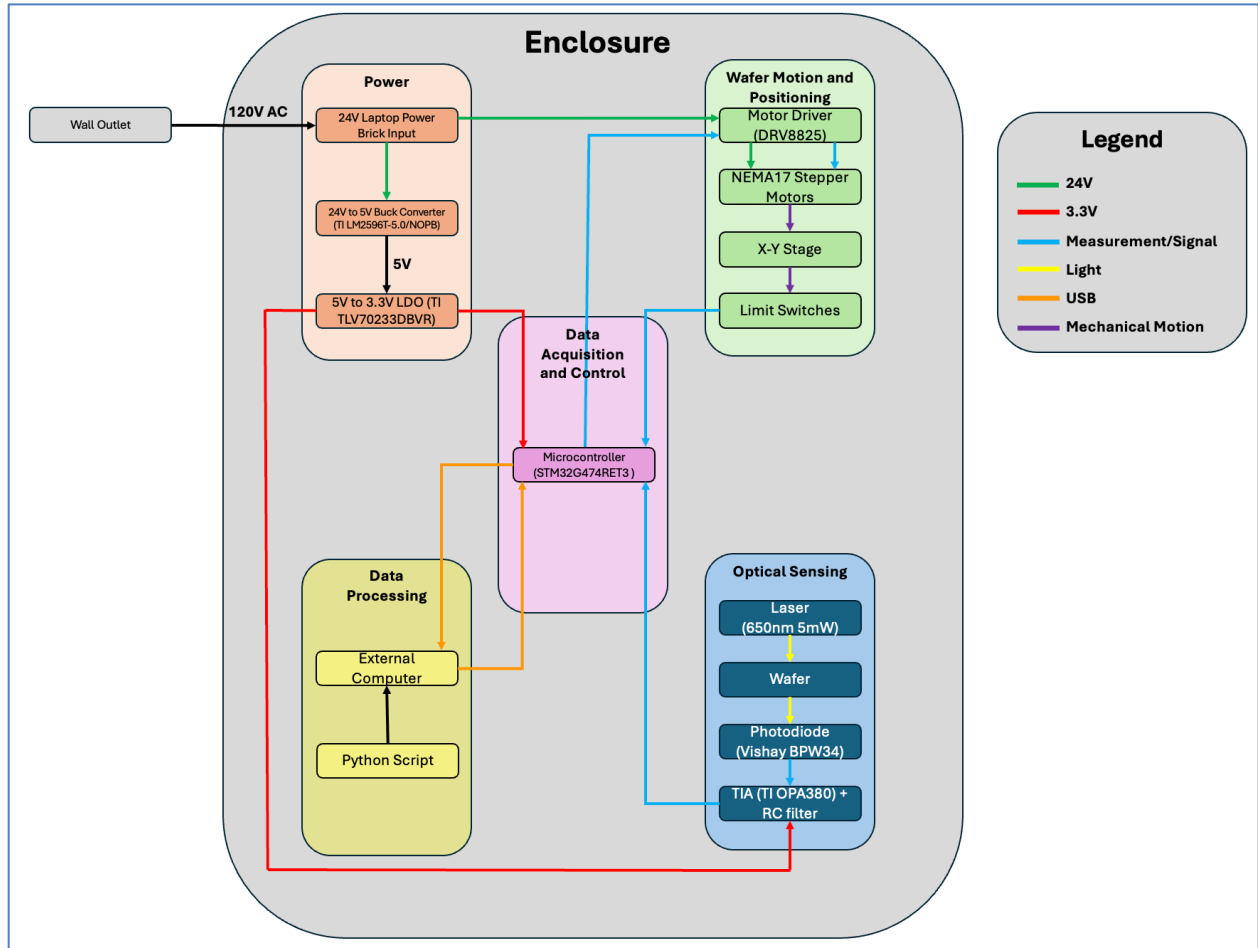


Figure 2: High-Level Block Diagram of the Proposed System

2.2 Subsystem Overview

2.2.1 Optical Sensing

The optical sensing subsystem will illuminate the wafer and measure the reflected or scattered light. A low-power laser will be used so that the system can provide a consistent optical measurement at a small, localized point. Lenses may be used to control the size and focus of the laser spot on the wafer, depending on the results of initial testing.

The subsystem will contain:

- Laser: 650nm 5mW laser, specific part will be chosen based on cost and availability
- Photodiode: Vishay BPW34
- Transimpedance amplifier: Texas Instruments OPA380

- Filtering: RC low-pass filter
- Optical components: Lens and mounts for the laser and photodiode

The photodiode will produce a current based on the amount of incident light. The transimpedance amplifier will convert this current into a voltage that can be measured by the microcontroller. Filtering will be used to reduce noise in the measurement.

The exact optical geometry and lens configuration will be selected during development based on the measured signal strength and repeatability.

2.2.2 Wafer Motion and Positioning

The motion subsystem will move the wafer through a predefined scan pattern and allow each optical measurement to be associated with a location on the wafer.

The subsystem will contain:

- Stepper motors: NEMA 17 stepper motors
- Motor drivers: Texas Instruments DRV8825
- Position sensors: Mechanical limit switches
- Stage: Custom X-Y motorized stage
- Wafer holder: Custom holder for a 4-inch wafer

The stage will be brought to a known origin using the limit switches before a scan begins. The microcontroller will then move the wafer to each measurement location based on the number of commanded motor steps. The system will pause briefly after each movement before taking a measurement so that vibrations from the motor do not significantly affect the optical measurement.

2.2.3 Data Acquisition and Control

The data acquisition and control subsystem will control the scan, collect the photodiode measurements, and communicate with the computer.

The subsystem will contain:

- Microcontroller: STM32G474RET3
- ADC: Integrated in the MCU
- Motor control: Digital step/direction outputs for the DRV8825 drivers
- Limit switch inputs: Inputs for bringing stage to origin
- Communication: USB or UART connection to a host computer
- Custom PCB: Contains the microcontroller, optical sensing circuitry, motor interfaces, and power regulation

The microcontroller will control the motors and take one or more photodiode measurements at each scan location. Each measurement will be stored along with the corresponding X-Y position and then transmitted to the host computer.

2.2.4 Data Processing and Wafer Mapping

The data processing subsystem will process the collected measurements and produce a map of the wafer.

The subsystem will contain:

- Host computer
- Python data processing software
- Python-based wafer mapping and visualization

A baseline scan will be used to determine the expected optical response for an ideal wafer condition. Measurements with a significant difference from the baseline will be marked as anomalies. The software will associate these measurements with their positions on the wafer and display the results as a two-dimensional map.

2.2.5 Enclosure

The subsystem will hold the wafer, stage, laser, and photodiode in fixed positions while limiting ambient light reaching the photodiode.

The subsystem will contain:

- Enclosure: Custom machined housing
- Mounts: Mounts for the laser and photodiode. Possibly integrated into the enclosure

The enclosure will provide an environment for optical measurements and reduce noise caused by ambient lighting.

2.2.6 Power

The power subsystem will provide regulated power to the optical sensing, wafer motion, and data acquisition and control subsystems.

The subsystem will contain:

- Power supply: 24V DC laptop charger brick
- 24V to 5 V buck converter: TI LM2596T-5.0/NOPB
- 5V to 3.3 V regulator: LDO TLV70233DBVR
- Protection and filtering: Decoupling capacitors and power filtering

The power subsystem will provide stable voltage rails to the system and reduce electrical noise from the motors that could interfere with optical measurements.

2.3 Subsystem Requirements

2.3.1 Optical Sensing

The optical sensing subsystem will use a 650 nm laser with an optical output power of approximately 5 mW to illuminate the wafer surface. Using that laser, the subsystem should produce a laser spot with a diameter of no more than 2 mm at the wafer surface to provide localized optical measurements. Consecutive measurements taken at the same wafer location under identical conditions should be within $\pm 10\%$ of the measurements' average value. The photodiode and transimpedance amplifier should produce an analog signal between 0.1V (0V ground + 100mV negative rail output swing) and 2.7V (3.3V supply – 600mV positive rail output swing) for the expected range of wafer measurements. The optical sensing subsystem should distinguish between the baseline wafer condition and an intentionally introduced optical anomaly producing at least a noticeable optical response. After the wafer stage stops moving, the optical measurement should settle to $\pm 5\%$ of its final value within 100 ms.

2.3.2 Wafer Motion and Positioning

The X-Y stage should provide at least 100 mm of usable travel in both the X and Y directions to accommodate scanning of a 4-inch wafer. The stage must position the wafer within ± 1 mm of the commanded position during normal operation. Repeated movements to the same commanded location should have a positional repeatability of ± 1 mm. The stage reset procedure should bring the stage back to the origin within ± 1 mm of the true origin. The controller should wait at least 100 ms after each commanded movement before collecting the optical measurement.

2.3.3 Data Acquisition and Control

The STM32G474RET3 should sample the conditioned photodiode signal using an ADC resolution of 12 bits, per the integrated ADC of the STM. The controller should collect at least 10 ADC samples spaced 50ms at each measurement location and calculate an average value before storing the measurement. Each stored optical measurement should include its corresponding X-Y stage position. The controller should detect activation of a stage limit switch within 10 ms and stop the corresponding motor command. The controller should successfully transmit all collected measurement records to the host computer without detected data corruption during a standard scan. The supply voltage provided to the optical sensing and control circuitry should remain within $\pm 5\%$ of its nominal value during normal operation.

2.3.4 Data Processing and Wafer Mapping

The data processing software will generate a two-dimensional wafer map using the X-Y position and optical measurement recorded at each scan location. The software should correctly associate all collected measurements with their corresponding X-Y coordinates during a complete scan. The software should be able to identify measurements that noticeably differ from the established baseline. The software should process and display all measurement points from a single wafer scan on a 2D wafer map. Processing the same measurement dataset multiple times should produce identical wafer maps.

2.3.5 Enclosure

The enclosure will accommodate the complete 4-inch wafer, X-Y stage, laser, photodiode, and associated optical mounts without interfering with the scan path. The enclosure should maintain the laser and photodiode mounting positions within ± 0.5 mm during normal operation. Ambient light reaching the photodiode should not change the photodiode current by more than 5%. The enclosure should prevent direct line-of-sight exposure of the photodiode to external room lighting during normal operation. Mechanical movement (enclosure vibration, optical misalignment) during a scan should not cause more than a 5% variation in the measurement.

2.3.6 Power

The power subsystem will start with a 24V DC input from the laptop charging brick and provide power to the motor drivers and buck converter. The buck converter will convert the 24V input to a 5V output. The 3.3V LDO will convert 5V to 3.3V for the microcontroller, optical sensing circuitry, and other 3.3 V components, with the output maintaining a $\pm 5\%$ tolerance. The power subsystem will provide sufficient current (1.5A max) for all connected components without causing the voltage rail to fall outside its specified voltage range during normal operation. The power subsystem will use decoupling capacitors and power filtering to reduce voltage fluctuations and electrical noise caused by switching of the stepper motor drivers. During a complete wafer scan, operation of the stepper motors should not cause power-related noise or voltage fluctuations that produce more than a 5% change in the measured optical signal at a fixed wafer location.

2.4 Tolerance Analysis

The main risks for this project are optical measurement repeatability and wafer positioning accuracy.

The laser wavelength was therefore considered when selecting the optical sensing components for optical measurement repeatability. The two primary abnormalities we expect to detect are scratches and photoresist (PR) residue. Scratches can produce significantly more scattered light than the reflective silicon surface, which can be detected using an off-axis photodiode. PR residue can also produce a different optical response from silicon because of its different absorption and reflection properties. Therefore, the laser wavelength must provide sufficient optical signal while remaining practical for the prototype.

Three laser wavelengths were considered to achieve our desired optical response: 405 nm, 532 nm, and 650 nm. A 405 nm laser would be strongly absorbed by the Shipley 1813 photoresist used in ECE 444 and would theoretically produce a smaller spot than the longer wavelengths.

Using the Rayleigh criterion, the spot diameter is approximately proportional to wavelength, so a 405 nm laser would produce a spot about 1.6 times smaller than a 650 nm laser. However, the BPW34 photodiode selected for the design has a specified spectral range of approximately 430-1100 nm, and its spectral sensitivity at 405 nm is significantly lower than at 650 nm. This would require a more specialized photodiode, increasing the cost and potentially the delivery time.

A 532 nm laser can still be used with the BPW34 and would provide a spot approximately 1.22 times smaller than a 650 nm laser, but its photodiode response is approximately half as strong. It also provides little additional benefit because a focusing lens may still be required for either wavelength.

A 650 nm laser was therefore selected as the baseline for the prototype. A 650 nm, 5 mW laser is readily available, cheap, and operates in a region where the BPW34 has substantially higher sensitivity than at the shorter wavelengths considered. This allows the system to use an inexpensive photodiode while maintaining a stronger measured signal. Although 650 nm light is not strongly absorbed by Shipley 1813, this also allows measurements to be performed on wafers with exposed PR without intentionally patterning the remaining photoresist. The final system can therefore focus on detecting differences in the wafer surface while avoiding unnecessary modification of the wafer during inspection.

The optical measurement requirement is that ten consecutive measurements at the same wafer location remain within $\pm 10\%$ of their average value. An intentionally introduced anomaly is targeted to produce a noticeable change from the baseline optical response. For example, if an anomaly produces a 20% change from a baseline measurement of 2.00 V, the normal measurement range would be 1.80-2.20 V, while the anomalous measurement would be 2.40 V or 1.60 V. This provides a 0.20 V separation between the normal measurement range and the target anomalous response. The STM32G474RET3 uses a 12-bit ADC with a 0-3.3 V input range, providing a resolution of approximately 0.806 mV per count. The 0.40 V change associated with the 20% anomaly corresponds to approximately 496 ADC counts, which is substantially larger than the ADC resolution. Therefore, the ADC should be capable of reliably resolving the expected optical change.

The X-Y stage is another potential source of error because the system must associate each optical measurement with the correct wafer location. The stage is required to position the wafer within ± 1 mm of the commanded position, while the minimum scan spacing is 1 mm. A positioning error of ± 1 mm could therefore cause adjacent measurement locations to overlap. The stepper motor's accuracy will be determined by the product of motor step angle (1.8°) and lead screw pitch selected during mechanical design. Although the theoretical step size is expected to be significantly smaller than the ± 1 mm positioning requirement, actual positioning accuracy will also depend on backlash, alignment, and other mechanical tolerances.

Mechanical tilt results from uneven placement also pose a threat to the accuracy of the system. A tilt angle of θ would deflect the reflected beam by 2θ , which can guide the beam off the photodiode's active area and reduce the measured signal. The wafer holder and stage will therefore be aligned so the wafer is set perfectly horizontal, and the alignment will be verified before scanning. It is worth considering a converging lens placed in front of the photodiode. It will focus the reflected beam onto the active area, so that beam deflection from residual tilt or wafer bow produces only a small shift in the focused spot and thus a smaller change in the measured signal. Further investigation into the lens' focal length and calculation of uncertainty might need the final dimension of the system to be carried out.

Finally, the resolution limit for detecting small PR residue is also of concern. The measured signal change scales with the fraction of the sample covered by PR residue, so residue much smaller than the spot will

produce a proportionally smaller response. The system is therefore intended to identify residue regions on the order of the sample's diameter with a scan pitch no larger than the sample's diameter. Smaller isolated particles may then not be detected.

After assembly, the optical system will be tested at fixed wafer locations to determine measurement repeatability and verify that scratches and PR residue produce measurable differences from the baseline silicon surface. The 650 nm laser will also be evaluated based on signal strength and repeatability to confirm the wavelength selection. The X-Y stage will be repeatedly moved to known coordinates to measure its actual accuracy and repeatability. These tests will determine whether the selected optical components and positioning tolerances provide sufficient margin for reliable wafer defect mapping.

3. Ethics, Safety and Societal Impact

3.1 Ethics

The primary ethical consideration for this project is ensuring that the wafer inspection system produces reliable results without presenting misleading information to the user. Since our system identifies potential wafer defects based on optical measurements, false positives and false negatives are possible. The software should therefore distinguish a measured optical anomaly for further human inspection of the area and make it known to the user that human inspection is required. Measurement data, system limitations, and known sources of error should be documented clearly so that users can understand the confidence and limitations of the inspection results. Our system is for the sole purpose of aiding users to quickly inspect the wafer for potential anomalies instead of confidently pinpointing every single anomaly on the board. The team will also avoid intentionally misrepresenting the accuracy or capabilities of the prototype when presenting the results.

3.2 Safety

The primary safety concern is the laser used by the optical sensing subsystem. Although the laser is low power, direct or reflected exposure to the eyes should be avoided. The laser will be mounted inside the enclosure so that it is not directly accessible during normal operation, and the enclosure will reduce the possibility of accidental exposure. Appropriate laser safety labeling will be placed on the system, and the laser will be turned off before adjusting the optical components. The moving X-Y stage also presents a potential pinch or mechanical hazard. Users should avoid placing their hands inside the enclosure while the motors are operating, and the system should be powered off before servicing the stage or making mechanical adjustments. Electrical safety will also be considered when designing the custom PCB by preventing exposed conductors and ensuring that the system operates at low DC voltages. Electrical safety is also to be considered when accessing the area close to the 24V DC input. Due to the high(er) voltage and the fact that the laptop charger will be plugged into a wall, users need to be cautious of touching anything near the cord or the power supply itself to avoid getting shocked. We will be aware of where we touch when dealing with the supply voltage and ensure that the wire is insulated properly.

3.3 Societal Impact

The project is intended to demonstrate a lower-cost approach to automated wafer inspection that could make basic semiconductor manufacturing inspection more accessible for educational and research applications, especially in classes like ECE 444. Automated inspection can reduce the amount of manual inspection required and can provide consistent measurements across a wafer. However, an inaccurate inspection system could also result in usable material being incorrectly classified as defective or actual defects being missed. For this reason, the prototype should be considered an inspection aid rather than a replacement for qualified semiconductor inspection equipment. The system may also reduce material waste by identifying areas of a wafer that show abnormal optical behavior before additional processing steps are performed. More broadly, developing accessible semiconductor inspection technology can support education and research by allowing students and smaller laboratories to experiment with wafer-level measurement techniques without requiring access to expensive commercial inspection systems.

4. References

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