



Research Proposal

2D Thermal Mapping of a Microchip Using Nitrogen-Vacancy Centers in Diamond

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1 Introduction

Infrared sensors are currently the most popular method for industrial temperature mapping, but they have limitations when applied to complex materials and micrometer-level scales. For example, infrared wavelengths can range from $0.7\mu\text{m}$ to $20\mu\text{m}$. In addition, factors such as the emissivity of a material, as well as changes in ambient temperature and humidity, drastically influence the accuracy of infrared sensors. Therefore, the aim of this project is to investigate an alternative option to thermal sensing that is more effective for mapping changes across microscopic electronic components.

This project will utilize the nitrogen-vacancy (NV) center point defects inside a diamond plate to create a sensor capable of mapping thermal signatures across microchips on a micrometer scale. The goal of this project is to replicate the experimental procedure described by [1] and evaluate its accuracy by mapping heat signatures across resistors, capacitors, and transistors, gradually working up in complexity until finally mapping a microchip.

Intellectual Merit

The research advances the field of quantum thermal mapping by establishing a high-resolution, non-invasive wide-field imaging platform that uses the temperature-sensitive spins of NV centers in diamonds. By using optically detected magnetic resonance, our project will account for interference from separate magnetic-field effects, which have been major problems for NV thermo-mapping in the past. It also pushes the boundary of thermal sensing on a microscale, offering an alternative to traditional thermal mapping by providing highly precise localized temperature mapping without disrupting the electronics of the chip.

Broader Impact

The study helps the semiconductor and microelectronic industries by giving them a diagnostic tool to monitor thermal data in the new generation's complex chips. By giving these industries a way of early detection of hot spots and other thermal stresses signifying structural issues, this imaging technology will help reduce error rates in microchip manufacturing and maintenance and improve the development of reliable electronic hardware. By integrating quantum mechanics, material science, and thermal engineering, it provides a foundation for future STEM professionals in the field of microelectronic technologies, which is a high priority for many nations around the world.

2 Background and Prior Work

Thermal imaging is key to the safety and functionality of computer chip production. As demand for safe and reliable electronics grows, heat management has become a concern in the chip industry [1]. As power increases and electronic components shrink to meet demand for space-optimized electronics, the number of regions prone to overheating increases. Especially hot regions can activate safety features such as thermal throttling, limiting the speed and processing power of computer chips, and additionally accelerate chip-damaging processes such as electromigration [2]. To test and preserve the effectiveness of computer-related electronics, manufacturers need to accurately measure and map heat across components to facilitate finding the location of defects and hot spots.

Current methods for mapping heat across electronic components are limited in effective size and accuracy. Contact methods, such as thermocouples and thermal probes, provide very low area coverage and can interfere with the temperature of the chip itself. Other non-contact methods such

as infrared are very limited in applications to computer chips [3]. Infrared readings are limited to specific wavelengths, and additionally depend on the emissivity of a measured object, making them prone to errors when evaluating temperature distribution across computer chips [4]. As electronic components shrink while power density stays constant or rises, hot spots become smaller and more prevalent, and these methods can introduce errors while locating them.

Alternatively, sensors that use the NV centers overcome many challenges faced by other sensing methods and offer additional benefits. NV centers are defects in a diamond lattice caused by a nitrogen atom adjacent to a vacancy. External fields shift the spin-state energies of electrons within the NV center, and microwaves at specific frequencies cause transitions that reduce fluorescence. Such microwave frequencies that trigger these changes are called resonances and can be analyzed via Optically Detected Magnetic Resonance (ODMR). The zero-field splitting of the NV center also changes with temperature due to diamond lattice expansion and electron interactions, and near room temperature this shift is linear [1]. Since the sensor is a solid-state crystal that determines temperature based on spin resonance as opposed to radiation, it requires no knowledge of material emissivity and works in varying temperature environments. NV-based sensors offer higher temperature sensitivity [5], and wide-field imaging with NV centers has been applied to chip surfaces [1].

NV center resonances are directly affected by both temperature and magnetic field. Changes in temperature shift the zero-field splitting by $74 \frac{\text{kHz}}{\text{K}}$ near room temperature, and move the ODMR resonances together in the same direction. Meanwhile, magnetic fields move the resonances in opposite directions, with a coefficient of $28 \frac{\text{GHz}}{\text{T}}$. Therefore, a single measurement cannot distinguish between temperature and magnetic field, which is an obstacle for many attempted applications of NV thermometry to circuits [1]. By using a bias field, the resonances can be split so that the average of the two dips tracks temperature and their separation tracks field.

Project Need / Research Gap. The use of NV centers for thermometry has already been established and tested. However, there are many limitations to its applications for the purpose of measuring heat across computer chips: magnetic field interference from computer chips can add ambiguity to a measurement with an NV center, because NV centers are affected by both external magnetic fields and temperature changes. Therefore, the purpose of this project is to replicate the experimental setup presented by [1], but to incorporate a bias field to split the resonance into two measurable dips, allowing for an analysis and mapping of temperature accurately for various electronic components.

3 Research Goals

Goal 1— Replicate Wide-Field NV Diamond Thermal Imaging Platform

Question / Objective: Replicate the non-invasive wide-field thermal imaging system developed in the reference study using diamond NV centers to detect thermal anomalies on microchip surfaces.

Approach: Constructing a replicated Optically Detected Magnetic Resource configuration, aligning a uniform magnetic field along the diamond’s crystal axis.

Measurement / Output: An operational quantum temperature sensing setup and chip surface thermograms to map the surface.

Success Criterion: Successfully reproduce stable 2D thermal outlines of the microchips

across different currents, matching the structural defect visualization detection described in the reference study.

Goal 2— Evaluate Performance Trade-offs and Cost Effectiveness

Question / Objective: Evaluate and quantify the difference in performance and financial cost savings when changing from optimal research instruments to more budget-friendly hardware components.

Approach: Substitute the laser, high-speed scientific camera, and precision electromagnet array with lower-cost alternatives, and record the results in ODMR spectral line contrast.

Measurement / Output: A detailed correlational strength between equipment budget restrictions and sensitivity of thermal readings.

Success Criterion: Achieve a target hardware cost of under \$10,000 while showing that the cheaper setup can still maintain a spatial resolution within $5\text{ }\mu\text{m}$ and track relative temperature shifts close to the original study's $\left(\frac{10\text{mK}}{\text{Hz}}\right)^{\frac{1}{2}}$.

4 Proposed Methods and Research Design

The goal of this research is to create a non-invasive wide-field thermal imaging system using NV diamonds to map the surface temperatures of microchips. The methodology is split into three parts: Construction, Calibration, and Testing.

Phase 1: Construction The new acousto-optic modulator will be integrated into the optical path of a continuous-wave green laser (532 nm). The AOM will act as a high-speed switch and modulator for the laser beam. The laser beam will pass through a wide-field beam expander to light up a diamond surface containing many NV centers. Simultaneously, a microwave loop antenna will be aligned to the diamond surface to give off the microwave frequencies needed for spin manipulation, and the microwaves will be swept to generate ODMR spectra.

Phase 2: Calibration Once the hardware is set up, a graph of a calibration curve of temperature against frequency will be made. Then, an external thermal controller will be used to change the temperature of the diamond's surroundings. Under each temperature setting, the diamond's photoluminescence using a high-sensitivity camera under a microwave frequency will be recorded. This allows the ODMR spectra to be tracked. This information will be used to map the relationship between spectral dips and temperature, and this phase will also involve MATLAB data-processing scripts to eliminate outside magnetic field interference.

Phase 3: Testing In the last phase, the calibrated NV diamond sensor will be placed on top of an active microchip. As the chip runs workloads, it will generate local thermal hot spots. Wide field photoluminescent imagery will then be used to capture images of the chip. The software will then process the ODMR spectra, translating it into a high-resolution 2D thermal map. This allows for the small hot spots to be visualized and the chip evaluated for any thermal irregularities.

5 Expected Results and Data Analysis

The expected result is the successful replication of an NV diamond-based thermal imaging system based on previously successful models that can reliably produce temperature maps of different electronic components [1]. The experiment is expected to demonstrate the relationship between temperature shifts and changes in the NV center ODMR frequency, confirming the relationship between temperature and ODMR resonance frequency.

The NV diamond thermal imaging system is expected to detect local heat variances within expected patterns by measuring temperature-dependent shifts of the NV diamond ODMR resonance frequency. It will be tested across multiple microelectronic components with different operating conditions to evaluate its ability to identify heating patterns.

The ODMR data collected from areas surrounding the NV diamond sensor system will be analyzed to determine resonance frequency shifts at varying locations. These changes in frequency will be converted to temperature values using a calibration curve obtained from controlled temperature measurements. A temperature map will be constructed from the collected data. The changes in temperature at different areas of the microchip compared to expected values are indicative of potential weak points in the chip. Multiple measurements will be performed to evaluate the repeatability and reliability of the system.

If the observed temperatures differ from the expected ODMR shift of a working electrical component, the results will be analyzed to determine whether the discrepancies are from material or experimental limitations, calibration errors, environmental temperature changes, or a variety of other possible causes of error.

6 Feasibility and Resources

The project is feasible because most of the required materials are already found in the quantum lab of TJHSST, including a laser, microscope setup, microwave generators, and high-sensitivity camera. Additionally, similar projects based on ODMR detection of NV diamond centers have been successfully completed in the lab in the past, which means much of the necessary equipment and expertise is already available.. The project will build upon the existing resources while adapting and optimizing the setup for the specific application of temperature imaging of specific electrical components.

Currently, the lab contains all necessary technologies except for an acousto-optic modulator (AOM), which is a device that uses sound waves to control different aspects of a laser beam. The cost of an AOM ranges from a few hundred to a few thousand dollars, and the purchase of one such device has been confirmed. Several microelectronic components will have to be acquired for testing, the purchase of which should range between 50 and 150 dollars. MATLAB and Python will be used to build and implement the software parts of the project.

7 Safety and Risk Considerations

The primary hazards are the laser, microwave excitation system, electrical components, and possibility of overheating the microchip being measured. The 532 nm laser presents eye and skin hazards, specifically optical radiation from exposure to the beam. Therefore, the optical path will be enclosed when possible, beam alignment will follow approved laser safety procedures, and wavelength-appropriate laser safety eyewear and other protective equipment will be worn when

required. The electrical components will be closely monitored whenever in use. Because the experiment requires measuring temperature changes in electronic devices, heat will be closely monitored to prevent damage to the microchip or the surrounding sensor area. Additionally, the electrical systems will use insulated wires connected to current-limited power supplies to ensure adjustments in power do not result in overheating of the chip.

8 Potential Pitfalls and Alternative Strategies

Potential pitfalls we could encounter include air gaps and uneven pressure on the chip, surface roughness, the laser could heat the diamonds unintentionally, background input could have an effect, and small movements/thermal expansion could affect the mapping

Goal 1: Replicate Wide-Field NV Diamond Thermal Imaging Platform

Challenge 1

There could be external inputs having an effect. Furthermore, unintended heating, surface roughness, air gaps, and uneven pressure could have an impact as well.

Solution: We can eliminate the effect of background noise with repeated controls like repeated scans, reference measurements, and magnetic field control, and minimize the effect of the other potential issues by making sure our components are aligned as well as they can be.

Goal 2: Evaluate Performance Trade-offs and Cost Effectiveness

Challenge 2

The cheaper components that we use could cause a large dropoff in performance.

Solution: We could budget the money allocated to us and leave some in reserve. That way, if we run into issues about performance drop-offs, we can upgrade parts that need upgrading in order to raise performance as much as possible.

9 Research Timeline

Milestone 1: Mid-September: Formal Project Proposal

Task — What will you do? Review completed NV diamond thermal mapping papers, define the research goals, identify available resources from previous experiments, and submit the formal proposal and preliminary apparatus design.

Objective — What measurable result should this work produce? Receive approval for the project scope, resource list, and safety plan. Develop viable design ideas based on previous experiments that can be continued or improved upon.

Goal — What larger research capability or milestone does this establish? Establish a plan for building the NV diamond thermal imaging system and collecting temperature-dependent ODMR data.

Milestone 2: Mid-November: Component Acquisition, Design Finalization, and Initial Assembly

Task — What will you do? Acquire required components, finalize the apparatus design, and begin assembly. Optimize the design for cost efficiency while integrating the microchip testing system to enable accurate measurements and data collection through ODMR.

Objective — What measurable result should this work produce? Produce finalized design sketches and a complete inventory of required materials. After confirming component availability, develop initial sensor prototypes and collect preliminary testing data for different diamond and microchip configurations.

Goal — What larger research capability or milestone does this establish? Establish the initial experimental apparatus and evaluate the feasibility of the proposed thermal imaging system within available resource constraints.

Milestone 3: End of December: Assembly Completion, Signal Calibration, and Safety Testing

Task — What will you do? Complete the assembly process, troubleshoot design issues, and validate the experimental setup. Demonstrate a detectable and repeatable NV center resonance frequency shift caused by localized temperature variations under steady-state laser excitation while ensuring safe operation of the laser and microchip systems. Begin collecting calibration data for ODMR measurements.

Objective — What measurable result should this work produce? Produce an initial testing dataset demonstrating system functionality, complete a secure and tested physical apparatus, and establish a calibrated bias-field ODMR baseline for future measurements.

Goal — What larger research capability or milestone does this establish? Establish the capability to collect normalized ODMR data and demonstrate that the sensor can detect localized temperature changes from active microchips.

Milestone 4: Mid-March: ODMR-Based Data Collection and Temperature Mapping

Task — What will you do? Collect ODMR data while microchips are active, testing multiple chips with varying operational conditions to identify temperature differences and evaluate the effectiveness of the thermal imaging system.

Objective — What measurable result should this work produce? Produce quality-controlled datasets from multiple microchip tests and generate corresponding temperature maps based on NV diamond resonance shifts.

Goal — What larger research capability or milestone does this establish? Complete the central research measurements, determine the conclusions supported by the apparatus, and compare the performance of the developed system with previously reported higher-resource experiments.

10 Group Responsibilities

Owen Chu

Primary responsibilities will include the physical construction and integration of the NV diamond thermal imaging system. This includes assembling the microwave antenna system, mounting the NV diamond sensor, connecting electronic components, and preparing the microchip testing platform. Supporting responsibilities will include assisting with calibration, troubleshooting experimental issues, and helping collect thermal mapping data. He will also work on the preparation and setup of the microchip and other electronic components.

Alexis Lwin

Primary responsibilities will include developing the software used to process and analyze ODMR and fluorescence data. This includes extracting measurements from the CMOS camera, analyzing resonance shifts, converting experimental data into temperature maps, and constructing visualizations of thermal data. Supporting responsibilities will include troubleshooting issues throughout the experiment, validating measurements and interpreting the results. She will focus specifically on the programming, analysis, and visualization aspects of the project, with specialized understanding of the CMOS and ODMR processing systems, as well as the data collection software.

Max Ritter

Primary responsibilities will include designing, aligning, and optimizing the optical pathway of the thermal imaging system. This includes aligning the laser excitation path, positioning the dichroic mirror and red filter, optimizing fluorescence collection through the CMOS camera, and maintaining optical stability during measurements. Supporting responsibilities include troubleshooting experimental issues, setting up the project hardware, and data collection. His roles will emphasize the optimization of the experiment and ensuring the most accurate data is collected, as well as ensuring the experimental setup is valid and correctly addresses the research objectives.

All group members will participate in experimental planning, safety reviews, data collection, interpretation of results, and preparation of the final paper and presentation. Although responsibilities are divided by technical focus, every member will be responsible for understanding the complete experiment and the research objectives.

Annotated Bibliography

- [1] Z. Shi, Z. Pan, Q. Li, and W. Li, “Non-invasive wide-field imaging of chip surface temperature distribution based on ensemble diamond nitrogen-vacancy centers”, *Sensors* **25**, 1947 (2025).

What did this work do? Shi et al. developed a wide-field NV-diamond temperature imaging system for mapping temperature distributions across the surface of an electronic chip. Their system used a 532 nm laser, microwave excitation, ODMR spectroscopy, a CCD camera, and an aligned bias magnetic field to produce two-dimensional temperature maps with high spatial resolution.

Why is it relevant? This experiment is very similar to our proposed setup and provides a direct model for using ensemble NV centers to image temperature variations across a chip. It also shows that the direction of the bias magnetic field strongly affects ODMR sensitivity and temperature-measurement accuracy.

How will we use it? We use this paper as the main reference for our experimental design. We plan to reproduce a similar NV-based wide-field thermal imaging system while investigating whether a permanent magnet can provide the required bias field instead of the adjustable electromagnet used in this study, potentially reducing the cost and complexity of the system.

- [2] P. Cheng, L.-F. Mao, W.-H. Shen, and Y.-L. Yan, “Electromigration failures in integrated circuits: a review of physics-based models and analytical methods”, *Electronics* **14**, 3151 (2025).

What did this work do? Cheng et al. reviewed the physical mechanisms and mathematical models behind electromigration failures in integrated circuits. The review identifies temperature, current density, material properties, geometry, and mechanical stress as important factors affecting the reliability of microelectronic devices. It also discusses the coupling between electrical and thermal effects, including Joule heating and temperature gradients in modern integrated circuits.

Why is it relevant? This source provides context for why measuring temperature distributions across electronic components is important. Localized heating and temperature gradients can contribute to reliability problems in microelectronic devices, making high-resolution thermal imaging useful for identifying potentially problematic regions of a chip.

How will we use it? We use this source to provide context for testing our NV-diamond thermal imaging system on electronic components. The paper supports our goal of identifying localized heating and temperature variations across operating devices and helps explain potential applications of the thermal maps produced by our system.

- [3] G. Chen, D. Wu, Y. Xue, W. Ma, F. He, G. Du, and L. Zhou, “Diamond nitrogen-vacancy color-centered thermometer for integrated circuit application”, *Review of Scientific Instruments* **94**, 104901 (2023).

What did this work do? Chen et al. investigated NV-center thermometry for integrated circuits and developed a numerical method for separating the effects of temperature and magnetic fields on the NV-center energy levels. Their model achieved a predicted temperature sensitivity of $22.9 \text{ mK/Hz}^{1/2}$ and a spatial resolution of approximately $20 \text{ }\mu\text{m}$.

Why is it relevant? NV centers respond to both temperature and magnetic fields, so magnetic-field changes can be mistaken for temperature changes in an ODMR measurement. This paper directly addresses that problem and demonstrates how the two effects can be separated.

How will we use it? We use this paper to explain the relationship between temperature, magnetic field, and the NV-center ODMR spectrum. It will also guide our analysis when determining whether shifts in measured resonance frequency are caused by actual temperature changes or by variations in the bias magnetic field.

- [4] C. Boué and D. Fournier, “Cost-effective infrared thermography protocol for $40 \text{ }\mu\text{m}$ spatial resolution quantitative microelectronic imaging”, *Infrared Physics & Technology* **48**, 122–129 (2006).

What did this work do? Boué and Fournier investigated infrared thermography for measuring temperatures in microelectronic devices. They identified major difficulties including limited spatial resolution and errors caused by differences in surface emissivity, and developed calibration and optical corrections to achieve quantitative temperature maps with spatial resolution better than $40 \text{ }\mu\text{m}$.

Why is it relevant? This paper demonstrates important limitations of conventional infrared thermography for microelectronics. In particular, emissivity differences between metallic and insulating regions can create infrared contrast that does not accurately represent the true temperature distribution, while spatial resolution limits the ability to resolve very small hotspots.

How will we use it? We use this source to motivate the need for an alternative temperature-imaging method. NV-diamond thermometry can potentially provide much higher spatial resolution while determining temperature from ODMR resonance shifts rather than relying directly on the infrared emissivity of the chip surface.

- [5] G. Petrini, G. Tomagra, E. Bernardi, E. Moreva, P. Traina, A. Marcantoni, F. Picollo, K. Kvaková, P. Cígler, I. P. Degiovanni, V. Carabelli, and M. Genovese, “Nanodiamond–quantum sensors reveal temperature variation associated to hippocampal neurons firing”, *Advanced Science* **9**, e2202014 (2022).

What did this work do? Petrini et al. used nitrogen-vacancy centers in nanodiamonds and optically detected magnetic resonance (ODMR) to measure small local temperature variations. The experiment demonstrated that shifts in the NV-center resonance can be used as a sensitive nanoscale thermometer.

Why is it relevant? This source demonstrates the fundamental principle behind our experiment: NV centers can detect small temperature changes through temperature-dependent changes in their ODMR spectrum.

How will we use it? We use this paper to support the use of NV centers as temperature sensors and to explain how changes in ODMR resonance frequency can be converted into measurements of local temperature.

- [6] I. Bisignano, P.-S. Shih, M. Imura, K.-P. Chen, and S. Ishii, “High-spatial-resolution near-infrared thermography using an uncooled silicon-based camera”, *ACS Photonics* **13**, 5139–5146 (2026).

What did this work do? Bisignano et al. demonstrated high-spatial-resolution thermography using near-infrared emission detected by an uncooled silicon CMOS camera. The method was developed as a lower-cost alternative to conventional infrared microbolometer systems and was used to image temperature distributions in electrically heated microstructures.

Why is it relevant? The study highlights several challenges associated with conventional infrared thermal imaging, including the spatial-resolution and cost limitations of microbolometer-based cameras. It also shows that radiometric temperature measurements remain dependent on factors such as sample emissivity, calibration, background subtraction, and image-processing conditions.

How will we use it? We use this paper to compare NV-diamond thermometry with modern infrared and near-infrared imaging techniques. It helps establish why a temperature-sensing method based on ODMR may be useful for obtaining high-resolution temperature maps without relying primarily on the thermal radiation emitted by the chip surface.