Capstone Project-CP302

Development of Gallium Oxide Thin Film Wafer-Scale Interconnected Solar-Blind Photodetector Array for Imaging

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ABSTRACT

This project focuses on the development and demonstration of a solar-blind ultraviolet (UV) photodetector array based on gallium oxide (Ga_2O_3) for imaging applications. Ga_2O_3, an ultrawide-bandgap semiconductor, exhibits intrinsic selectivity to deep UV radiation (<280 nm), enabling noise-free detection without the need for optical filters. In this work, a prototype interconnected photodetector array was designed to detect the spatial distribution of UV light and convert it into an electronic image. Each pixel in the array functions as an individual UV-sensitive element, generating photocurrent when illuminated, while the designed readout circuitry identifies which pixels are active.

The resulting current matrix provides a real-time mapping of the UV intensity pattern, forming the basis for solar-blind imaging. This approach demonstrates a feasible pathway for wafer-scale Ga_2O_3-based imaging systems, with potential applications in flame detection, environmental monitoring, and space or defense sensing technologies.

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INTRODUCTION

The detection and imaging of ultraviolet (UV) radiation have gained significant importance due to their applications in areas such as flame monitoring, space exploration, environmental sensing, and secure optical communication. In particular, the solar-blind UV region (200–280 nm) is of great interest because this portion of the spectrum is completely absorbed by the Earth's atmosphere, eliminating interference from natural sunlight. Devices that respond only to this spectral range are called solar-blind photodetectors, and they enable highly selective UV detection with excellent signal-to-noise performance.

Conventional semiconductor materials such as silicon (Si) and gallium nitride (GaN) are sensitive to visible and near-UV light, making them unsuitable for solar-blind operation without additional optical filters. To overcome this limitation, gallium oxide (Ga_2O_3) has emerged as a promising material because of its ultra-wide bandgap (~4.8–4.9 eV), which naturally restricts photoresponse to deep-UV wavelengths. In addition, Ga_2O_3 offers excellent thermal stability, chemical robustness, and the ability to form high-quality thin films on inexpensive substrates—making it ideal for large-area photodetector fabrication.

The use of photodetector arrays enables spatially resolved UV detection, where each detector element (pixel) corresponds to a point on the image plane. By measuring the photocurrent generated in each pixel when illuminated, an intensity map of the UV light distribution can be reconstructed, forming a UV image. Such imaging systems are crucial for applications requiring real-time monitoring under strong visible backgrounds, such as missile plume tracking, industrial flame detection, and environmental UV mapping.

This project focuses on the development and analysis of a solar-blind photodetector array based on Ga_2O_3, along with the design of a readout circuit capable of identifying which detector elements are illuminated. The work demonstrates how an interconnected n×n array can be used to detect spatial UV patterns and convert them into electronic signals for imaging. Through this, the project aims to provide a foundational understanding of Ga_2O_3-based solar-blind imaging and its potential for future high-performance optoelectronic systems.

OBJECTIVE

- To design and demonstrate a solar-blind ultraviolet (UV) imaging system using a gallium oxide (Ga_2O_3) photodetector array.
- To develop an interconnected n×n photodetector network capable of identifying which detectors (pixels) respond to incident UV light.
- To design a readout circuit that converts photocurrent variations across the array into corresponding electronic signals.
- To reconstruct the illumination pattern and generate a spatial UV image based on the active detector responses.
- To explore the principles of solar-blind imaging and evaluate its potential applications in flame detection, environmental monitoring, and aerospace systems.

THEORETICAL BACKGROUND

1. Principle of Photodetection:

A photodetector is a semiconductor device that converts incident light into an electrical signal. When photons with energy greater than or equal to the material's bandgap energy strike the surface, they generate electron–hole pairs. These charge carriers are separated and collected under an applied bias, resulting in a measurable photocurrent.

The magnitude of this photocurrent depends on the intensity and wavelength of the incident radiation, as well as the material's absorption characteristics and the efficiency of carrier transport. In darkness, a small residual current known as dark current flows due to thermal excitation. The ratio of photocurrent to dark current defines the sensitivity and signal-to-noise ratio (SNR) of the device.

2. Solar-Blind Photodetectors:

The solar-blind region corresponds to UV wavelengths below approximately 280 nm, which do not reach the Earth's surface because they are absorbed by the ozone layer. Therefore, a detector responsive only in this range is inherently "blind" to sunlight, providing high selectivity and zero background noise in daylight conditions.

Materials with ultra-wide bandgaps (≥4.5 eV) such as Ga_2O_3, AlGaN, and diamond are ideal for solar-blind photodetectors.

3. Gallium Oxide (Ga_2O_3):

Gallium oxide (Ga_2O_3) is an emerging ultra-wide bandgap (UWBG) semiconductor that has gained immense attention for applications in power electronics, UV photodetectors, and optoelectronic devices. Among its five polymorphs (α, β, γ, δ, and ε), the β-phase is the most stable and widely used for device fabrication.

Key Properties:

Property	Description
Crystal structure	Monoclinic (β-phase)
Bandgap energy	~4.8–4.9 eV

Absorption edge	~260–280 nm
Electron mobility	100–150 cm²/V·s
Breakdown field	~8 MV/cm (much higher than Si or GaN)
Thermal stability	High (melting point ~1900 °C)

Why Ga_2O_3 for Solar-Blind Photodetectors

- Its wide bandgap allows absorption only of deep-UV photons, making it inherently solar-blind.
- Exhibits low dark current and high detectivity, ensuring excellent signal-to-noise ratio.
- Can be grown on cost-effective substrates like sapphire, Si, or quartz, enabling wafer-scale fabrication.
- Offers chemical inertness and radiation hardness, suitable for harsh environments (space, high temperature, etc.)

Ga_2O_3 is commonly used in MSM (Metal–Semiconductor–Metal) or Schottky diode configurations. Its stable performance, reproducibility, and compatibility with standard microfabrication techniques make it a leading material for next-generation solar-blind imaging arrays.

4. Imaging Using Photodetector Arrays:

Imaging through photodetector arrays is based on the principle of converting spatial light intensity into corresponding electrical signals. When light of a certain wavelength falls on a photodetector surface, it generates charge carriers that produce a measurable photocurrent. By arranging several such detectors in a regular grid or array, each element acts as an independent pixel that senses illumination at a specific point.

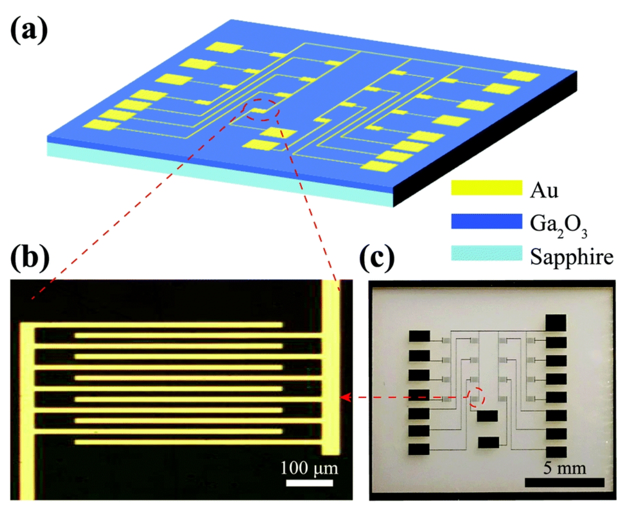

Fig: 1 (a) Schematic of the photodetector array comprising 16 Ga2O3 photodetector cells. (b) Microscope image of a single photodetector cell. (c) Photograph of the photodetector array.

In a typical n×n photodetector array,

The magnitude of the photocurrent from each pixel is proportional to the local light intensity. When the photocurrents from all pixels are collected and processed, they form a two-dimensional electrical representation of the light pattern. This mapping between optical intensity and electrical response allows for the reconstruction of an image.

The use of solar-blind Ga_2O_3 photodetectors further enhances imaging precision by making the array selectively responsive to deep ultraviolet (UV) light (<280 nm), thereby eliminating interference from visible or infrared wavelengths.

METHODOLOGY:

The methodology focuses on implementing the imaging concept practically through the design and analysis of a Ga_2O_3-based solar-blind photodetector array and a supporting readout circuit capable of detecting active pixels under UV illumination.

1. Photodetector Array

An n×n array configuration was modeled, where each element behaves as an individual light-sensitive pixel.

- Each photodetector is represented as a current source that becomes active under UV exposure.
- The array's layout allows multiple pixels to respond simultaneously, forming a spatial current distribution pattern.
- The interconnection of all pixels ensures that illumination on any point in the array contributes to the overall electrical output, which is later processed for imaging.

2. Readout Circuit and Signal Detection

To identify which detectors are active and quantify their response, a readout circuit was developed.

- Each detector is connected to a bias voltage through a sensing resistor.
- When UV light strikes a detector, a photocurrent flows, causing a voltage drop across the resistor.

- These voltages are monitored using multiplexing or scanning techniques to determine the active pixels.
- The collected data are converted into digital signals that can be plotted as an image.

3. Imaging and Data Interpretation

The readout system translates photocurrent variations into a two-dimensional data matrix representing the UV illumination pattern.

- The illuminated detectors appear as high-intensity regions, while the unilluminated ones remain at background levels.
- The resulting matrix of signals corresponds to a UV image, clearly indicating which parts of the array were exposed to light.

This implementation demonstrates the working principle of solar-blind imaging, where selective Ga_2O_3 photodetectors provide high signal-to-noise response even under bright visible-light conditions.

CIRCUIT DESIGN AND WORKING

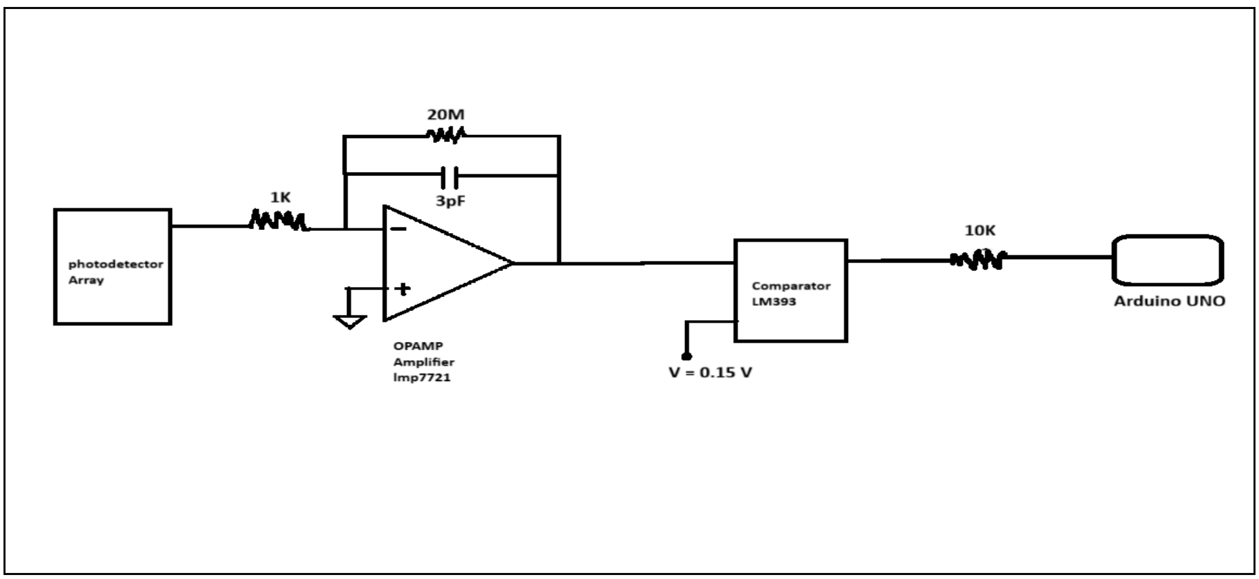

Fig: 2 photodetector imaging circuit diagram

The designed circuit functions as the signal processing and readout unit for the Ga_2O_3-based solar-blind photodetector array. Its purpose is to amplify the weak photocurrent generated by UV illumination, compare it against a threshold, and process the detected signal through an Arduino microcontroller to identify the illuminated pixels.

The schematic should include:

- Photodetector connected to a common ground
- 1 kΩ resistor connected to the inverting terminal of the op-amp (LMP7721)
- Feedback network of resistor and capacitor in parallel
- Comparator stage with reference voltage (~0.15 V)
- Arduino connection through a 10 kΩ resistor

Operational Amplifier LMP7721:

The LMP7721 operational amplifier is an ultra-low input bias current op-amp specifically designed for high-impedance and low-current applications such as photodiode detection.

In this circuit, it is configured as a transimpedance amplifier (TIA), which converts the small photocurrent generated by the Ga_2O_3 photodetector into a proportional voltage signal. Its exceptionally low input

Fig : 3 LMP7721 OPAMP

bias current (as low as 3 fA) and low noise characteristics make it ideal for precise current-to-voltage conversion in UV detection. A feedback resistor connected between the output and inverting input determines the amplifier gain, while a parallel capacitor is used for noise filtering and circuit stability.

Comparator LM393:

The LM393 is a dual differential comparator commonly used for voltage comparison and signal threshold detection. It compares an input voltage with a fixed reference and produces a digital HIGH or LOW output.

In this project, the LM393 is used because the amplified voltage from the op-amp (LMP7721) is still smaller than the Arduino's digital HIGH threshold voltage that's why

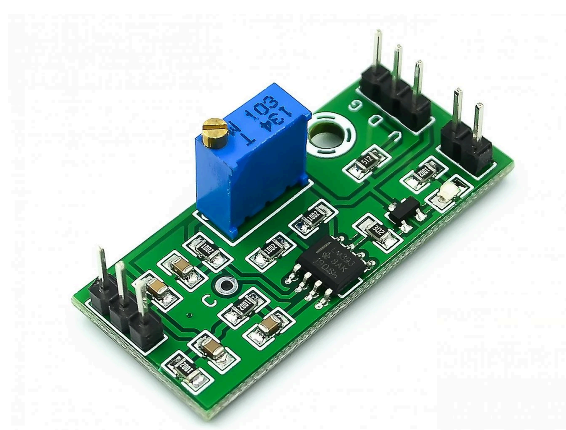

Fig:4 LM393 Comparator

it can not detect the voltage amplified by the amplifier as HIGH. Therefore, the comparator is employed to convert this small analog voltage into a clear digital logic signal.

When the amplified voltage from the op-amp exceeds the reference voltage (~0.15 V), the comparator output switches to logic HIGH (1), indicating that light has fallen on that pixel. Conversely, when the signal is below the threshold, the output remains logic LOW (0), representing a non-illuminated pixel.

Arduino UNO:

The Arduino Uno is a microcontroller board based on the ATmega328P, often used for data acquisition, control, and automation applications. It operates at 5V or 3.3V, and provides 14 digital I/O pins, making it ideal for small-scale multi-detector interfacing and imaging applications.
In this setup, it is used to read digital outputs from the comparator, process them, and identify which photodetectors in the array are active. The Arduino then reconstructs the UV illumination pattern based on the detected signals.

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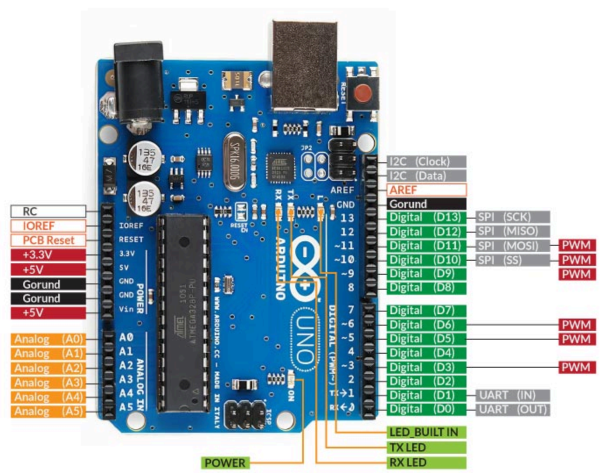

Fig: 5 Arduino Uno

WORKING:

1. Photocurrent Generation:
   When UV light falls on the Ga_2O_3 photodetector, it generates a small photocurrent proportional to the intensity of the incident radiation. One terminal of the detector is connected to ground, while the other terminal is connected to a 1 kΩ resistor.

2. Current-to-Voltage Conversion:
   The small current passes through the resistor, developing a corresponding voltage drop. This node is connected to the inverting terminal of the LMP7721 op-amp, configured as a transimpedance amplifier (TIA). The non-inverting terminal is grounded.

3. Amplification and Filtering:
   The feedback resistor (Rf) and capacitor (Cf) connected in parallel determine the

amplifier gain and filter out high-frequency noise. The output voltage from the op-amp is thus a clean, amplified signal proportional to the light intensity received by the photodetector.

4. Threshold Detection using Comparator:
   The amplified voltage from the op-amp output is fed to the non-inverting input (+) of a comparator as the output voltage of OPAMP is still not large enough that it can be detected as HIGH by the arduino.The inverting input (−) is connected to a reference voltage of 0.15 V.

   - If the signal voltage > 0.15 V → The comparator output switches HIGH (logic 1).
   - If the signal voltage < 0.15 V → The output remains LOW (logic 0).

   This converts the analog light signal into a digital output, indicating whether a particular photodetector is illuminated.

5. Signal Processing with Arduino:
   The comparator output is passed through a 10 kΩ resistor to the Arduino input pin, ensuring current protection. The Arduino reads the HIGH/LOW digital signals from all detectors in the array and determines which pixels are active.

6. Imaging Representation:
   The Arduino processes the input data and displays the illumination pattern — effectively reconstructing a UV image showing which detectors received light and which remained dark.

RESULT AND DISCUSSION:

Even though the practical implementation of the designed circuit was not carried out, the expected behavior and performance were carefully analyzed based on the theoretical design and simulation principles. The circuit aims to identify the illuminated pixels in a Ga_2O_3-based solar-blind photodetector array and convert the optical pattern into an electrical representation suitable for UV imaging.

When UV light falls on any pixel of the photodetector array, a small photocurrent is produced, which is then converted to voltage and amplified by the LMP7721 operational amplifier. The output voltage from the amplifier is expected to vary linearly with light intensity. However, since the amplified voltage is still relatively small compared to the Arduino's digital threshold, the LM393 comparator plays a crucial role. It acts as a decision-making element, converting analog voltage variations into clear digital levels — providing a logical HIGH output for illuminated pixels and LOW output for dark ones.

The Arduino Uno, interfaced with the comparator outputs, would process these digital signals to generate a simple binary map corresponding to the illuminated pattern. This binary data could then be used to recreate the UV light distribution across the detector array, essentially forming an electronic image of the UV illumination. In practice, the output might appear as a grid of 1s (bright pixels) and 0s (dark pixels), representing the regions where light has fallen.

The overall circuit design demonstrates how analog photo-signals can be translated into digital imaging information using simple, low-cost components. The approach highlights the importance of using a transimpedance amplifier for weak signal amplification and a comparator for threshold-based detection before microcontroller-level processing.

In the absence of experimental data, simulation and theoretical analysis predict:

- A stable and low-noise voltage amplification due to the ultra-low input bias current of LMP7721.
- Accurate digital switching behavior from the LM393 comparator at the defined reference voltage (~0.15 V).
- Reliable signal acquisition by the Arduino, capable of distinguishing illuminated pixels from dark ones.

Overall, the design showcases a compact and scalable approach for UV imaging systems. The use of Ga_2O_3 photodetectors ensures solar-blind selectivity, making the system suitable for specialized applications such as flame monitoring, UV pattern detection, and environmental sensing.

APPLICATION:

The Ga_2O_3-based solar-blind photodetector imaging system has promising potential in a variety of technological and scientific fields due to its high sensitivity to ultraviolet (UV) light and complete insensitivity to visible and infrared radiation. Such selective detection makes it suitable for use in extreme environments and specialized imaging applications where conventional detectors fail.

Some of the key applications include:

- **Flame Detection and Monitoring:** Ga_2O_3 photodetectors can precisely detect UV emissions from flames, even under strong ambient light, enabling use in industrial safety systems and combustion monitoring.

- **Environmental Sensing:** The system can detect UV radiation from natural sources, aiding in atmospheric studies, ozone layer monitoring, and pollution tracking.

- **Aerospace and Defense:** Useful for missile plume detection, UV-based navigation, and monitoring of high-energy radiation in space environments.

- **UV Imaging and Mapping:** Enables visualization of UV patterns or sources invisible to the human eye, suitable for research in material science, semiconductor processing, and micro-pattern analysis.

- **Scientific Instrumentation:** Can be integrated into optical diagnostic tools or spectroscopic systems for UV detection and imaging in laboratory environments.

In the future, such Ga_2O_3-based imaging systems can be scaled up into wafer-level photodetector arrays, allowing for high-resolution UV imaging and integration into compact, low-power optoelectronic platforms.

FUTURE IMPLEMENTATION:

The present circuit design is suitable for a small-scale photodetector array, up to 4×4 configuration, primarily due to the limited number of digital and analog pins available on the Arduino Uno (12 digital and 6 analog pins). While this setup is ideal for proof-of-concept and basic imaging demonstrations, it is not scalable for larger arrays where a higher number of pixels require simultaneous readout.

In future work, the system can be improved by integrating microcontrollers or data acquisition systems that support a greater number of input channels, such as Arduino Mega, FPGA boards, or dedicated multiplexing circuits. These alternatives would allow the implementation of larger detector arrays without compromising speed or accuracy.

Moreover, optimizing the circuit for lower power dissipation and faster response will enhance its efficiency for real-time imaging applications. The addition of software-based image reconstruction or graphical display interfaces can also make the system more user-friendly and effective for practical use.

CONCLUSION:

This project focused on the conceptual design and analysis of a Ga_2O_3-based solar-blind photodetector imaging system, aimed at detecting and mapping ultraviolet illumination through an array of photodetectors. A circuit was developed using an LMP7721 operational amplifier, LM393 comparator, and Arduino Uno to amplify, process, and digitally interpret the weak photocurrent signals from the detectors.

Although the experimental implementation was not performed, the theoretical design demonstrates the feasibility of converting analog photocurrent responses into digital imaging data. The expected results show that the proposed setup would successfully identify illuminated pixels, translating UV intensity patterns into a binary electronic image.

The study highlights the practical importance of Ga_2O_3 as a solar-blind material for UV detection, offering strong potential in safety, defense, and scientific imaging applications. Future work can involve hardware realization of the circuit, optimization of the comparator threshold for improved sensitivity, and interfacing with a graphical output system for real-time UV imaging visualization.

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