Polarimetric SWIR Imaging: Initial Results and Pathway to 3D Heterogeneous Integration

Michael D'Agati[1*], Krishna Linga[2], and Rodrigo Castillo-Garza[1]

[1]RTX Technology Research Center (RTRC), East Hartford, CT USA
[2]Sensors Unlimited, Inc. (A Raytheon Company), Princeton, NJ USA

ABSTRACT

Polarimetric short-wave infrared (SWIR) imaging is emerging as a powerful tool for enhanced scene understanding, material characterization, and target discrimination in complex operational environments. This article presents initial results from polarimetric SWIR imaging experiments, showcasing its ability to extract polarization-specific information that complements traditional intensity-based imaging. By leveraging polarization-sensitive focal plane arrays (FPAs) in the SWIR spectrum, the technique demonstrates improvements in object detection, surface texture analysis, and material identification, even under challenging conditions such as camouflage or low-contrast scenes. Additionally, the article outlines a preliminary pathway toward 3D heterogeneous integration, combining polarimetric SWIR FPAs with advanced readout integrated circuits (ROICs) and other sensor modalities. This integration promises to deliver compact, high-performance imaging systems with enhanced functionality, such as simultaneous depth sensing and polarization analysis. Key challenges in material development, fabrication, and system-level optimization are discussed.

Keywords: SWIR imaging, focal plane arrays, surface texture analysis, polarimetric detection

1. INTRODUCTION

Polarimetric imaging uses the polarization properties of light to extract information about a scene of interest. This contrasts with imaging that uses the intensity of light to reproduce a scene [1] or with spectral imaging that extracts scene information by measuring light intensity in different color ranges [2]. Polarization imaging provides new information about the materials, shapes, textures, structural details, and surface gloss of the elements in the scene of interest. [3] Since the information obtained with polarization imaging is not always correlated to the information acquired with intensity or spectral imaging, it can be fused with it and increase the contrast of the scene of interest [4]. This type of imaging is used in applications such as industrial metrology, remote sensing, surveillance, chemical spectroscopy, and robot perception [5].

Polarimetric Short Wave Infrared (SWIR) imaging extracts the polarization properties of the scene in the wavelength range between ~0.9 μm and ~1.7μm. The advantage of using SWIR wavelengths for this type of imaging relies on the distinctive response materials have when light of these colors impinges on them. Glass, for instance, is transparent to SWIR wavelengths. In addition, these wavelengths are preferred in remote sensing applications because they have larger transmittance in obscurants such as haze, fog, or smoke than visible light, mid-wave infrared or thermal imaging [1]. Another advantage is that polarimetric SWIR imaging can use daylight and nightlight - night glow - as a source of light to extract a scene's polarization information [1].

*michael.dagati@rtx.com; phone: 1 860 610-7662

Polarization: Measurement, Analysis, and Remote Sensing XVII, edited by David B. Chenault, Meredith K. Kupinski, Bradley M. Ratliff, Proc. of SPIE Vol. 14041, 140410J · 2026 Published by SPIE
0277-786X · doi: 10.1117/12.3095109

In this article, we experimentally explore the potential for polarimetric SWIR imaging to determine that ground soil has been disturbed due to burying or concealing objects. For this, polarimetric images of SWIR-illuminated scenes with disturbed and undisturbed soils are compared and analyzed. We use soils with different textures/roughness, grain size, and SWIR reflectance to simulate relevant environments and avoid material specificity.

Detection of concealed threats buried in the ground is crucial to population safety. In the deployment of these threats, either from the burying and/or the concealing process, the ground soil around them is disturbed. Common techniques to determine ground disturbances use ground penetrating radar [6] or multispectral imaging [2]. The former compares the reflected radar signatures from disturbed and undisturbed soil at frequencies of ~GHz. This scheme is limited by the variation of the soil conditions such as moisture, the unknown properties of the soil, and the lack of accurate soil models. Multispectral imaging uses the ground soil's SWIR, MWIR, and LWIR spectral signatures to determine if the soil was disturbed, exploring active and passive techniques, as well as reflective and emissive mechanisms. It has been shown that this method can predict key soil surface properties [7] and, under certain conditions, can determine that the ground soil has been disturbed. It is still challenging to make an accurate statement due to signal disruption by soil moisture, surface conditions, and changing conditions in the field, e.g., the angle of the sun when passive camera systems are used. This study demonstrates a method to detect ground disturbances using active and passive short-wave infrared (SWIR) polarization imaging.

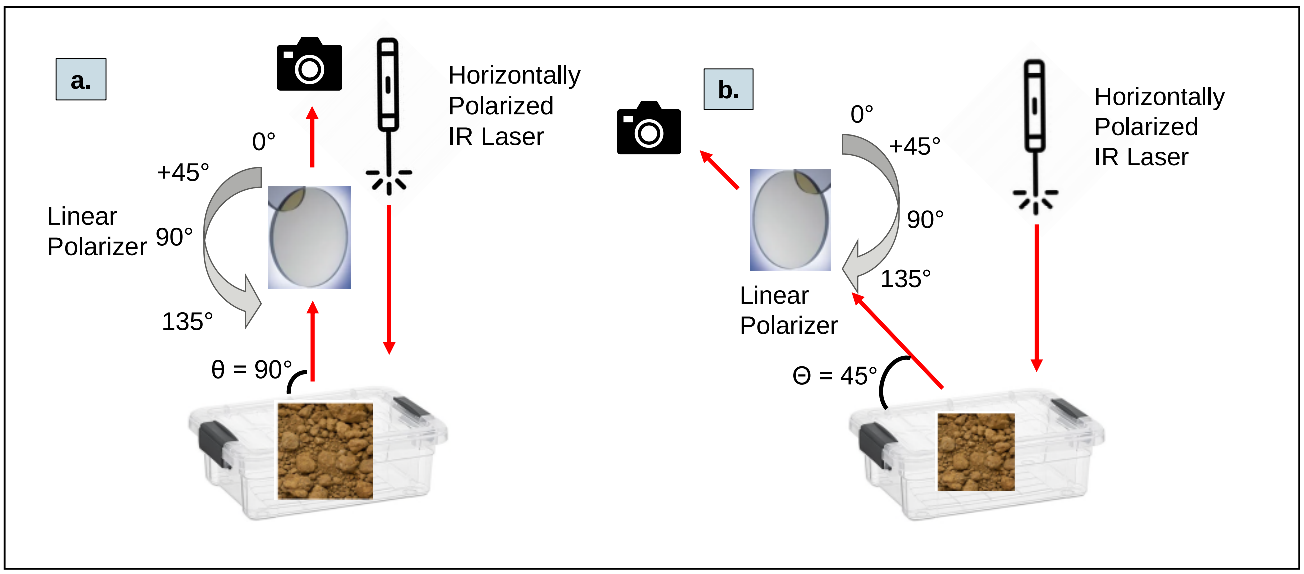

Figure 1: Cartoon schematic of the testing setup for both a 90° incidence case (a) and a 45° incidence case (b). Each test setup utilizes a horizontally polarized IR laser that reflects off the sand/clay soil, goes through a linear polarizer, and into the SUI SWIR camera.

2. METHODS

To demonstrate the ability for SWIR detection of disturbed ground, a ThorLabs LDM1550 laser was used to send 4.5mW of linearly polarized 1550nm infrared (IR) light at a container holding clay and sand normal to the ground. When the IR light reflects off the dirt surface, its polarization content can change due to factors such as angle of incidence or complex material properties. The reflected light then is collected by a Sensors Unlimited 320CSX camera after going through an Edmund Optics 36-654 linear polarizer with >10,000 contrast ratio. At the time images were captured, access to a pixelated wire-grid polarizer was not available. To get around this, four images were taken, changing the linear polarizer to 0°, 45°, 90°, and 135°. The camera was positioned at 45° and 90° with reference to the ground to determine the effect that angle of incidence might have on the polarization data. The images were post-processed using a custom code to obtain the Stokes parameters, the degree of linear polarization (DoLP), and the angle of linear polarization (AoLP). The method was completed for both undisturbed (just sand) and disturbed (clay mixed into sand) dirt, allowing for easy visualization in an optical image between the undisturbed and disturbed cases. Cartoon schematics of the testing setups are shown in Figure 1.

3. RESULTS

The four images taken at different linear polarization angles are utilized as the basis for forming the Stokes images. The Stokes images are formed from the Stokes vector values at each pixel in the captured images. S_0 is the intensity sum between the vertical and horizontal linear polarizations. To form the S_0 image, the images taken at 0° and 90° are added together. S_1 is the difference between vertical and horizontal linearly polarized light and is formed by taking the difference at each pixel between the 0° and 90° images. S_2 describes the intensity difference between the 45° and 135° images and is formed by taking the difference at each pixel of those images, similar to that of S_1. For completeness, S_3 describes the intensity difference between right-hand-circular and left-hand-circular polarized light but was not captured in these experiments since there was no access to a retarder and therefore won't be included in the following discussion. Figure 2 shows a process schematic of how the Stokes images were formed.

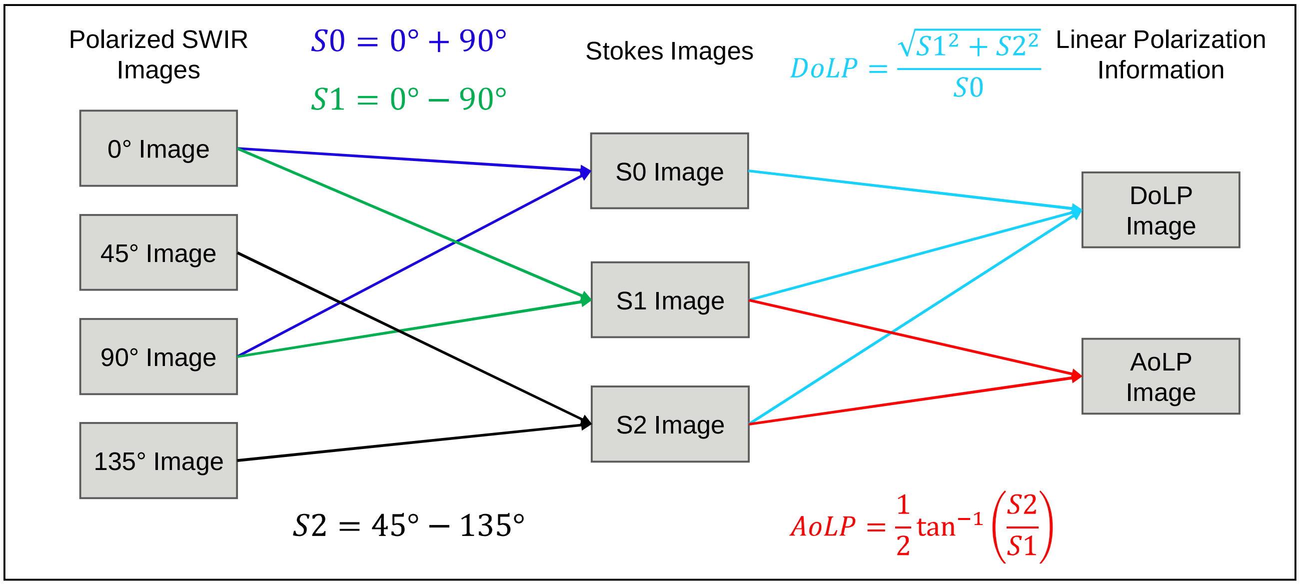

Figure 2: Schematic showing the calculated process for obtaining polarization image information. Four original images are captured at different polarization angles. Those images are used in calculating the Stokes images, which in turn are used to calculate the DoLP and AoLP images.

Once the Stokes images are formed, information can be extracted that gives information about the state of the dirt. The Degree of Linear Polarization (DoLP) describes how much of the received light is linearly polarized, with higher values indicating pure linear polarization and lower values indicating no linear polarization. The DoLP is defined by (1)

$$DoLP = \frac{\sqrt{S_1{}^2 + S_2{}^2}}{S_0} \tag{1}$$

The Angle of Linear Polarization (AoLP) describes the orientation of the linearly polarized light and has a value between 0° and 180°. The AoLP is defined by (2)

$$AoLP = \frac{1}{2}\tan^{-1}\left(\frac{S_2}{S_1}\right) \quad (2)$$

These images, along with the Stokes images, provide substantial information about the state of the imaged dirt. Figures 3 and 4 show the captured images at 90° and 45° incidence angles before and after mixing the dirt, respectively. Each image set includes an optical visible light image, initial SWIR image, the Stokes images (S0, S1, S2), the DoLP image, and the AoLP image.

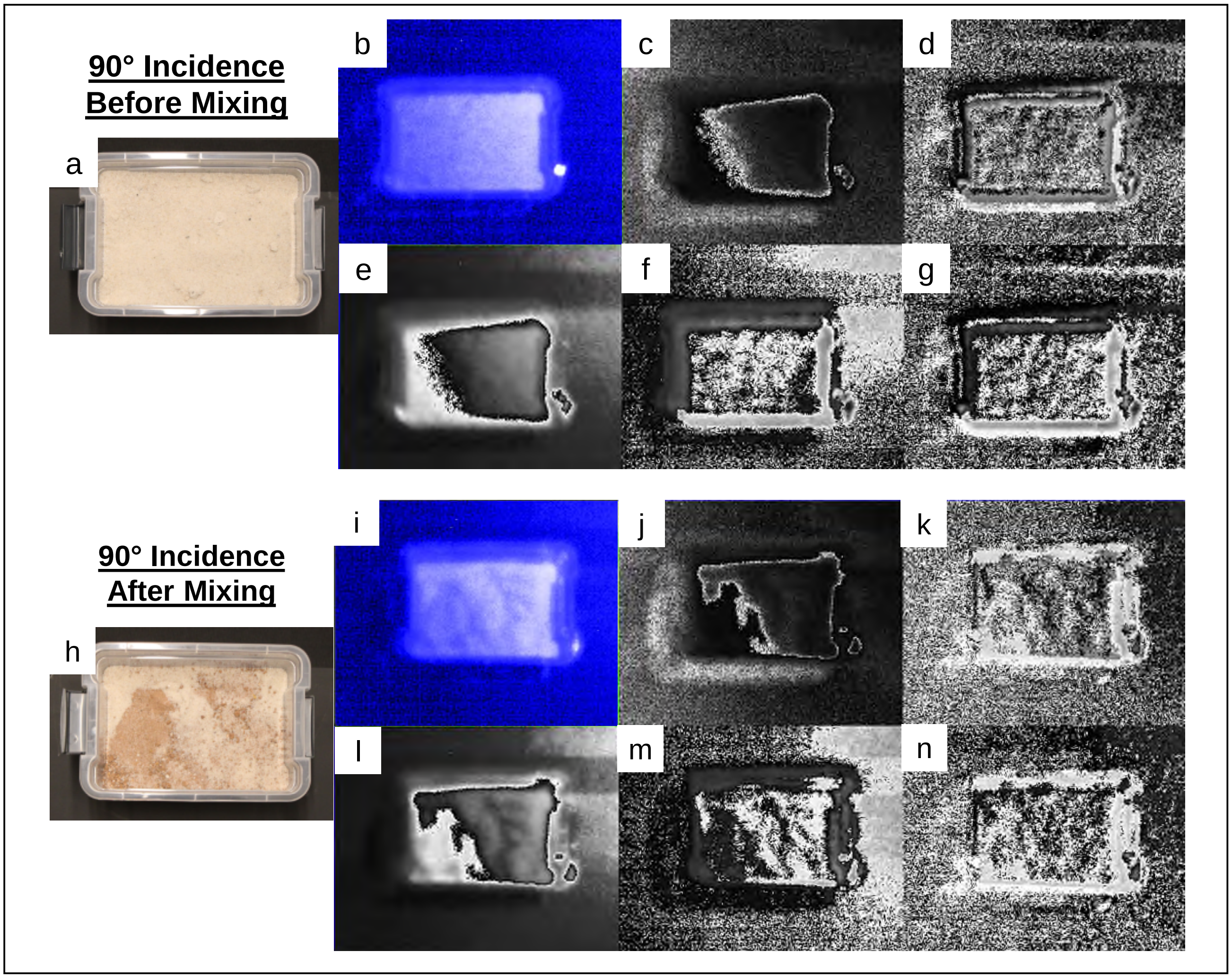

Figure 3: Images taken at 90° incidence before (a-g) and after (h-n) mixing the clay and sand. Optical (a,h), unpolarized SWIR (b,i), DoLP (c,j), AoLP (d,k), S0 (e,l), S1 (f,m), and S2 (g,n) are included for comparison.

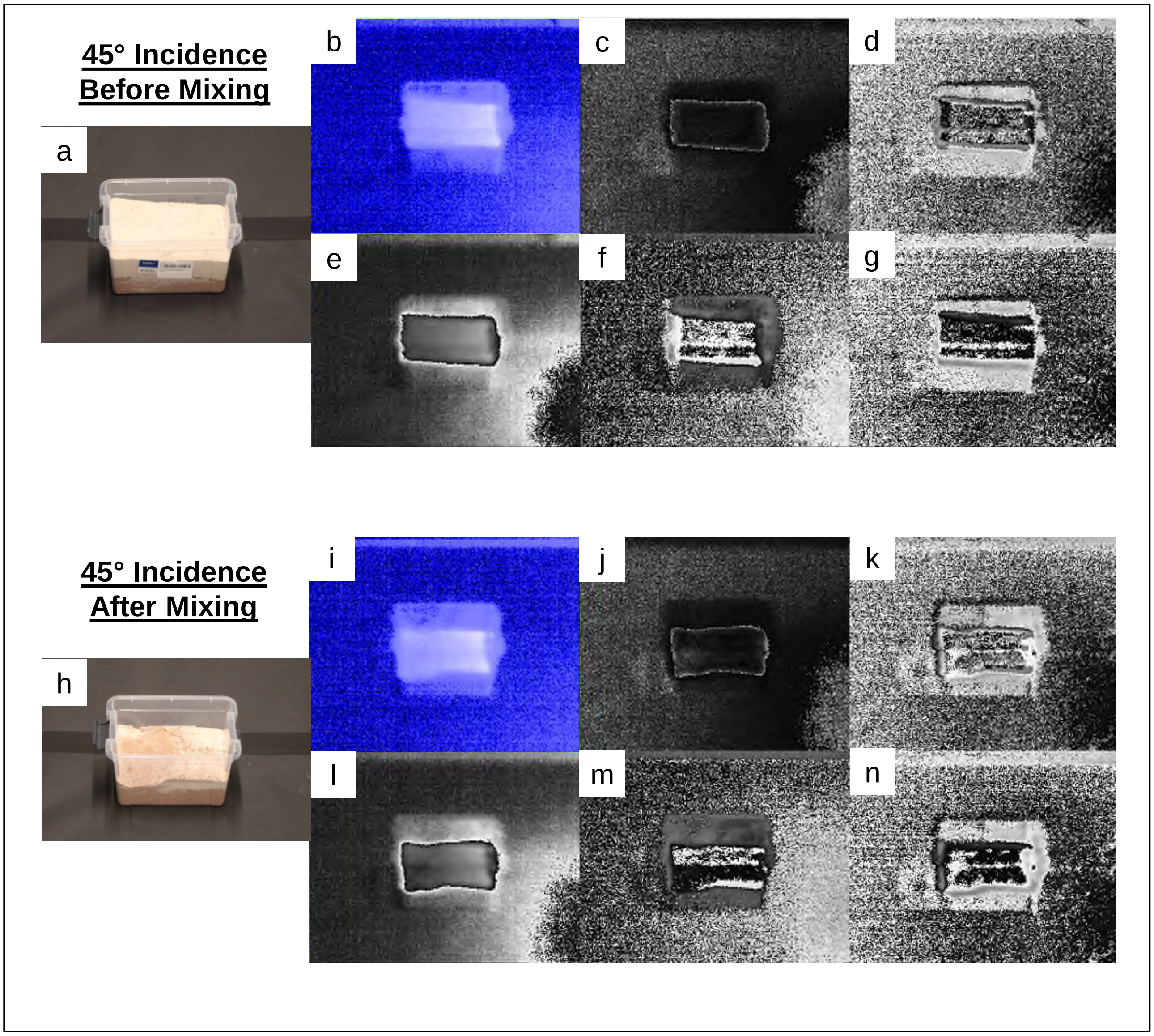

Figure 4: Images taken at 45° incidence before (a-g) and after (h-n) mixing the clay and sand. Optical (a,h), unpolarized SWIR (b,i), DoLP (c,j), AoLP (d,k), S0 (e,l), S1 (f,m), and S2 (g,n) are included for comparison.

4. DISCUSSION

The captured images show significant variance in polarization information before and after disturbing the sand and clay. Before mixing, Figure 2 shows a smooth surface, with more contrast between 0° and 90° polarization than between 45° and 135°. Additionally, the DoLP image shows a smooth surface of the sand without much topographical complexity before any disturbance. The polarization of the light reflected from the sand is primarily not very linear, as shown by the darker regions. Linearly polarized light is mostly present towards the edges of the box. After the sand and clay were mixed, the DoLP image has a different pattern to it. There is a clear alteration in the amount of linearly polarized light in the bottom left corner of the box that wasn't there before. Additionally, the S0 and S1 images show a valley towards the middle of the box after the sand and clay were mixed. The valley also faintly appears in the DoLP image, indicating the reflected light has slight linear polarization.

Figure 3 also shows a change in polarization information before and after disturbance, however it was not as significant as in Figure 2. The DoLP image did not show as distinct of a change after the sand and clay were mixed. In addition to the fine surface topography the 90° incidence images capture, the 45° incidence provides information about the initial surface angle at the top of the container and can show macroscale changes in the surface changes as well. Also, while the DoLP image did not show distinct differences before and after disturbance, information about the angle of linear polarization captured in the AoLP image showed larger changes. The intensity of the pixels within the box surface area increased after the sand clay mixture was disturbed. This corresponds to a higher angle of linear polarization compared to before. Therefore, the angle of the incoming SWIR light is crucial when the intensity, or degree to which the SWIR light is linear, is low.

5. CONCLUSION

The images captured in this work show good promise towards utilizing SWIR light for soil surface monitoring of concealed threats. The combination of the Stokes images along with the degree and angle of linearly polarized light reflected by the soil provides significant information to determine if the soil surface was disturbed. While the results show initial promise for this technology, future experiments could benefit from some changes and upgrades to the setup.

First, the containers used had small openings for observation. As seen in both Figure 3 and 4, the top edge of the containers reflected light in front of the soil, especially in the 45° incidence angle case. Future experiments should use a shallow container with a larger surface area opening for observation. In this way, images could capture disturbances on one side and compare that to undisturbed soil on the other side.

Another upgrade to the test setup would include using a pixelated wire-grid polarizer, such as those provided by MoxTek, to capture all polarization information in one image. Currently, when the linear polarizer is rotated to capture the 4 angles, it is possible for the camera to shift very slightly from its original position. While great care was taken to prevent this from happening, any change to the camera position will result in noisy Stokes images (and therefore DoLP and AoLP images) when combining the original 4 images as referenced in Figure 2. The pixelated polarizers would capture all 4 polarization angles in a single image, preventing any noise due to physical camera translation.

Future image capture would ideally be performed with a single camera using a Three-dimensional Heterogeneously Integrated (3DHI) SWIR photodetector in the focal plane array. The current photodetector in the SUI camera utilizes a p-type, intrinsically un-doped, n-type doped (PIN) photodiode array based on indium phosphide (InP) and indium gallium arsenide (InGaAs) technology. The structure is formed from an epitaxially grown intrinsic InGaAs absorption layer and an InP cap layer on a highly doped n-type InP substrate [8]. Future integration of the pixelated wire-grid polarizer could be grown directly on top by typical deposition, patterning, and etching techniques. The nanowire pattern would provide a fully integrated SWIR photodetector used for polarimeter data acquisition. This fully integrated solution would also reduce the amount of data needed and allow for seamless AI/ML post-processing to detect small changes and patterns in typical disturbed earth scenarios.

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