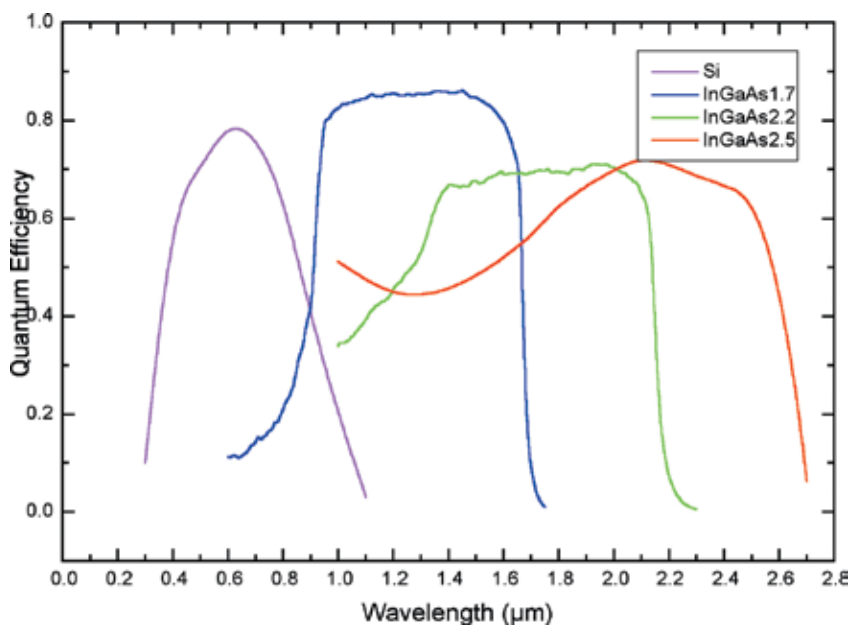


# A D V A N C E D IMAGING

## Machine Vision in the Shortwave Infrared

by Marshall J. Cohen and Martin H. Ettenberg



*Room temperature InGaAs cameras enable machine vision users the same capabilities as visible cameras, while detecting phenomenology not seen in the visible.*

*Left: InGaAs typically refers to lattice-matched  $In_{0.53}Ga_{0.47}As$  (blue curve) detecting where Si (purple curve) loses responsivity. The composition of  $In_xGa_{1-x}As$  can be varied to adjust its spectral detection range to cover the entire shortwave infrared spectrum as indicated by the blue, green and red curves.*

**C**ameras operating in the shortwave infrared (SWIR, typically  $1\mu\text{m}$  to  $3\mu\text{m}$ ) were first introduced more than ten years ago. For many years, they were technical curiosities, as they were large and difficult to use, and they had low resolution. In fact, it was unclear why, with the possible exception of astronomy, one would want to image in the SWIR band in the first place.

In recent years, there have been substantial advances in the performance of SWIR-sensitive indium gallium arsenide (InGaAs) focal plane arrays (FPAs) and cameras, as well as a much greater understanding of a wide variety of useful SWIR-band phenomenology. The original InGaAs FPAs were limited to  $128 \times 128$   $60\mu\text{m}$  pixels and were operated in large-size cameras ( $10\text{cm} \times 10\text{cm} \times 25\text{cm}$ ) that required equally large power sup-

plies. In contrast, the current state-of-the-art InGaAs FPAs include 1024x1024 element arrays with 18 $\mu\text{m}$  pixels flying in space, 1024 element linear arrays for spectroscopy and line-scan imaging, and 640x512-x 25 $\mu\text{m}$  arrays used in a wide variety of commercial applications. At present, the smallest camera that operates in an infrared wavelength band includes a 320x256-x-25 $\mu\text{m}$  InGaAs FPA and is roughly the size of a 9V battery.

InGaAs FPAs and cameras are used in a wide variety of commercial, industrial and scientific applications. For our purposes, we will focus on their use in machine vision applications in which a camera is used to control industrial processes.

### CONSIDERING THE WHYS AND WHEREFORES OF INGAAS

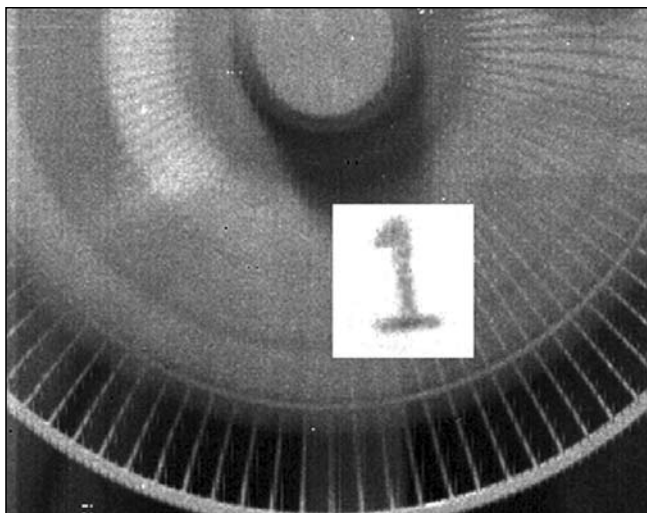
InGaAs is a member of the indium-gallium-arsenide-phosphide family. By mixing the four binary alloys (GaAs, InP, InAs, GaP) into ternary and quaternary alloys, it is possible to customize both the semiconductor energy bandgap that determines the optical properties, and also the crystal lattice structure.

As can be seen in Figure 1, when InAs and GaAs are mixed in a 53/47 ratio, the resulting  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  ternary alloy has a direct energy bandgap of 0.734-eV, allowing sensitivity out to nearly 1.7 $\mu\text{m}$  and a lattice constant of 5.868-Å, matching that of InP.  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  photodiodes typically have the photoactive material grown on an InP substrate and capped with an epitaxially grown layer of InP. As InP with its energy bandgap of 1.35-eV absorbs light with wavelengths shorter than 0.9 $\mu\text{m}$ ,  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  FPAs and cameras are generally restricted to the 0.9 $\mu\text{m}$  to 1.7 $\mu\text{m}$  portion of the SWIR band. As reported in the 1999 annual meeting of the Lasers and Electro-Optics Society (LEOS)<sup>1</sup> and in the September 2003 issue of *Advanced Imaging* magazine,<sup>2</sup> it is possible, using specialized processing techniques, to extend the sensitivity of  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  FPAs into the visible.

It is commonly said that InGaAs starts where silicon leaves off. This axiom is illustrated in Figure 1. By increasing the portion of InAs in the InAs/GaAs alloy, the optical sensitivity can be pushed out beyond 2.5 $\mu\text{m}$ . "Lattice-matched" (to InP)  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  exhibits very high crystal quality, leading to near-theoretical dark currents. It can be operated at room temperature and is used for a wide variety of imaging applications including night vision, covert surveillance using SWIR illuminators that cannot be seen by the human eye, visible cameras, or night vision goggles, and the alignment and assembly of telecommunica-

tions components that operate in the vicinities of 1.3 $\mu\text{m}$  and 1.55 $\mu\text{m}$ .

In addition, linear InGaAs FPAs are used as the detectors in SWIR spectrographs, with applications as diverse as monitoring the lasers used in optical networks employing wavelength division multiplex-



*An image of a spinning fan blade with a 320x256 InGaAs sensor at 60 f/sec does not show any information on the individual blades, but when a 64x64 frame (inset) is running at 1000 f/sec, the information on the individual blade can be read (in this case, a number "1").*

ing (WDM) and studying the composition of surface minerals as a detector in the Near-Infrared Spectrometer aboard NASA's Near-Earth Asteroid Rendezvous (NEAR) mission.<sup>3</sup>

### INGAAS FPAS VS. CMOS SENSORS: WHAT'S THE DIFFERENCE?

The short answer to this question is, "less than you might think." The original solid state imagers were fabricated in silicon PMOS technology and consisted simply of an array of photodiodes combined with a two-dimensional multiplexer. Almost immediately, hybrid infrared focal plane arrays were demonstrated by attaching an infrared-sensitive FPA to the PMOS imager using an array of indium columns to connect the individual photodiodes to corresponding PMOS pixels.

While the emphasis in visible imaging switched to CCDs, development of infrared FPAs continued with most of the readouts fabricated in CMOS. The in-pixel architecture of these readout integrated circuits (ROICs) became more and more sophisticated in order to enhance the performance of the infrared photodiode arrays.

The circle was completed when, leveraging off the huge volumes and low cost of CMOS technology, silicon active pixel sensors (APs, also known as CMOS imagers) became widespread. From the perspective of

integrating an imager into a camera, there is very little fundamental difference between a visible CMOS sensor and an infrared focal plane array.

For SWIR FPAs with  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  photodiode arrays, the FPA operates at room temperature so there is no difference. The  $\text{In}_{.53}\text{Ga}_{.47}\text{As}$  sensors have nearly all of the functionality of standard visible sensors. This allows the cameras to have incredibly high functionality while also being compact and lightweight, and using low power.

This point is illustrated in Figure 2, which shows an SWIR image of a spinning fan captured from a video-rate InGaAs camera. Using capabilities common to InGaAs and visible imagers, a small region of interest (window) was defined on the FPA that could be read out at high speeds. In this case, a 64x64 window was imaging at 1000 frames/s. This permits a section of the spinning blade to be caught in a stop-action image. The InGaAs Microcamera, about the size of a 9V battery, has this windowing function and many more capabilities integrated into its electronics.

### INGAAS FPAS & CAMERAS FOR MACHINE VISION

In a visible machine vision camera, manufacturing engineers typically look to automate processes by capturing and analyzing the same images they would have been able to see directly. In order to use an infrared camera for machine vision, the initial challenge

is to determine what exactly you want to “see.” In other words,



Figure 3: A hot wine glass in false color, imaged using a Sensors Unlimited, Inc. 320x240 InGaAs MiniCamera. The signal levels can be calibrated to temperature; in this case, the hottest part of the glass is 330°C (above). The second image shows the same glass with a business card behind it, demonstrating that glass is completely transparent in this wavelength band (right).



what phenomenology is visible to the camera but not to the human eye?

Three (of many) applications that have emerged in recent years are hot-end glass inspection, the inspection of semiconductor wafers and integrated circuits, and the sorting of different types of plastics in recycling

plants.

Figure 3 is an SWIR image of a heated wine glass captured with an InGaAs camera. As the SWIR band is invisible to the human eye, all SWIR images are, by nature, “false color.” In this case, we are displaying different temperatures as different colors—*i.e.*, the red/orange indicates higher temperatures.

The SWIR band is a natural fit for this application. The thermal emission from an object at glass manufacturing temperatures (500°C to 600°C) occurs at wavelengths too long to be seen by visible cameras. While cameras operating in the midwave IR (3μm to 5μm) and longwave IR (8μm to 12μm) are more sensitive to thermal radiation than SWIR cameras, they cannot see through glass. The inset illustrates that glass maintains its transparency in the SWIR band.

A common problem in the production of glass bottles is the occurrence of thin strands of glass inside the bottles. This is highly undesirable, as it leads to sharp glass fragments when the bottle is filled. The solution is simple and inexpensive: simply reject the unacceptable bottle and melt the glass for reuse. It is important, though, to catch the process mistake early, before many other bottles are manufactured in the same manner. This minimizes the amount of scrapped glass. Detection of the flawed bottles is enhanced by the thermal contrast that is visible with a SWIR camera.

SWIR cameras are also finding increasing utility in semiconductor applications. Silicon wafers, for example, are opaque when viewed with a visible camera. On the other hand, silicon is transparent to wavelengths longer than 1.1μm, ideal for viewing with an SWIR camera.

Silicon IC manufacturing has rapidly advanced from using 100mm wafers through 150mm wafers, to the point where the majority of devices being used today are produced on 200mm wafers, and 250mm wafers are just starting to be used. As the diameter of the silicon boule increases, it is critical that the crystal quality be maintained. SWIR light passing through the “transparent” silicon wafers scatters off of defects, allowing them to be seen using an SWIR camera. Microscopic inspection is

also used to diagnose failure mechanisms in silicon integrated circuits.

As the metal features on the top of the chip are opaque in all wavelength bands, the ICs are inspected through the back of the device. Most current inspection systems use silicon cameras, and the ICs must be

thinned to allow some transmission through the otherwise opaque substrate. Newer systems are beginning to use InGaAs SWIR cameras.

Our third example uses InGaAs SWIR line-scan cameras to differentiate different types of plastics in a recycling plant. In such a scenario, each camera is actually a spectrometer looking down at a point on the conveyer belt. As a bottle passes under the field-of-view of the camera, its reflectance spectrum is measured. The characteristic shape of the spectrum allows the type of plastic to be identified. In this particular example, InGaAs FPAs with 74% InAs in the alloy are used to provide sensitivity out to 2.2 $\mu$ m (see Figure 1). Coming off the belt, the different types of bottles are separated for subsequent reprocessing.

This example requires multiple cameras. In each camera, the lens is replaced by a diffraction grating so that each pixel of the linear InGaAs FPA represents a wavelength rather than a position. This implementation requires multiple cameras, and the entire width of the conveyer belt is not imaged at once.

Instead of using multiple line-scan cameras to achieve the above solution, some find an imaging spectrograph to be a simpler solution. This device is mounted on the front of a two-dimensional camera. The imaging spectrograph preserves position information in one direction while separating the light into its wavelength components in the perpendicular direction.

The result is a line-scan camera that allows each point across the conveyor belt to be imaged with a full intensity-vs.-wavelength spectrum measured at each point. As modern cameras allow multiple regions-of-interest to be measured at very high speed, algorithms can be developed that allow chemical analysis to be performed in real-time in Web processing applications.<sup>4</sup>

The cameras are now becoming smarter and more powerful with the advent of field-programmable gate arrays (FPGAs) and less expensive memory. With these enhancements, the camera can now conduct more extensive processing on an image.

This processing will not only allow the camera to correct an image to make it pleasing to the human eye, but it will also permit analysis to be conducted on what is being imaged. This image analysis removes the burden from a computer or a user and allows the camera to be a measurement instrument. The most common basic image analysis is calibrating the signal detected by the camera from the emission of a hot object with the temperature. In hot-end glass processing, for instance, it is important to find the cooling

rate across a piece of glass for high yield. In the above recycling example, an imaging spectrograph combined with windowing functions will allow the camera to look at many specific individual wavelengths of interest at high speeds. The camera can then conduct the analysis on the material in question. Using pre-programmed algorithms, the camera can then determine if that pixel is detecting polypropylene or polyvinyl chloride by comparing the signal from the various wavelengths.

## THE FUTURE

The examples discussed above have all used InGaAs PIN photodiodes. A recent DARPA-sponsored program demonstrated photodiode arrays and SWIR FPAs that incorporate avalanche photodiodes. The added sensitivity derived from the built-in gain of APDs, together with their wide electronic bandwidth, makes them useful for imaging laser radar or 3D imaging. As their performance improves and the cost comes down, these advanced InGaAs FPAs will find their way into more and more commercial applications. ♦

## NOTES:

<sup>1</sup> Ettenberg, M.H.; Cohen, M.J.; Lange, M.J.; Dixon, P.; Olsen, G.H., "A Thin Film Indium Gallium Arsenide Focal Plane Array for Visible and Near-Infrared Hyperspectral Imaging," *LEOS '99*. IEEE Lasers and Electro-Optics Society 1999 12<sup>th</sup> Annual Meeting (1999).

<sup>2</sup> Hoelter, T., "Broad Spectrum Performance Via VISGaAs," *Advanced Imaging*, Volume 18, Number 8, September 2003.

<sup>3</sup> [http://near.jhuapl.edu/PDF/SC\\_Inst.pdf](http://near.jhuapl.edu/PDF/SC_Inst.pdf).

<sup>4</sup> Ettenberg, M.H. and Cohen, M.J., "Spectroscopic Line-scan Systems Open Shortwave Infrared Applications," *Laser Focus World*, October 2003.

*Photos: Sensors Unlimited, Inc.*

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