

Focal-Plane Arrays Open New Near- Infrared Vistas

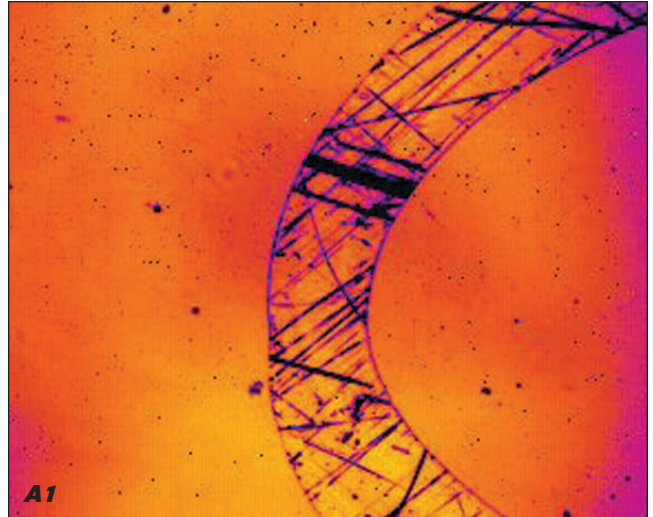
Semiconductor materials and processing developments prompt advanced cameras for the 900 to 1700nm waveband...

by Austin Richards, Ph.D.

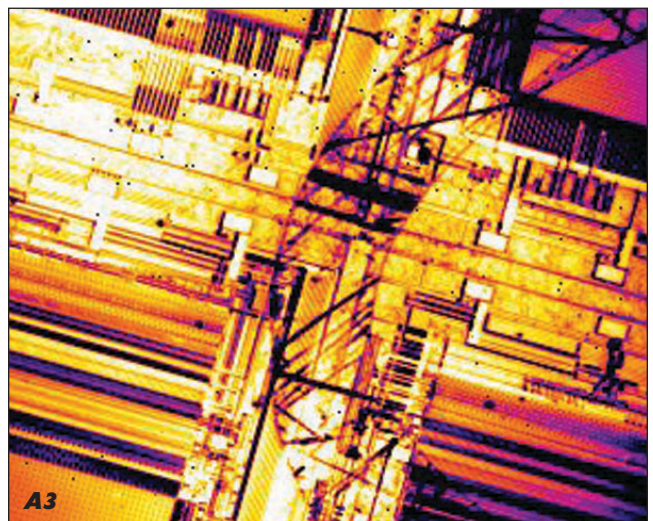
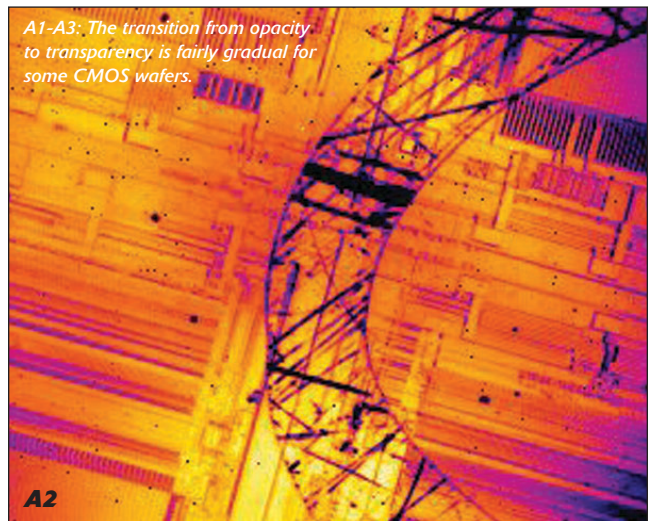
Recent developments in component and materials technology have made possible highly sensitive near-infrared (NIR) cameras that deliver excellent image quality with a spectral sensitivity in the 900 to 1700 nm near-infrared band. The performance of these cameras results from advances in commercially available indium-gallium-arsenide (InGaAs) focal-plane array (FPA) photovoltaic detectors, as well as the availability of higher-quality III-V semiconductor material in bulk wafers.

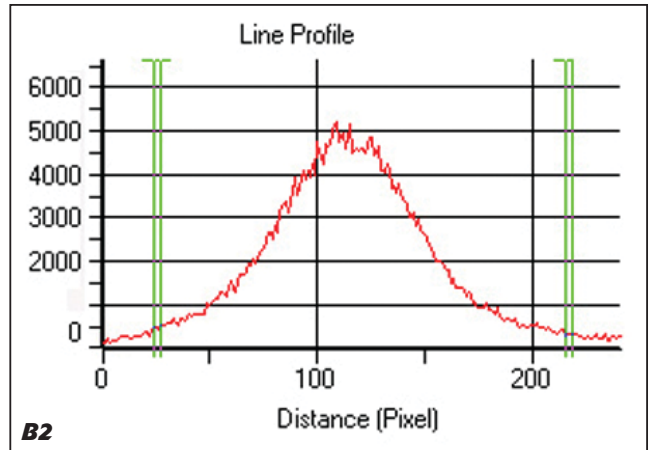
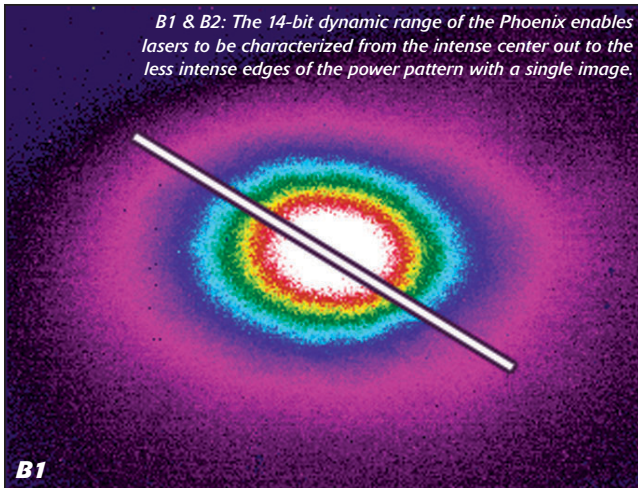
The image quality of these cameras competes favorably with that of cameras built using silicon CCD detectors, but their spectral sensitivity in the 900-1700 nm band opens a broad range of applications not possible using CCD detectors. These applications include laser-beam characterization, agricultural and petrochemical inspection, forensics and NIR imaging spectroscopy. InGaAs detectors deliver high quantum efficiencies (~85%) in the 900-1680 nm waveband, outperforming the competing technologies of lead-oxysulfide vidicons and coated CCD cameras.

Silicon becomes transparent to wavelengths longer than 1100 nm, making silicon-based cameras ineffective at wavelengths longer than that unless they are coated with a wave-shifting material. But this coating drastically lowers quantum efficiency to 1-2% in the 1100-1700 nm band, which is not useful in many applications other than laser beam profiling, where intensities are high.



A1-A3: The transition from opacity to transparency is fairly gradual for some CMOS wafers.





High sensitivity is important because NIR scenes often span a wide dynamic range, and light signals can be quite low in intensity. That is especially true in NIR imaging spectroscopy, where only a small portion of the InGaAs sensors' passband is admitted. Indium antimonide (InSb) FPAs have high quantum efficiency in the NIR band, but they require cooling to cryogenic temperatures. Their spectral response is from 1 to 5.5 microns, requiring that the sensor be combined with a bandpass filter to make a camera that operates solely in the NIR band.

The cost of this type of camera is high, and mechanical cryocooler life is a limiting factor. The coolers cost about \$10,000, making replacement costly in applications where the camera runs continuously. Because the bandgap energy of InGaAs is much higher than the bandgap energy of InSb, InGaAs FPAs can operate at temperatures around ambient (25° C), with noise performance comparable to InSb sensors at liquid nitrogen temperatures. The thermoelectric coolers used with these FPAs cost about \$20, making the overall camera much less expensive.

FABRICATING THE ARRAY

The FPAs are fabricated by growing photodiodes onto 3-inch-diameter InGaAs wafers. The wafers are made by metal-oxide chemical vapor deposition (MOCVD) of InGaAs onto indium phosphide (InP) wafers. The 30-micron-square detectors are made by diffusing a p-type zinc material through a diffusion mask into an n-type InGaAs substrate.

Next, metal is deposited and diffused into the InGaAs layer to form ohmic contacts. A total of 82,000 cone-shaped bumps of indium are then deposited onto the contact metal pads to make a 320 by 256 pixel array. The same number of indium bumps are deposited onto a silicon mixed-signal IC die. The indium bumps on the InGaAs detector dies are then fused to the bumps on the readout IC (ROIC) wafer under pressure in a cold-forming process.

Technicians bond wires between the FPA and a motherboard inside of a dewar package. The motherboard traces are then wire-bonded to the package pins. The package incorporates a glass or quartz window that has an anti-reflection (AR) coating optimized for use in characterizing 1550-nm telecommunication lasers. Without the benefit of an AR coating, interference fringes can be generated from reflections off the two window surfaces.

An AR coating is also deposited directly on the detec-

tors. The combination of the AR window coating and the detector AR coating results in extremely high transmissivity in the 1300-1550 nm range. The vacuum package also incorporates thermoelectric cooling to stabilize the FPA at an operating temperature that falls typically within the range of 0 and 20 degrees C.

The FPAs that are used in cameras have 99.5% operability and few cluster defects. Further, algorithms are used that substitute neighboring good pixels for the few bad pixels. These semiconductor and software advancements result in image quality that competes favorably with silicon CCD detectors.

IN THE CAMERA

Indigo Systems designs and fabricates its own ROICs and detectors, then integrates them into its line of cameras. This assures that the FPAs have an ROIC optimized for use with InGaAs detectors. One of the ROICs used with InGaAs detectors is the ISC9809, which is designed for ultra-low noise operation in very-low-background applications, including environments in which there is a very weak signal from the target object.

Indigo offers three varieties of InGaAs cameras with varying levels of performance for different applications. The highest-performance member of this camera family is the Phoenix NIR camera, which enables the user to select exposure times as short as several microseconds and as long as 660 milliseconds—approximately five orders of magnitude change in sensitivity. This wide operational range enables the camera to be used both for extremely low light levels as well as for high brightness conditions.

Indigo's ISC9809 FPA has four separate outputs, and can stream image data at rates up to 40 megapixels/second into a computer. This rate corresponds to frame rates of 346 Hz at the full 320 x 256 array size, enabling high-time-resolution recording of very dynamic events, such as missile launches and explosions. A new version of the Phoenix camera uses a 640 by 512 pixel InGaAs array for applications requiring higher sensor resolution.

INSPECTING WAFERS

NIR cameras using InGaAs FPAs are useful in a variety of applications, including semiconductor wafer inspection, laser and optical device characterization, water detection, and NIR spectroscopy. The cameras deliver accurate images of semiconductor wafer surface features, even though the images are taken through the back side of the wafer. The underside is opaque to visible

light, but the silicon becomes transparent at wavelengths longer than 1100 nm.

The transition from opacity to transparency is fairly gradual for some CMOS wafers, occurring over a span of 100 nm in wavelength. Figures A1-3 shows three wafer images taken through the backside of a silicon wafer bearing CMOS ROICs. The InGaAs camera is fitted with one of three bandpass filters, having center wavelengths of 1000 nm, 1050nm and 1100 nm, respectively. The filters all have a width of 20-nm full-width half-maximum (FWHM).

The black line in the 1000-nm image is an ink mark made on the wafer's surface. The circuitry is barely visible through the silicon at this wavelength. But at 1050 and 1100 nm, progressively deeper layers of circuitry are exposed, allowing voids, cracks, and other defects within the wafer's volume to be detected, and their position in x, y and z coordinates to be determined.

LASER BEAM PROFILING

Internet usage has spurred demand for orders-of-magnitude improvement in telecommunication bandwidth. This demand has driven the development of higher-bandwidth optical fiber using dense-wavelength-division multiplexing, or DWDM. These developments have triggered a need for high-speed laser transmitters and receivers for long-haul data links in the 1300-nm and 1550-nm wavebands, where silicon optical fiber exhibits very low losses.

Manufacturing the vertical-cavity surface-emitting laser (VCSEL) transmitters requires precise measurements of the spatial distribution of the laser energy to efficiently couple that energy into a fiber, waveguide or other optical device.

InGaAs sensors outperform other materials in this beam-profiling application, which is best done using a two-dimensional detector array that is directly illuminated by the laser light. Uncoated silicon CCD detectors cannot be used for profiling 1300-1550-nm laser light. Lead-oxysulfide vidicon cameras—the relatively low-cost sensors traditionally used for imaging laser energy in these wavebands—suffers from various drawbacks, including high non-linearity, limited dynamic range, image retention, and a low damage threshold. In contrast, InGaAs sensors offer high resistance to damage—typically 1 watt/cm²—which is two orders of magnitude greater than is possible with lead-oxysulfide, and without suffering image retention.

The 14-bit dynamic range of the Phoenix camera enables laser beams to be characterized from the intense center region out to the much less intense edges of the power pattern with a single image. Figure B1 shows a 1550-nm laser beam cross-section, along with a line profile, Figure B2, that corresponds to the diagonal line over the beam spot. The vertical axis is in analog-to-digital converter counts, which range from 0 to 16,383 for the 14-bit Phoenix camera.

DETECTING WATER

Another application of NIR imaging uses the wavelength-dependent reflectance of materials containing



C1-C3: A photo imaged through filters passing 900-1000 nm and 1400-1600 nm light respectively, with a third false-colored in red to show the difference between the two.

water to detect the material's presence in a scene. Water is strongly absorbing in the NIR band at wavelengths of 1350 nm or higher, but not nearly as absorbing at shorter wavelengths. This causes certain objects imaged at wavelengths around 1100 nm to be quite reflective, while the same objects at 1350 nm or higher can appear quite dark, all because of molecular absorption by water.

Figure C1 shows a person imaged with an InGaAs camera through a filter that passes 900-1000-nm light. The skin is quite reflective. Figure C2 shows the same scene through a filter that passes 1400-1600-nm light. The exposed skin appears quite dark. Figure C3 shows the difference between the other two images, but false-colored in red and overlaid onto the 900-1000-nm image.

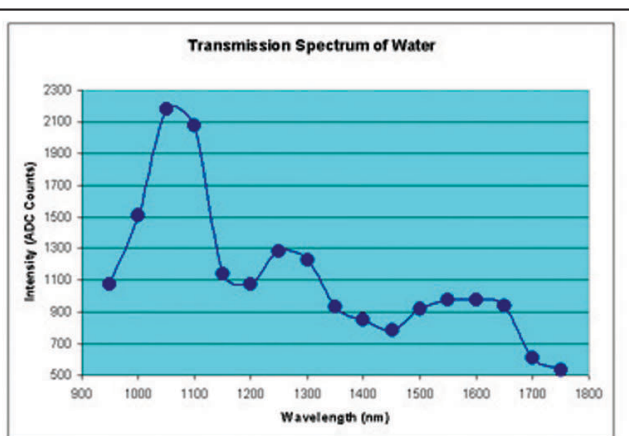
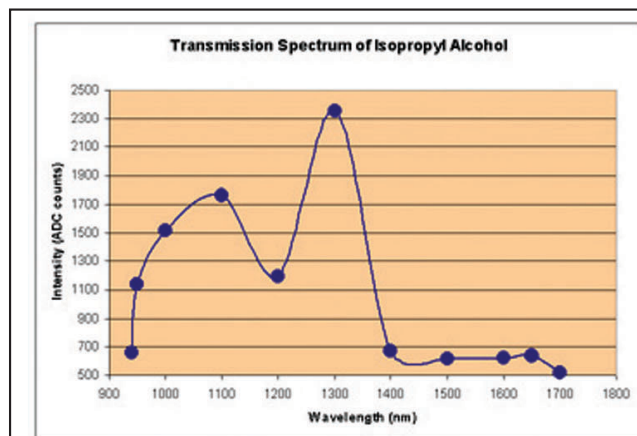
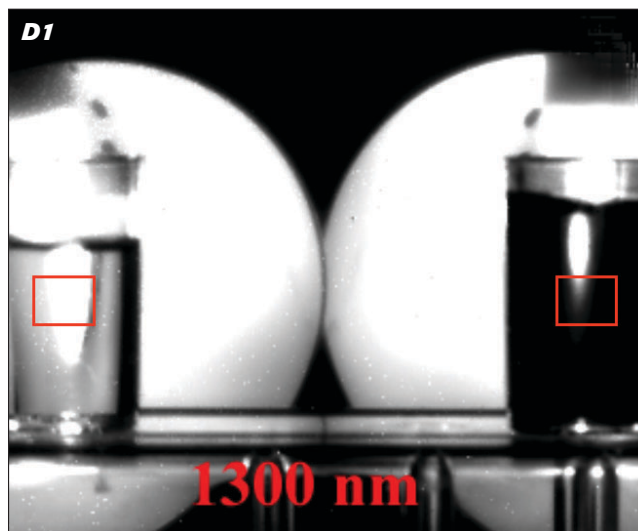
Exposed skin is readily apparent because of its water content, as is the background vegetation for the same reason.

SPECTROSCOPY APPLICATIONS

NIR spectroscopy is a quick non-destructive method to analyze the chemical composition of materials. It involves measuring the intensity of NIR light that is reflected or transmitted through a material as a function of wavelength. The resulting intensity-versus-wavelength curves are called NIR spectra, and the shapes of the curves convey information about the chemical species in the material. Imaging spectrometers are used in agricultural inspection, remote sensing, exhaust-gas analysis and

automation, enabling further cost reduction and opening new markets for this imaging technology. (Photos: Indigo Systems Corporation) ♦

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D2

Transmission spectra (D2) of containers (D1) containing methanol (left) and water (right).

pharmaceutical formulation analysis.

Figure D1 shows an image of two containers of liquid. The one on the left is methanol, and the one on the right is water. The red boxes within each image were the points used to extract NIR transmission spectra, shown in Figure D2. The two chemicals' transmission curves have very different shapes, called signatures, which can be used to uniquely identify compounds within a scene. An application for this imaging might be the detection of spilled chemicals, such as gasoline, by an unmanned aerial vehicle with an InGaAs camera.

Commercially available InGaAs cameras are enabling many new applications in NIR imaging, making possible high-performance imaging in an important region of the electromagnetic spectrum at a cost that is lower than for cooled-sensor technology. The focal plane arrays in these cameras are made with techniques developed for the semiconductor industry that are inherently scalable to high-volume production. They also lend themselves to



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