Near-IR focal-plane arrays improve camera performance

The recent improvement in performance of InGaAs-based detectors and cameras has opened up a wide range of applications, according to **Austin Richards** of Indigo Systems.

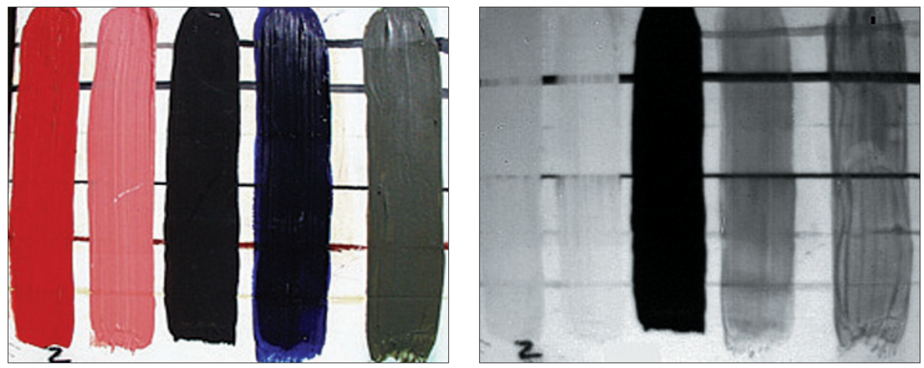


Fig. 1. An oil-paint test panel imaged with visible (left) and NIR (right) sensors. All the pigments except black show a degree of transparency in the NIR (900–1700 nm) band.

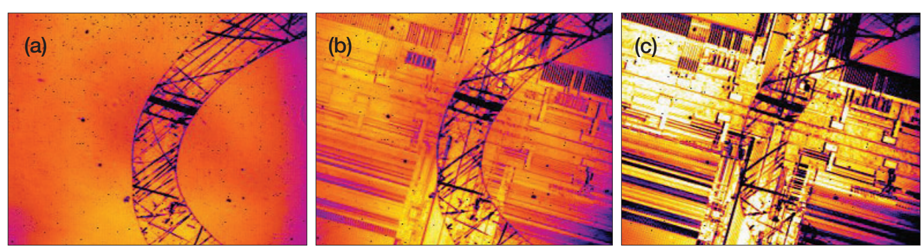


Fig. 2. Three images through the backside of a CMOS readout IC wafer taken with an InGaAs camera with filters at 1000 nm (a), 1050 nm (b) and 1100 nm (c).

Advances in focal-plane array (FPA) design, along with the availability of higher quality III-V material, have enabled the fabrication of high-performance, commercial 2D arrays using InGaAs photovoltaic detectors. These advanced InGaAs FPAs have become instrumental in the creation of highly sensitive near-infrared (NIR) cameras that deliver excellent image quality, rivaling that associated with silicon CCD detectors, but with a spectral sensitivity that is shifted into the NIR band, from 900 to 1700 nm.

The ability to produce high-quality images of objects in the 900–1700 nm waveband with high sensitivity opens up a range of applications, including laser-beam characterization, agricultural and petrochemical inspection, forensics, NIR imaging spectroscopy and astronomy. InGaAs detectors offer high quantum efficiencies (around 85%) in the 900–1680 nm band, unlike the competing technologies of lead-oxysulfide vidicons and coated CCD cameras. At wavelengths longer than 1100 nm silicon becomes transparent, making silicon-based cameras ineffective unless coated with a wavelength-shifting material. This coating results in a quantum efficiency of about 1–2% in the 1100–1700 nm band, which is useful in laser-beam profiling applications where intensities are high, but not in many other applications.

High sensitivity is important, since NIR scenes often span a wide dynamic range and light signals can be quite low in intensity, especially in NIR imaging spectroscopy where only a small portion of the InGaAs sensors' passband is admitted. InSb FPAs have high quantum efficiency in the NIR band, but require cooling to cryogenic temperatures using mechanical cryocoolers that cost about $10,000. Their spectral response is from 1 to 5.5 µm, so the sensor must be combined with a bandpass filter to make a camera that operates solely in the NIR band. Because the bandgap energy of InGaAs is much higher than 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 cost about $20, making the overall camera cost much lower.

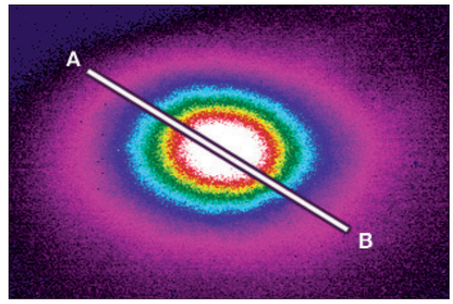
The FPA sandwich

The FPAs are made from InGaAs photodiode arrays fabricated on 3 inch, MOCVD-grown InGaAs-on-InP epiwafers. The $30 \times 30\ \mu m^2$ detectors are made by diffusing zinc (a p-type dopant) through a diffusion mask and into an n-type (S- or Si-doped) InGaAs epilayer. After forming ohmic contacts, a total of 82,000 truncated-cone-shaped bumps of indium are deposited onto the contact metal pads to make a 320×256 pixel array. The same number of indium bumps are deposited onto a silicon mixed-signal IC die, which Indigo Systems designs and offers as a standard readout IC (ROIC) product.

After a proprietary cleaning process, the indium bumps on the InGaAs detector dies are fused to the bumps on the ROIC wafer under pressure in a cold-forming process. The technicians probe the ROIC bond pads and check for operational hybrid interconnection, before wire-bonding the FPA to a motherboard inside a dewar package.

The combination of an anti-reflection (AR) coating on the BK-7 glass or quartz window of the package, and an AR coating deposited directly on the detectors, results in extremely high transmissivity in the 1300–1550 nm range. The vacuum package also incorporates thermoelectric cooling to stabilize the FPA at an appropriate operating temperature, typically between 0 and 20 °C.

The FPAs that are incorporated into cameras have 99.5% operability and few cluster defects. In addition, algorithms have been



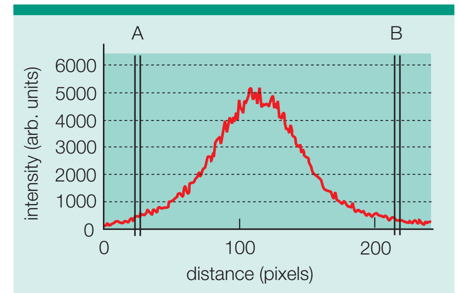


Fig. 3. Cross-sectional image of a 1550 nm laser beam (left), along with an intensity profile that corresponds to the diagonal line over the beam spot (right).

Fig. 4. Image from an InGaAs camera with a 900–1000 nm filter (a) and a 1400–1600 nm filter (b). The third image (c) shows the difference between the other two images, false-colored in red and overlaid onto (a). Exposed skin and vegetation are clearly apparent.

developed that substitute neighboring good pixels for the few isolated bad pixels. These semiconductor and software advancements result in an image quality that competes favorably with silicon CCD detectors.

InGaAs camera performance

Because Indigo Systems designs and fabricates its own ROICs and detectors, and then integrates them into its line of cameras, the company controls the supply chain, assuring that the FPAs have an ROIC optimized for use with InGaAs detectors. One of the ROIC chips used with InGaAs detectors – the ISC9809 – is designed for ultra-low-noise operation in very-low-background applications, i.e. environments in which there is a very weak signal from the target object. The ISC9809 has the additional feature that the integration capacitor used in each unit cell on the focal plane is selectable, enabling 20 times gain changes without appreciable noise increases. Indigo Systems manufactures three varieties of InGaAs cameras. The highest performance camera is the Phoenix, which has a 14-bit dynamic range in its A/D converter. This enables the user to select exposure times as short as several microseconds and as long as 660 ms – a change in sensitivity of approximately five orders of magnitude. The on-chip gain can also be switched by a factor of 20. The tremendous operational range of camera sensitivity means that the camera can be used both for the extremely low light levels typical of applications in astronomy, and for the high-brightness conditions encountered in laser-beam measurement.

The ISC9809 FPA has four separate outputs, and can stream image data at rates up to 40 megapixels per second into a computer. This corresponds to frame rates of 346 Hz at the full 320 × 256 array size, enabling high-time-resolution recording of very dynamic events such as missile launches and explosions. In one embodiment of the Phoenix camera system, two serial data links transmit image data from the camera to a PC equipped with a special frame grabber board and 1 gigabyte of RAM, allowing large data bursts to be acquired. A new version of the Phoenix camera contains a 640 × 512 pixel InGaAs array for applications needing higher sensor resolution.

Unmasking art forgeries

Art dealers, museums and collectors now have a new tool to protect themselves from multi-million dollar liabilities caused by elaborate forgeries. Works of art can be authenticated by imaging through surface pigments to detect the presence of any "underdrawings" beneath the top layer. The art conservator can thus verify that the style of the underdrawing matches that of the artist's other works, and can also detect the possible existence of another painting beneath. Silicon CCD detectors have historically been used to image through art materials such as dirty varnish that can obscure the painting, but standard silicon detectors begin to lose their effectiveness at about 1000 nm, and cut off completely at 1100 nm. In contrast, InGaAs sensors can be used to view through traditional paint pigments, which exhibit a high degree of transparency at wavelengths longer than 1100 nm.

Figure 1 shows an oil pigment test panel imaged with visible and NIR sensors. The horizontal black lines are made by a variety of media, including pencil and charcoal. All the pigments show some degree of transparency in the 900–1680 nm band, with the exception of the black pigment, which contains carbon particles that are highly absorbing across the NIR band. Imaging through black pigment requires X-ray techniques.

Semiconductor wafer inspection

NIR cameras using InGaAs FPAs are also proving useful for inspecting semiconductor wafers because the cameras deliver accurate images of wafer surface features, even though the images are taken looking at the backside 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 silicon wafers bearing CMOS circuits, occurring over a span of 100 nm in wavelength. Figure 2 shows three images of a silicon wafer with CMOS readout ICs fabricated onto it. The images are taken through the wafer's backside. The InGaAs camera is fitted with one of three bandpass filters (20 nm FWHM), having center wavelengths of 1000 nm, 1050 nm and 1100 nm, respectively.

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 nm and 1100 nm, progressively deeper layers of circuitry are exposed. The selective use of bandpass filters, coupled with an optical system with small depths of field, helps to enable the construction of a 3D characterization of a wafer, which has potential applications in the wafer inspection field. Voids and cracks within the wafer's volume can be detected and their position in X, Y and Z co-ordinates can be determined.

Optical device characterization

Manufacturing 1300 and 1550 nm lasers requires precise measurements of the spatial distribution of the laser energy in order to efficiently couple that energy into a fiber, waveguide or other optical device.

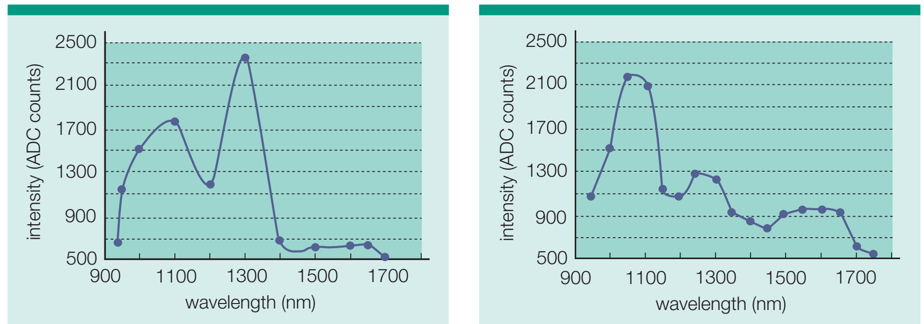


Fig. 5. Near-infrared transmission spectra of methanol (left) and water (right).

InGaAs sensors outperform other materials in this so-called beam-profiling application, which is best done using a 2D detector array that is directly illuminated by the laser light. Uncoated silicon CCD detectors cannot be used for profiling 1300–1550 nm laser light, while lead-oxysulfide vidicon cameras suffer from various drawbacks, including high nonlinearity, limited dynamic range, image retention and a low damage threshold. In contrast, InGaAs sensors offer high resistance to damage – typically 1 W/cm^2 – which is two orders of magnitude greater than is possible with lead-oxysulfide, and do not suffer from image retention.

Related applications are in the area of laser designators used for targeting guided munitions that operate at 1064 and 1540 nm, and laser range-finders operating at 1570 nm. InGaAs cameras are used to image the laser designator or range-finder spot on a target at varying distances during system development and as a way of calibrating and focusing field systems.

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. Figure 3 shows a 1550 nm laser-beam cross-sectional image and a line profile that corresponds to the diagonal line over the beam spot.

Water detection

Another application of NIR imaging uses the wavelength-dependent reflectance of materials containing water to detect the materials' presence in a scene. Water is strongly absorbing at and above 1350 nm, but not nearly as absorbing at shorter wavelengths. This behavior causes certain objects imaged at wavelengths around 1100 nm to be quite reflective, while the same objects imaged at 1350 nm or higher can appear quite dark.

Figure 4a shows a person imaged with an InGaAs camera through a filter that passes 900–1000 nm light. The skin is quite reflective. In 4b, which shows the same scene imaged through a filter that passes 1400–1600 nm light, the exposed skin appears quite dark. Figure 4c shows the difference between the other two images, 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. The difference in contrast between water-filled objects and "dry" objects can also be used to detect the absence of water in a scene.

NIR spectroscopy

NIR spectroscopy is often called the most rapid non-destructive method of analyzing the chemical composition of a material. It involves measuring the intensity of NIR light 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.

An imaging spectrometer is an instrument that can generate NIR spectra for each pixel in the scene being imaged. The spectrometer uses a variable filter or diffractive optic for spectral selection. The dataset generated by an imaging spectrometer is known as an image cube because there are three dimensions to the data set: X and Y spatial co-ordinates and the center wavelength of the filter passband of the pixel along the Z axis. Imaging spectrometers are used in agricultural inspection, remote sensing, exhaust-gas analysis and pharmaceutical formulation analysis. Figure 5 shows the NIR transmission spectra of two liquids, methanol and water, which have transmission curves with very different shapes. These shapes, known as signatures, can uniquely identify compounds within a scene. One possible application is the detection of spilled chemicals, such as gasoline, by an unmanned aerial vehicle with an InGaAs camera.

Summary

Commercially available InGaAs cameras are enabling many new applications in NIR imaging, making high-performance imaging in an important region of the electromagnetic spectrum possible at a cost that is lower than cooled sensor technology. The FPAs in these cameras are made with techniques developed for the semiconductor industry, which are inherently scalable to high-volume production and lend themselves to automation, enabling further cost reduction and the penetration of new markets with this imaging technology. ●

Austin Richards is a senior applications engineer with Indigo Systems Corporation of Goleta, CA. Web www.indigosystems.com.