COMPOUND SEMICONDUCTOR

Three-Fives and Silicon Heterostructures

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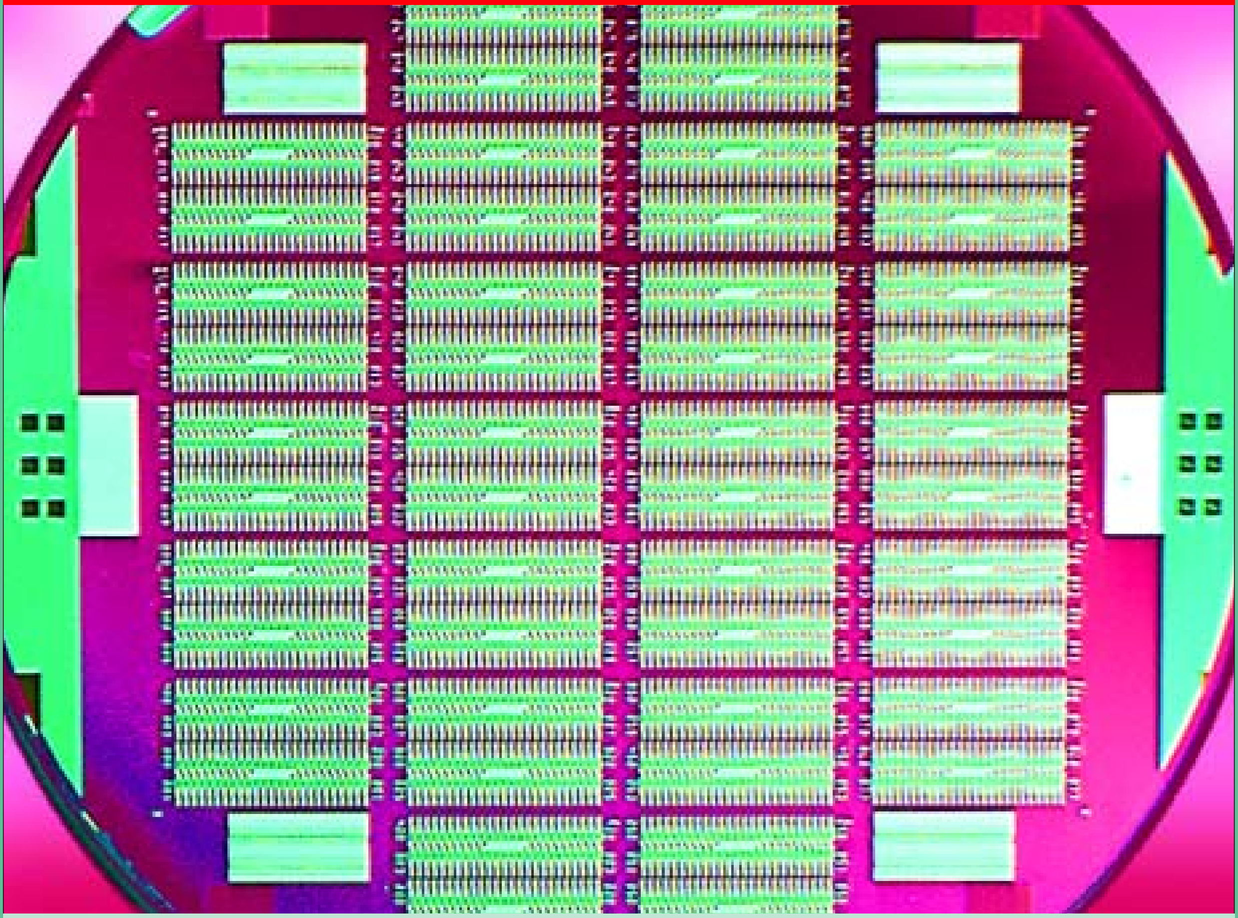

INDIUM PHOSPHIDE

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Wafer-making advances fuel InGaAs camera sales boom

InGaAs cameras are now being used to find bruising in fruit, sort plastics for recycling, and help the glass-bottle manufacturing industry detect defects. This penetration into new markets is being driven by the availability of cheaper, higher-quality InGaAs material, reports **Martin Ettenberg** of Sensors Unlimited.

The falling cost of InGaAs cameras is driving their increased deployment in areas as diverse as spectroscopy, object identification, and military and thermal imaging. These more affordable detectors, which operate in the spectral band between 750 nm and 2.6 µm, are just starting to be used for applications as varied as sorting plastics, determining fill levels in opaque plastic bottles and imaging under starlight conditions.

Improvements in material quality have accompanied these increases in sales, leading to devices with greater uniformity and lower dark current, and room-temperature-operation imaging arrays with greater sensitivity. Further advances are expected to follow, fueling the trend for higher volumes, improved performance and falling prices that Sensors Unlimited Inc. (SUI) of Princeton, NJ, has witnessed for over a decade.

Straining to increase coverage

SUI's detectors cover the 900–2600 nm spectral range with various $In_xGa_{1-x}As$ alloys, and the company has recently developed a new processing technique to extend this range down to 400 nm at the blue end of the visible spectrum. The detector uses three alloy compositions: $In_{0.53}Ga_{0.47}As$, which is lattice-matched to InP (referred to simply as InGaAs); strained $In_{0.71}Ga_{0.29}As$; and strained $In_{0.82}Ga_{0.18}As$. Varying the InGaAs composition allows the camera to detect emission at wavelengths of up to 2.6 µm, far beyond the 1 µm cut-off associated with silicon-based imagers (see figure 1).

Lattice-matched InGaAs has seen the greatest improvements. During the last six years dark currents have fallen by 95% and pixel operability (the proportion of working pixels) has risen substantially. This unstrained material has also generated the highest increase in demand for new applications.

InGaAs arrays also contain a CMOS readout integrated circuit (ROIC). The InGaAs device converts incident photons to electrons, and the ROIC amplifies and stores the electrical signal, which permits simultaneous light-collection by all the pixel elements and serial read-out of the signal.

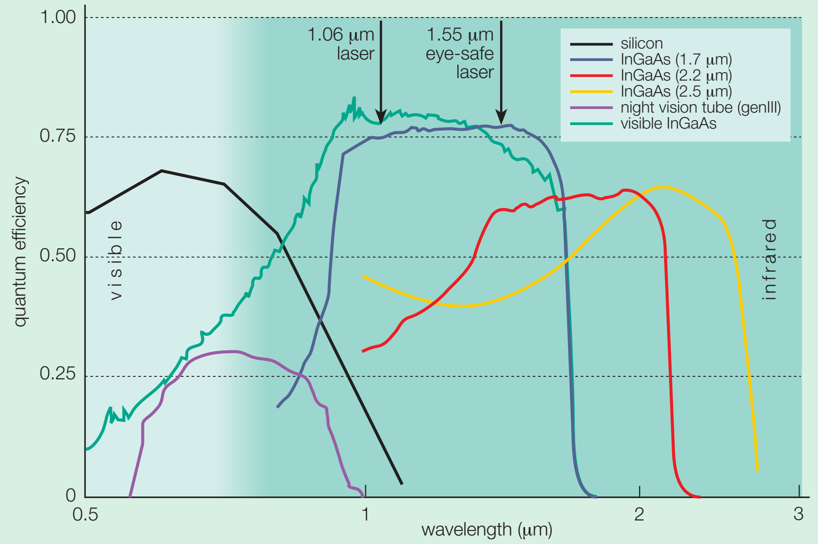
The detectors have a linear response to light intensity over more than five orders of magnitude. However, these detectors are limited by the storage capacitor size on the CMOS ROIC, which places an upper limit on the collected signal and dictates acceptable dark current values. Dark current cannot be eliminated, but reducing this unwanted signal improves signal-to-noise ratios. Changes to structural design and processing improvements have significantly improved the dark current in standard *pin* detectors, and typical dark currents for an InGaAs pixel in a 320 × 256 array with a 25 µm pitch are now below 75 fA at reverse biases of 300 mV.

High-performance detectors also demand uniform dark current, because it is the pixel with the highest dark current that determines the detector's longest integration time or the largest gain. SUI has improved its detector uniformity, and dark current variations are now below 20% for a 640 × 512 InGaAs array measuring 16 × 12.8 mm. In this device containing more than 325,000 separate detectors, over 99.5% of the pixels are operable. Linear arrays with 1024 pixels and a 25 µm pitch have even higher operability figures of 100%.

Detecting the enemy

Military imaging is the largest application sector for shortwave infrared (SWIR) detectors, followed by spectroscopy, the sorting of products and materials, and thermal sensing. Each application places different demands on the detectors, and fulfilling these requirements has driven the production of higher-quality, lower-cost imagers.

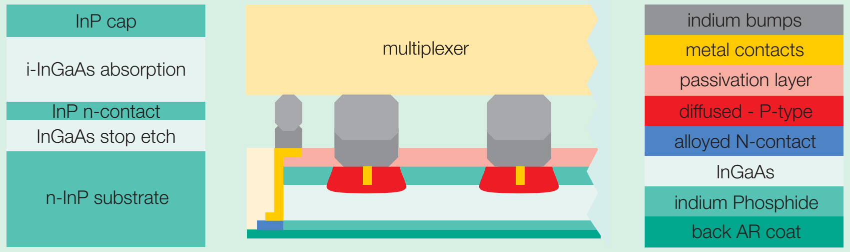
During the last few years improvements in InGaAs material quality have raised the detector's performance to such a level that it is now starting to penetrate the military market.



SENSORS UNLIMITED

Fig. 1. By adjusting the InGaAs strain and removing the absorbing InP substrate, Sensors Unlimited's imagers can cover the spectral range from 0.4–2.6 µm, which includes the 1.06 µm and 1.55 µm lasers used by the military.

Extending detection to visible wavelengths



InP layers prohibit InGaAs detectors from performing in the visible region because the material is highly absorbing at these wavelengths. Sensors Unlimited has solved this problem by incorporating etch-stop layers into the device (left). This structure is then combined with the CMOS read-out integrated chips to form detector arrays (right) before the InP and InGaAs etch-stop are removed by chemical etching.

Fig. 2. Short-wave imaging (right), unlike visible imaging (left), can be used to see through plastic and determine liquid levels inside opaque containers.

Developments in InGaAs manufacturing

Sensors Unlimited was the first optoelectronic company to have a 4 inch line, but most InGaAs/InP detector fabrication facilities still use 2 or 3 inch InP substrates. 4 inch wafers offer high-volume processing with improved uniformity, although the strained InGaAs material required for longer-wavelength detectors is often only available on 2 and 3 inch substrates.

Production quantities have increased in recent years, and a reduction in epitaxial defects has led to a ten-fold reduction in dark current. Longer-wavelength strained InGaAs material, which has a higher dark current, is now more common, and many linear arrays incorporating this material are now available off-the-shelf.

The refinements in material quality and processing have reduced the dark current, which benefits applications involving the detection of weak signals such as spectroscopy. The reduction in dark current has also improved the yield of higher-speed devices, which has in turn lowered the cost of cameras used to track moving objects, such as those used in machine-vision arrays.

Lower sales prices have in turn driven greater application and increased wafer volumes, thereby continuing the trend of better performance, lower costs and larger product volumes.

SUI has also extended the response of its 2D arrays to visible wavelengths by removing the InP substrate, which absorbs light below 920 nm. Removing the substrate using the InGaAs etch-stop layer allows for backside-illuminated detectors with a thin (<<1 µm) InP layer for an n-side contact (see "Extending detection to visible wavelengths"). Light can then penetrate InP and reach the InGaAs absorption layer, allowing visible light detection.

SUI's detector prices have been in continual decline, as demonstrated by the sales history of its linear array detectors to the optical telecoms market. In 1997 256-element linear arrays with a 50 µm pitch and 99% pixel operability cost $6000 in single-piece quantities. Five years later, similar arrays sold for $1300 each in quantities of 1000 and delivered 100% operability.

This trend has been mirrored in the 2D array market. In 1993, SUI sold its first 128 × 128 (60 µm pitch array) InGaAs camera offering room-temperature operation. The camera weighed over 2 kg, had a pixel operability of 98% and cost $25,000 in single-piece quantities.

Today 320 × 256 InGaAs imagers with just a 25 µm pitch, in a camera the size of a matchbox and weighing less than 70 g, cost $22,000 in single-piece quantities. For 100-piece quantities the cost of each detector is reduced to $11,000.

> **High-performance InGaAs material is now starting to penetrate the military market.**

These instruments allow both imaging and the transmission of digital pictures under starlight-only conditions, so images can be shared between soldiers on the battlefield (see figure 3). This feature is not possible with the standard-issue night-vision goggles which only allow direct viewing. InGaAs arrays can also image nearly all types of battlefield laser, including the newer 1.55 µm eye-safe sources. Other technologies can provide digital images at night, for example electron-bombarded active pixel sensors and image-intensified charge-coupled devices. However, both these detectors have a small dynamic range and don't allow the user to see 1.55 µm eye-safe sources.

Although the latest thermal weapon sights (8–12 µm detection range) currently being developed and deployed can also detect people or military vehicles, they have several drawbacks. They are unable to see laser target designators and ranging devices, cannot image through glass windows, and suffer from inferior performance at dawn and dusk. SWIR imagers can complement these thermal imagers, and images can be fused together to generate a very informative picture.

The spectroscopic detector market is dominated by linear arrays, but recently there has been a surge in the use of their 2D counterparts, which can record spectroscopic information on one axis, while using the other to detect spatial information. InGaAs arrays are already the first choice for monitoring the optical output from telecom networks using dense-wavelength division multiplexers, while the research market has seen steady growth over the last decade as detector performance has improved.

Spectroscopy can also be used to sort materials, and it has been used for several years in recycling plastics by analyzing reflected light intensity at different wavelengths. One camera is used for each wavelength, and specific plastic types can be identified by comparing these images. This "machine vision" application requires high-speed cameras to minimize blurring, which demands a detector with high uniformity, high speed and fast read-out.

Developing instruments to cater for the two vastly different applications of spectroscopy and imaging under low light-levels has led to performance improvements that are proving useful outside these specific applications.

Imaging on the production line

For example, InGaAs cameras are just beginning to be used to measure the fill levels of liquids in containers. In the last year, SUI has installed detector systems within the pharmaceutical industry to replace slower and simpler methods such as using scales to determine container fill levels (see figure 2).

The food industry is also now starting to use InGaAs detectors as an affordable alternative to silicon-based cameras to reveal the level of bruising in fruit.

The smallest market, thermal imaging, has been dominated by microbolometers or detectors containing mid- and long-wavelength infrared materials (>3 µm detection range) such as HgCdTe and InSb. Although these instruments are good solutions for imaging room-temperature objects, InGaAs detectors offer distinct advantages above 120 °C. This feature has led to SUI selling InGaAs cameras to the glass manufacturing and smelting industries during the last four years.

Fig. 3. InGaAs cameras can give soldiers the edge during night-time combat by delivering clear images, even in the darkest conditions.

One advantage InGaAs cameras have over their competitors for thermal imaging is their compatibility with glass optics, which circumvents the need for germanium or sapphire windows. This means they can be used in factories in already-qualified standard protective enclosures, to image through plain glass windows that were built for visible cameras which was the previous state-of-the-art technology. In glass manufacturing, the camera measures the glass temperature during cooling and checks for defects on the inside of glass bottles. This application doesn't work with a traditional thermal imager because glass is opaque at longer wavelengths, so internal defects can't be seen. The InGaAs imagers do not require cooling, so running costs are lower than those of many other imagers that require either liquid nitrogen or multi-stage thermo-electric coolers. Some of the cheaper thermal imagers that operate without cooling struggle to operate at high frame rates, making them unsuitable for machine-vision applications.

InGaAs cameras are already suitable for a wide variety of applications. And as their cost continues to drop, they are in a strong position to penetrate these markets further still. ●