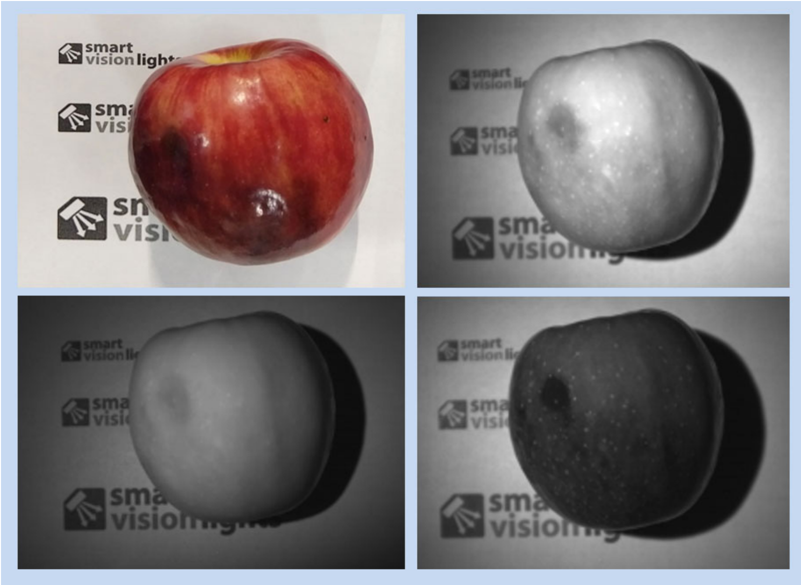
Technology White Paper

A Short Introduction to Shortwave Infrared (SWIR) Imaging

SHORT WAVE INFRARED



An overview of SWIR technology and principals. Contains examples and suggestions for practical implementation of SWIR imaging in machine vision systems.

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A Short Introduction to Shortwave Infrared (SWIR) Imaging

Occupying the electromagnetic spectrum just above the near-infrared, the shortwave infrared (SWIR) range – between 1,050 and 2,500 nm – lies firmly beyond the reach of conventional silicon-based imaging sensors. Yet despite this, the SWIR band is finding increasing application in machine vision for the unique capabilities it offers for inspection, sorting, and quality control, as well as for ambient light applications such as surveillance and remote

Because silicon's quantum efficiency quickly fades beyond 800 nm, SWIR sensors build on other chemical compositions such as indium gallium arsenide (InGaAs) or mercury cadmium telluride (MCT). Newer SWIR imagers are also leveraging unique sensor architectures, such as quantum dot technology. Selection of the right imaging modality depends on the application. But all these technologies significantly extend imaging capabilities beyond visible sensors – not only through the extended spectrum they open up, but also by the unique ways that SWIR light changes how familiar materials appear.

SWIR wavelengths that lie nearer the mid-wave IR (MWIR) spectrum – where MCT cameras are more effective – share that spectral region's ability to capture energy emitted from an object itself. Also, the comparatively longer wavelength of photons in this range makes them less susceptible to Rayleigh scattering caused by particles of smaller diameter. In practical terms, this simply means that SWIR imagers can see through smoke, haze, or fog.

Shorter SWIR wavelengths — from roughly 900 nm to 1,700 nm — behave similarly to photons in the visible range. While the spectral content of targets in SWIR is different, the images produced still are more visual in their characteristics and less like the lower resolution thermal behavior of the MWIR and LWIR light bands. This advantage aligns more closely with the needs of many industrial machine vision applications. Compared to MWIR and LWIR, SWIR's shorter wavelengths enables images with higher resolution and stronger contrast, both of which are important criteria for inspection and sorting.

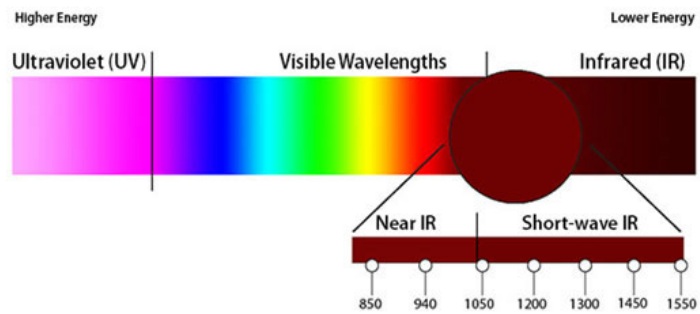

Figure 1 - SWIR occupies a spot in the non-visible light spectrum between near infrared (NIR) and longwave IR. It behaves more like visible light than the thermal energy of the IR spectrum.

Further, while cameras operating at SWIR's shallow end share similar light capture techniques with visible cameras, the images they collect appear very differently than those captured with silicon sensors – even when imaging the same item.

The reason for this is a mix of physics and chemistry. In general, any interaction of light and matter involves some transaction of energy. If electromagnetic energy is transferred to the molecules comprising an object, the object's surface absorbs that energy. If not, the energy is reflected. Since each discrete wavelength has its own unique energy definition, materials that appear similar at one wavelength will appear entirely different at another.

This explains the unique capability of SWIR cameras to capture high resolution images of familiar items that appear completely different to a conventional silicon imager operating in the visible range.

SWIR Detectors Arrayed

InGaAs sensors are currently the prevailing camera technology operating within the 900 to 1,700 nm window of the SWIR range. They are comparatively cost-effective and mature versus other SWIR imaging modalities, which makes them the most commonly used technology for machine vision applications involving inspection, sorting, and quality control.

Like silicon-based detectors operating in the visible range, InGaAs sensors offer high detection performance and fast response speeds, though their photo sensitivity is dependent on wavelength. These solid-state devices incorporate no shutters or other moving parts, making them resistant to the vibration common on factory floors. Unlike SWIR cameras targeting thermal imaging applications, InGaAs devices can also forgo expensive silicon or germanium lenses to leverage conventional glass optics.

In general, InGaAs cameras targeting SWIR applications in industrial machine vision do not require cooling. However, as this comparison of three Hamamatsu InGaAs cameras illustrates, cooling the sensor can significantly reduce dark current for improved image quality and longer exposure times in some applications.

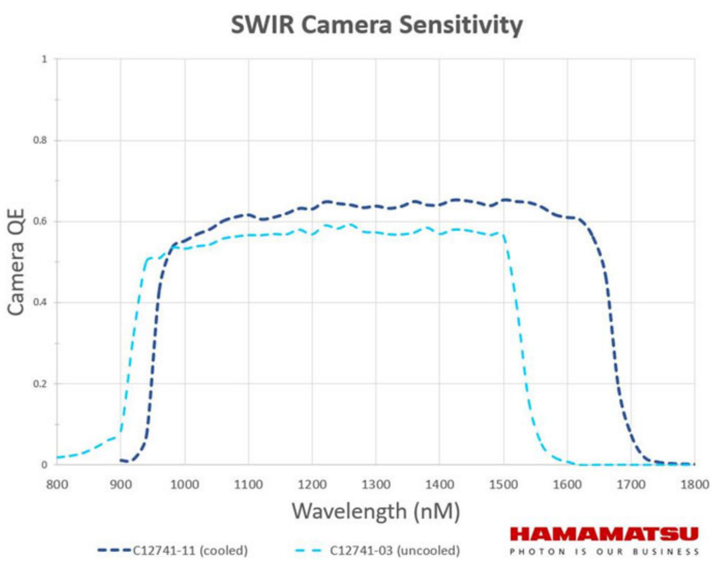

Figure 2 - Typical InGaAs SWIR Camera Performance

It is worth noting that cameras built on quantum dot technology are a comparatively new SWIR imaging technology that is also gaining traction. The spectral band these devices operate in overlaps that of InGaAs sensors, making quantum dot cameras a direct competitor to the incumbent technology. One consideration when applying quantum dot-based cameras is their lower quantum efficiency (QE) compared to InGaAs imagers. This could be seen as a drawback, as it translates to lower camera sensitivity. With SWIR lighting in controlled machine vision applications, the sensitivity may not be a limiting factor and the QE can also be expected to improve as the technology matures.

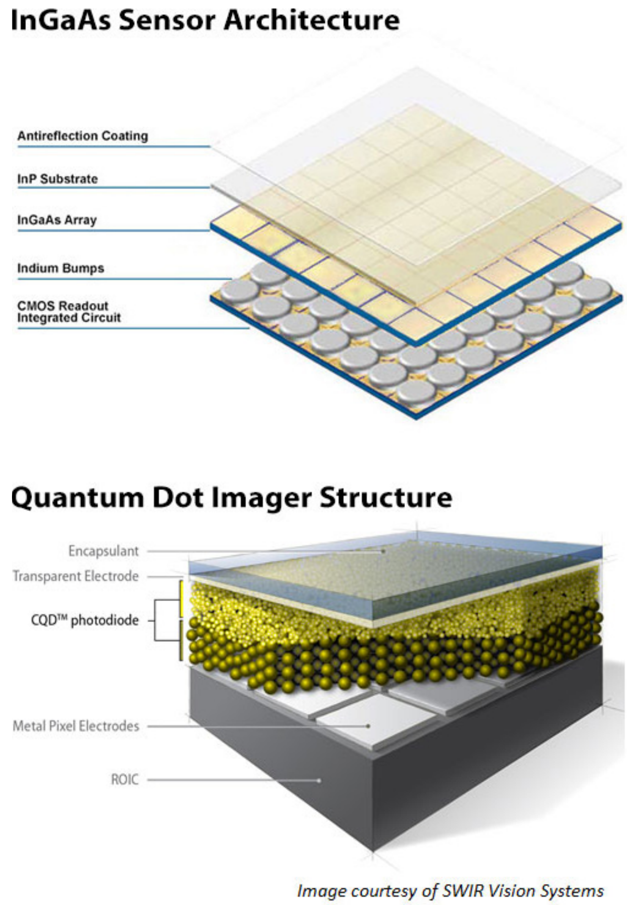

Figure 3 - InGaAs versus Quantum Dot Structure

Because quantum dot cameras are relatively new to the market, their costs tend to be comparatively high. But that is likely to change as the technology matures. This trend also applies to InGaAs cameras, however. As interest in SWIR's potential for machine vision grows, improved manufacturing techniques, better yields and economies of scale will all combine to drive down the cost of both camera technologies.

Different Is Better

As noted earlier, SWIR's longer wavelengths versus those in the visible range cause them to interact very differently with atomic structures, which provides some new and unique imaging possibilities for machine vision applications. Familiar items appear very differently when imaged in the SWIR spectrum. Focusing strictly on the industrial machine vision side of things, this phenomenon has enabled many applications that would be difficult or impossible to perform using visible lighting and cameras.

While the bandgap of silicon molecules causes the material to absorb visible and NIR wavelengths, for example, silicon transmits lower energy SWIR wavelengths making semiconductor wafers transparent in this spectral range. This allows unique options for raw material inspection applications, such as imaging defects both on the surface and inside of silicon wafers. This quality of SWIR light also benefits wafer bonding applications, allowing fiducial marks for alignment to be seen through the back surfaces of both wafers, improving accuracy.

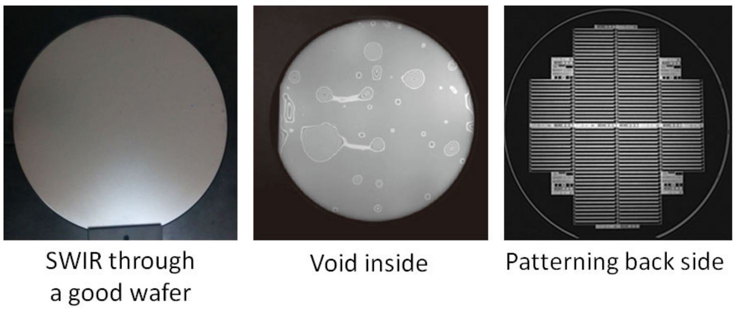

Figure 4 - Silicon turns translucent and passes SWIR light. This property aids many machine vision applications related to the semiconductor manufacturing process.

One of SWIR's most promising machine vision applications is the inspection and sorting of produce. Water is highly absorbent at both 1,450 nm and 1,900 nm, which makes it appear almost black in images of objects illuminated at that wavelength. As a result, applying an appropriate filter or light source can help make moisture content highly evident in bruised fruit, well-irrigated crops, or bulk grains.

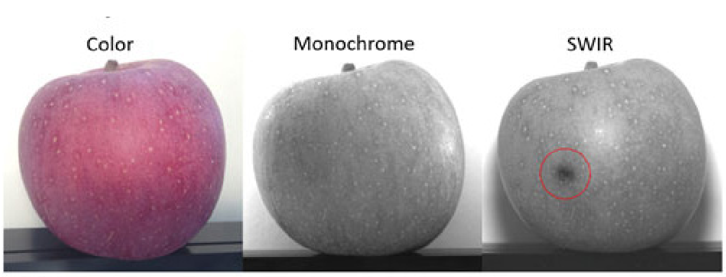

Figure 5 - When fruit is bruised, the cell walls break down and the area develops a higher moisture content. Water absorbs many bands of light in the SWIR range. This absorption allows SWIR imaging to see bruises that aren't detectable by visible camera technologies.

The value of moisture detection isn't limited to produce and crops. SWIR imaging can help confirm that dyed textiles or particle board are dry enough for further processing. It can also inspect the seal integrity and quality of packaging, especially if high-moisture goods are contained within.

Many plastics that appear opaque at visible wavelengths are translucent in the SWIR range, which offers new options for inspecting product volume within sealed plastic containers. In addition to consumer goods, the ability of SWIR light to penetrate plastic also introduces new ways to inspect fill levels of pharmaceuticals dispensed in white plastic bottles.

Figure 3 - A 1550 nm SWIR light can enable a SWIR camera to see through a plastic continer and show the fluid level.

The term "plastic" comprises a wide range of different polymer chemistries. While they may all appear alike in the visible range, different plastics can be easily distinguished from each other when illuminated with SWIR light. This benefits recycling operations that leverage SWIR cameras operating from 1,100 to 2,200 nm to identify different polymers traveling down a sortation conveyer.

SWIR light's unique interaction with different materials is only beginning to be explored. It is not always predictable how complex chemical compositions, such as pharmaceuticals, will appear when illuminated by SWIR wavelengths and imaged. But the potential implications for inspection are clear.

Illumination Beyond the Visible

As with machine vision applications in the visible range, inspection and other operations often benefit from active illumination within narrow bands to promote higher contrast of objects and features.

To date, LEDs in the SWIR range have been low output and spanned relatively broad ranges in the spectrum. Recent technology advances have allowed higher outputs in more controlled, narrow spectrums. Though SWIR LEDs will still be lower output and broader spectrum than their equivalents in the visible spectrum, they have reached a point where they are bright and controlled enough for imaging. Emitting at peak wavelengths of 1,050, 1,200, 1,300, 1,450, and 1,550 nm, these light sources now offer high enough powers to offer appealing new options for machine vision lighting.

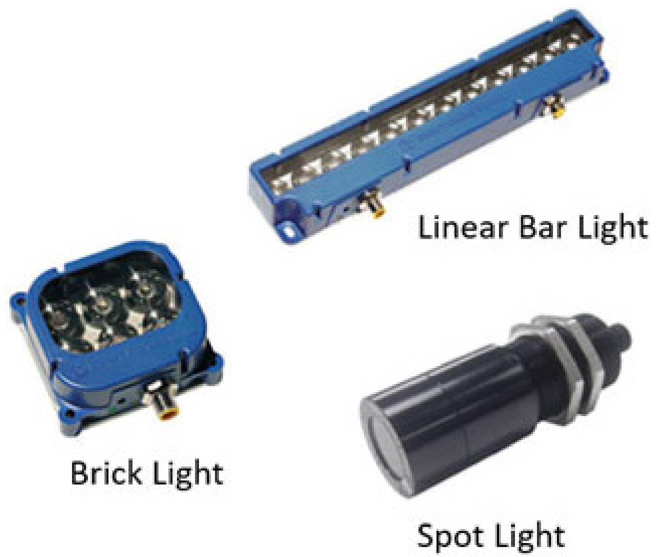

Figure 7 - SWIR LED lighting is available in many common form factors and easy to use. There is a good selection of wavelengths from 1050-1550 nm.

With the latest technology, LED sources operating in the SWIR range are comparable in configuration to those used in conventional visible-range machine vision applications. Their use is easy and similar to visible LED lighting that everyone is familiar with. They may be combined or strobed individually much the same way as visible-light LEDs, and to enable similarly complex image capture.

Conclusion

The yields of InGaAs sensors continue to increase and new SWIR imaging technologies are coming online – all of which help drive costs down and make this technology a more accessible option for machine vision integrators. Meanwhile, the biggest impediment to wider adoption of SWIR imaging may be that much of it remains undiscovered territory.

While broadband light sources are adequate for some applications in this range, capturing data within specific bands will commonly provide more useful image data. Often, the first question new users must ask is what wavelength is most effective for their particular application – and the SWIR spectrum encompasses many more wavelengths than the visible. Even with tools such as hyperspectral spectrometers, finding an answer to this question can require some trial and error.

On a more positive note, broader imaging options await once users have determined the optimal SWIR wavelength for their application. Narrowing the spectrum is no longer reliant on the use of filters or algorithms to make the most of poor imaging schemes. With the introduction of SWIR LEDs able to deliver intense illumination at a wide selection of SWIR wavelengths, integrators can be more confident they will be able to match the optimal light source to their camera and application, and capitalize on the potential opportunities that await them in the SWIR spectrum.