SWIR Sensing with Colloidal Quantum Dots

Colloidal quantum dot (QD) materials are breaking through in new markets and are unlocking technological challenges in a wide range of optical and electronic applications across the electromagnetic spectrum (**Figure 1**). Based on the unique QD platform of composition and size dependent optical properties, the materials cover applications across the visible and infrared regions. Unlike in the visible region, where QDs are mostly used for their ability to convert light and emit very specific wavelengths, most infrared applications of QDs rely on the conversion of photons to electrical signal, based on Einstein's internal photoelectric effect. This enables their use as an absorber material in thin film photodetectors where QDs are combined with complementary metal-oxide-semiconductor (CMOS) read out integrated circuits (ROICs) to produce a high performance and low cost alternative to incumbent InGaAs technology for short-wave infrared (SWIR) sensing.

In this paper, we will discuss the benefits of high resolution imaging using SWIR light and explain how colloidal QDs are poised to impact this field. Starting from the applications, we will explore advantages of imaging at different wavelengths, followed by a discussion of the current technology landscape in this market. Further, we will take a deep dive into QD-CMOS sensor technology and discuss Nanoco's technology and position in the market. SWIR typically refers to radiation in the electromagnetic spectrum with wavelengths between 1000 – 3000 nm. While invisible to the human eye, SWIR shares more of the properties of visible light over its longer wavelength relatives, such as MWIR and LWIR (mid- and long-wavelength infrared, respectively), which are predominantly emitted by objects. Like visible light, SWIR interacts with matter based on reflection and absorption, facilitating its technological use for high resolution imaging with features such as high contrasts and shadows.

SWIR sensing enhances vision and reveals valuable information invisible to the human eye

Compared to shorter wavelength alternatives, SWIR light exhibits distinct advantages over visible light that can be leveraged in a variety of environmental imaging scenarios. For example, SWIR experiences less scattering from fine airborne particles, such as haze, smoke or fog, as demonstrated in **Figure 2** – left. Under normal visible light imaging, parts of the scene are obscured by smoke, particularly at the front of the image. In contrast, SWIR imaging – here 1000 to 2000 nm – provides a clear image of all features in the frame, and also allows the viewer to identify the source of the smoke, the active fire. The scene in **Figure 2** demonstrates that using SWIR can provide improved imaging tools that enable better visibility through adverse environmental conditions. Another important property of SWIR is

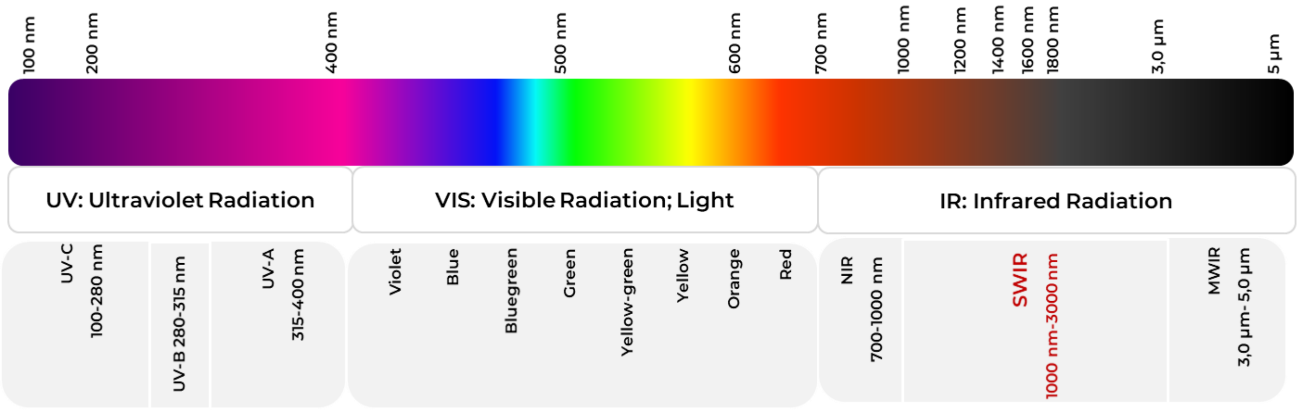

Figure 1: Electromagnetic spectrum from the UV to the IR, highlighting the SWIR region (1000 – 3000 nm).

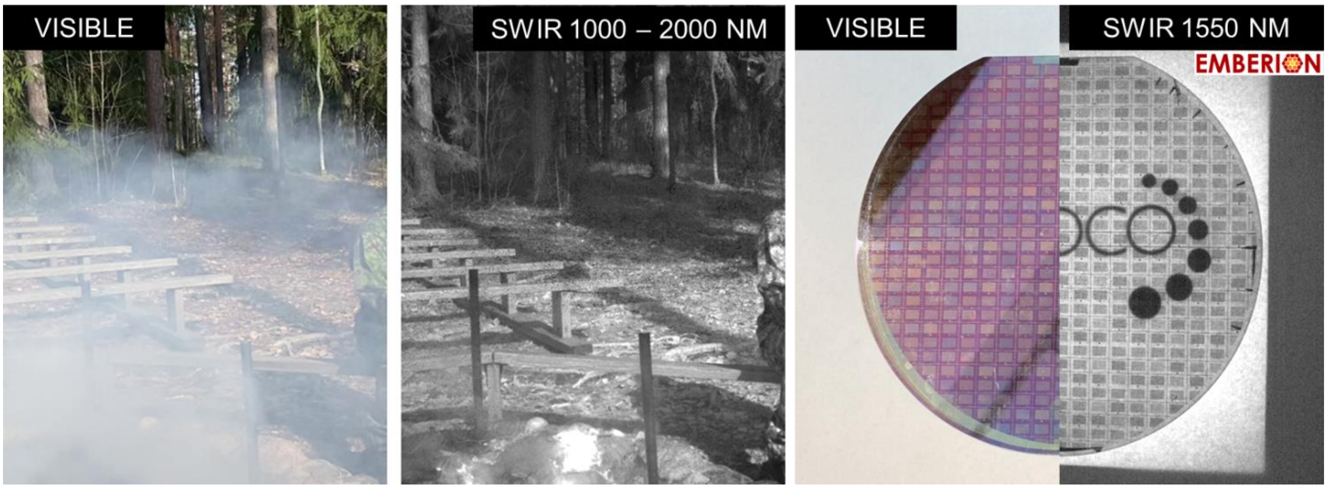

Figure 2: Images recorded with an Emberion camera, using Nanoco's HEATWAVE® QDs.

about specific interactions with a variety of materials and compounds. While some materials become transparent in the SWIR, thus allowing to image through them (**Figure 2** – right: silicon wafer), other compounds (e.g. water) show strong absorption bands at specific SWIR wavelengths. Given the non-invasive optical nature of these interactions, SWIR imaging enables a wide range of exciting applications and use cases, some of which will be explored in more detail in the next section.

SWIR APPLICATIONS

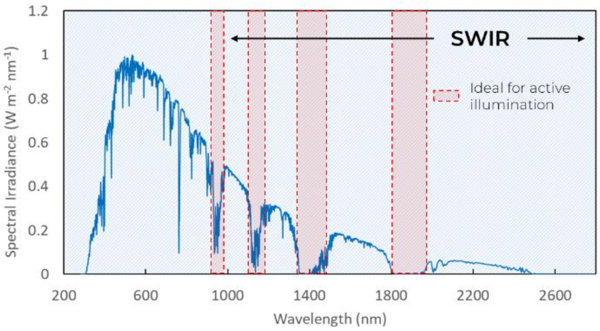

Figure 3: Reference solar irradiance spectrum (AM1.5 at earth surface) showing irradiance across the visible, NIR and SWIR region with indicated atmospheric absorption gaps. Adapted from [1].

Before getting deeper into individual applications, it is worth pointing out that due to specific atmospheric absorptions, the SWIR range offers some unique imaging opportunities with minimal solar background radiation (940 nm, 1100 nm, 1400 nm, 1900 nm – see **Figure 3**). This is of particular interest in applications that target improving visibility in challenging weather conditions, since broad solar background can negatively impact contrast through scattering and glare. Operating in these atmospheric absorption regions with an active light source maximises signal-to-noise ratio and improves the robustness of imaging systems.

Apart from the absence of background light, these bands are of particular interest due to the strong light absorption of water molecules – the cause for the atmospheric absorption in the first place. These specific absorption features can be used in a large number of existing and prospective consumer-based applications. One of these applications is moisture detection and monitoring from human skin using a wearable technology platform **(Figure 4** – left).[2] While early versions exist, more advanced technology could unlock a variety of promising use cases in cosmetics, sports and most importantly health monitoring, given the general health benefits of maintaining optimal hydration levels. Further, SWIR imaging may bring more advanced biometric authentication technology, since longer wavelengths combine deeper skin penetration with improved eye safety. Another interesting area is in industrial- and consumer-based food safety monitoring, since water-rich areas can indicate early signs of degeneration. Hyperspectral imaging applications in the SWIR are another example for improving management of complex challenges, such as crop monitoring. Large area monitoring with unmanned aerial vehicles (UAVs) may help with early disease detection in plants or water stress assessments, as shown in **Figure 4** – middle, for a vineyard (based on 1485 nm

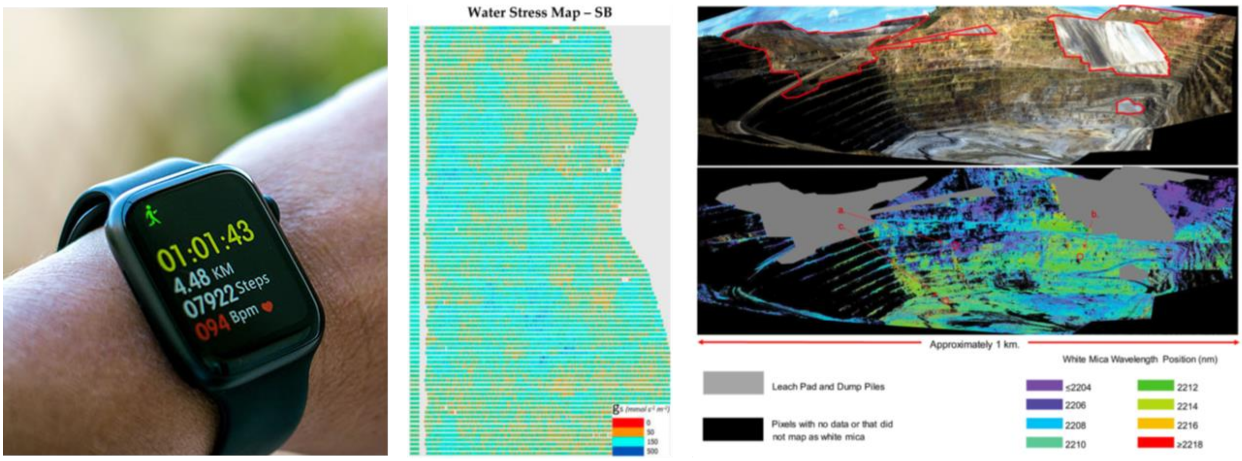

Figure 4: Left to right – SWIR sensing could unlock several interesting lifestyle- and health-related use cases in wearable consumer devices. Hyperspectral image showing a water stress map of a vineyard, recorded using a UAV mounted SWIR camera.[3] Hyperspectral image exhibiting the difference in mineral distribution in an open pit mine.[4]

reflectance). Similar concepts also apply to mining operations (**Figure 4** – right) where a wider adoption of high-resolution hyperspectral imaging can enable more frequent geological assessments (different minerals show varying spectral responses, here around 2200 nm), thus directing operations to areas of high value.

While these applications are based on specific molecular interactions and strong absorption of SWIR light, the other family of applications is based around transparency and reduced interactions of SWIR radiation, for example with certain types of plastics. Utilising SWIR provides visibility of features that are hidden in the visible and can enhance quality control processes in manufacturing and packaging lines. Also, due to the longer wavelengths compared to NIR and visible light, SWIR experiences less scattering by fine airborne particles, thus enabling longer range sensing/imaging in environmentally challenging conditions, caused by smog, fog or smoke. This finds use in a wide array of important areas, such as firefighting and search and rescue missions, as well as several defence applications. Based on the above, SWIR also enables improved vision capabilities in automotive applications, such as advanced driver assistance systems (ADAS), which currently rely on shorter wavelength technologies. An important wavelength for these applications is 1550 nm, as it balances longer detection ranges with improved eye safety and low solar background, as well as specific materials interactions. From a systems perspective, applications operating at 1550 nm also benefit from the widespread adoption of fibre optic communications and the established commercialisation of various optical components. While this is beyond the scope of this article, systems considerations are a driver for the success of specific applications, in particular for those requiring active illumination.

1450 and 1550 nm are key wavelengths for high volume SWIR applications

While SWIR technology has found adoption in several niche markets beyond the reach of NIR, its high cost remains a barrier to broader use. As a result, cost-effective CMOS-based NIR solutions continue to dominate many IR sensing applications. Looking ahead, significant cost reductions in SWIR sensors are expected to drive wider adoption across a range of markets. In a world driven by data, the production of low cost sensors capable of recording a wide range of spectral data could unlock a wave of exciting new applications and innovations, particularly in the consumer space. As mentioned above, areas of high interest include personal healthcare and cosmetics, where sensors could transform mobile devices into powerful, non-invasive diagnostic tools.

COMPARING SWIR IMAGE SENSING TECHNOLOGIES

SWIR sensing has been a niche area of the overall image sensor market. After entering in 2021, Sony has dominated the market for sensors, while other participants have included small vertically integrated companies developing their own sensors and cameras, as well as high end camera suppliers. Due to the absorption limit of silicon at 1100 nm, all SWIR sensors are based on the concept of combining silicon CMOS ROICs with SWIR-sensitive semiconductor materials. The most established system is based on thin layers of InGaAs, a narrow bandgap semiconductor which in its standard composition $In_{0.53}Ga_{0.47}As$ (bulk bandgap of 0.75 eV) is lattice matched to the InP substrate material it is grown on. The standard composition of InGaAs covers a spectral range up to 1700 nm and offers excellent performance with minimal defects in the lattice matched InGaAs layer.[5] While this approach yields sensors with minimal noise and record high sensitivity, fabrication of the InGaAs focal plane array is a complex and costly process requiring the use of expensive InP substrates, as well as subsequent flip-chip bonding using small columns of metal as connectors. Furthermore, there are limits in sensor resolution due to the size of the indium connectors and composition-related limits in the spectral range. The use of higher In ratios expands the absorption to the extended SWIR region up to 2500 nm, however, the increasing lattice mismatch with the InP substrate results in lower performance.

To tackle the challenges with InGaAs manufacturing, alternative narrow bandgap semiconductors have been explored. Another approach has been established by growing a SWIR sensitive layer of germanium (direct bandgap of 0.8 eV) on a silicon substrate (Ge-Si), thus negating the need for costly InP substrates.[6] While this approach lowers the manufacturing costs drastically, meeting the performance of InGaAs technology has proven to be difficult. One major obstacle for this technology is the reduction of dark current (noise), which emerges due to defects in the semiconductor as a result of imperfect lattice match at the silicon-germanium interface. Another weak point of the technology is that the spectral range is limited to 1650 nm. A comparison of the technologies is provided in **Table 1.**

QD technology combines some of the advantages of InGaAs and Ge-Si technologies. Due to the inherent scalability of solution processing methods, manufacturing costs can be reduced by at least one order of magnitude compared to InGaAs. The absence of substrate-based

Table 1: Comparison between the main SWIR sensing technologies.
*results reported for a QD sensor with peak sensitivity at 1400 nm.

Technology	InGaAs[5]	Colloidal Quantum Dots[7]	Ge-Si[6]
Spectral range	up to 1700 nm	up to 3000 nm	up to 1650 nm
Efficiency	>80% (flat)	60% (peak)*	>50%
Pixel pitch	5-15 µm	>1.6 µm*	5-15 µm
Dark current	<0.1 nA/mm^2	<2.5 nA/mm^2*	>1000 nA/mm^2
Cost	High	Low	Low
Status	Mature products	Early stage products	Early stage products
Main Markets	Machine vision, Defence, Space	Machine vision, Defence, Consumer & Automotive	Machine vision

semiconductor growth and required lattice matching also means that QD technology gives access to the full range of narrow bandgap semiconductor materials, thus expanding spectral ranges up to 3000 nm and beyond.

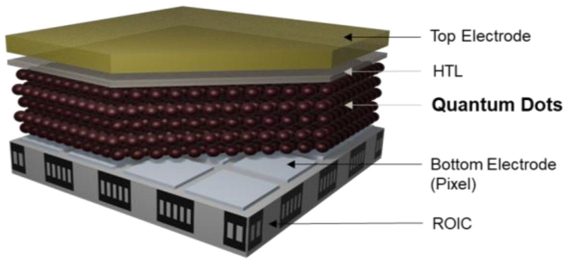

Figure 5: Schematic of a QD-CMOS image sensor stack with the necessary layers of the photodiode.

While the full range of QD materials systems for SWIR sensing will be covered in more detail in the following section, the most common materials today are PbS and InAs, both theoretically offering spectral ranges well beyond 2000 nm. In practice, the maximum spectral range of QD materials depends on fundamental characteristics of the material, such as the bulk bandgap and exciton Bohr radius, as well as more practical considerations like the ability to grow uniform nanocrystals to the required size. For example, to achieve a first excitonic absorption peak at 2000 nm for PbS, uniform growth of ~9 nm nanocrystals is required.

QD sensor fabrication is based on the deposition of a QD layer on top of a Si CMOS ROIC, either in photoconductive mode or as part of a photodiode stack (see **Figure 5**). Currently, the best devices have been demonstrated using PbS QDs, due to the material's extensive history of development. In 2021, STMicroelectronics reported a QD global shutter sensor at 1400 nm with peak external quantum efficiencies of 60% and dark currents of less than 2.5 nA/mm^2 (2V, 60 °C).[7] Furthermore, these results were reported on a wafer level platform with a 1.62 µm pixel size, highlighting the potential of this technology for mass manufacturing and device miniaturisation. While sensor performance data has clearly demonstrated the potential of QD SWIR sensing, the technology still requires optimisation, particularly for applications demanding higher resilience to elevated temperatures. To address this, Nanoco is developing the next generation of materials (III-V QDs) with the goal to meet the high performance benchmarks of PbS QD devices and improve the stability.

QD-CMOS is a high performance, low cost alternative to incumbent InGaAs technology

The rising interest in III-V materials was recently confirmed by Sony publishing its first results on the development of InAs QD SWIR sensors with a spectral range covering close to 1600 nm (peak at 1450 nm).[8] The paper demonstrated a clear path forward for these devices and showed wafer level processing with high uniformity, highlighting the technology's advantage in low cost and high volume manufacturing. This combination of high performance and low cost will drive technology adoption in a set of new markets, ranging from consumer electronics to automotive, where SWIR sensing offers key advantages over visible and NIR sensing, as discussed in the previous section. While QD-CMOS technology is unlikely to replace InGaAs in some of the high-end industrial, defence and space applications, it is still poised to impact these markets by enabling new applications where the high cost of InGaAs technology has previously been prohibitive.

QUANTUM DOT SWIR MATERIALS

All QD materials being developed in this area are narrow bandgap semiconductors, enabling the ability to shift the first excitonic absorption peak from the NIR for small nanocrystals to the far end of the SWIR, with some materials even reaching the MWIR (>3000 nm).

Lead sulphide (PbS) has been the dominant material in this field due to a combination of its narrow bandgap and available precursor chemistry, facilitating growth of high quality nanocrystals. Prior to commercial development, the material was studied for two decades in academia with early reports of PbS photodetectors dating back to 2005.[9] Today, PbS QDs can be found in a range of commercial

Table 2: Comparison of materials properties for Nanoco's HEATWAVE® QDs, relevant for SWIR sensing.

Material	Bulk Bandgap (eV)	Current absorption range (nm)	Bulk e$^-$ mobility (cm^2/Vs)	RoHS	Status at Nanoco
PbS	0.41	800-1800	600	Restricted	**Commercial production**
InAs	0.35	800-1800	≤ 40 000	Compliant	**Pilot production**
InSb	0.17	800-1600	≤ 77 000	Compliant	**Ready for sampling**

image sensor and camera products with spectral ranges covering up to 2000 nm, while further expansion of the spectral range up to 2500 nm is expected soon. At Nanoco, PbS QDs have reached full commercial maturity, producing nanocrystals of very high shape and size uniformity at commercial scale (see **Figure 6**). Uniformity is a critical parameter for image sensor applications, as uniformly shaped nanocrystals form more densely packed layers with improved absorption at the target wavelength. Further, good nanocrystal uniformity reduces the number of energy barriers that can hinder efficient charge transport and provides a more controlled environment for effective chemical passivation of surface defects, thus enabling the fabrication of high performance SWIR sensing devices.

While PbS is currently the most mature system, several other materials are in development for SWIR sensing applications, including mercury telluride (HgTe) and silver telluride (Ag_2Te), as well as the III-V materials indium arsenide (InAs) and indium antimonide (InSb). At Nanoco, we have focussed on the development of RoHS compliant III-V materials due to their unique combination of very high electron mobilities, low permittivity and more covalent nature – see **Table 2**. Translating these characteristics to device properties, these materials promise SWIR sensors with nanosecond response times, as well as improved temperature stability, thus giving access to a broader range of applications and markets.

To improve lead-free device performance, we have developed unique synthesis methods based on Nanoco's proprietary molecular seeding technology for the fabrication of high quality InAs and InSb QDs (see **Figure 7**).[10] InAs is the more mature system today, where we have achieved uniform nanocrystal growth up to 1800 nm,

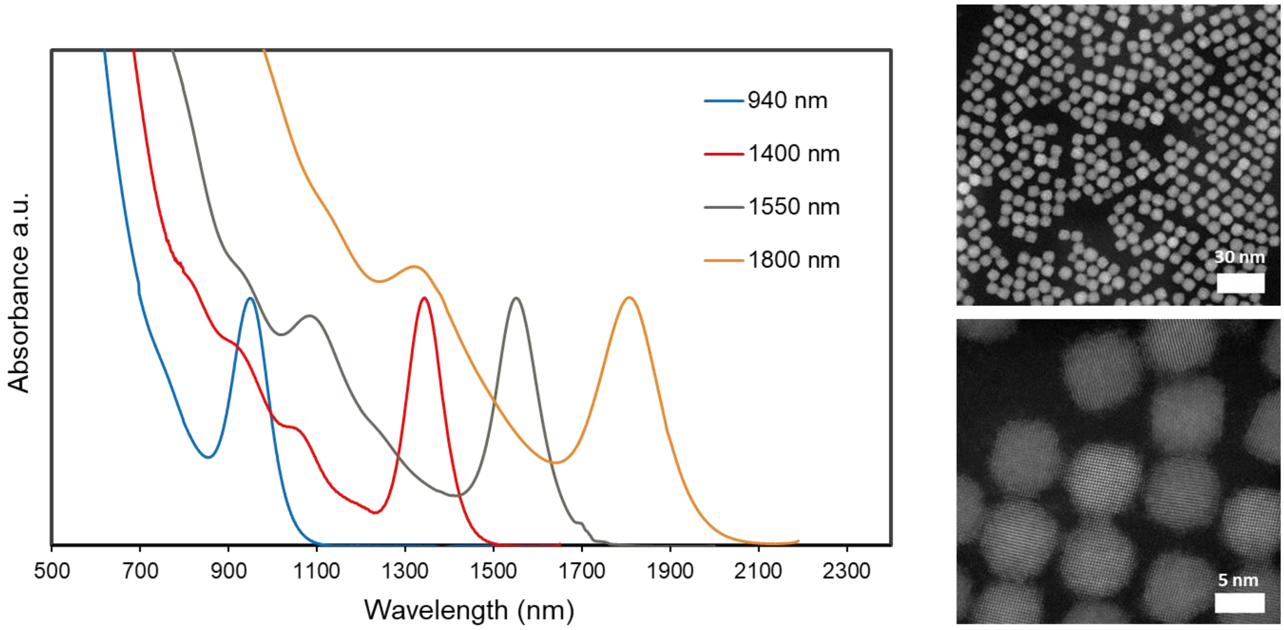

Figure 6: Absorption spectra and TEM images of commercial HEATWAVE® PbS QDs. TEM images show very uniform nanocrystals of around 8 nm in size, corresponding to a first absorption peak at 1800 nm.

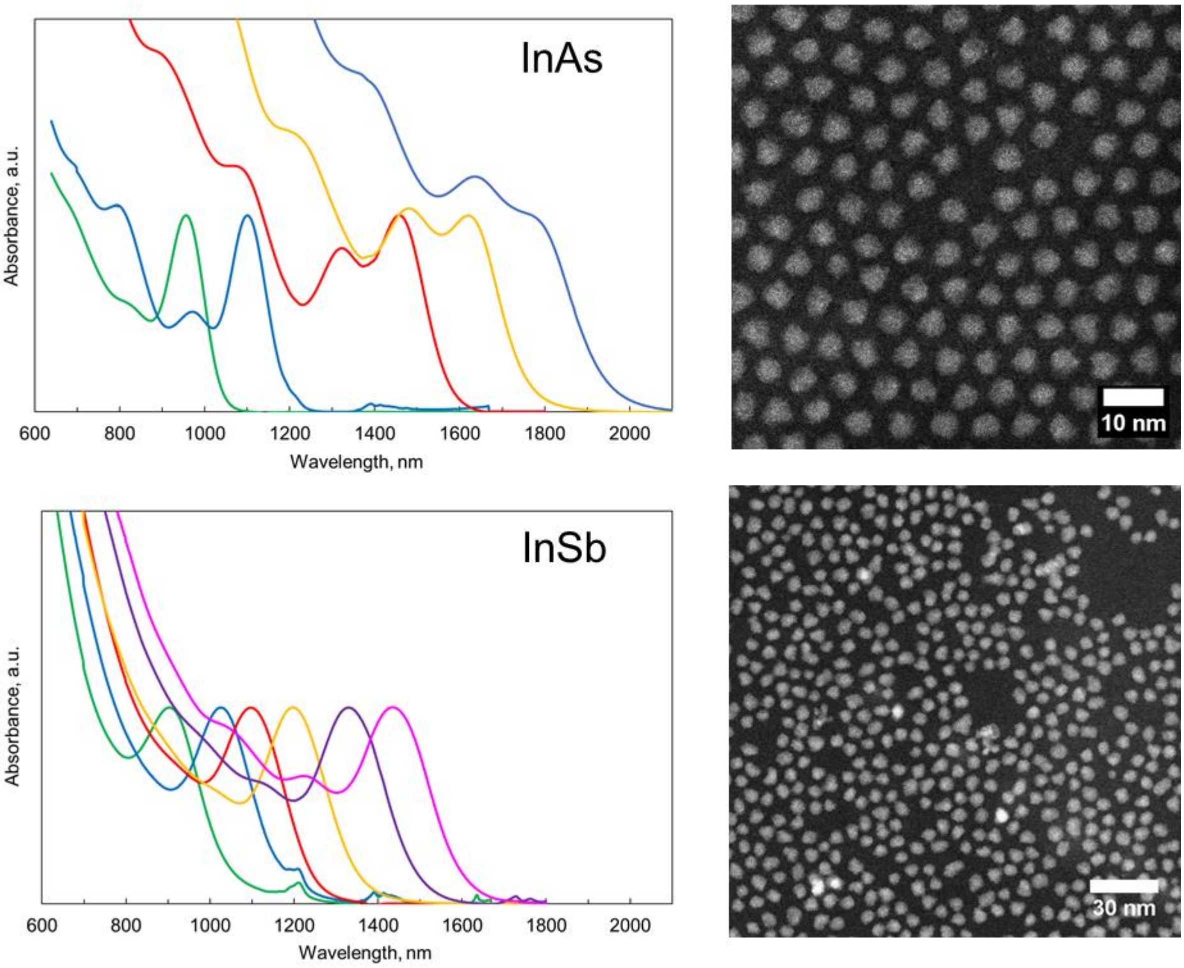

Figure 7: Absorption spectra for various sizes of HEATWAVE® InAs and InSb QDs, all showing defined excitonic absorption features, indicating uniform ensembles of nanocrystals. The TEM images confirm the high quality for both InAs (top – 1100 nm) and InSb (bottom – 1400 nm) QDs.

covering the key wavelength ranges of around 1450 nm and 1550 nm. Best in class size and shape uniformity is demonstrated by the very narrow half-width at half-max of the first excitonic absorption peak, as well as the well resolved higher order excitonic absorption features. For InSb, we have achieved breakthrough results, seeing well defined first absorption peaks well beyond 1400 nm – a key indicator for uniform size distributions. Given the material's narrow bandgap, we see further opportunities to target longer wavelengths up to 3000 nm, offering a unique materials solution for this spectral range, free of restricted heavy metals.

Nanoco is ready to supply high volumes of electronic-grade QD SWIR materials

Nanoco is the leading provider of electronic-grade QD SWIR materials, with our high-quality HEATWAVE® QD portfolio ready for seamless integration into semiconductor fabrication environments. Backed by deep expertise spanning early-stage materials development through to scale-up and commercial production, we deliver support across the full materials lifecycle. Our commitment to excellence is reflected in our ISO 9001 and 14001 certifications, ensuring the highest quality standards throughout. We are excited about the future of this technology and, together with our valued partners, are working to expand its reach across a wide range of applications and markets.

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