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Organ of Spectaris,
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Low Light Leading to Enlightenment

THERMOELECTRICALLY COOLED INDIUM GALLIUM ARSENIDE OR MERCURY CADMIUM TELLURIDE AREA SENSORS APPLIED IN SWIR CAMERAS

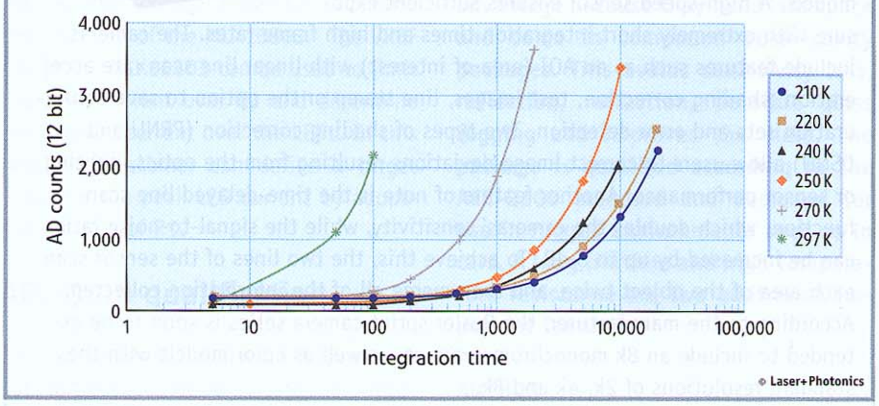
The spectrum of low-level photon emissions caused by semiconductor crystal lattice defects matches exactly the most sensitive realm of SWIR cameras fitted with thermoelectrically cooled InGaAs- or HgCdTe area sensors. Such sensors are therefore well suited for failure analysis and quality assurance tasks in semiconductor manufacturing. The positive results of these procedures can be successfully migrated to the economical characterization of nano-technology devices.

RAF VANDERSMISSEN

All chip manufacturers aim for highest possible yields to meet ever tighter cost constraints. As a precondition, any imaginable source of failure must be uncovered already in the design phase, during pilot processing as well as in volume manufacturing. This includes barely noticeable process irregularities that later-on could cause a functional failure of the application. An examination of components failed during operation will yield valuable information about the production site's process stability and the success of quality assurance measures.

Crystal defects in semiconductor structures expose themselves by weak emissions in the short-wave infrared (SWIR) which deviate from the regular pattern. This makes modern, highly sensitive SWIR cameras well suited for quick and unambiguous defect localization. The procedure is known as photon emission microscopy (PEM). As a novel material examination methodology, PEM yields such encouraging results that it has conquered the material

Dark current vs. time



1 **Cooling the sensor reduces dark current and increases sensitivity through extended integration time (f. e. up to 20 sec with a XEVA 1.7 320 TE3).**

sciences and is now widely used in the characterization of nano materials.

Photon emission microscopy

Photon emission microscopy is a relatively new fault analysis technique to uncover crystal defects. PEM utilizes the light of various wavelengths that is emitted primarily by the carrier recombination mechanism during operation [1]. These luminescence effects, however, are so weak that their intensity levels are below the threshold of the human eye even when adapted to low ambient light.

Accordingly, photon emission microscopy has to deploy powerful image amplification techniques to raise the low luminescence levels emanating from photon-emitting defects to a securely provable level. The resulting radiation image is superimposed to a photomicrograph of the chip surface under examination. This way, the locus of tell-tale defect emissions can be unambiguously matched to a defined chip location. The procedure requires just a sensitive infrared camera and a computer.

The sensitivity of an infrared camera can be significantly improved by cooling its image capture chips. **Figure 1** shows how the dark current of a typical SWIR image sensor in InGaAs technology accumulates at various sensor temperatures. This reveals already at first glance that cooling by 30 K will allow a tenfold increase of the integration time, at the same error level. F. e. integration times of up to 20 s can be used with a ›Xeva 1.7 320 TE3‹. After pinpointing the defect location there are procedures to uncover the physical anomaly that caused the light emission deviating from the regular pattern.

1. Fault validation
2. Defect localization
3. Sample preparation
4. Defect characterization
5. Analysis of root causes

A The five steps of failure analysis

Targeted failure analysis

Targeted failure analysis as applied in microelectronics is usually carried out in a five-step sequence (**Table A**): First is fault validation, followed by localizing the defect as accurately as possible. Then the defect location is prepared and traced for analysis; the nature of the defect is determined and, finally, an investigation of its root causes is initiated. The crucial step in this sequence is defect localization. The more accurately this is done, the less is to be spent in the subsequent examination procedure.

There are active and passive procedures for fault characterization and defect localization. Photon emission microscopy is a passive technique because it works without external stimulation, for instance by a laser source. PEM is often complemented by photon emission spectroscopy (PES) if defect location and also the emitted spectrum, especially the infrared spectrum, are of importance.

The short-wave infrared is of special interest in the case of examining silicon semiconductors, because their bandgap energy of 1.12 eV between conducting and valence bands, which is of crucial importance for the recombination mechanism, equals a recombination emission wavelength of around 1107 nm.

Photon emission is generally produced by a forward or reverse biased pn junction, a transistor in saturation or by dielectric breakdown. Depending on the stimulation mechanism of the charge carriers involved, the emission spectrum can be fairly wide.

At present, semiconductor devices are of a flat structure, which permits examination via SWIR radiation from both sides, front or back. But the growing number of metallization layers complicates examination from the front because they act as a photon shields. Fortunately, silicon at low doping levels is relatively transparent to SWIR light. Thus, backside examination is the favorable option. In case the material is highly doped the substrate can be thinned.

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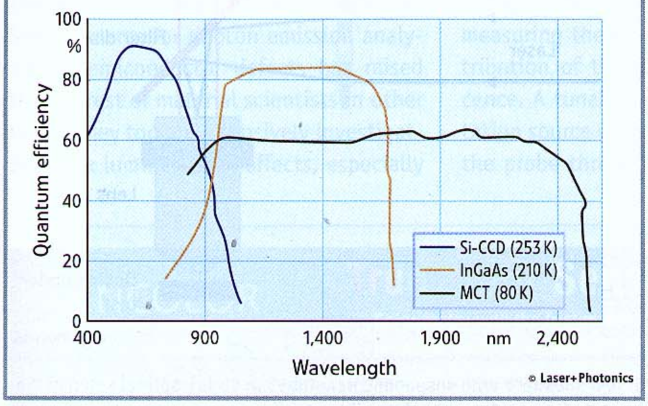
Spectrum sensitivity of utmost importance

The recombination radiation used to localize defects covers a spectral area that is defined by the silicon bandgap wavelength. But it tends to be shifted to

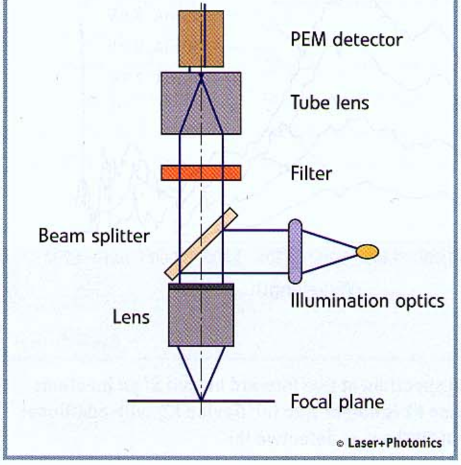
▶

Comparing quantum efficiencies



2 **Smooth quantum efficiency curve of various sensor arrays covers a wide spectral range**

Photon emission microscope



3 **Structure of a versatile photon emission microscope fitted with illumination unit**

larger wavelengths by low-energy transitions between the conduction and valence bands. Accordingly, the sensor must cover this spectral area as well. Qualifying sensor materials are shown in **Figure 2**, based on the quantum efficiency of silicon CCD sensors, as well as InGaAs- and HgCdTe-based imaging systems. Silicon appears not to be suited because it can't really catch the recombination radiation. Significantly better are InGaAs camera chips having a usable spectrum area from 900 to 1700 nm, and MCT (Mercury Cadmim Telluride, HgCdTe) imagers reaching from 850 to 2500 nm. **Table B** lists key data of SWIR cameras fitted with these two sensor types. Multi-stage Peltier cooling to 200 K will significantly lower noise levels and raise sensitivity.

Type	XEVA-FPA-1.7-320		XEVA-FPA-2.5-320
Technology	InGaAs		HgCdTe
Spectral range	900 to 1700 nm		850 to 2500 nm
Resolution	320 x 256 in 30 μm grid		
Quantum efficiency	80 %		
Cooling	3-stage Peltier to 210 K at 293 K ambient temperature		4-stage Peltier to 200 K
Dark current at 210 K	6250 electrons per second and pixel		
Shutter	Snapshot integration		
Operational modes	High amplification	Low amplification	
- Linear drive range (full well capacity)	1,87 x 10^5 e^-	3,75 x 10^6 e^-	1,39 x 10^6 e^-
- Dark noise	150 e^-	1100 e^-	
- Dynamics	60 dB	66 dB	69 dB
- Integration time	1 μs to 20 s	1 μs to 400 s	100 μs to 20 ms

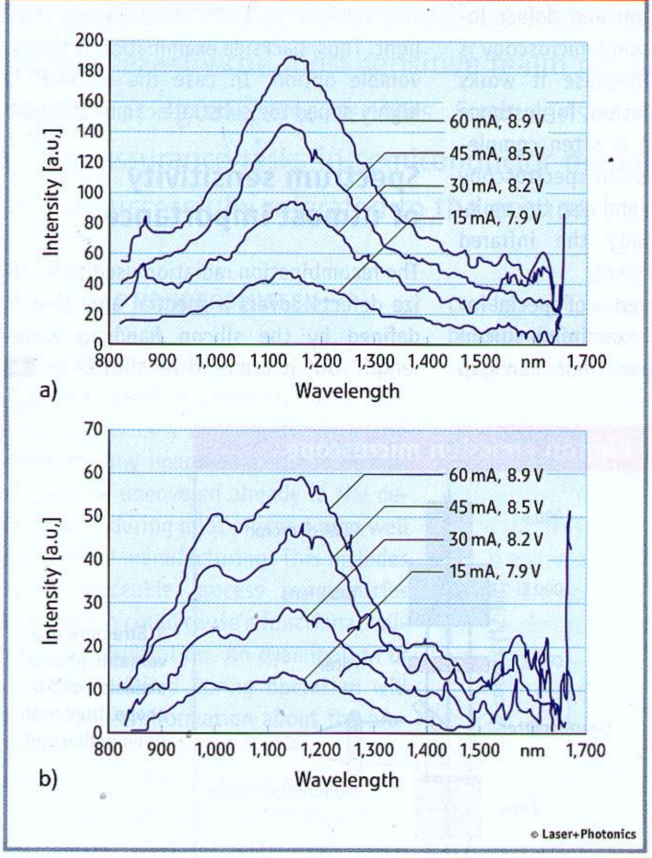
B Key data of SWIR sensors especially suited for low-light appliations

Photon emission microscopy

Figure 3 shows the optical configuration of a versatile photon emission microscope. After removing the filter and beam splitter it can be used for just proving suspicious emissions. Alternatively, it can be used to overlay the radiation image and chip surface to better facilitate the localization of defects. This configuration can be expanded into a spectroscope by substituting beam splitter and filter by an appropriate dispersive element (basically also a filter). Spectral analysis of photon emissions promises to yield much more detailed information – because every defect has its own spectral signature. Most SWIR cameras are already prepared for this task by offering a C-mount and mounting holes for a spectrometer.

How accurately an SWIR spectrum analysis of photon emission can uncover

Emission spectrum: Si pn junctions



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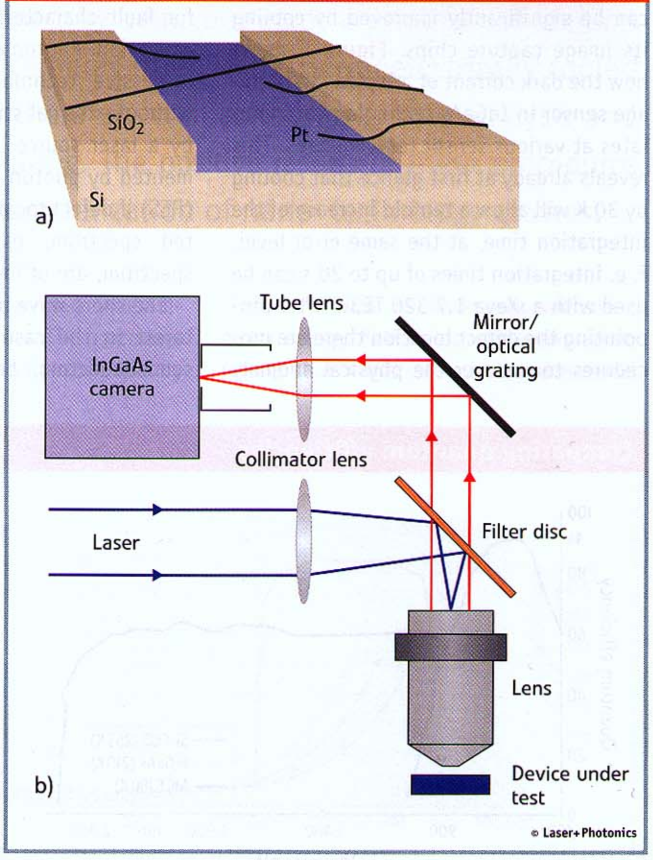
4 The photon emission spectrum of two forward biased Si pn junctions uncovers defects. Device #1 is defect-free (a); Device #2, with additional strong radiation peak at 1000 nm, is defective (b)

Application: Carbon nanotubes



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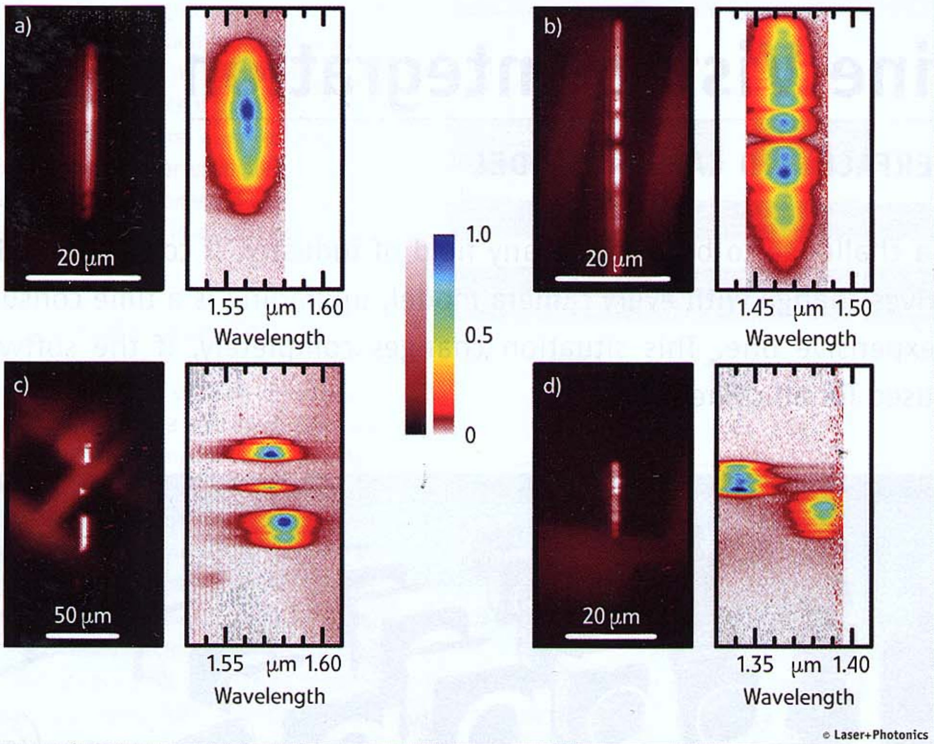
5 Test substrate with suspended nanotubes in air (a); optical setup of the test structure with tunable laser (b)

Nanotubes: Spectral images



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6 **Spectroscopic examination using a sensitive SWIR camera enables unambiguous carbon nanotube classification**

typical defects is shown in **Figure 4** for a reverse biased pn junction. Both test objects clearly exhibit the broad emission maximum related to the band gap energy. ›Device #2‹ additionally exhibits a significant second peak around 1000 nm. This additional radiation may be caused by a local disturbance of the electrical field, and it is sufficient cause for a more detailed examination to optimize the manufacturing process towards highest possible quality.

Migration to nano technologies

The successful use of highly sensitive SWIR cameras for photon emission analysis of semiconductor defects has raised the interest of material scientists in other fields. They too are intensively investigating weak luminescence effects, especially photoluminescence. As an active analysis procedure, photoluminescence imaging excitates the probe through laser radiation. This can be used in the identification and classification of carbon nanotubes [2] with the aim of optimizing their manufacturing processes in terms of specifically desired properties.

Carbon nanotubes are formed by chemical vapor deposition (CVD). A silicon substrate patterned with minute trenches partly filled with thermal silicon dioxide serves as a carrier for the examination (**Figure 5a**). The carbon nanotubes to be examined are suspended in air across the trenches.

Figure 5b shows the optical setup for measuring the intensity and spectral distribution of the observed photoluminescence. A tunable laser serves as the excitation source whose energy is guided onto the probe through a filter disk and lens. The ensuing photoluminescence reaches the NIR camera through the upper mirror. As an alternative, a grating can be used.

This setup has delivered three-dimensional spectral images with a vertical axis and an orthogonal spectrum axis (**Figure 6**). Examination of 30 samples yielded the four classes of spectral and intensity distributions shown. On the left hand side are two-dimensional images of the nanotubes indicating the intensity distribution of the photoluminescence. To the right are their three-dimensional spectra. ■

Summary: SWIR cameras support nano technology

Such images can depict the interactions between the nanotubes themselves and with the substrate. This procedure yields unambiguous and reproducible results for a technical implementation. Highly sensitive and user-friendly SWIR cameras have paved the way for this very productive technique.

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