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# Effective quality sorting of crystalline wafers

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# Effective quality sorting of as-cut multicrystalline and cast-mono wafers using an in-line PL imaging system

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## ABSTRACT

Improvements in quality and efficiency as well as in cell-line yield rely on the in-line measurement of critical parameters. Physical metrics – such as cracks, chips and thickness – as well as electrical resistivity are common criteria for the sorting of under-performing wafers. A new method of in-line photoluminescence (PL) imaging enables wafer performance to be assessed in an early production step by measuring crystal defects and impurities, which are key parameters in determining the achievable cell efficiency.

### Introduction

Productivity and quality improvement of multicrystalline (mc) or cast-mono solar cell production is dependent on the in-line measurement of crucial parameters as early as possible in the production flow. Typical failures and defects are:

- Mechanical failures, such as breakage, chipping and (μ-) cracks
- Doping concentration failings (inhomogeneity)
- Crystallization defects, such as dislocations and grain boundaries
- Impurities, mainly iron

Actual operating cell production lines (mc or cast-mono) mainly qualify and sort the incoming wafers by physical parameters, such as geometry, saw marks, thickness, μ-cracks and chips. These parameters have an influence on the uptime (breakage rate): sorting out, for example, μ-cracked wafers prevents wafer loss in the downstream handling step and downtime for the necessary maintenance or cleaning.

The electrical parameters resistivity and lifetime are sometimes measured, even though these physical measurements do not influence efficiency. While they could yield valuable information about the wafer quality and achievable efficiency, they have specific shortcomings. Resistivity measurements (after calibration by the wafer thickness) give only information about the minority-carrier concentration. Lifetime measurement of the bare wafer is mainly influenced by the surface recombination. Because of its large measurement area there is not enough spatial resolution for resolving, for example, thin dislocation lines.

The photoluminescence (PL) intensity $\Phi$ is known to be proportional to the doping concentration and the bulk lifetime, i.e. $\Phi \sim N \cdot \tau$. Since both these parameters have a significant effect on the achievable efficiency of the finished cell, it is clear that the PL intensity can provide a good prediction of the cell efficiency; this has been confirmed by various authors, for example Haunschild [1], Johnston [2] and True & Stavrides [3]. The main reasons for the reduced PL intensity are dislocations (i.e. irregularities in the crystal structure) and impurities (e.g. iron originating from an impure coating of a crucible).

### PL imaging

The measurement of photoluminescence is a technology that was first used in the 1970s, when strong laser sources became available. It was extensively employed for characterizing the band gap and carrier lifetime of semiconductor materials. When CCD cameras became available at the end of the last century, imaging of the PL signal was also implemented, for example in the biomedical sciences. Over the last few years, high-sensitivity CCD cameras, together with good homogenized laser illumination, have allowed PL imaging of as-cut wafers with cycle times that meet state-of-the-art throughputs (3600 wafers/hour). From the end of 2012 Hennecke Systems offered a fully automated wafer sorter with a modular PL measurement station, as well as a PL inspection unit as an upgrade to existing wafer sorters.

For a full understanding of the PL effect in the doped silicon wafer, a good knowledge of solid-state physics is necessary. A *simplified model* will be presented here which explains the most important principles.

When illuminated with light, a material can absorb it, and a photon can then excite an electron from the valence band to the conduction band. Since the semiconductor has a band gap, which is a forbidden energetic zone, it is logical that the energy of the photon has to be greater than the gap energy $E_g$. The reverse process, so-called 'recombination', is possible, whereby the electron returns to a lower energy state of the valence band. The remaining energy is converted into a photon again, which creates the PL light, but of a very weak relative intensity.

The reason for this phenomenon can be found in physics. Silicon is referred to as an 'indirect band gap material', which means that changes in energy state from the conduction band to the valence band can only happen when a momentum is transferred, which is in fact an oscillation in the crystal and called a 'phonon' (Fig. 1). The excitation to the conduction band is not difficult, since a phonon can be generated. The reverse process to the valence band, however, needs a suitable phonon (which is not very likely) in order for it to happen. This is the reason why PL imaging systems need sensitive cameras and strong laser light sources.

After excitation, there are other possible ways for recombination to occur. In crystal defects – such as dislocations and grain boundaries – recombination takes place without radiation, so there is no PL light emitted. If the PL image has sufficient spatial resolution, dark lines at the crystal dislocations can be identified.

One other important influence on the PL radiation is that of impurities. For example, interstitial iron atoms change the energy pattern, as they present a distribution of energy states in the band gap region. This allows the emitted PL light to have a lower energy than the band gap $E_g$ (Fig. 2).

There will be PL light, but with a different, and thus longer, wavelength. As the imaging system cannot detect this wavelength, local regions with impurities will appear darker. This effect is mainly seen in the corner or edge regions of the wafers, where iron impurities are located (Fig. 3).

Wafer quality can be evaluated after image processing to obtain the *wafer-quality metrics*:

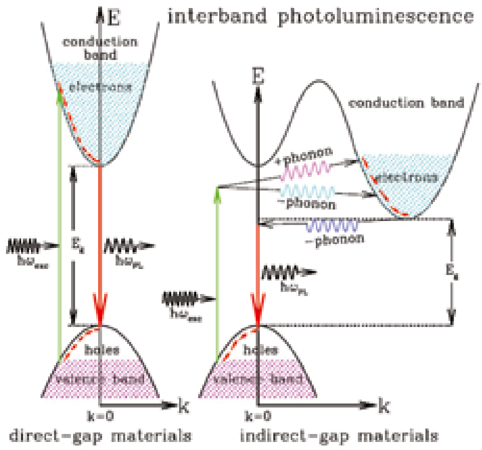


*Figure 1. Band structure of direct and indirect band gap materials.*

- Average PL intensity
- Number of crystal boundaries
- Number of dislocations or dislocation clusters
- Impurity areas

Each of these metrics will have the effect of reducing the maximum achievable cell efficiency. A reduction in efficiency of finished cells has been studied and documented by several authors, for example Haunschild [1] and True & Stavrides [3]. By combining the wafer-quality metrics, a predicted efficiency can be calculated, which is known to have good

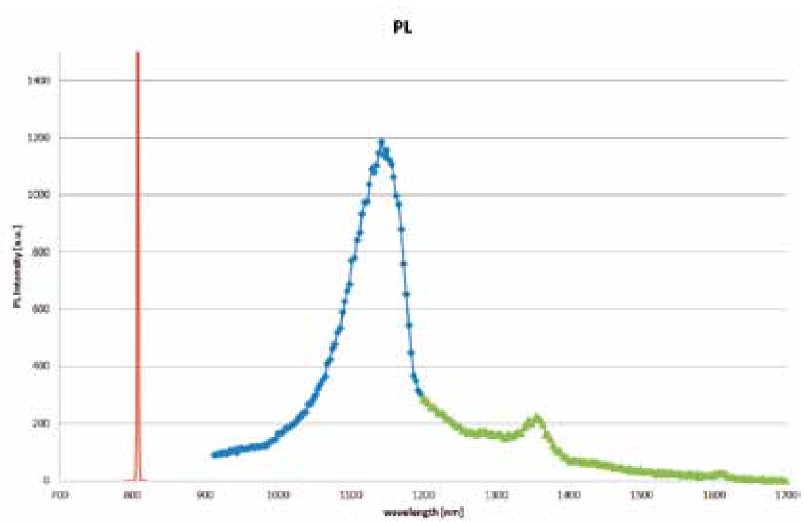


*Figure 2. Spectrum of PL radiation: red = illuminating laser wavelength, blue = normal PL from band–band recombination, and green = PL light from band–defect recombination.*

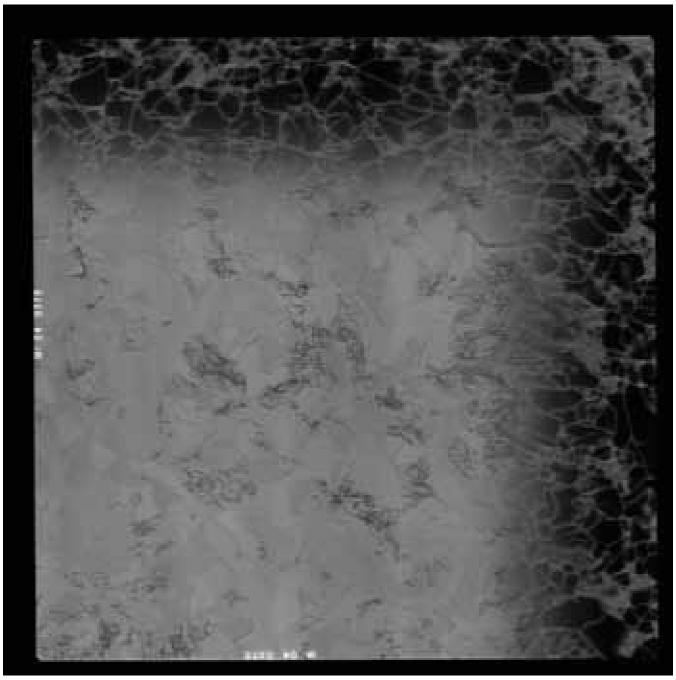

*Figure 3. Impurities in this corner brick result in the dark areas seen here in the upper and right sides of the wafer. Dislocations result in dark lines.*

correlation with the achievable wafer efficiency (Fig. 4).

## Instrument set-up

The technical realization of a PL imaging system which can be used for in-line inspection is in principle quite simple, but many system components require advanced technology. The wafer surface is illuminated with a laser light source in the location where the PL light is generated. In order to block the diffracted laser light and only allow the higher wavelength PL light to pass into the camera, a high-pass filter is employed (Fig. 5). A CCD camera monitors the wafer plane.

To obtain high-resolution images and a short- and long-term stable assessment of the wafers, it is important not to neglect some critical aspects of the set-up. The stability of the laser light places certain demands on the cooling system. Furthermore, the illuminating optics have to be homogeneous and eventually corrected by baseline

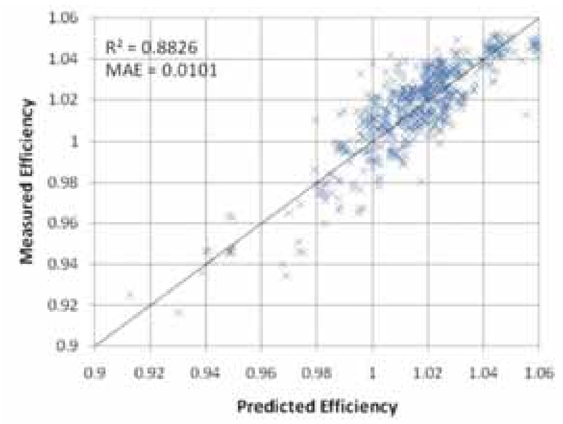


*Figure 4. Correlation of the predicted efficiency and the measured efficiency [3].*

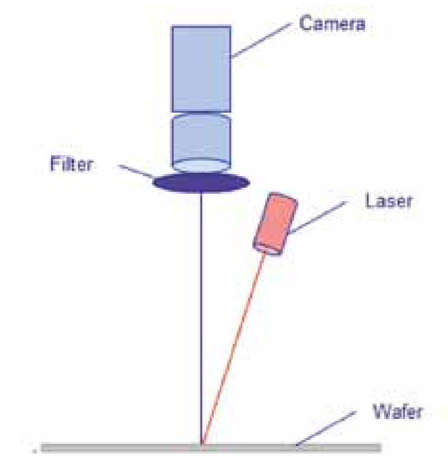


*Figure 5. PL imaging system principle.*

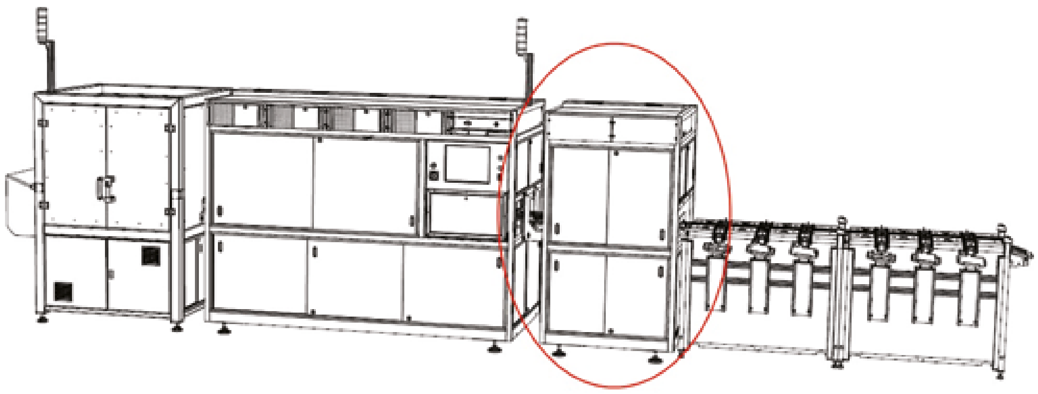

*Figure 6. Hennecke Systems PL imaging module integrated in a Hennecke Systems wafer inspection system.*

methods. The filter combination needs to have the property of high dynamic suppression in order to ensure that the laser light is sufficiently eliminated. The imaging optics should be designed for the near-infrared (NIR) range, which is chosen for optimal image contrast. The camera must be state of the art and of a high sensitivity with a low noise level.

The following guidelines are recommended for comparing PL systems:

- Upgrade possibilities of the existing wafer sorter
- Integration in a standard wafer inspection tool, such as recipe handling, sorting and MES (Fig. 6)
- Image size: 1 megapixel PL images are state of the art
- Image resolution, i.e. sharpness of dislocation lines
- Image contrast, i.e. clearness of local structures
- Noise level in the images
- Throughput: can the system meet current production rates, for example 3600 wafers/hour
- Maintenance needs
- Laser safety
- System repeatability
- System reproducibility

## Some examples of PL image features

### Crystal boundaries

Impurities located in crystal boundaries reduce the band gap and lower the PL intensity. The density of crystal boundaries is reported to have a negative impact on cell efficiency, as it creates 'barriers' through which electrons cannot pass. A PL imaging system with high resolution and good contrast can detect crystal boundaries as dark lines (Fig. 7). For the detection of grain boundaries in particular, a low-noise image

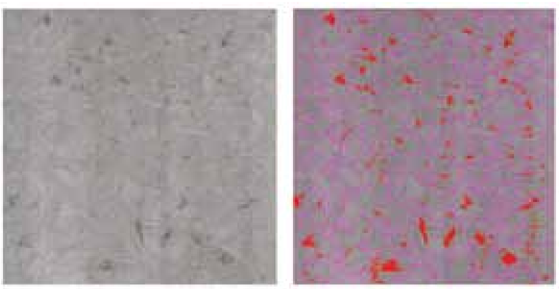

*Figure 7. Automatic evaluation of crystal boundaries and dislocations (in the right-hand image, purple = grain boundaries with low lifetimes, and red = dislocation clusters).*

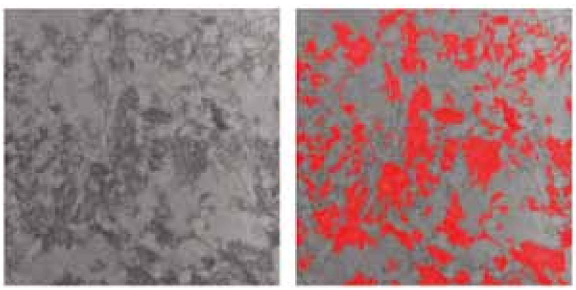

*Figure 8. Automatic evaluation of dislocation clusters, appearing as dark regions (left) and red regions (right).*

*Figure 9. An obviously well-grown mono-cast wafer without any visually apparent crystal borders (left) may still contain lots of dislocations, visible in the PL image (right).*

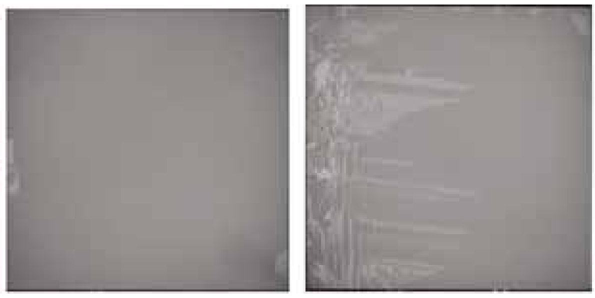

*Figure 10. Visual images of a cast-mono wafer with high mono-fraction (left) and low mono-fraction (right).*

is necessary. The number of boundaries can be calculated by image processing and serves as a metric for the wafer quality.

### Dislocations

Dislocations reduce the lifetime and have a similar effect on cell efficiency to that of crystal boundaries. In dislocations, the neighbouring crystals have the same orientations, but are somewhat shifted. By eye, only the crystal orientations can be observed, and zones with high dislocation density cannot be detected. PL is the only method that can detect these areas, which are very often small (Fig. 8). The number of dislocations – as with grain boundaries – is a metric for wafer quality.

## Cast-mono wafers

**Dislocations**

Cast-mono wafers were reported to be one of the most important trends in c-Si manufacturing during 2012. (Many names are used to describe this type of wafer: mono-poly, MLM (mono-like-multi), cast-mono, quasi-mono and near-mono; cast-mono will be used in this paper.) Although, visually, cast-mono wafers may look like perfect mono wafers, they may be very different in reality. Even if the crystal orientation is the same over the entire wafer, there might be a high density of dislocations. These dislocations are the major reason why the efficiency of cast-mono wafers rarely reaches that of true mono wafers.

PL imaging provides the *only* way of detecting this failing (Fig. 9). For cast-mono wafer producers, PL imaging therefore offers a new way to optimize the casting parameters with the aim of achieving better quality. Sorting out of such wafers with a high number of dislocations, according to defined levels, allows

- an early recycling of poorly performing wafers;
- the feeding of high-performance (and perhaps more costly) process lines with only suitably performing wafers.

**Fraction of monocrystalline area**

For cast-mono wafers there are still regions of multicrystalline structures which can, to a certain extent, spread over the wafer surface. The optimum, of course, would be a 100% monocrystalline area. Moreover, an alkaline texturing process will be best for this material, as it delivers an absolute efficiency improvement of around 0.5%. But, when the mono-fraction is lower, this gain is lost and the wafer is better processed by iso-texturing.

Since the PL image does not resolve the crystals, both visual and PL techniques are necessary for inspecting cast-mono wafers: visual for estimating the mono-fraction in order to decide the texturing process (Fig. 10), and PL for assessing the dislocations in order to decide the production quality level, or even whether or not to recycle the wafer.

### Impurities

Impurities are a common evil in polycrystalline wafers. The main impurity found in the wafers is iron (Fe), which diffuses from the crucible. The bricks near the edge of the ingot are

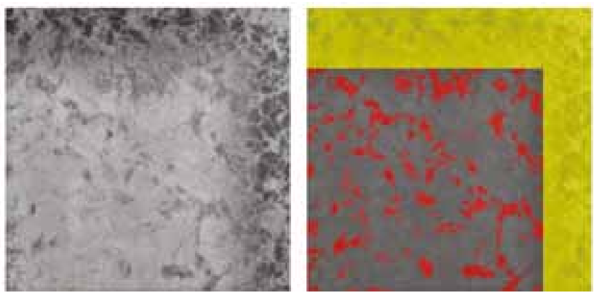

*Figure 11. Automatic evaluation of the fraction of impurities, shown here at the corner of the wafer as dark regions along the top and right sides (in the right-hand image, yellow = impurity region, and red = dislocation clusters).*

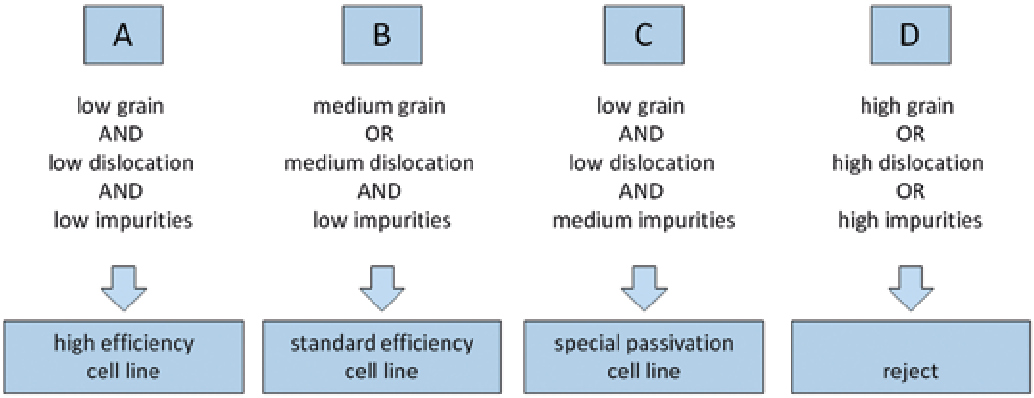


*Figure 12. Wafer sorting strategies based on quality metrics.*

*Figure 13. Manual loading and automatic sorting PL image inspection (Hennecke Systems GmbH).*

*Figure 14. PL imaging module with stack loading and automatic sorting (Hennecke Systems GmbH).*

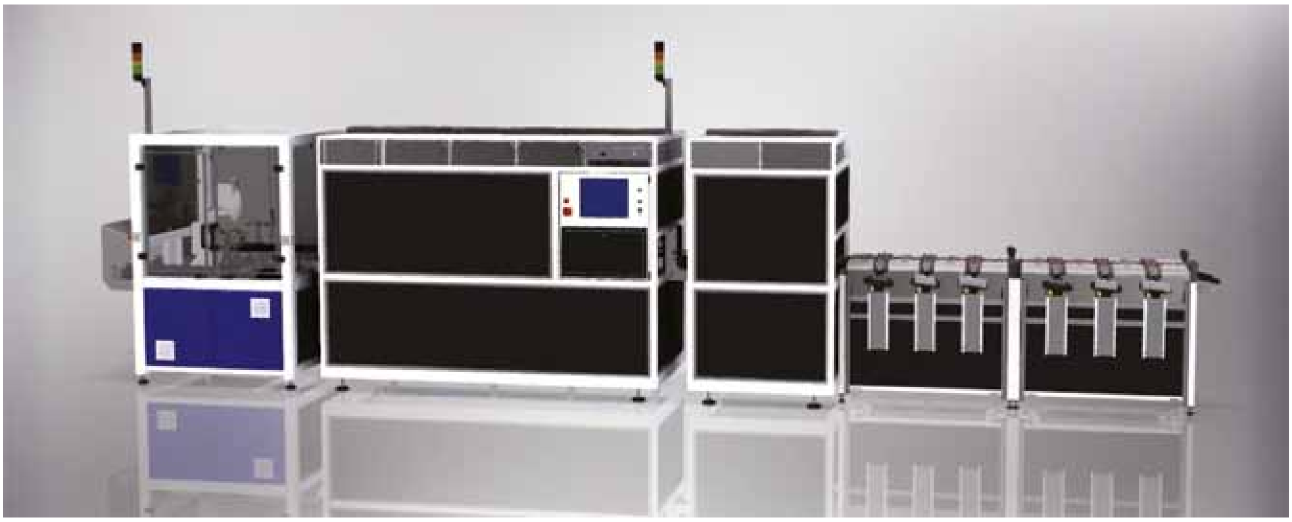

*Figure 15. PL imaging module integrated with the He-WI-04 inspection system (Hennecke Systems GmbH).*

most commonly affected, although the wafers at the top or bottom of the brick can also suffer from impurities. Iron is very detrimental to cell efficiency, as it reduces the band gap. Impurities do not behave the same in every cell line, and the effect on efficiency depends mainly on the passivation process. Although efficiency in a very robust cell line producing standard cells might only be affected to a very small degree, the impact on a high-efficiency cell line might be significantly greater.

## Wafer sorting

Sorting can be carried out not only according to crystal boundaries, dislocation density and impurities, but also on the basis of the forecast efficiency of the future cell. The simplest method of sorting is to sort out the bad wafers (quality D in Fig. 12). It may be economically beneficial to recycle these wafers, but this has to be determined by weighing the processing cost against the wafer cost, predicted efficiency and market price.

For cell producers who operate different quality production lines, a more complex sorting strategy makes sense (Fig. 12). Feeding only the best wafers (quality A) into the high-efficiency lines will increase output. Wafers with medium drains or dislocations (quality B) can then be fed into the standard lines, while wafers with impurities (quality C) can be diverted to a special treatment production line which can handle the impurities.

## Conclusion

In-line PL imaging is a recently developed technique for inspecting as-cut wafers. It offers the benefit of quality assessment on the basis of wafer-quality metrics (dislocations, grain boundaries, impurities), all of which have a direct influence on predicted efficiency. Current PL imaging systems integrate well with wafer sorters and are able to apply a range of sorting strategies. The design of laser illumination and camera systems enables the realization of high cycle times, low noise levels and adequate sharpness, which are necessary for image processing.

## References

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