Where are high sensitivity cameras needed?

Fig. 1 shows application fields where high sensitivity cameras are needed. High sensitivity cameras are useful in fields where lighting is not available or is inadequate or when sharper images are needed, etc.

<table>
<thead>
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<th>Fields where no lighting is available</th>
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<td>• Fluorescence/luminescence observation</td>
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<td>• Luminous body and scintillator observation</td>
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<td>• Astronomical observation</td>
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<td>• Spectrometer readout</td>
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<td>• Electric discharge observation</td>
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<th>Fields where lighting is inadequate</th>
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<td>• Monochromatic wavelength observation using interference filter</td>
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<td>• Fluorescence observation by laser excitation</td>
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<td>• Observation of biological cells</td>
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<td>• Nighttime surveillance</td>
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<th>Fields where sharper images are needed</th>
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<tr>
<td>• Observation of low contrast objects</td>
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<td>• High precision measurements</td>
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Fig. 1  Application fields using high sensitivity cameras

What is a high sensitivity camera?

Though there is no particular definition, cameras that can acquire images of dark objects impossible for ordinary cameras to capture are usually referred to as high sensitivity cameras. These are special cameras that reveal images even in locations where an ordinary camera is useless because of inadequate light. Cameras using image intensifiers are a typical example of a high sensitivity camera. What might remain fresh in your memory is TV news images of nighttime scenes such as of the Iraq war where green-colored images are often shown. These exclusively green images were captured using a camera having an image intensifier.
Here let’s take a quick review of some basic camera knowledge. Information on position and intensity of light entering the camera is converted to electrical signals and output as video signals. To complete this process, a photovoltaic converter is first of all used to convert the light into electrons. This photovoltaic conversion efficiency is usually called “quantum efficiency” (QE) and expressed in percentage. Some caution is needed here because the photovoltaic conversion efficiency is also sometimes expressed in radiant sensitivity (mA/W). The electrons after photovoltaic conversion are sequentially converted into voltages per pixel by an electronic circuit. A synchronizing signal is also simultaneously added to give position information and this is then output as a video signal. The sharpness of the image is usually shown by the signal-to-noise ratio (or SN).

High sensitivity cameras are broadly grouped into charge-integration and electron-multiplication types according to their basic operating method. The charge-integration types are cameras having enhanced sensitivity from increasing the available light intensity to boost signal strength by extending the charge-integration time (exposure time). The electron-multiplication types are cameras having enhanced sensitivity from boosting the signal strength by some kind of electron multiplication method. Cameras called cooled CCD cameras fall within the charge-integration type, while ICCD (intensified CCD) cameras, SIT (silicon intensified target) cameras, EB-CCD (electron bombardment CCD) cameras, and the latest focus of attention called EM-CCD (electron multiplier CCD) cameras fall within the electron-multiplication type. These multiplication type high sensitivity cameras are capable of capturing images at a frame rate of 30 frames per second which is the so-called television rate. The frame rate is basically the number of images per second while outputting consecutive images and usually expressed in frames per second (fps) or Hertz (Hz). This frame rate determines whether or not a moving image can be captured, so this frame rate is a crucial factor when selecting a camera. ICCD cameras also include a photon counting camera capable of capturing photons one by one. Fig. 2 shows the main high sensitivity camera categories. photons one by one. Fig. 2 shows the main high sensitivity camera categories.

**Introduction to high sensitivity cameras**

Here we briefly describe the principle of the charge-integration camera using the cooled CCD camera as an example. We will then deal with electron-multiplication cameras by describing the principles of ICCD, EB-CCD and EM-CCD cameras.

### 1. Cooled CCD cameras

◊ **Noise in CCD cameras**

The charge-integration high sensitivity camera is generally known as the cooled CCD camera. The cooled CCD camera differs from normal CCD cameras in how it suppresses the 3 types of noise components shown in Fig. 3.

- **Readout noise**
  - Noise caused by camera operation and electrical circuit
- **Dark current noise**
  - Noise dependent on silicon dark current characteristics
- **Shot noise**
  - Noise caused by light intensity

Readout noise is caused by CCD camera operation and electrical circuit. Readout noise can be suppressed by low-speed readout (slow scan) and low noise circuit technology. One readout noise component is added in each readout cycle. Dark current noise is generated by the flow of dark current in silicon and is temperature-dependent. Dark noise usually reduces in half for every 7 or 8 °C decrease in temperature. The cooling effect of the cooled CCD camera drastically cuts down on its dark current noise. On the other hand, dark current noise increases in proportion to the exposure time.

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**Fig. 2 High sensitivity camera types**

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<td>• Cooled CCD cameras</td>
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**Electron-multiplication high sensitivity cameras**

- SIT cameras
- EB-CCD cameras
- EM-CCD cameras
- ICCD cameras (photon counting cameras)

**Fig. 3 CCD camera noise**
Since charge-integration cameras boost sensitivity by extending the exposure time, suppressing the dark current is very important. This makes it essential to provide cooling.

Shot noise is noise originating from the light intensity. The lower the light intensity or actually, the smaller the electrical charge converted from the light, the greater the statistical fluctuation in the signal or, in other words, the greater the shot noise. Shot noise can be reduced by increasing the signal charge by using a CCD with a high QE. For this reason, frame transfer CCD, on-chip microlens CCD, and back-thinned illuminated type CCD are used. Fig. 4 shows typical high quantum efficiency of the back-thinned illuminated type CCD over a wide spectral range from the ultraviolet to the infrared.

Cooling methods

Cooling methods for CCD cameras generally consist of cooling using liquid nitrogen and cooling using Peltier elements. Liquid nitrogen cooling is effective when the CCD must be maintained at very low temperatures, but handling and keeping track of the liquid nitrogen is a bothersome chore. When using a Peltier element, there are three methods for secondary cooling on the hot side of the Peltier element: natural air cooling, forced air (fan) cooling, and forced water cooling. Forced water cooling is effective for stabilizing the cooling temperature, but this method requires a water circulator. Forced air cooling using a fan is also effective but the fan oscillation affects the measurement so caution is needed. Measures taken to prevent condensation from forming during Peltier element cooling are the nitrogen purge and vacuum sealed-off method. The nitrogen purge method requires caution since condensation may form with the passage of time, making it necessary to re-purge with nitrogen. The vacuum sealed-off method on the other hand is capable of maintaining a vacuum of $10^{-7}$ to $10^{-8}$ Torr semi-permanently, so that no maintenance is needed unlike the nitrogen purge method. Another benefit is that there is no heat propagation caused by convection of the internal nitrogen. This prevents heat from flowing to the CCD chip and therefore keeps the cooling temperature low. Fig. 5 shows a typical vacuum sealed-off structure.

2. SIT cameras

In the operation of SIT cameras, incoming photons are converted into electrons at the photocathode and those electrons are accelerated by a voltage to strike the silicon target where a large number of electron-hole pairs are generated. The charges accumulated on the silicon target are then scanned by an electron beam to obtain a video signal. Compared to the ICCD camera, SIT cameras offer clear images with less multiplication fluctuation because they do not use a Micro Channel Plate (MCP) for multiplying electrons and have a large afterimage or image lag. However, the SIT cameras have large spatial distortion so measurements of distance, dimensions and shape must be corrected by image processing. Another shortcoming is that the linearity of the output signal brightness versus the input light intensity is poor, so image processing is also required to correct this. The SIT cameras are also not ideal for capturing fast-moving objects because of its large afterimage.

The SIT cameras are now being replaced by the EB-CCD and EM-CCD cameras.
3. Image intensifier cameras (ICCD camera)

As mentioned previously, the main trend in high sensitivity cameras was to attach an image intensifier on the front of a video camera. These are assembled by relay lens coupling or fiber coupling. Basically, an image intensifier can be coupled by a relay lens to the front of any type of video camera. However, most image intensifier cameras currently available have an image intensifier attached to the front of CCD cameras, so here we will introduce ICCD cameras. Fig. 6 illustrates the principle of the ICCD camera. Photons entering the ICCD are converted to electrons at the photocathode. These electrons are multiplied in number by a microchannel plate (MCP), and clusters of the multiplied electrons then strike the phosphor screen to cause intensified light emission. This intensified light is then focused onto the CCD camera via the relay lens or the fiber optic plate. Each single electron input to the MCP produces multiple secondary electrons when it strikes the inner wall of the MCP. These multiple electrons are further accelerated by a voltage applied across the MCP to produce additional secondary electrons. The electron multiplication factor or gain per MCP is an average of 1,000 times, so that an average of 1,000 electrons is output when a single electron is input. This gain is just an average and will vary with each individual event. This variation is called the gain fluctuation.

In addition to alkali photocathodes, semiconductor photocathode image intensifiers offering high quantum efficiency have been available for a number of years now. These image intensifiers can also be coupled by a relay lens to the front of any type of camera. Granular noise called "ion noise" usually occurs as the voltage applied to the image intensifier is raised. To suppress this ion noise, image intensifiers using a 2-stage MCP are available.

4. EB- CCD cameras

The EB-CCD camera is a simple structure device having no MCP, phosphor screen and relay lens. Fig. 7 illustrates the principle of the EB-CCD camera. Incoming photons are converted into electrons at the photocathode and these electrons are accelerated by an applied voltage of several kilovolts to collide with the back-thinned illuminated type CCD. The energy from that collision serves to multiply the number of electrons. Basically, all of the collision energy from these voltage-accelerated electrons is converted into generating electrons so there is little variation in the number of generated electrons. Theoretically, the EB-CCD exhibits little of the gain fluctuation that usually occurs in ICCD and EM-CCD cameras, so that an image having little fluctuation or jitter is obtained. Electron multiplication or gain can be adjusted up to 1,200 times by changing the applied voltage. Recently, semiconductor photocathodes with high quantum efficiency have been developed the same as with ICCD cameras. Benefits that EB-CCD cameras offer versus SIT cameras include: 1) no afterimage, 2) no image distortion, and 3) adequate linearity. Advantages offered versus ICCD and EM-CCD cameras are that the image has little fluctuation as already mentioned and that the EB-CCD is highly effective for acquiring images of low-contrast objects. EB-CCD cameras also contain a spot noise reducer to eliminate granular noise called ion noise which appears as the applied voltage is raised.
5. EM-CCD cameras

The EM-CCD camera is a CCD camera having an electron multiplication function on the CCD chip for boosting the number of electrons. EM-CCD technology is young, having reached the commercial product stage a mere 2 years ago. Fig. 8 illustrates the principle of the EM-CCD camera. An electron multiplier section added to the final part of a frame transfer CCD camera is capable of multiplying and outputting all electrons. The electron multiplier section transfers the electrons at a higher voltage than normally used and the resulting transfer energy allows one electron to generate one more electron. The probability of generating an electron is about 1 to 2 percent yet there are 400 or more transfer stages in the electron multiplier section to yield a gain (electron multiplication factor) averaging 2,000 times, so that one electron that is input can be output as 2,000 electrons. This gain is just an average, and will vary with each individual event. This variation is called the gain fluctuation. The gain can be adjusted by changing the voltage and can even be set to a gain of 1. This EM-CCD camera can therefore function either as an electron-multiplication type high sensitivity camera by raising the gain or as a charge-integration type high sensitivity camera by lowering the gain and extending the charge accumulation time. Features that EM-CCD cameras offer versus high sensitivity cameras using a photocathode include: 1) no image burn-in that may occur on photocathode surface, 2) uniform sensitivity distribution, 3) high quantum efficiency offered by back-thinned illuminated CCD, and 4) high resolution of 1000x1000 pixels, etc.

The EM-CCD camera is basically a device having expanded cooled CCD camera functions. Elements essential to the cooled CCD camera are also essential to the EM-CCD camera. Cooling is also critical not only because of the dark current noise suppression, but because a feature of EM-CCD cameras is that the gain rises as the temperature on the CCD chip lowers. So it is important not only to have a low cooling temperature but also essential to keep the cooling temperature stable to minimize variations in the gain. Fig. 9 shows typical output images obtained when the gain was raised with the light intensity kept constant.

![Fig. 8 Basic principle of EM-CCD camera](image)

![Fig. 9 Multiplied output images obtained by EM-CCD camera](image)
6. Photon counting cameras

An ICCD camera having high gain yet little dark noise from the photocathode can be used as a photon counting camera. A two-stage MCP is usually required to perform photon counting. Because the signal of a photoelectron that corresponds to one photon is output with amplitude large enough to be separated from the CCD camera noise. The amplitude of each output signal slightly differs due to fluctuation during multiplication by the MCP, but this difference is meaningless for photon counting and only the position information has value. A proper discrimination level must be set to separate the photoelectron signals from the readout camera noise. The separated readout noise can then be eliminated and ignored by binary processing. The photon counting camera’s signal-to-noise ratio is therefore determined by the quantum efficiency and dark current noise of the photocathode and is not affected by readout noise.

Detection methods after binary processing include a slice mode and a center-of-gravity detection mode. Fig. 10 illustrates the principle of signal processing in the slice mode and center-of-gravity detection mode. The slice mode provides a large area per photon and therefore offers good visual recognition, although this mode is subject to effects of gain fluctuation. The center-of-gravity detection mode has high resolution and a high S/N ratio not susceptible to gain fluctuation. Fig. 11 shows an example of photon counting images acquired by varying the integration time. Random photon signals that appear only sporadically at low light intensities per unit time in 0.03 seconds can be formed as images equivalent to high light intensity images, by increasing the integration time or total light intensity.

Other techniques

Here we introduce output methods and special techniques involving high sensitivity cameras.

1. Output methods

Up until recently, most video cameras mainly used the so-called analog output. However, there has been a shift towards digital outputs along with the spread of computer data storage and image processing. Analog output is not only limited to resolution in the vertical direction due to scanning lines but also has a limited frame rate.

Interfaces for digital output vary in different ways according to the camera manufacturer. There is currently is a gradual shift away from individual manufacturer interfaces and towards the RS422, LVDS (RS644), CameraLink, and IEEE1394 interfaces.

2. Camera API library

Until recently, the application software had to be changed each time a different camera or camera interface was used. Now, however, a camera API library can be used to absorb the differences in each camera and camera interface so the user can change cameras or camera interfaces without even thinking about the software. This type of camera API library is available from each manufacturer. Fig. 12 shows a concept view of the API library.
3. Binning readout

The binning readout method delivers high sensitivity as a tradeoff for resolution, by summing signals of adjacent pixels in a CCD. Fig. 13 shows the basic principle of the binning operation. In 2x2 binning, the electrical charge of 4 pixels is summed in the CCD to increase the signal component 4-fold, but the readout noise is still only equal to 1 time so the S/N ratio is improved. Though the number of pixels that can be summed depends on the design specifications, up to 16x16 multi-pixel binning is available to improve the S/N ratio.

4. Subarray readout

In this method, an optional area is selected from the total number of effective pixels, and only the signal from that selected area is readout from the CCD. The CCD charge on areas other than the selected one are dumped at high speed. Fig. 14 shows the basic principle of subarray readout. Using this method drastically cuts the time needed for reading 1 frame and allows increasing the frame rate. The frame rate can be raised even higher by combining this method with binning mode.

5. TDI readout

When the movement speed of the camera target is large compared to the exposure time, the incoming photons are dispersed among many pixels along the direction of movement. This causes a blurry image and lowers signal brightness. However, if that object's motion is at a fixed speed and fixed direction such as on a belt conveyor then that direction and speed can be synchronized with the charge transfer direction on the CCD to eliminate blurry images without causing a drop in signal brightness. This method is called "time delay integration" (TDI) and its basic principle is shown in Fig. 15.
Conclusion

High sensitivity cameras are needed for applications in a wide range of light intensities from single photon levels to low-light levels where ordinary camera cannot capture any image. In general applications, a filter or shutter can be used to reduce the light intensity to a level matching the camera sensitivity. However, at very low light levels this simply won’t work. Also the required frame rate and resolution changes according to what it is you want to see. There are also an infinite range of applications and conditions with their own particular problems such as the fact that camera sensitivity changes according to the wavelength and just a little vibration makes the camera unusable. This means that selecting the best camera for each application is not an easy task.

The smart thing to do when making a selection is to talk to the manufacturer’s sales representative. In this kind of case, a well-experienced representative can save the customer a lot of trouble since he knows what type of camera to use in what type of situation. He may also know about special technology not yet listed in any catalog and might share that knowledge with you. When consulting with the sales representative, give him a brief summary of what it is that you want to capture images of, what changes you want to see in what section, and what it is you want to observe or measure. Unless there is already a past record of the same type of observations, before making a purchase you should first borrow a demo model from the manufacturer and confirm that you can actually view what you want to see.

Measurements and observations made by using light and especially measurements and observations using high sensitivity cameras have still not spread to many fields. This is probably because the high sensitivity camera itself is still not well known and also because high sensitivity cameras are expensive. Use of high sensitivity cameras to make measurements is still in its growing phase and new progress and applications can be expected in new fields. This will happen because the high sensitivity camera allows us to view what would otherwise be missed by an ordinary camera.

Seeing what has not been seen up to now may lead to new discoveries. The high sensitivity camera represents a potential treasure trove of future possibilities.