Frame Transfer Cameras

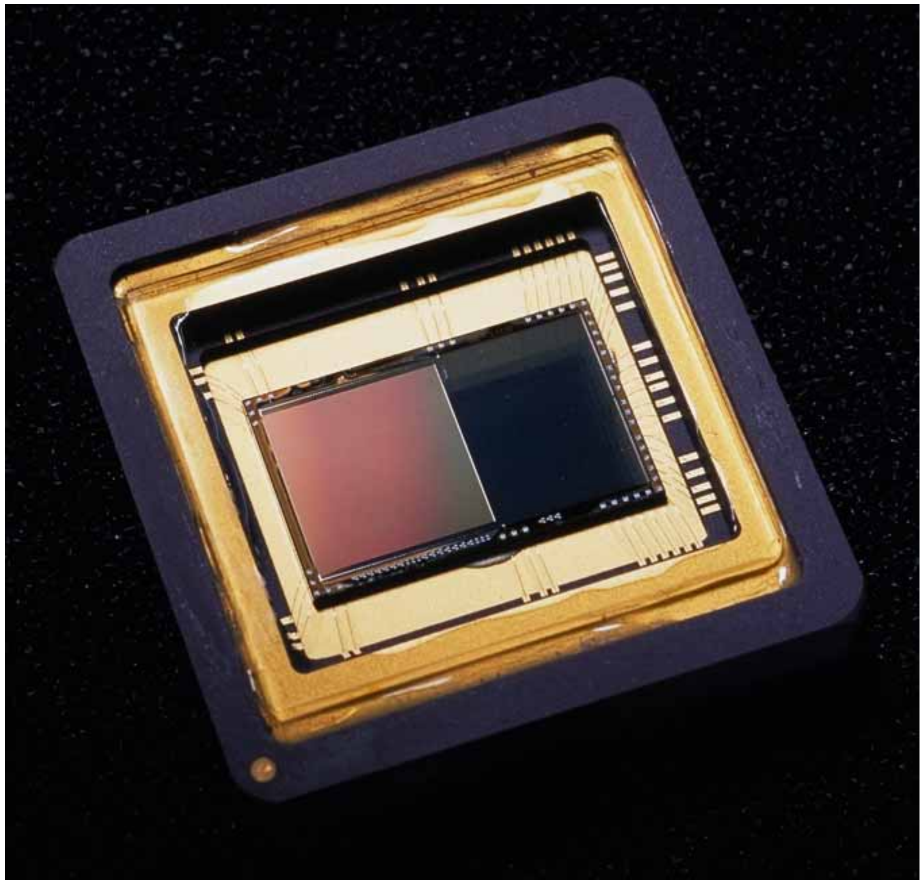
Frame transfer is a powerful mode of CCD operation available for many Princeton Instruments CCD cameras. By operating in a frame transfer mode a shutter is not necessary, and the exposure duty cycle jumps to nearly 100%.

Principles of Frame Transfer Operation

In full frame CCD operation, the CCD must alternate between exposure and readout. During readout the CCD is still sensitive to light, so a mechanical shutter is used to prevent additional exposure. Due to the time necessary to open and close the shutter, and the time needed to read out the CCD, the percentage of time available for exposures is limited.

The maximum frame rate is also limited by the shutter. For a given pixel readout rate, the only way to achieve a faster frame rate is to lower the exposure time. As the exposure time is shortened, the CCD records less signal, and the camera becomes less sensitive. In addition, events that occur during readout are missed completely. Lastly, as the frame rate increases, the lifetime of the mechanical shutter becomes an issue.

Frame transfer operation of a CCD attempts to resolve these problems. As shown in Figure 1, only half of the CCD (the image area) is exposed to light. The other half is masked and is used to temporarily store images. This schematic diagram of frame transfer operation shows how an image focused on the image area of the array is shifted in a few milliseconds to the storage area (panel b and c). Once this image (now in the form of electrical charge) is shifted, the image area of the CCD can start collecting the next frame while the storage area is read out and digitized.



The 512 x 512 x 2 frame transfer CCD. On-chip aluminization masks half the array.

Smearing Issues

When operating without a shutter image smearing may occur, depending on the exact nature of the experiment. This effect, caused by light falling on the CCD as the charge is shifted to the masked area, occurs only if the CCD is illuminated during shifting. In the case of intensified cameras (ICCDs), this effect can be eliminated by using a fast phosphor and gating the intensifier at the same frame rate as the CCD.

The fraction of total signal due to smearing is the ratio of the amount of time spent shifting divided by the exposure time between frames. Faster shifting and/or longer exposure times will minimize this effect (see Table 1). Note that while 1% smearing is insignificant in an 8 bit camera (256 gray levels), in a 16 bit camera (65,000 gray levels) 1% smearing is over 600 counts, enough to obscure faint features in a high dynamic range image.

Exposure Time Limitations

The minimum exposure time (without a shutter) is the time required to read out the storage section of the CCD array. To shorten the readout time, PI's flexible hardware binning and/or subimaging modes are available. Full resolution readout times for all frame transfer arrays appear in Table 2.

Advantages and Disadvantages of Frame Transfer Operation

There are many advantages of frame transfer operation, including the following:

- ❑ Light collection is continuous, so the system is more sensitive and will not miss transient events.
- ❑ Readout and light collection are simultaneous, so for a given resolution and pixel rate, frame rates are higher.
- ❑ A mechanical shutter is not required, so reliability is higher, particularly at the high frame rates that result from subimaging or binning.
- ❑ The ability to take two images in rapid succession. This is helpful in multispectral imaging where images at two

wavelengths need to be taken with as little time in between them as possible (e.g., cell calcium experiments). When used this way, frame transfer is a simple form of kinetics imaging (in which typically 5-20 images are taken in rapid succession). This type of operation can be done with any CCD array, as it does not require independent control of the upper and lower regions.

The main disadvantages of frame transfer are:

- ❑ Detection area is smaller (typically half the size of the standard array)
- ❑ There can be smearing during the frame transfer if the illumination is continuous.

CCDs Available for Frame Transfer Operation

Arrays for operation in frame transfer mode are shown in Table 1. Although there are many scientific CCD arrays available for frame transfer operation, most are not available with masking directly on the array. It therefore becomes the responsibility of the system optics to prevent light from falling on the storage area of the array. CCD arrays supported by Princeton Instruments and available with on-array masking are the EEV 576 x 384, 512 x 1024, 1152 x 770, and 1152 x 1242 CCDs.

An advantage of cameras built with non-masked arrays is that they can also be used for full-frame (non-frame transfer) operation. Addition of the frame transfer circuitry to the detector head does not preclude this.

Manufacturer	Total Number of Pixels on array	Number of imaging pixels	Availability of on-array masking (aluminization)
EEV	576 x 384	288 x 384	Yes
EEV	1152 x 298	576 x 298	No
EEV	1152 x 770	576 x 770	Yes
EEV	1152 x 1242	576 x 1242	Yes
SITe	1024 x 1024	512 x 1024	No
PI	1100 x 330	1100 x 165	No
PI	1752 x 532	1752 x 266	No
EEV	512 x 1024	512 x 512	Yes

Table 1. CCD arrays available for frame transfer cameras.

A number of arrays do not provide independent clocking of the top and bottom halves of the array and therefore cannot be operated in frame transfer mode. These arrays include the EEV 1024 x 256, the SITe 512 x 512, and all of the Kodak arrays.

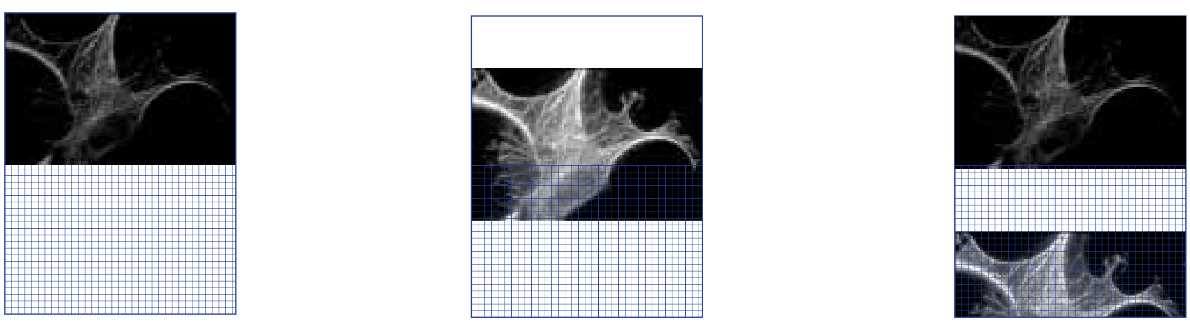
Customers should note that frame transfer operation is a special option on a CCD detector head. It requires additional circuitry in the camera and mechanical modifications. Thus even if a CCD array is itself capable of frame transfer operation, a camera head built with that CCD array will not necessarily be able to operate in frame transfer mode unless these additional mechanical and electrical changes are made at the time of purchase.

Masking on the CCD Array

The EEV 576 x 384, 512 x 1024, 1152 x 770, and 1152 x 1242 CCDs are available with half of the array masked by a layer of aluminum. In measurements in our laboratory, we find that no detectable signal is generated in this masked region, except near the edges. At the interface between the two halves, there can be 1 or 2 rows in the masked area with significant signal (>10% of the signal in the open area) and 3-5 more rows with slight light leakage. Around the other edges light leakage under the aluminum is low (<1%), and it extends at most 5-10 pixels in from the edge. No pin holes have been observed.

Mechanical Masking of Arrays

Since most frame transfer CCD arrays are not available with masking directly on the silicon, mechanical masking provides a practical alternative. In this approach, a mechanical mask is mounted just above the surface of the silicon, shielding the storage area of the array. This type of



(a) **(b)** **(c)**

Figure 1. The above drawing illustrates frame transfer operation. An initial exposure (a) illuminates the upper half of the CCD. This charge is shifted to the masked section of the array (b). Once this shift is complete this charge is read while another exposure is taking place (c).

Array	Size	Shift time per row, microseconds	Frame transfer time, milliseconds	A/D rate	Full resolution readout time, milliseconds	Smearing when exposure time is minimum read time
EEV	576 x 384, non-MPP	3.0	0.87	500 kHz/1 MHz	234/133	0.7%
EEV	1152 x 298, non-MPP	3.0	1.73	500 kHz	369	0.5%
EEV	1152 x 770, non-MPP	4.8	2.76	500 kHz	900	0.3%
EEV	1152 x 1242, non-MPP	4.8	2.76	500 kHz/1 MHz	1458/811	0.3%
SITe	1024 x 1024 front, MPP	15.0	7.68	430 kHz/1 MHz	1248/656	1.2%
SITe	1024 x 1024 back, MPP	153.6	78.64	430 kHz	1396	5.6%
EEV	512 x 1024, non-MPP	3.0	1.54	1 MHz	271	0.6%

Table 2. Frame rates for various CCDs calculated using the maximum A/D speeds. Values are for TE/CCD cameras only.

masking causes a soft edge (0.1-1 pixel wide) and thus somewhat fewer usable pixels. It is possible to align this mask to within one millimeter of the center of the CCD array, and the mask to within one millimeter of the surface of the silicon. Mechanical masking in this way is not as good as masking on the array, as some light can leak in under the mask. To minimize the reflections between the mask and the CCD the masks are black anodized. Below are two examples of the typical performance of mechanical masks.

Example #1
If f/5 optics are used, a mask 1 mm from the CCD surface causes a shadow with an edge 0.2 mm wide. On a CCD with 24 µm pixels (e.g., SITe 1024 x 1024), this results in a "soft edge" 8 pixel wide. Our ability to center the mask only within 1 mm (fine adjustment provided) adds another 40 pixels. The resulting useful area is therefore at least 1024 x (512-48) = 1024 x 464, i.e. 90% of what it would be if on-array masking were available. For many applications, this performance is acceptable.

Example #2
As a second example, assume that f/1.4 optics are used. The shadow of a mask 1 mm from the silicon surface in this instance has an edge 0.7 mm wide. With 13 µm pixels (e.g., Reticon 1024 x 1024) this results in a 54 pixel soft edge. Our ability to center the mask only within 1 mm adds another 74 pixels. This reduces the useful area from 1024 x 512 to 1024 x 384, i.e. 75% of what it would be if on-array masking were available. The acceptability of this performance depends on the user's application.

Note that masking can occur anywhere in the optical system and there are advantages to masking in places other than directly above the array. One possibility is to mask the illumination, so that only the portion of the subject seen by the top half of the array is illuminated. Alternatively, a black mask can be placed between the subject and the lens (or other optics), limiting the field of view and hence the portion of the array which is illuminated. These approaches may allow use of a higher fraction of the array, closer to the level achieved by on-array masking. They also retain the option of imaging with the entire CCD illuminated.

Performance of Specific CCD Arrays

The amount of time required to shift the image into the storage area depends on the number of rows to be shifted and the vertical shift time per row. These values vary from array to array and between front and back illuminated configurations. Generally, Princeton Instruments systems use standard vertical shift rates that are known to be "safe", i.e., rates that maintain full vertical well capacity, charge transfer efficiency, and linearity. For some arrays these "safe" values may be very conservative. Contact the factory for the most current information on readout rates.

Table 2 reflects speeds that have been confirmed experimentally. If these arrays must be read at higher rates, they will probably have lower signal levels (lower full well capacities). At the highest transfer rates, the charge transfer efficiency suffers, resulting in blurred images. Performance degradation begins at the center of a CCD as higher and higher vertical shifting rates are used. Note that the vertical shift time is user selectable through software, and is independent of the A/D speed.

Note: all of these times in Table 2 are for TE/CCD cameras. LN/CCD models often shift much more slowly.

For the most up-to-date information on maximum performance for a particular array, please contact your Princeton Instruments sales representative.

Availability

All of the arrays listed in Table 1 are currently available in a Princeton Instruments frame transfer camera. These are offered as thermoelectrically cooled (TE/CCD) models, with air or liquid used for heat dissipation. Liquid nitrogen cooled (LN/CCD) cameras, which generally have slower shift rates and are used primarily for long exposures, are not normally available with frame transfer operation.

A frame transfer 576 x 384 ICCD is available from Princeton Instruments, with a special moveable intensifier masking. In this type of detector the intensifier can be used as a shutter, preventing smearing due to continued exposure during the frame shift time. Intensified CCD cameras for use in frame transfer mode should also use a high speed phosphor in the intensifier, to minimize smearing due to phosphor lag during the frame shifting. Since these high speed phosphors have 3-10 times less light output per photoelectron, fiber optic coupling between the intensifier and CCD is even more important than in normal operation. Without it, single photoelectron detection is nearly impossible.