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CCD chips demistified

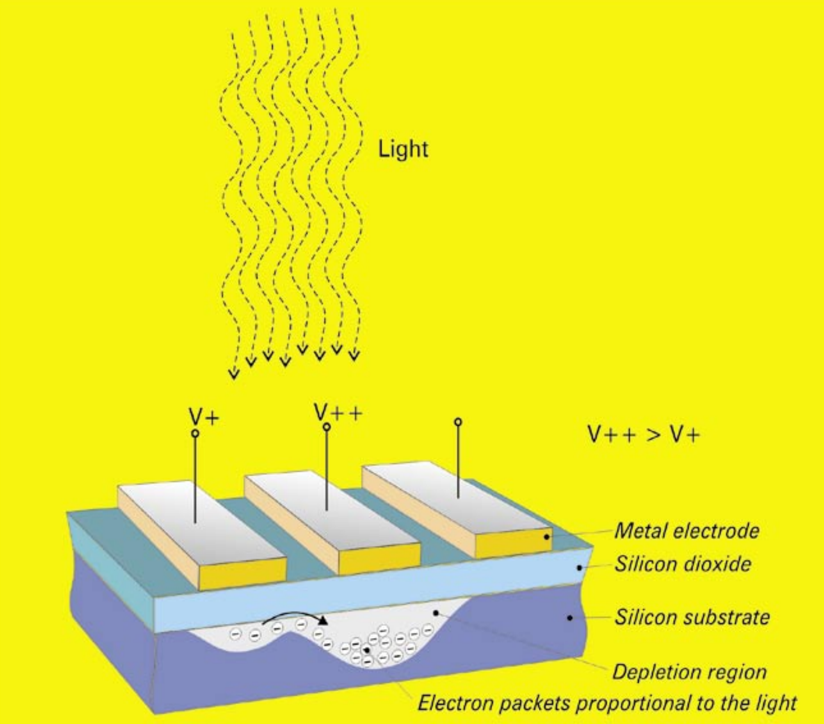
The very first and most important element in the CCTV chain is the element that captures the images – the camera.

The term "camera" comes from the Latin camera obscura, which means "dark room."

This type of room was an artist's tool in the middle ages. A lightproof room, in the form of a box, with a convex lens at one end and a screen that reflected the image at the other was used by the artists to trace images and later produce paintings.

In the 19th century, "camera" referred to a device for recording images on film or some other light-sensitive material. It consisted of a lightproof box, a lens through which light entered and was focused, a shutter that controlled the duration of the lens opening and an iris that controlled the amount of light that passed through the glass.

Today, we use the term "camera" in film, photography, television and multimedia. Cameras project images onto different targets, but they all use light and lenses.



The basic concept of transferring charges in a CCD chip

To understand CCTV you don't need to be an expert in cameras and optics, but it helps if you understand the basics.

In photographic and film cameras optical information (images) is converted into a chemical emulsion imprint (film). In television cameras, the optical information is converted into electrical signals.

Cameras use lenses with certain focal lengths and certain angles of view, which are different for different formats.

Lenses have a limited resolution and certain distortions (or aberrations), but this is more obvious in the film cameras. This is because the film resolution is still far better than the electronic camera resolution, although there are higher resolution chips coming out daily.

To illustrate, high-resolution CCD chips in CCTV these days have around 752 × 582 pixels (picture elements), while 100 ISO 35-mm colour negative film has a resolution equivalent to 8000 × 6000 elements (film grains). This is based on a typical film resolution of 120 lpm (lines per milimetre).

In the 1970s, when personal computers were born, experiments were made with solid-state electronic elements called charge-coupled devices (CCD), which were initially intented to be used as memory devices.

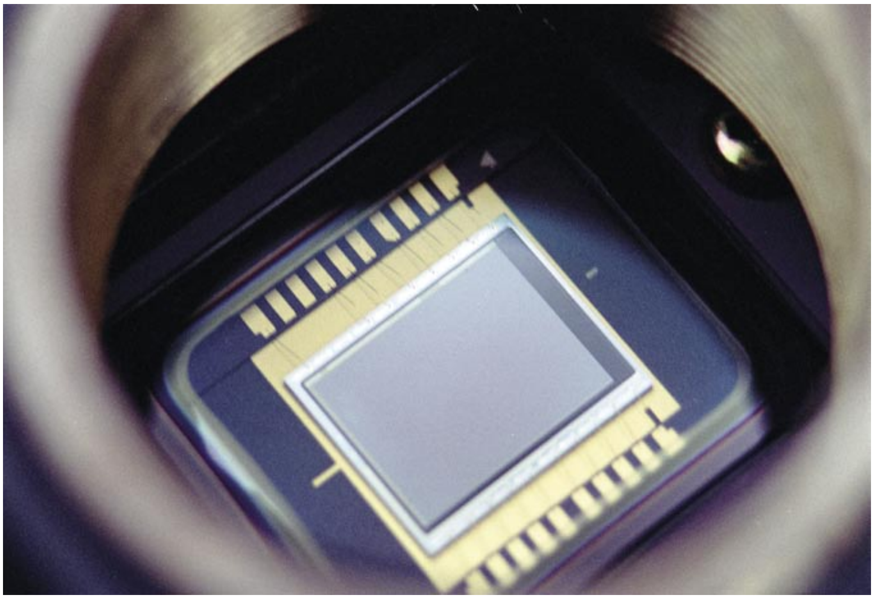
Very soon it was found that CCDs are very sensitive to light, so they could be used more effectively as imaging devices rather than as memory devices.

The basic principle of CCD operation is the storing of the information of electrical charges in the elementary cells and then, when required, to shift these charges to the output stage.

When a CCD chip is used as an imaging device, the shifting concept stays the same, but instead of injecting charge packets as digital information (which would be the case if the CCD chip is used as a memory device), we have a photo-effect generating electrons proportional to the amount of light falling on the imaging area, and then, these charges are shifted out vertically and/or horizontally, in the same manner as shift registers in digital electronics shift binary values.

So, in effect, we have charge packets, once they have been collected in each photosensitive cell, "sliding down" to the output stage by using charge coupling methods. Thus, an electrical coupling is done by means of voltage and timing manipulation of each cell, called a picture element (or pixel).

One of the pioneers of CCD technology, Gilbert Amelio, in his article written in 1974, describes charge coupling as "a collective



transfer of all the mobile electric charge stored within a semiconductor storage element to a similar, adjacent storage element by the external manipulation of voltages. The quantity of the stored charge in this mobile packet can vary widely, depending on the applied voltage and on the capacitance of the storage element. The amount of electric charge in each packet can represent information."

The construction of CCD chips is either in the form of a line area (linear CCD) or in the form of a two- dimensional matrix (array CCD). It is important to understand that they are composed of discrete pixels, but CCDs are not digital devices. Each of these pixels can have any number of electrons, proportional to the light that falls onto it, thus representing analogue information.

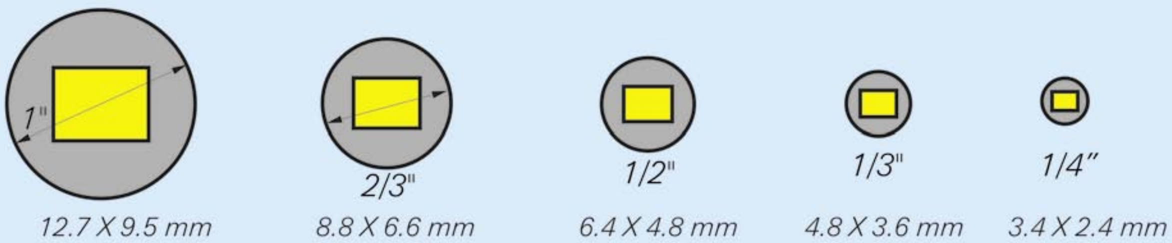
These discrete packets of electrons are then transferred (once the exposure time is over), by simultaneous shifting of row and column packets, to the output stage of the chip.

This is why we can say CCDs are, in essence, analog shift registers sensitive to light.

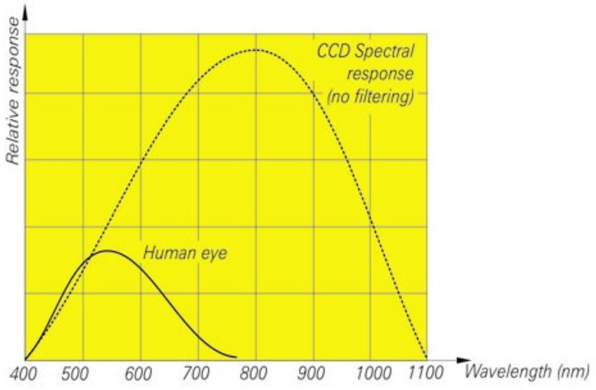
CCDs come in all shapes and sizes, but the general division is into linear and two-dimensional matrices. Linear chips are used in applications where there is only one direction of movement by the object (like with facsimile machines or scanners).

CCDs can be found in many objects of daily use: facsimile machines use linear CCD chips; image and OCR scanners also use linear CCDs; many auto-focusing photographic cameras use CCD chips for auto-focusing; geographic aerial monitoring, spacecraft planet scanning and industrial inspection of materials also use linear CCD cameras and last, but not least, most of the television cameras these days, both in broadcast and CCTV, use CCD chips.

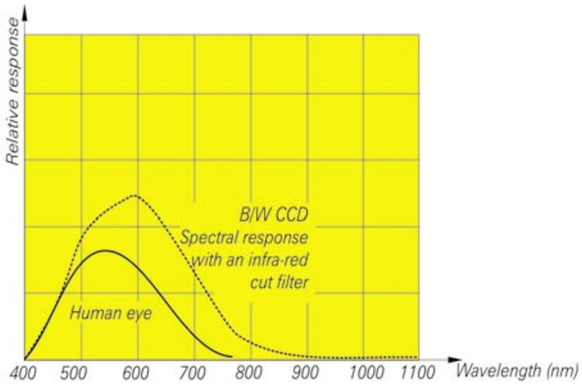
In CCTV we are only interested



Actual sizes of the image area in CCD chips



The eye's and the CCD chip's spectral sensitivity



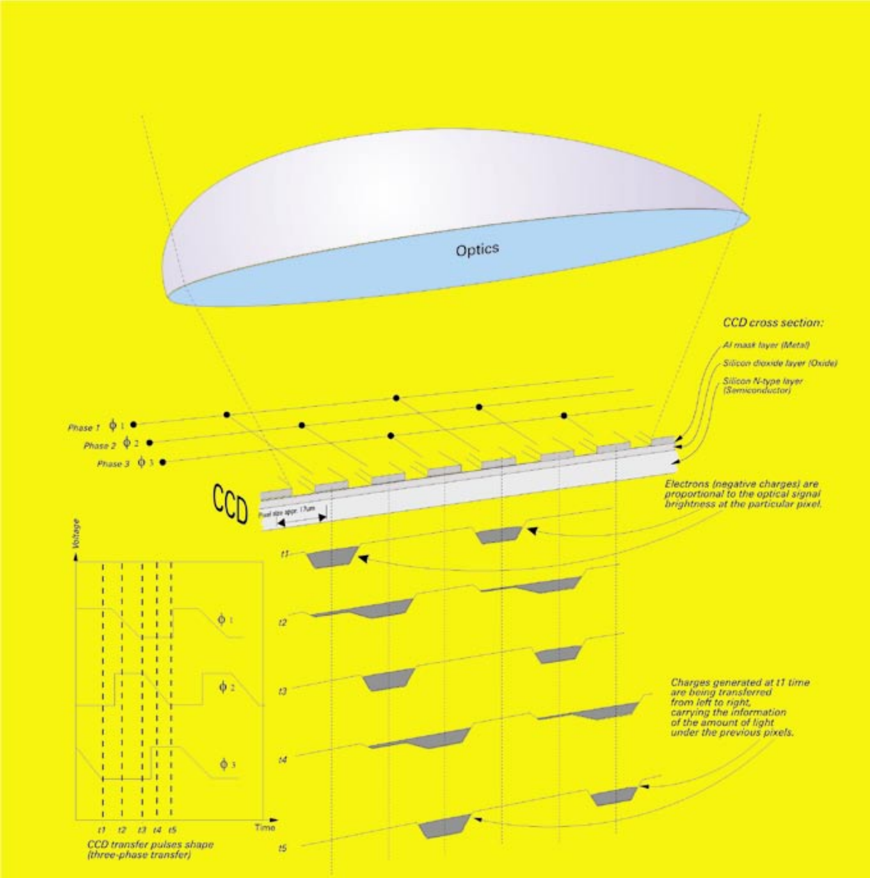
Infra-red cut filter modifies the CCD response

in two-dimensional matrices, the so-called 2/3", 1/2", 1/3" and 1/4" sizes.

These sizes do not represent the diagonal sizes of the chips, as many assume, but rather they are the sizes people use to refer to the diameter of the tube that would produce such an image. The actual imaging area sizes are shown on the drawing on the previous page.

Comparing sensitivities will show the advantage of CCD chips relative to the film emulsion.

The 100 ISO film is the most commonly used in photography, although we can buy 200 ISO film (twice as sensitive), or 400 ISO (four times more sensitive than the 100 ISO film). Sometimes, we may even come across 1600 ISO film, and this is usually used for extremely low light level situations (at least in photographic terms).



Charge-coupled device principle of operation

It can be shown that an average B/W CCD chip has a very high light sensitivity compared to a film emulsion. On a full sunny day, a typical 100 ISO film camera will require a setting of 1/125 s and F-16. When the same scene is observed by a CCD camera, of which the normal PAL exposure speed is 1/50 sec, a lens with approximately F-1000 needs to be used (give or take an F-stop or two, since the camera's AGC plays a role too). If we convert the 1/50 to 1/125 (2.5 times shorter), in order to have the same exposure the lens needs to have an opening 2.5 F-stops wider, in order to compensate for the shortening of the exposure. This brings us from F-1000 to approximately F-400 (F-numbers goes in sequence: 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22, 32, 44, 64, 88, 128, 180, 250, 360, 500, 720, 1000, 1400, etc.). Now, in order to convert the sensitivity of the film emulsion to get from the 100 ISO settings of 1/125 and F-16 to the equivalent settings of a higher film sensitivity, and knowing that double sensitivity occurs with doubling the ISO number, we get 9.5 F-times from F-16 to F-400. And this is approximately $2^{9.5}$ = 720 times. So, the average B/W CCD chip sensitivity, expressed in photographic ISO units, is approximately 100 ISO × 720 = 72,000 ISO!

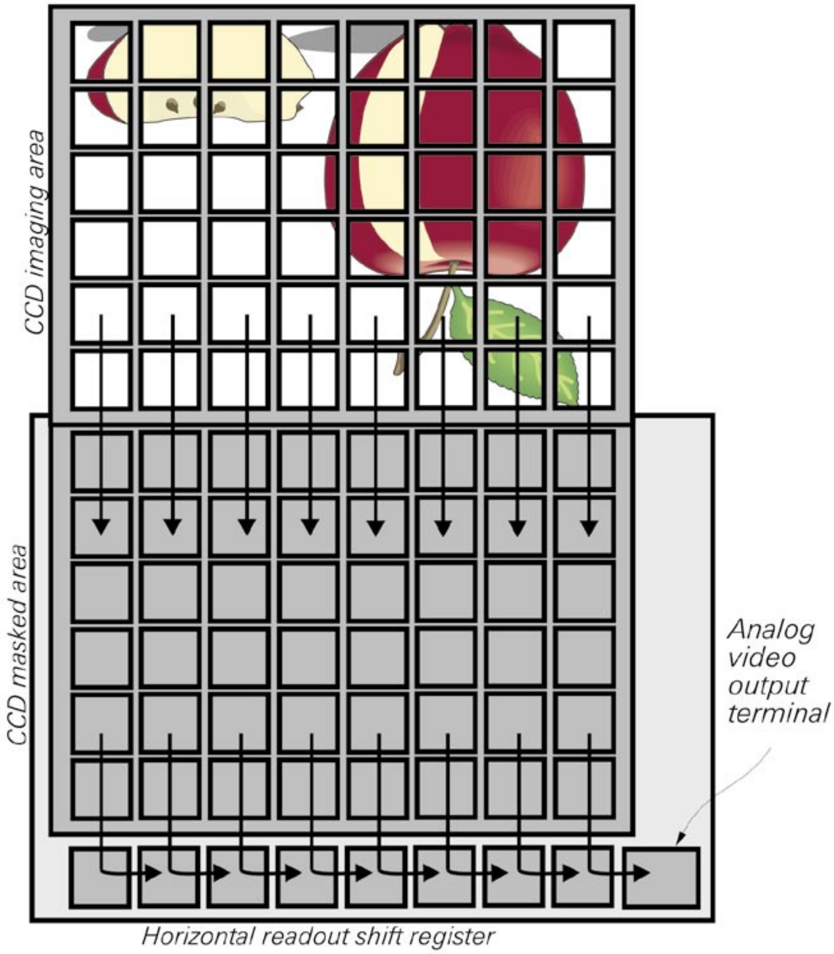
Similarly, we will find that a colour CCD camera has the equivalent sensitivity of approximately 5000 ISO, which is still very high compared to the photographic standards.

Chemical (film) photography is slowly being replaced by the electronic photography, which is based on CCD technology. The pixels count of such CCDs has increased dramatically, approaching the film grain structure.

Such still cameras are not dependent on the TV standard; therefore, there is no practical limitation on the number of pixels and aspect ratio. Manufacturers are producing chips with an area size of 62mm × 62mm (equal to medium format film size of 6X6cm), with no less than 5120 × 5120 picture elements. As already mentioned, these are still cameras and should not be confused with CCTV cameras.

The spectral sensitivity of CCD chips varies with various silicon substrates, but the general characteristic is a result of the photo-effect phenomenon: longer wavelengths penetrate deeper into the CCD silicon structure. This refers to the red and infrared light. A typical CCD chip spectral curve is shown on the drawings above.

Even though this "light penetration" may seem beneficial (CCD chips seem more sensitive), there are reasons for preventing some of the longer waves from getting too deep inside the chip. Namely, such wavelengths might be so strong that they could produce electron carriers in areas that are not supposed to be exposed to light. As a result the picture may lose details because the next door pixels will melt their content into each other, losing high-resolution components and causing a "blooming effect". The masked areas, which are supposed to only temporarily store charges and are not supposed to be exposed to light, can also be affected, so that noise and smear increase significantly. Because of these reasons, special optical infrared cut filters have been introduced as part of a well-designed CCD camera. These filters are optically precise plan-parallel pieces of glass, mounted on top of the CCD chips. As the name suggests, they behave as optical low pass filters, where the cutting wavelength is near 700 nm, i.e., near the colour red.



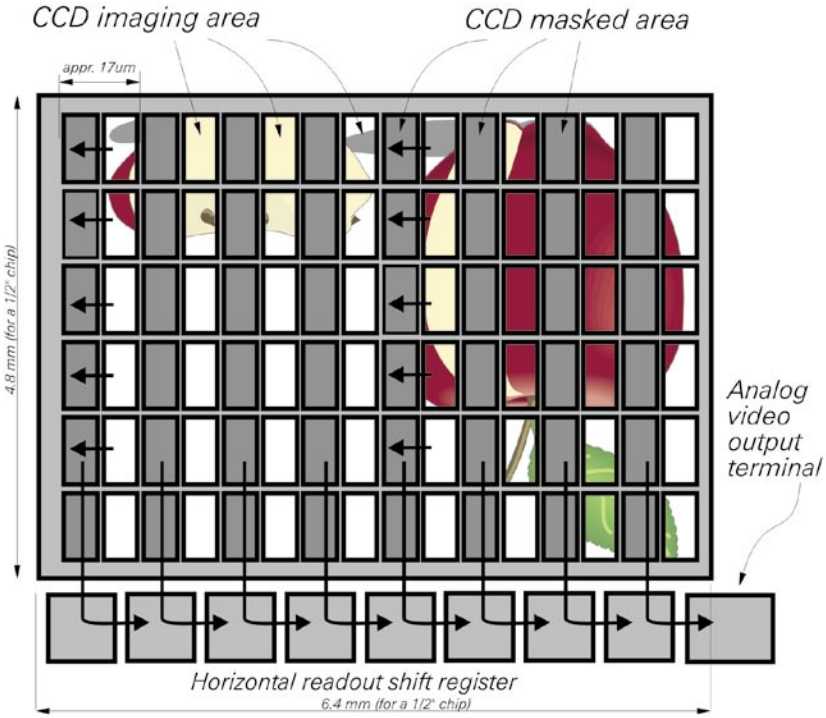
Frame transfer (FT) concept

There are a number of manufacturers of B/W cameras, though, that prefer not to put such filters on their chips, to make their cameras more sensitive. This might be acceptable, especially when cameras for lower light levels need to be used and infrared illuminators are to be part of the system, however, from a theoretical point of view, cameras with infrared cut filters will show better resolution (compared to the same chip without an IR cut filter), better S/N ratio and more natural colour-to-gray conversion, at the expense of a not so low minimum illumination response.

Colour CCD cameras, on the other hand, must use an IR cut filter, as the CCD chip's spectral response, which we saw is different to that of the eye, must be made similar to the human eye's spectral sensitivity. This is also one of the reasons why colour CCD cameras are less sensitive than B/W.

A typical B/W CCD chip, without an infrared cut, can produce a reasonable level of video signal at as low as 0.01 lx. The same camera with a filter will be quoted 0.1 lx for the same object illumination.

Colour cameras these days are quoted to have 1-lx minimum illumination at the object, with an F/1.4 producing a video signal of



Interline transfer (IT) concept

white with a reasonable level (0.3 to 0.5 V).

Matrix (array) CCD chips, as used in CCTV, can be divided into three groups based on the techniques of charge transfer.

The very first design, dating from the early 1970s, is known as frame transfer (FT) CCD. This type of CCD chip is effectively divided into two areas with an equal size, one above the other, an imaging and a masked area.

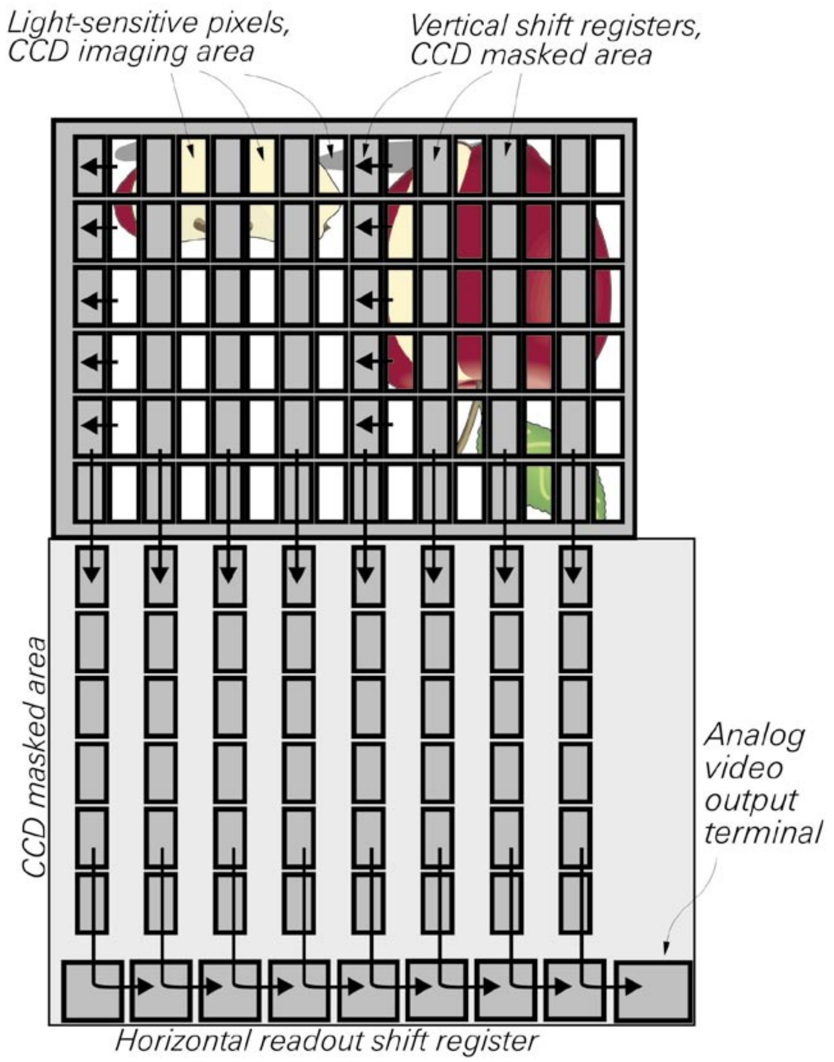
The imaging area is exposed to light for 1/50 second for a CCIR standard video (1/60 second for EIA). Then, during the vertical sync period, all photo-generated charges (electronically representing the optical image that falls on the CCD chip) are shifted down to the masked area (see the simplified drawing on the next page). Basically the whole "image frame" comes down.

Note the upside-down appearance of the projected image, since that is how it looks in a real situation, i.e., the lens projects an inverted image and the bottom right-hand pixel is recreated in the top left-hand corner when displayed on a monitor.

For the duration of the next 1/50 second, the imaging area generates the electrons of the new picture frame, while the electron packets in the masked area are shifted out horizontally, line-by-line. The electron packets (current) from each pixel are put together in one signal and converted into voltage, creating a TV line information.

Technically, perhaps, it would be more precise to call this mode of operation "field transfer" rather than "frame transfer," but this has been used since the early days of CCD development and we'll accept it as such.

This first design of the CCD chip was good, but it came with a new problem that was unknown



Frame interline transfer (FIT) concept

to tube cameras: vertical smearing. Namely, in the time between subsequent exposures when the charge transfer was active, nothing stopped the light from generating more electrons. This is understandable since electronic cameras do not have a mechanical shutter mechanism as photographic or film cameras do. So where intense light areas were present in the image projection, vertical bright stripes would appear.

To overcome this problem, design engineers have invented a new way of transference called interline transfer (IT) CCD. The difference here is (see the simplified drawing) that the exposed picture is not transferred down during the vertical sync pulse period, but it is shifted to the left masked area columns. The imaging and masked columns are next to each other and interleave, hence the name, interline. Since the masked pixel columns are immediately to the right of the imaging pixel columns, the shifting is considerably faster; therefore there is not much time for bright light to generate an unwanted signal, the smear.

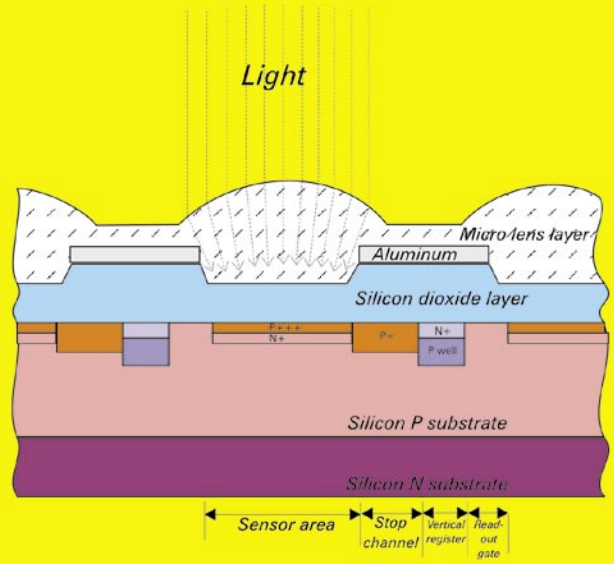
To be more precise, the smear is still generated, but in a considerably smaller amount. As a result, we also have a much higher S/N ratio.

There is one drawback to the IT transfer chips, which is obvious from the concept itself: in order to add the masked columns next to the imaging columns on the same area as the previous FT design, the size of the light-sensitive pixels had to be reduced. This reduces the sensitivity of the chip. Compared to the benefits gained, however, this drawback is of little significance.

One new and interesting benefit from the IT design is the possibility of implementing an electronic shutter in the CCD design. This is an especially attractive feature, where the natural exposure time of 1/50 second (1/60 for NTSC) can be electronically controlled and reduced to whatever shutter speed is necessary, still producing a $1V_{pp}$ video signal.

Initially, with the IT chip, manual control of the CCD-shutter was offered, but very soon automatic versions became available. This type of control is known as automatic CCD-iris, or electronic iris. The electronic iris replaces the need for AI controlled lenses. So an MI lens can be used with an electronic iris camera even in an outdoor installation. It should be noted, however, that an electronic

On the left a camera with visible smear and on the right almost invisible smear



A typical structure of the cross section of a CCD chip with micro lens design

iris cannot substitute the depth of field function produced by the mechanical iris in a lens. Also, it should be remembered that when the electronic iris switches at higher shutter speeds, and due to lower charge transfer efficiency, the smear increases.

So, when the electronic iris is enabled, it switches from a normal exposure speed of 1/50 (1/60) to a higher one (shorter duration), depending upon the light situation. Theoretically, exposures longer than 1/50 second (1/60 for EIA) could not be used because of loss of motion. With some CCD cameras though, longer exposures are possible, and this mode of operation is called integration. With some of the latest camera designs incorporating digital signal processing, integration is automatically turned on when object illumination falls below a certain level. This is especially helpful with colour cameras, where low light level pictures are produced, until now possible only with B/W cameras. The price paid for this is the loss of smoothness in motion (in integration mode we cannot have 50 fields), which is substituted with a motion appearance similar to a playback from a TL VCR.

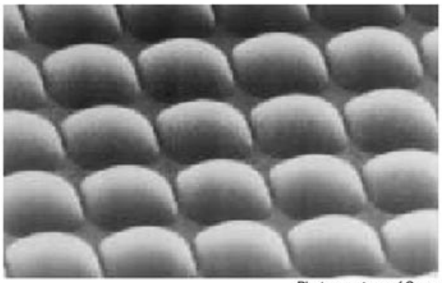


Photo courtesy of Sony

An electronic microscope photo of the on-chip microlens structure

Reducing the pixel size in the IT design, we said, indirectly reduces the chip's minimum illumination performance. This problem is solved with a very simple concept (technologically not as easy though) of putting micro lenses on top of every pixel. Micro lenses concentrate all of the light which falls on them to a smaller area, that is actually the pixel itself, and effectively increase the minimum illumination performance.

The most common types of CCD cameras in CCTV today have IT chips.

The best design so far is the frame interline transfer (FIT) chip, offering all the features of the interline transfer plus even less smear and a better S/N ratio. As it can be concluded from the simplified drawing, the FIT CCD works as an interline transfer in the top part of the chip, thus having the electronic iris control, but instead of holding the image in the masked columns for the duration of the next field exposure, it is shifted down to the better protected masked area.

This is the reason for even less smearing in the FIT design, but there is also gain in the S/N ratio. Micro lenses are also used here to increase the minimum illumination performance. FIT chips have an even further advanced micro structure, with a lot of cells and areas designed to prevent spills of excessive charges to the area around, trap the thermally generated electrons and so on. With all these fine tune-ups, FIT chips have a very high dynamic range, low smear and high S/N ratio, which makes them ideal for external camera surveillance and news gathering in broadcast TV.

The FIT CCD chips are expensive for CCTV, and their main use today is in broadcast TV.

In the end we should point out that no matter how good the camera electronics are, if the source of information – the CCD chip – is of an inferior quality, the camera will be inferior too. The opposite statement is also true, i.e., even if the CCD chip is of the best quality, if the camera electronics cannot process it in the best possible way, the total package becomes second class.

It should also be noted that most of the handful of chip manufacturers have CCD products of the same type divided into a few different classes, depending on the pixel quality and uniformity. Different camera manufacturers may use different classes of the same chip type. This is in the end reflected not only in the quality but also in the price of the camera. ▯▯▯