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HIGH DEFINITION CCD'S FOR ENHANCED DEFINITION TELEVISION

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ABSTRACT

CCD's have become serious competitors to camera tubes, even for HDTV. The challenge set by HDTV requirements implies to solve the sensitivity / resolution antinomy with presently available VLSI technologies.
This paper presents the various designs used by CCD's manufacturers and details the main performances of the two devices realized. These performances are related to the various technological choices and compared to physical limits.

1. INTRODUCTION

Imaging is, since its birth, a race going toward sensitivity. Starting from the first photographic plates (films) to reach the today's ones, through the electronic pick-up tubes - from vidicons to modern Harpicon [1] - this requirement applies now to CCD's.
That goal is antinomic with the increase in resolution required by HDTV :
- The optical format must stay within standards - 1 or 2/3 inch.
- No way of extending the wavelength spectrum range : it is defined by the eye at get colour reproduction.
- No more way through increased exposure time : The TV standards set the frame rate to 50 or 60 Hz.

The problem for CCD designers is thus reduced to "How to realize, over the smallest area, an array detector able to deliver the biggest number of spatially independent informations under the lowest illumination ?".

Quality criterias to be met are
- Sensitivity, quantified by the electrical signal to noise ratio for a given illumination input.
- Resolution, including MTF and aliasing problems inherent to the sampling process by the CCD pixels.
- Lag, that is parasitic residual image from frame to frame.
- Dynamic range with the mandatory anti blooming protection.

To those quality goals, let us add the industrial considerations applying to power consumption and ease of operation.

2. EXISTING ARCHITECTURE AND DESIGNS

Among the solutions used by different manufacturers to improve sensitivity one aims at a noise reduction, others at an increase of spectral response. The first one is mainly related to the design rules used for the output circuit ; some tens of electrons r.m.s. even for bandwidth extending to 36 MHz are currently reported [2, 3, 4]. Anyhow that limiting value is set by the quality of the surrounding electronic as much as by the CCD itself.
The single requirement at the CCD level is to maintain the Fixed Pattern Noise at a lower level of visibility than the temporal noise.

TSMC EX. 1017 Page 2 of 11

-The pixel design contains the answers to the other way. On a CCD area array, both functions of light conversion and charge transfer must be made. As charge transfer requires conductive gates that are generally made of polysilicon, the light transmission is very poor, mainly in the blue part of the visible spectrum. Ways to avoid that loss of light conversion include virtual phase [5], locally omitted gates[6], transparent gates and backside illumination after thinning.

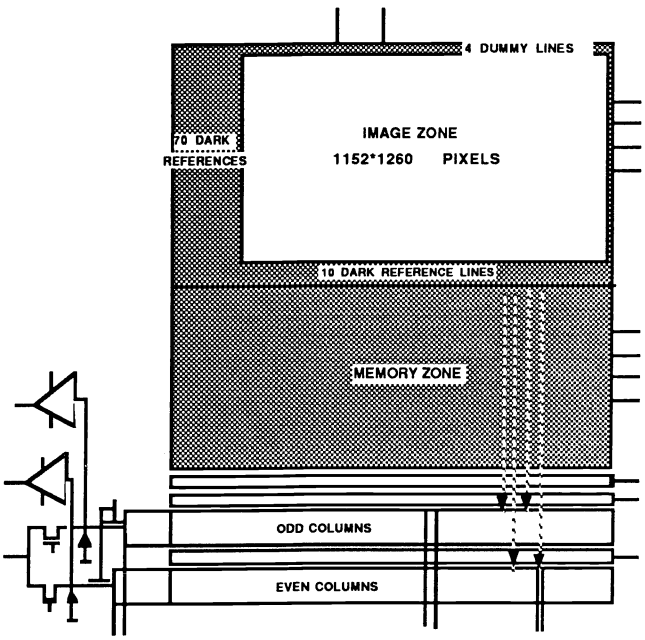
Other approaches are to amplify the photo generated charge at the pixel level before transfer[7, 8] That cannot compensate for a low Quantum Efficiency (Q.E) when the shot noise concerns packets of a few thousands' photoelectrons per pixel.

Last orientation, mainly preferred chosen by Japanese manufacturers, is called Interline Transfer or Frame Interline Transfer : the total die area is split into two parts : one dedicated to light conversion, the other to charge transfer. The resulting fill factor (Ratio of photosensitive area to image area) is low and limits the Q.E.
Improvements already exist to minimize that limitation including micro lenses on each individual photodiode [9] or coating of the image area with a continuous photodetection layer similar to those of pick-up tubes [10]. In each case those "added improvements" are made at the expense of a more difficult process. The interline organization itself requires a leading edge VLSI process the investments of which are returned through large volume consumer products.

3. ORGANIZATION OF THOMSON CCD SENSORS

3.1. Design of the EDTV CCD's

Organization of the EDTV CCD's



Two types of CCD's have been designed and realized. One is frontside illuminated "FI", the other is thinned and backside illuminated "BI". Both are electrically and optically compatible and allow a "FI" device to be put in the red channel with two "BI" ones used for green and blue channels.
Their optical format is one inch, 16/9 aspect ratio including 1152 lines of 1260 pixels. The pixel is therefore 11 µm (H) by 13.6 µm (V).
The readout is made through two registers fed by odd and even columns respectively through two demultiplexing gates. They are separately driven at 24 MHz.
The design rules used are 1.5 µm.
The useful die area is 2.2 square centimeters including memory area required by frame transfer operation.

3.2. Manufacturing process

Starting from an epi P over P+ Si substrate, the process is that of a standard buried channel : four phases, three polysilicon levels, with lateral anti blooming drain and two aluminum levels dedicated to electrical interconnection and optical shield.

TSMC EX. 1017 Page 3 of 11

The thinned device does not include the last aluminum masking layer ; The thinning process is made over full four inche wafers. A 300 µm thick glass substrate is glued upon the thinned side. This glass substrate includes optically opaque parts that are aligned, during the gluing process, to delimit the dark reference pixels.
Cutting of individual chips is then done just before assembly in a special cavity down case.

4. PERFORMANCES

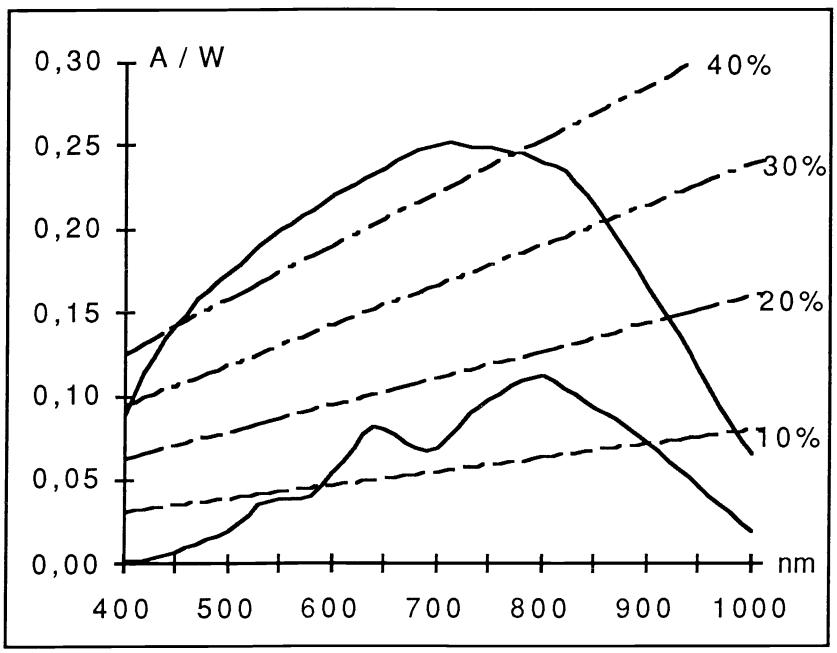
4.1. Sensitivity

4.1.1 Noise level

As already stated the temporal noise level is set by the design rules used and technology performances. The output node capacitance is 15 fF resulting in a kTC noise of 50 electrons. The amplifier bandwidth has been extended to 120 MHz to reduce rise and fall times and to allow a good rejection of kTC noise through CDS processing.
Total measured noise after CDS is 400 µV.
Fixed Pattern Noise (FPN) in darkness has been measured after integration time of 2 to 4 seconds. The r.m.s. non uniformity is less than 5% of the mean value of dark signal ; that sets the FPN value, under normal operating conditions, well below the temporal noise.

4.1.2 Spectral response

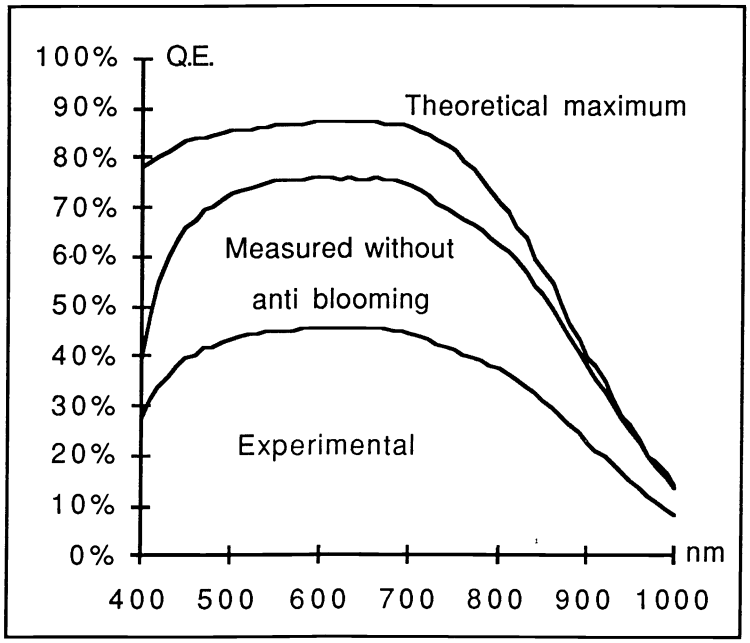
Spectral response of Frontside and Backside illuminated EDTV CCD's



Attached figure clearly shows the advantage of "BI" device compared to "FI" one. The sensitivity of the "FI" is limited, at short wavelengths, by the absorption of polysilicon gates, and in the whole spectrum, by the fill factor of the pixel with lateral anti blooming protection. However this anti blooming mode avoids the loss of red and infra-red sensitivity related to buried overflow drains associated to Interline organization.

TSMC EX. 1017 Page 4 of 11

Absolute Q.E. of thinned EDTV CCD's



The "BI" device could, theoretically, approach the 100% Q.E. The gap with experimental present values is fully explained and will reduce with technological progresses.
First, the optical reflection by the silicon is naturally lowered by the assembly process that inserts the glass substrate between air and silicon. The index matching is still improved with anti reflection coatings : a SiO layer is deposited on the silicon after the thinning process ; A high efficiency anti reflection coating matched to the visible spectrum is deposited on the front side of the glass substrate.
The resulting transmission of those layers has been calculated and defines the maximum theoretical Q.E.

At long wavelengths, the transparency of the thinned membrane of silicon sets an other limit to theoretical Q.E. The general so called theoretical curve is represented on the above figure.
For colour TV, where spectrum of interest is limited to 400 - 700 nm range, a thickness of 15 µm of silicon seems a good compromise between sensitivity in the red channel and mechanical strength of the thinned wafer during last steps of the process.
The most important part of the deviation between experimental and theoretical Q.E. comes from the collection of useful signal by the anti-blooming drain. On devices the rate of loss has been measured as 40% of collected photoelectrons, slightly depending upon the respective biasing of anti-blooming drain and integrating gates.
The total number of collected photoelectrons has been measured while keeping the anti-blooming drain not connected.
Compared to the theoretical limit, it makes apparent the last origin of the discrepancy between theory and experiment, which is the recombination of electron-hole pairs. This effect is the most important near the backside interface for extreme blue part of the spectrum where absorption length of photons is a few tenths of microns.
Careful optimization of the Si doping profile and thermal process after thinning will still improve that figure.

4.1.3 Photoelectron noise limited sensitivity

Whatever the Q.E. value and amplification before readout, if the noise in darkness is sufficiently low, it always exists an illumination level at which the image becomes photoelectron noise limited. That limitation hardly appears with standard measurements of signal to noise ratio where the noise is measured in darkness.
Main characteristics of the photoelectron noise are :
- Amplitude rising as the square root of electron number

TSMC EX. 1017 Page 5 of 11

- Frequency distribution uniformity from line frequency (after clamp) to Nyquist frequency.

Fortunately the eye is less sensitive to noise in the white parts of an image than in the dark ones ; The photoelectron noise should therefore be weighted by gray levels before comparison to noise in the dark.

A first rough figure of the photoelectron noise limitation may be approached through the saturation level of the device. Assuming an illumination level high enough to reach the maximum full well of 100 000 electrons, the maximum signal to noise ratio attainable, is 50 dB.

To reach that number of electrons with an ideal pixel of 11 µm x 13.6 µm, 100% Q.E., integrating green light during 20 ms, 15 lux of 3200 K light are required in the focal plane. That means around 2000 lux over the scene when shooting with a perfect F/5.6 lens.

To deal with more realistic conditions of scene illumination, scene reflectance, transmission of the lens and Q.E. of the sensor, the camera operator must open the lens iris . . . and loose depth of focus therefore resolution on 3D scenes.

The practical level at which an image becomes photoelectron noise limited is hard to define as it depends upon the content of the images and upon the required level of quality. As a rule of thumb one should consider that a studio quality picture cannot be taken with less than 3 to 10 thousands electrons in the white parts of images.

The above figures clearly show the intrinsic advantage of a sensor design allowing to approach the theoretical limit for Q.E. They prove too, the direct relationship between sensitivity and size of the pixel that in turn defines resolution.

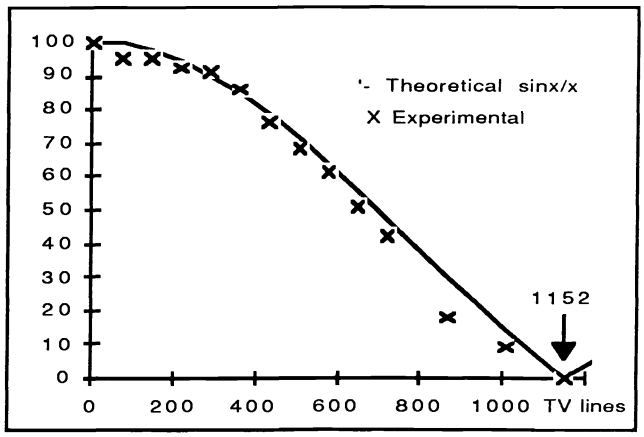
4.2. Resolution

The first global quantization of the resolution of a CCD is the number of active pixels over the image area. This figure sets the spatial sampling frequency and has to be refined by the modulation transfer fonction.

For a given pitch of the pixel, the MTF is related to the fill factor of the pixel, the greater the fill factor, the lower the MTF - again revealing sensitivity / resolution antinomy -.

The measurements of the MTF in horizontal and vertical direction may be made through CTF using black and white bar patterns of variable frequency, or by Fourier transform of the line spread function. We used the last solution with the knife edge method. Results include the lens MTF which is around 90 % at 40 line pairs/mm and are presented on figures hereunder.

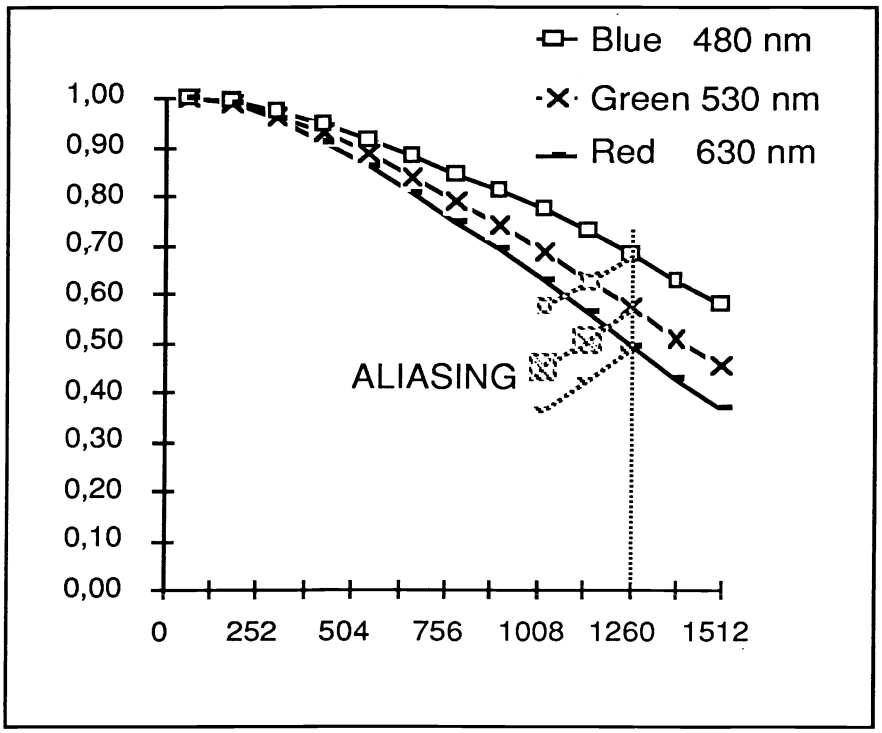
Vertical MTF of EDTV CCD's



The vertical MTF is the same for both "FI" and "BI" device and is not strongly dependent upon the light wavelength. It is very close from the theoritical sinc function applied to the 13.6 µm vertical pitch of the pixel. The spatial sampling process includes a shift of half a pitch from frame to frame resulting in 1152 interleaved samples within the image height. This locates the apparent Nyquist Frequency at 1152 TV lines (576 line pairs). The pixel pitch being twice the sampling pitch, the modulation is zero at Nyquist frequency and almost no aliasing occurs.

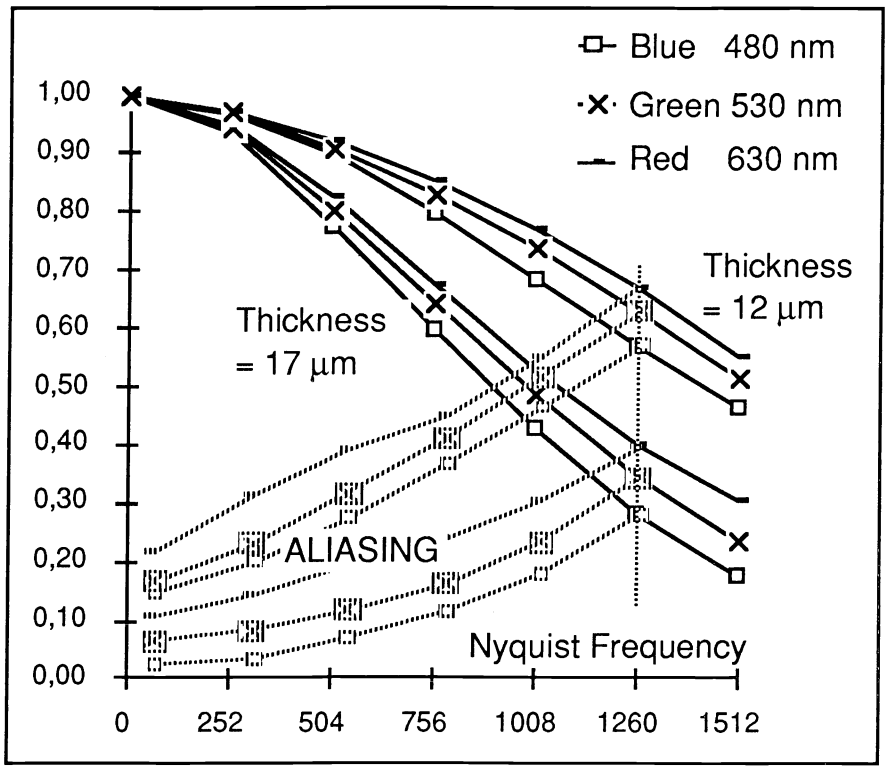
TSMC EX. 1017 Page 6 of 11

Horizontal MTF of "Frontside illuminated" device



The horizontal MTF behavior is different : For "FI" devices the geometrical fill factor is around 65 % and gives rise, mainly at short wavelengths where electron diffusion is small, to a very high 70 % modulation at Nyquist frequency. This figure is slightly impaired for green and red part of the spectrum by electron diffusion as shown on attached figure.

Horizontal MTF of backside illuminated EDTV CCD's



The "BI" device exhibits a reverse variation vs. wavelengths but, at present, due to the collection by the drain, the appearent fill factor is about the same as the "FI", and results in the same 70 % modulation for devices thinned down to 12 µm. That value may be considered as too high regarding aliasing phenomena, and optical low pass filter is almost mandatory.

The control of the modulation at Nyquist frequency could be done through tight tolerances of the thickness during thinning process, but would induce manufacturing yield reductions.

TSMC EX. 1017 Page 7 of 11

The next developments intended on that device should sharply reduce the collection by the drain and therefore bring the fill factor near unity. The resulting modulation at Nyquist will be mostly defined by the diffusion phenomena and result in a 30 % value. This seems a good compromise between the absolute filtering to zero in order to avoid any aliasing, and a higher value that allows sharper image rendition.

4.4. Dynamic range

As for sensitivity, the lower limit is set by the most visible noise. Some "noises" are however generated by the higher values of the signal : They are blooming and smearing.
To cancel the first one we chose to use a lateral protecting system. Eventhough, as detailed before, it causes a reduction of the fill factor, it does not limit the Q.E. value at long wavelengths and allows electronic shutter operation without high amplitude values of driving signals. Its efficiency was revealed satisfactory, even under strong overilluminations.
The smearing, this original sin of the CCD, is, for the frame transfer organization, fully transmitted to the readout. Its amplitude is proportionnal to the vertical transfer time operation and the vertical transfer frequency cannot be chosen it high enough to make (the smearing) negligible. The solution is therefore brought at the camera level by using an optical shutter during vertical blanking time. The smearing is, then fully cancelled. If this solution is not suitable for consumer camcorders, it does not seem a major drawback when adressing studio or ENG cameras.

The higher limit of the dynamic range is of course set by the anti-blooming protection that limits the output voltage when the device is overilluminated. That adjustment must be made at the highest possible value to leave margin to camera manufacturer to manage the rendition of high dynamic range scenes.
The physical limitation appears at the CCD level through transfer efficiency degradation when the charge to be transferred reaches the full well capacitance. This level depends upon the size of the storing part of the pixel - which becomes smaller and smaller when the resolution increases - and upon the processing parameters as doping level of buried channel and substrate or oxyde thickness.
Actually the first limitation met when increasing the charge to be transferred, is related to the attenuation of driving signals through the polysilicon gates. The one inch format, choosen to deal with sensitivity and resolution requirements, implies large loading capacitance between gates and substrate. The polysilicon resistivity causes RC time constants limiting the amplitude of the applied signal when the transfer frequency increases. Even with both side adressed gates, that effect is the limiting factor at the lowest transfer frequency allowed by available vertical blanking time.
That limitation appears today on every organization of 16 / 9 format CCD's including the large line number of HDTV.
Future developments of those devices will include a drastic reduction of time constant effects through aluminum connecting buses over the whole imaging area. That may be done without any impairment of the sensitivity of the "BI" device, and - at expense of few lithographic improvements - of the "FI" device too, routing over the non sensitive anti-blooming area.

4.5. Lag

That performance of imaging sensor relates to their ability to transmit moving scenes without blurring. It implies a complete readout of each frame to avoid any "ghost" of the previous one. That problem was mainly encountered with pick-up tube photoelectric layers, and CCD technology had put it in the museum.

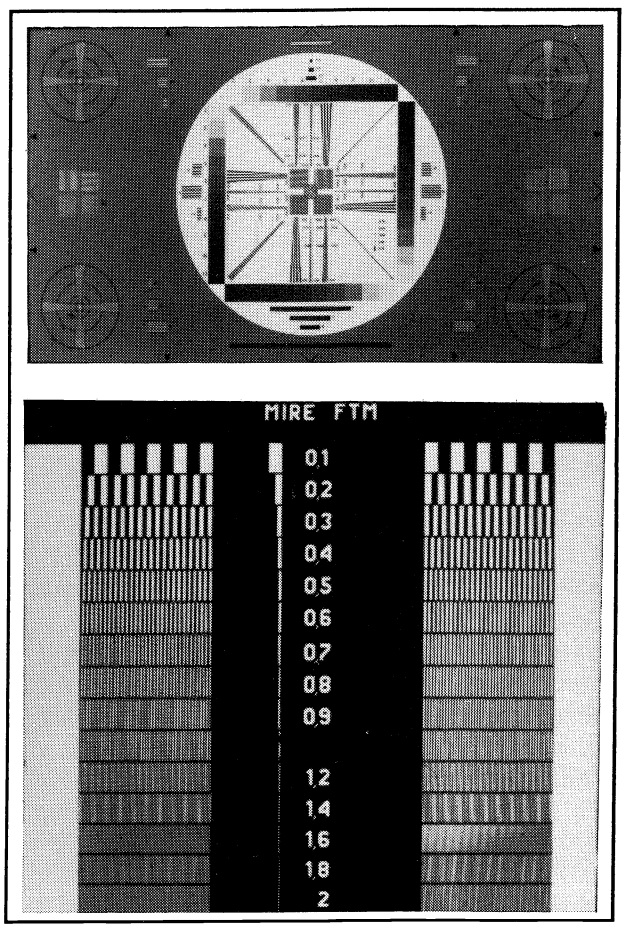
TSMC EX. 1017 Page 8 of 11

But with tiny pixels, that effect appears again with interline organization due to incomplete transfer from the photoconversion part to the charge transfer part. To avoid that effect, manufacturing process must include alignments of masks to 0.1 µm accurac [11]. If that condition is not fulfilled the residual image, not transferred, can be suppressed by anti-blooming system, but it is at the expense of a loss of sensitivity. Besides that loss may be not proportionnal to the signal, inducing, at low levels, non linearities.
The frame transfer organization is, thanks to its principle of operation, free of that type of defect.

4.6. Industrial viewpoint

The thinning process is yet a small volume technology, but it fits to studio and ENG camera's market, more strongly driven by performance than consumer market.
Another technical argument for the thinned technology relates to the depth of focus. After processing, silicon wafers exhibit a curvature that can reach up to 30 µm over a 2 square centimeter chip. That curvature is opposite direction of the standard curvature of best optical focus surface of lenses. This results in a loss of resolution when using large aperture number even for 2D scenes. The thinning process makes the imaging area soft enough to be glued flat over the perfect optical plane of the glass substrate. An overall flatness less than 10 µm is currently achieved and appears necessary for area array with pixel size of 11 µm or less.
The following images show a 16/9 resolution chart, a home made FTM pattern (Fnyquist = 1260 points/line corresponds to 1.6 spatial frequency) and image taken from a drawing.

16/9 Resolution chart



Home made resolution bar pattern

TSMC EX. 1017 Page 9 of 11

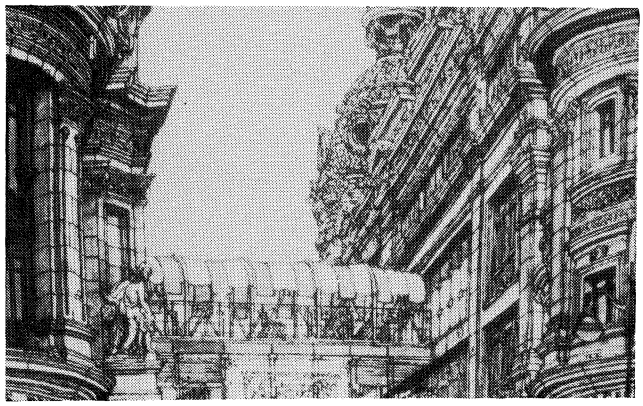


Image taken from a drawing

4. CONCLUSION

The general design choices made for those EDTV CCD's aim at the main objective of sensitivity.
That parameter has always been a major one for imaging technology, and becomes even more crucial to deal with high definition television. The necessary compromises include the use of a mechanical shutter at the camera level and limited number of pixels compared to 1920 HDTV standard. They allow, with available technology, to realize industrial products with few blemishes. Up to now, technology progresses had been fast enough to improve from one generation to the following, both the resolution AND the sensitivity. With HDTV the physical limits of photoelectron noise limited images, have become very close and make mandatory the use of large aperture number lenses. Fronted now to the choice of getting more resolution OR more sensitivity, it is mandatory to carefully size the pixel to avoid loosing through depth of focus what has been improve by pixel shrink.

5. ACKNOWLEDGMENTS

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TSMC EX 1017 Page 10 of 11

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TSMC EX. 1017 Page 11 of 11