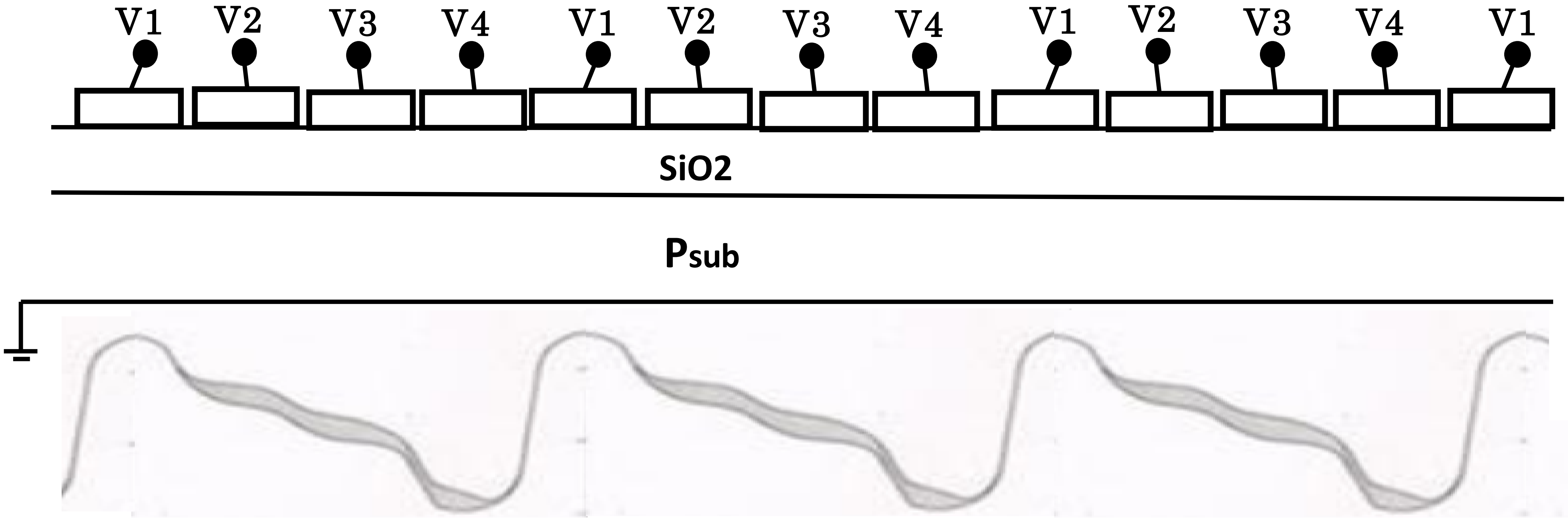
Yoshiaki Hagiwara

4　CCD/MOS type PDD and CTD

Under Construction

4 CCD/MOS type PDD and CTD

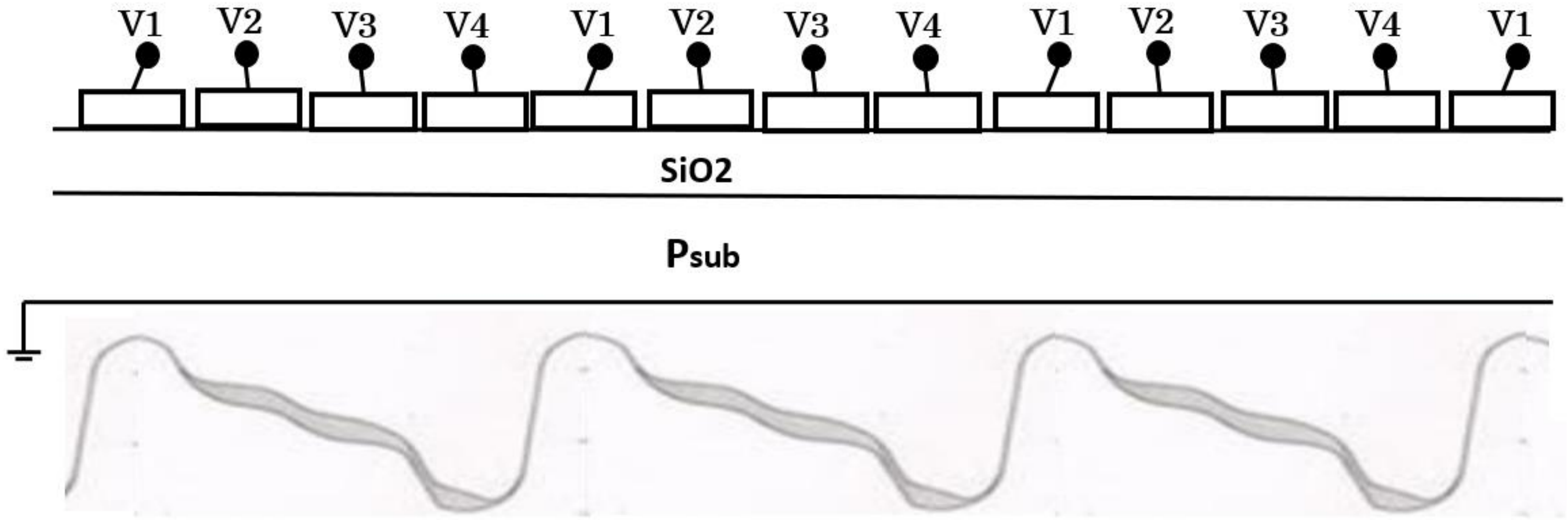
In 1970, Boyle and Smith in Bell Labs showed that a single charge packet in a MOS structure could be stored in a potential well under a depletion biased metal electrode.



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

The MOS structure moved a charge packet from under one electrode to the next by appropriate pulsing of the electrode potentials.



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

The minority carriers, injected in response to a digital or analog signal or generated by photos, are stored as charge packets in these potential wells resulting in a decrease in depth of the potential well.

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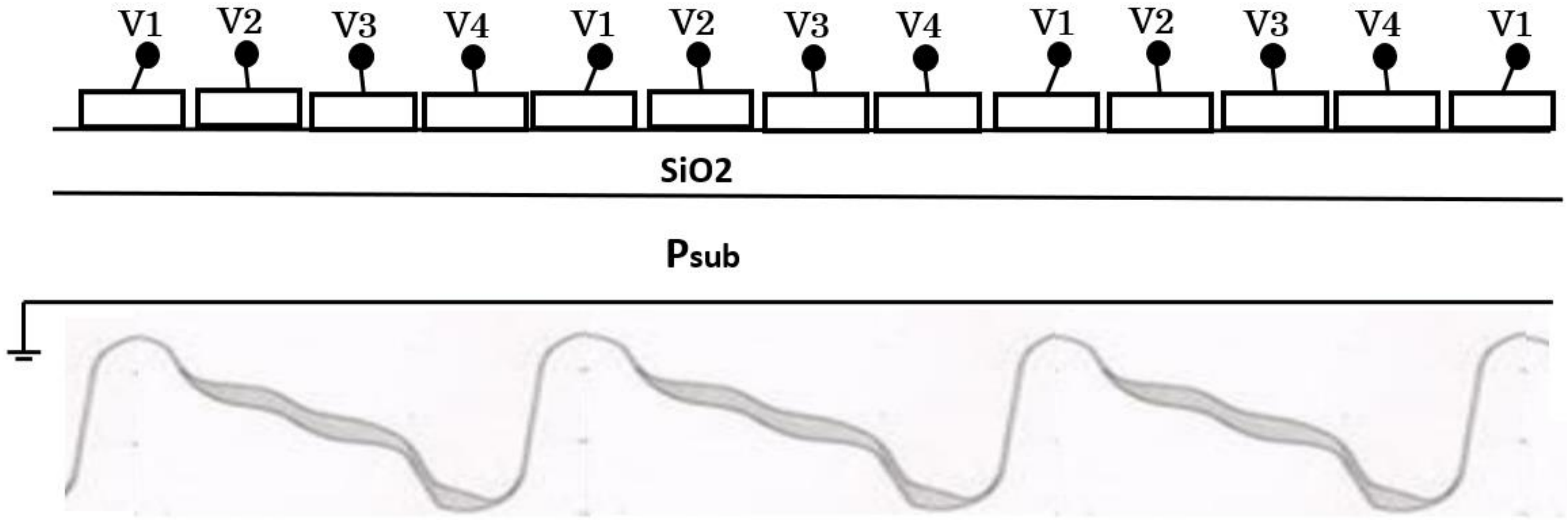
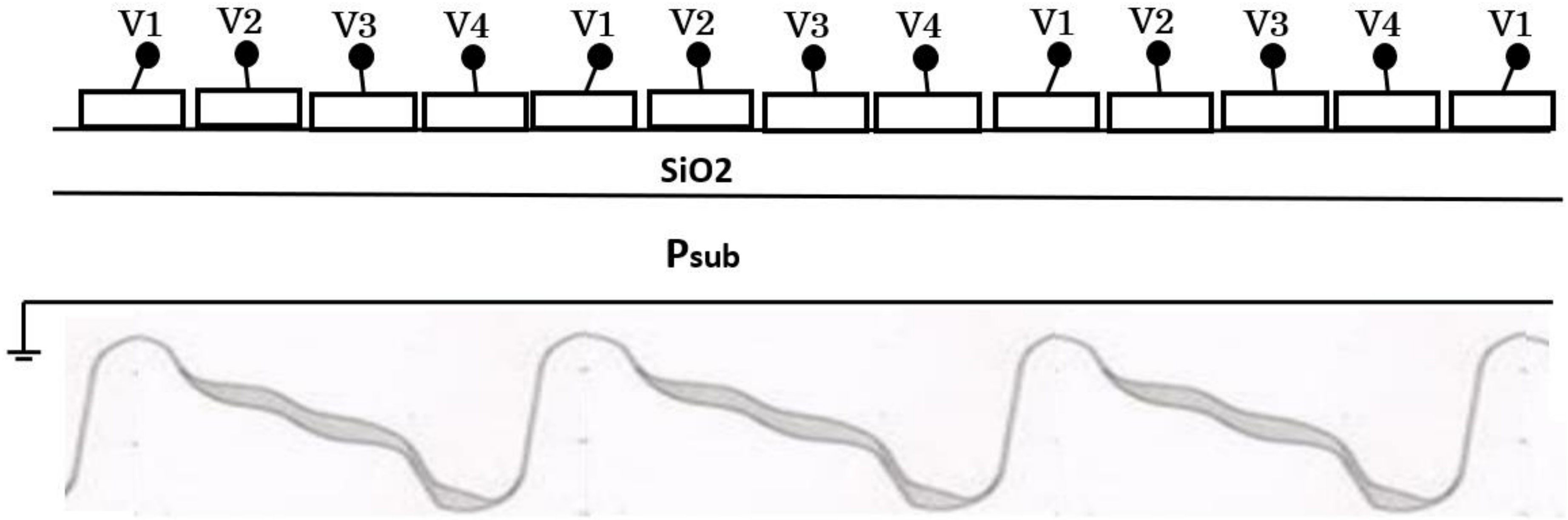


W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

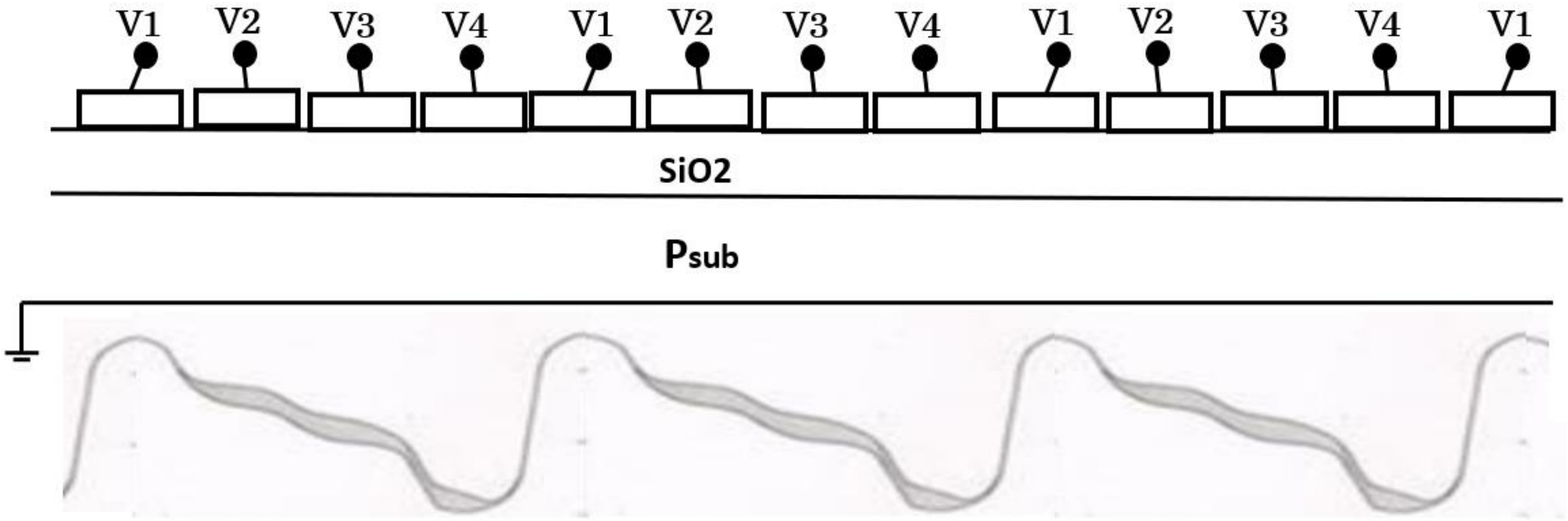
The storage and transfer of the charge packets are controlled by the clocking pulses driving the closely spaced electrodes.



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

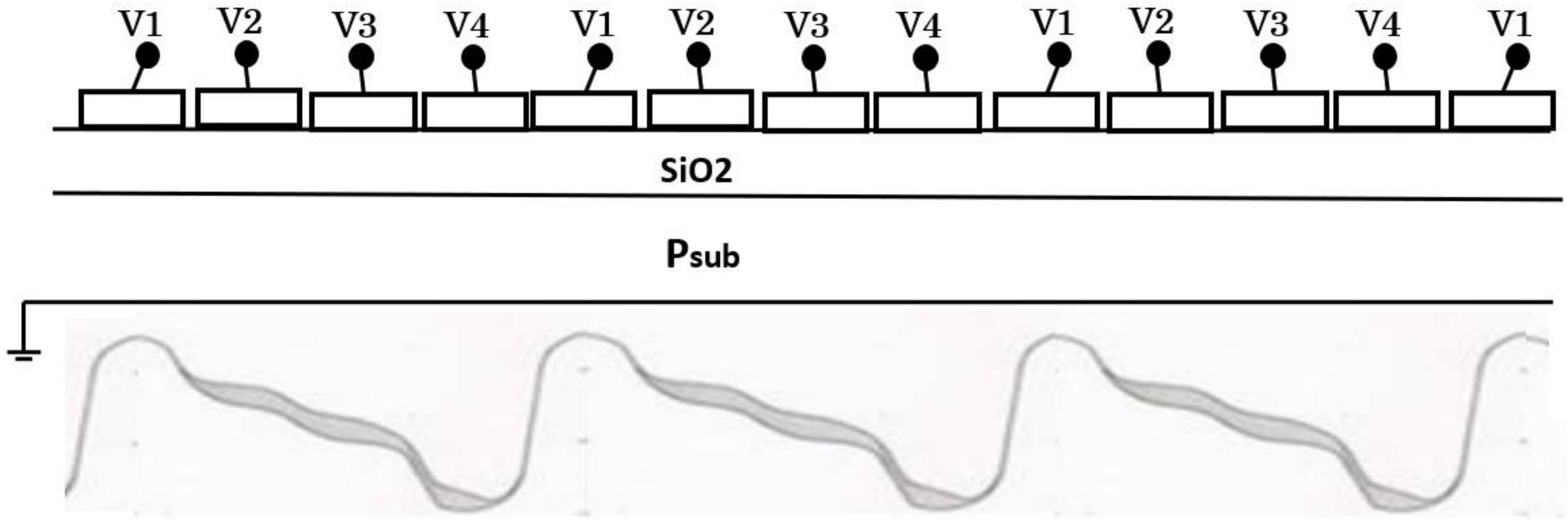
For the structure to be used as a signal processing device, the electrodes must be placed close enough to make the potential wells couple and the signal charge packets move smoothly from one well to the next.



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

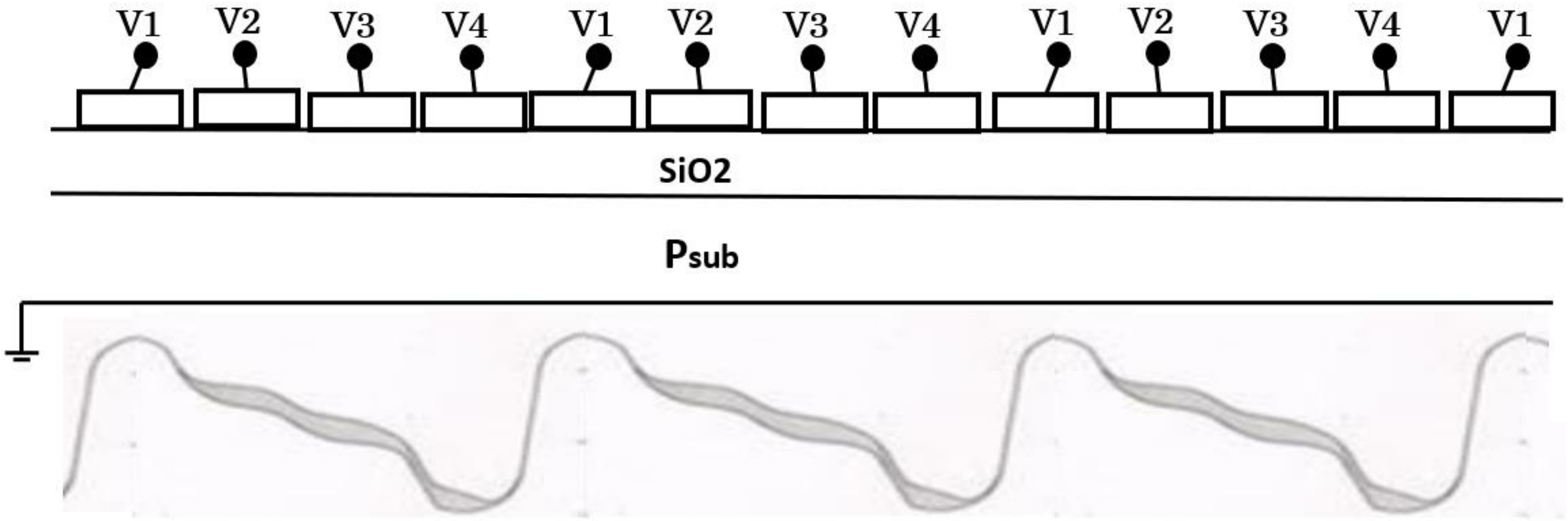
This special type of the charge transfer device (CTD) is now commonly known as the charge coupled device (CCD).



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

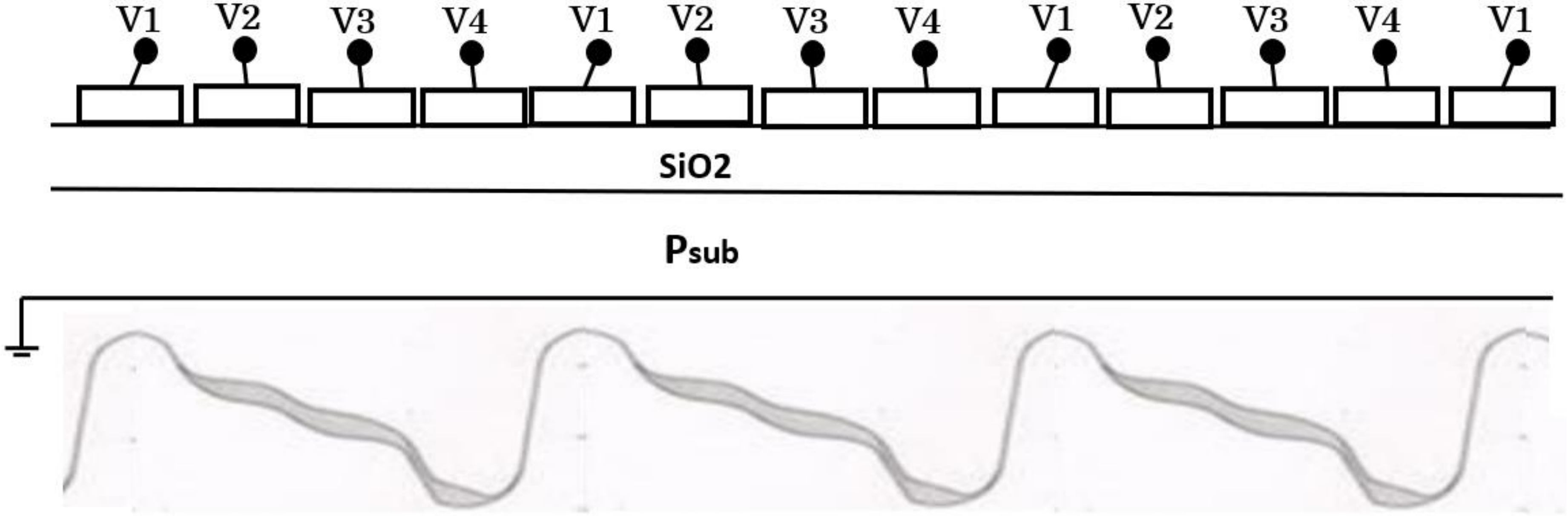
The original charge coupled device (CCD) , as introduced in 1970, is referred as the surface channel type charge couple device (SCCD) .



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

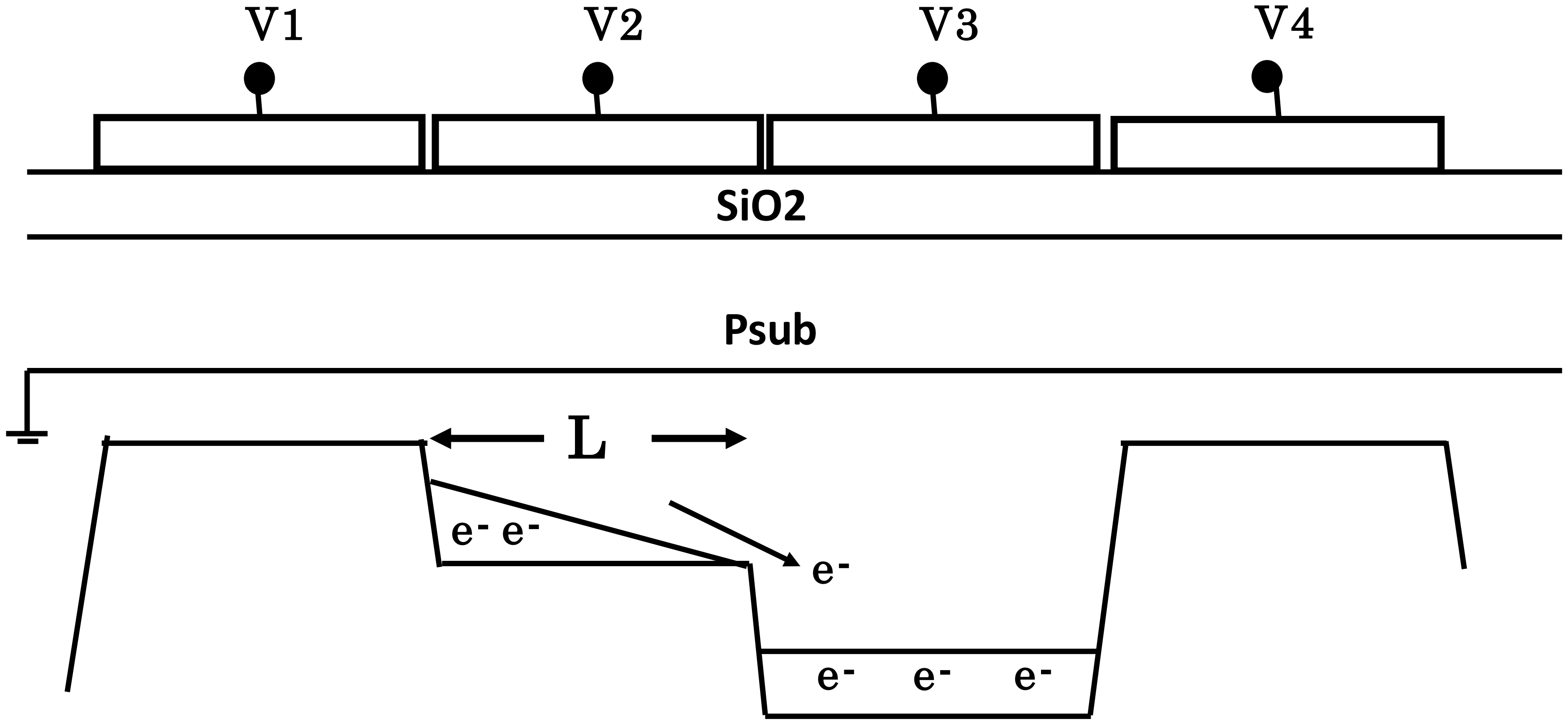
The original surface channel type charge coupled device (SCCD) operates by transferring minority carriers along the inversion layer of the semiconductor surface by voltage pulses applied to metal electrodes which are separated from the semiconductor surface by an insulating oxide layer (SiO2).



W. S. Boyle and G. E. Smith "Charge Coupled Semiconductor Devices," B.S.T.J.,49, No.4 (April 1970) pp.587-593

4 CCD/MOS type PDD and CTD

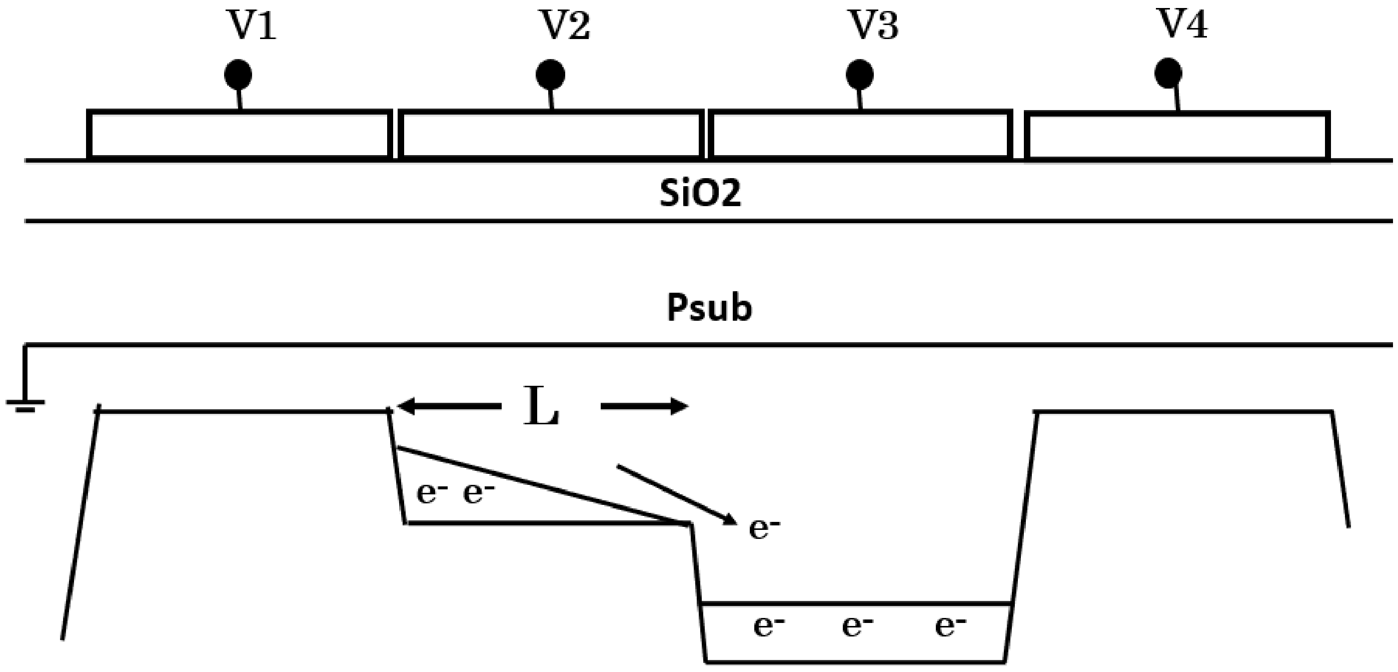
The transport limitations are largely determined by device geometry.



Yoshiaki Daimon Hagiwara et al, “Final Stage of the Charge Transfer Process in Charge Coupled device”, Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

For long electrodes, thermal diffusion is predominantly responsible for preventing the free movement of the last remaining signal charge.



$$Je = D_{th}\frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

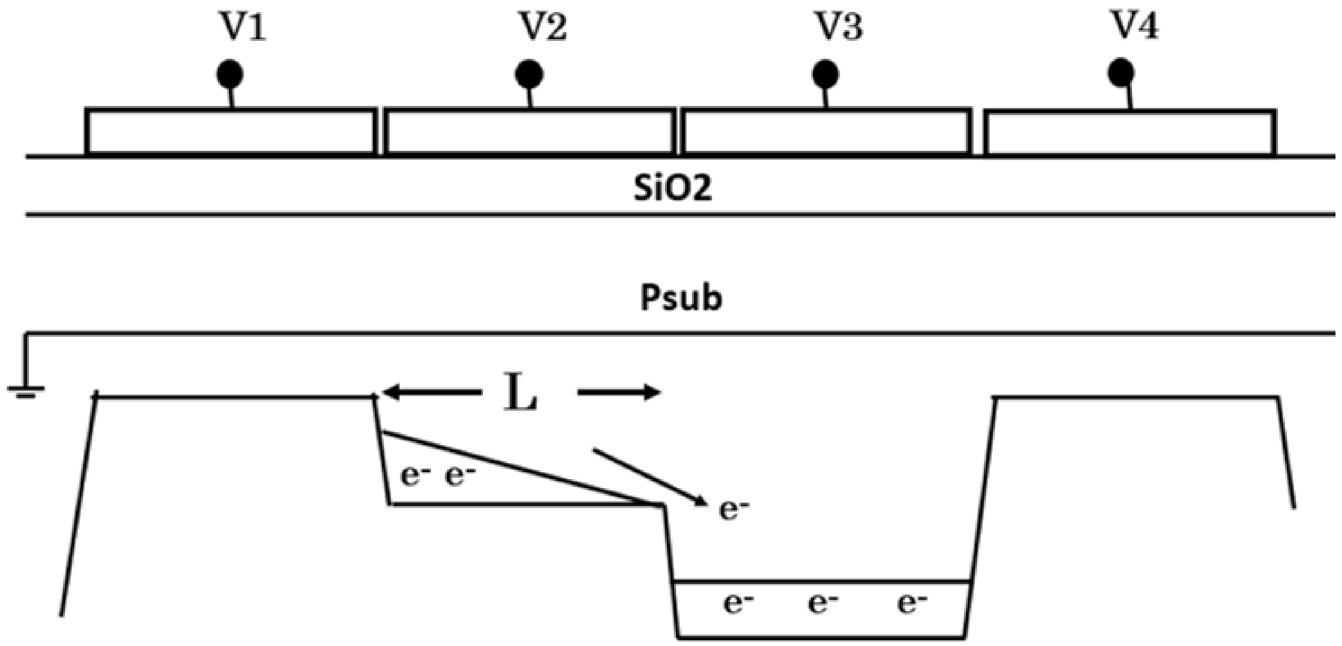
Last Remaining Signal Charge $Q(t)$

$$Q(t) = Q(0)\exp(-t/\tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

Long electrodes of the surface channel CCD type charge transfer device (CTD) limit the efficient operational clock frequency less than 10 M Hz.



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

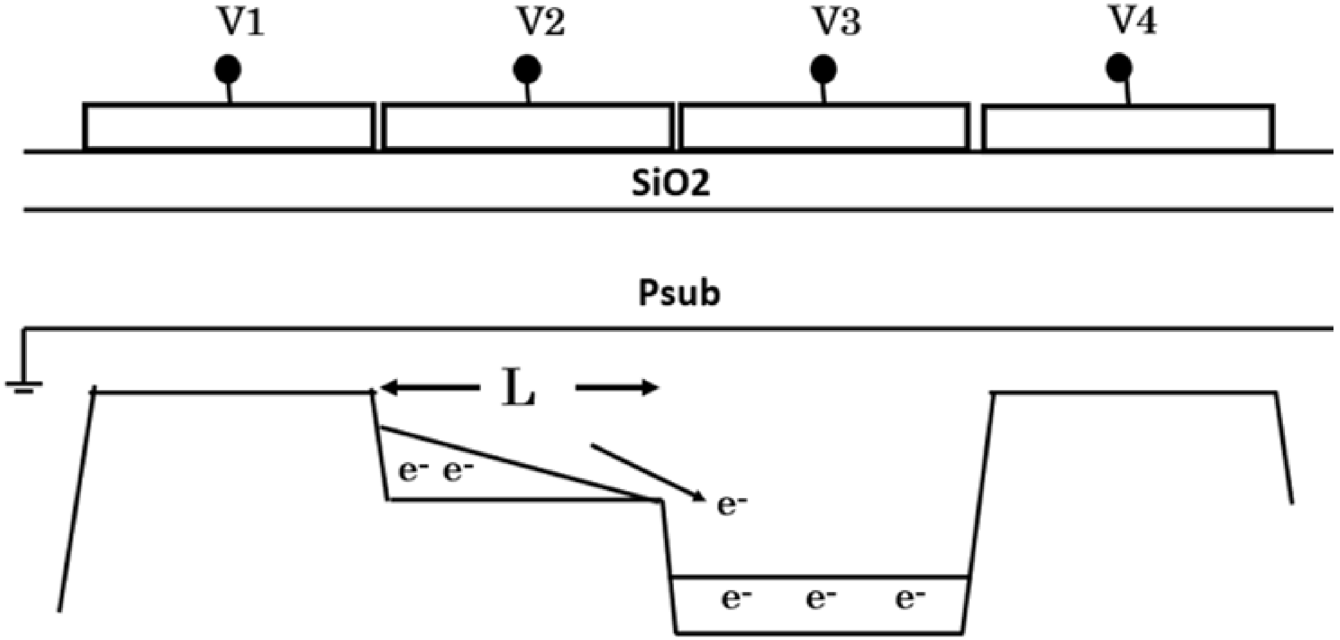
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp(-t / \tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

However, the analog signal charge packet transfer needed at least the operational frequency of 13.1818 MHz.



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

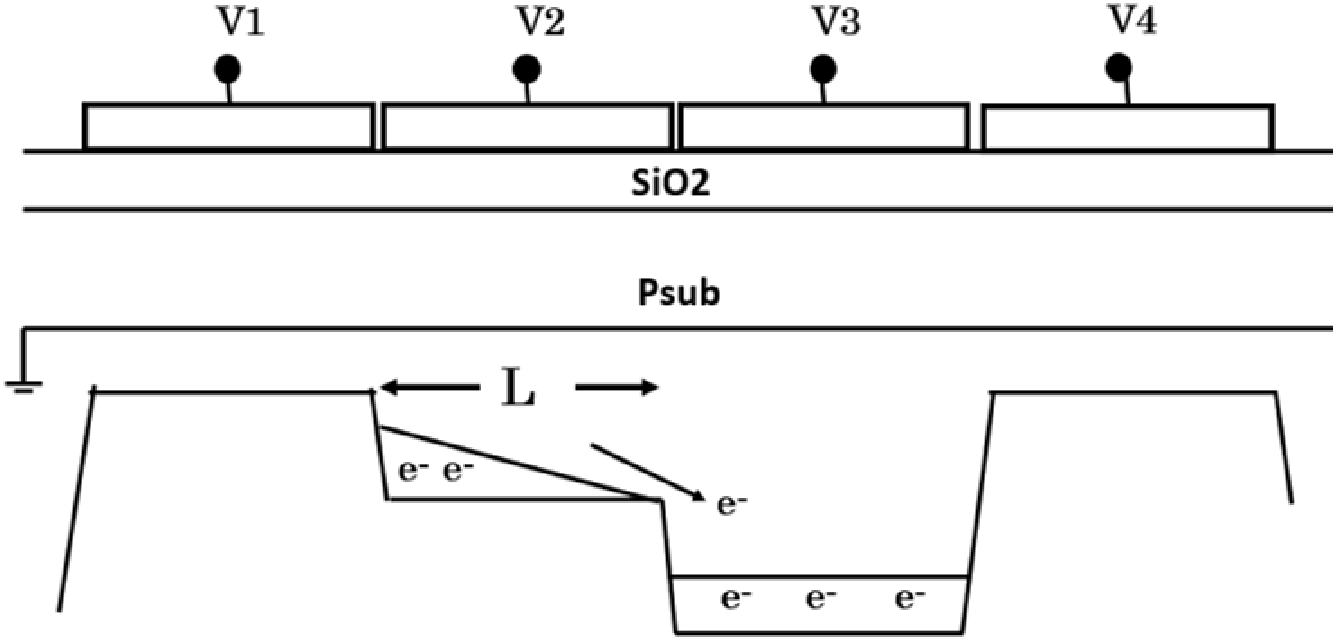
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp(-t/\tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

But the clock frequency of 10 MHz was too slow for the picture format of the 800H x 500V pixels standard NTSC analog TV system.



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

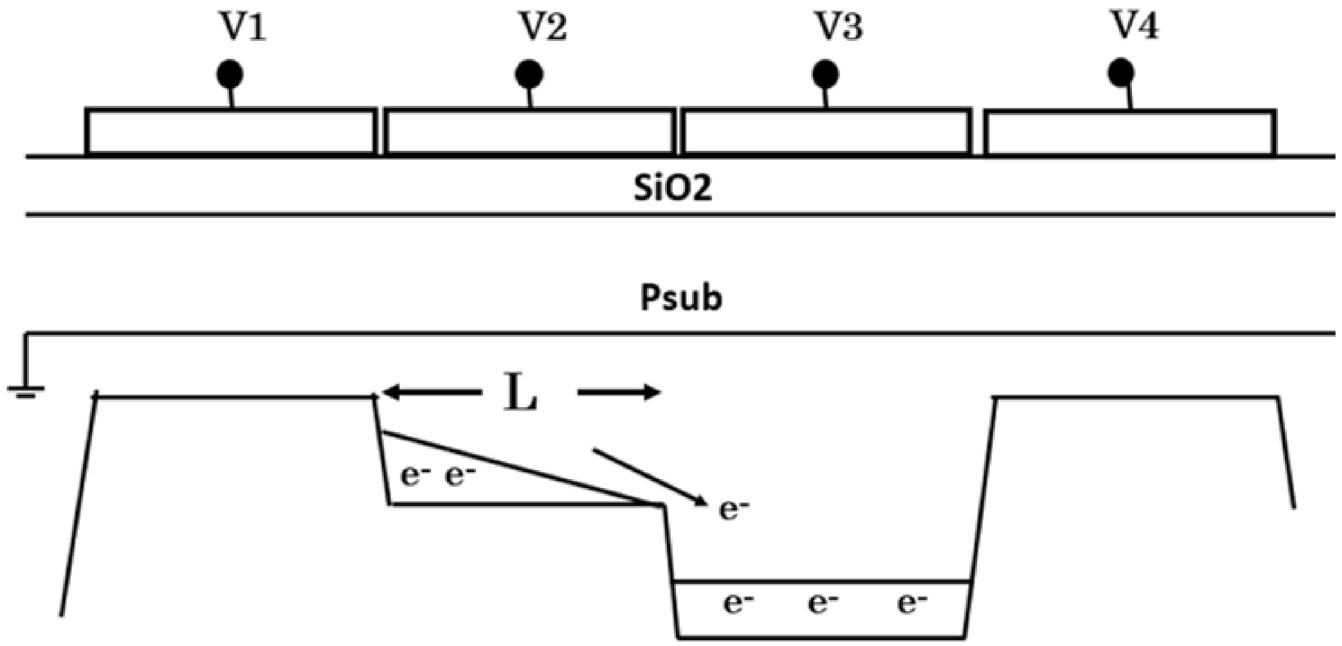
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp(-t/\tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

The charge transfer device (CTD) for the solid state imager required at least the 13.1818MHz signal charge packet transfer frequency for the standard NTSC analog TV picture format of 800H x 500V .



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4 L^2}{\pi^2 D_{th}}$$

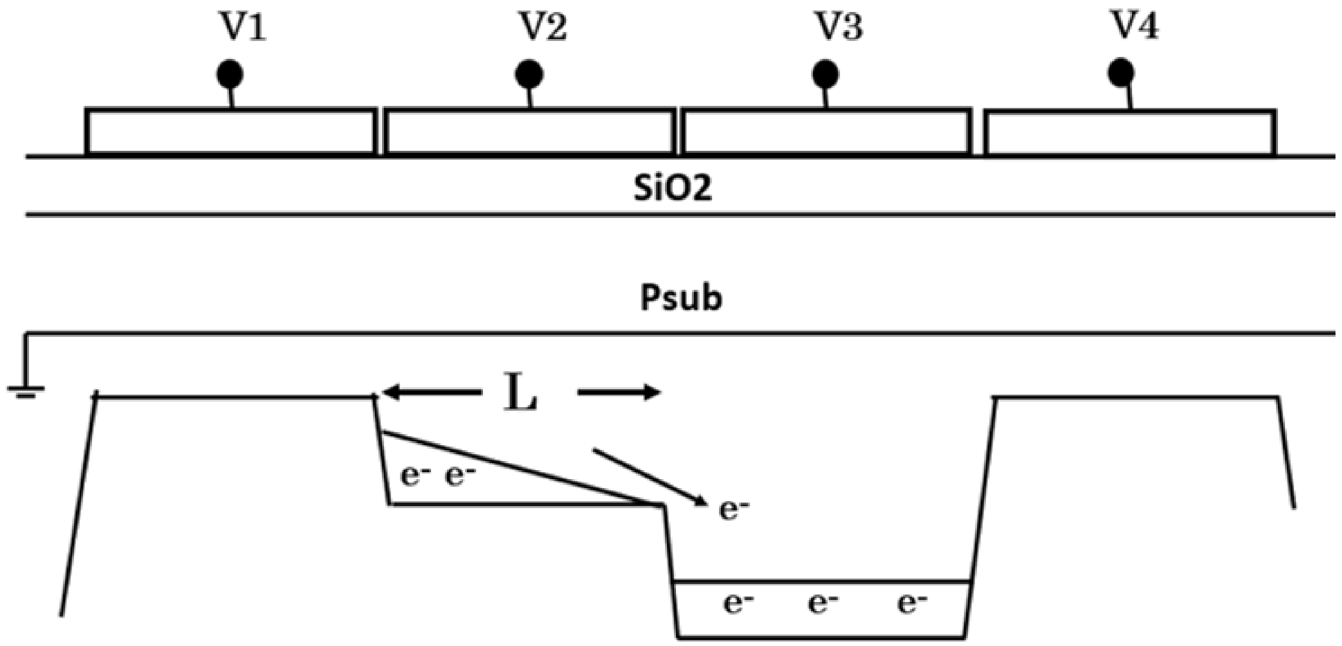
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp (- t / \tau_{th})$$

R. H. Walden, R.H. Krambeck, R.J. Strain, J.McKenna, N.L.Schrywer and G.E. Smith, "The Buried Channel Charge Coupled Devices", B.S.T.J. BRIEF, 51, No.7 (September 1972), pp. 1635-1640.

4 CCD/MOS type PDD and CTD

That is, the analog signal charge packet transfer needed at least the operational frequency of 13.1818 MHz.



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

Last Remaining Signal Charge Q(t)

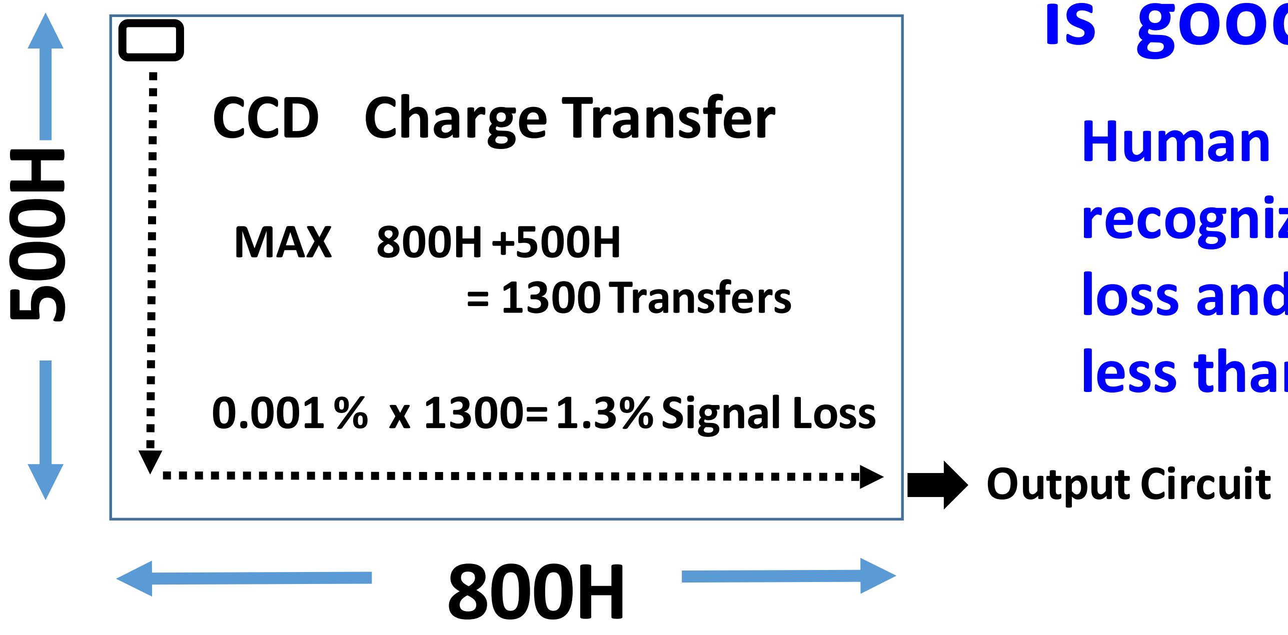
$$Q(t) = Q(0) \exp(-t/\tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

The limited clock frequency of 10 MHz was too slow for the standard NTSC television system picture format of 800H x 500V pixels.

CCD Charge Transfer Efficiency < 99.999%



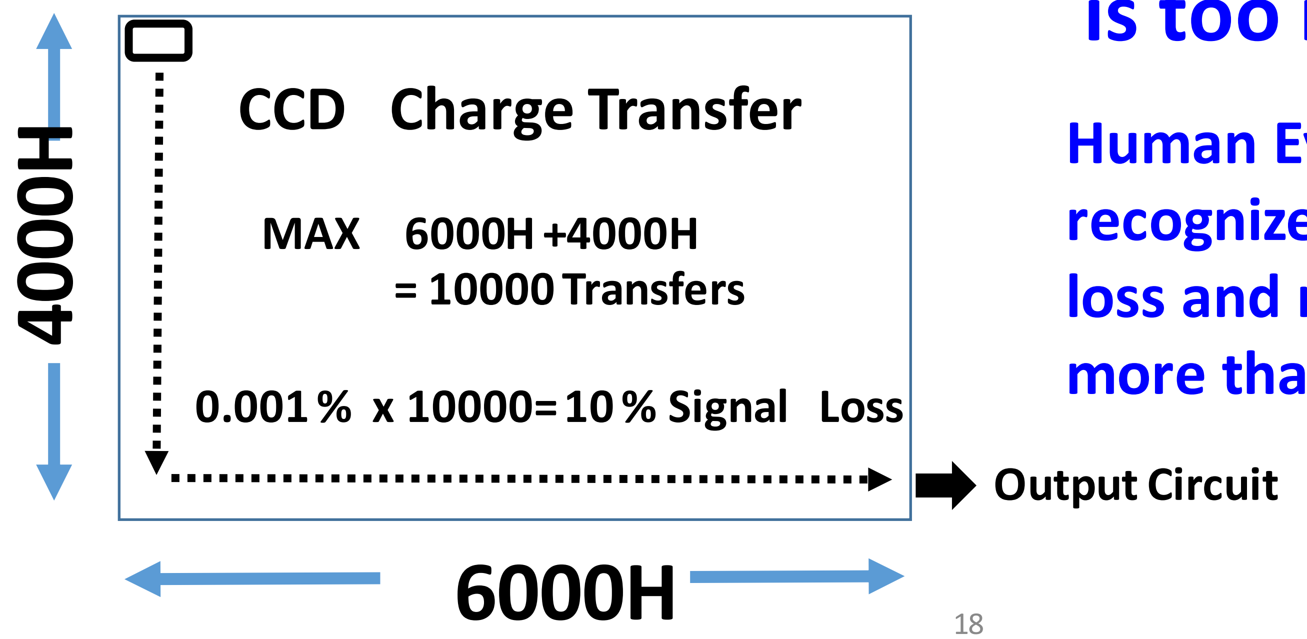
1.3 % signal loss is good and OK.

Human Eyes cannot recognize the signal loss and noise of less than 3 % .

4 CCD/MOS type PDD and CTD

In the present High Definition Television System of 6000H x 4000V pixel picture format, we need 13.1818 M Hz. x 6000 / 800 = 100 M Hz.

CCD Charge Transfer Efficiency < 99.999%

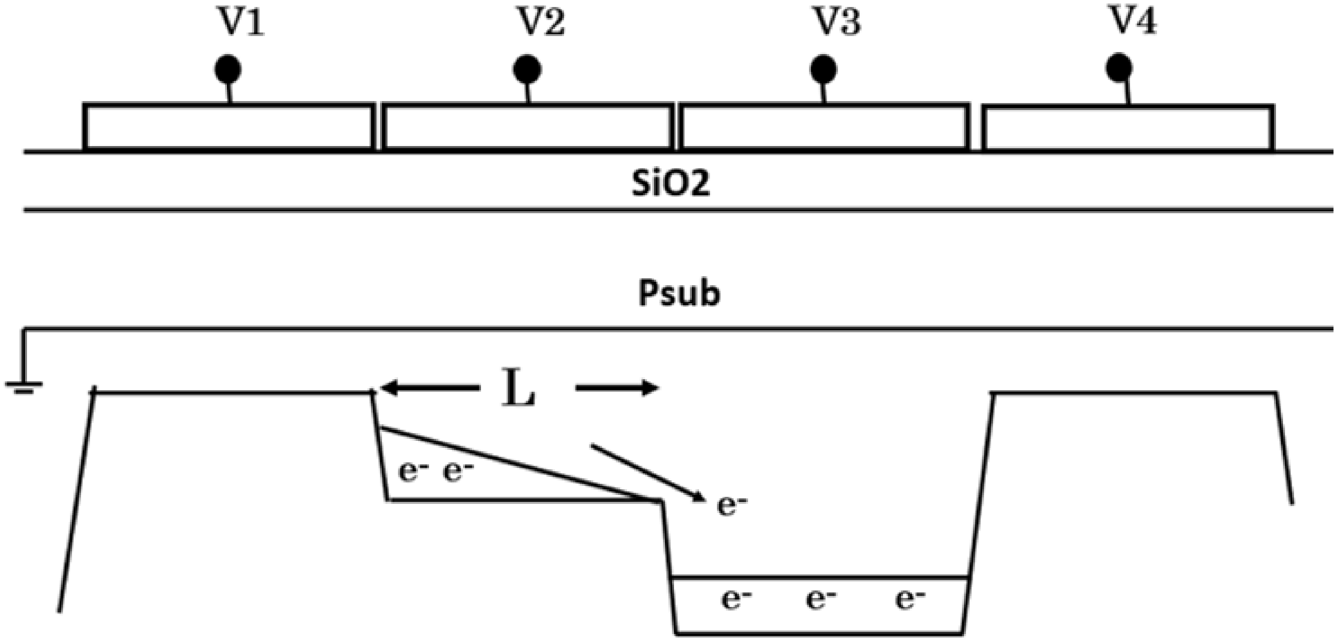


10% signal loss is too much.

Human Eyes can recognize the signal loss and noise of more than 3 % .

4 CCD/MOS type PDD and CTD

Besides, the surface channel CCD with the charge transfer efficiency of about 99.9 % was not suitable to serve as a practical charge transfer device (CTD).



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4 L^2}{\pi^2 D_{th}}$$

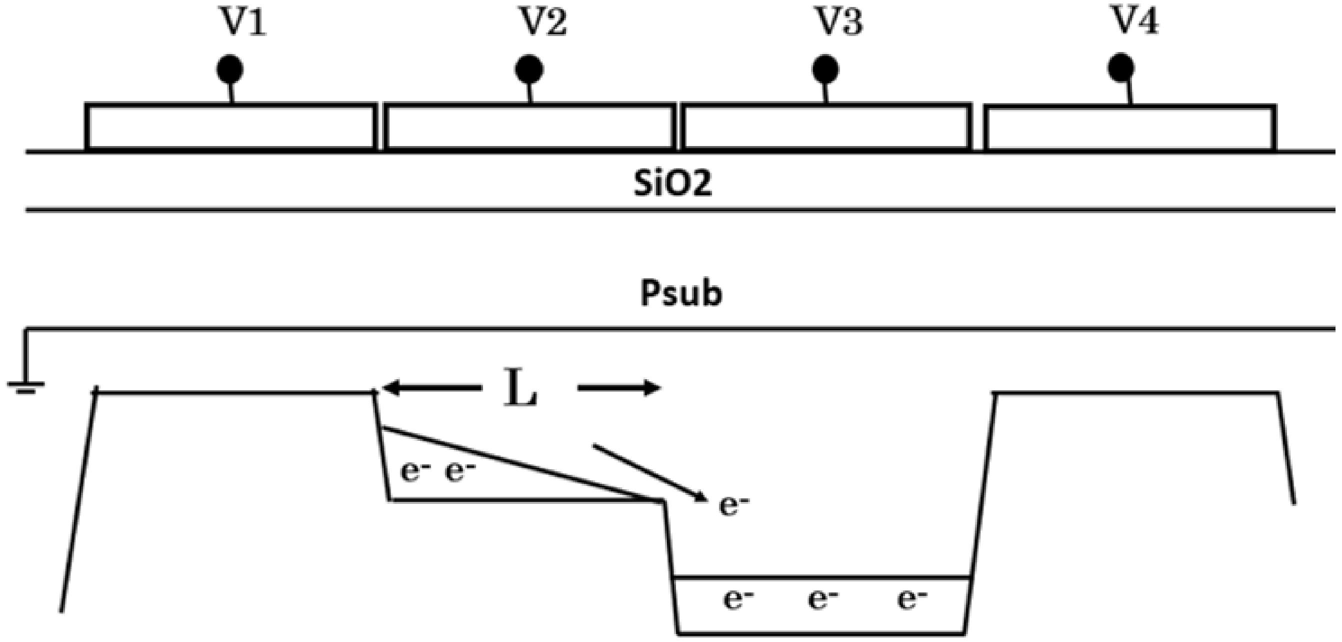
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp (- t / \tau_{th})$$

Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

Since at least 800H +500V = 1300 charge transfers for each picture frame was needed. The surface channel CCD gives the charge loss of 1300 x 0.1 % = 130 % , which was not practical at all.



$$Je = D_{th} \frac{dq(x)}{dx}$$

$$\tau_{th} = \frac{4 L^2}{\pi^2 D_{th}}$$

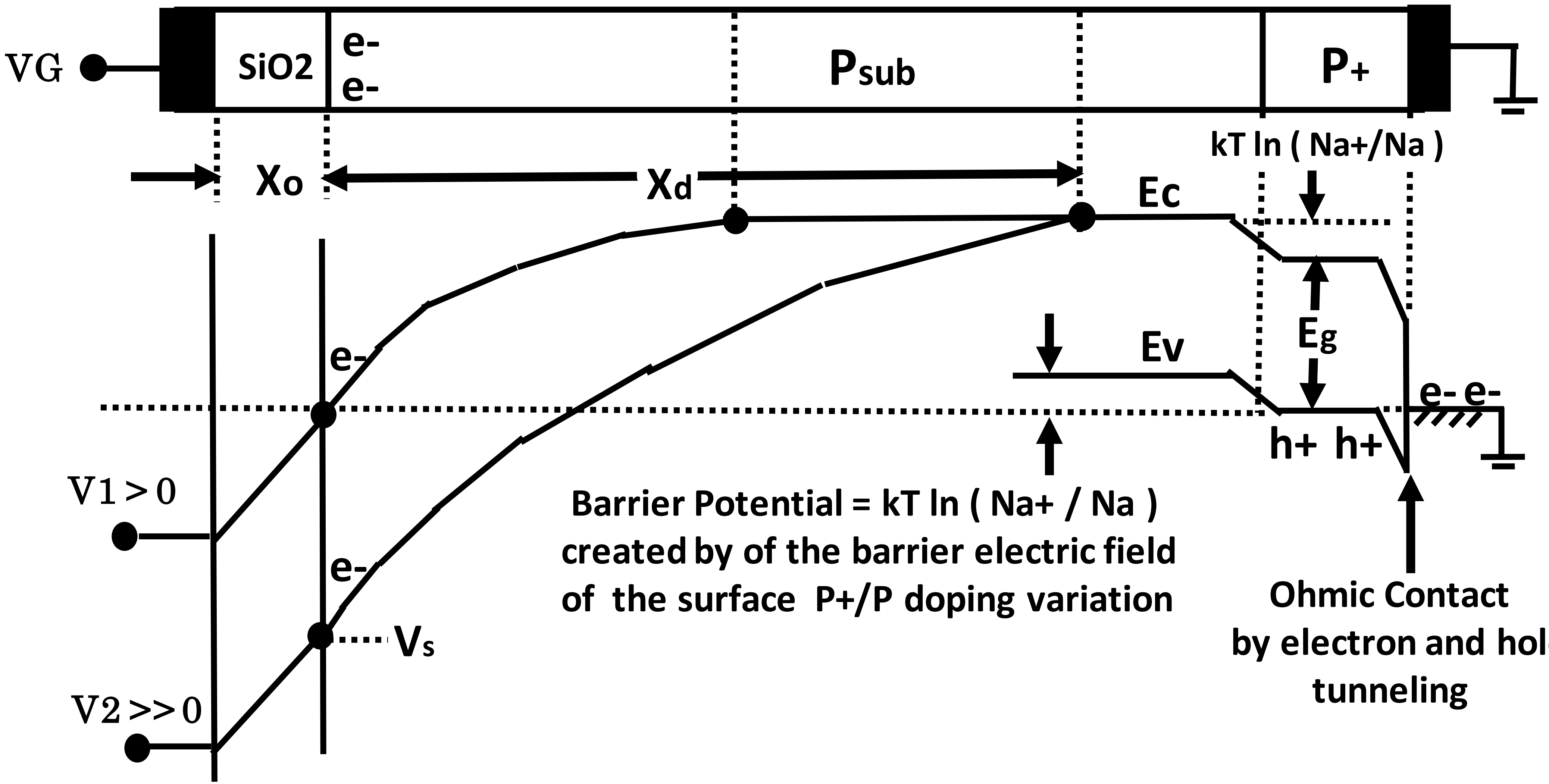
Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0) \exp(-t / \tau_{th})$$

Yoshiaki Daimon Hagiwara et al, “Final Stage of the Charge Transfer Process in Charge Coupled device”, Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

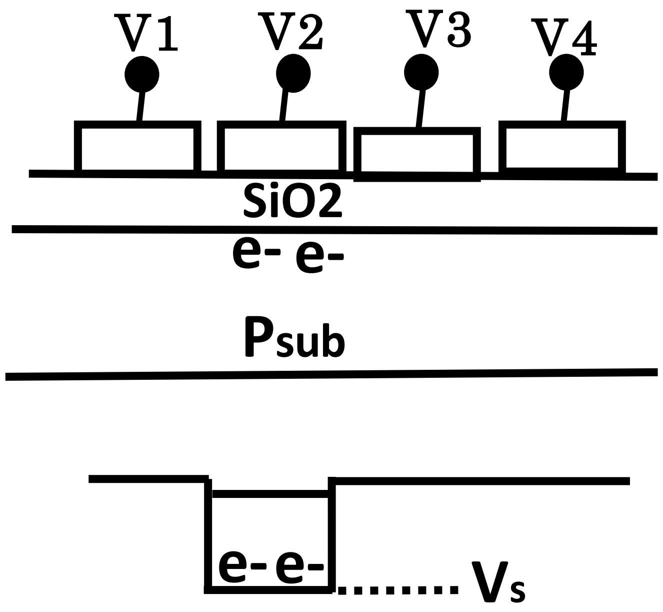
4 CCD/MOS type PDD and CTD

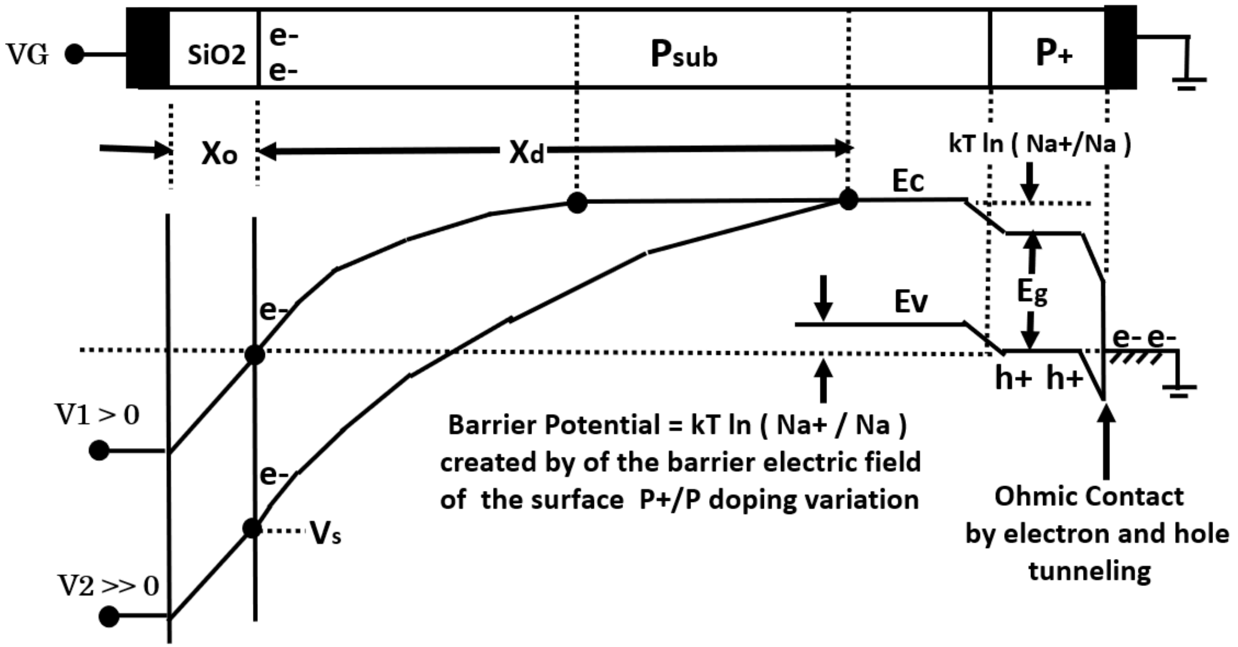
But the charge loss was not only due to the slow free charge movement.



4 CCD/MOS type PDD and CTD

But also the charge loss was due to the tapping by fast interface states were central to the intelligent design and proper estimation of the usefulness of this device concept.

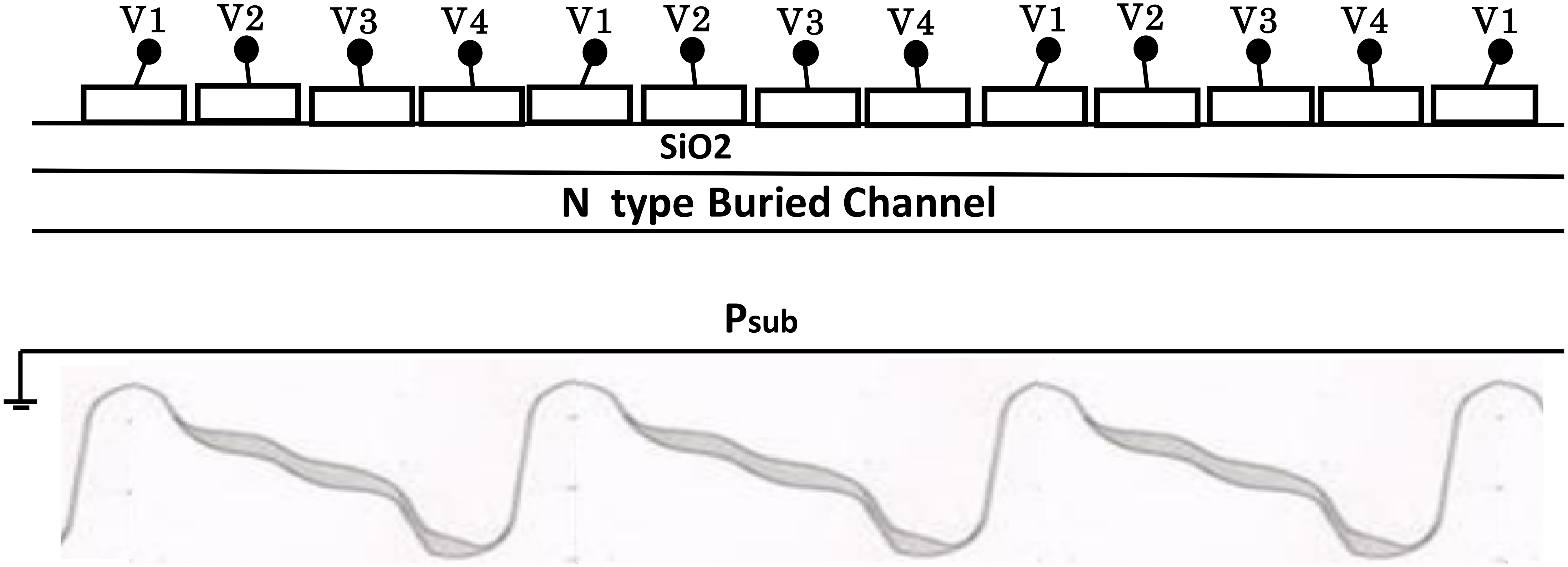




A.M. Mohsen, T.C. McGill, Yoshiaki Daimon Hagiwara, and C.A. Mead , " The Influence of Interface States on Incomplete Charge Tranfer in Overlapping Gate Charge Coupled Devices", IEEE Journal of Solid State Circuits, Vol. SC 8, No.2, April 1973, pp. 125-138.

4 CCD/MOS type PDD and CTD

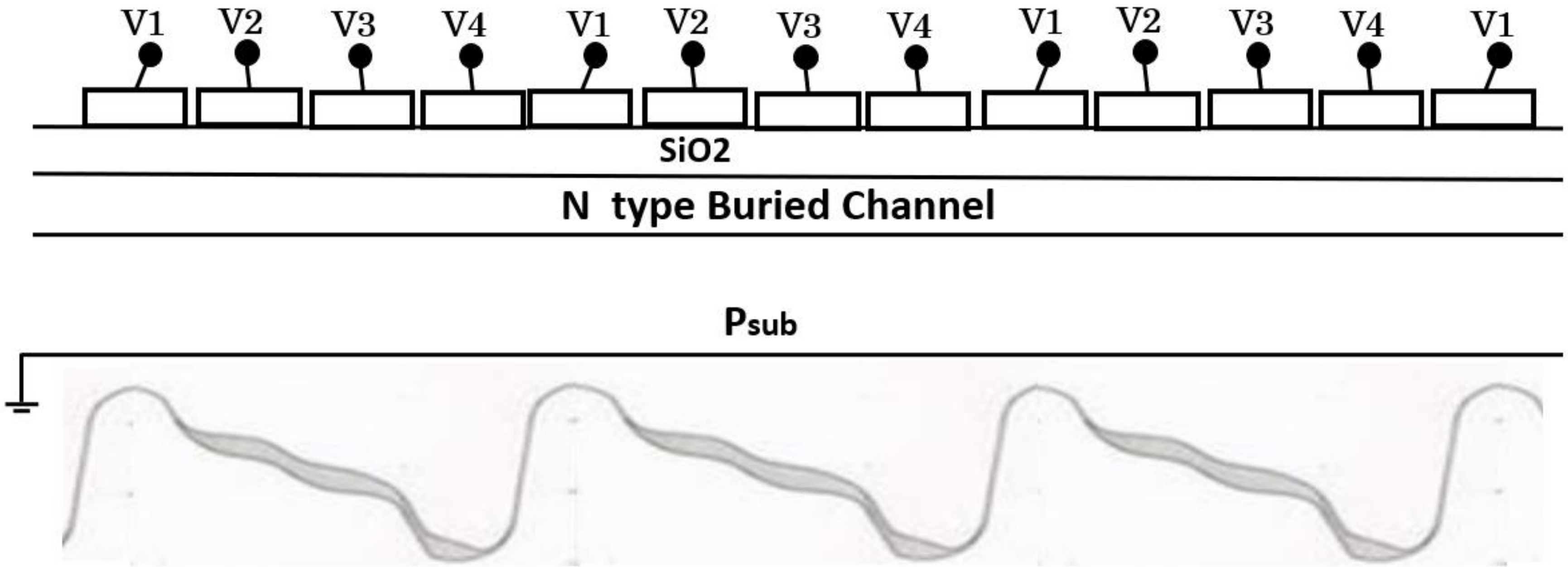
To overcome these problems in 1972, a modified CCD structure was introduced by a group of scientists in Bell labs.



R. H. Walden, R.H. Krambeck, R.J. Strain, J.McKenna, N.L.Schrywer and G.E. Smith, "The Buried Channel Charge Coupled Devices", B.S.T.J. BRIEF, 51, No.7 (September 1972), pp. 1635-1640.

4 CCD/MOS type PDD and CTD

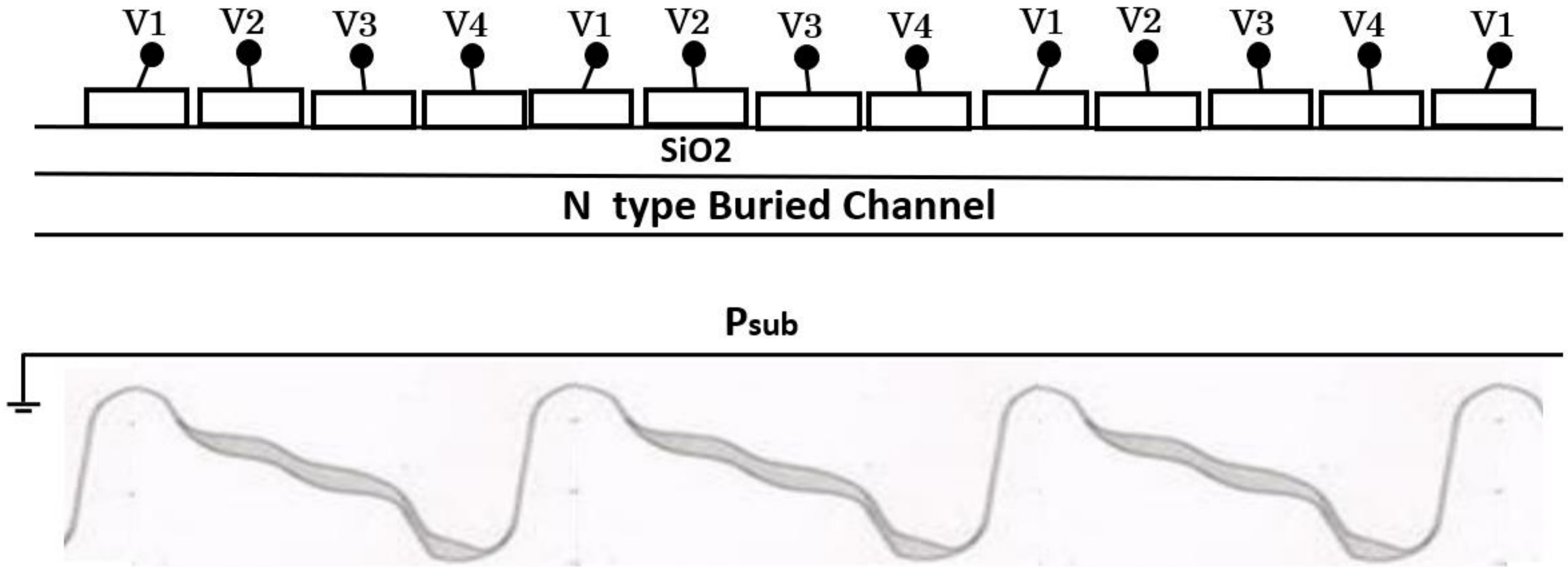
However, due to the additional complexity in structure, the first-fabricated devices did not work at all. Further detailed experimental and theoretical investigations remained to be carried out.



R. H. Walden, R.H. Krambeck, R.J. Strain, J.McKenna, N.L.Schrywer and G.E. Smith, "The Buried Channel Charge Coupled Devices", B.S.T.J. BRIEF, 51, No.7 (September 1972), pp. 1635-1640.

4 CCD/MOS type PDD and CTD

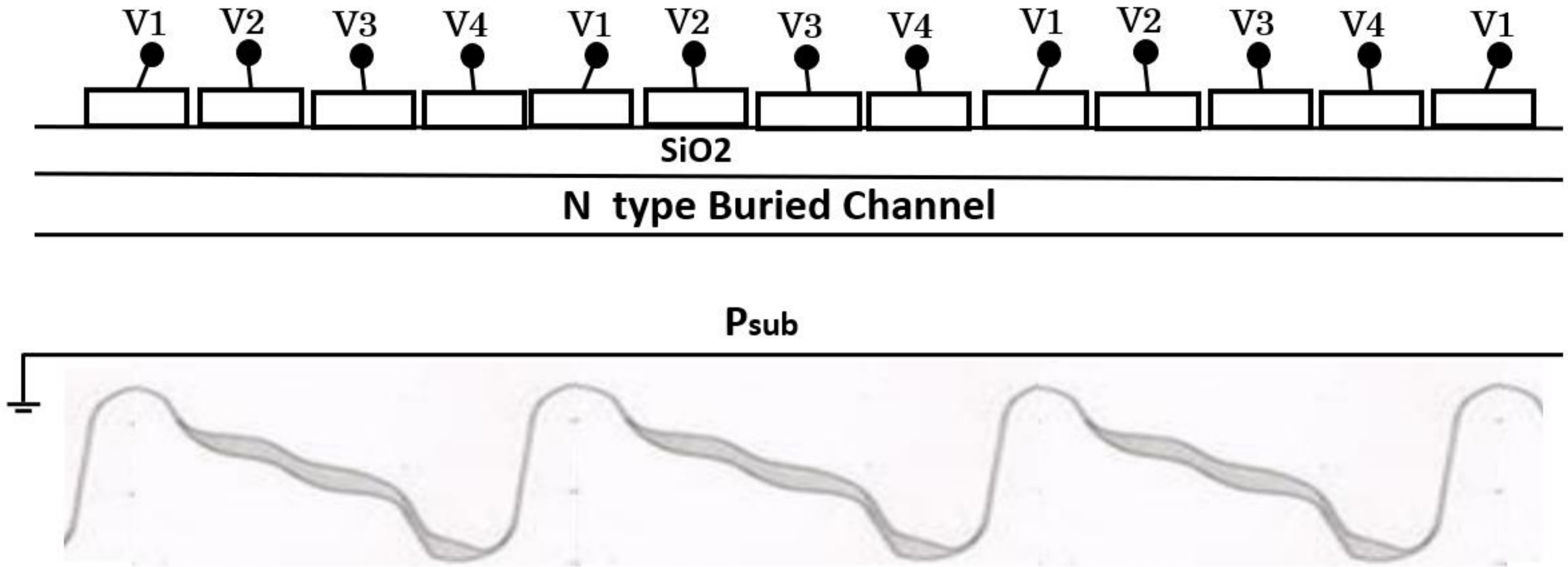
This modified CCD structure is now called as the buried channel charge coupled device (BCCD) which gave rise to increase fringing fields under the electrodes.



Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

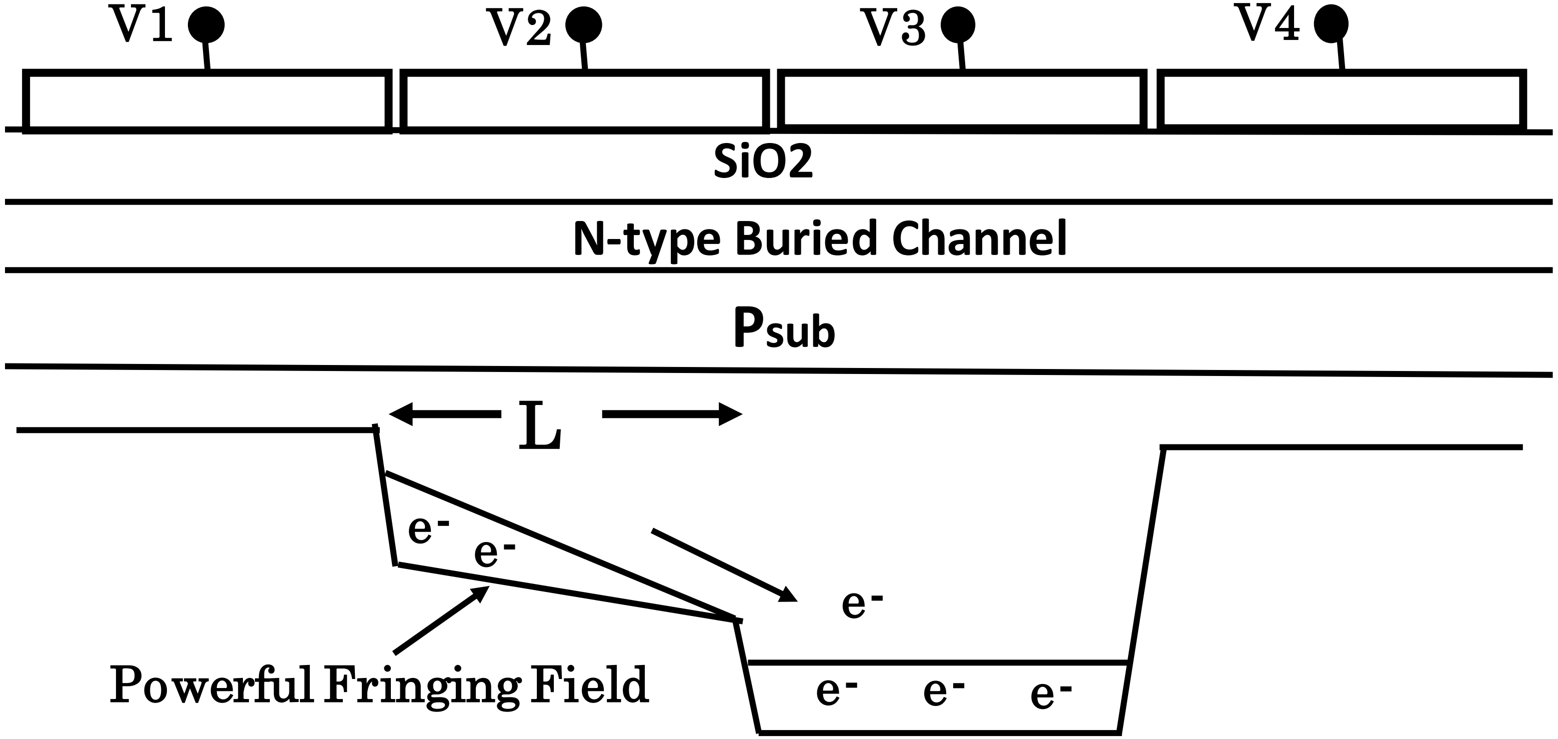
The thermal diffusion is now replaced by the more powerful electric field charge transfer as an important factor in the final charge transfer process



Yoshiaki Daimon Hagiwara et al, “Final Stage of the Charge Transfer Process in Charge Coupled device”, Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

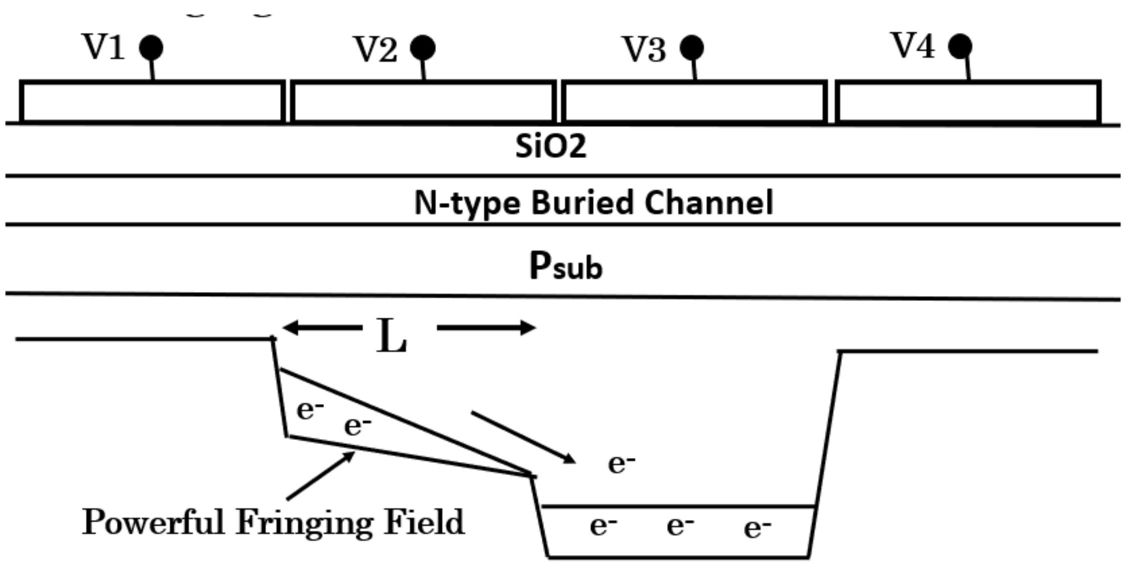
The more powerful fringing electric field E_{fr} led to fast, efficient charge transport even when even little charge remains to be transferred in the low light level imaging.



Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

The more powerful fringing electric field E_{fr} led to fast, efficient charge transport even when even little charge remains to be transferred in the low light level imaging.



$$Je = D_{th}\frac{dq(x)}{dx} + \mu E_{fr} q(x)$$

$$\tau_{th} = \frac{4L^2}{\pi^2 D_{th}}$$

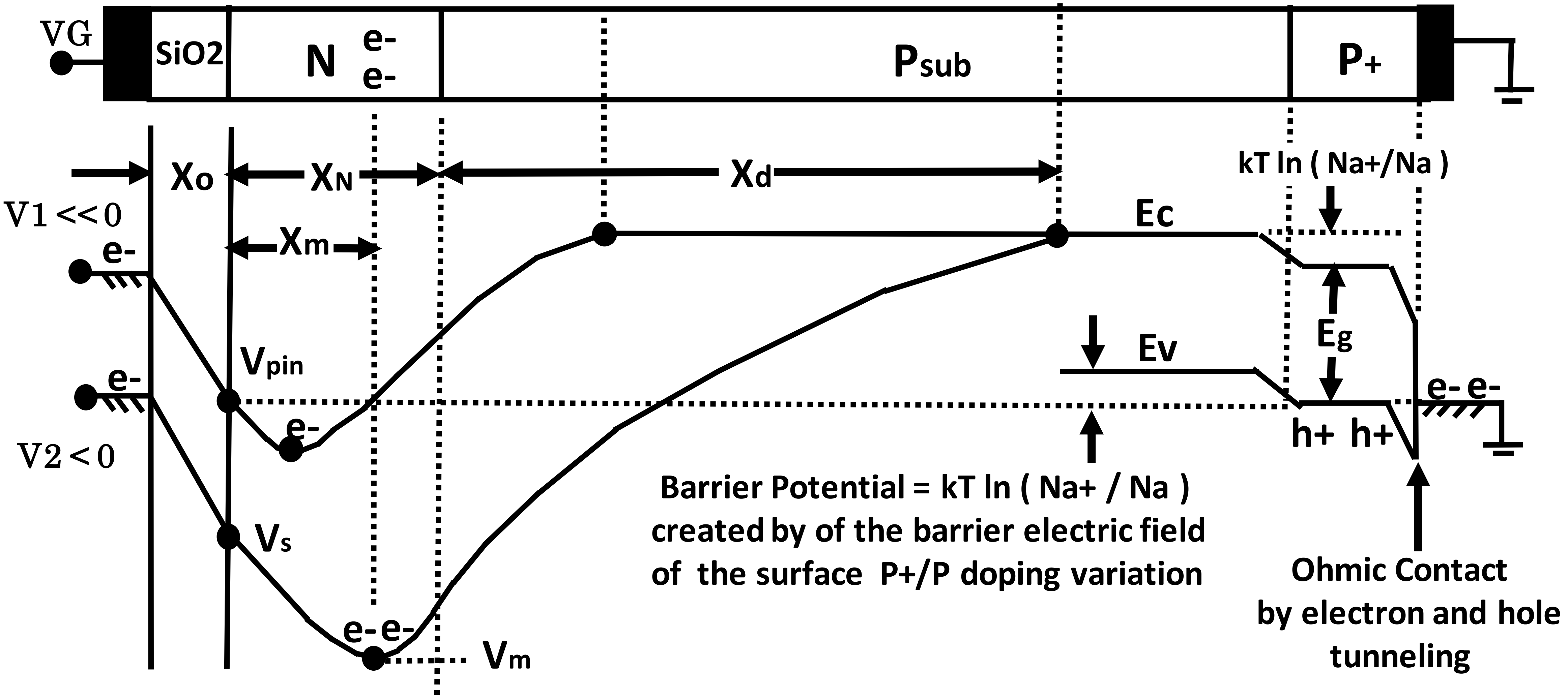
$$\frac{1}{\tau_{final}} = \frac{4}{\tau_{th}} + \frac{\mu^2 E_{fr}}{4D_{th}}$$

Last Remaining Signal Charge Q(t)

$$Q(t) = Q(0)\exp(-t/\tau_{final})$$

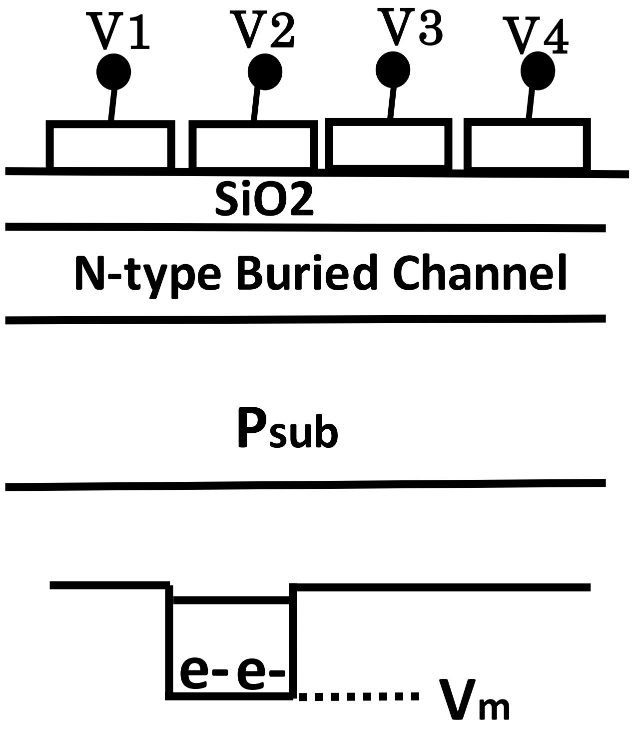
Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

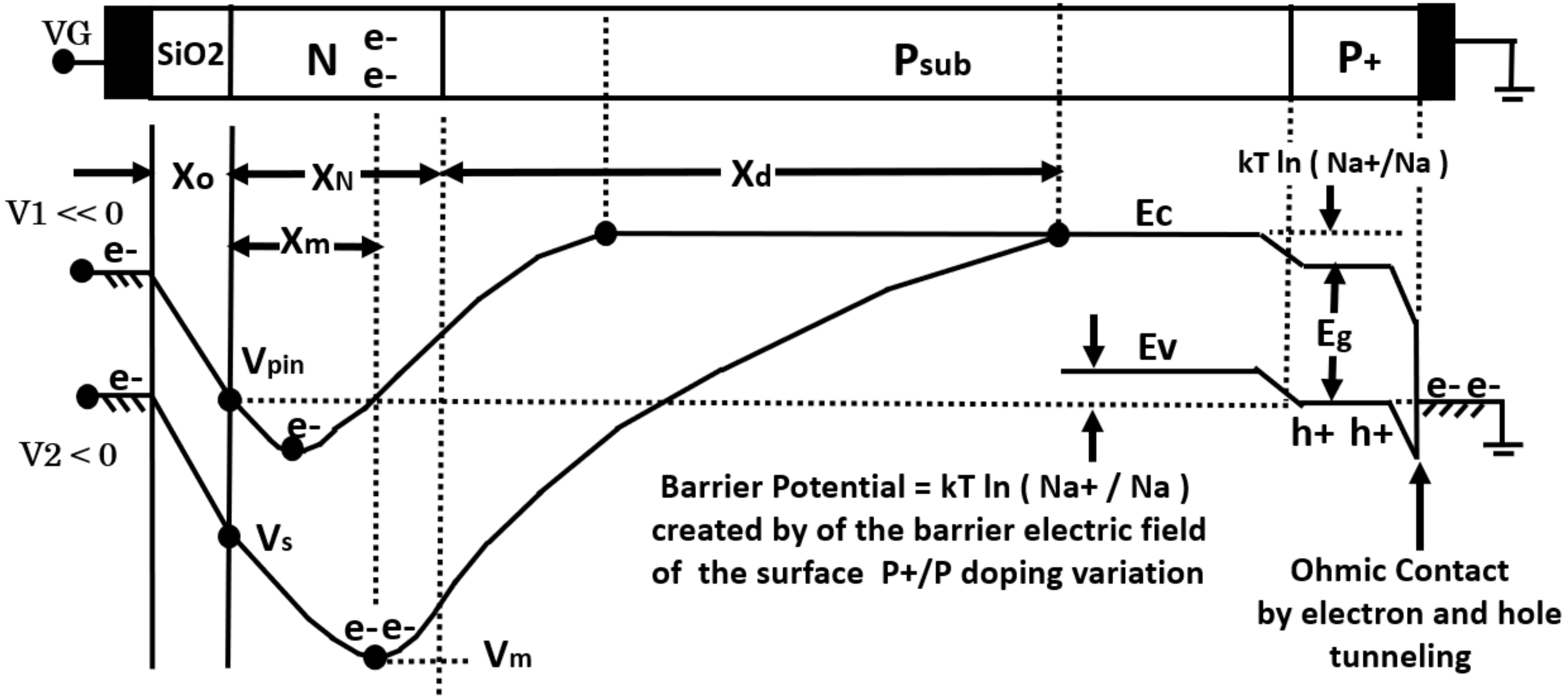
4 CCD/MOS type PDD and CTD



4 CCD/MOS type PDD and CTD

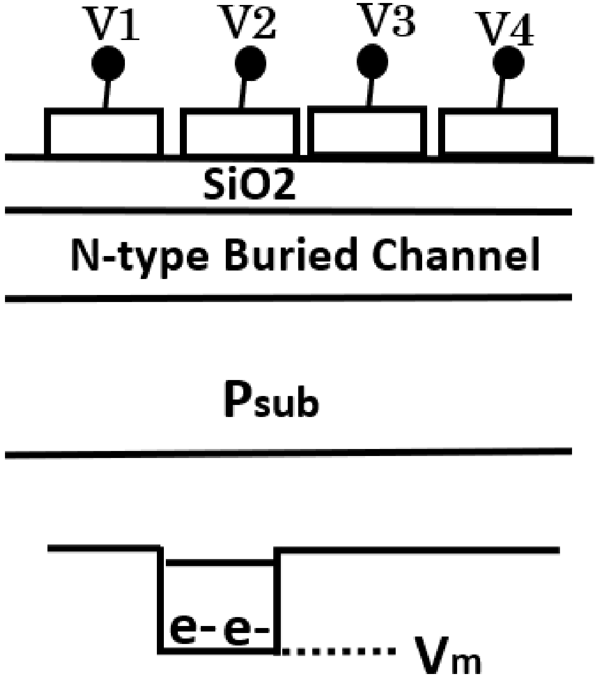
When a strong negative gate voltage V1 << 0 is applied, the silicon surface will be inverted and create a surface hole accumulation layer which is pinned to the ground potential level V_{pin} = 0. That is, the surface potential Vs is pinned to the ground 0 V.

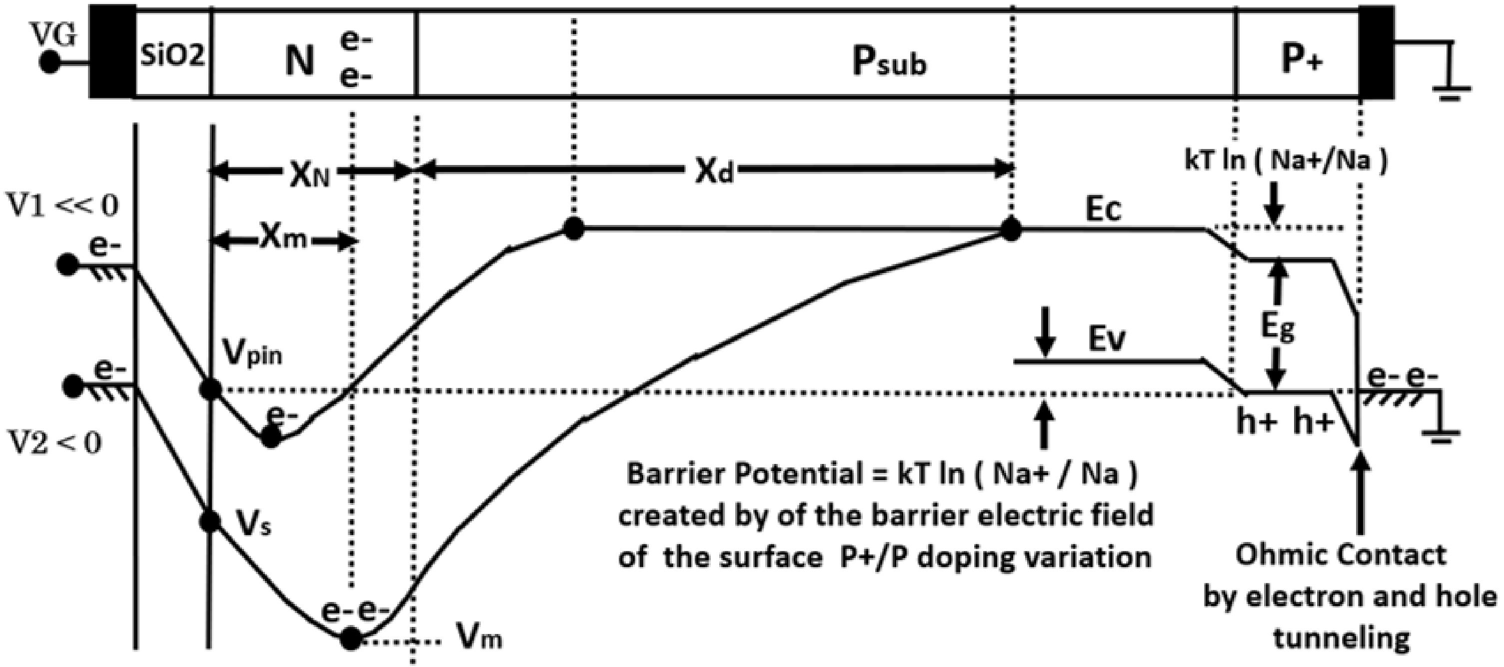




4 CCD/MOS type PDD and CTD

Besides the electron charge carriers move in the N-type buried channel and suffered no charge transfer loss, being protected from the surface trapping interface states.

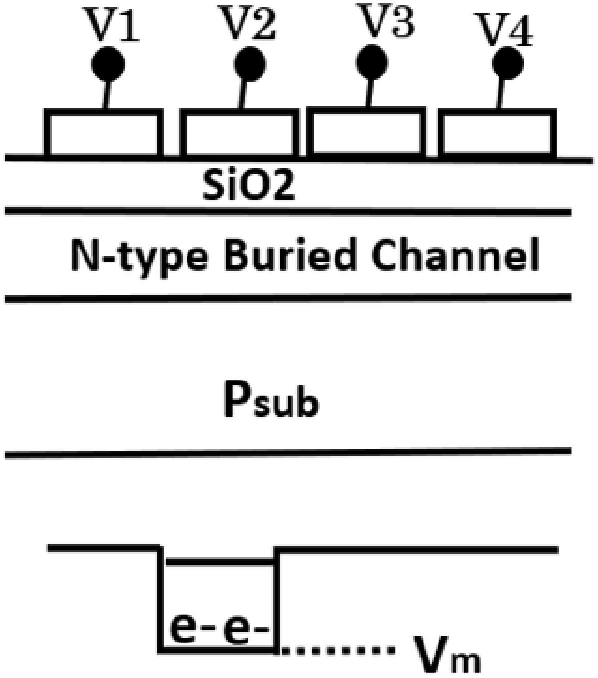


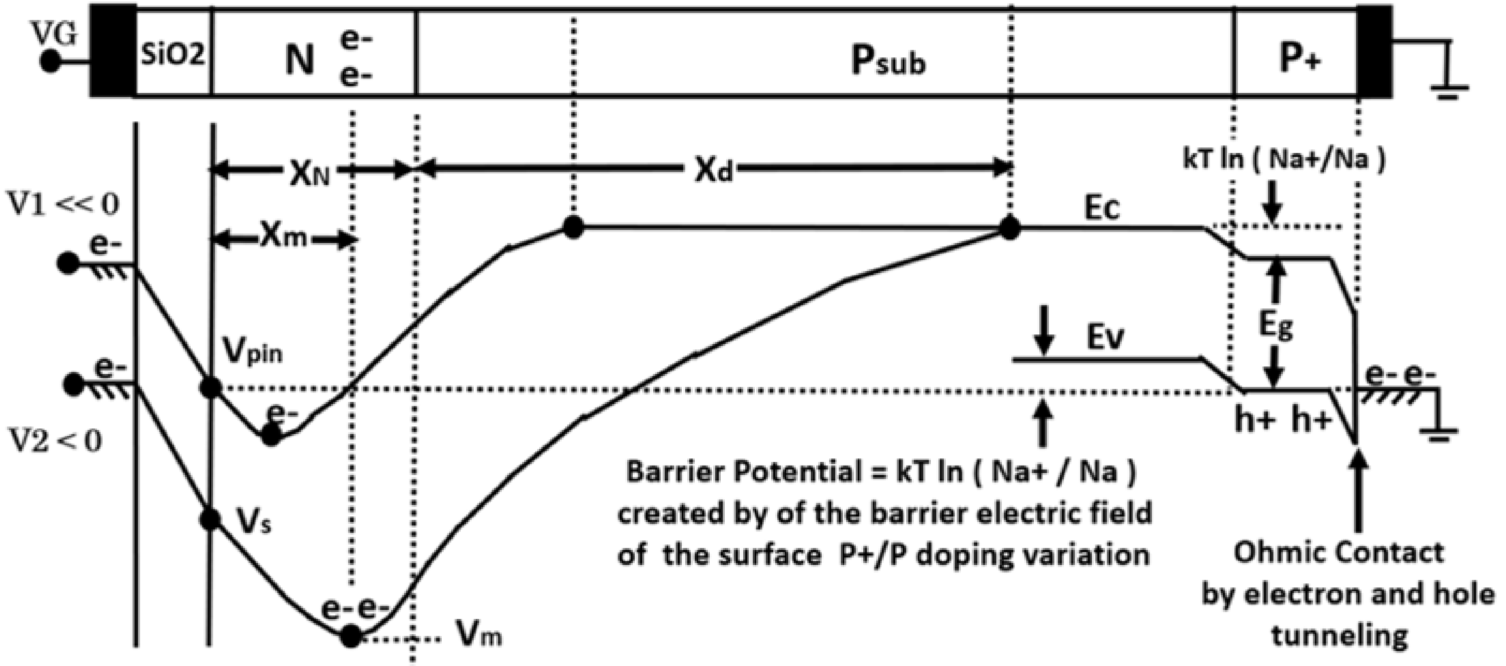


Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

The buried channel charge coupled device (BCCD) with the charge transfer efficiency of about 99.999% was suitable to serve as the charge transfer device (CTD) for solid state imagers for the NTSC analog TV era.

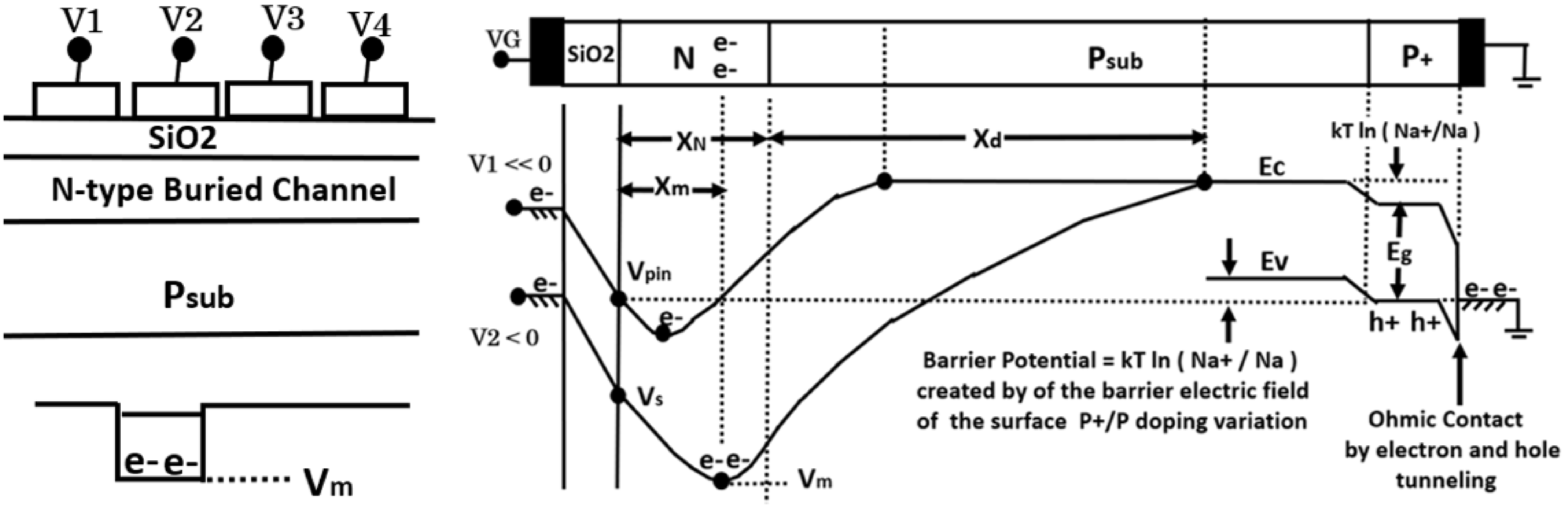




Yoshiaki Daimon Hagiwara et al, “Final Stage of the Charge Transfer Process in Charge Coupled device”, Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

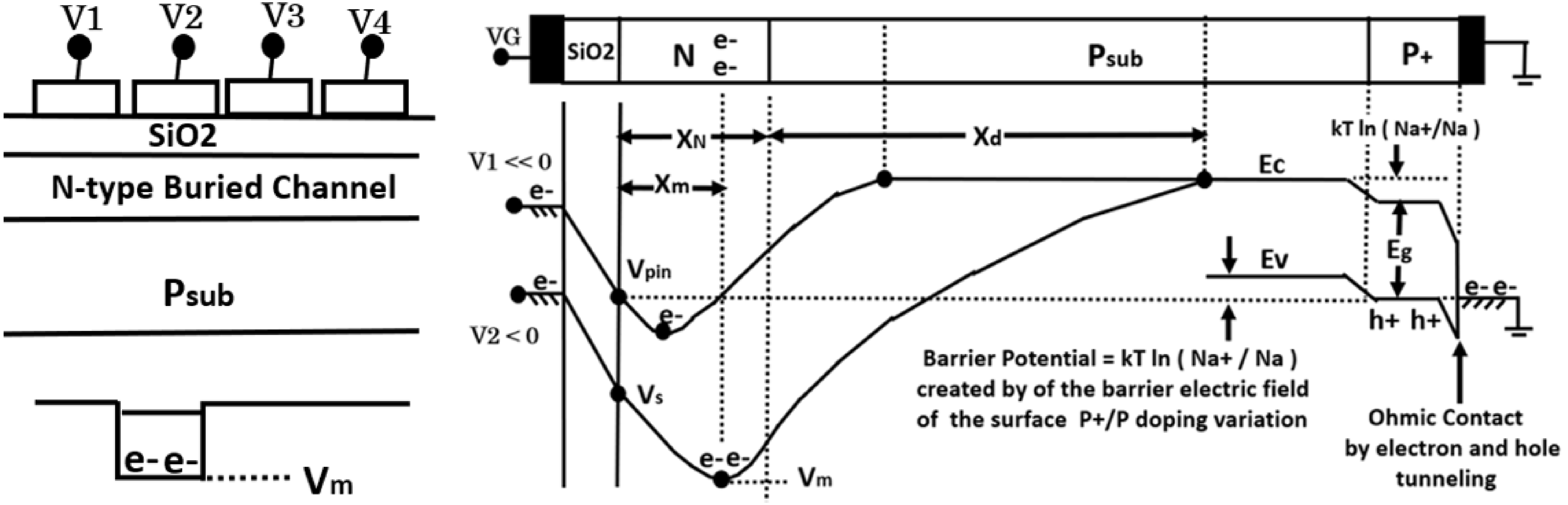
Buried channel charge coupled device (BCCD) was suited for the solid state imager required in the NTSC analog TV format of 800H x 500 V with the required signal charge packet transfer frequency of 13.1818MHz



Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

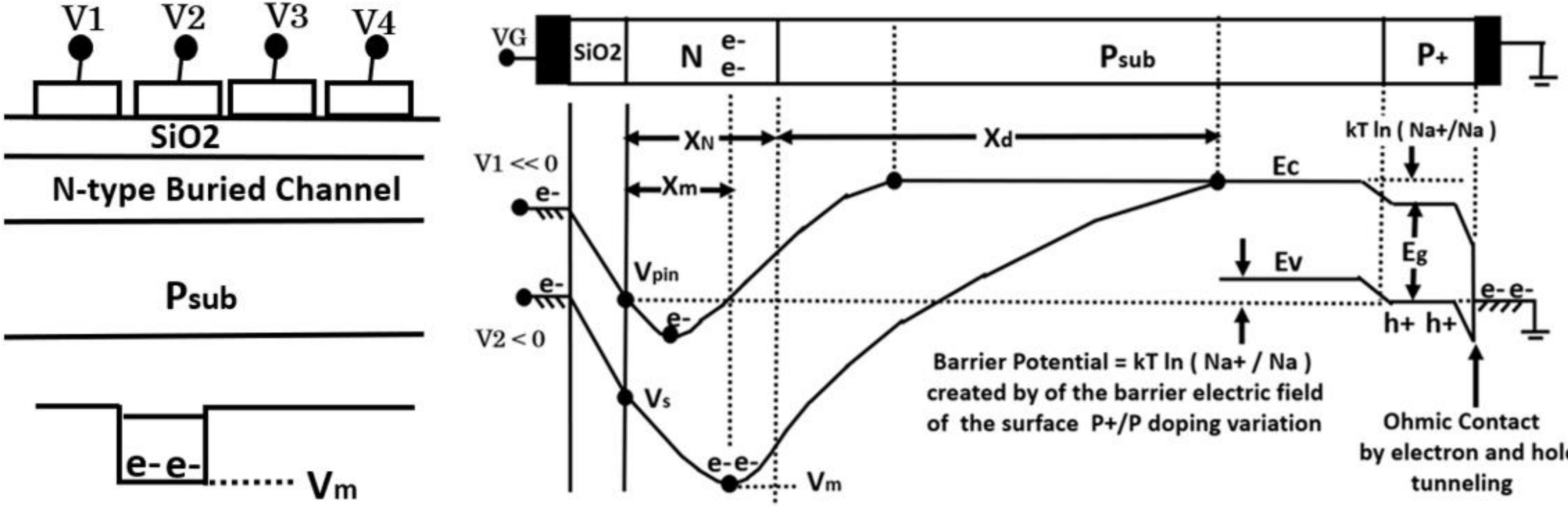
For each frame at most 800H + 500V = 1300 charge transfers must be performed, losing about 1300 x 0.001 % = 1.3 % of each output circuit of the BCCD type CTD analog delay line.



Yoshiaki Daimon Hagiwara et al, “Final Stage of the Charge Transfer Process in Charge Coupled device”, Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

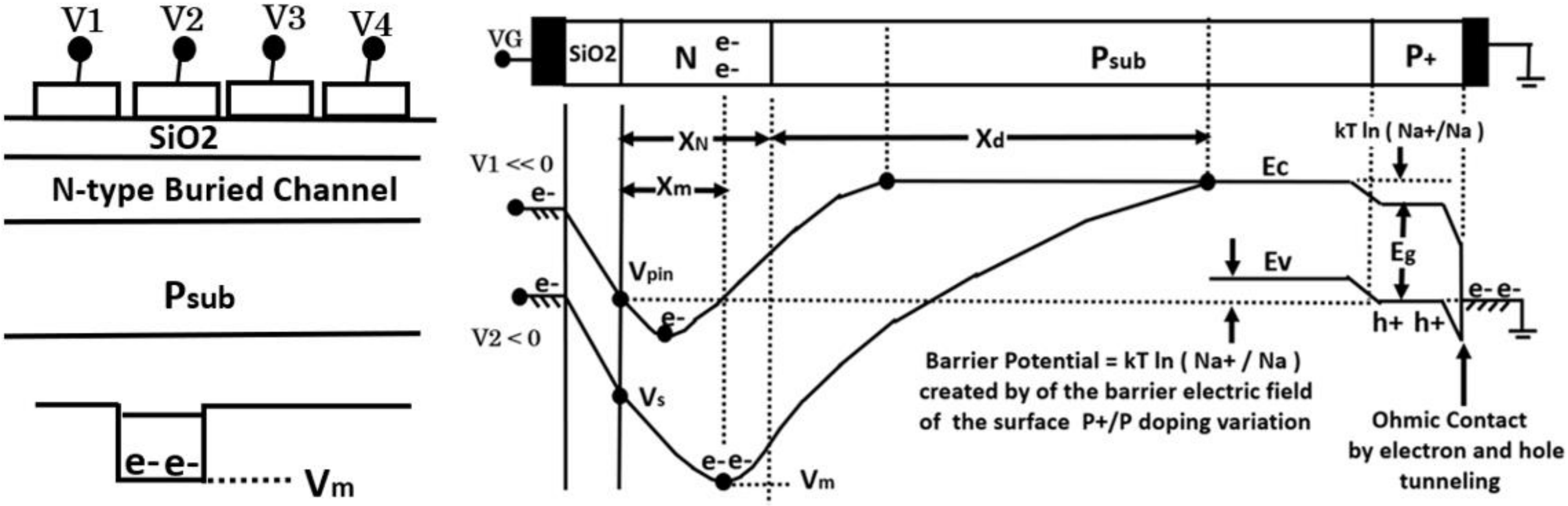
Since human eyes cannot recognize any noise less than 3 %, the signal charge transfer loss of 1.3 % by the BCCD type CCD analog delay line is small enough and negligible for human eyes.



Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

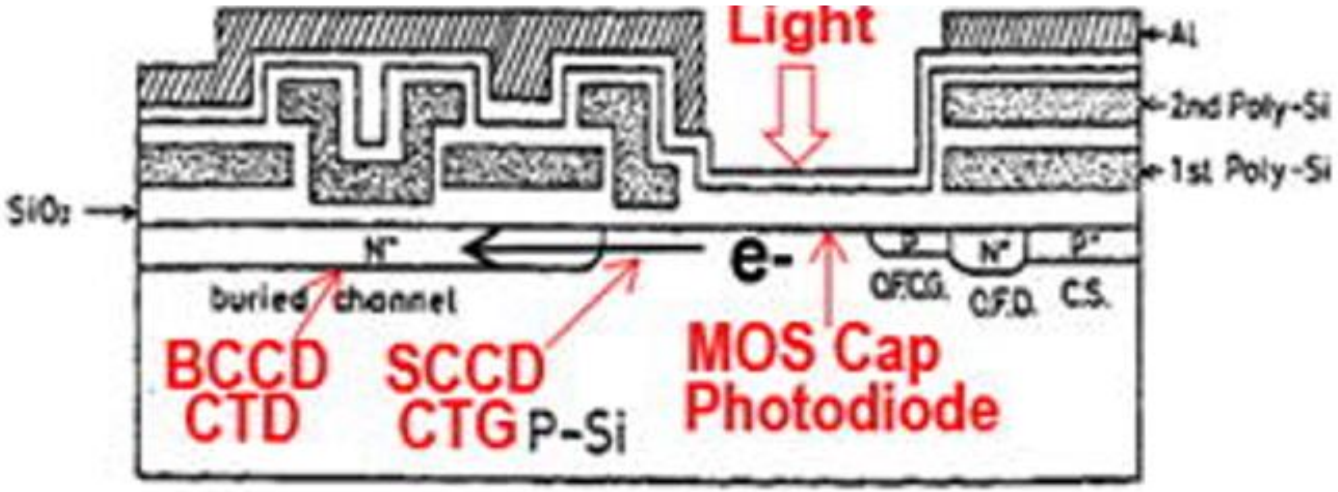
The BCCD/MOS type CTD performed excellently as the main important component of the CCD type CTD image sensors in the NTSC TV format system era in 1980s thru 1990s.



Yoshiaki Daimon Hagiwara et al, "Final Stage of the Charge Transfer Process in Charge Coupled device", Electron Transaction on Electron Devices, Vol. Ed-21 , No.4 , April 1974.

4 CCD/MOS type PDD and CTD

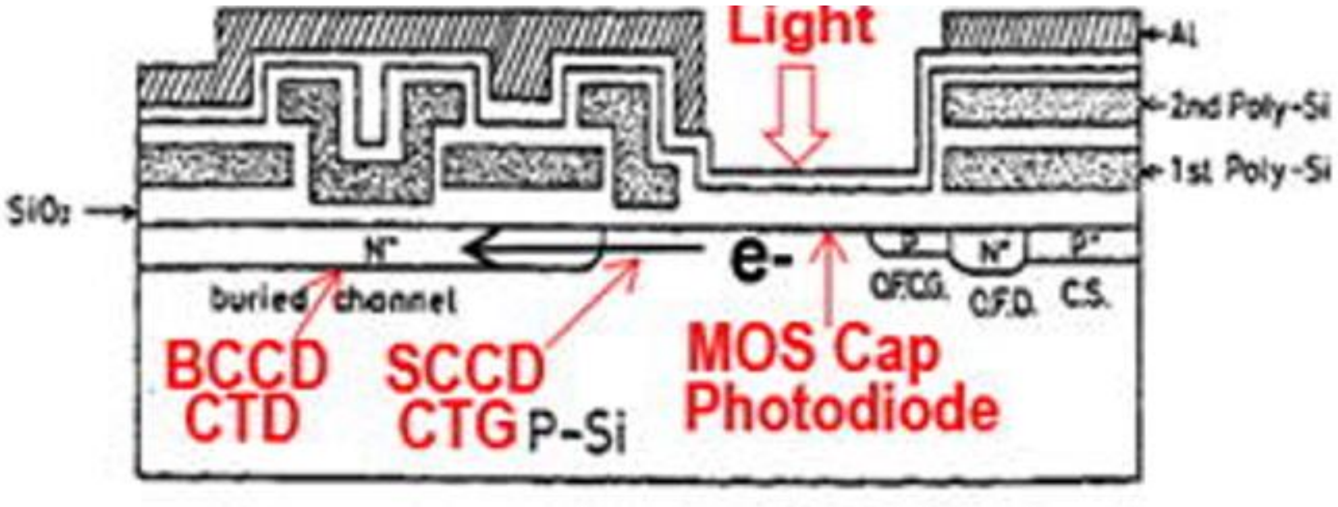
The CCD/MOS type CTD has no serious image lag problem since the charge transfer efficiency is about 99.999% which is considered as the complete charge transfer, good enough for the NTSC analog TV system. The CCD/MOS type CTD was used widely for image sensors.



Y. Kanoh, T. Ando, H. Matsumoto, Y. Hagiwara and T. Hashimoto, "Interline Transfer CCD Image Sensor", Technical Journal of Television Society, ED 481, pp.47-52, Jan 24, 1980.

4 CCD/MOS type PDD and CTD

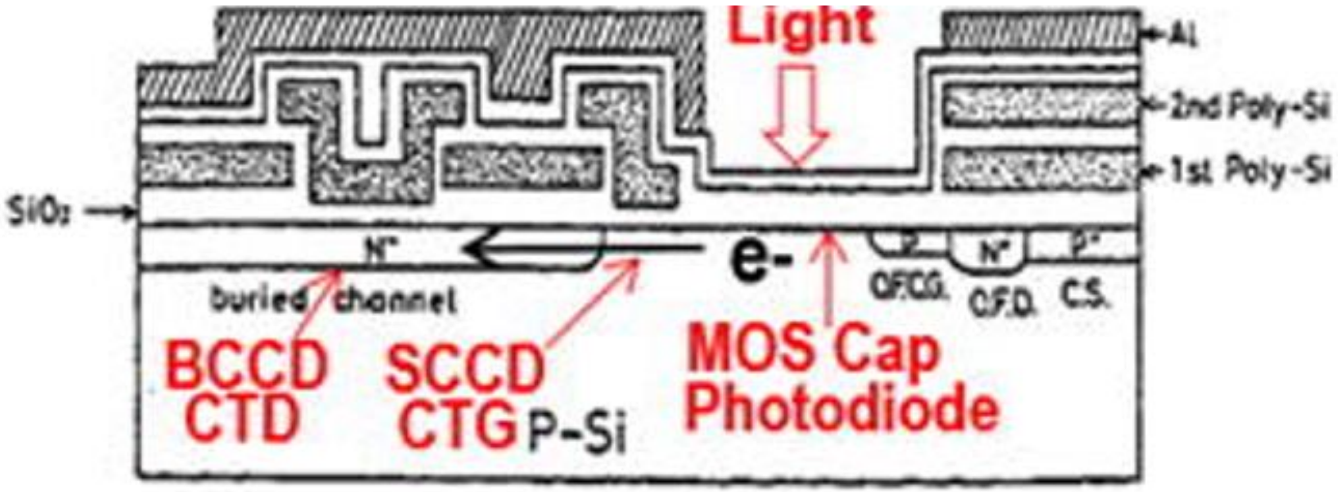
The image lag free video camera was desired to obtain fast and clear action pictures. The CCD/MOS type CTD was very attractive to Sony since Sony was challenging to build image lag free video cameras for fast and clear action pictures.



Y. Kanoh, T. Ando, H. Matsumoto, Y. Hagiwara and T. Hashimoto, "Interline Transfer CCD Image Sensor", Technical Journal of Television Society, ED 481, pp.47-52, Jan 24, 1980.

4 CCD/MOS type PDD and CTD

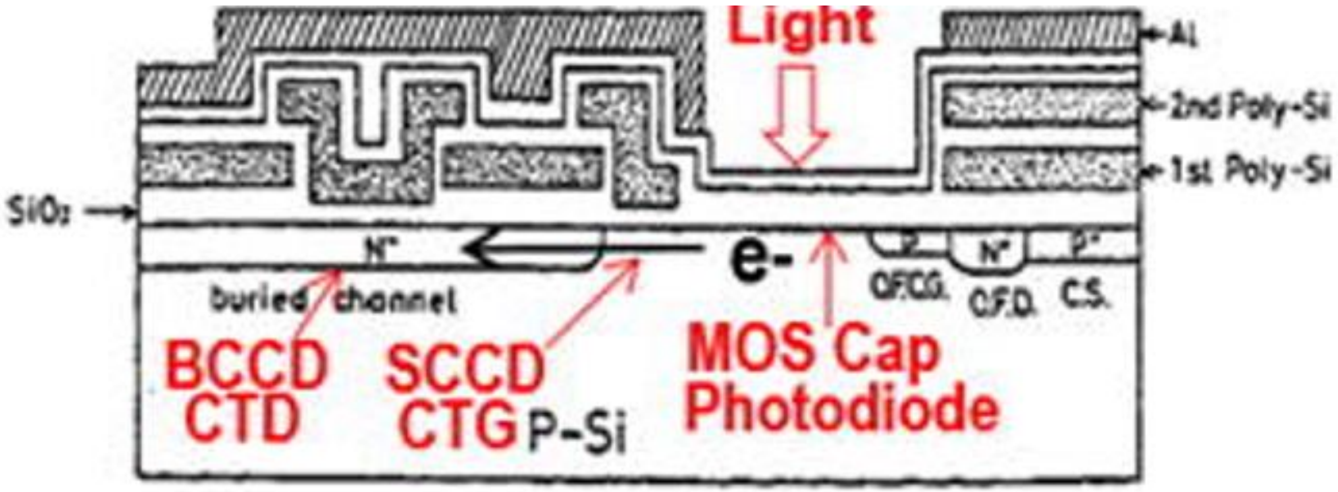
But the P+N single junction type dynamic photodiode has the serious image lag. Hence Sony used the SCCD/MOS type Photo Detecting Device (PPD) with no image lag. However the metallic thick heavily doped polysilicon gate does not pass the short wave blue light



Y. Kanoh, T. Ando, H. Matsumoto, Y. Hagiwara and T. Hashimoto, "Interline Transfer CCD Image Sensor", Technical Journal of Television Society, ED 481, pp.47-52, Jan 24, 1980.

4 CCD/MOS type PDD and CTD

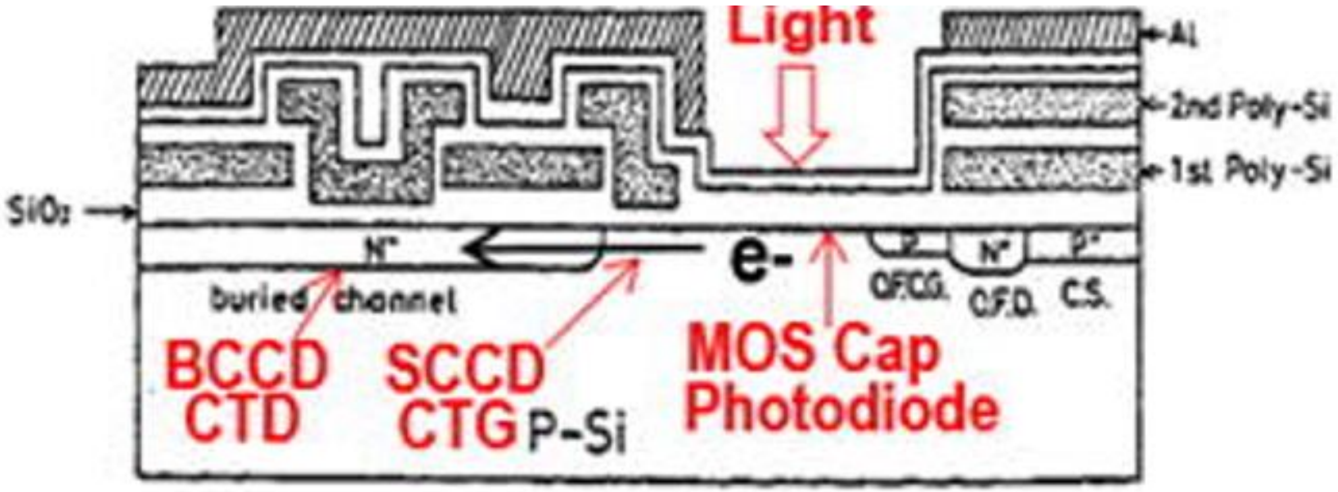
Sony used thinned polysilicon electrodes for the SCCD/MOS type Photo Detecting Device (PPD) and used it for the BCCD type Interline Transfer Image Sensor in 1980, instead of the P+N single junction type dynamic photodiode for the Photo Detecting Device (PDD) which was known to have the serious image lag problem.

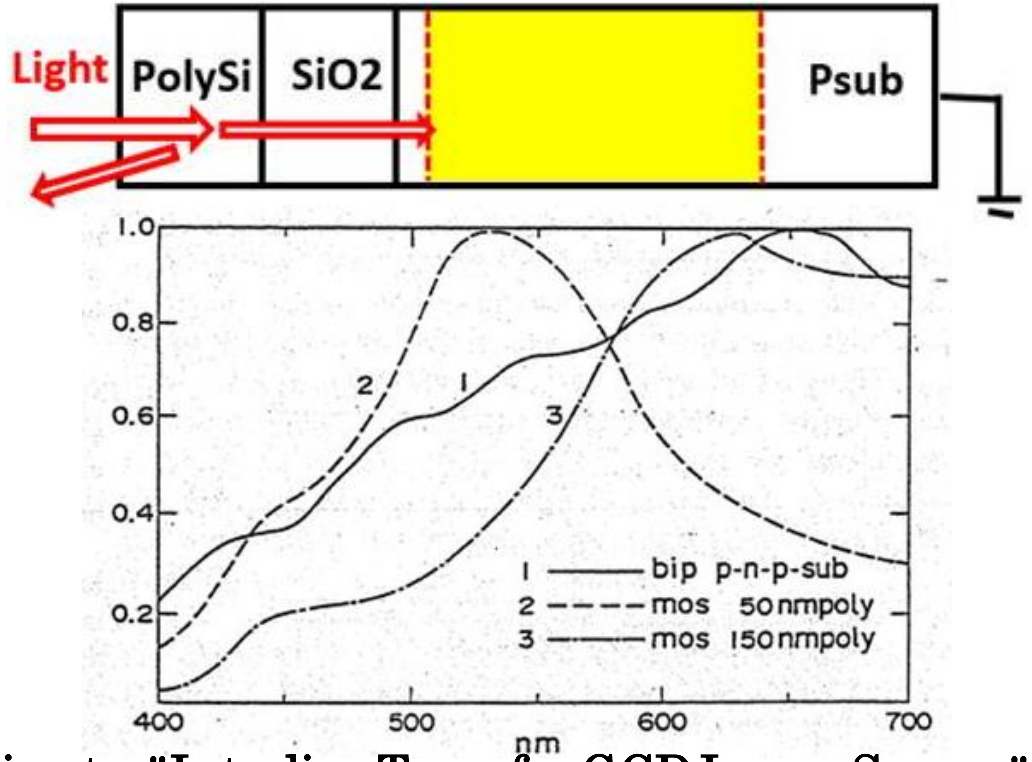


Y. Kanoh, T. Ando, H. Matsumoto, Y. Hagiwara and T. Hashimoto, "Interline Transfer CCD Image Sensor", Technical Journal of Television Society, ED 481, pp.47-52, Jan 24, 1980.

4 CCD/MOS type PDD and CTD

In 1980 Sony introduced two chip Interline CCD charge transfer device (CTD) type image sensor with the thinned polysilicon gate.





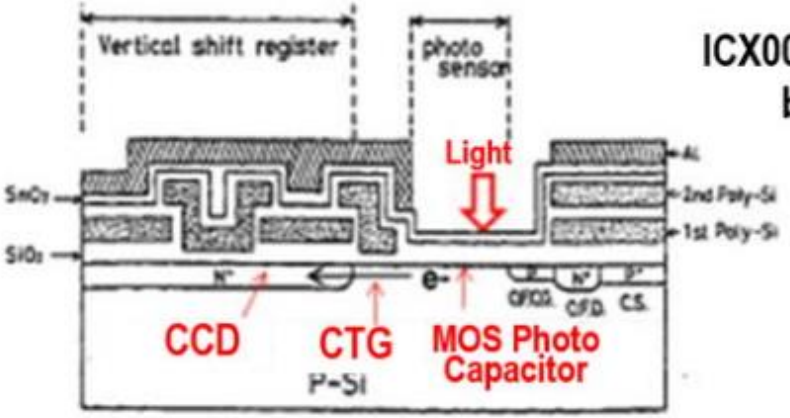
Y. Kanoh, T. Ando, H. Matsumoto, Y. Hagiwara and T. Hashimoto, "Interline Transfer CCD Image Sensor", Technical Journal of Television Society, ED 481, pp.47-52, Jan 24, 1980.

4 CCD/MOS type PDD and CTD

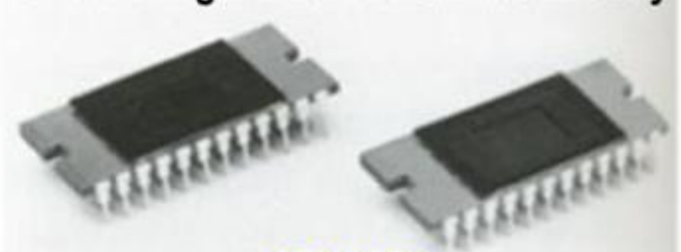
Sony developed Two Chip ILT CCD Image Sensor
with the completely image lag free feature
installed in the ANA 747 Jumbo Jet cockpit in 1980 .

XC-1 1980
Two-Chip Color Video
Camera

all solid state = robustness



ICX008 CCD chips designed and developed in 1980
by Yoshiaki Hagiwara and his team at Sony



<ICX008>

CCD/MOS Dynamic Photo Capacitor Sensor has the Complete Charge Transfer and no Image Lag Feature, but had the strong MOS Surface Electric Field generating a large undesired Surface Dark Current.

Silicon chip yield was very poor with many white spot defects.

4 CCD/MOS type PDD and CTD

In 1975 Hagiwara at Sony invented the double and triple junction type dynamic photo transistors which needed no MOS polysilicon electrode and consequently had excellent short wave blue light sensitivity.

for the excellent short wave blue light sensitivity.

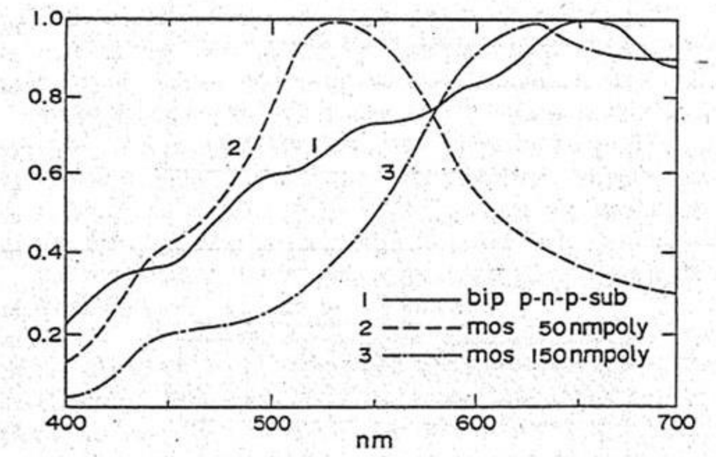
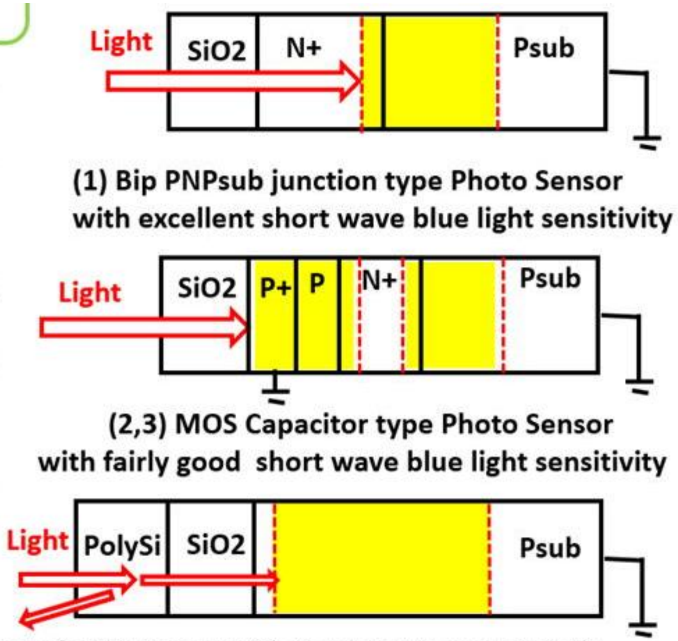


Fig. 7. Relative spectrum response. The relative response of the bipolar-type SiO_2–P2–N1–P1–SUB structure is compared with poly–SiO_2–N2–P(SUB) structures of the polysilicon thickness of 50 and 150 nm.

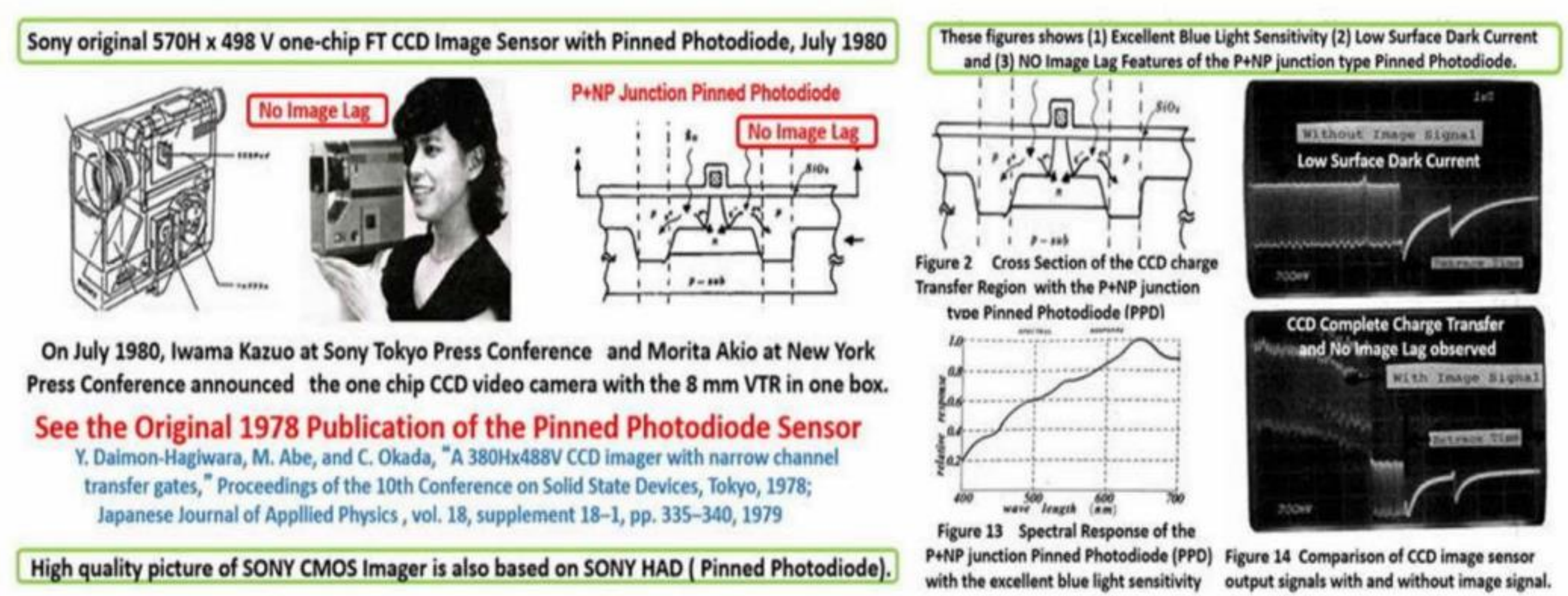


Yoshiaki Hagiwara,"High Density and High Quality Frame Transfer CCD Imager with Very Low Smear, Low Dark Current and Very High Blue Sensitivity", IEEE Transaction on Electron Devices, Vol 43, no. 12, December 1996
http://www.aiplab.com/P1996_Pinned_Photodidoe_used_in_Sony_1980_FT_CCD_Image_Sensor.pdf

Yoshiaki. Hagiwara, Japanese Patent Applications JPA 1975-127647, JPA 1975-127647 and JPA 1975-134985.

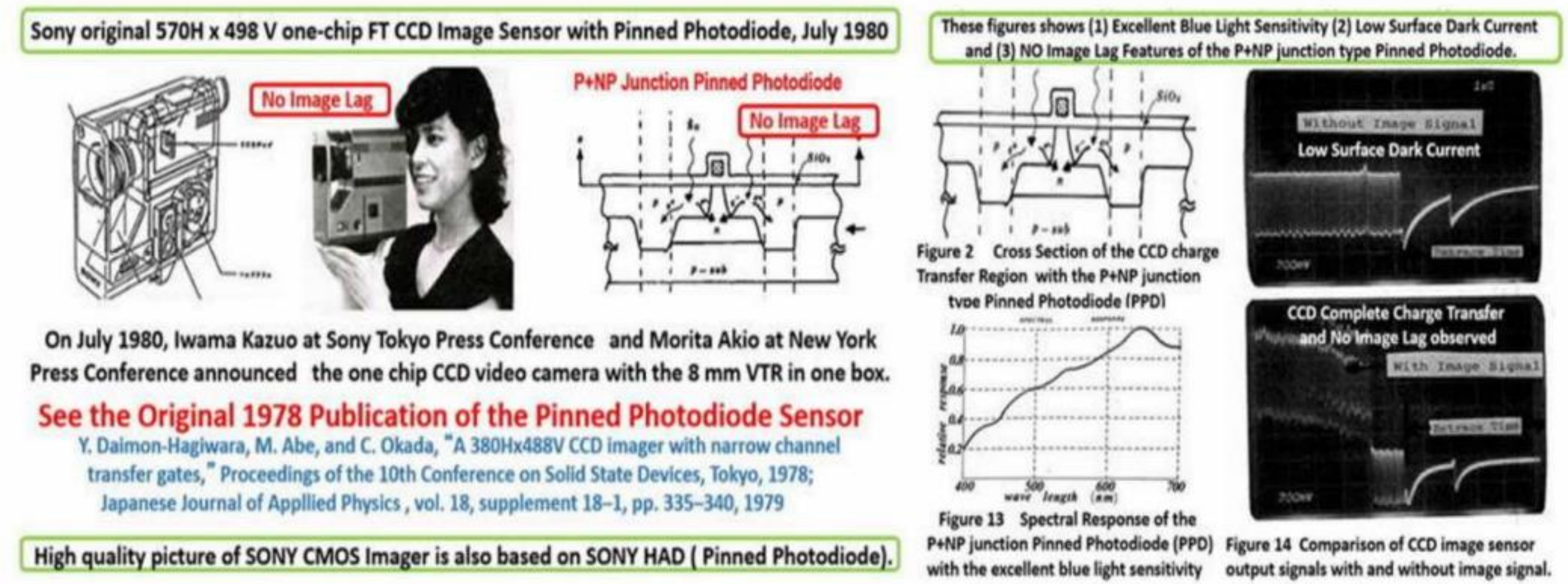
4 CCD/MOS type PDD and CTD

In 1978 Hagiwara team at Sony developed a P+NP photo sensor of double junction type dynamic photo transistor with surface P+ hole accumulation layer which was pinned by the adjacent heavily doped P+ channel stops.



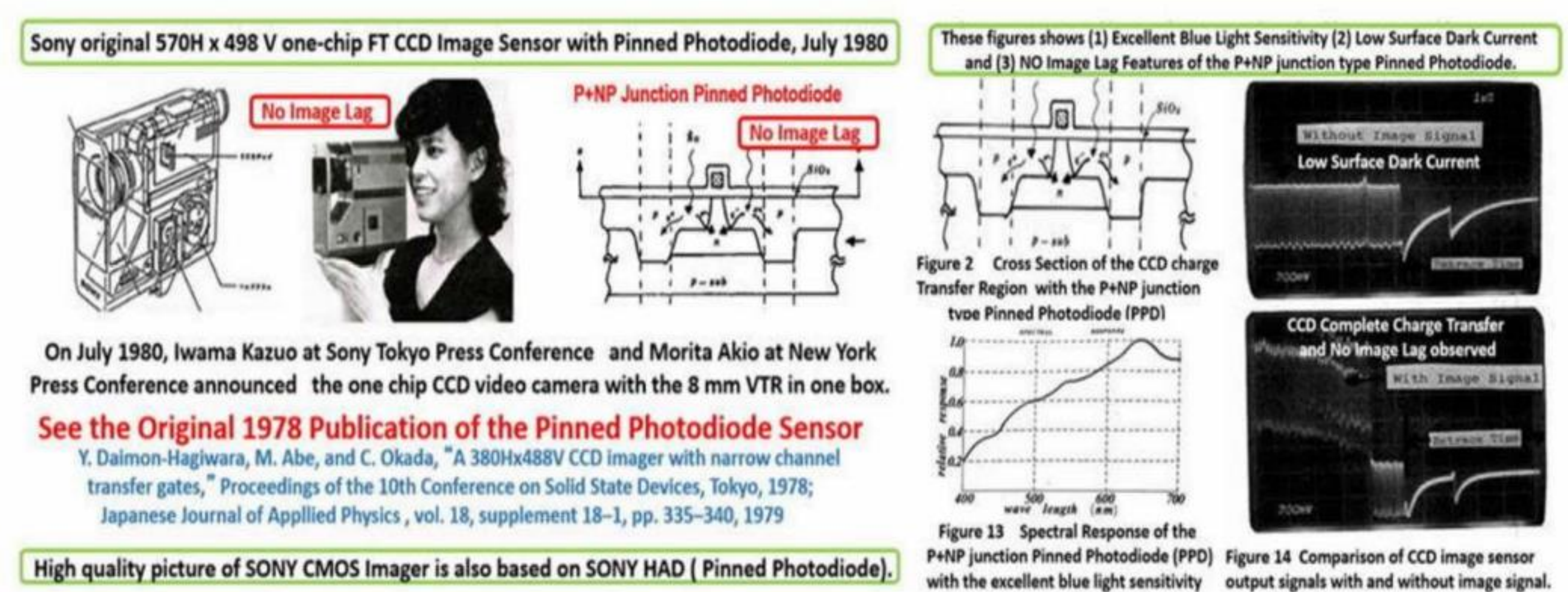
4 CCD/MOS type PDD and CTD

In 1980 Hagiwara team at Sony also used the P+NP photo sensor for the 570H x 498V one chip FT BCCD type CTD image sensor with excellent blue light sensitivity, no image lag and low surface dark current features.



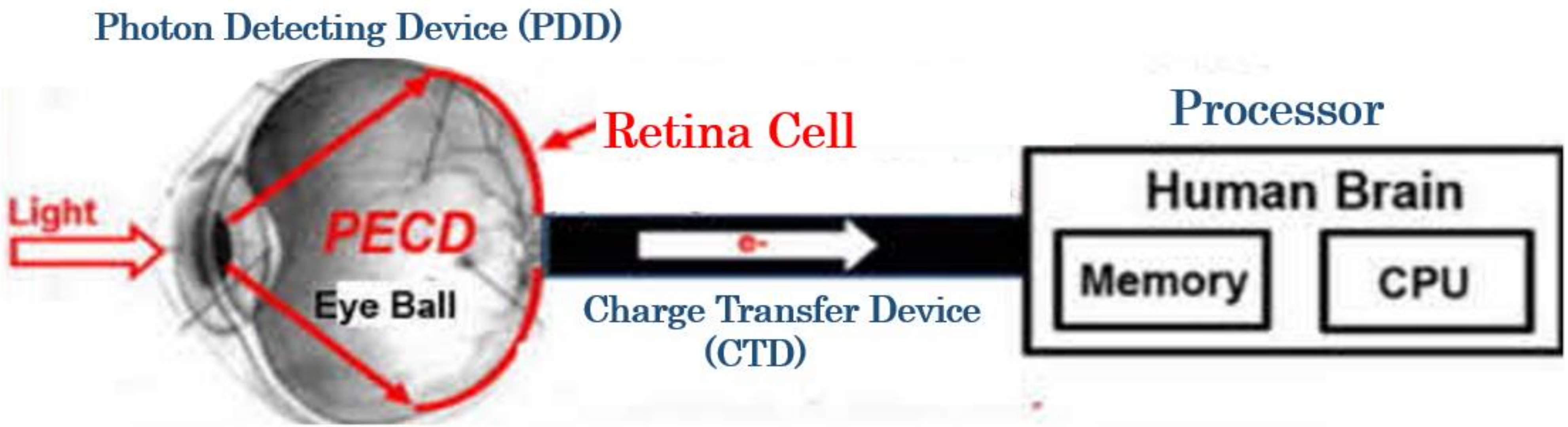
4 CCD/MOS type PDD and CTD

The CMOS process scaling technology was still not mature in1980s thru 1900s. And the in pixel active CMOS type CTD image sensor was not feasible for mass production. Instead the CCD/MOS type CTD image sensor was produced widely in the analog TV era.



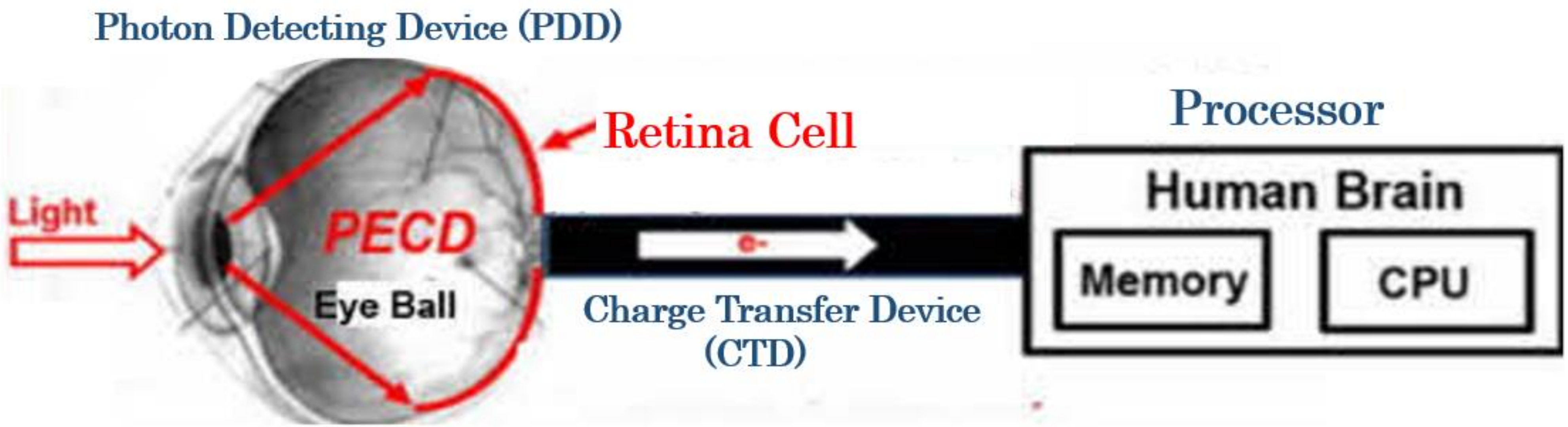
4 CCD/MOS type PDD and CTD

And finally when the digital TV era arrived, the charge transfer efficiency of 99.999% was not enough for the high definition 6000H x 4000V picture format. Because we needed 6000H + 4000V = 10000 charge packet transfers at each high definition picture frame, the signal charge loss will be 0.001 % x 10000 = 10% which is too large to be ignored by human eyes.



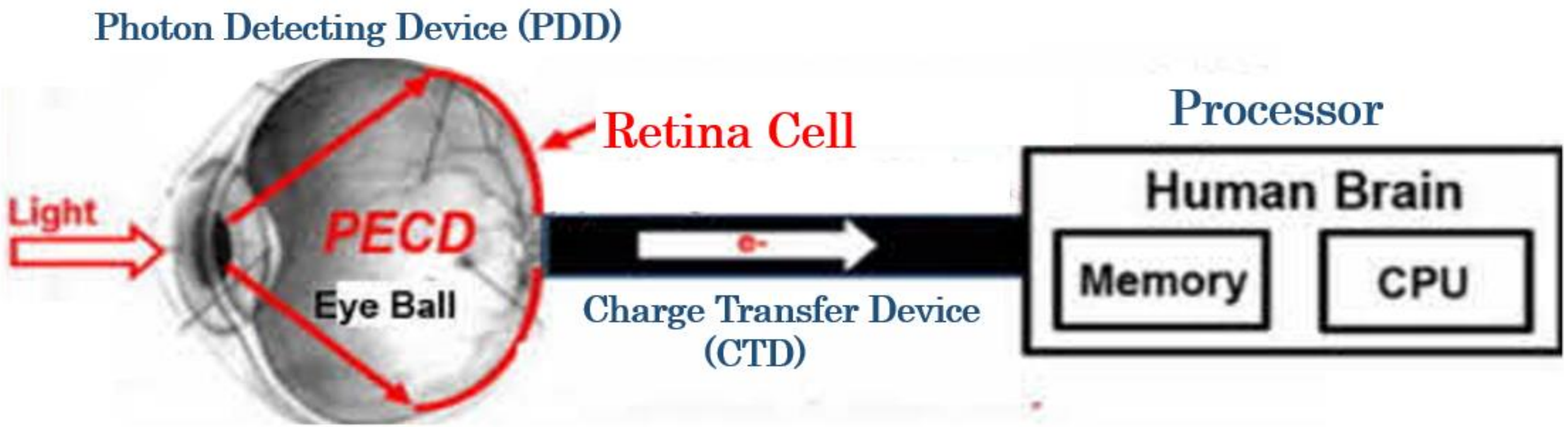
4 CCD/MOS type PDD and CTD

A typical classical image sensor had a single N+P floating junction type PDD, a simple MOS One Transistor One Capacitor (1T1C) DRAM type CTD while CCD/MOS dynamic capacitor type PDD and CTD were used widely in high performance solid image sensors. However, presently active pixel AMP CMOS image sensors have replaced CCD image sensors completely in the image sensor market.



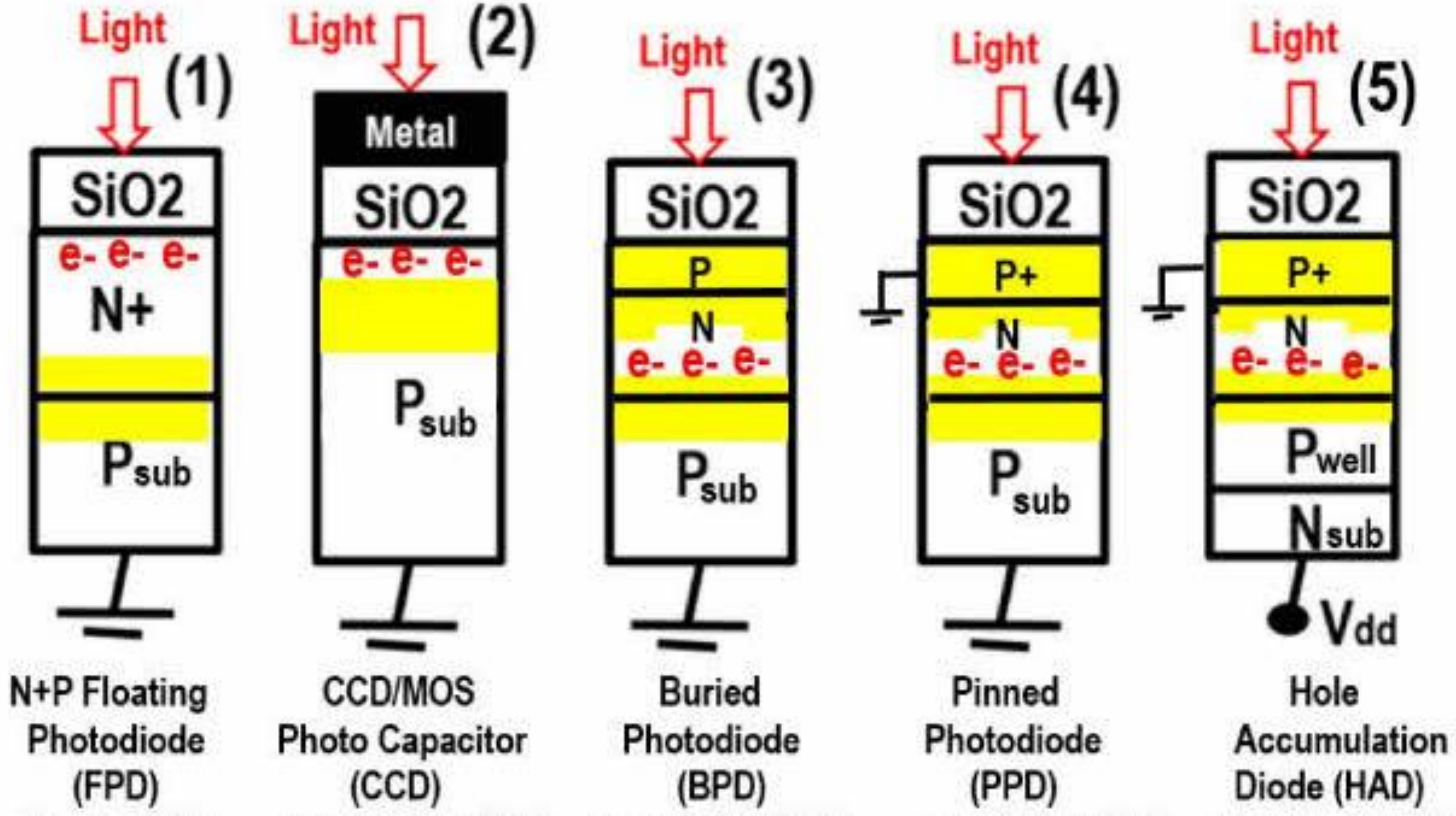
4 CCD/MOS type PDD and CTD

Both the single N+P floating junction type PDD and the CCD/MOS type PDD are now completely replaced by the double and triple dynamic junction type PDD with a vertical overflow drain (VOD) function, which was originally invented by Yoshiaki Hagiwara in 1975, with the completely mechanical free shutter function, realizing high speed action pictures.



4 CCD/MOS type PDD and CTD

Different kinds of Photon Detecting Device (PDD)



4 CCD/MOS type PDD and CTD

A modern CMOS image sensor is also composed of three parts, PDD, CTD and output circuit. However, a modern CMOS image sensors now has much improved parts.

Different kinds of Photon Detecting Device (PDD)