Correlated Double Sampling (CDS) for Solid-State Image Sensors

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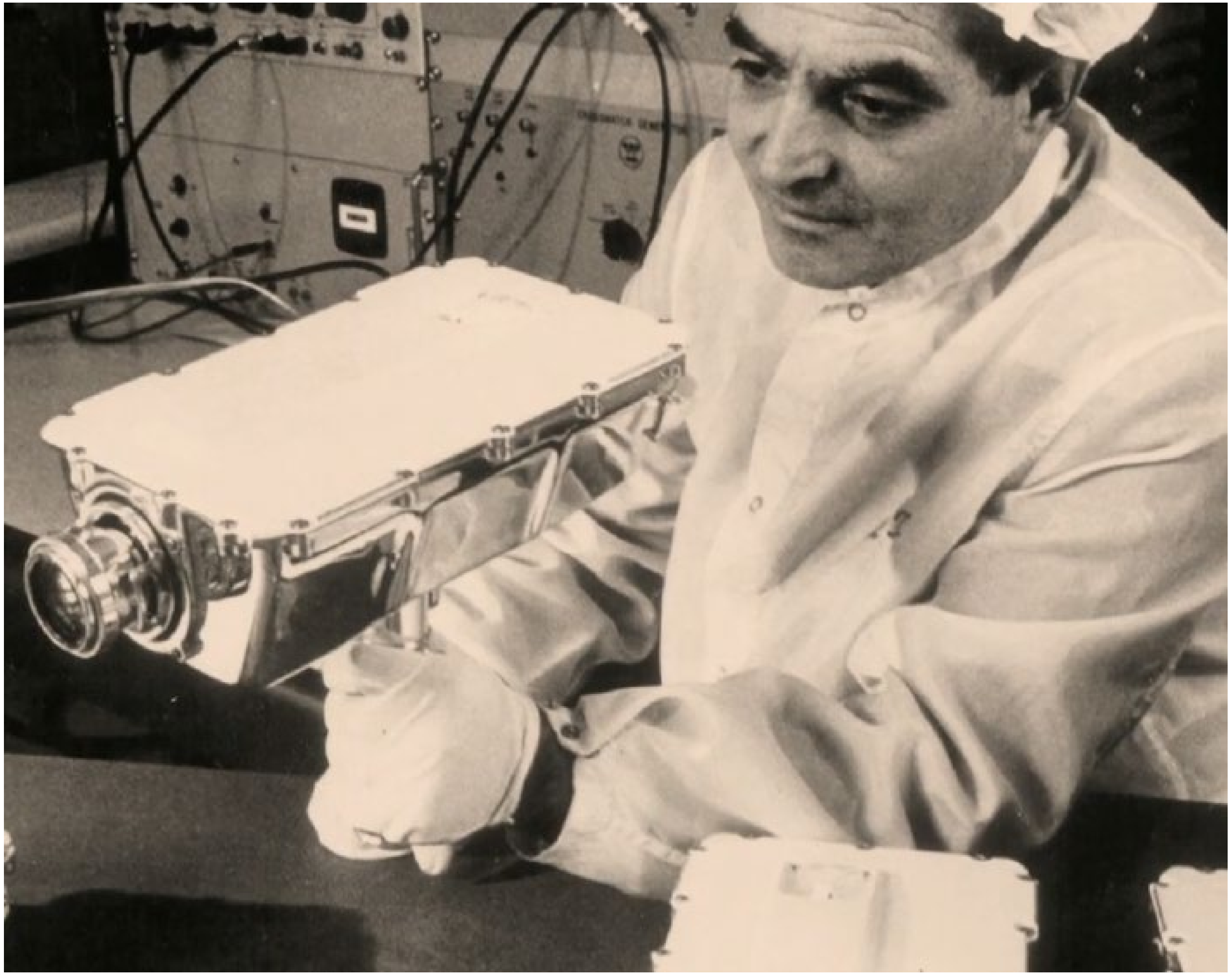
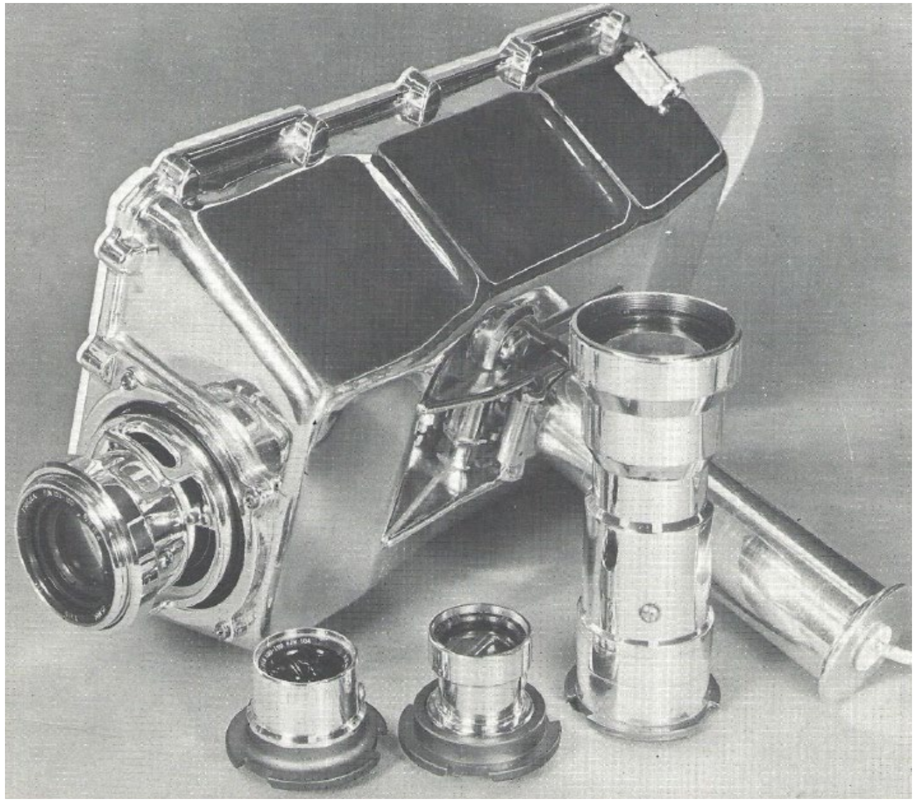
- History - Imaging with Vacuum Tubes

A Little History: Stan Lebar (Emmy® Award Recipient) Project Manager for the Lunar TV Camera in 1969



Stan and I were in the Westinghouse Air Arms Division in Baltimore, Md. He was project manager of the Lunar TV Camera Neil Armstrong used on the moon. I was working with engineers on the readout of photodiode line arrays and later, in a newly acquired Advanced Technology Laboratory (ATL) facility, on CCD line arrays to reduce the readout noise associated with sampling the pixels in these arrays.

Apollo LUNA CAMERA

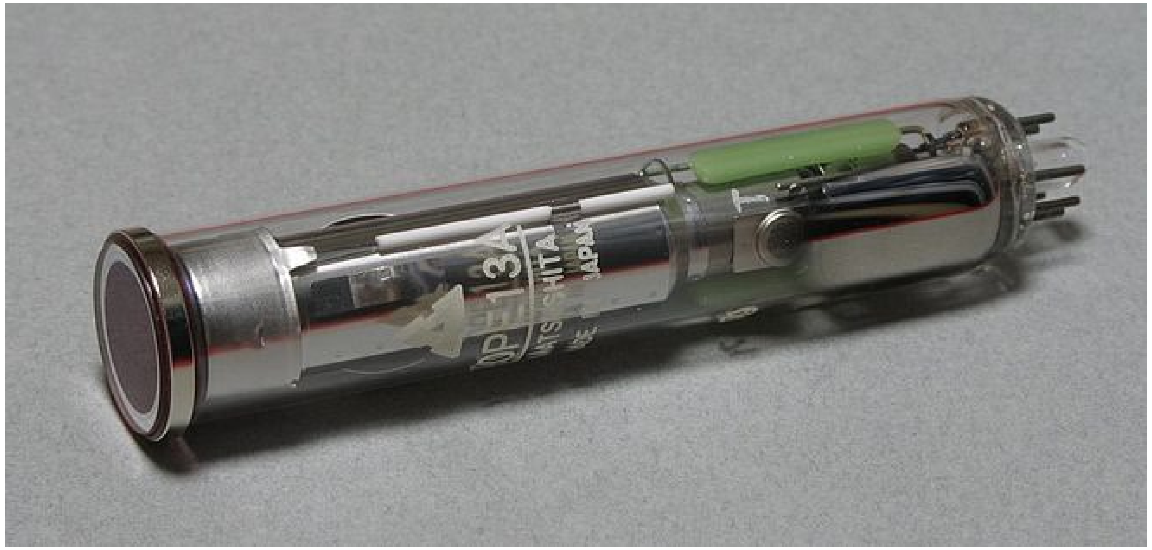


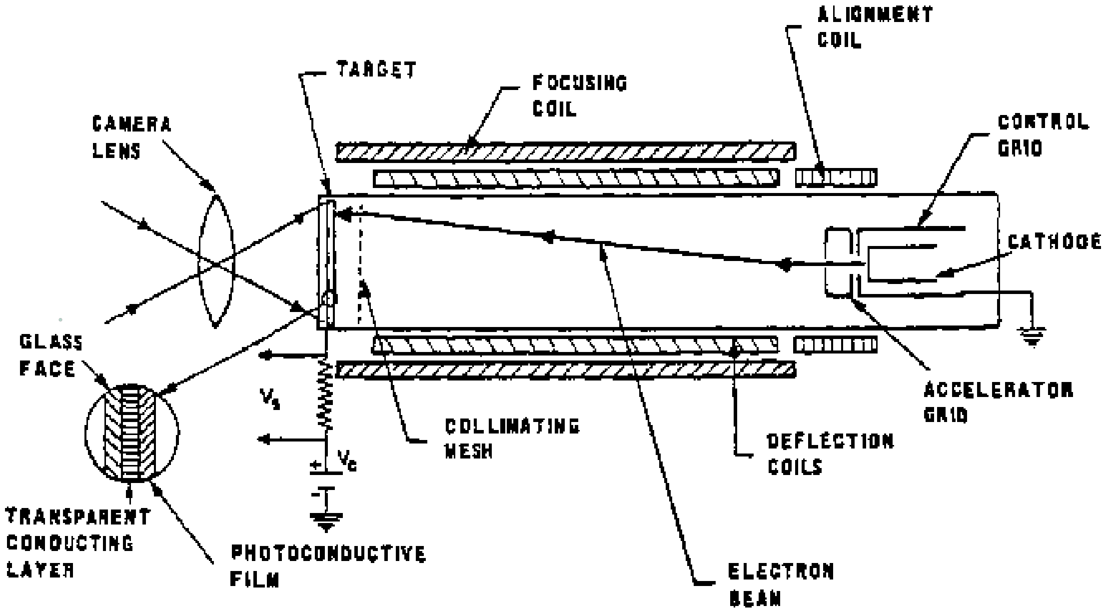
Reliability was a prime factor in the selection of the integrated circuit for the camera electronics, although size, weight and power consumption were also a consideration. Of the 43 IC's used, 24 were of different types and 19 of these types were designed and fabricated in the Westinghouse Solid-State Technology Laboratory, which became the Advanced Technology Laboratory (ATL) when the Laboratory staff moved from the Air Arms Division to a new facility previously called the Westinghouse Molecular Electronics Division.

The transmission of pictures back to the earth was accomplished with the output video modulating an S-band transmitter. The signals were transmitted in analog form because NASA studies showed that such a system required only one-fourth of the bandwidth (500 kHz) of a digital scheme.

The Apollo camera used a 10-frames-per-second, 320 line scan format called 'slow scan'. In telecasting fast actions, for example, a person quickly raising a hand would cause a brake-up or smear below 15 frames per second and would be very pronounced at 10 frames per second; however the astronauts moved slowly and the slow-scan operation was acceptable.

Image Vidicon and Signal Storage in the Photoconductive Film

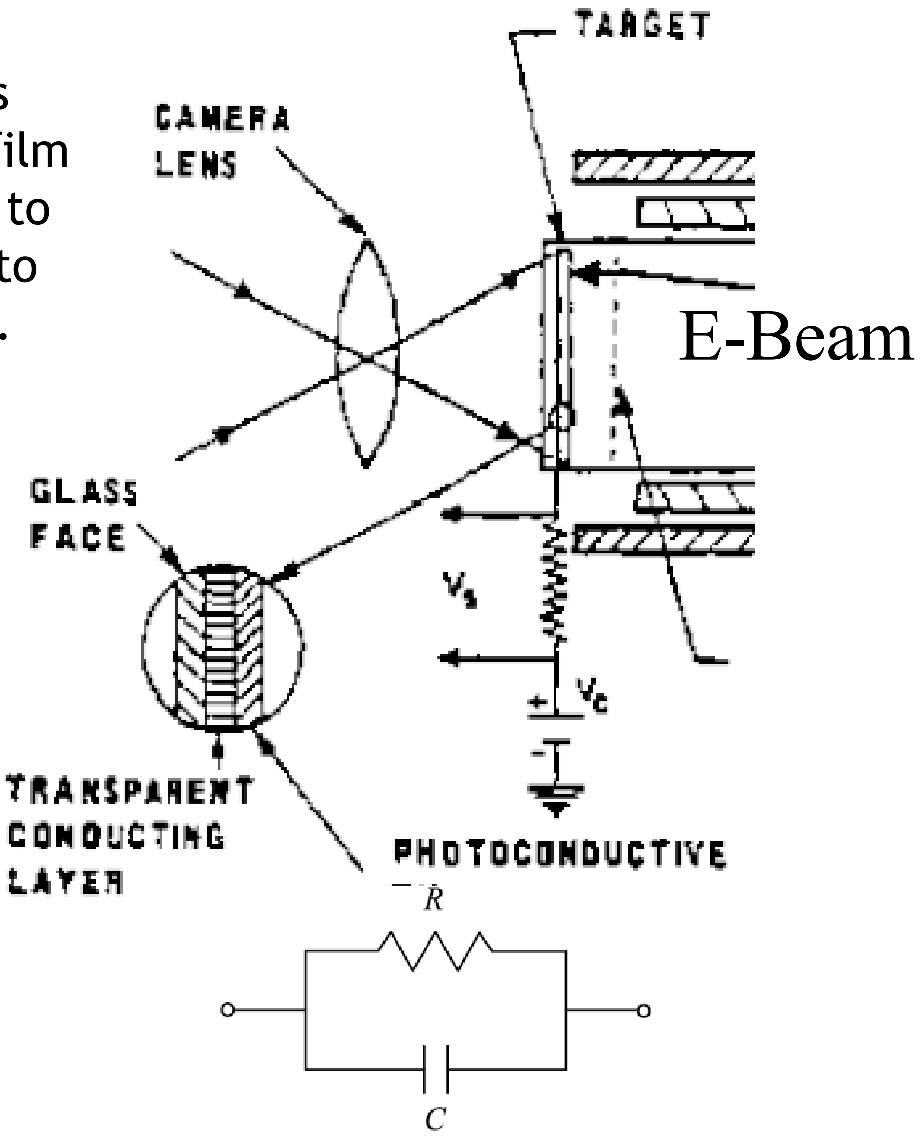




Note: The LEM camera used an image intensified Secondary Electron Conduction (SEC) camera with a vidicon readout.

Integration - The Principle of Information Storage to Achieve Improved S/N Ratio

The electron gun scans a contiguous photoconductive film depositing charge to bring the surface to cathode potential.



$$R=\rho\frac{d}{A},\quad C=\frac{\varepsilon_F}{d}A$$

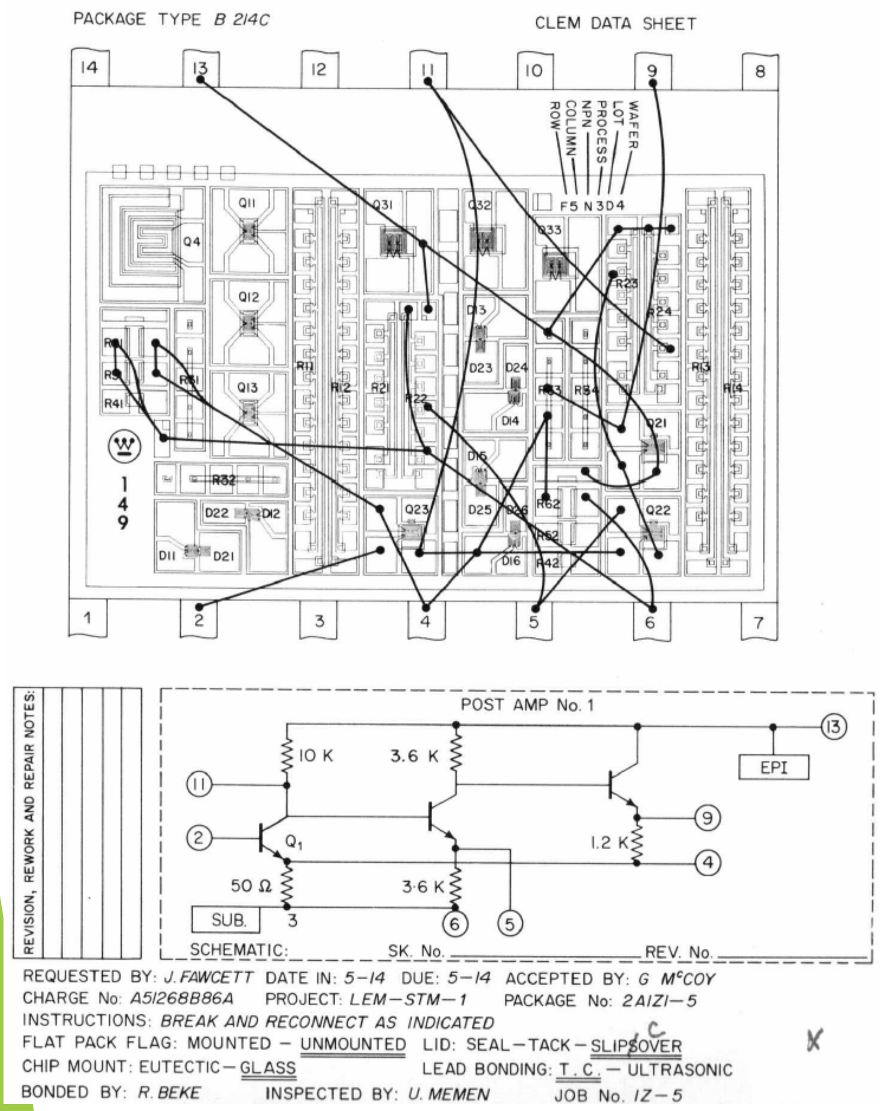
A is the E-Beam area

d is the thickness of the photoconductor film

$RC=\rho\varepsilon_F>>t_f$

(t_f Beam Frame Time)

Breadboard Chip - CLEM


PACKAGE TYPE B 214C

CLEM DATA SHEET

SCHEMATIC: SK. No. ______ REV. No. ______

REQUESTED BY: J. FAWCETT DATE IN: 5–14 DUE: 5–14 ACCEPTED BY: G McCOY

CHARGE No: A51268B86A PROJECT: LEM–STM–1 PACKAGE No: 2A1Z1–5

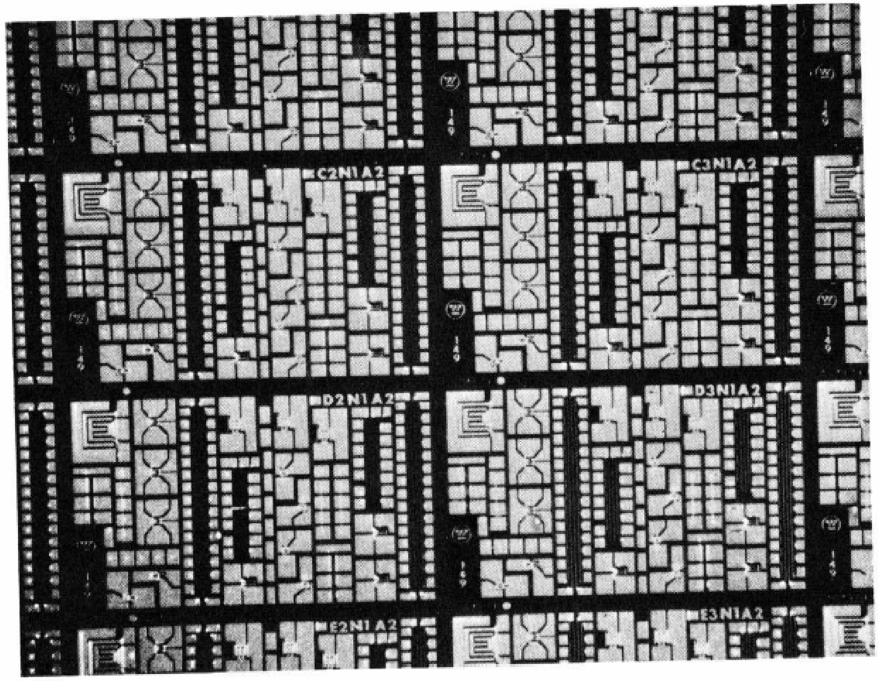
INSTRUCTIONS: BREAK AND RECONNECT AS INDICATED

FLAT PACK FLAG: MOUNTED – [✓ UNMOUNTED] LID: SEAL–TACK–[✓ SLIP~~S~~COVER] X

CHIP MOUNT: EUTECTIC–[✓ GLASS] LEAD BONDING: [✓ T. C.] – ULTRASONIC

BONDED BY: R. BEKE INSPECTED BY: U. MEMEN JOB No. 1Z–5

We used a general purpose silicon chip (CLEM) in the 60-70’s to accomplish flexible, fast and economical breadboarding because there were no simulation tools like SPICE and SUPREM and we did not know the what parasitic interactions would happen at the chip level. The CLEM block consisted of an epitaxial collector design with diffused p-n junctions, tapped resistors and n-p-n bipolar transistors The different elements were assigned a special coding sequence.



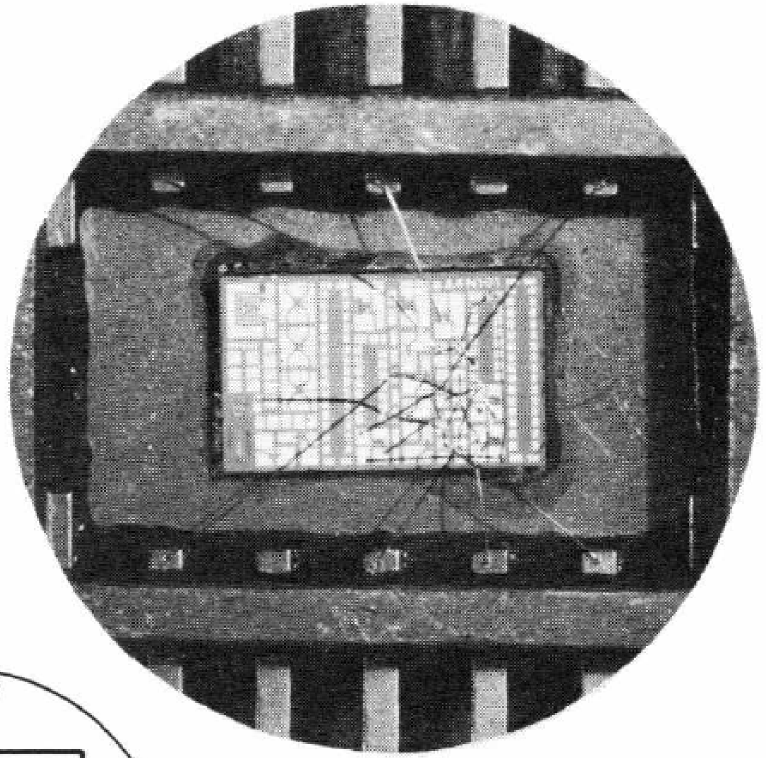
CLEM Breadboard with Wire Bonding

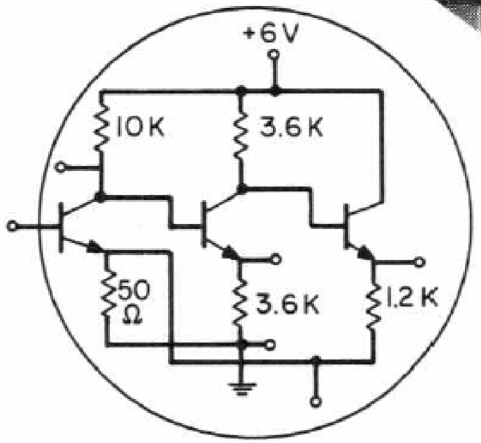
LEM TV CAMERA CIRCUITS
BREADBOARDED WITH CLEM

OPERATING ON POWER SUPPLIES
-8 V, +6 V, +25 V

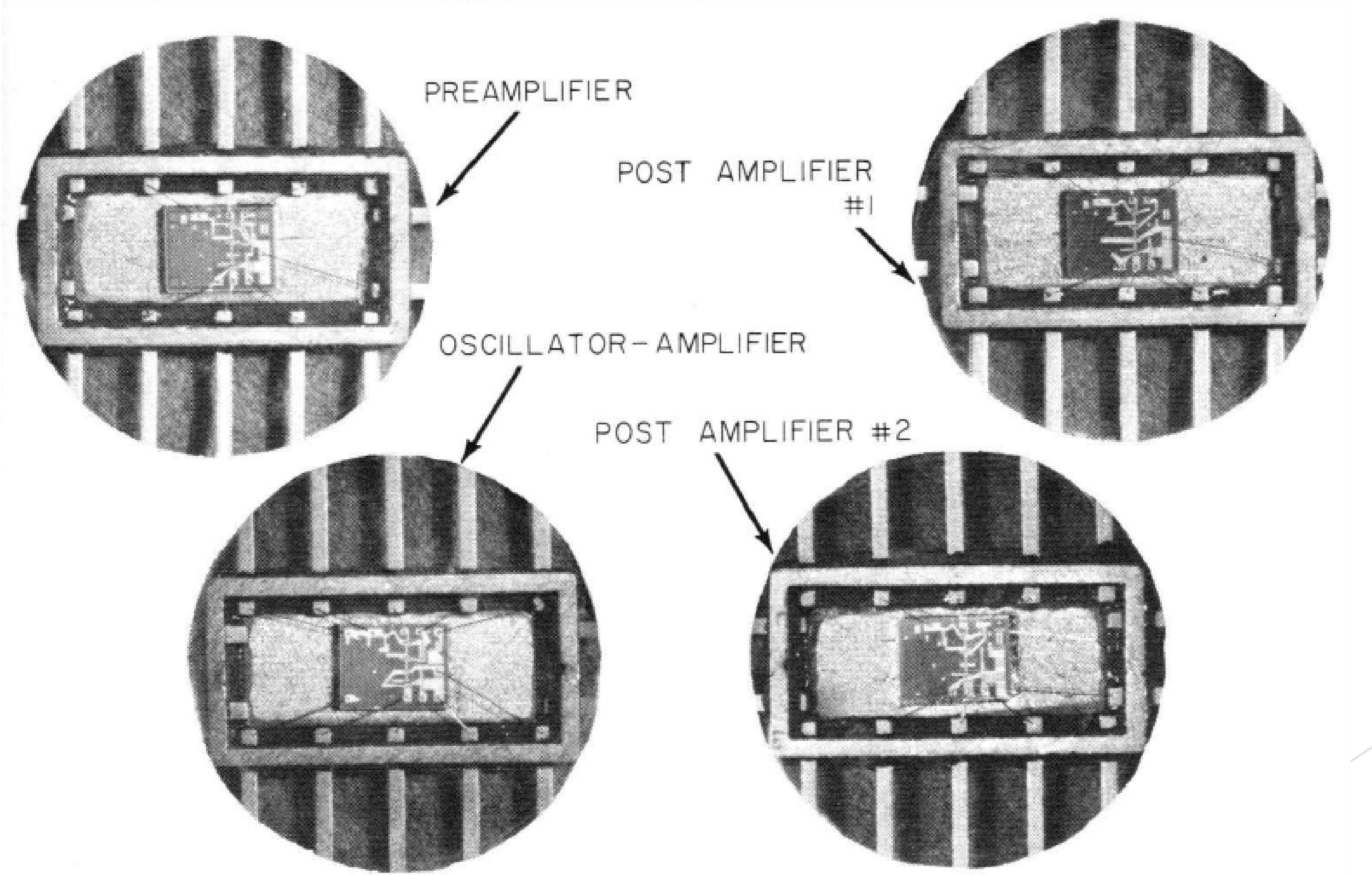
- ALC DETECTOR
- ALC DRIVER
- CORRECTION NETWORKS
- AGC ATTENUATOR
- LINEAR PRE-AMPLIFIER
- POST AMPLIFIER NO. 1
- POST AMPLIFIER NO. 2
- OSCILLATOR-AMPLIFIER
- BLANK DRIVER
- MIXER
- SAW TOOTH GENERATORS
- DIFFERENTIAL AMPLIFIERS
- OUTPUT DRIVERS
- MULTIVIBRATORS
- INVERTER DRIVERS
- LINE REGULATORS
- LINE SWITCHES
- VOLTAGE REGULATORS

TYPICAL CLEM BREADBOARD





Compatible Family of Linear Amplifiers with Metallized Interconnects after Breadboarding



Astronauts on Apollo Lunar Mission[1] - 1969


Neil Armstrong, Michael Collins, Edwin ‘Buzz’ Aldrin Jr.

The Westinghouse LEM camera was stored for flight in the lunar module’s Modular Equipment Stowage Assembly (MESA), a compartment near the ladder that Armstrong climbed down to reach the Moon’s surface. To activate the camera, he pulled on a handle that in turn released the door to the MESA. Engineers attached the camera upside down to secure it to the door, and tilted at an 11-degree angle because of how the door rested in its final position. Both issues were overcome in retransmission of the signal back on Earth.

[1] Space Frontiers/Getty Images

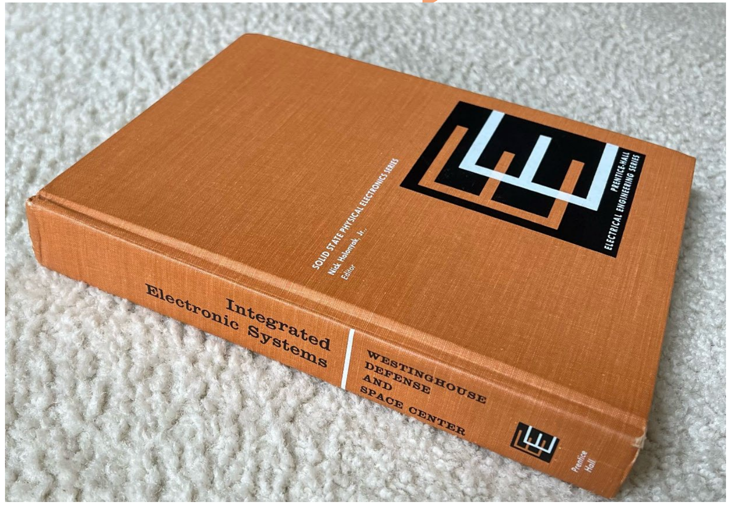
Apollo 11 Ascent Stage (Eagle) to join the Lunar Module*

The Apollo 11 Eagle ascent stage, with astronauts Armstrong and Aldrin aboard, is photographed by Collins in lunar orbit. The lunar module was making its docking approach. The large, dark-colored area in the background is Smyth's Sea; Earth rises above the lunar horizon. The picture was taken by Michael Collins.

On July 20, 1969, the Apollo 11 Lunar Module landed with two cameras, but only one went outside — carried by Neil Armstrong. That explains why nearly every photograph of an astronaut on the surface during that first landing is of Armstrong crewmate Edwin "Buzz" Aldrin. Armstrong had the only camera for nearly the entire two-and-a-half hours the two walked around the Sea of Tranquility.

*Scott Neuman, WOSU –npr- “The Camera That Went To The Moon And Changed How We See It” July 13, 2019.

Westinghouse Defense and Space Center Authors of Integrated Electronic Systems - 1970



NATO Solid-State Imaging Conference - 1975

SOLID STATE IMAGING

edited by

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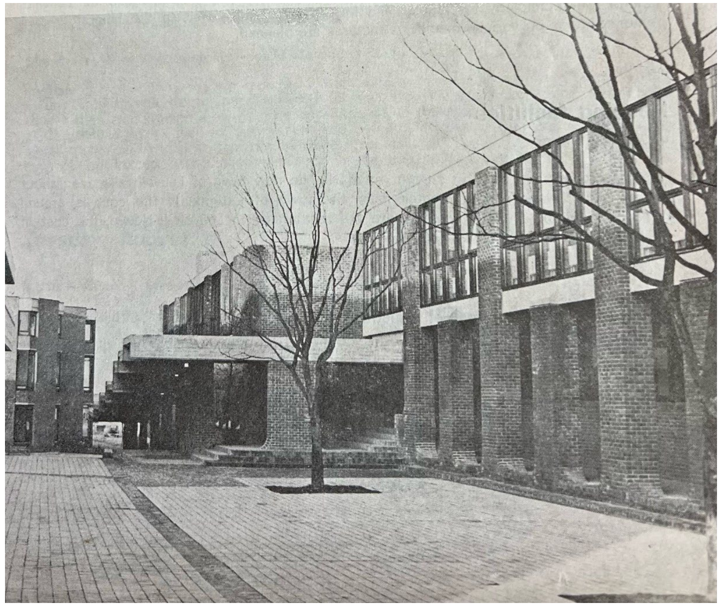


In 1975 I worked with two professors, Jespers and van de Wiele in Belgium to organize a NATO Conference on Solid-State Imaging. One of the topics was on the use of CDS in Image Sensors. As a result, a book was published.

Advanced Technology Labs (ATL) - 1972 in Linthicum, MD outside of Baltimore, Md.

This complex was formerly called the Westinghouse Molecular Electronics Division (1963-1970) – a commercial supplier of IC’s.

Solid-State Imaging and Noise Sources

Noise Sources Affecting Performance of Solid-State Image Sensors

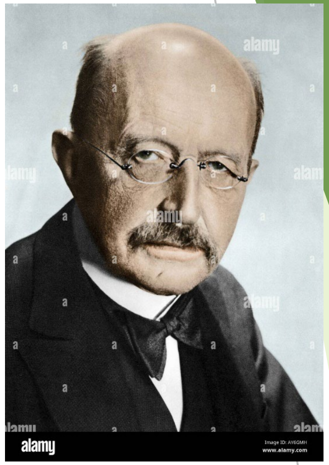
- The following noise sources are encountered in Solid State Sensors, such as CCDs and Photodiodes:
- 1. Thermal Noise (e.g. Reset Noise)
- 2. Shot Noise
  - a. Electronic (Electrons over an Energy Barrier)
  - b. Optical (Photons from the Scene)
- 3. Flicker (1/f) Noise (Surface and Bulk Traps)
- 4. Fixed Pattern Noise (FPN) (e.g. Switch Feedthroughs)

We needed a technique to remove or suppress these noise sources!

Planck’s Radiation Law - 1

In 1900, Max Planck examined the radiation from a cavity (e.g. blackbody) and found the spectrum could be fit with the following empirical expression:

$$H_S(\lambda,T)=\frac{c_1}{\lambda^5(e^{\frac{c_2}{\lambda T}}-1)}\ (j/m^3\mu m)$$



Max Planck
1858-1947

With the help of the Rayleigh-Jeans Law at increasing wavelengths and Einstein’s postulate that the radiation was generated by oscillators with photon radiation energy

$$E=nh\nu=n\frac{hc}{\lambda}$$

We have

$$c_1=8\pi ch\ and\ c_2=hc/k_B$$

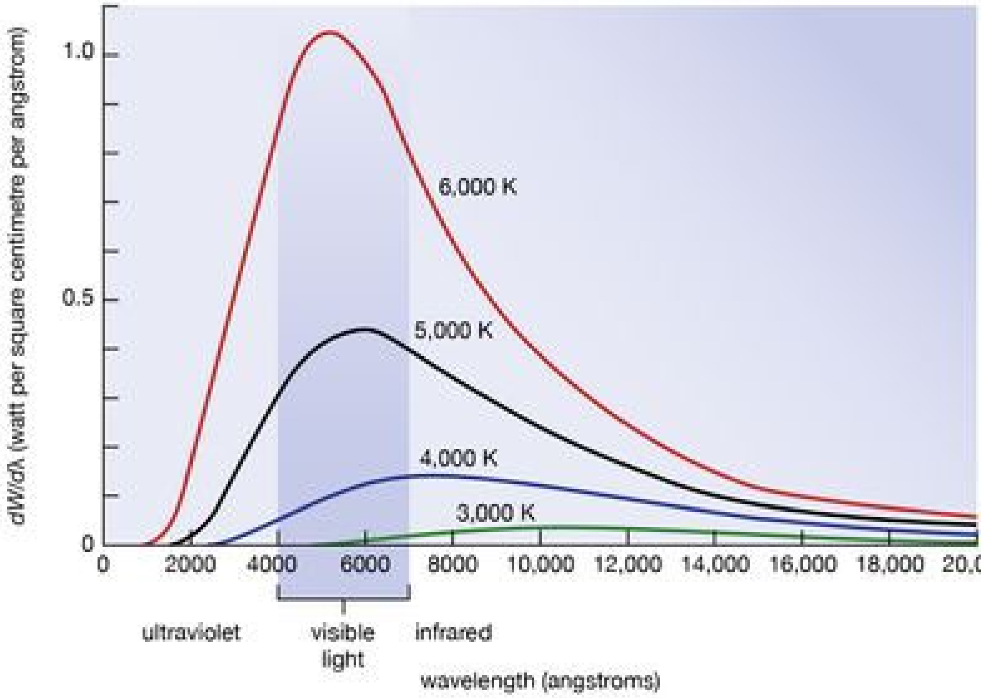
Planck’s Radiation Law - 2

$$H_\lambda = \frac{2\pi c^2 h}{\lambda^5 \left(e^{hc/\lambda k T_s} - 1\right)} \left(\frac{W}{m^2 \cdot \mu m}\right)$$ Irradiance

$$H_{\text{eff}} = \int_{\lambda_1}^{\lambda_2} \mathrm{H}_\lambda \, d\lambda$$ Effective Irradiance

$$= \int_{400}^{800} \frac{2\pi c^2 h}{\lambda^5 (e^{hc/\lambda k T_s} - 1)} d\lambda \; \left(W/m^2\right)$$

$$\left(\frac{\lambda_1 = 400\,nm \quad \lambda_2 = 800\,nm}{\bar{\eta} = 0.7 \quad T_s = 6000^0\,K}\right)$$



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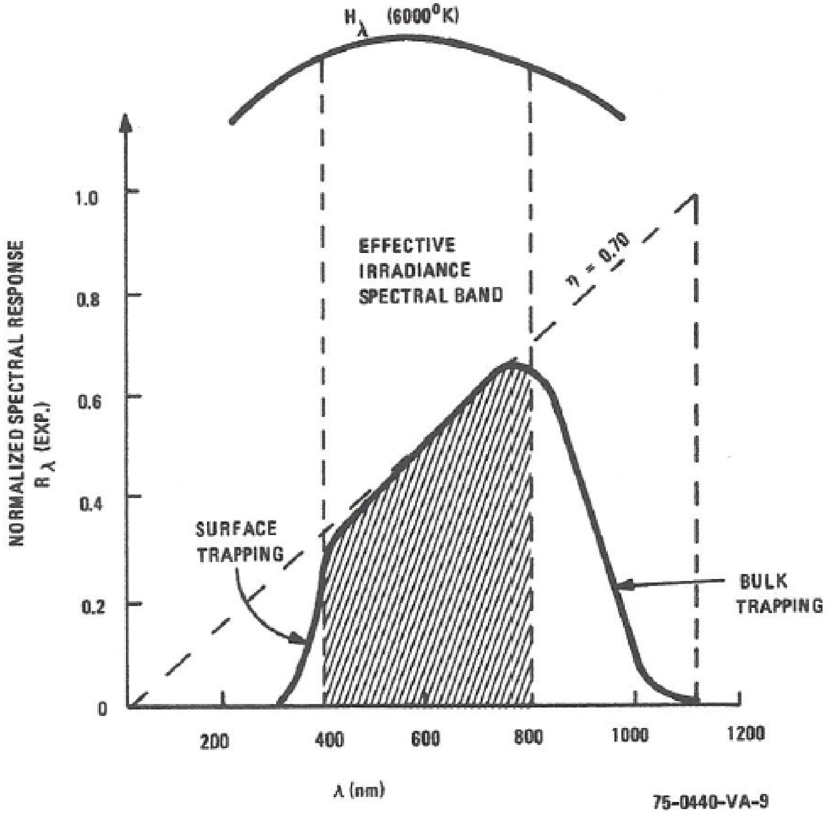
Detector Responsivity

$$R_{\lambda} = \frac{q\eta(\lambda)A}{hc/\lambda} \quad \left(\frac{pA}{mW/m^2}\right)$$ Detector Spectral Responsivity

$$R_D = \frac{\bar{I}_s}{H_{eff}} = \frac{\int_{\lambda_1}^{\lambda_2} R_{\lambda} H_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} H_{\lambda} d\lambda}$$ Effective Responsivity

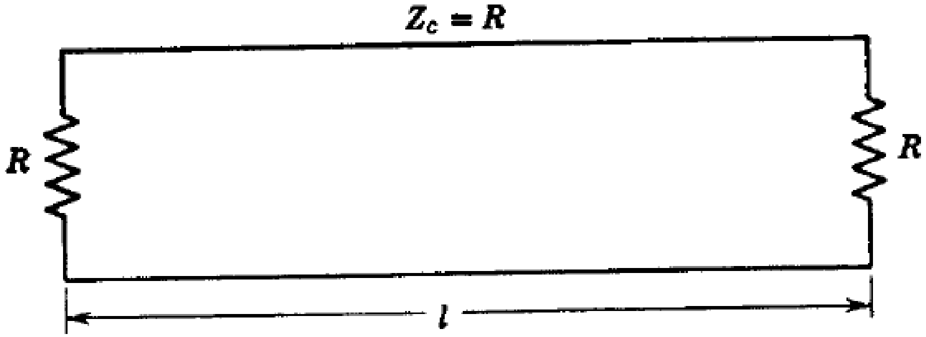
$$\square \frac{q\bar{\eta}}{kT_s} \frac{\int_{x_1}^{x_2} x^2 e^{-x} dx}{\int_{x_1}^{x_2} x^3 e^{-x} dx} = 0.33 \frac{A}{W/m^2} \left(\frac{C}{\mu J/m^2}\right) \quad x \, \square \, \frac{hc}{\lambda k T_s}$$



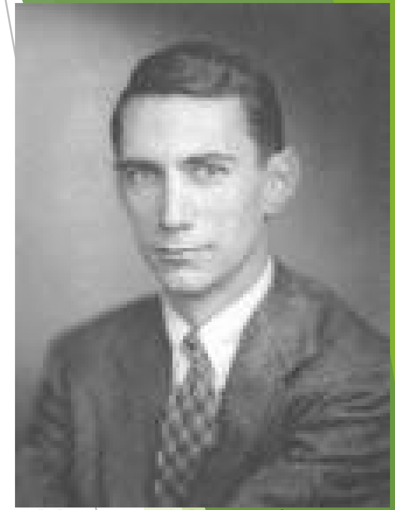
$\bar{I}_S = qR_D H_{eff} \tau = qR_D E_{eff}$, where τ is the exposure time

and E_{eff} is the Effective Exposure Density ($\mu J/m^2$)

Thermal Noise[1]



Lossless Transmission Line, at temperature T, with Matched Terminations R



Harry Nyquist
1889 - 1976

The transmission line has two electromagnetic modes (one in each direction) in the frequency interval

$$\Delta f = \frac{v}{l}$$

where v is the propagation velocity on the line. Each mode, following Planck's Radiation Law, has a mean energy at low frequencies

$$\overline{E} = \frac{hf}{e^{\frac{hf}{kT}} - 1} \approx kT$$

The mean energy on the line in the frequency interval is $2kT\Delta f$ with the energy in one direction of $kT\Delta f$. The power radiated from one resistor will be completely absorbed by the other and conversely. This power absorbed is

$\overline{i_n^2} R = kT\Delta f$ and since $\overline{v_n} = \overline{i_n} 2R$, we have $\overline{v_n^2} = 4kTR\Delta f$

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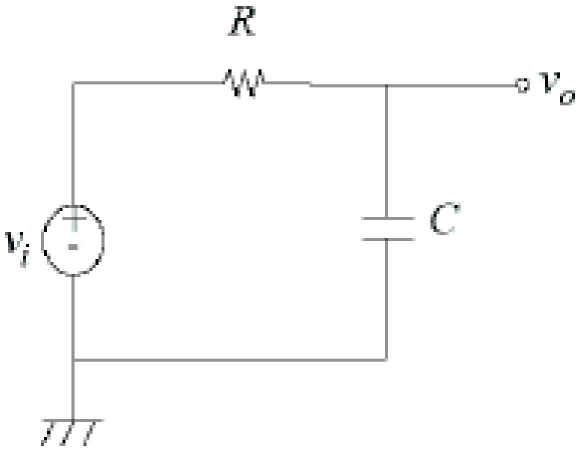
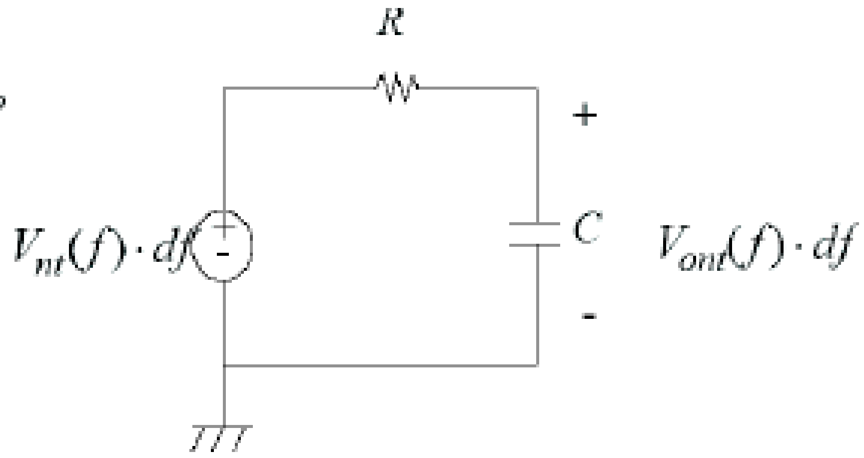
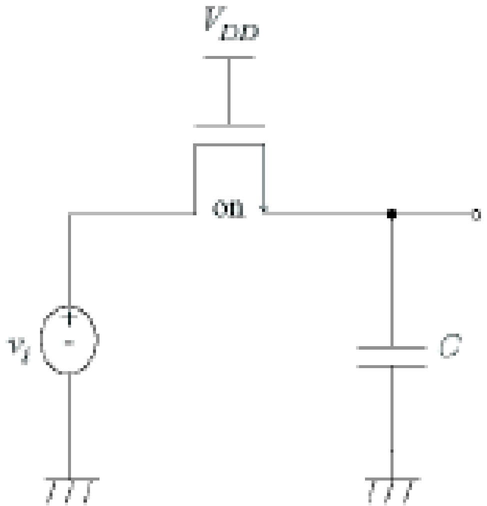
[1] H. Nyquist, Phys. Rev., **32**, 110 (1928).

Integrated Thermal Noise (Reset Noise)







$$\overline{v_n^2} = 4kTR\Delta f = 4kTR\int_0^\infty |H(f)|^2\, df = 4kTR\int_0^\infty \frac{df}{1+f^2/f_c^2}$$

$$\overline{v_{nc}^2} = 2\pi kTRf_c = \frac{2\pi kTR}{2\pi RC} = \frac{kT}{C} \qquad H(f) = \frac{1}{1+jf/f_c} \qquad f_c = \frac{1}{2\pi RC}$$

$$(\overline{q_n^2})^{1/2} = \sqrt{kTC} = 400\sqrt{C(pF)}\ \text{noise electrons}$$

Note : The Reset Noise is integrated and stored on C

‘Shot’ Noise and Exposure Time

$\overline{i_n^2} = 2q\bar{I}\Delta f$ (average current $\bar{I}$ across a junction), where $\bar{I} = \bar{I}_L$ (*l*eakage) + $\bar{I}_S$ (signal)

The $\bar{I}_L$ = Leakage Current from (SRH) Generation-Recombination occurs in surface and bulk traps in the semiconductor. If we collect the signal and leakage charge carriers, in a reverse-biased photodiode or CCD well for an exposure time τ, then the Fourier Transform of the above equation is multiplied by a square wave transform as

$$\overline{q_n^2} = \int_0^\infty \left(\frac{\overline{i_n^2}}{\Delta f} \right) \tau^2 \left(\frac{\sin \pi f \tau}{\pi f \tau} \right)^2 df = q \bar{I} \tau$$

*w*here the exposure time 'τ' serves as a filter for the 'white' noise spectrum of the 'shot' noise. Thus, we have the expression

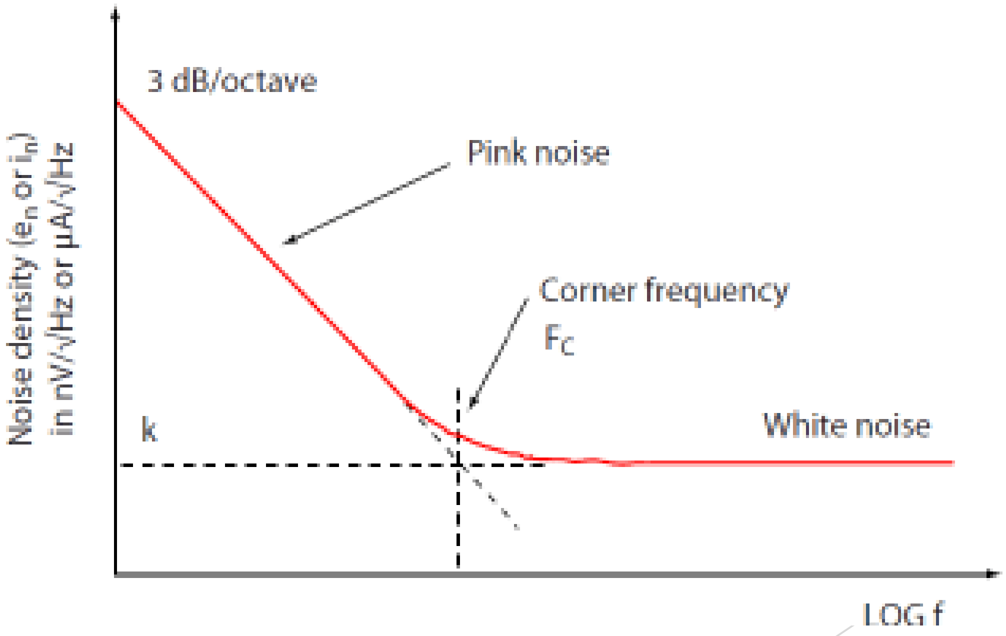
$$\overline{q_n^2} = \underbrace{q R_D E_{eff}}_{\text{photon}} + \underbrace{q \bar{I}_L \tau}_{\text{leakage}} \qquad E_{eff} = H_{eff}\,\tau$$

1/f Noise in Image Sensors

$R_n(f) = R_{n0}\left(1+\frac{f_0}{f}\right)$ $\quad f_0 \approx \mathrm{D_{it}}(\mathrm{E_t})$ Interface Trap Density $\left(\mathrm{Traps/cm^2eV}\right)$

$S_v(f) = 4kTR_n$ Spectral Noise Voltage ($\overline{\mathrm{v}}_n^{\,2}/Hz$). In a MOSFET the corner frequency $\mathrm{f_0}$ maybe much larger than shown in this figure and may be as large as 500 kHz due to the reduced area (WL) of the device and the interface traps.

On a Spectrum Analyzer, ‘white noise’ is the flat part of the spectrum and 1/f or ‘pink’ noise starts at the corner frequency f_c and rises at 3 dB/octave . f_c is determined by the traps at the interface and the bulk of the device. It is also inversely proportional to the MOSFET area.



Challenges in the Design of Sensor Arrays

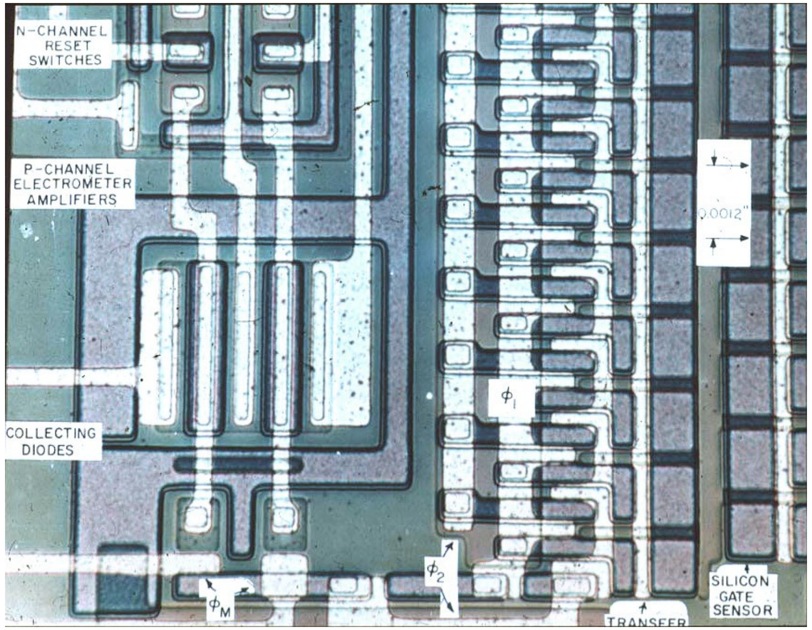
A challenge in the design of sensor arrays was and still remains to

- Remove the thermal ‘Nyquist’ noise associated with the reset switch
- Suppress the ‘shot’ noise due to generation-recombination current (bulk and surface)
- Filter the 1/f noise - so-called ‘flicker’ noise
- Restore the system DC level
- Remove the fixed pattern noise (FPN) – switch feedthroughs, variation in capacitance and gain of the source-follower amplifier

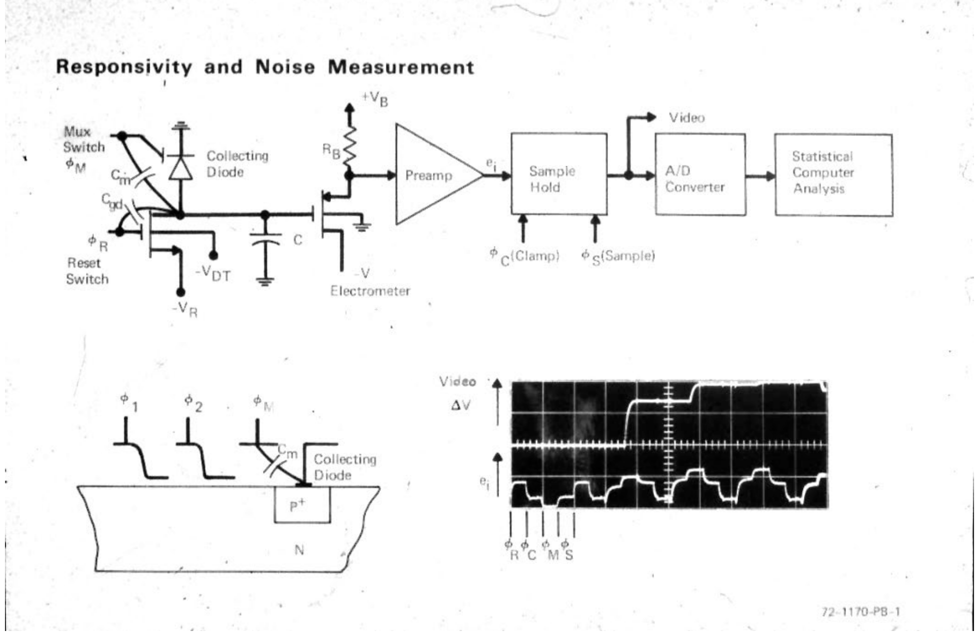
We assume the Spectral Responsivity and associated sensor ‘quantum’ efficiency can be controlled by the fabrication process.

- **CDS with CCD Imagers**

The Development of Correlated Double Sampling (CDS) for Image Sensors (1972)



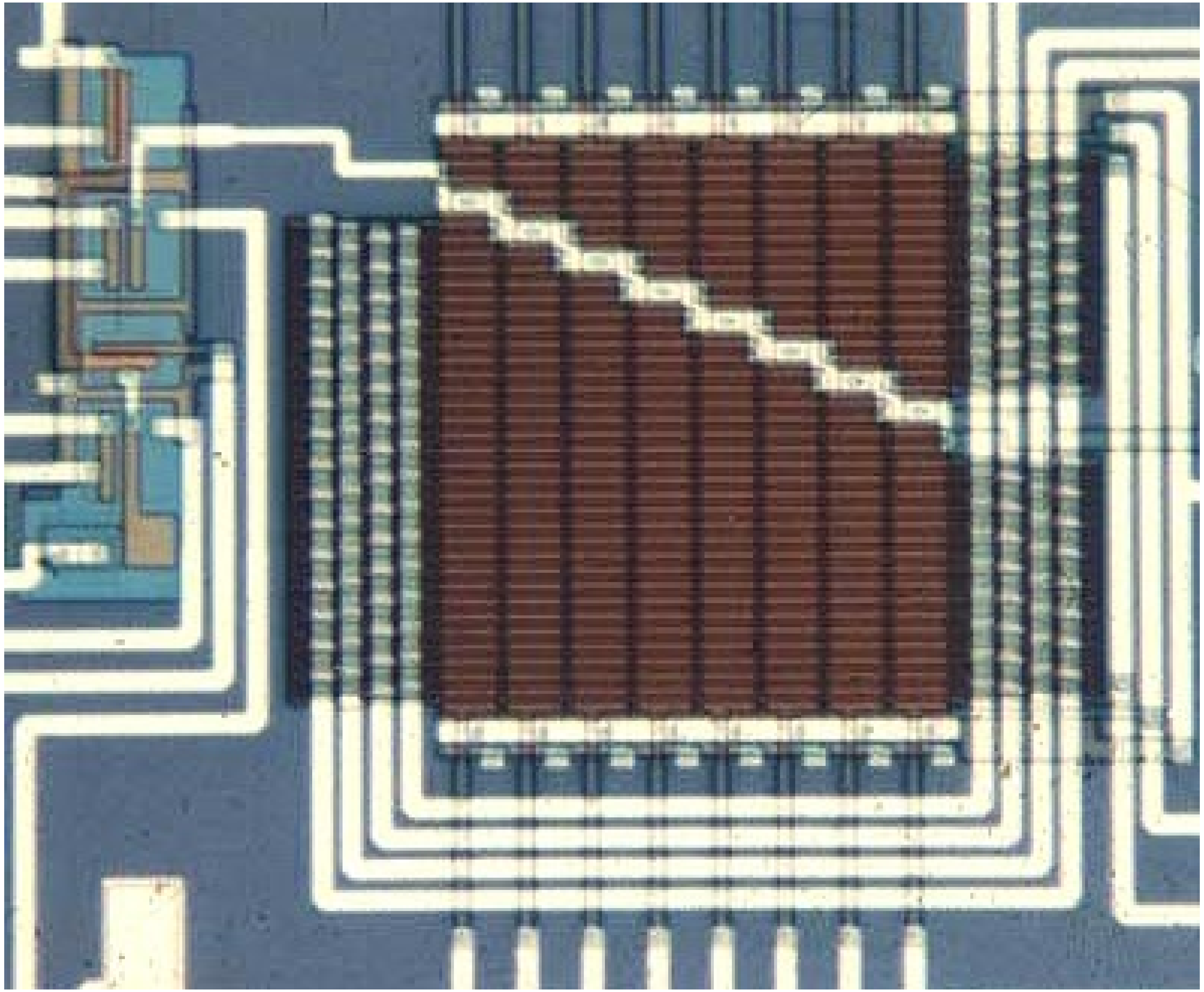
(a) CCD Line Array Imager (ΔX=18μm, ΔY= 22μm, P=15μm, Polysilicon Gate Sensors) with CMOS Correlated Double Sampling (CDS) Output Circuit



(b) CCD Line Array Imager Data Acquisition with CMOS Correlated Double Sampling (CDS) Output Circuit

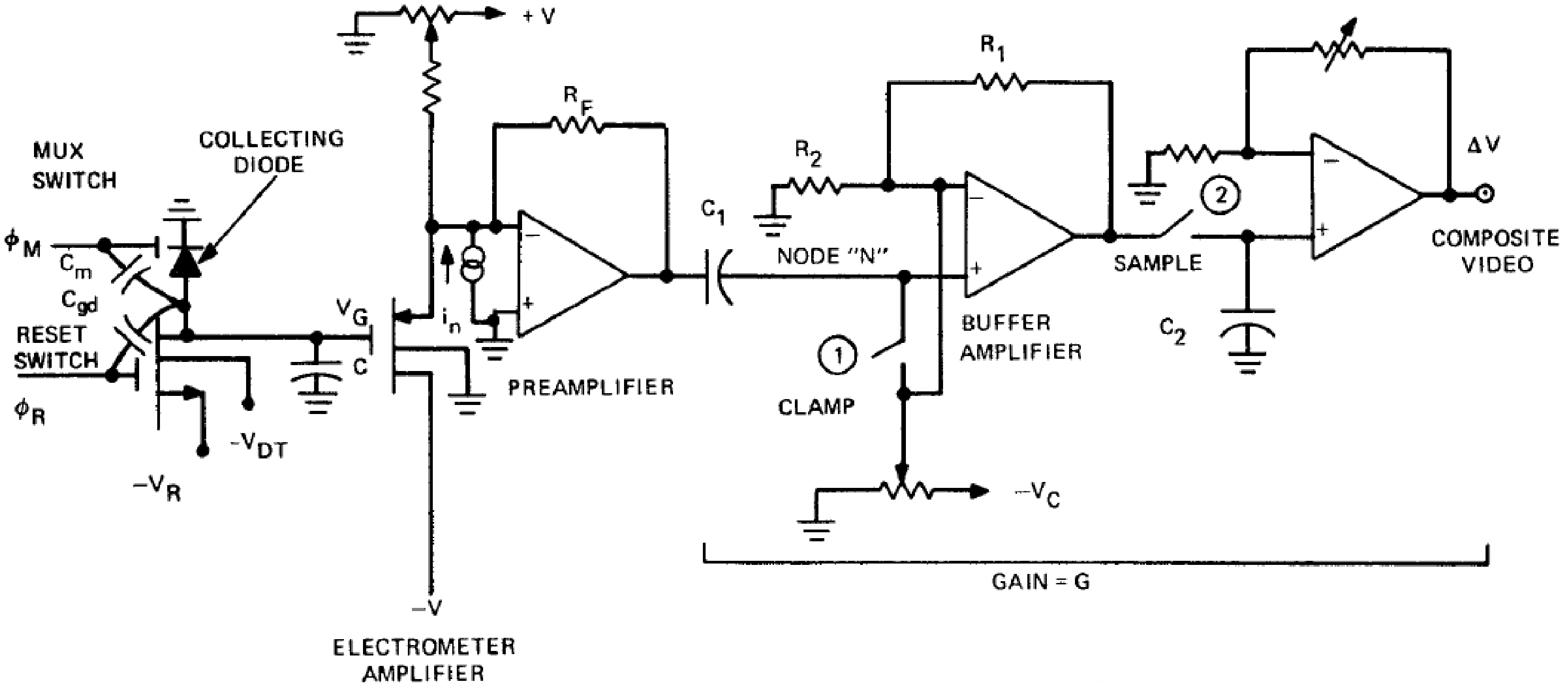
Note: These pictures are my early research on Charge-Coupled Device (CCD) Imaging with Correlated Double Sampling (CDS). Notice, the clean output video signal ΔV that results from suppression of feedthroughs and noise. In this early work we worked with p-channel devices and 'hole' transport to the output detection node with the n-channel reset switch in a p-well. The reason for an inverted CMOS was the inability to control 'channeling' and leakage currents on p-type substrates. Later, with the LOCOS process and 'stopper' diffusions, the standard CMOS (p-substrate) was developed.

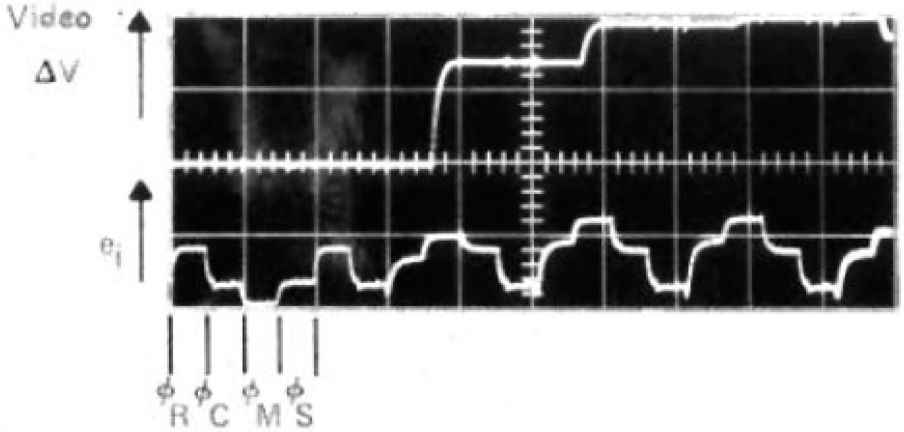
CCD Beamformer with CDS - 1977



Charge Coupled Device (CCD) 16 Input Beamformer with an Organ Pipe Geometry and Correlated Double Sampling (CDS) CMOS Readout Circuit.

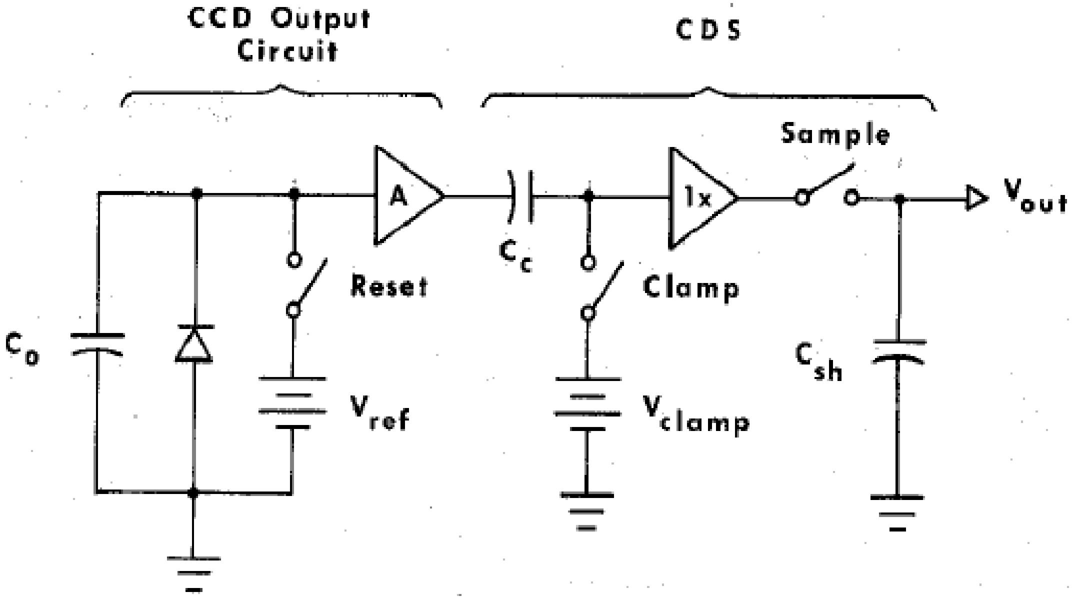
CDS Readout Circuit with Composite Video



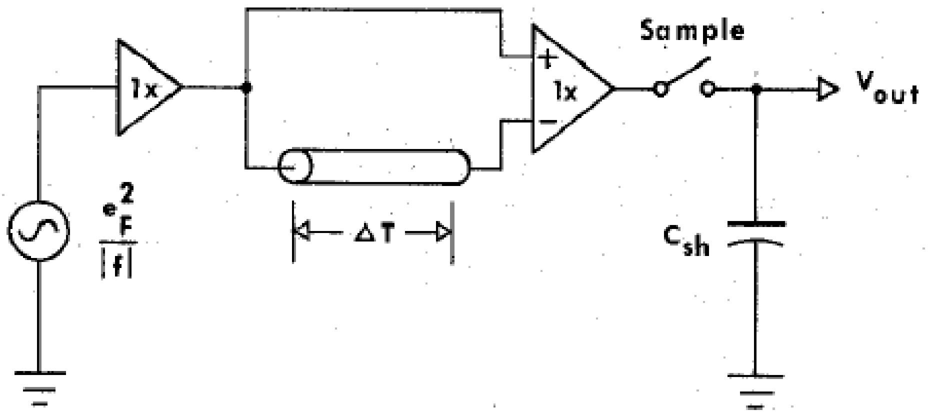


In a CCD we had a single readout circuit, which collected the charge from each pixel. In a pixel time, we have 4 operations: (1) Reset, (2) Clamp (Read Reset), (3) Mux, (4) Sample (Clean Signal)

CDS Circuit* Analysis



Simplified CDS Circuit - one path

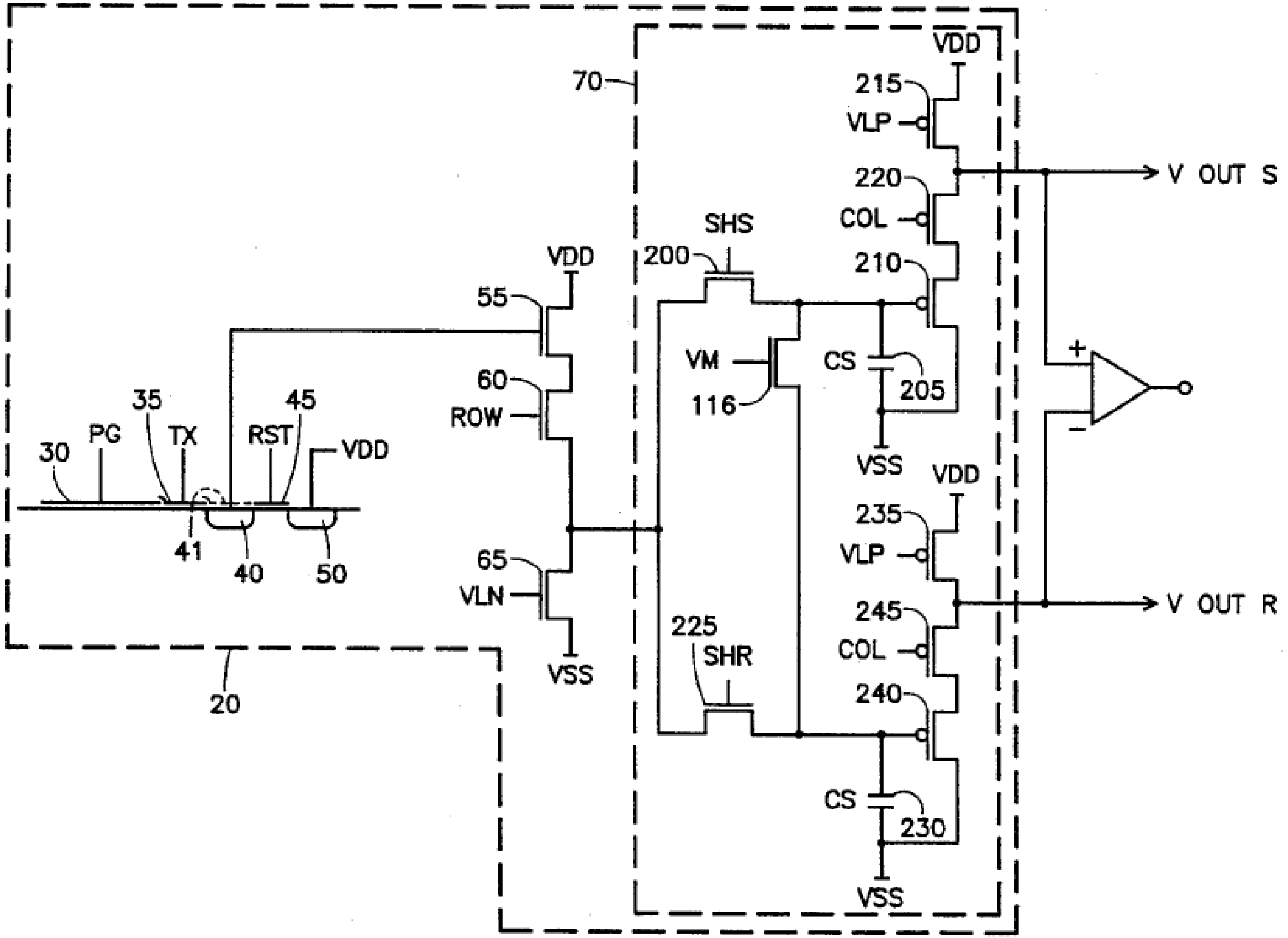


Equivalent CDS Circuit - two paths

I should mention an important point: The equivalent CDS circuit is a useful mathematical technique, but it is not a representation of the original CDS Circuit. The reason is in the original CDS circuit the Read Reset (Clamp) and Read Signal (Sample) traveled through the same path to the output. In the equivalent circuit the differencing of the Clamp and Sample signals occurs in a summing amplifier as they proceed through separate paths. This method is used; however, to minimize amplifier bandwidth requirements.

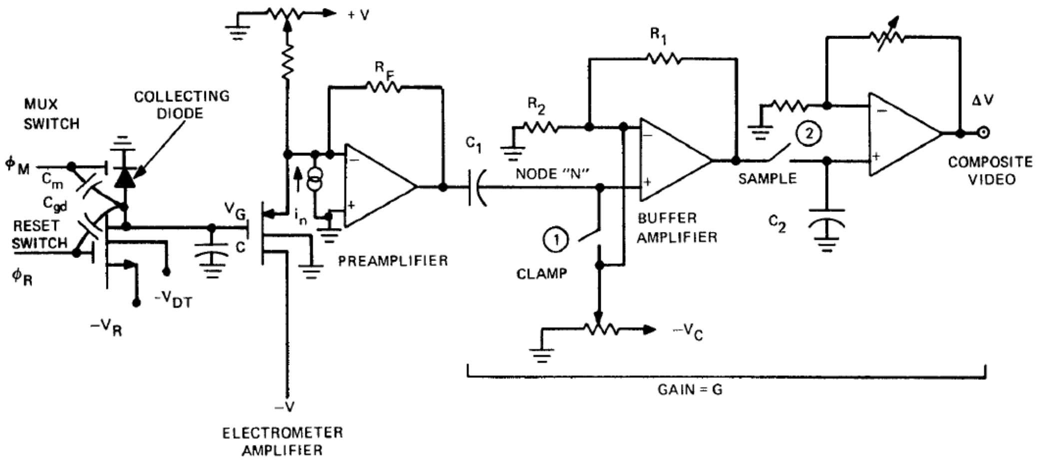
*Robert J. Kansy, IEEE J. Solid-State Circuit, SC-15, 373 (1980)

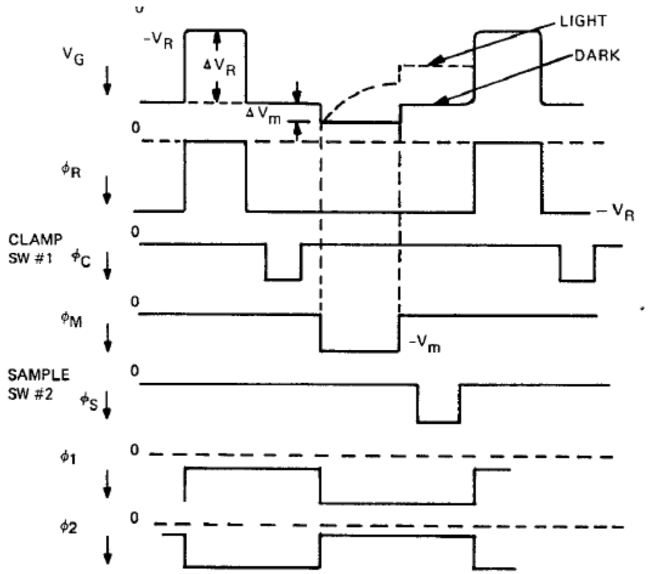
APS with a modified CDS



This is from a patent by Eric Fossum. The CLAMP and SAMPLE travel in separate paths before subtracting. This technique has been used in APS Photodiode Arrays, but it is different than the original invention where the paths are the same.

Original CDS Readout Circuit to Produce Composite Video - RESET

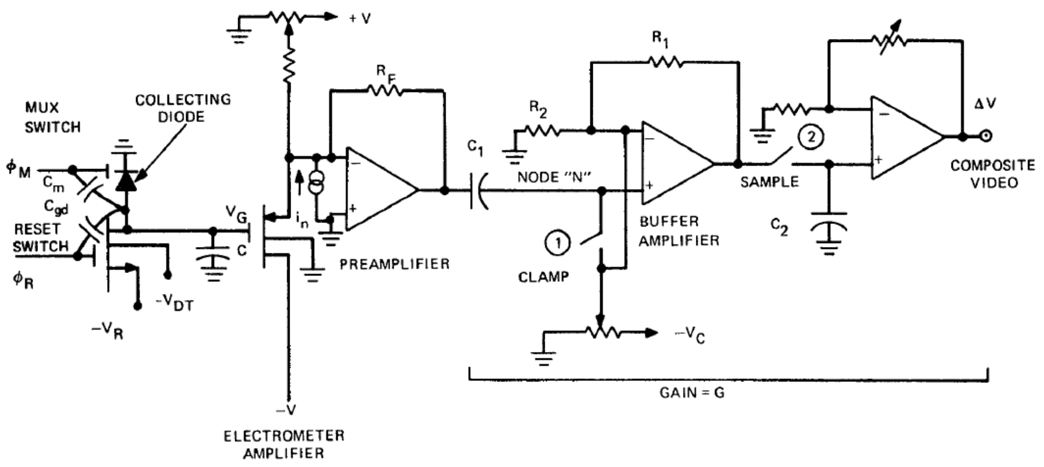


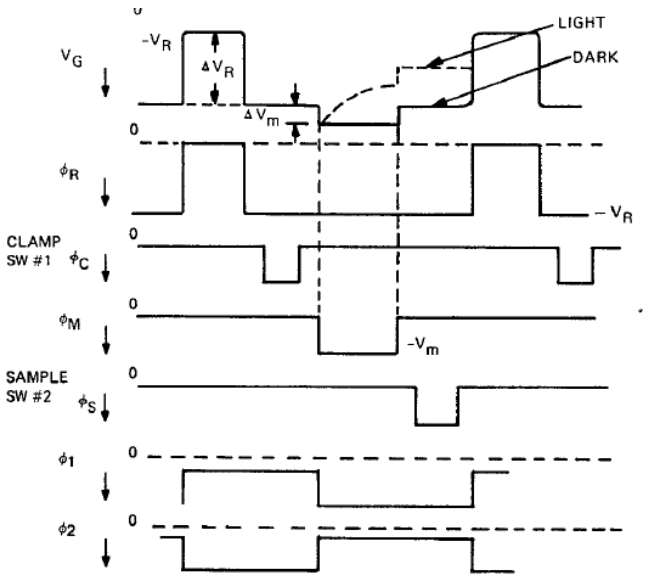


1. RESET

The n-channel MOSFET reset switch is turned on and the voltage across the the capacitor C is reset to the reference voltage V_R. This reset operation introduces a Nyquist rms noise charge $\overline{q}_n = \sqrt{kTC}$ and perhaps noise from inadequate filtering of the reference supply voltage. There is a feedthrough pedestal $\Delta V_R = \frac{C_{gd}}{C_{gd} + C} V_R$, where C_{gd} is the feedthrough capacitance.

Original CDS Readout Circuit to Produce Composite Video - CLAMP

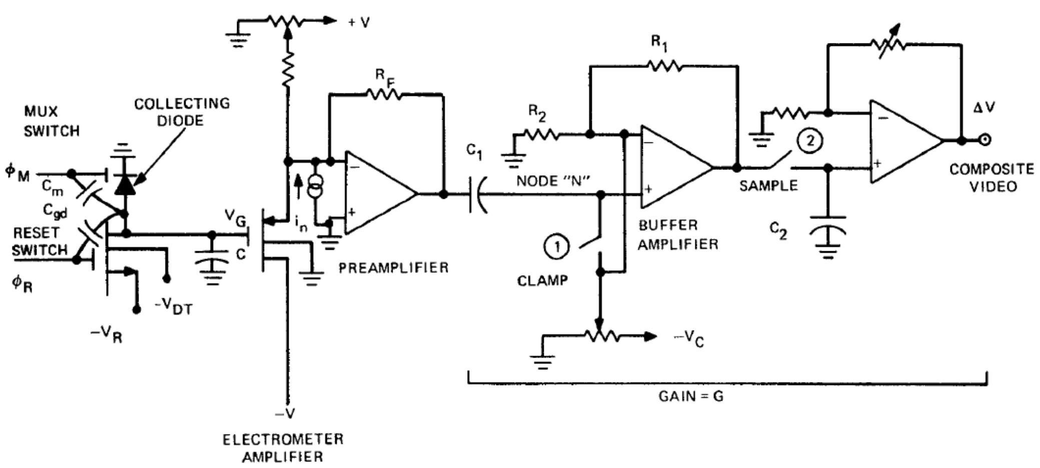


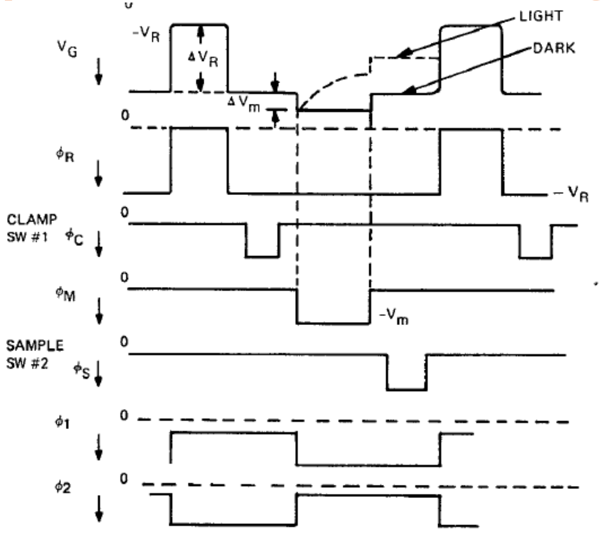


2. CLAMP (Read RESET)

When the reset switch is turned off, the voltage on the gate of the electrometer consists of the noise voltage $\overline{v}_n = \frac{\overline{q}_n}{C}$, ΔV_R and V_R. These voltages are resting on a high impedance node with a time constant of seconds. In the Read RESET time interval the CLAMP switch is turned on and capacitor C_1 is charged to a voltage $g_m R_F(V_R + \Delta V_R + \overline{v}_n)$ indicative of the voltage on the p-channel electrometer amplifier. The CLAMP switch is turned off and this voltage remains on C_1.

Original CDS Readout Circuit to Produce Composite Video – MUX Signal





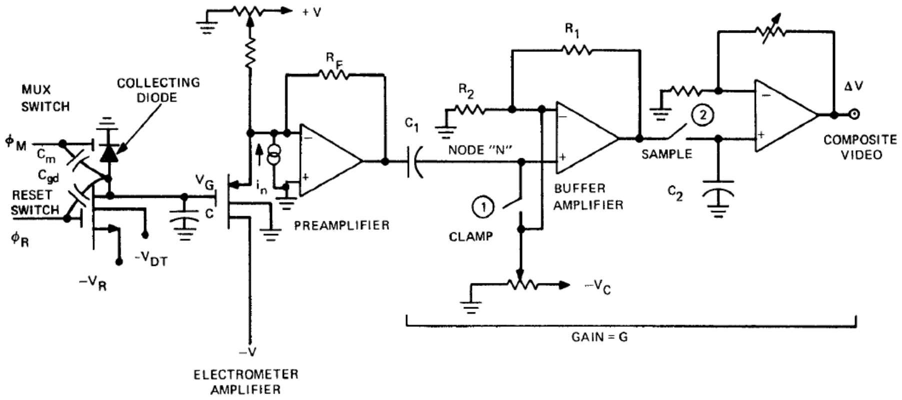
3. MUX SIGNAL (Inject the Signal)

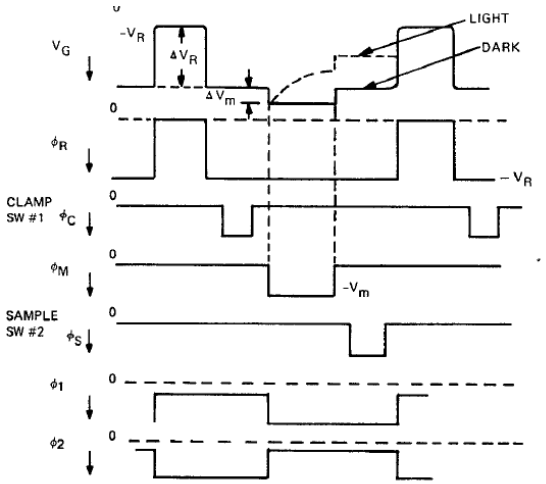
In the case of a Charge-Coupled Device the signal charge is stored under a capacitor (pixel) and transferred to the output node, where there is a single readout circuit [a CMOS Active Pixel Sensor (APS) circuit has a similar front-end readout circuit at every pixel]. The MUX SIGNAL operation in a CCD transfers a signal charge, Q_S, (as well as 'leakage' charge, Q_L) over an exposure interval, from the sensor with a shift register to the output node. The MUX gate at the output node transfers each pixel charge to the capacitor C. The feedthrough voltage step $\Delta V_m = C_m V_m/(C_m + C)$, where V_m is the MUX voltage. ΔV_m is removed when the MUX is turned off assuming that rise and fall times are about the same. There is also a noise charge $\overline{q}_n = \sqrt{kTC_m}$ introduced, which can be minimized. The voltage at node N is

$$g_m R_F\left[(v_s + V_R + v_n) - (V_R + v_n)\right] = g_m R_F v_s$$

where $v_s = q_s / C$. C is the total capacitance at the gate of the electrometer.

Original CDS Readout Circuit Produce Composite Video - SAMPLE

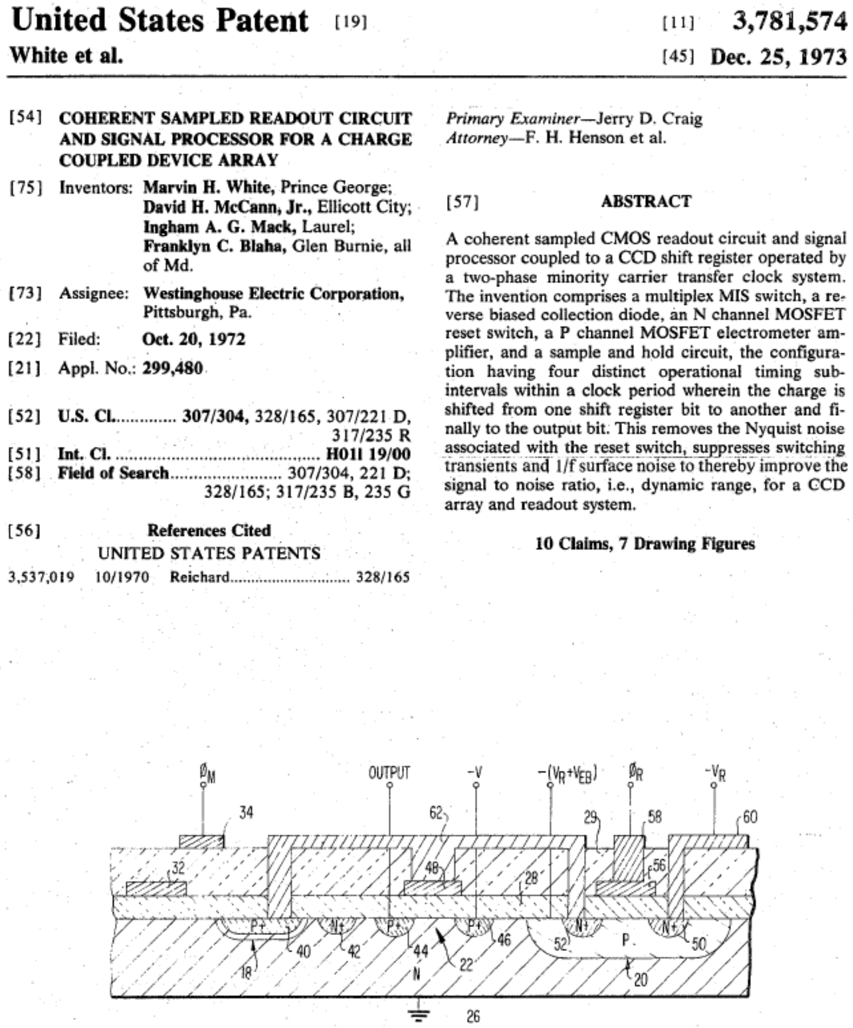




4. SAMPLE (Read Signal)

After the mux signal is turned OFF, the running output voltage $V_N = g_m R_F v_s$ on node N is the difference between the previously CLAMP reset level and the same reset level plus signal. The sample switch places the amplified signal on the capacitance C_2 and appears at the output node as a composite video signal.

CDS Patents for Image Sensors Issued (1973) and Re-Issued (1979)



United States Patent [19] [11] **3,781,574**

White et al. [45] **Dec. 25, 1973**

[54] **COHERENT SAMPLED READOUT CIRCUIT AND SIGNAL PROCESSOR FOR A CHARGE COUPLED DEVICE ARRAY**

[75] Inventors: **Marvin H. White,** Prince George; **David H. McCann, Jr.,** Ellicott City; **Ingham A. G. Mack,** Laurel; **Franklyn C. Blaha,** Glen Burnie, all of Md.

[73] Assignee: **Westinghouse Electric Corporation,** Pittsburgh, Pa.

[22] Filed: **Oct. 20, 1972**

[21] Appl. No.: **299,480**

[52] **U.S. Cl.**............ **307/304,** 328/165, 307/221 D, 317/235 R

[51] **Int. Cl.** **H01l 19/00**

[58] **Field of Search**...................... 307/304, 221 D; 328/165; 317/235 B, 235 G

[56] **References Cited**

UNITED STATES PATENTS

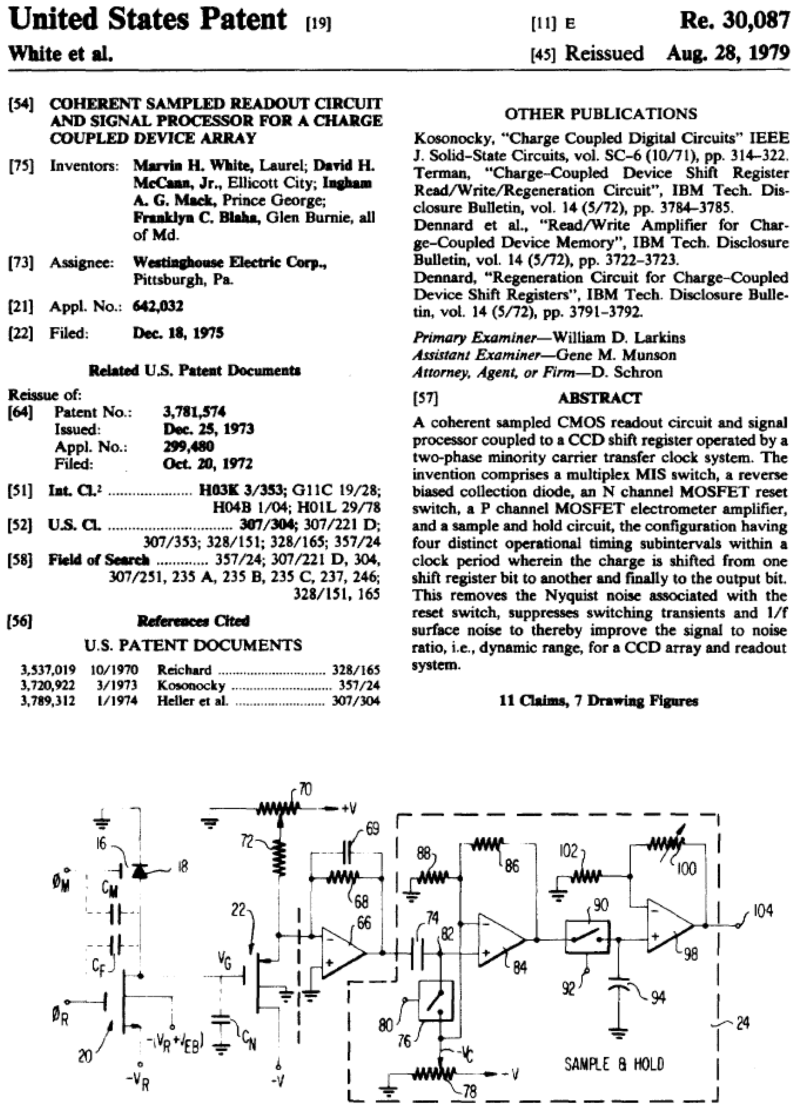
3,537,019 10/1970 Reichard........................... 328/165

Primary Examiner—Jerry D. Craig
Attorney—F. H. Henson et al.

[57] **ABSTRACT**

A coherent sampled CMOS readout circuit and signal processor coupled to a CCD shift register operated by a two-phase minority carrier transfer clock system. The invention comprises a multiplex MIS switch, a reverse biased collection diode, an N channel MOSFET reset switch, a P channel MOSFET electrometer amplifier, and a sample and hold circuit, the configuration having four distinct operational timing subintervals within a clock period wherein the charge is shifted from one shift register bit to another and finally to the output bit. This removes the Nyquist noise associated with the reset switch, suppresses switching transients and 1/f surface noise to thereby improve the signal to noise ratio, i.e., dynamic range, for a CCD array and readout system.

10 Claims, 7 Drawing Figures



United States Patent [19] [11] E **Re. 30,087**

White et al. [45] Reissued **Aug. 28, 1979**

[54] **COHERENT SAMPLED READOUT CIRCUIT AND SIGNAL PROCESSOR FOR A CHARGE COUPLED DEVICE ARRAY**

[75] Inventors: **Marvin H. White,** Laurel; **David H. McCann, Jr.,** Ellicott City; **Ingham A. G. Mack,** Prince George; **Franklyn C. Blaha,** Glen Burnie, all of Md.

[73] Assignee: **Westinghouse Electric Corp.,** Pittsburgh, Pa.

[21] Appl. No.: **642,032**

[22] Filed: **Dec. 18, 1975**

Related U.S. Patent Documents

Reissue of:

[64]	Patent No.:	**3,781,574**
	Issued:	**Dec. 25, 1973**
	Appl. No.:	**299,480**
	Filed:	**Oct. 20, 1972**

[51] **Int. Cl.**^{2} **H03K 3/353;** G11C 19/28; H04B 1/04; H01L 29/78

[52] **U.S. Cl.** .... **307/304;** 307/221 D; 307/353; 328/151; 328/165; 357/24

[58] **Field of Search** .... 357/24; 307/221 D, 304, 307/251, 235 A, 235 B, 235 C, 237, 246; 328/151, 165

[56] **References Cited**

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Terman, "Charge-Coupled Device Shift Register Read/Write/Regeneration Circuit", IBM Tech. Disclosure Bulletin, vol. 14 (5/72), pp. 3784-3785.
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Dennard, "Regeneration Circuit for Charge-Coupled Device Shift Registers", IBM Tech. Disclosure Bulletin, vol. 14 (5/72), pp. 3791-3792.

Primary Examiner—William D. Larkins
Assistant Examiner—Gene M. Munson
Attorney, Agent, or Firm—D. Schron

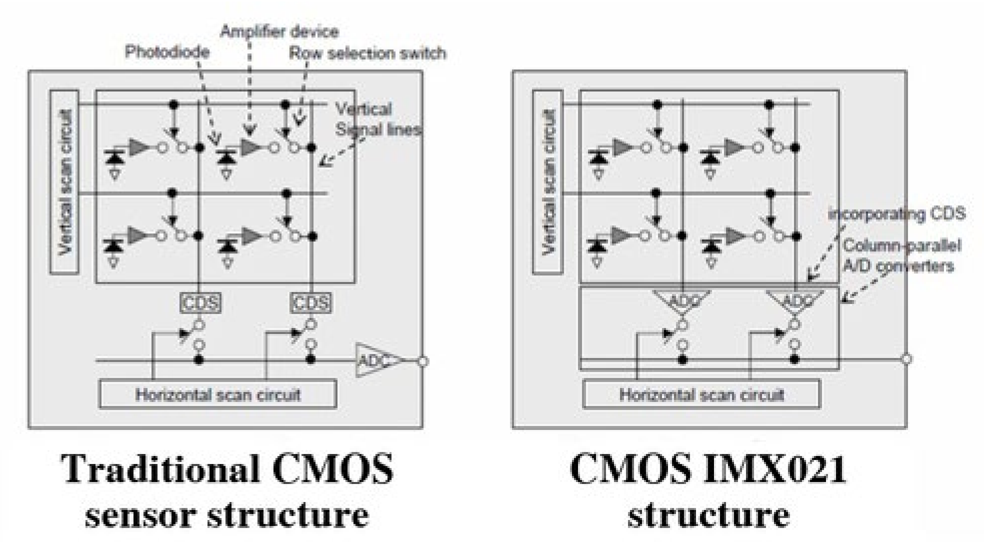
[57] **ABSTRACT**

A coherent sampled CMOS readout circuit and signal processor coupled to a CCD shift register operated by a two-phase minority carrier transfer clock system. The invention comprises a multiplex MIS switch, a reverse biased collection diode, an N channel MOSFET reset switch, a P channel MOSFET electrometer amplifier, and a sample and hold circuit, the configuration having four distinct operational timing subintervals within a clock period wherein the charge is shifted from one shift register bit to another and finally to the output bit. This removes the Nyquist noise associated with the reset switch, suppresses switching transients and 1/f surface noise to thereby improve the signal to noise ratio, i.e., dynamic range, for a CCD array and readout system.

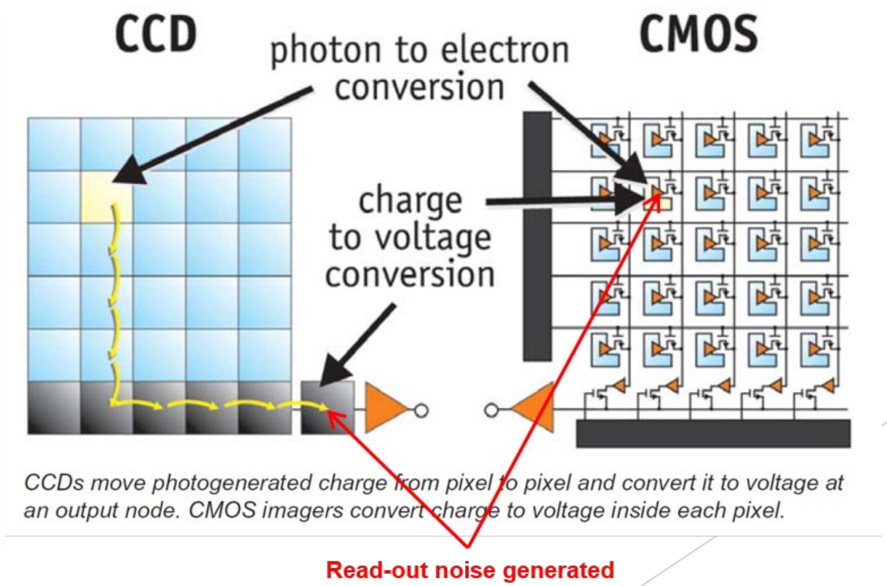
11 Claims, 7 Drawing Figures

The Integrated Circuit Replacement of the Electron Beam-Scanned Image Vacuum Tube

In the past, the electron beam scanned and replaced the charge on a continuous surface of a photoconductive film that was exposed to irradiance. In this instance the electron beam served as an almost perfect commutator. The photoconductive film had an appropriate dielectric constant and resistivity to achieve the storage of optical information over a frame time of scan. The integrated circuit replaced the continuous surface with a ‘mosaic’ of capacitors or p-n junctions picture element (called pixels) with suitable spectral responsivity and storage in a CCD ‘well’ or reverse-biased junction. The interrogation of these mosaic patterns is performed by either a transfer gate or a solid-state switch both controlled by shift registers.



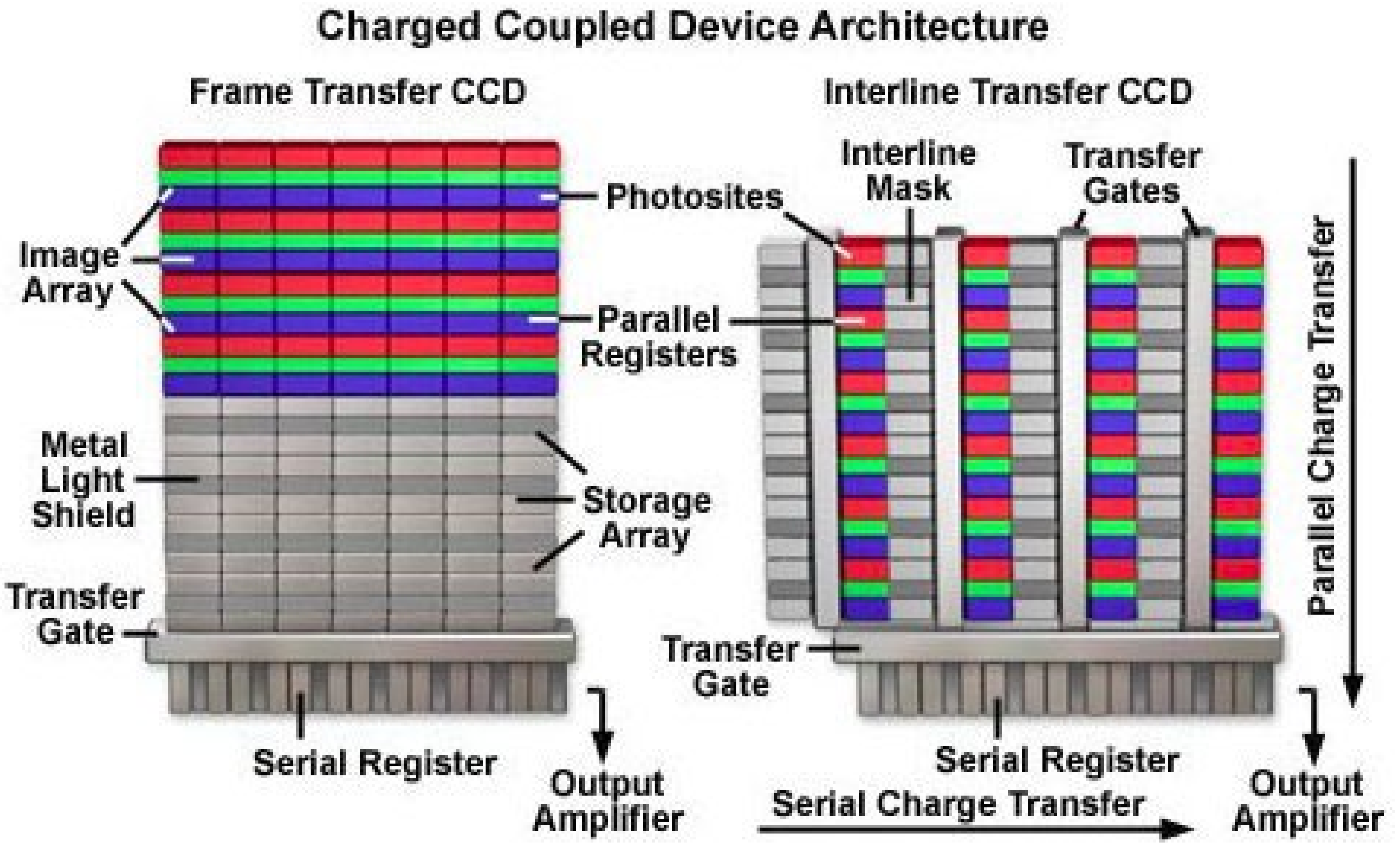
Images from SONY Digital SLR Cameras



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

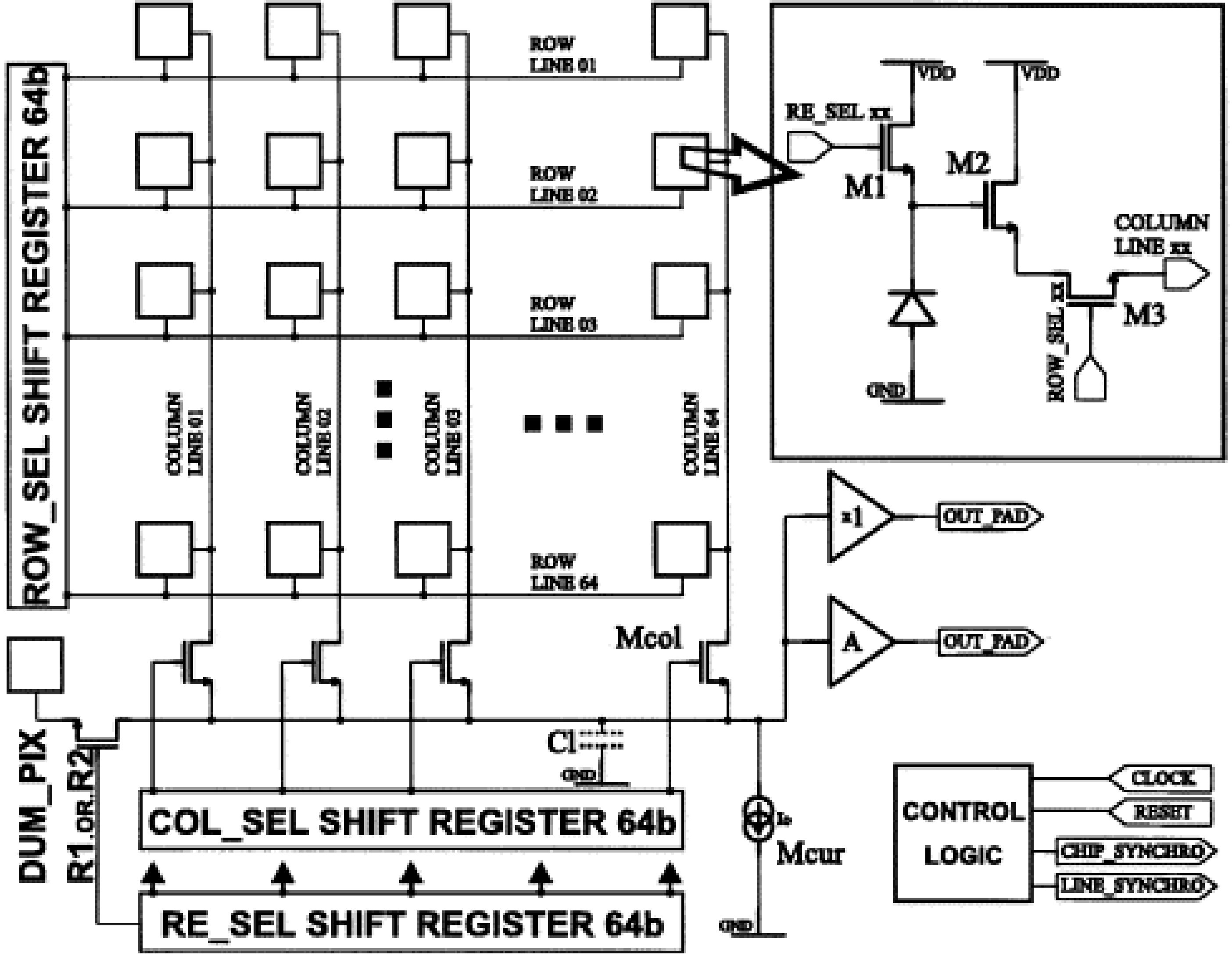
Images from GATAN - Ametek

Charge-Coupled Device (CCD) Architectures for Image Sensor Arrays*

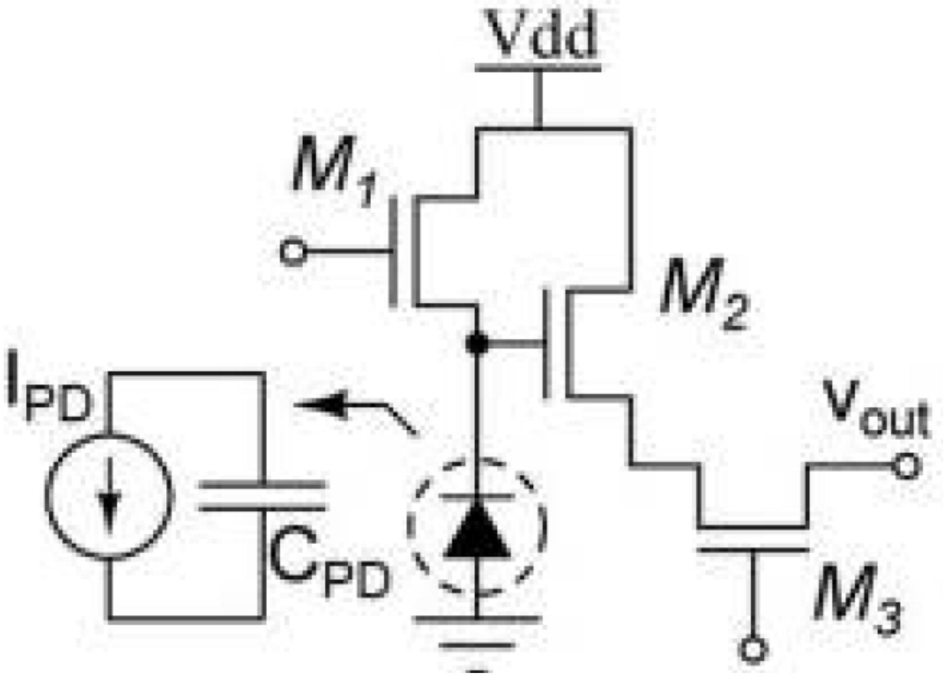


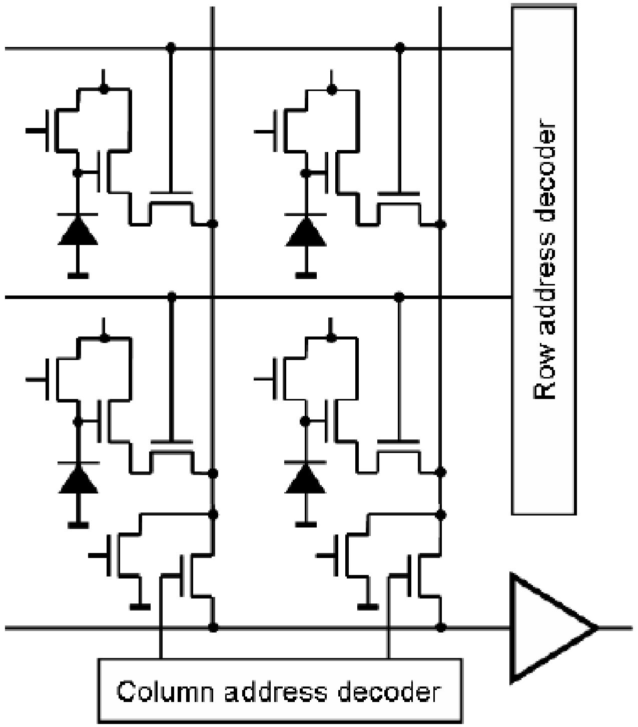
* Quora.com

Photodiode Imaging Arrays



A basic 3-Transistor Active Pixel Sensor Unit Cell in a Photodiode Imaging Array



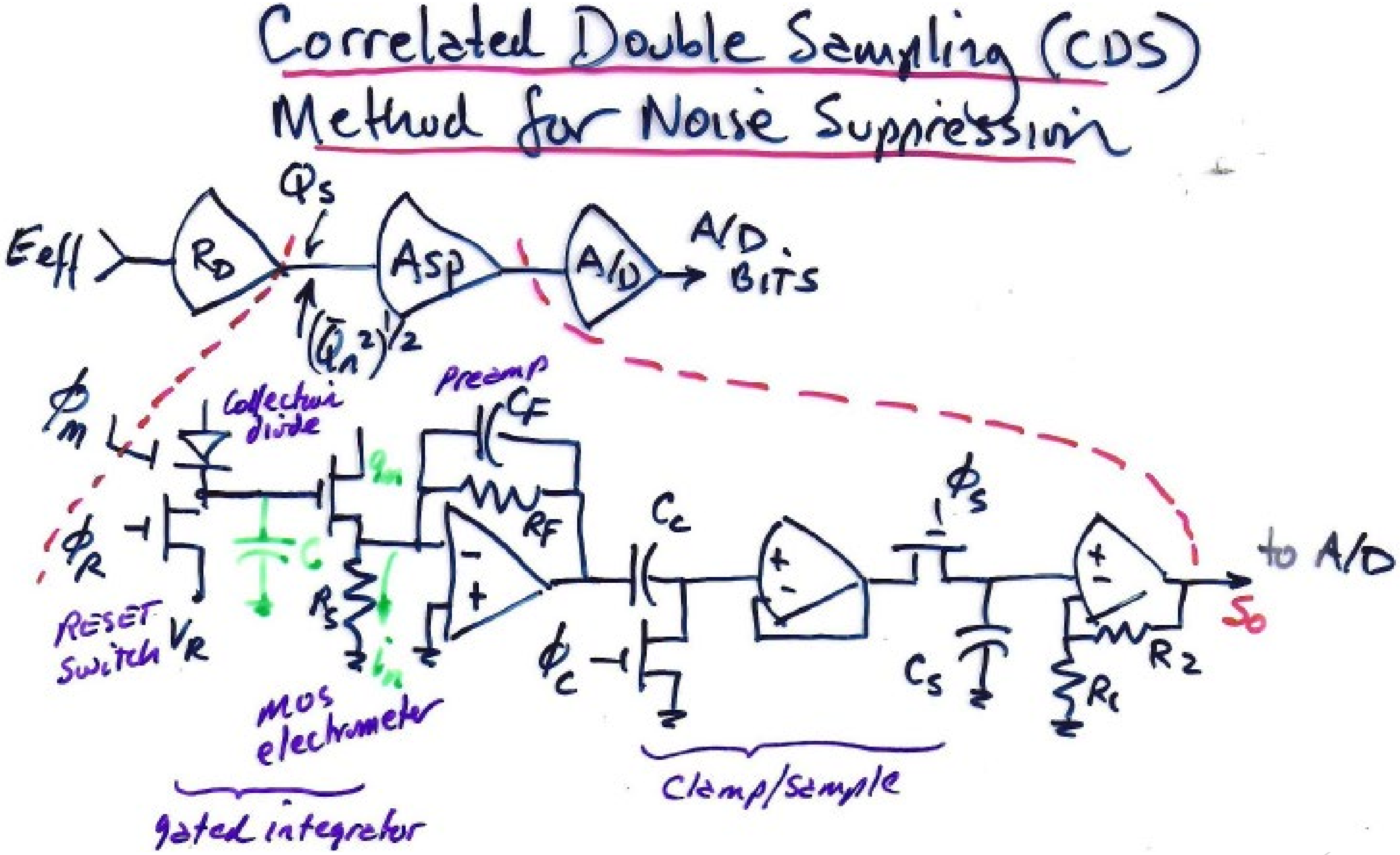


My ATL Management Team

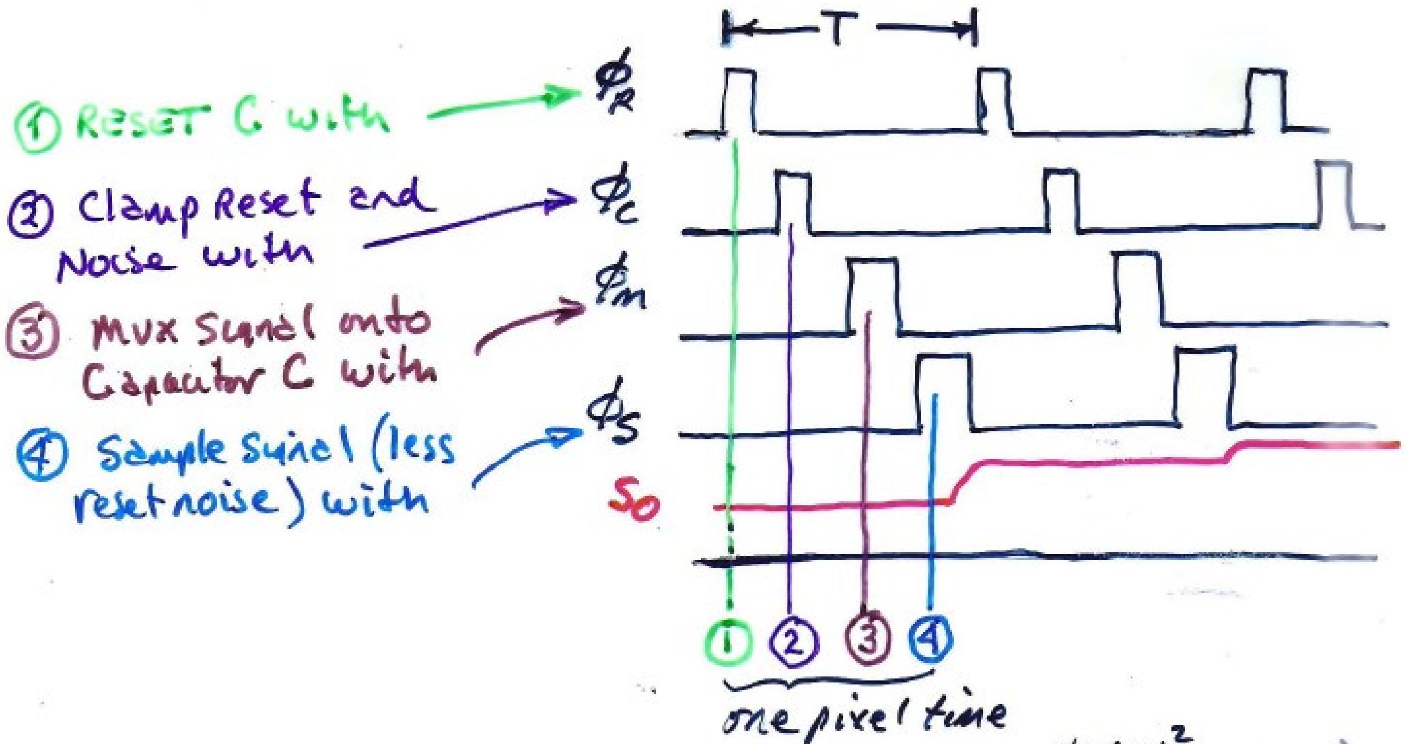
Bill Corak, Marvin White, Ben Vester, Gene Strull

Correlated Double Sampling (CDS) - Analysis and Transfer Functions

Correlated Double Sampling (CDS) and the Filtering of Noise in Image Sensor Arrays



Correlated Double Sampling (CDS) Transfer Function



① Reset C with

② Clamp Reset and Noise with

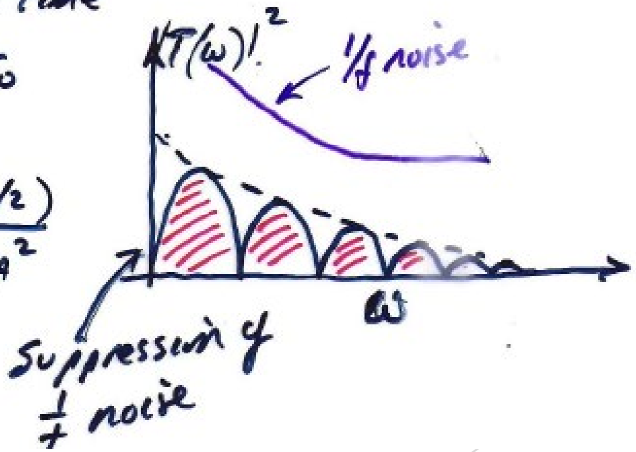
③ Mux Signal onto Capacitor C with

④ Sample Signal (less reset noise) with

$$T_{preamp} = \frac{1}{1+s/\omega_A} \qquad T_{c/s} = 1 - e^{-sT_0}$$

$$|T(\omega)|^2 = T_{preamp}\, T_{c/s} = \frac{4\sin^2(\omega T_0/2)}{1+\omega^2/\omega_A^2}$$

- removes kTC Noise
- suppresses 1/f noise

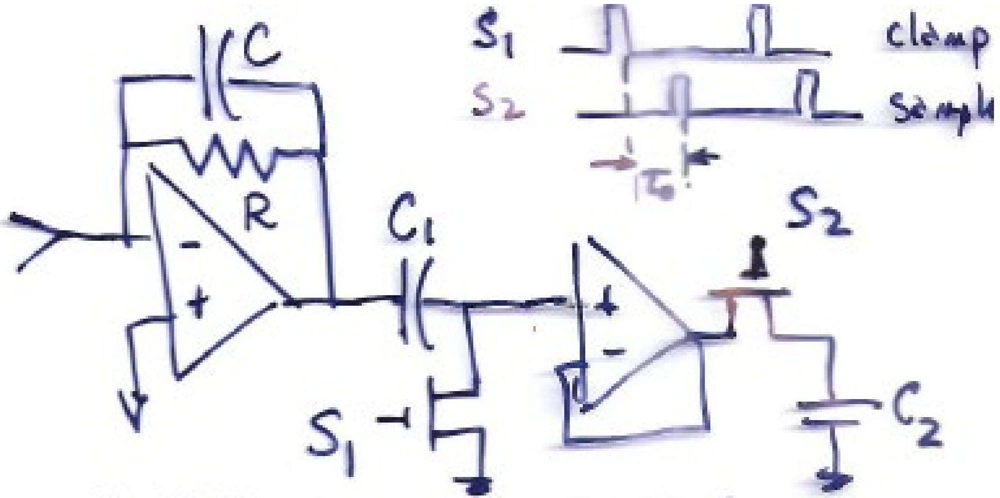


Suppression of $\frac{1}{f}$ noise

Correlated Double Sampling (CDS)

For example,

we consider the ASP with the normalized transfer function



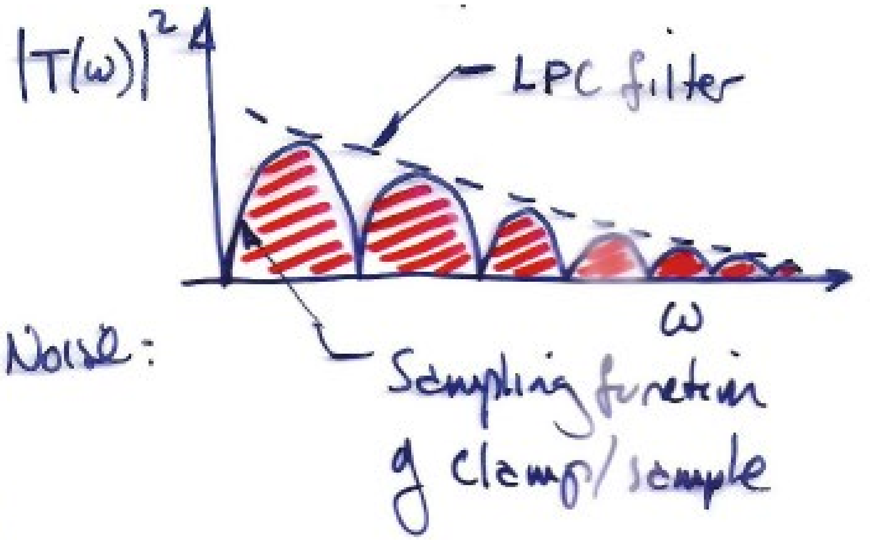
$$T_1 = \frac{1}{1+s/\omega_A} \qquad T_2 = 1-e^{-s\tau_0}$$

$$T = T_1 T_2$$

$$= \frac{1-e^{-s\tau_0}}{1+s/\omega_A}$$

$$|T(\omega)|^2 = T(j\omega)T(-j\omega) = \frac{4\sin^2(\omega\tau_0/2)}{1+\omega^2/\omega_A^2}$$

Correlated Double Sampling (CDS) - White Noise



Case (a)

We consider a 'white'
Noise spectrum of Shot Noise:

$$\therefore B_{eff} = \int_0^\infty [T(\omega)]^2 df$$

$$= \int_0^\infty \frac{4\sin^2(\pi f \tau_0)}{1+(f/f_A)^2} df = \pi f_A \left(1 - e^{-2\pi f_A \tau_0}\right)$$

and $$\overline{q_n^2} = 2\pi q I_0 f_A \left(1 - e^{-2\pi f_A \tau_0}\right)\left(\frac{C}{g_m}\right)^2$$

$$= q I_0 \omega_A \left(1 - e^{-\omega_A \tau_0}\right)\left(\frac{C}{g_m}\right)^2$$

Input Noise to the MOS Electrometer based on Nyquist and 1/f Noise and CDS Signal Processing

Spectral Noise Current Intensity

$$S_{I_D}(f) = \left(\frac{\breve{i}_n^2}{\Delta f}\right) = \frac{I_D^2 k_B T}{\lambda W L f}\left[\frac{1}{N_n} + (\alpha + \beta)\mu\right]^2 \cdot \rho_t(E_{fn})$$

λ = Tunneling distance, α = Remote Coulomb Scattering, β = Surface Rougness

$$\frac{\breve{v}_n^2}{\Delta f} = \left(\frac{\breve{i}_n^2}{\Delta f\, g_m^2}\right) = 4kT\left(\frac{2}{3g_m}\right) + \frac{D_{it} f_0}{C_{ox} W L f}$$

Output Spectral Voltage Noise Density

Nyquist 1/f

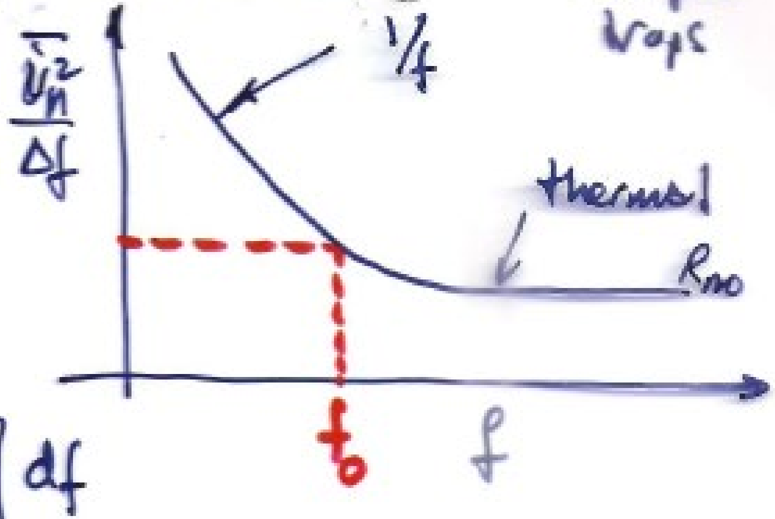
$$\breve{Q}_n^2 = \left(\frac{\breve{i}_n^2}{\Delta f}\right) B_{eff} \left(\frac{C}{g_m}\right)^2$$

Input Referred Charge

Correlated Double Sampling (CDS) – 1/f noise

Case (b) We consider a '1/f' noise spectrum caused by interface traps

$f_0 \sim D_{it}$ interface traps



Effective noise resistance

$$R_n = R_{no}\left(1 + \frac{f_0}{f}\right)$$

and bandwidth,

$$B_{eff} = \int_0^\infty \left(1 + \frac{f_0}{f}\right)\left[\frac{4\sin^2 \pi f \tau_0}{1 + f^2/f_A^2}\right] df$$

$$= \pi f_A \left(1 - e^{-2\pi f_A \tau_0}\right) + (\pi f_A \tau_0)^2 f_0 \int_0^\infty \frac{\sin^2 x \, dx}{x\left[x^2 + (\pi f_A \tau_0)^2\right]}$$

Correlated Double Sampling (CDS)
1/f Noise and Effective Bandwidth

Case (b):

We can model the 1/f – Noise Spectrum in the MOS Electrometer Amplifier, associated with so-called ‘interface traps’, with the expression:

$$R(f) = R(1 + \frac{f_0}{f})$$

with bandwidth

$$B_{eff} = \int_0^\infty (1 + \frac{f_0}{f}) \frac{4\sin^2(\pi f \tau)}{1 + (\frac{f}{f_A})^2} df$$

$$= \pi f_A (1 - e^{-2\pi f_A \tau}) + (\pi f_A \tau)^2 f_0 \int_0^\infty \frac{\sin^2 x}{x[x^2 + (\pi f_A \tau)^2]} dx$$

$$\breve{Q}_n^2 = (\frac{\breve{i}_n^2}{\Delta f}) B_{eff} (\frac{C}{g_m})^2 \quad \text{Input Referred Charge}$$

CDS Bandwidths for the MOS Electrometer

$$C(y) := \pi^2 \cdot y \cdot a \cdot \int_0^\infty \frac{(\sin(x))^2}{x \cdot \left[x^2 + (\pi\ y)^2\right]}\, dx$$

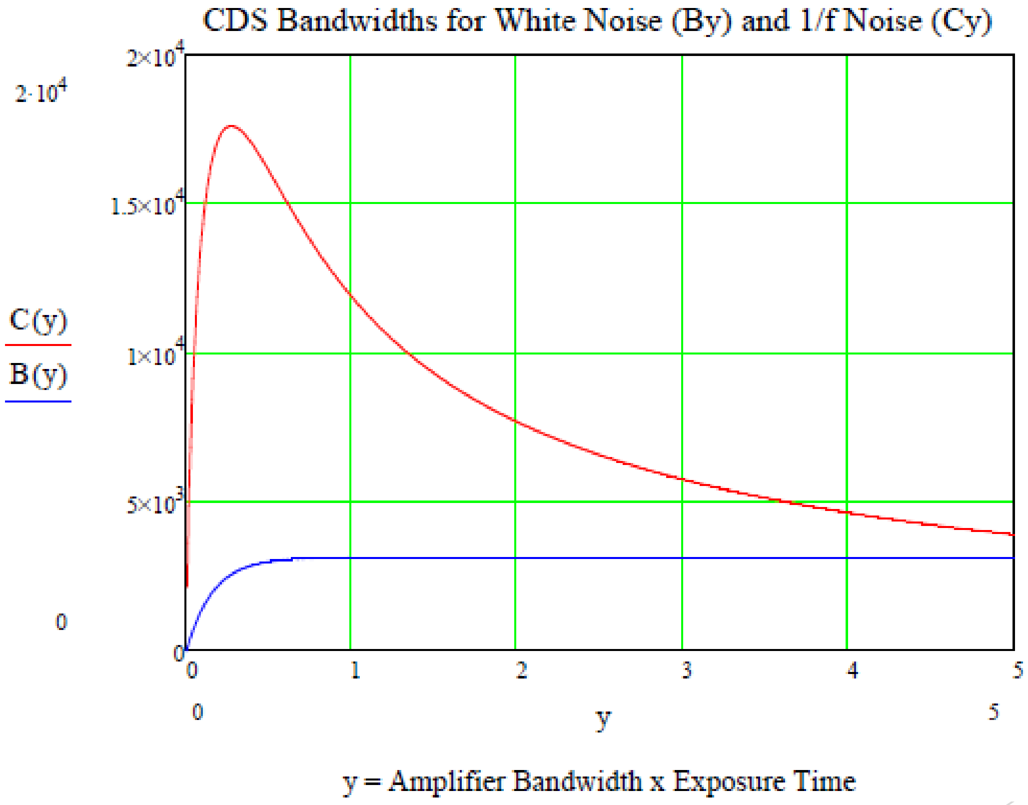
$$B(y) := \frac{\pi}{\tau}\left(1 - e^{-2\pi\ y}\right)$$

White Noise Bandwidth $B_{eff} = yB(y)$

1/f Noise Bandwidth $B_{eff}(f) = yC(y)$

τ = 1 msec

$$\breve{Q}_n^2 = \left(\frac{\breve{i}_n^2}{\Delta f}\right) B_{eff} \left(\frac{C}{g_m}\right)^2$$

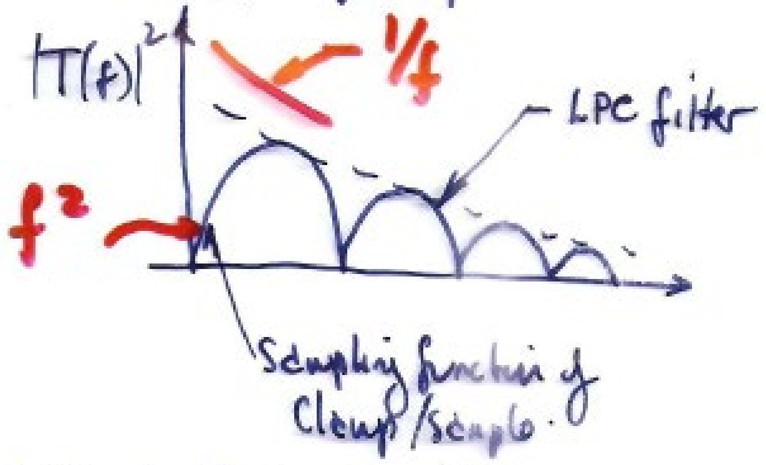


Correlated Double Sampling (CDS)

'double zero' of Clamp Sample
Suppresses Noise due to
'$\frac{1}{f}$' Spectrum

$$\frac{\breve{v}_n^2}{\Delta f} = \left(\frac{\breve{i}_n^2}{\Delta f\, g_m^2}\right) 4kT\left(\frac{2}{3g_m}\right) + \frac{D_{it} f_0}{C_{ox} WLf}$$

1/f noise is suppressed by
Clamp/Sample operation

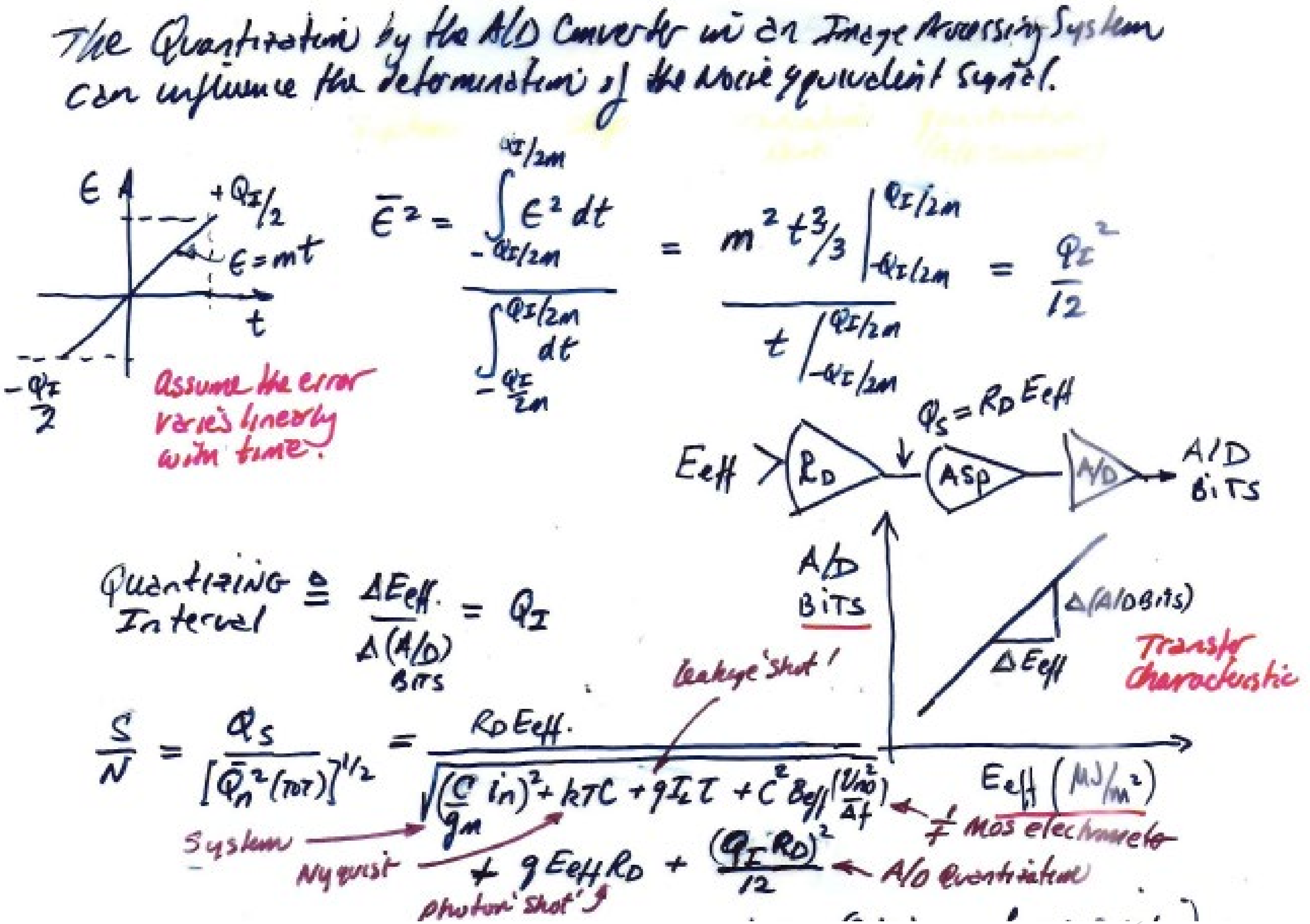


Total Noise Referred to Gate of MOS Transistor

$$\overline{Q}_{nT}^2 = \overline{Q_n^2}(\text{Nyquist}) + \overline{Q}_n^2(\text{shot}) + \overline{Q}_n^2(\text{gen/rec + amplifier noise})$$

$$= \underbrace{kTC}_{\text{Nyquist}} + q\underbrace{I_0\tau}_{\text{Leakage 'shot'}} + q\underbrace{R_D E_{eff}}_{\text{photon 'shot'}} + \underbrace{\left(\frac{C}{g_m}\right)^2 B_{eff}\left(\frac{\overline{i_{no}^2}}{\Delta f}\right)}_{\text{gate referred amplifier noise + g-r noise}}$$

Total Noise Equivalent Signal (NES)



The Quantization by the A/D Converter in an Image Processing System can influence the determination of the noise equivalent signal.

assume the error varies linearly with time.

$$\bar{\epsilon}^2 = \frac{\int_{-Q_I/2m}^{Q_I/2m} \epsilon^2 \, dt}{\int_{-Q_I/2m}^{Q_I/2m} dt} = \frac{m^2 t^3/3 \Big|_{-Q_I/2m}^{Q_I/2m}}{t \Big|_{-Q_I/2m}^{Q_I/2m}} = \frac{Q_I^2}{12}$$

$Q_S = R_D E_{eff}$

$$\text{Quantizing Interval} \triangleq \frac{\Delta E_{eff}}{\Delta(\text{A/D BITS})} = Q_I$$

Transfer characteristic

$$\frac{S}{N} = \frac{Q_S}{[\bar{Q}_n^2(\text{TOT})]^{1/2}} = \frac{R_D E_{eff}}{\sqrt{\left(\frac{C}{g_m} i_n\right)^2 + kTC + qI_L\tau + C^2 B_{eff}\left(\frac{V_{no}^2}{\Delta f}\right) + qE_{eff}R_D + \frac{(Q_I R_D)^2}{12}}}$$

System

Nyquist

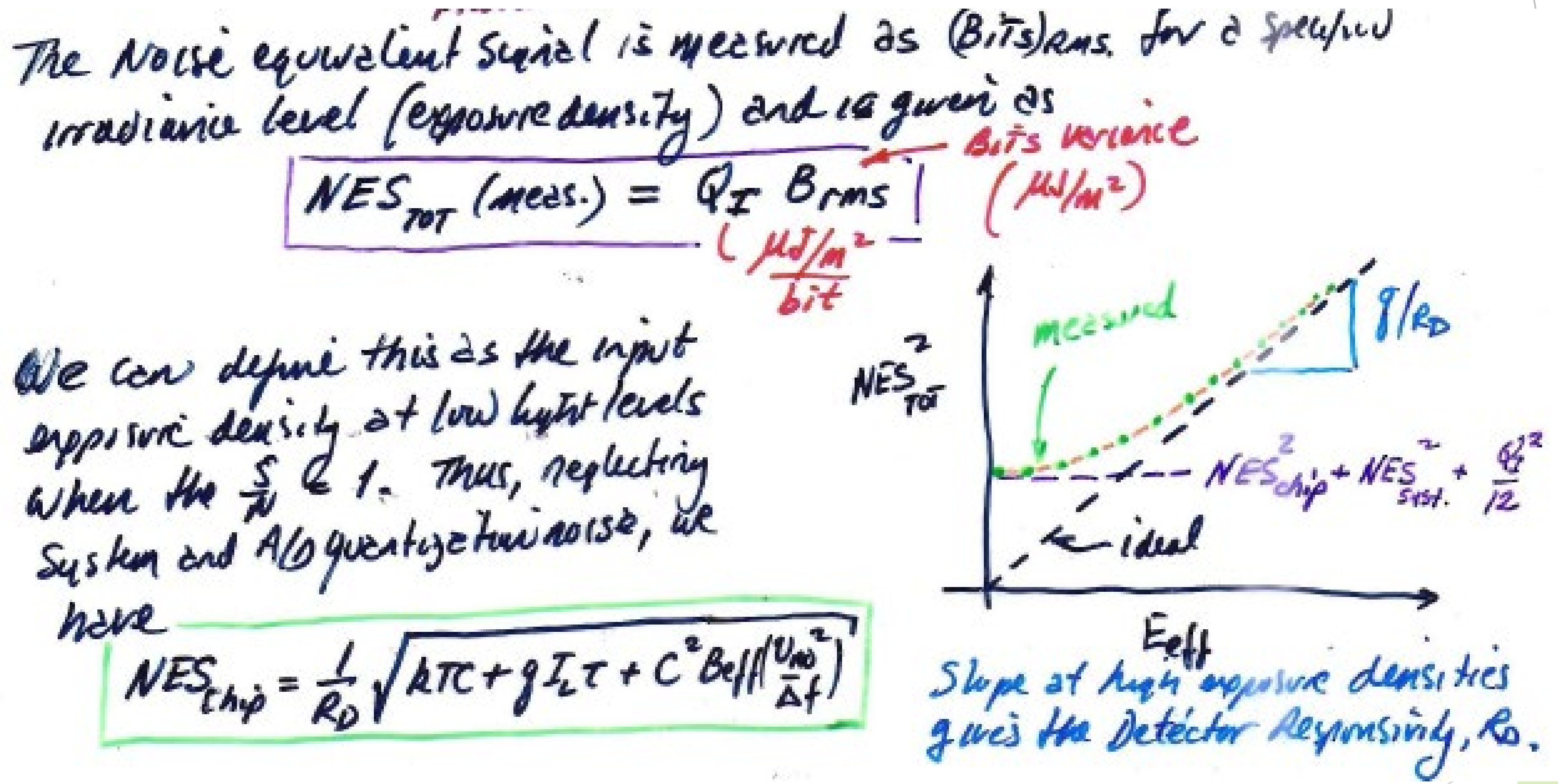
leakage 'shot'

1/f MOS electrometer

photon 'shot'

A/D Quantization

Specification of the NES



The Noise equivalent Signal is measured as (Bits)rms for a specified irradiance level (exposure density) and is given as

$$\boxed{NES_{TOT}\,(\text{meas.}) = Q_I\, B_{rms}}$$

$\left(\frac{\mu J/m^2}{bit}\right)$

Bits variance $(\mu J/m^2)$

We can define this as the input exposure density at low light levels when the $\frac{S}{N} \ll 1$. Thus, neglecting System and A/D quantization noise, we have

$$\boxed{NES_{chip} = \frac{1}{R_D}\sqrt{kTC + gI_L\tau + C^2 B_{eff}\left(\frac{V_{no}^2}{\Delta f}\right)}}$$

Slope at high exposure densities gives the Detector Responsivity, R_D.

The S/N and NES

$$\frac{S}{N} = \frac{Q_s}{(\overline{Q_n^2})^{1/2}}$$

$$= \frac{qR_DE_{eff}}{\sqrt{kTC + qI_L\tau + qR_DE_{eff} + (\frac{\overline{i_{no}^2}}{\Delta f})B_{eff}\left(\frac{C}{g_m}\right)^2 + \frac{(R_DQ_I)^2}{12} + (\frac{C}{g_m})^2\overline{i_{ne}^2}}}$$

Reset Leakage Photon MOS Electrometer Quantizing External

When S/N = 1, we have the Noise Equivalent Signal (NES), which is the Exposure Density at the input to the pixel that will give a S/N = 1 at the gate of the MOS Electrometer. Wth CDS we could remove the Reset noise and resistive portion of the MOS Electrometer noise, while filtering and suppressing the low-frequency 1/f noise of the MOS Electrometer.

Correlated Double Sampling Applications

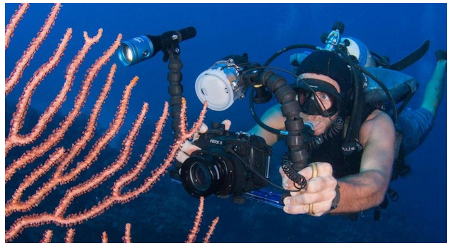
Cameras

Cell Phones

Television

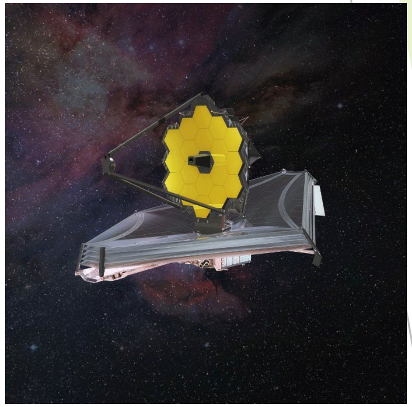
Camera Crew

Sports



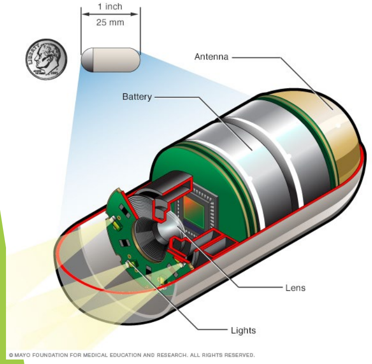
Underwater Photography

Science



James Webb Space Telescope (JWST)

Medical



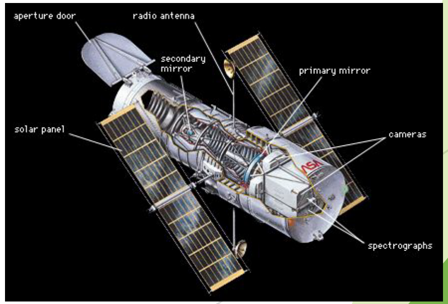
Endoscopy

Intraoral Digital Photography

Military

Satellites - Defense and Earth Resources Monitoring

Drones



Hubble Space Telescope

CDS Summary

- Correlated Double Sampling (CDS) is a ubiquitous technique with many applications. CDS employs two samples during each clock period (pixel time in solid-state imagers) to integrate the first sample (CLAMP the RESET). After a period of time (exposure period in an imager), CDS subtracts the second sample (SAMPLE) of an accumulation (integration) of information over the exposure time. CDS removes the reset level and noise associated with resetting this level while introducing a time domain filter. The subtraction removes the accumulated Nyquist noise while the time-domain filter suppresses the so-called, low-frequency, 1/f or ‘flicker’ noise.
- In addition, CDS extends the dynamic range of sensor imaging to reach BLIP conditions at low-light levels (Background Limited Imaging Performance) due to the ‘shot’ noise of the arriving photons and leakage current. CDS restores the DC level and suppresses objectional fixed pattern noise (FPN) due to switching transients associated with RESET and MUX operations.

The CDS method is used in other signal processing applications, such as ‘Switched-Capacitors’ signal processing used to replace resistors in integrated circuits and in telecommunications and power conversion.

The 73rd Technology & Engineering Emmy® Awards
April 25th, 2022 Las Vegas, NV

History of the Emmy® Awards

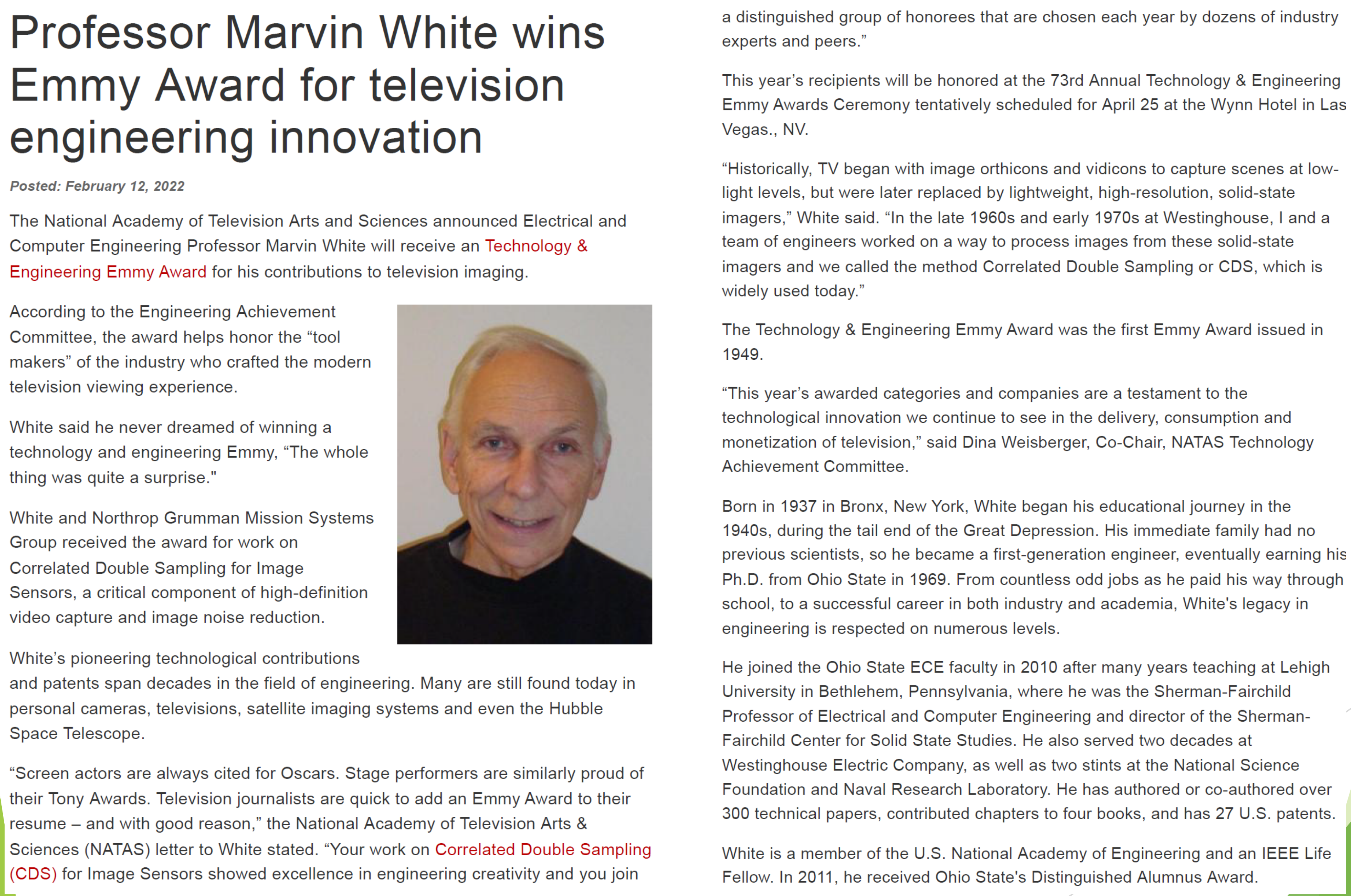
The Emmy statuette was designed by an engineer who said he used his wife for the model. The statuette depicts a winged woman holding an atom with spinning electrons.

- The first Emmy® award was presented to an engineer in 1949. The 73rd Annual Award is to be held in Las Vegas, NV on April, 25th of 2022 by the National Academy of Television Arts & Sciences (NATAS) - called the 73rd Annual Technology & Engineering Emmy Awards. I will receive the award with my company Northrop Grumman.
- Historically, TV began with Image Orthicons and Vidicons to capture scenes at low-light levels, but were later replaced by light-weight, high-resolution, solid-state imagers. In the late 1960's and early 1970's at Westinghouse's Defense and Space Center's in the Air Arms Division (West Bldg.), I and a team of engineers worked on photodiode line arrays and later moved to the Advanced Technology Laboratory (ATL) where we continued our work on CCD line arrays to reduce the readout noise in these solid-state imagers. We called the technique *Correlated Double Sampling* (CDS), which is widely used today in imaging systems, such as cameras, cell-phones, medical instruments (endoscopy and intraoral digital photography) and scientific instruments, satellites, and space borne telescopes, (e.g. Hubble and recently launched James Webb Space Telescope).
- The above awards are given for artistic and technical merit in the television industry. The Emmy is considered one of the four major entertainment awards in the United States. The others are the Grammy Award given for music, the Oscar Award for film and the Tony Award for theatre (Broadway theatre).

Further Notes on the Emmy® Award

- Through the early 1950s, the Television Academy's stature rose significantly with the emergence of the one event that would give it unparalleled visibility—the Emmys. Influenced by the New York-based American Television Society, founded in 1945 by Syd Cassyd (sp is correct), who initially rejected the idea of television awards. Indeed, when the Television Academy was formally incorporated as a nonprofit organization, its stated objective was "to promote the cultural, educational and research aim of television.“ Evidently, cultural dominated!
- Cassyd's earnest stance was admirable, but ultimately the Television Academy's founding fathers, recognizing the image-building and public-relations opportunities associated with an annual awards ceremony, changed his mind. Once they agreed to go forward with awards, the founders were faced with two daunting questions: what to name the award, and what it should look like.
- Cassyd initially proposed that the award be called "Ike," the nickname for a television iconoscope tube, but it was deemed too evocative of WWII hero General Dwight D. "Ike" Eisenhower. Henry Lubcke, the third Television Academy president, eventually prevailed with "Immy,“ popularized by TV engineers and technicians, after the image-orthicon camera tube, which was instrumental in the development of television. "Immy" was feminized as "Emmy" to complement the design chosen for the statuette, which depicted a winged, idealized woman holding an atom.
- Her wings represented the muse of art, and the atom and its electrons the science and technology of the new medium. The Television Academy rejected 47 proposals before accepting the statuette designed by television engineer Louis McManus in 1948, whose wife Dorothy served as its model. He won a special Emmy award in 1949 for the original design of the Emmy. The statuette has a bronze base metal, which is electroplated with zinc, copper, nickel, pure silver and dipped in 24 carat gold.

Ohio State University Announcement



Professor Marvin White wins Emmy Award for television engineering innovation

Posted: February 12, 2022

The National Academy of Television Arts and Sciences announced Electrical and Computer Engineering Professor Marvin White will receive an Technology & Engineering Emmy Award for his contributions to television imaging.

According to the Engineering Achievement Committee, the award helps honor the “tool makers” of the industry who crafted the modern television viewing experience.

White said he never dreamed of winning a technology and engineering Emmy, “The whole thing was quite a surprise."

White and Northrop Grumman Mission Systems Group received the award for work on Correlated Double Sampling for Image Sensors, a critical component of high-definition video capture and image noise reduction.

White’s pioneering technological contributions and patents span decades in the field of engineering. Many are still found today in personal cameras, televisions, satellite imaging systems and even the Hubble Space Telescope.

“Screen actors are always cited for Oscars. Stage performers are similarly proud of their Tony Awards. Television journalists are quick to add an Emmy Award to their resume – and with good reason,” the National Academy of Television Arts & Sciences (NATAS) letter to White stated. “Your work on Correlated Double Sampling (CDS) for Image Sensors showed excellence in engineering creativity and you join a distinguished group of honorees that are chosen each year by dozens of industry experts and peers.”

This year’s recipients will be honored at the 73rd Annual Technology & Engineering Emmy Awards Ceremony tentatively scheduled for April 25 at the Wynn Hotel in Las Vegas., NV.

“Historically, TV began with image orthicons and vidicons to capture scenes at low-light levels, but were later replaced by lightweight, high-resolution, solid-state imagers,” White said. “In the late 1960s and early 1970s at Westinghouse, I and a team of engineers worked on a way to process images from these solid-state imagers and we called the method Correlated Double Sampling or CDS, which is widely used today.”

The Technology & Engineering Emmy Award was the first Emmy Award issued in 1949.

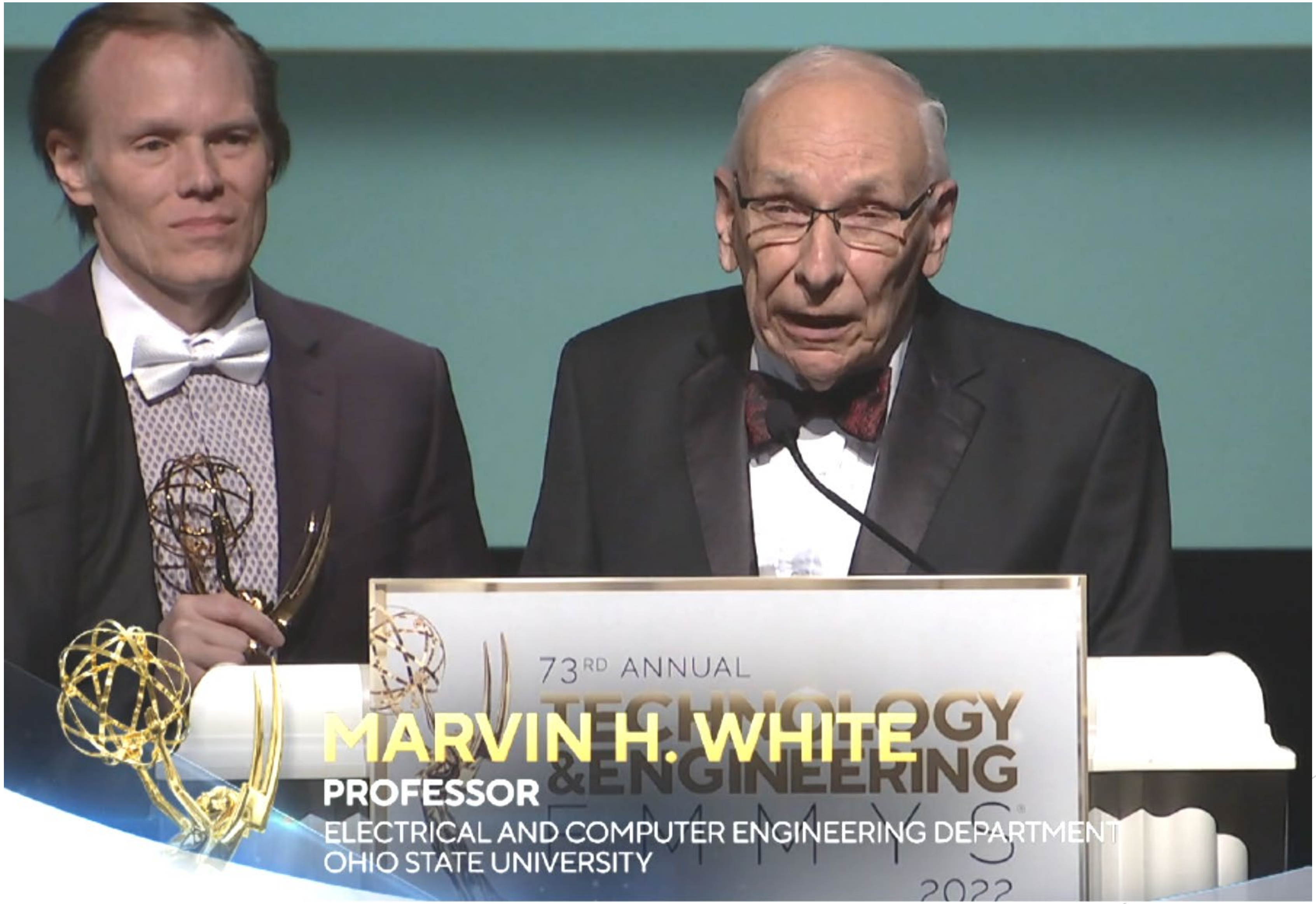
“This year’s awarded categories and companies are a testament to the technological innovation we continue to see in the delivery, consumption and monetization of television,” said Dina Weisberger, Co-Chair, NATAS Technology Achievement Committee.

Born in 1937 in Bronx, New York, White began his educational journey in the 1940s, during the tail end of the Great Depression. His immediate family had no previous scientists, so he became a first-generation engineer, eventually earning his Ph.D. from Ohio State in 1969. From countless odd jobs as he paid his way through school, to a successful career in both industry and academia, White's legacy in engineering is respected on numerous levels.

He joined the Ohio State ECE faculty in 2010 after many years teaching at Lehigh University in Bethlehem, Pennsylvania, where he was the Sherman-Fairchild Professor of Electrical and Computer Engineering and director of the Sherman-Fairchild Center for Solid State Studies. He also served two decades at Westinghouse Electric Company, as well as two stints at the National Science Foundation and Naval Research Laboratory. He has authored or co-authored over 300 technical papers, contributed chapters to four books, and has 27 U.S. patents.

White is a member of the U.S. National Academy of Engineering and an IEEE Life Fellow. In 2011, he received Ohio State's Distinguished Alumnus Award.

CDS Presentation On-Stage at the Wynn Encore Ballroom in Las Vegas 2022



The Making of the Emmy® Statuette

- The making of the Emmy® by Chicago-based R. C. Owens & Co. is shown in this video:

Emmy Statuettes

Group Backstage at the Emmy® Awards

The Moral of the Story

It Takes 50 Years!