Multi-Aperture Imaging Devices

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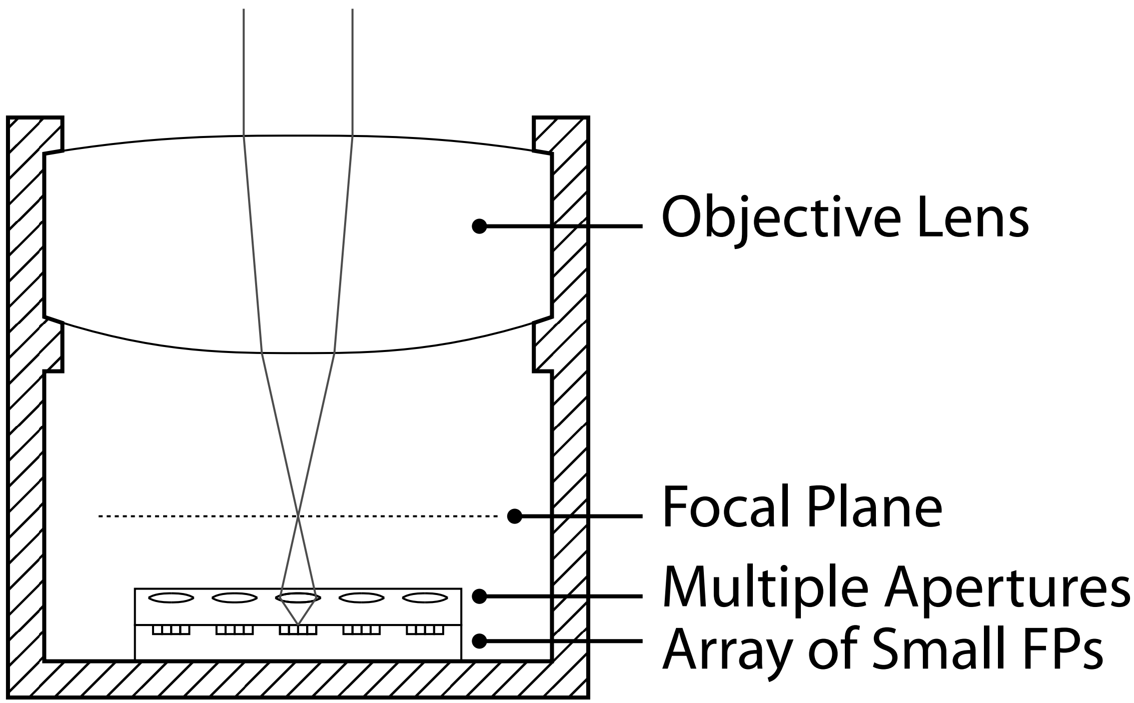
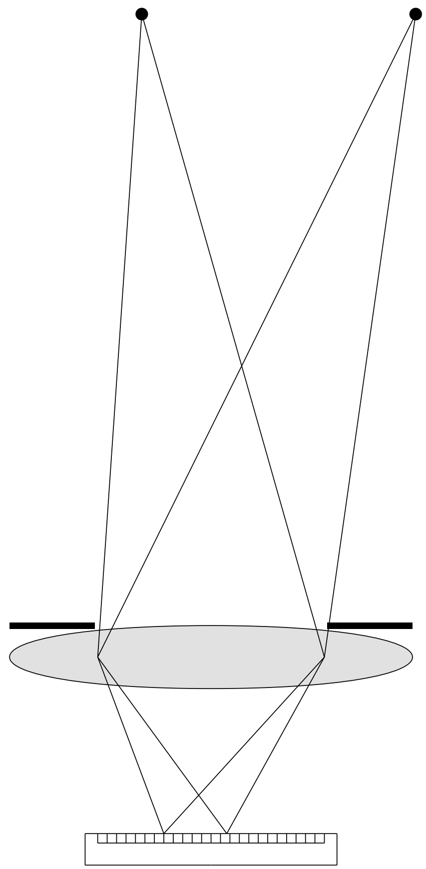
Multi-Aperture System

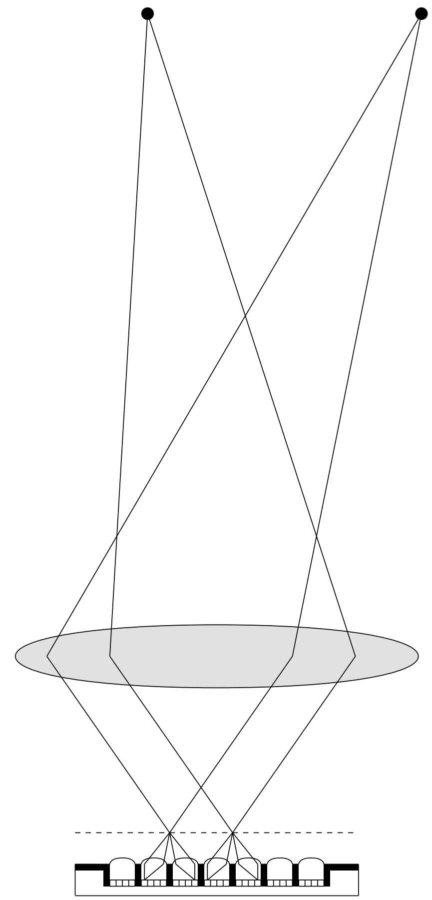
- **Scene focused via objective lens above detector plane**
- **Re-imaged via local optics onto disjoint arrays**
- **Arrays have overlapping fields of view**
- **Image is formed using digital signal processing**



Traditional vs Multi-Aperture



Traditional optical configuration



Multi-aperture optical configuration

Why Multi-Aperture Imaging?

- Capture depth information
- Reduce requirements of objective lens (cheaper optics)
- Achieve better color separation (less crosstalk)
- Redundant data allows for manufacturing defect correction
- Facilitate new circuit design architectures
- Benefit from pixel scaling

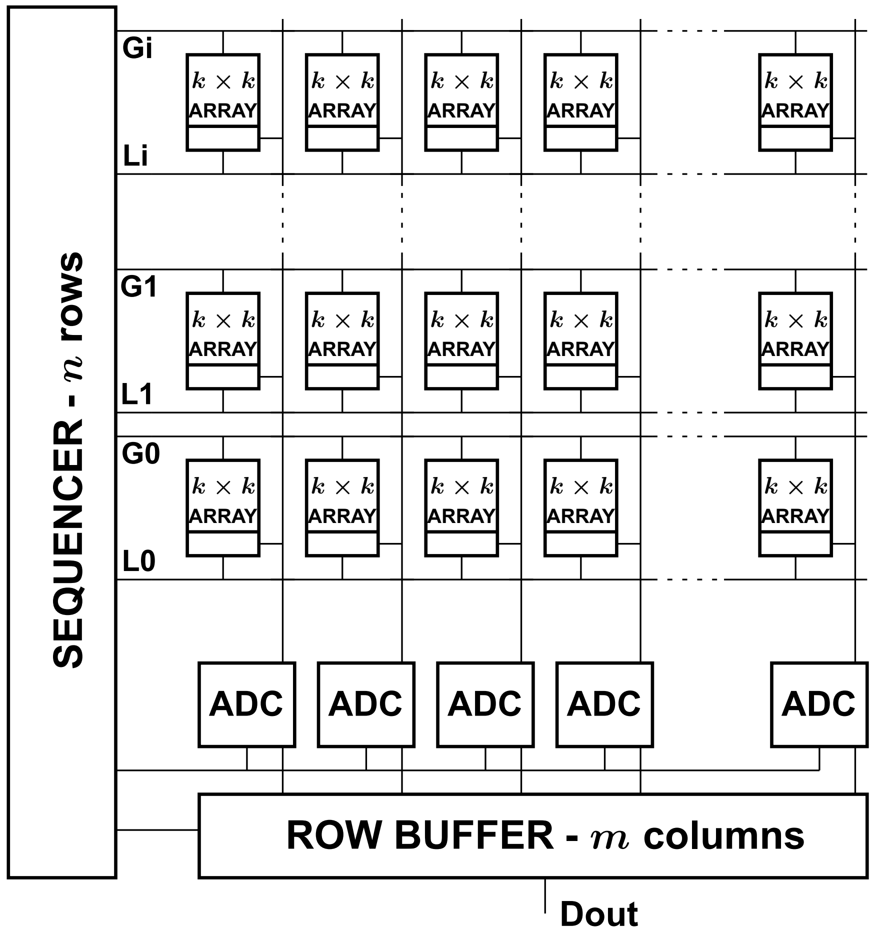
Why Image Sensors in CMOS?

- **Enable integration of analog and digital circuits along with the sensor**
  - **Camera on a Chip**
- **Leverage high-volume, mainstream process**
  - **Potentially lower cost**
- **Create new applications**
  - **High Speed**
  - **High Dynamic Range**
  - **Low power**
  - **Region of Interest and random access**

Our goal is to use CMOS technology to create *multiple* cameras on a chip.

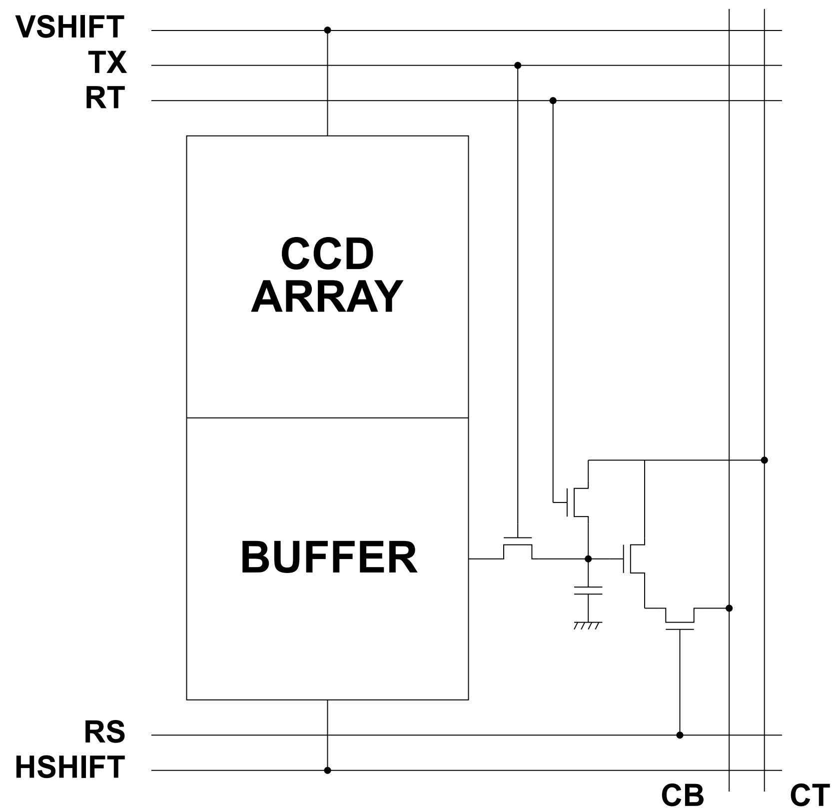
Multi-Aperture Architecture

- The sensor contains an $m \times n$ array of $k \times k$ pixel groups



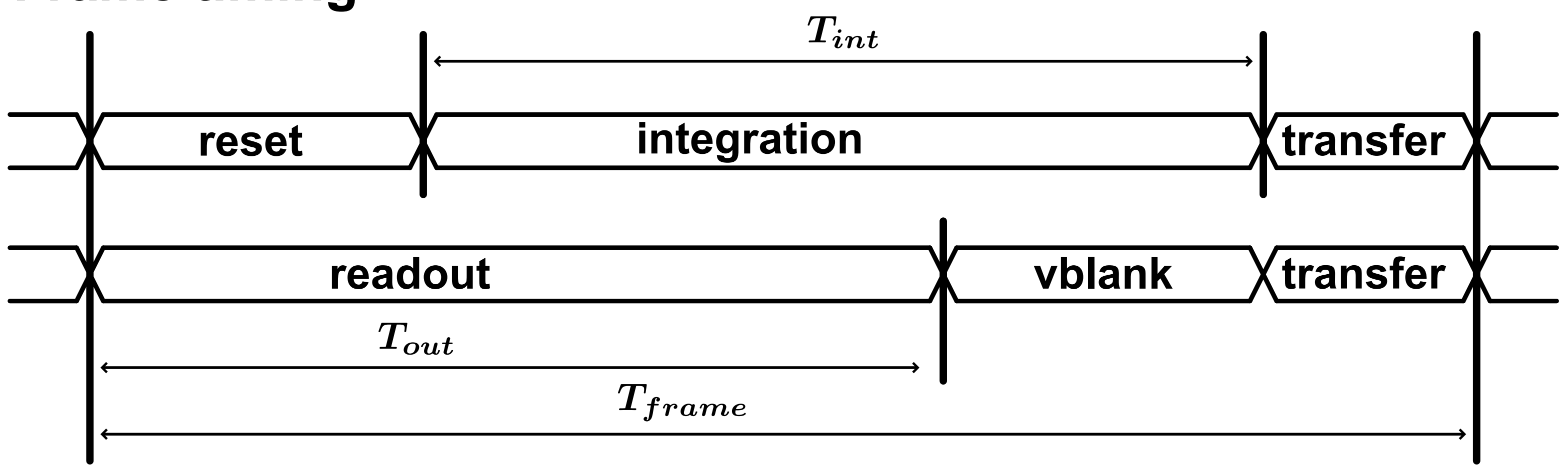
Array Structure

- Single aperture array with local readout
- Architecture enables global exposure

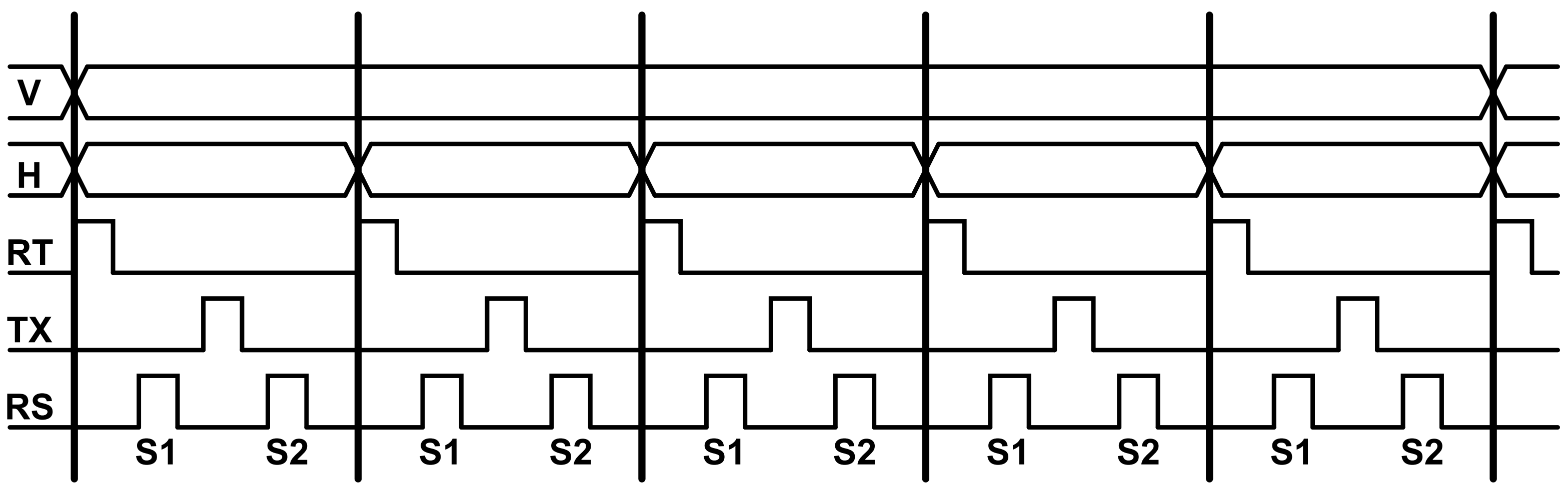


Capture and Readout Sequence

- **Frame timing**

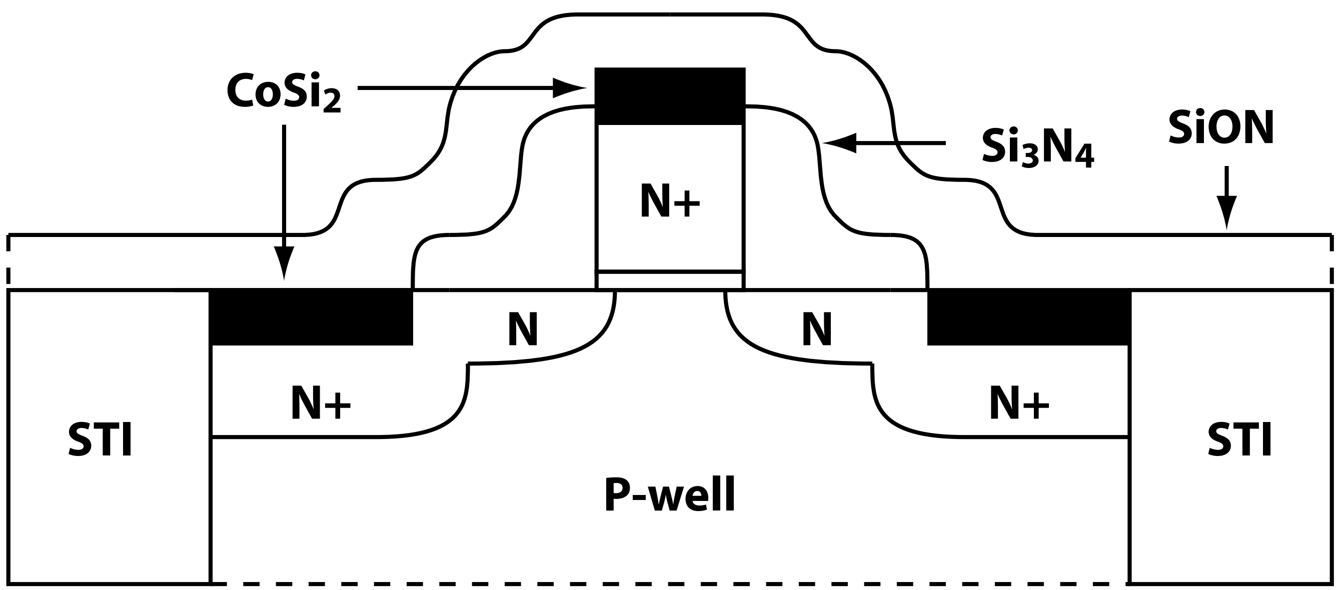


- **Row timing**



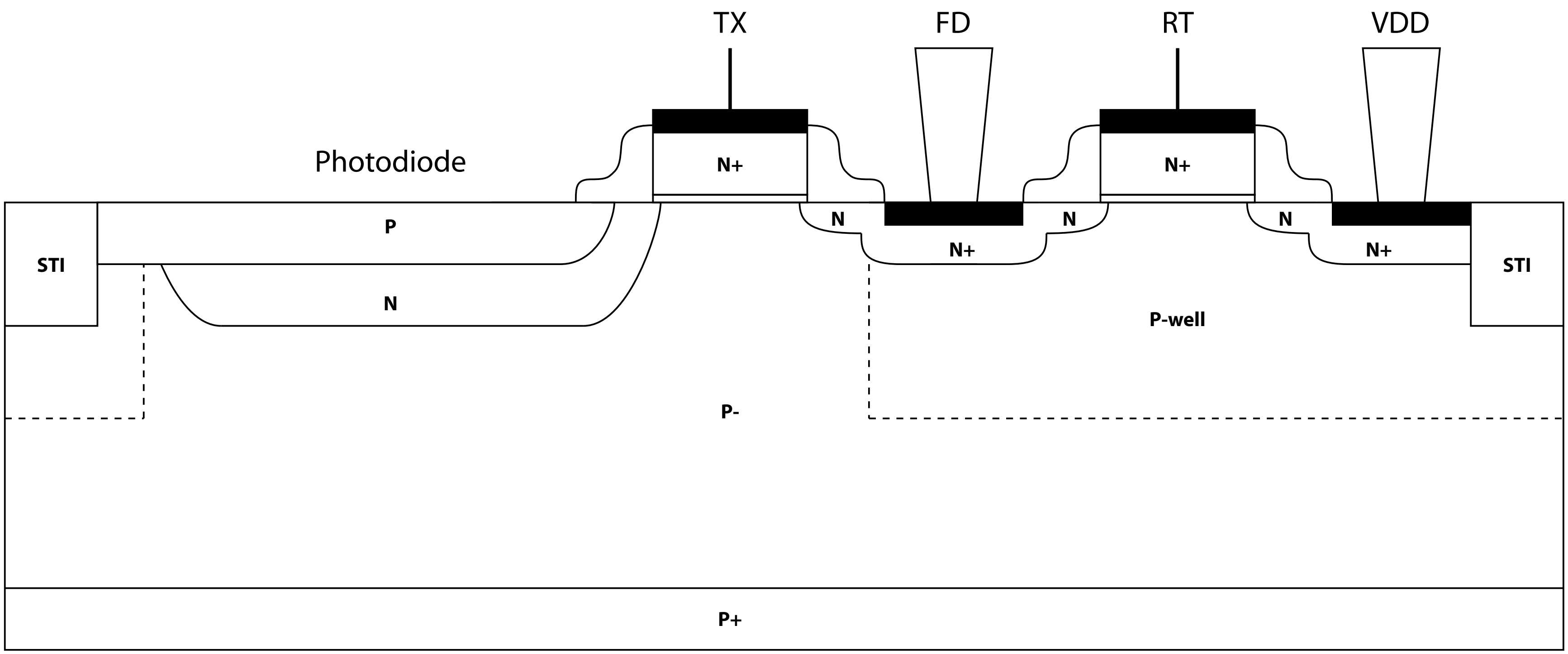
MOS Structure for Typical Process

- **Silicided regions: S/D and Poly**
- **STI, Nitrided spacers, SiON for BLC**



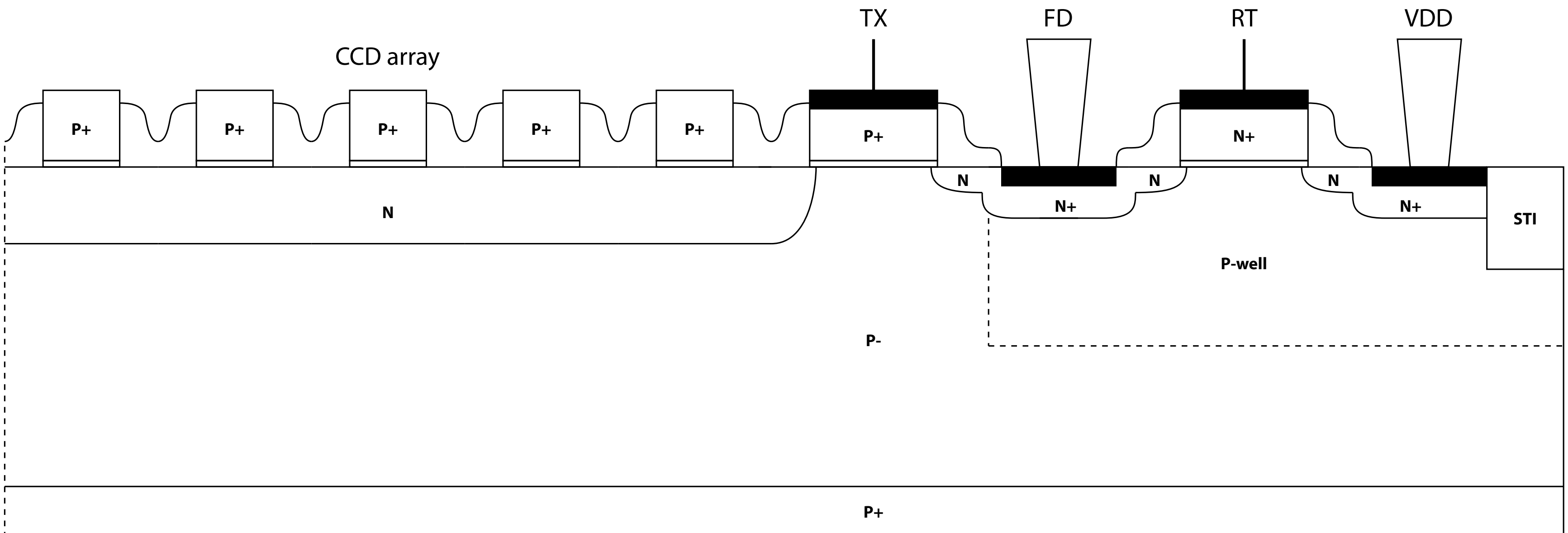
Typical 4T Pixel

- **Diode is fully depleted of electrons during readout**
- **Surface of diode is pinned at substrate potential**
- **Charge to voltage conversion occurs at each pixel**
- **Floating diffusion (FD) is doubled sampled**



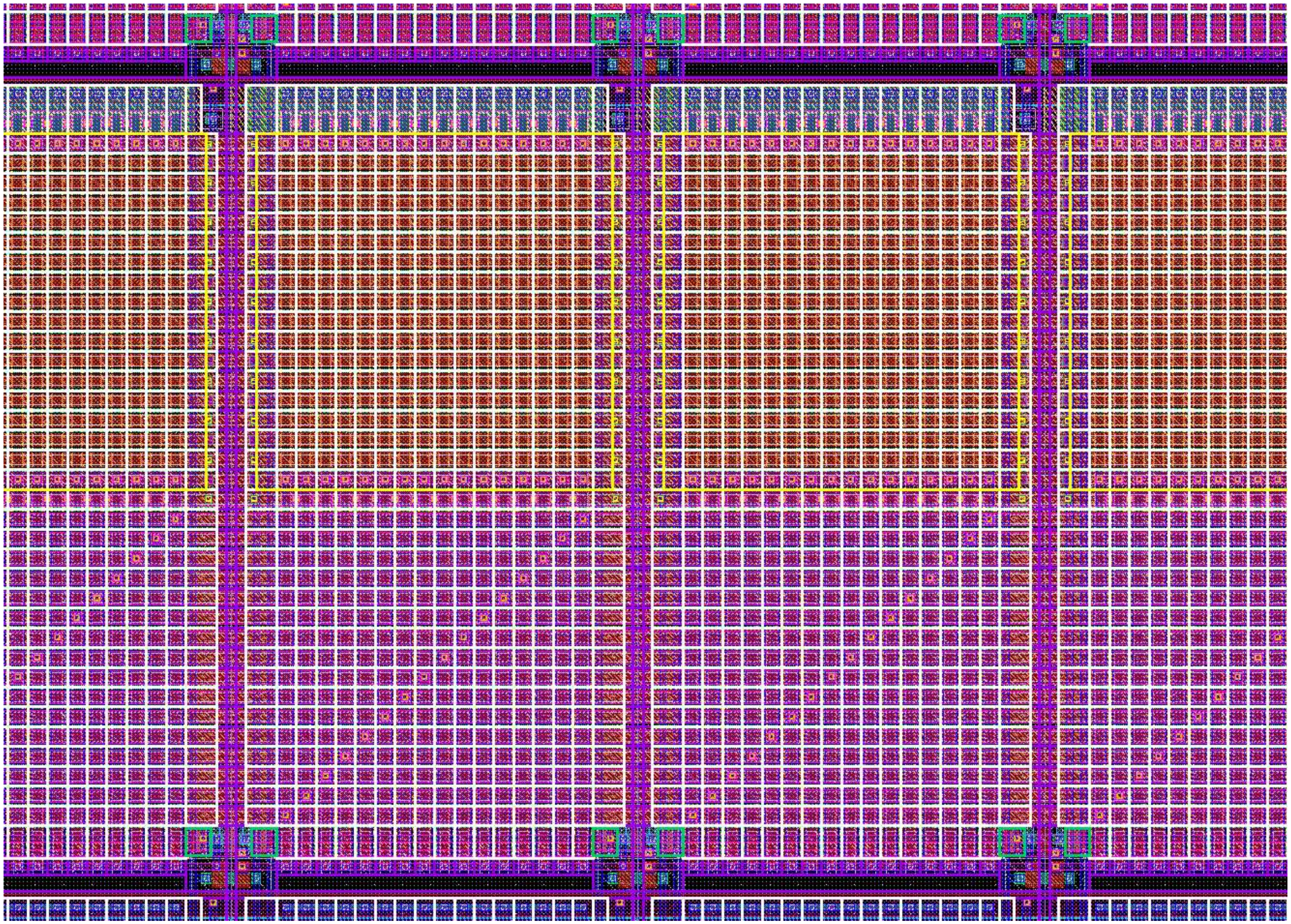
Multi-Aperture Pixels

- CCD channels and channel stops created with CIS implants
- Polysilicon used in active array with no silicide
- Charge confined under electrodes and shifted to output
- No metal layers are needed in the imaging area



Array Layout

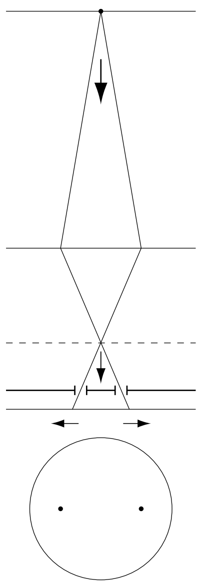
- **Each array is a 16 $\times$ 16 Full Frame Transfer CCD**



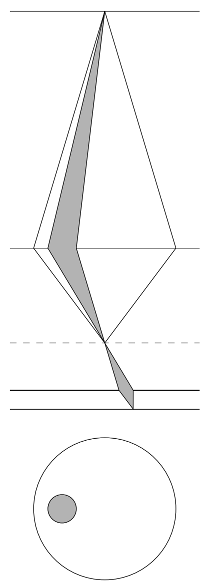
2D and 3D Image Extraction

- **Depth information is obtained from the disparity between apertures.**
- **Object movement translates to lateral displacement between corresponding points imaged by disjoint arrays.**
- **Solving the correspondence problem is eased by using several local apertures.**
- **The 2D image is formed by solving for the local correspondence and integrating the result across the sensor.**

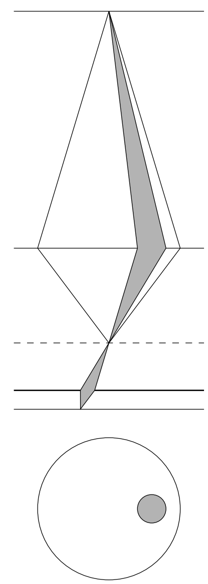
Virtual Aperture Views



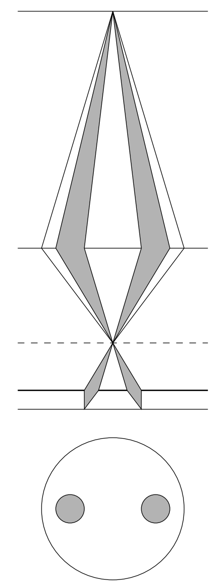
Chief rays for a pair of apertures



Left virtual objective aperture

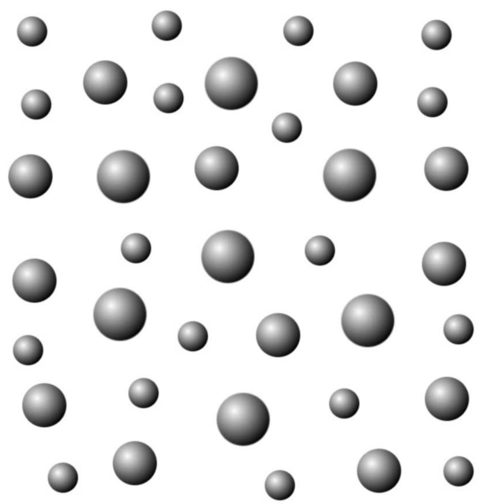


Right virtual objective aperture

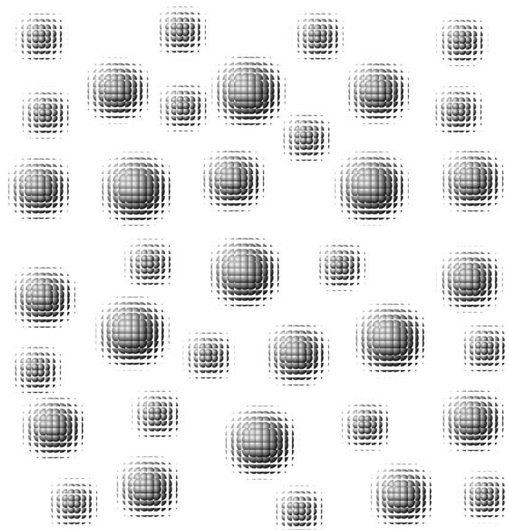


Virtual apertures for stereo view

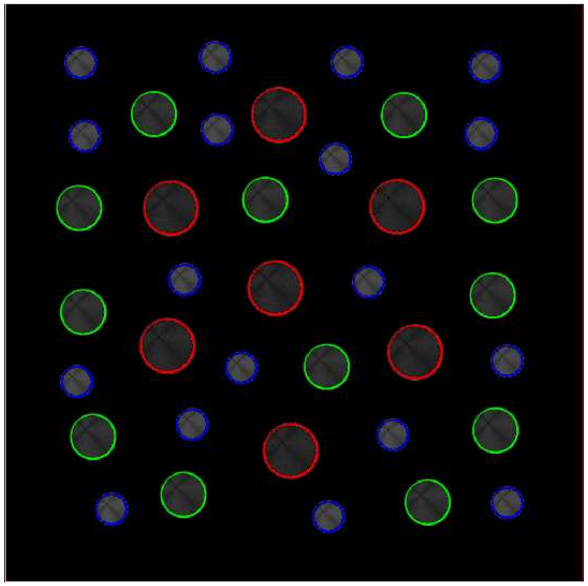
Concept of Depth Extraction



Objects at varied distance



Objects captured with several apertures



Distances calculated from edge displacements

Depth Calculations

- **By the geometry of the local optics and focal plane,**

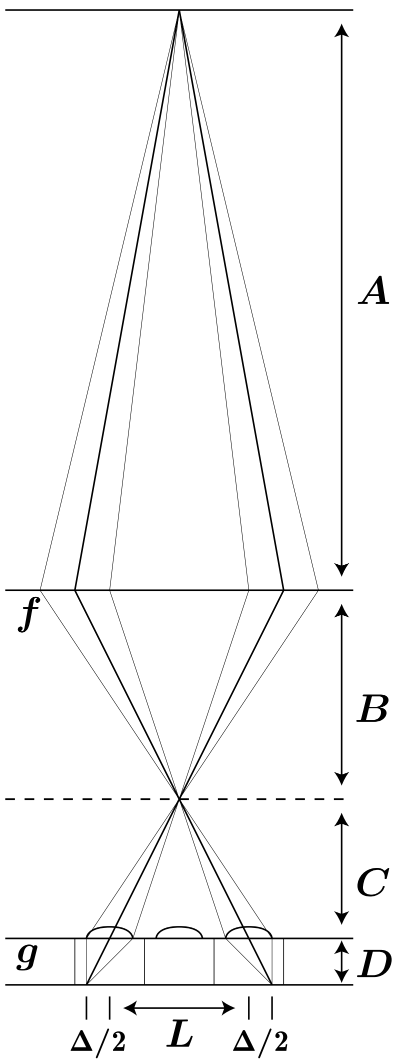
$$C/L = D_0/\Delta$$

- **Using the lens law for A as a function of B and making the substitution $B = E - C = B_0 + C_0 - C$,**

$$A = \left(\frac{1}{f} - \frac{1}{B}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{B_0 + C_0 - C}\right)^{-1}$$

- **Solving for A in terms of Δ with $M = B/A$ and $N = D/C$ gives the depth equation,**

$$A = \left[\frac{1}{f} - \frac{1}{(M_0 + 1)f + D_0/N_0 - D_0L/\Delta}\right]^{-1}$$



Depth Resolution Decreases with Distance

- **The amount of depth information available falls off with the square of the object distance.**
  - **Solving for a measured displacement gives,**

$$\Delta = \frac{D_0 L}{(M_0 - M)f + D_0/N_0}.$$

  - **As M decreases, Δ rapidly approaches its limit of $D_0 L/(M_0 f + D_0/N_0)$.**
  - **The rate of change in Δ with A,**

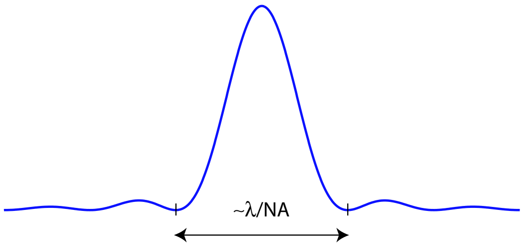
$$\partial\Delta/\partial A \approx -\frac{f^2}{A^2}\frac{DL}{C^2} \longrightarrow \partial\Delta/\partial A \approx -M^2 N^2 \frac{L}{D}.$$

Spatial Resolution and Pixel Size

- **Spatial resolution is limited to the total number of pixels mnk^2.**
- **In order to achieve redundancy, the local magnification factor is set to $N < 1$.**
  - **Spatial resolution is reduced by $1/N^2$.**
  - **The total recoverable resolution is $\approx mnk^2N^2$**
- **Example: A 16×16 array of 0.5μm pixels with a magnification factor of $N_0 = 1/4$ produces a maximum resolution 16 times greater than the aperture count and 16 times lower than the pixel count.**

Spot Size Comparison

- **The minimum spot size for a diffraction limited system is approximately λ/NA.**



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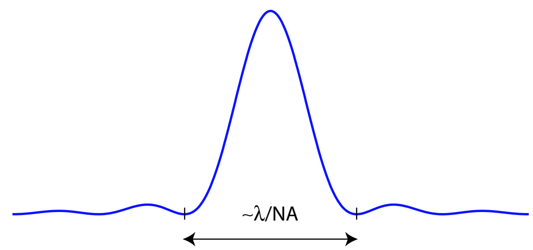
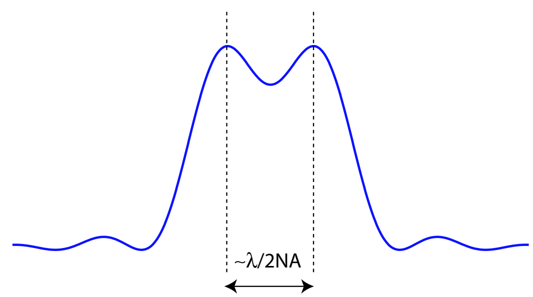


- The minimum useful pixel pitch is half the spot size using Rayleigh criterion.



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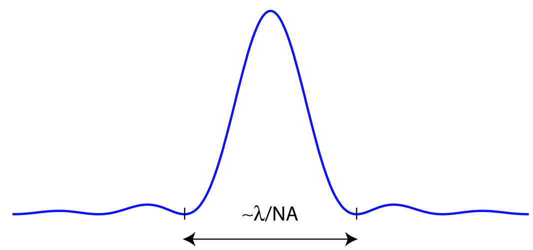

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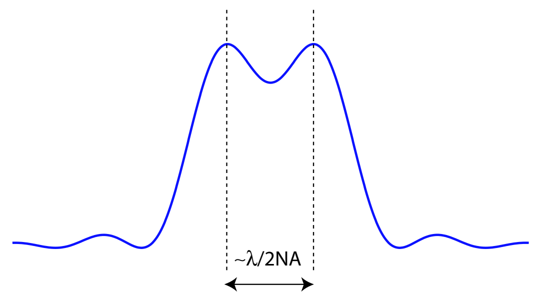
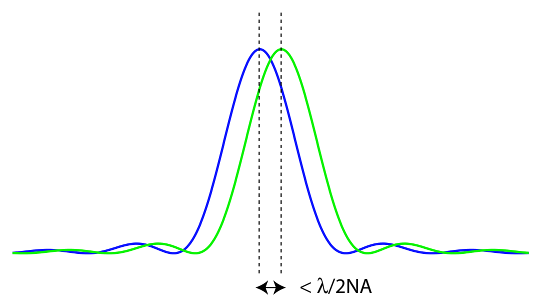
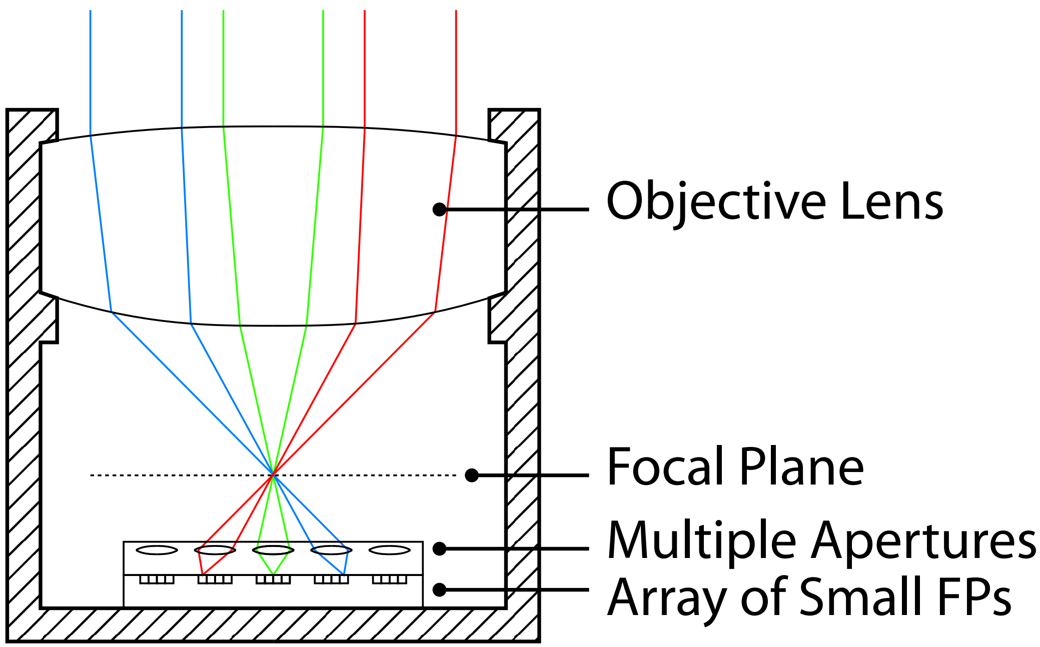


- **Disparity from a Multi-Aperture system gives displacement which can be smaller than diffraction limit.**



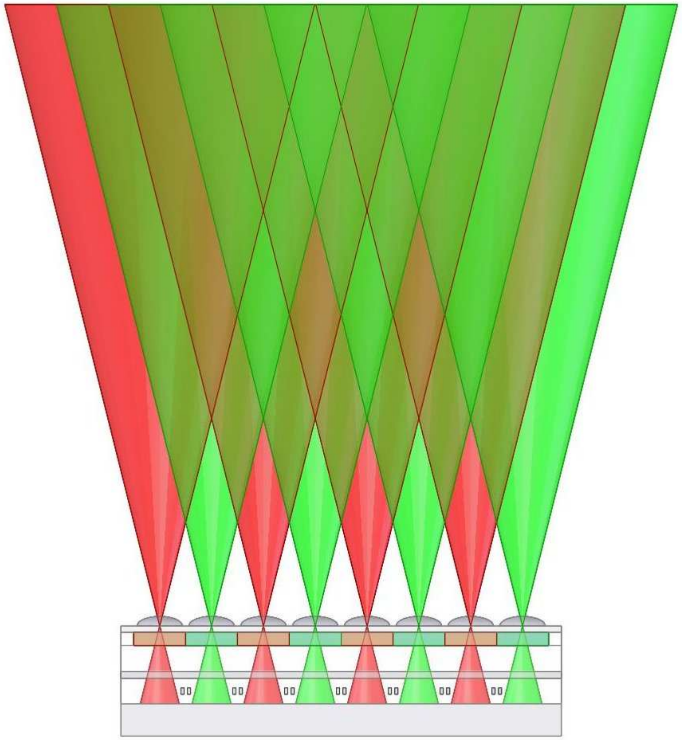
Multi-Aperture Color System

- **Spectral separation by aperture**
- **No color contamination from neighboring pixels**
- **Facilitates the use of large dielectric stack height which allows high logic density**



Projected Color Channels

- **Color channels only overlap in the space above the detector**



Conclusion

- **CMOS technology is used to create multiple cameras on a chip**
- **Depth map is extracted by solving the correspondence problem between multiple views of the same points in the primary focal plane.**
- **The amount of depth resolution available increases with decreasing pixel size while the 2D spatial resolution remains limited.**
- **The sensor architecture may be useful in improving the performance of color imaging by employing a per-aperture color filter.**