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Optical Flow Paper Reading

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Signal Sensing and Application Laboratory

Outline

- Introduction of Optical Flow
- A Simplified Normal Optical Flow Measurement CMOS Camera
  - Motivation
  - Algorithm
  - Hardware Implementation
  - Results

Introduction of Optical Flow

Optical Flow

- Optical flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and a scene.

A Simplified Normal Optical Flow Measurement CMOS Camera

Mehta S, and Etienne-Cummings R. 2006. IEEE Transactions on Circuits and Systems I: Regular Papers

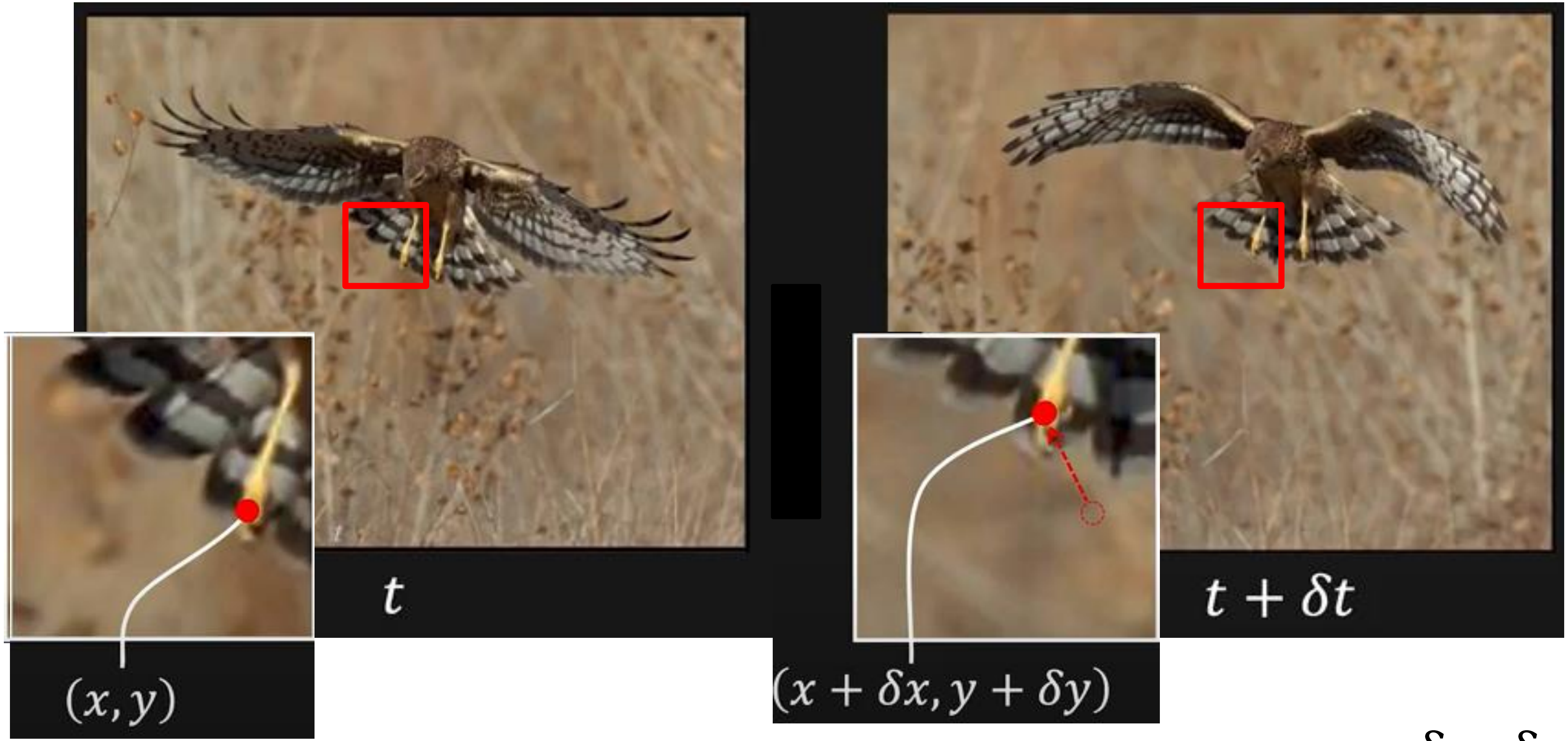
Introduction

- This paper presents a two-dimensional dense simplified normal optical flow measurement chip implemented in 0.5-um CMOS process that combines imaging and processing on the same chip efficiently.
- The algorithm outputs the image, computes partial derivatives with respect to time and space, and uses their ratio to compute a simplified version of the normal flow velocity.

Motivation

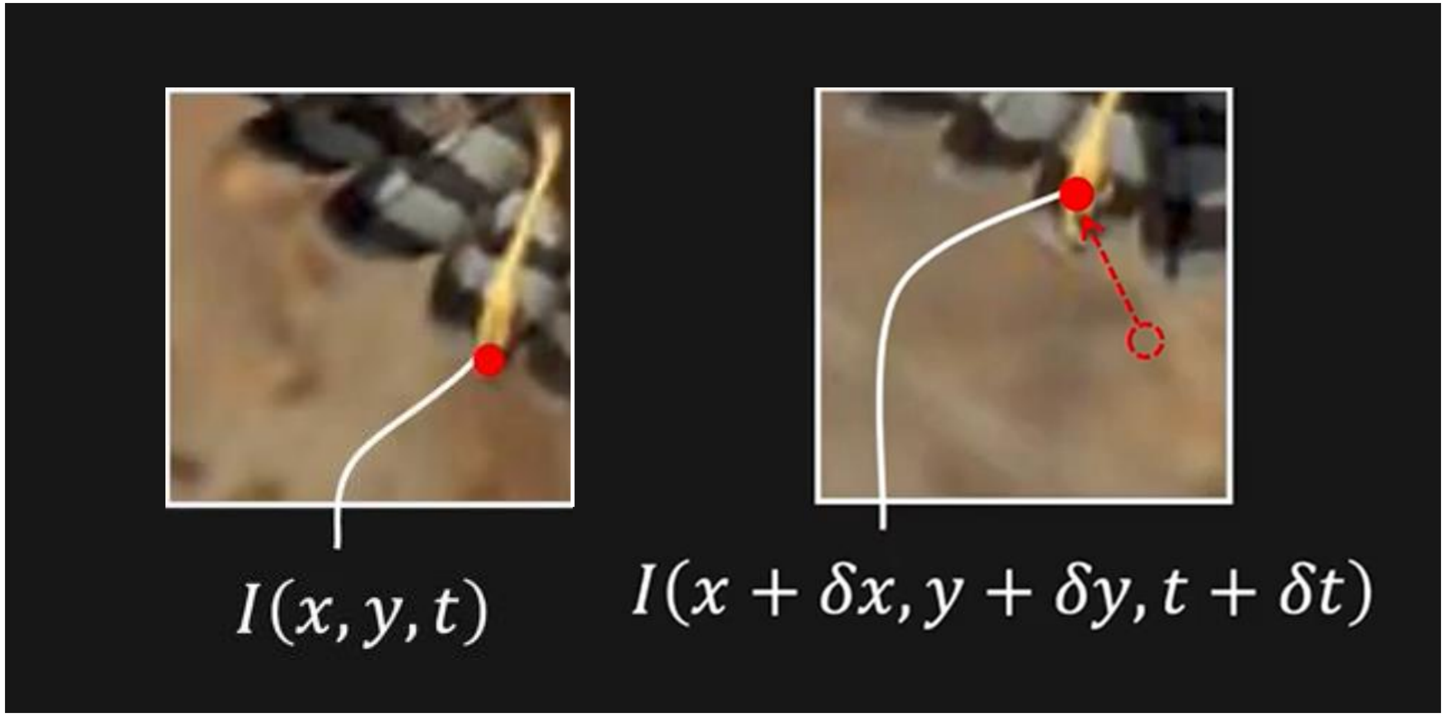
- In previous works, imaging resolution, the size of the pixel, and the wiring complexity between different blocks are tradeoff whenever processing was combined with imaging.
- To overcome the tradeoff, multi-chip systems have also been proposed. However, it may cause high-power consumption.
- The design has a low-power high-resolution CMOS imager at the core

Algorithm -- Differential method



$$Displacement = (\delta x, \delta y) \qquad optical\ flow: (V_x, V_y) = \left(\frac{\delta x}{\delta t}, \frac{\delta y}{\delta t}\right)$$

- Assumption 1: Brightness of image point remains constant over time.



$$\boxed{I(x, y, t) = I(x + \delta x, y + \delta y, t + \delta t)}$$

- Assumption 2: Displacement $\delta x, \delta y$ and the time step δt are small.

$$f(x+\delta x) = f(x) + \frac{\partial f}{\partial x}\delta x + \frac{\partial^2 f}{\partial x^2}\frac{\delta x^2}{2!} + \cdots + \frac{\partial^n f}{\partial x^n}\frac{\delta x^n}{n!}$$

If δx is small:

在這裡鍵入方程式。

$$f(x+\delta x) = f(x) + \frac{\partial f}{\partial x}\delta x + \boxed{O(\delta x^2)} \rightarrow \text{Almost Zero}$$

$$\rightarrow f(x+\delta x, y+\delta y, t+\delta t) \approx f(x,y,t) + \frac{\partial f}{\partial x}\delta x + \frac{\partial f}{\partial y}\delta y + \frac{\partial f}{\partial t}\delta t$$

$$\boxed{\rightarrow I(x+\delta x, y+\delta y, t+\delta t) = I(x,y,t) + \frac{\partial I}{\partial x}\delta x + \frac{\partial I}{\partial y}\delta y + \frac{\partial I}{\partial t}\delta t}$$

$$\begin{cases} I(x,y,t) = I(x+\delta x, y+\delta y, t+\delta t) \;\ldots.(1) \\ I(x+\delta x, y+\delta y, t+\delta t) = I(x,y,t) + \frac{\partial I}{\partial x}\delta x + \frac{\partial I}{\partial y}\delta y + \frac{\partial I}{\partial t}\delta t \ldots(2) \end{cases}$$

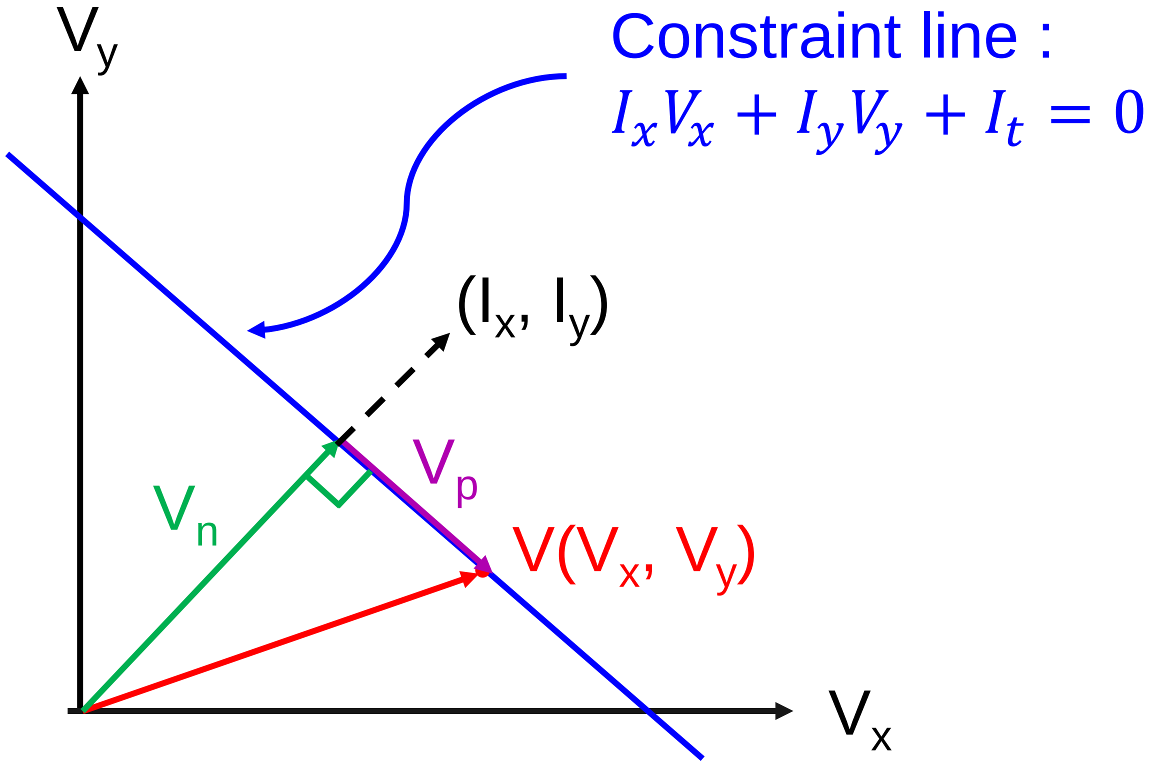
$\rightarrow \;(2)-(1) = \frac{\partial I}{\partial x}\delta x + \frac{\partial I}{\partial y}\delta y + \frac{\partial I}{\partial t}\delta t = 0 = \mathrm{I_x}\delta x + I_y \delta y + I_t \delta t$

$\rightarrow \;divide\ by\ \delta t, and\ take\ limit\ as\ \delta t \rightarrow 0\ :\ I_x \frac{\partial x}{\partial t} + I_y \frac{\partial y}{\partial t} + I_t = 0$

$\rightarrow \;we\ note \frac{\partial x}{\partial t}\ as\ V_x\ and\ \frac{\partial y}{\partial t}\ as\ V_y\ .$

$\rightarrow \;\boxed{constraint\ equation:\ I_x V_x + I_y V_y + I_t = 0}\ \boxed{optical\ flow: (V_x, V_y)}$

$$constriant\ equation: \ I_x V_x + I_y V_y + I_t = 0, \ \ optical\ flow: (V_x, V_y)$$



$$\widehat{V_n} = \frac{(I_x, I_y)}{\sqrt{I_x^2 + I_y^2}}, \quad |V_n| = \frac{|I_t|}{\sqrt{I_x^2 + I_y^2}}$$

$$\rightarrow V_n = \frac{|I_t|}{I_x^2 + I_y^2}(I_x, I_y) = (V_{nx}, V_{ny})$$

$$\rightarrow adding\ smoothing\ constraint$$

$$V_n = (V_{nx}, V_{ny}) = \left(\frac{I_t}{I_x}, \frac{I_t}{I_y}\right)$$

Hardware Implementation

- Image
- Correlated Double Sampling
- Memory
- Gradient
- Absolute Value & Direction
- Ratio & Confidence

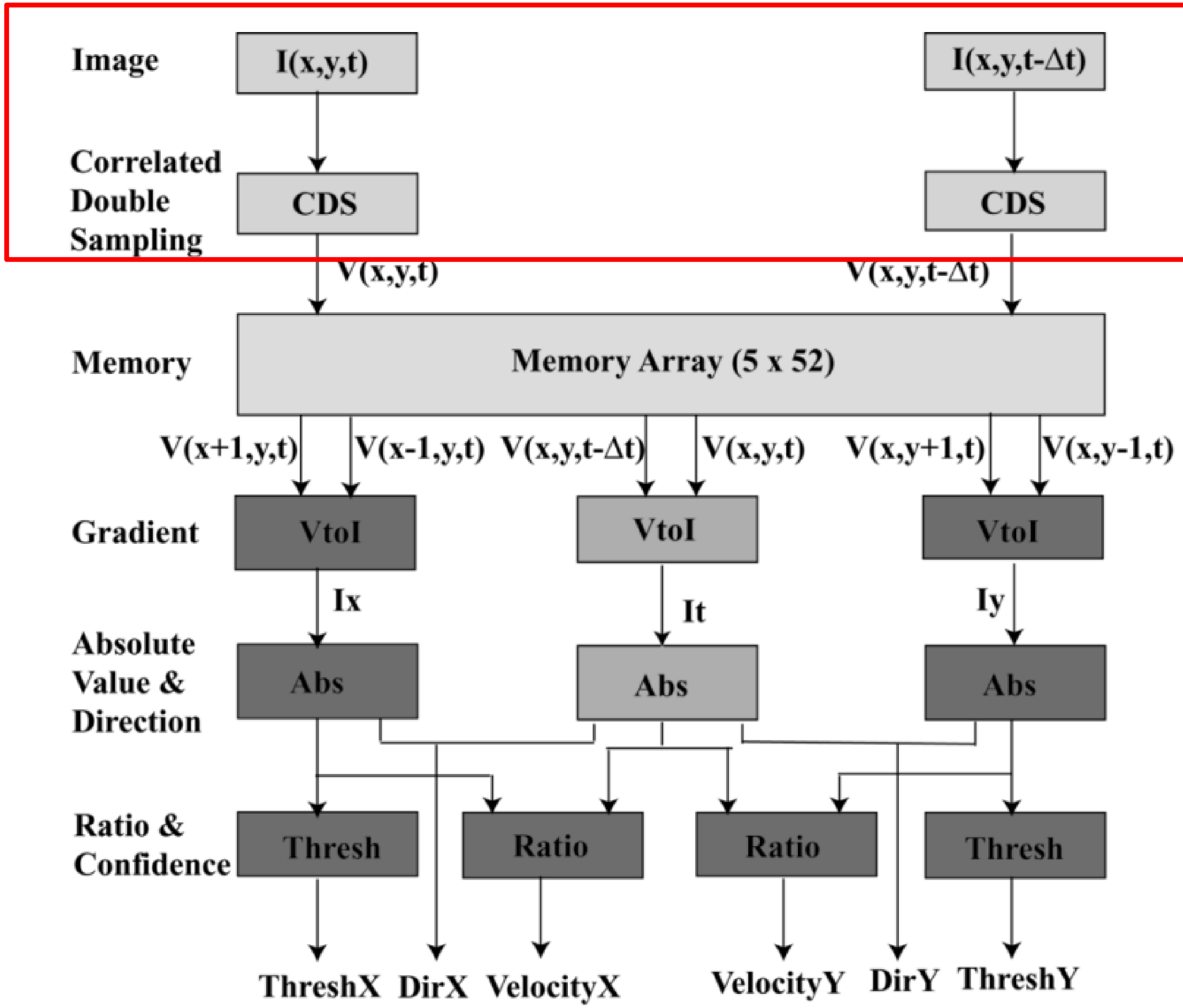
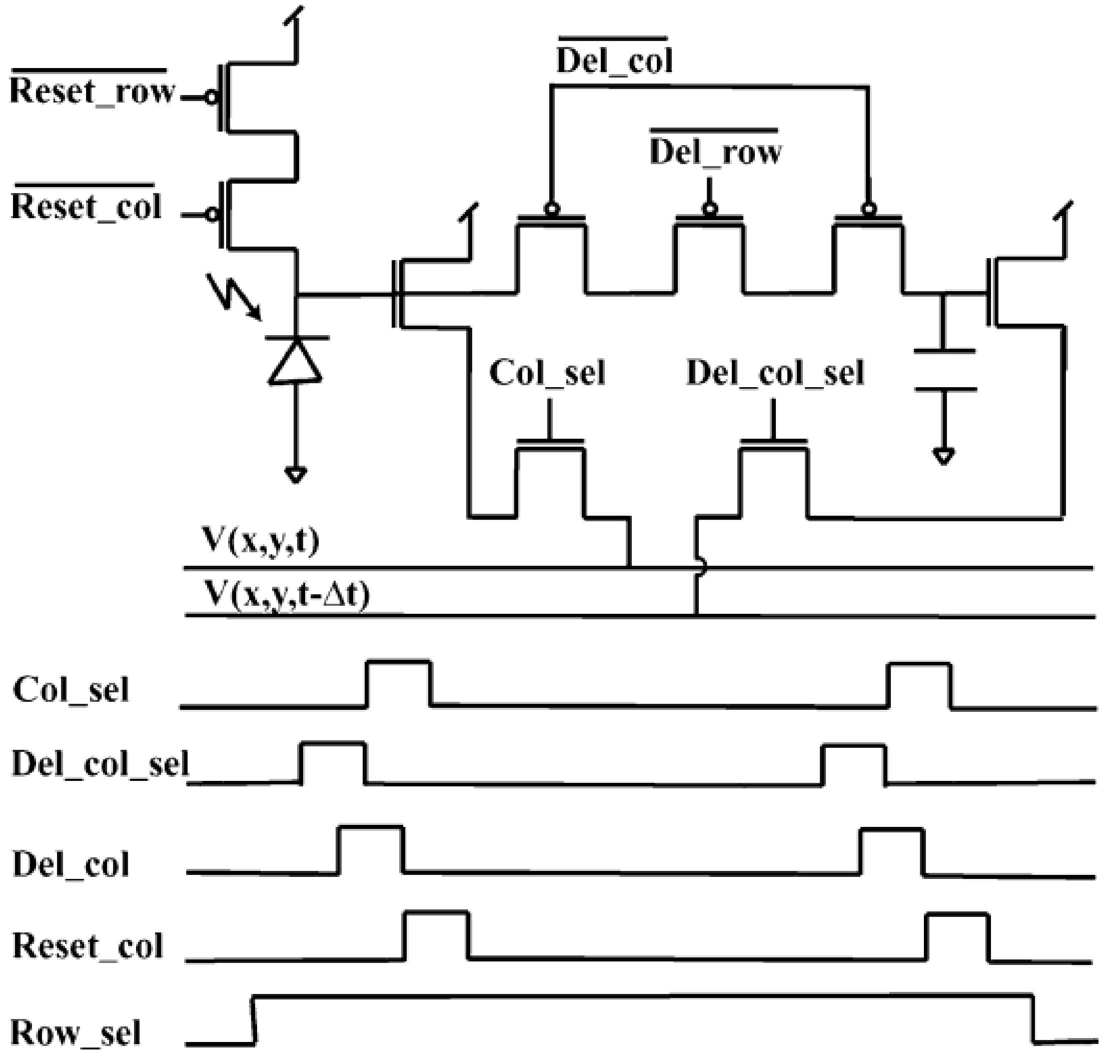
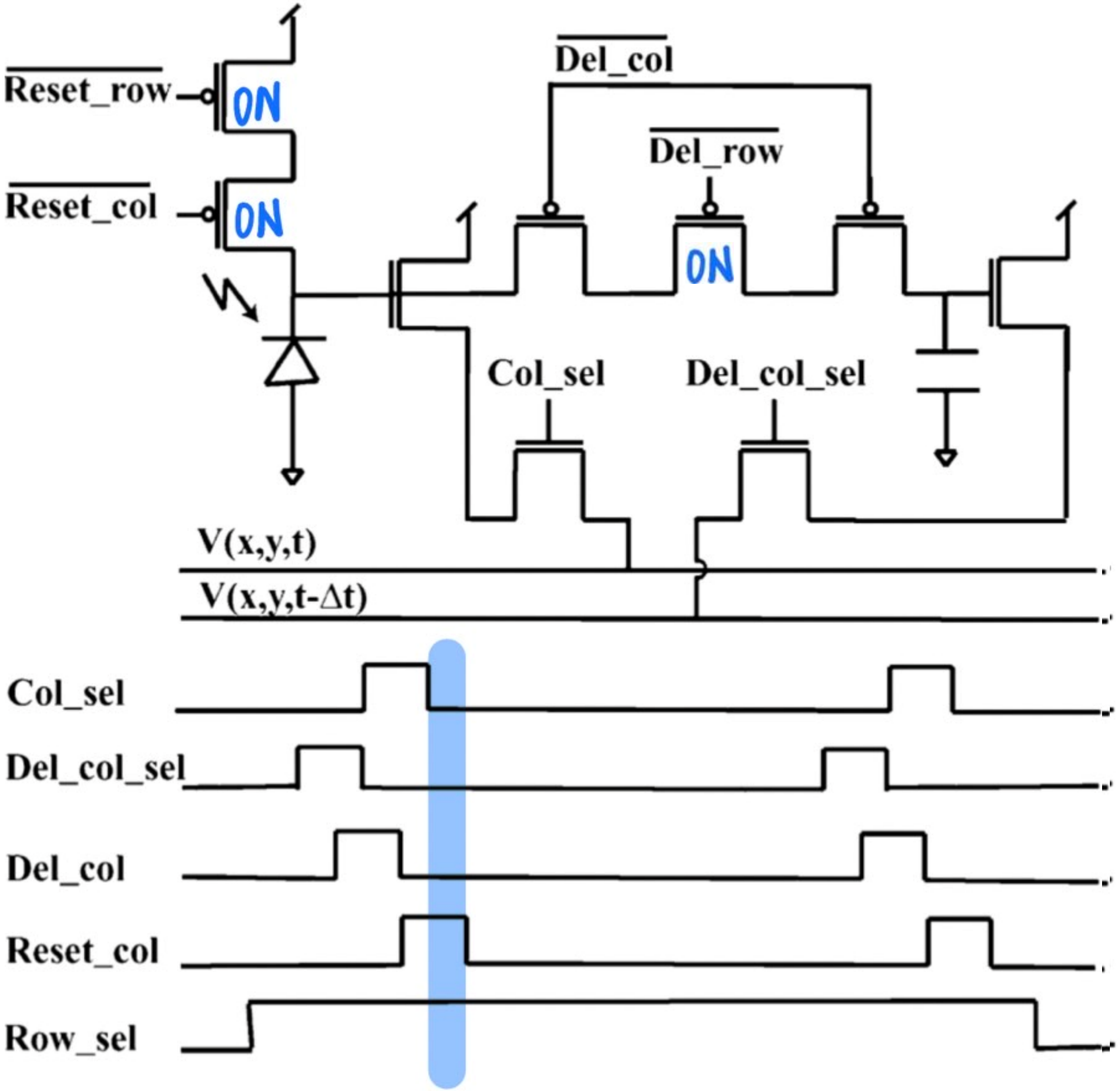


Image
I(x,y,t)
I(x,y,t-Δt)
Correlated Double Sampling
CDS
CDS
V(x,y,t)
V(x,y,t-Δt)
Memory
Memory Array (5 x 52)
V(x+1,y,t)
V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
Gradient
VtoI
VtoI
VtoI
Ix
It
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

Imaging Array

- The imaging array is composed of a 92x52 array of APS pixels with local analog memories for temporal processing in each pixel.




Reset_row
ON
Reset_col
ON
Del_col
Del_row
ON
Col_sel
Del_col_sel
V(x,y,t)
V(x,y,t-Δt)
Col_sel
Del_col_sel
Del_col
Reset_col
Row_sel

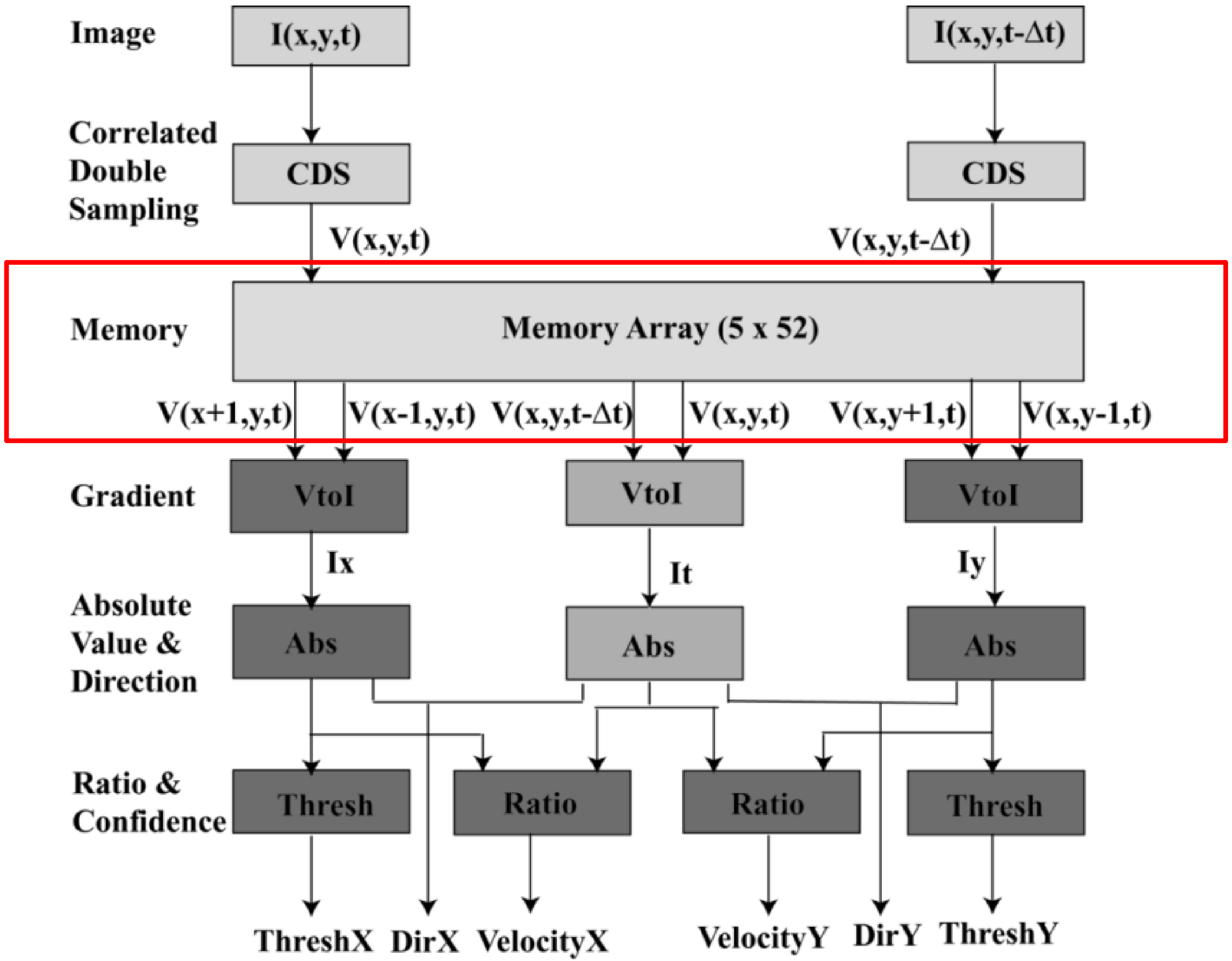


Image
I(x,y,t)
I(x,y,t-Δt)
Correlated Double Sampling
CDS
CDS
V(x,y,t)
V(x,y,t-Δt)
Memory
Memory Array (5 x 52)
V(x+1,y,t)
V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
Gradient
VtoI
VtoI
VtoI
Ix
It
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

Analog Memory

- The (5x52) analog memory block gets its input from the two CDS circuits and stores three rows of present frame image output and two rows of previous frame delayed image output.

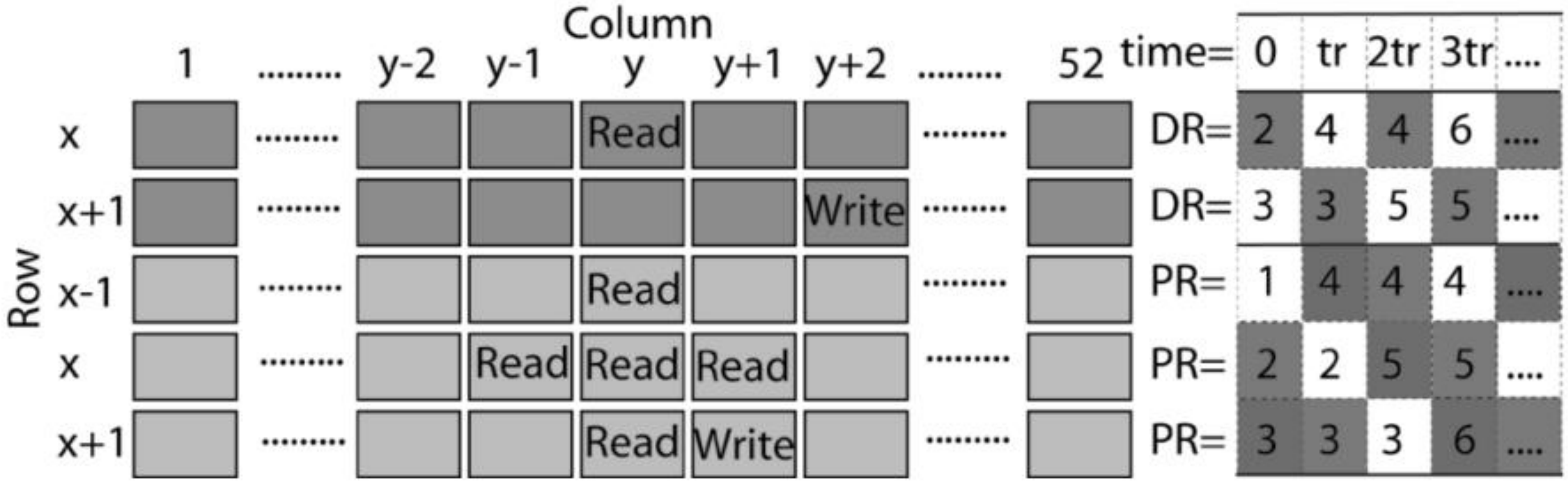


Fig. 4. Analog memory operation and timing. Three rows of analog memory are reserved for the present image and two rows for the previous image.

- This block outputs six signals which correspond to

① $V(x, y, t)$
② $V(x, y, t - \Delta t)$
→ To calculate I_t

③ $V(x - 1, y, t)$
④ $V(x + 1, y, t)$
→ To calculate I_x

⑤ $V(x, y - 1, t)$
⑥ $V(x, y + 1, t)$
→ To calculate I_y

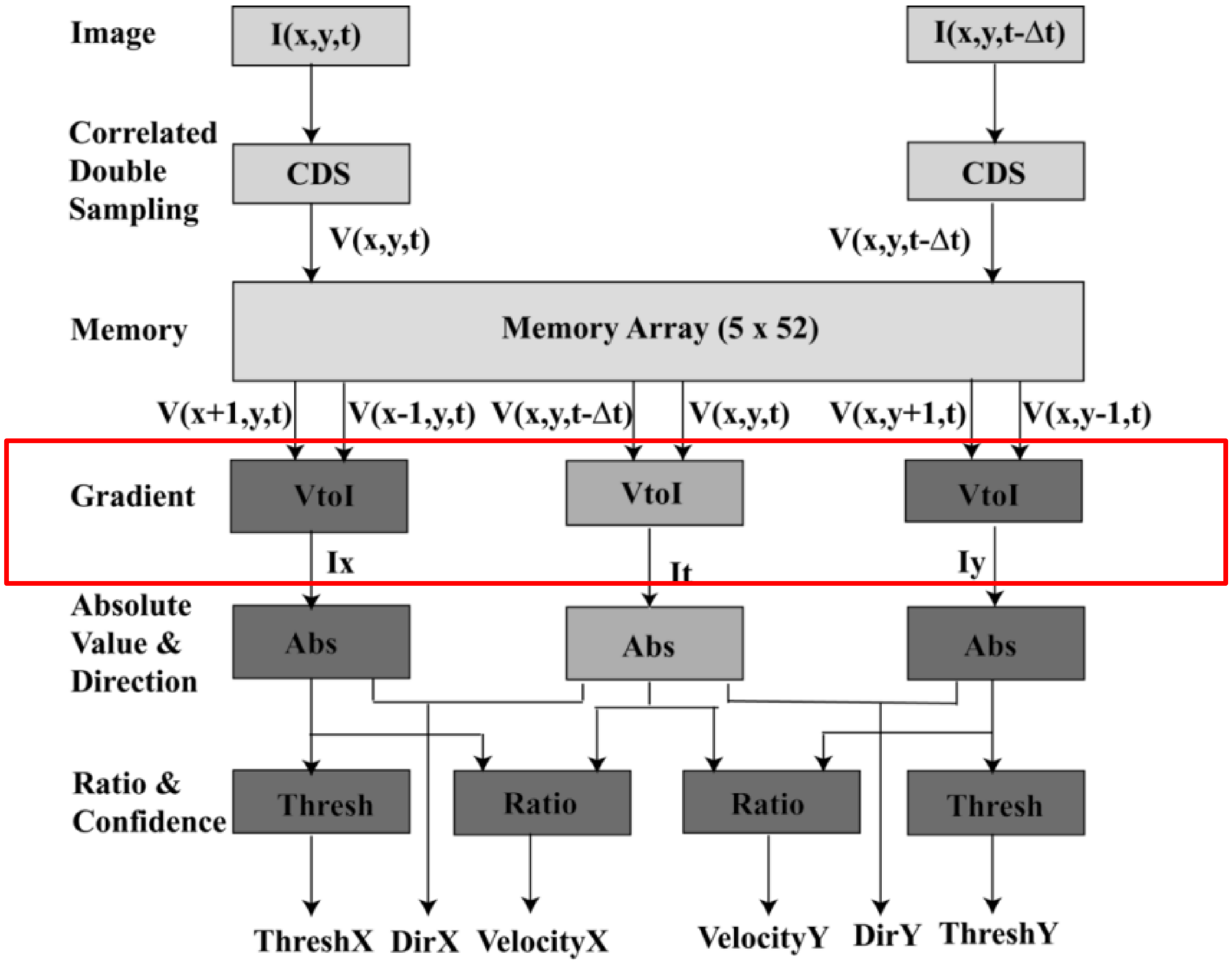
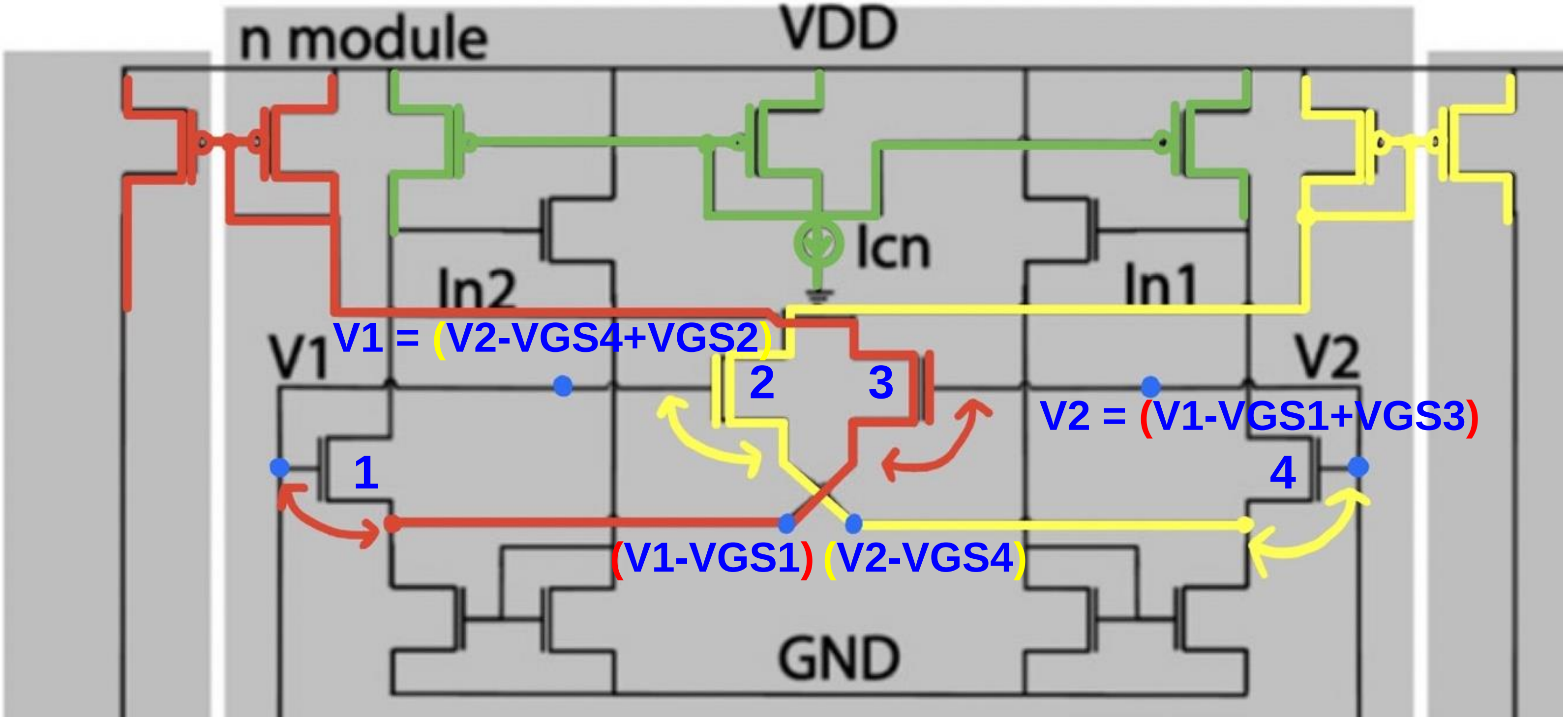


Image
I(x,y,t)
I(x,y,t-Δt)
Correlated Double Sampling
CDS
CDS
V(x,y,t)
V(x,y,t-Δt)
Memory
Memory Array (5 x 52)
V(x+1,y,t)
V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
Gradient
VtoI
VtoI
VtoI
Ix
It
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

V–I Converters



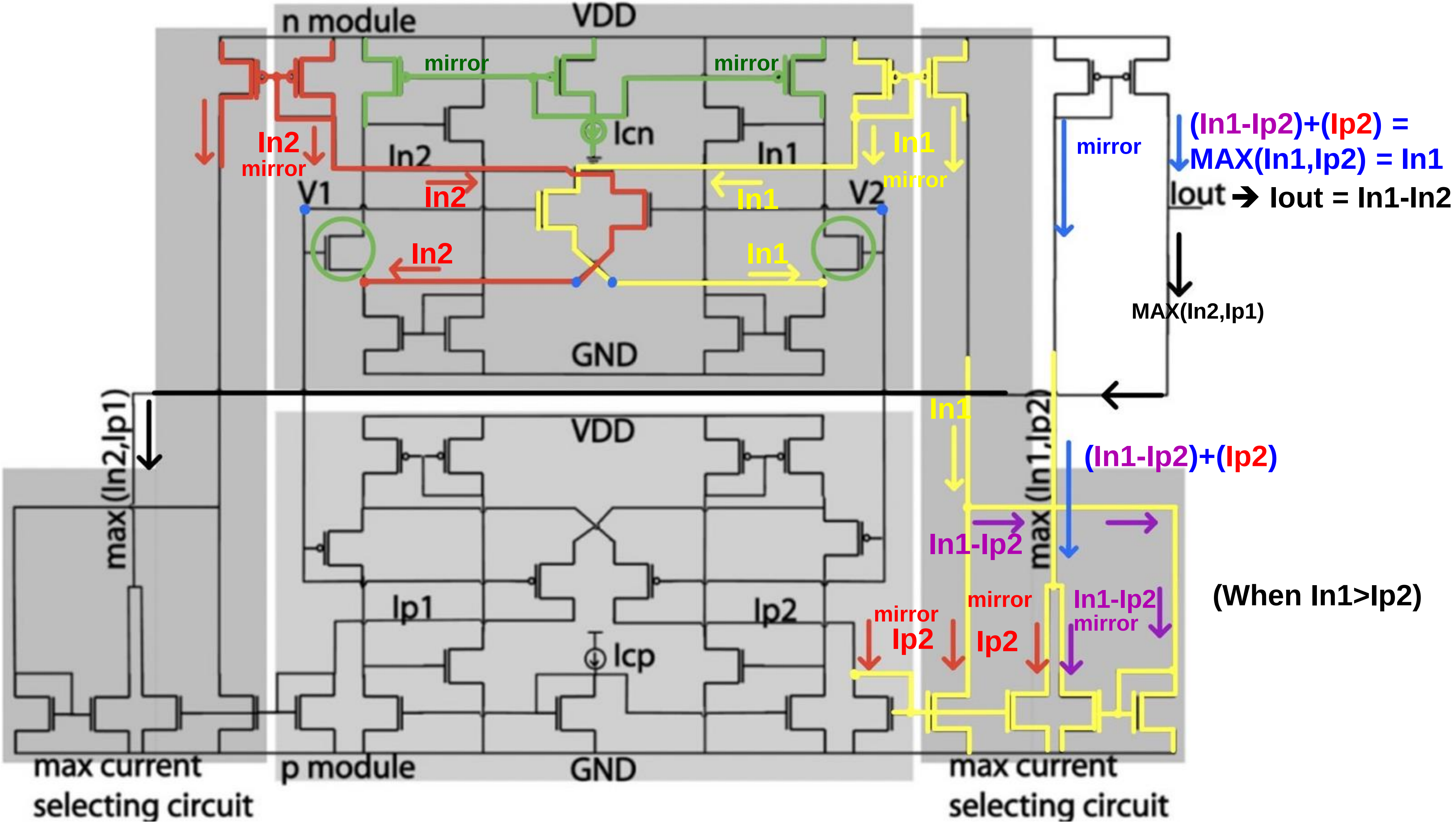
$$V1 - V2 = VGS2 - VGS4 = VGS1 - VGS3$$

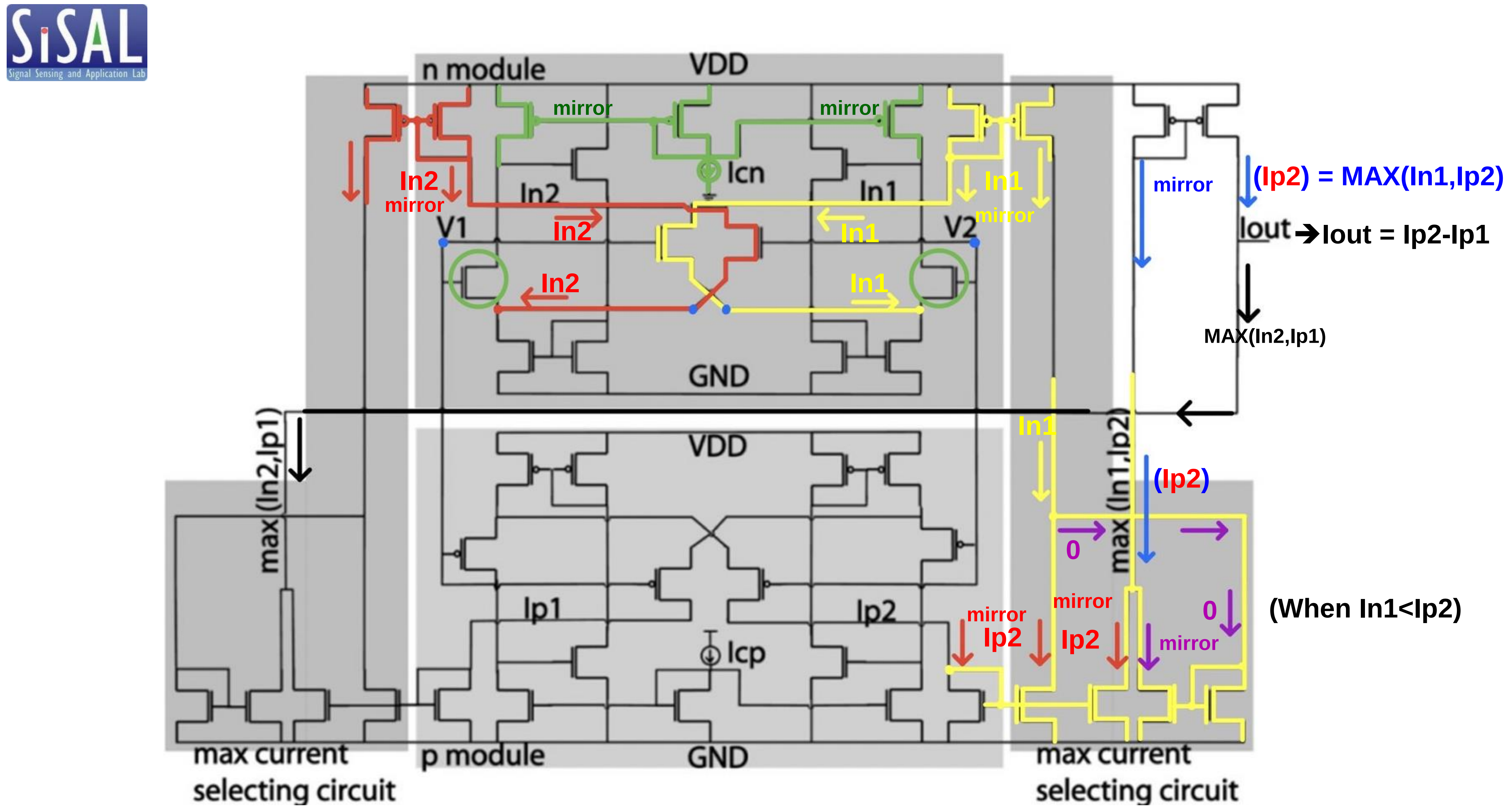
$$= \sqrt{\frac{2In1}{K}} + Vth - \left(\sqrt{\frac{2Icn}{K}} + Vth\right) = \sqrt{\frac{2Icn}{K}} + Vth - \left(\sqrt{\frac{2In2}{K}} + Vth\right)$$

$$V1 - V2 = VGS2 - VGS4 = VGS1 - VGS3$$

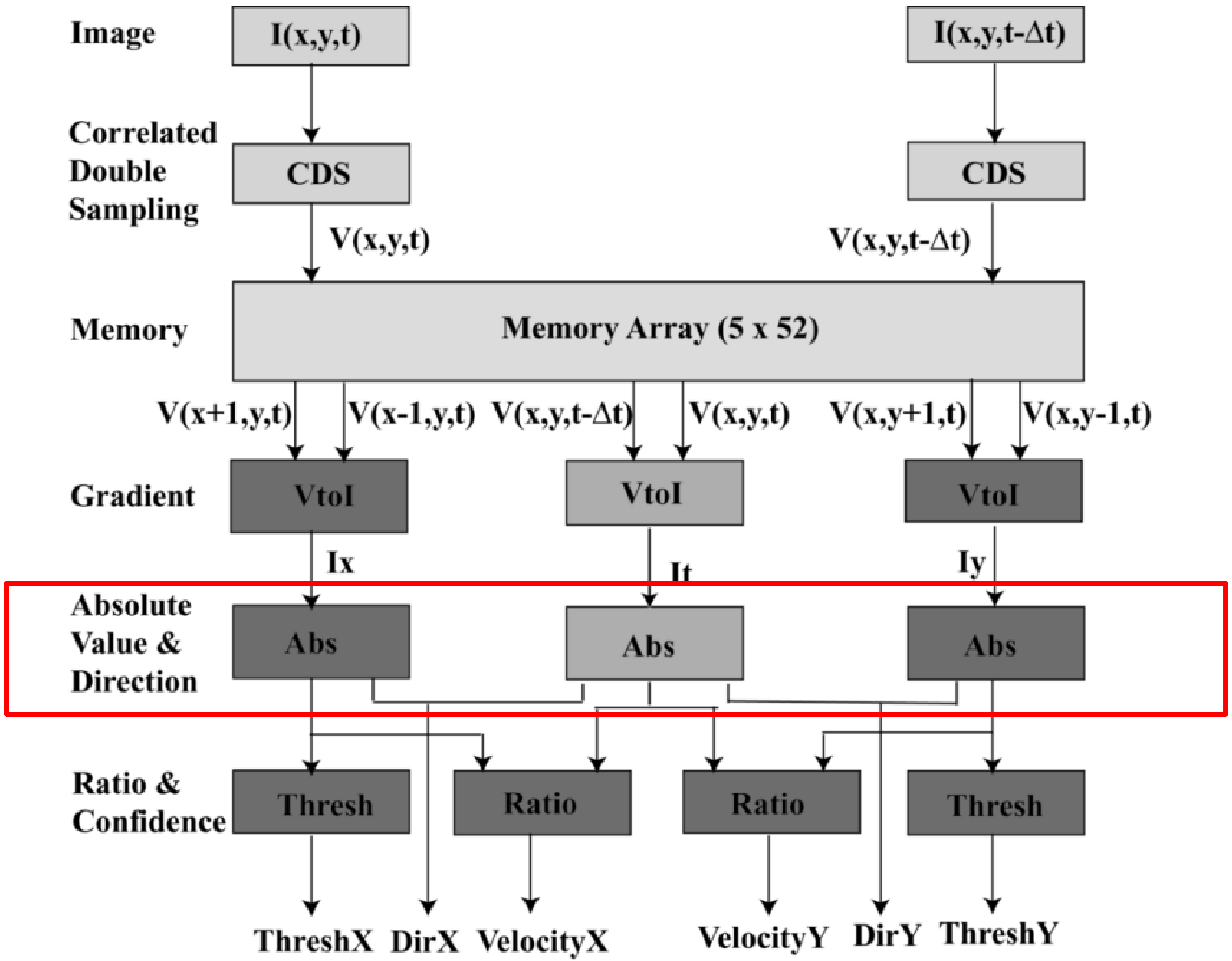
$$= \sqrt{\frac{2In1}{K}} + Vth - \left(\sqrt{\frac{2Icn}{K}} + Vth\right) = \sqrt{\frac{2Icn}{K}} + Vth - \left(\sqrt{\frac{2In2}{K}} + Vth\right)$$

$$\begin{cases} V1 - V2 = \sqrt{\frac{2In1}{K}} - \sqrt{\frac{2Icn}{K}} \\ V1 - V2 = \sqrt{\frac{2Icn}{K}} - \sqrt{\frac{2In2}{K}} \end{cases} \rightarrow \quad (V1 - V2)\sqrt{8KIcn} = (In1 - In2)$$


n module
VDD
mirror
mirror
Icn
In2
mirror
In2
In1
In1
mirror
V1
In2
In1
V2
In2
In1
GND
(In1-Ip2)+(Ip2) =
MAX(In1,Ip2) = In1
mirror
Iout ➔ Iout = In1-In2
MAX(In2,Ip1)
max(In2,Ip1)
max(In1,Ip2)
In1
VDD
(In1-Ip2)+(Ip2)
In1-Ip2
Ip1
Ip2
mirror
mirror
Ip2
Ip2
In1-Ip2
mirror
(When In1>Ip2)
Icp
max current
selecting circuit
p module
GND
max current
selecting circuit



SiSAL
Signal Sensing and Application Lab
n module
VDD
mirror
mirror
Icn
In2
mirror
In2
In1
In1
mirror
V1
In2
In1
V2
In2
In1
GND
In1
max(In2,Ip1)
max(In1,Ip2)
(Ip2)
VDD
0
Ip1
Ip2
mirror
0
mirror
Icp
mirror
Ip2
Ip2
mirror
max current
selecting circuit
p module
GND
max current
selecting circuit
mirror
(Ip2) = MAX(In1,Ip2)
Iout
→Iout = Ip2-Ip1
MAX(In2,Ip1)
(When In1<Ip2)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I(x,y,t-Δt)
Correlated Double Sampling
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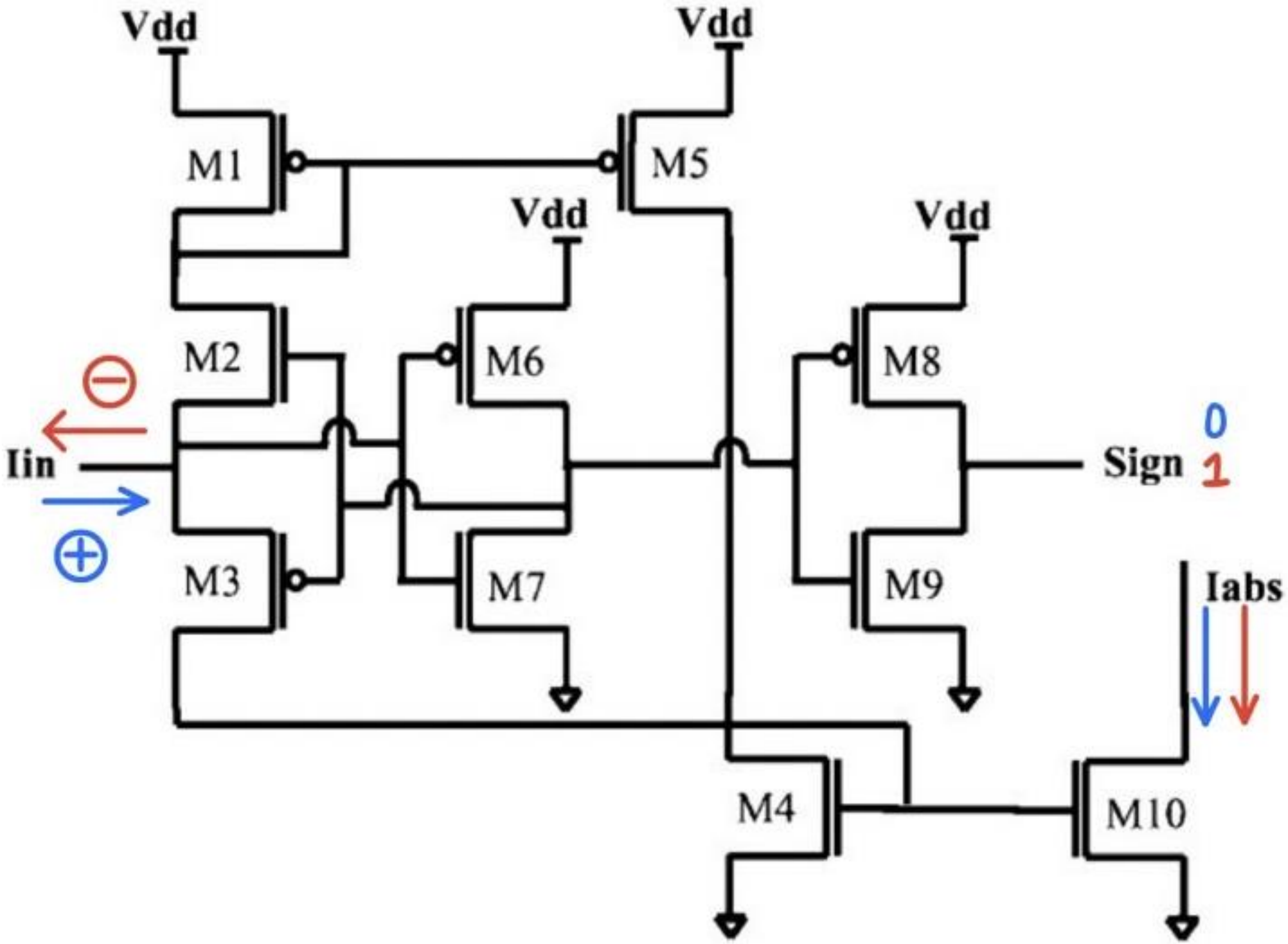
V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
Gradient
VtoI
VtoI
VtoI
Ix
It
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

Absolute Value Circuits



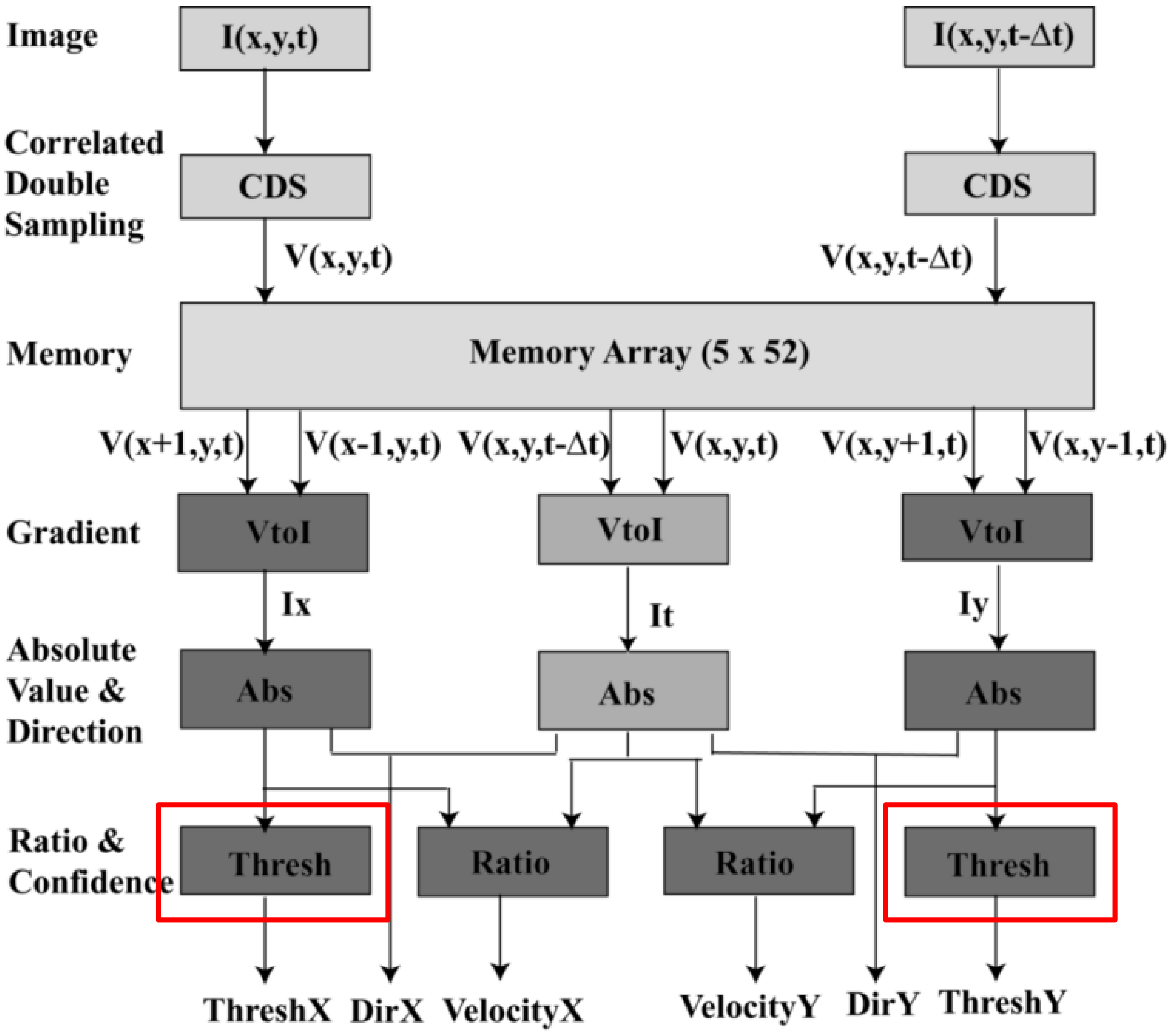


Image
I(x,y,t)
I(x,y,t-Δt)
Correlated Double Sampling
CDS
CDS
V(x,y,t)
V(x,y,t-Δt)
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Memory Array (5 x 52)
V(x+1,y,t)
V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
Gradient
VtoI
VtoI
VtoI
Ix
It
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

Threshold Circuits

- This step is useful in eliminating erroneous measurements in low contrast scenes.

$$
\begin{aligned}
V_{nx}^{\text{est}} &= V_{nx} \text{ if } I_x > I_{\text{thresh}} \\
&= 0 \text{ if } I_x \leq I_{\text{thresh}} \\
V_{ny}^{\text{est}} &= V_{ny} \text{ if } I_y > I_{\text{thresh}} \\
&= 0 \text{ if } I_y \leq I_{\text{thresh}}.
\end{aligned}
$$

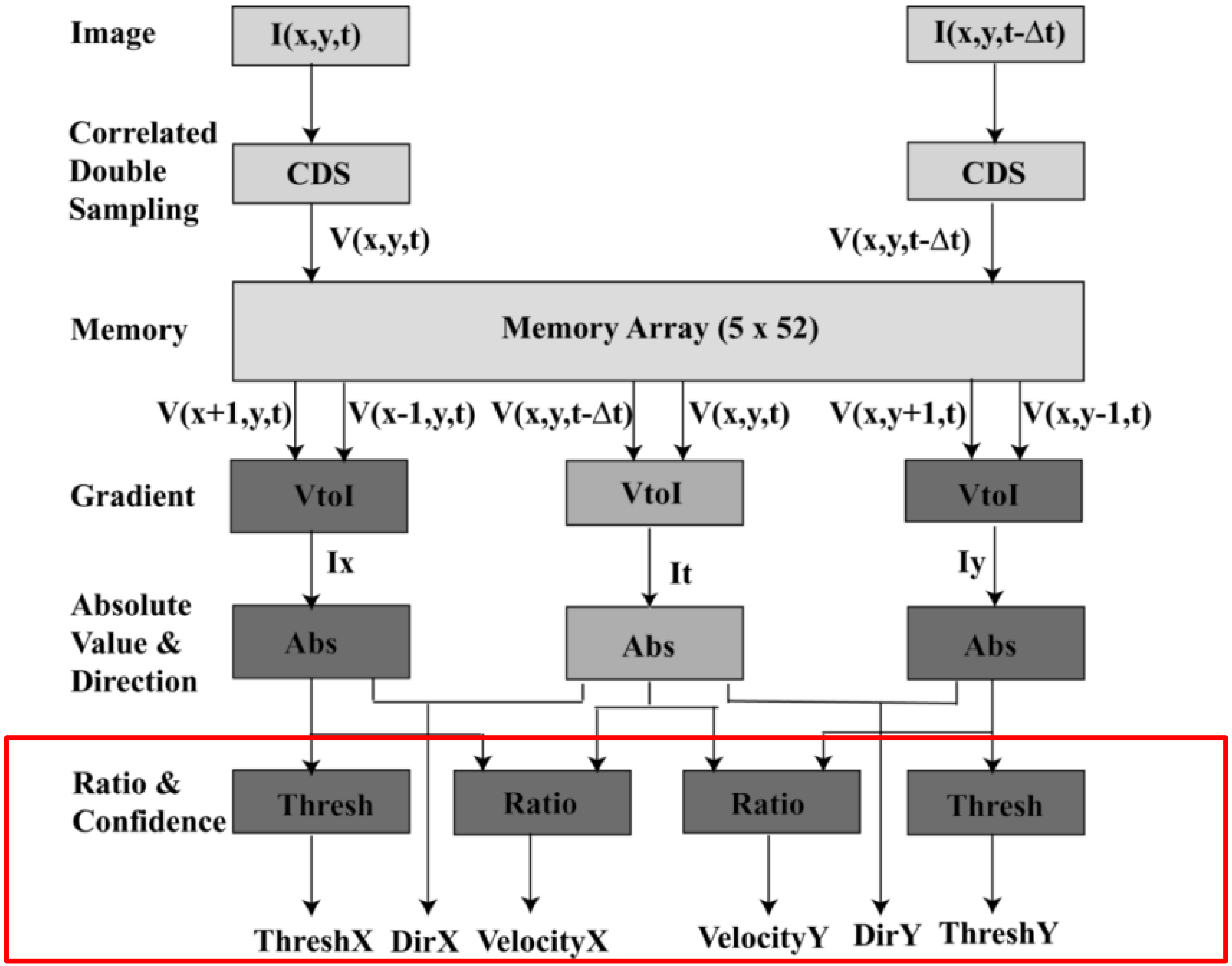

Image
I(x,y,t)
I(x,y,t-Δt)
Correlated Double Sampling
CDS
CDS
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V(x,y,t-Δt)
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V(x-1,y,t)
V(x,y,t-Δt)
V(x,y,t)
V(x,y+1,t)
V(x,y-1,t)
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VtoI
VtoI
Ix
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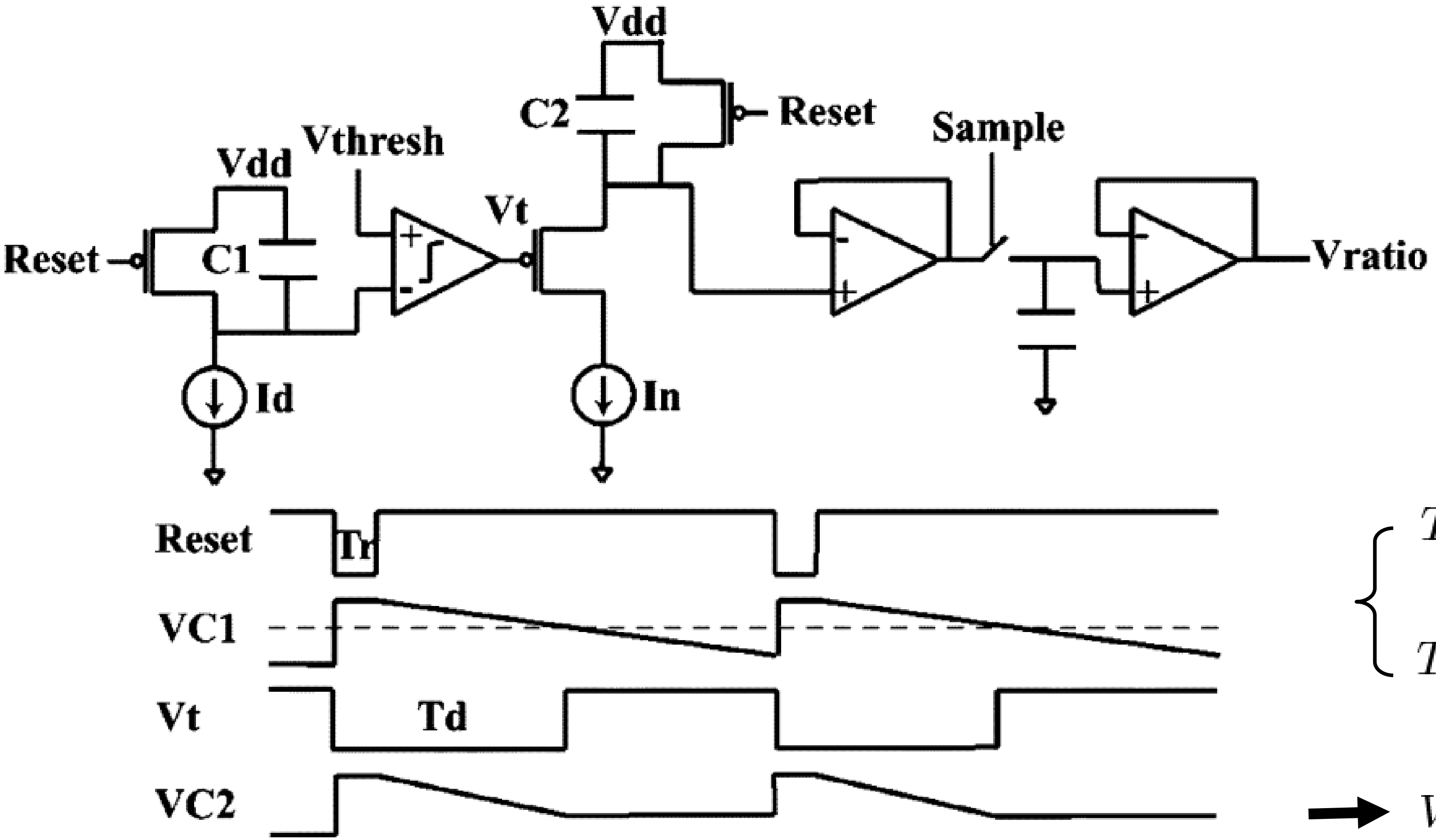
Iy
Absolute Value & Direction
Abs
Abs
Abs
Ratio & Confidence
Thresh
Ratio
Ratio
Thresh
ThreshX
DirX
VelocityX
VelocityY
DirY
ThreshY

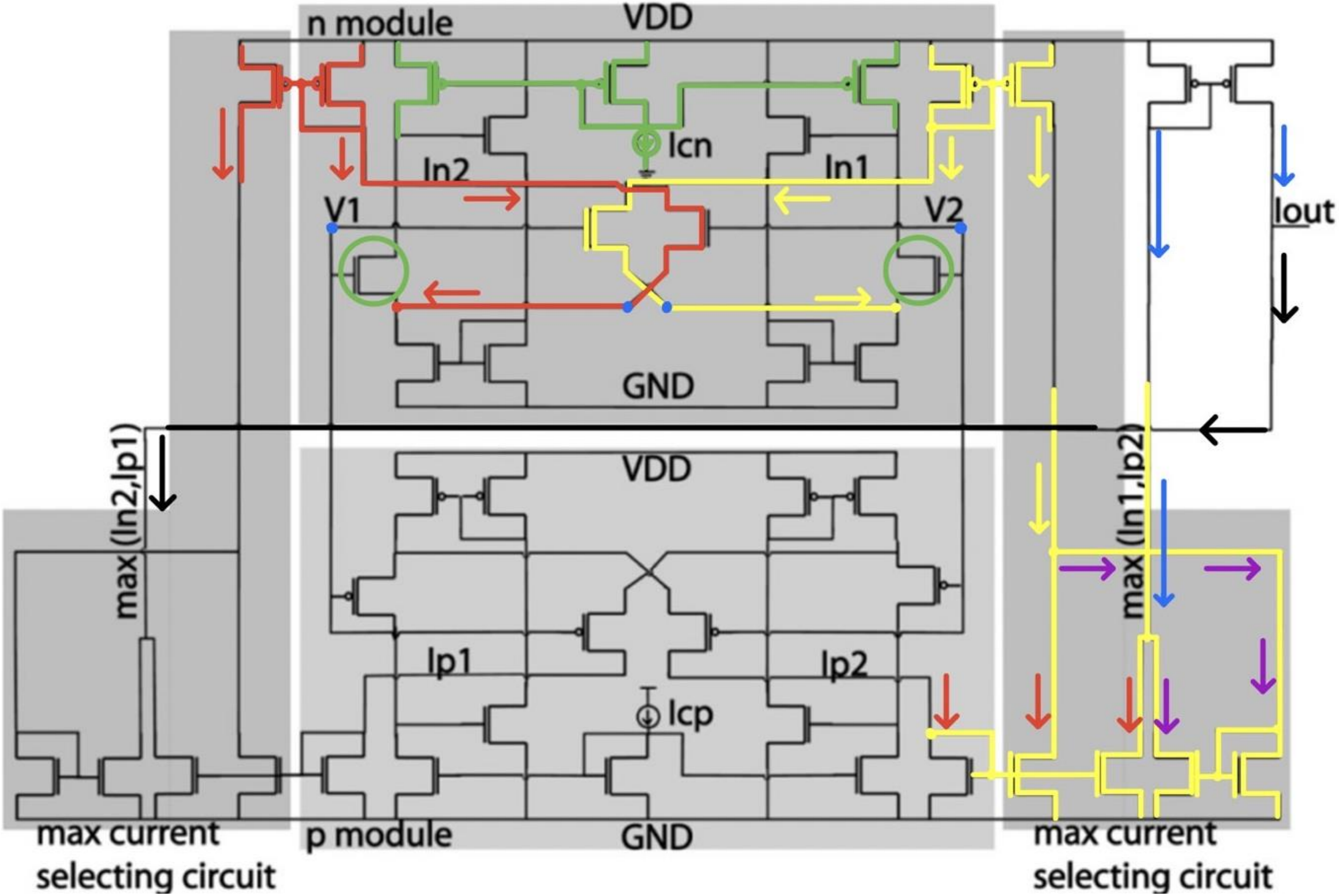
Ratio Circuits



$$\begin{cases} T_d - T_r = \dfrac{C_1(V_{dd} - V_{\text{thresh}})}{I_d}. \\ T_d - T_r = \dfrac{C_2(V_{dd} - V_{C2})}{I_n}. \end{cases}$$

$$\rightarrow V_{dd} - V_{C2} = \frac{C_1}{C_2}(V_{dd} - V_{\text{thresh}})\frac{I_n}{I_d} = k\frac{I_n}{I_d}.$$

Results — Block result



$-V_2).$

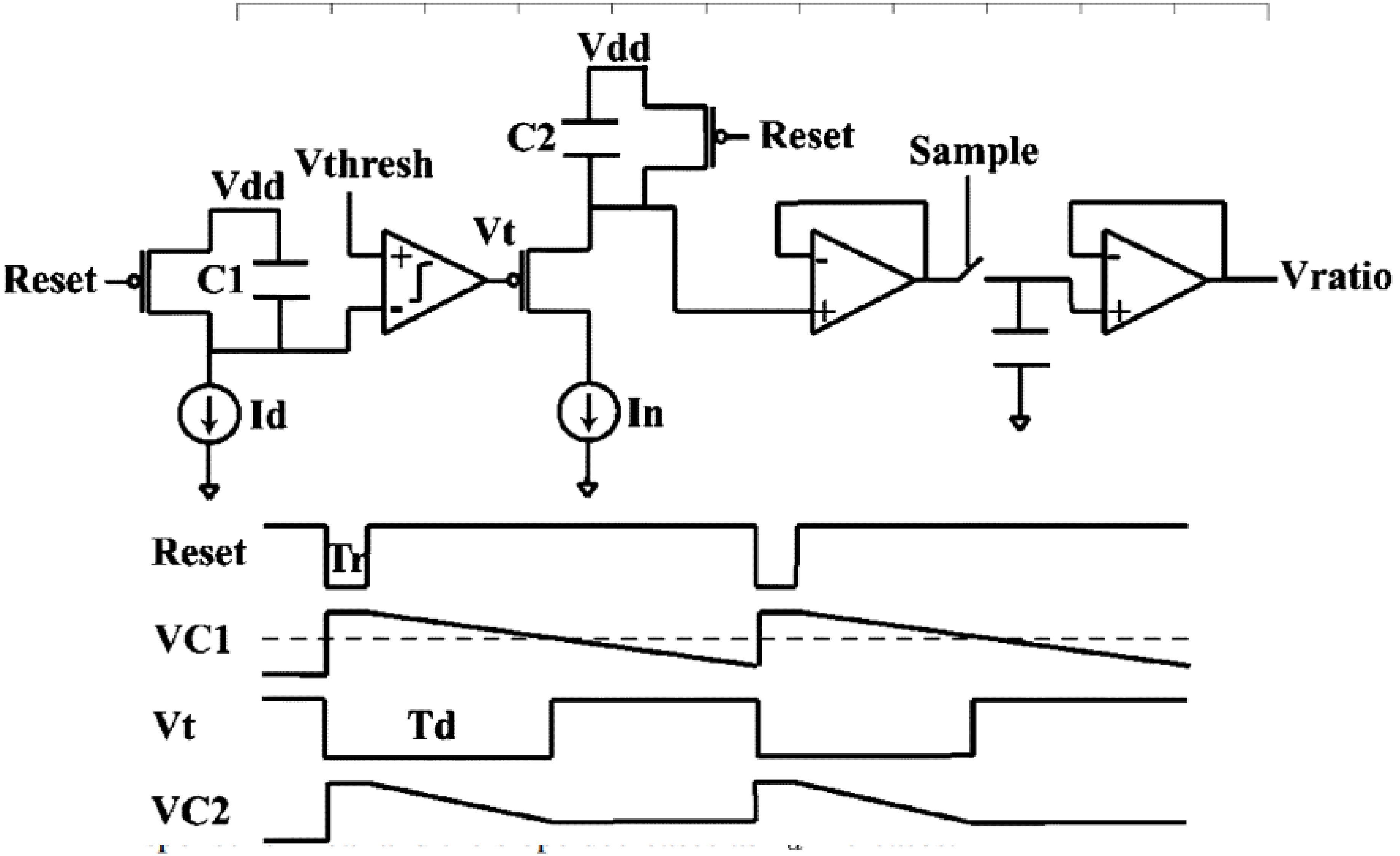
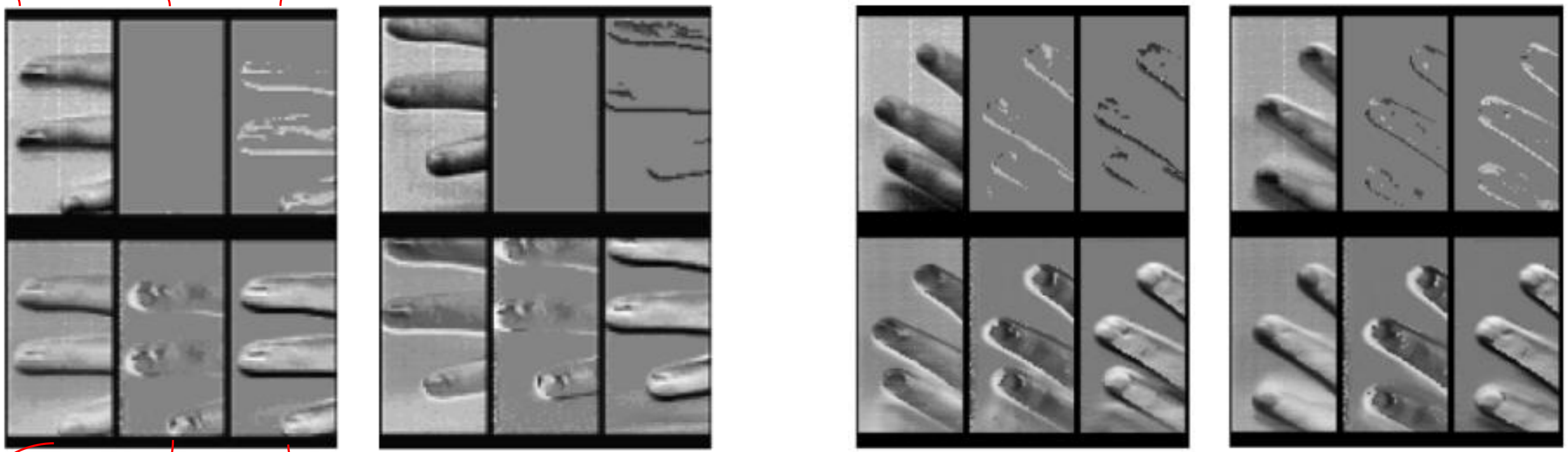

Vdd
C2
Reset
Sample
Vdd
Vthresh
Vt
Reset
C1
Vratio
Id
In
Reset
Tr
VC1
Vt
Td
VC2

image velocity_X velocity_Y



gradient_T gradient_X gradient_Y

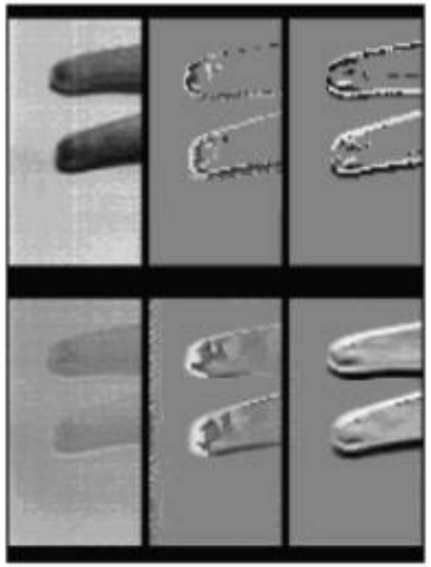
(a) (b) (c) (d)

upward motion

downward motion

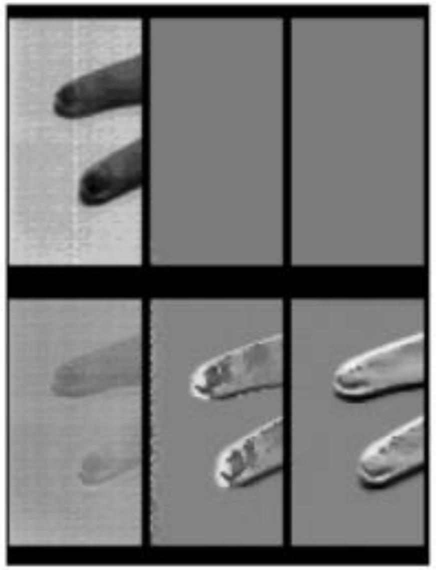
Diagonal motion towards bottom left

Diagonal motion towards top right



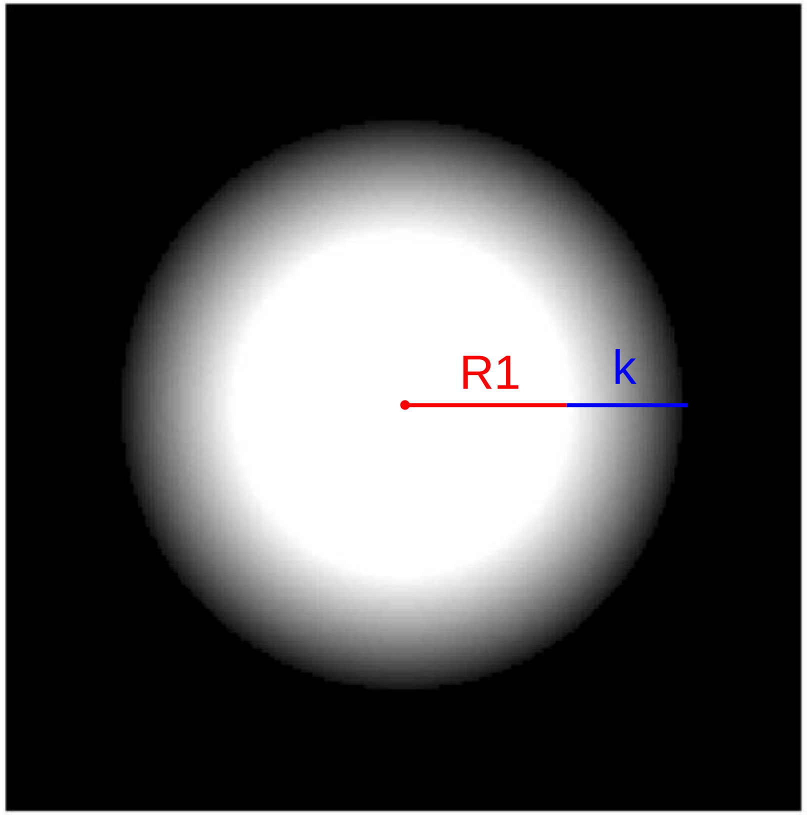
(e)

Output for no motion and no threshold on temporal derivative



(f)

Output for no motion but threshold on temporal derivative



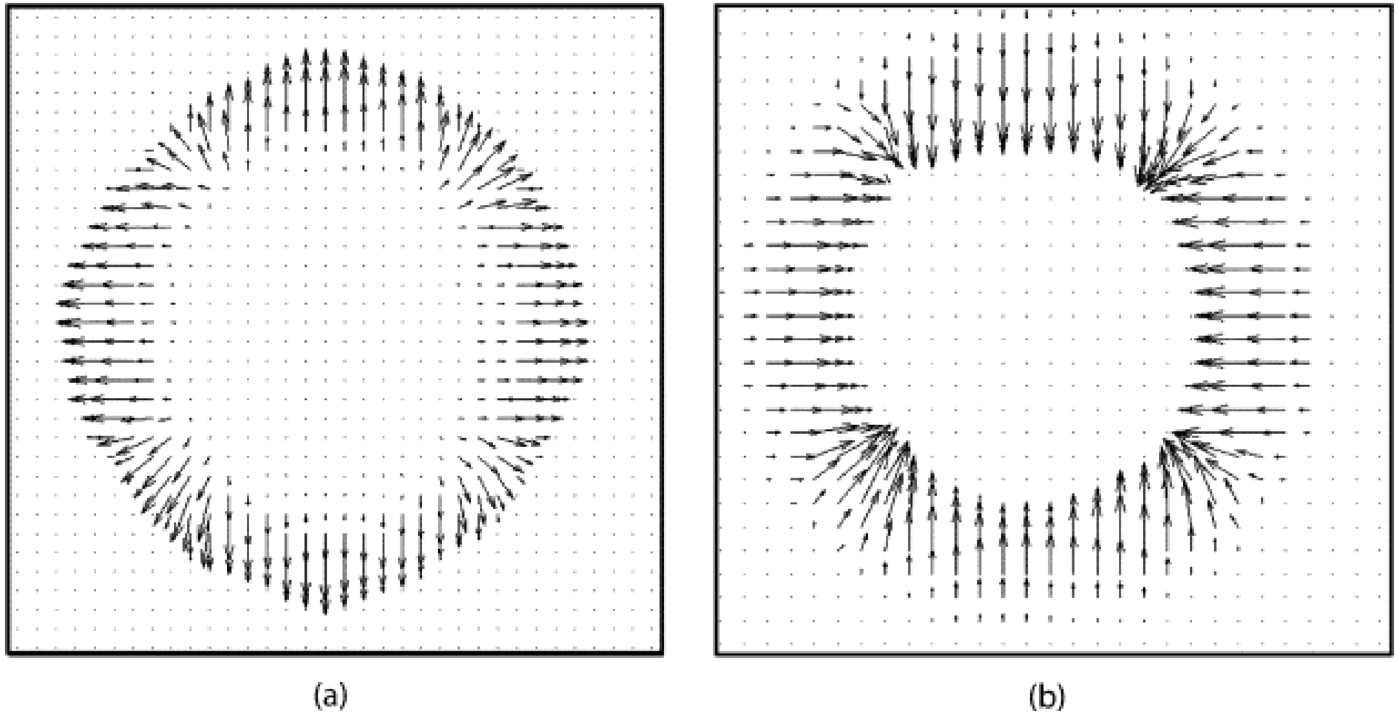


Fig. 15. Velocity measurements for different directions at the same speed. (a) Diverging movement i.e., $R_2 > R_1$. (b) Converging movement i.e., $R_2 < R_1$.

Quantitative Evaluation of Chip Performance Against Matlab Computations

$$\mu_{\text{err}} = \frac{\frac{1}{N}\sum_N \text{abs}\left(\frac{\partial I}{\partial x}\Big|_{\text{Matlab}} - \frac{\partial I}{\partial x}\Big|_{\text{chip}}\right)}{\frac{1}{N}\sum_N \text{abs}\left(\frac{\partial I}{\partial x}\Big|_{\text{Matlab}}\right)}$$

$$\sigma_{\text{err}} = \frac{\sqrt{\frac{1}{N}\sum_N \left(\frac{\partial I}{\partial x}\Big|_{\text{Matlab}} - \frac{\partial I}{\partial x}\Big|_{\text{chip}} - \mu_E\right)^2}}{\frac{1}{N}\sum_N \text{abs}\left(\frac{\partial I}{\partial x}\Big|_{\text{Matlab}}\right)}.$$

- The normalized average error measure for gradient computation on our chip was found to be 3.0% while the standard deviation was calculated to be 3.8%.

- Examine the effects of the assumptions we made in our normal flow calculation to simplify the implementation by comparing the measurements obtained from the chip versus the exact normal flow calculations.

$$full\,normal\,flow:\ V_n = \left(\frac{I_t I_x}{I_x^2+I_y^2}, \frac{I_t I_y}{I_x^2+I_y^2}\right) = \left(V_{nx}, V_{ny}\right)$$

$$simplified\,normal\,flow:\ V_n = \left(V_{nx}, V_{ny}\right) = \left(\frac{I_t}{I_x}, \frac{I_t}{I_y}\right)$$

- Use the angular measure of error where the error between the true velocity V_t and the estimated velocity V_e is given by

$$\psi_E = \arccos(\vec{V_t}^T \cdot \vec{V_e})$$

($\overrightarrow{V_{t1}}$ is the high precision division of gradients in Matlab to implement the simplified normal flow.)
($\overrightarrow{V_{t2}}$ is the velocity obtained by computing the full normal flow equations in Matlab.)

- comparing against $\overrightarrow{V_{t1}}$ the average error measure obtained is $0.56°$ with a standard deviation of 1.91
- comparing against $\overrightarrow{V_{t2}}$, the average error measure obtained is $0.87°$ with a standard deviation of 3.39.

TABLE I
SUMMARY OF CHIP'S PERFORMANCE

Technology	0.5 μm CMOS Process
Array Size	92x52
Pixel Size	20.3μm x 20.3μm
Fill-factor	10%
Chip Size	3mm x 1.5mm
Power Consumption	2.6mW. (V_{dd} = 5V)
Frame-rate	30fps
FPN (Std. Dev/Full-scale)	0.92% for present frame 1.01% for previous frame

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Thank you !

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