Design of a high-dynamic range CMOS active pixel sensor with adjustable response

Raphael Cherney

Problem


HYATT

Process

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 19, NO. 15, AUGUST 1, 2007 1169

A High-Dynamic-Range Integrating Pixel With an Adaptive Logarithmic Response

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***Abstract*—A majority of charge-coupled device and complementary metal–oxide–semiconductor imaging sensors obtain a linear response by integrating the photocurrent in the pixel. This is a simple transduction method; however, the dynamic range of the resulting pixels is smaller than that of many scenes. A biologically inspired approach to solving this problem is to create a pixel with a logarithmic response. A new design for an integrating pixel with a logarithmic response is presented in this letter. The theory of operation of the pixel is described before results are reported that show that the pixel has an adaptive response and a dynamic range of more than 120 dB.**

***Index Terms*—Adaptive logarithmic pixel, complementary metal–oxide–semiconductor (CMOS) image sensor, logarithmic pixel.**

I. Introduction

NATURALLY illuminated scenes may simultaneously contain areas of bright sunlight and shadows with the result that the intrascene dynamic range can be as large as 100 dB. This dynamic range is larger than the dynamic range of the majority of existing digital imaging sensors with the result that saturation can occur in images of this type of scene. Most imaging sensors convert the input photon flux to a voltage by integrating a photogenerated current onto a capacitor for a known integration time. The resulting linear response makes it very difficult to capture high-dynamic-range images while preserving all the observable details in the scene.

Several techniques have been proposed to increase the input dynamic range of complementary metal–oxide–semiconductor (CMOS) pixels [1]. Some of these techniques are based upon using multiple integration times to capture an image [2]–[4]. Although these techniques achieve a high dynamic range, the response of these imagers is piece-wise linear and a large number of bits are required to capture all the visible details within a high-dynamic-range scene. The processing needed to form a displayable image from this data simply adds to the complexity, power consumption, and cost of the final system.

An approach to avoiding the problems that arise with "linear" pixels that is inspired by biological systems is to design pixels with a logarithmic response. Pixels with logarithmic responses, based upon using a metal–oxide–semiconductor field-effect transistor (MOSFET) load device operating in weak inversion, have been investigated by several groups [5]–[7]. This type of pixel has a high dynamic range and reduces the dynamic range of the output. However, these pixels also have a high level of fixed pattern noise and both a slow response and poor responsivity at low light levels.

The ideal pixel should combine the low-light performance of integrating pixels with a high input dynamic range and the lowest output dynamic range consistent with creating good quality images. Integrating pixels with a logarithmic response and a digital output have been described previously [8]–[10]. These pixels contain a digital memory within each pixel that increases the area, and hence cost, of each pixel.

In this letter, an alternative integrating pixel with a logarithmic response is described. Unlike the previous designs [8]–[10], this has an analogue output which avoids the need for a multibit memory within each pixel. The result is a pixel with fewer transistors, and hence smaller area when made on the same process. In Section II of this letter, the operation of the new integrating pixel with a logarithmic response is described. Then in Section III, results obtained from testing this type of pixel are presented which show that its response can be adapted by the user and that it can operate over a dynamic range of more than 120 dB.

II. Theory of Operation

To achieve low-light sensitivity in a pixel with a logarithmic response, consider a pixel in which a photocurrent I_{ph} is integrated onto a capacitance C. If the voltage on C is reset to V_{DD}, then after an integration time τ, it will be

$$V_C = V_{DD} - \frac{I_{ph}\tau}{C}.$$

If the integration time is a constant, the result is a pixel with a linear response. To compress the response of the pixel to obtain a high dynamic range, the integration time must become dependent upon the pixel photocurrent. In addition to maintaining low-light sensitivity, the pixel should integrate the smaller photocurrents for longer to minimize the effects of shot noise. This suggests that compression should be achieved by reducing the integration time at the larger photocurrents.

A pixel for which the integration time of the individual pixel can depend upon the pixel photocurrent is shown in Fig. 1. This pixel contains the usual photodiode, reset transistor, and source follower readout circuit. In addition there is a comparator whose output controls transistor M_{dis}. This device means that the gate of the source-follower can be disconnected from the photodiode. Since it is the voltage on the gate of the source-follower device that determines the output from the pixel, the effective integration time of the pixel is the time between when the reset transistor becomes an open-circuit and when the gate of the source-follower is disconnected from the photodiode.

Manuscript received March 8, 2007; revised April 24, 2007.
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Digital Object Identifier 10.1109/LPT.2007.901466

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A Wide Dynamic Range CMOS Image Sensor with an Adjustable Logarithmic Response

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ABSTRACT

A wide dynamic image CMOS image sensor with a user adjustable logarithmic photo-response is presented. A pMOS switch and a time-dependent reference voltage are integrated into a three-transistor (3T) pixel structure to implement a logarithmic response. Several pixels have been manufactured using a 0.25μm standard CMOS technology. Compared to the conventional logarithmic response pixel based on a diode-connected transistor, the proposed pixel combines a wide dynamic range of 120dB with much higher responsivity (250mV/decade) and better dark response.

Keywords : CMOS image sensor, wide dynamic range, logarithmic response, pMOS switch

1. INTRODUCTION

A wide dynamic range CMOS image sensor that can capture a scene containing both bright and dark areas is highly desirable for applications including automobile driver aids, security cameras and consumer products. Numerous approaches have been proposed to expand the dynamic range of CMOS image sensors. Most of these can be divided into one of three principal groups. The first group convert photocurrents into a time-to-saturation signal by integrating a comparator in each pixel [1-2]. However, this approach increases the pixel area with the result that these pixels are at a disadvantage when costs must be controlled or reduced whilst increasing pixel count. The second more evolutionary group samples the photocurrent several times within one or more integration periods and then synthesizes the wide dynamic range image [3-6]. The main disadvantage of these systems is the cost of the processing needed to synthesize the final image. The last group realizes a logarithmic compression of the input photocurrent to the output voltage using the current-voltage characteristics of MOSFETs working in weak inversion [7-10]. The small maximum output swing (typically 0.3V) and responsivity (50mV/decade) of these pixels make them vulnerable to both fixed pattern and temporal noise. Furthermore, although the continuous output available from these pixels can be an advantage in some applications, it means that these pixels are slow to respond to a sudden decrease in photocurrent.

The ideal pixel should combine the speed of response of an integrating pixel with the dynamic range compression of logarithmic pixels. This can be achieved using a comparator within each pixel to vary the effective integration time of the pixels so that the output voltage is proportional to the logarithm of the photocurrent [11]. However, the large pixel size and low fill factor resulting from the use of an in-pixel comparator makes it impractical for most applications. To overcome these problems a novel wide dynamic range CMOS pixel has been developed that is described for the first time in this paper.

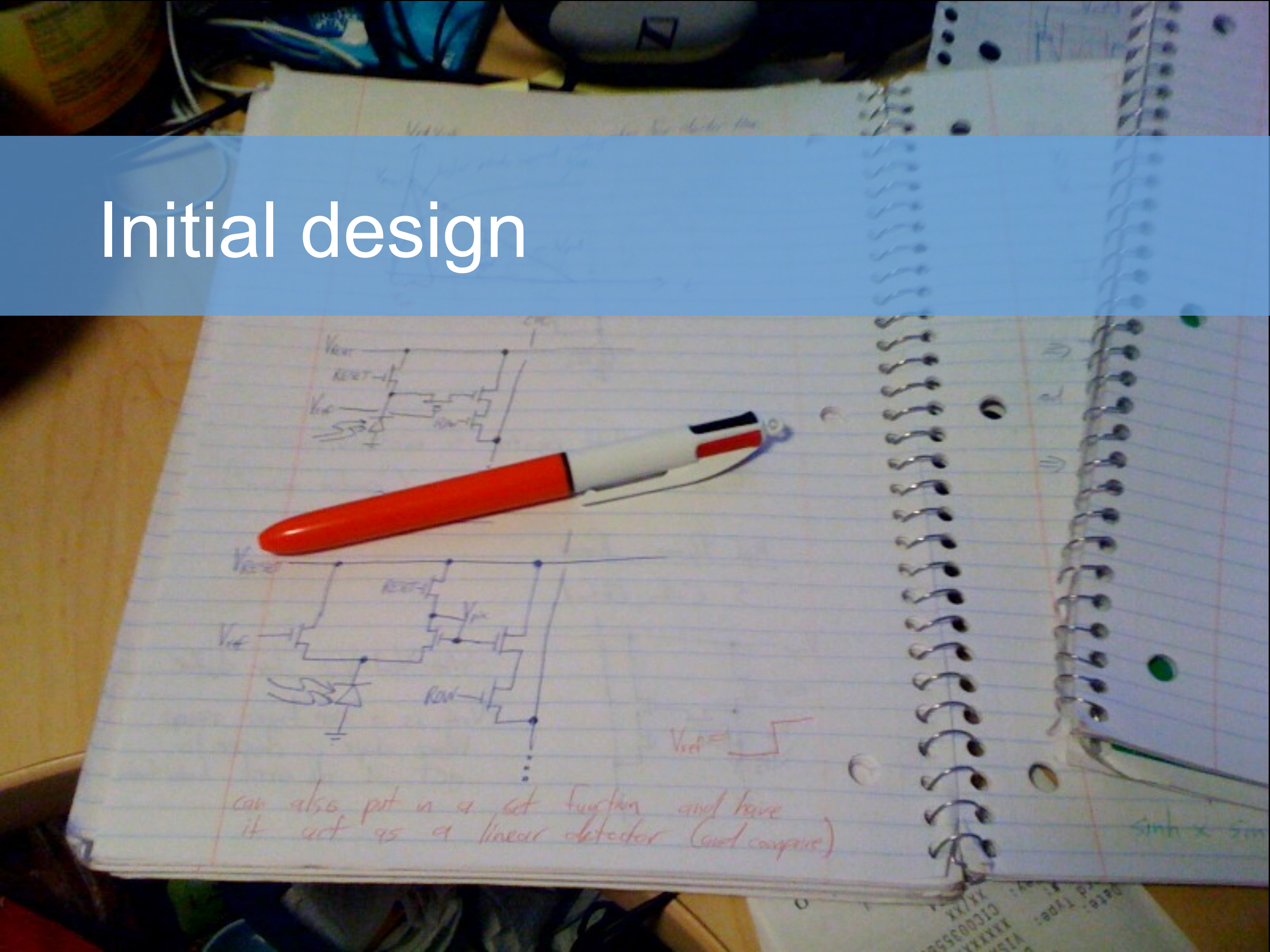
The rest of this paper is organized as follows. In section 2, the pixel and its operation are described. The design and characterization results of the prototype pixel are presented in section 3. In section 4, the measurement results of the low dark signal pixel is presented.

2. THE PIXEL

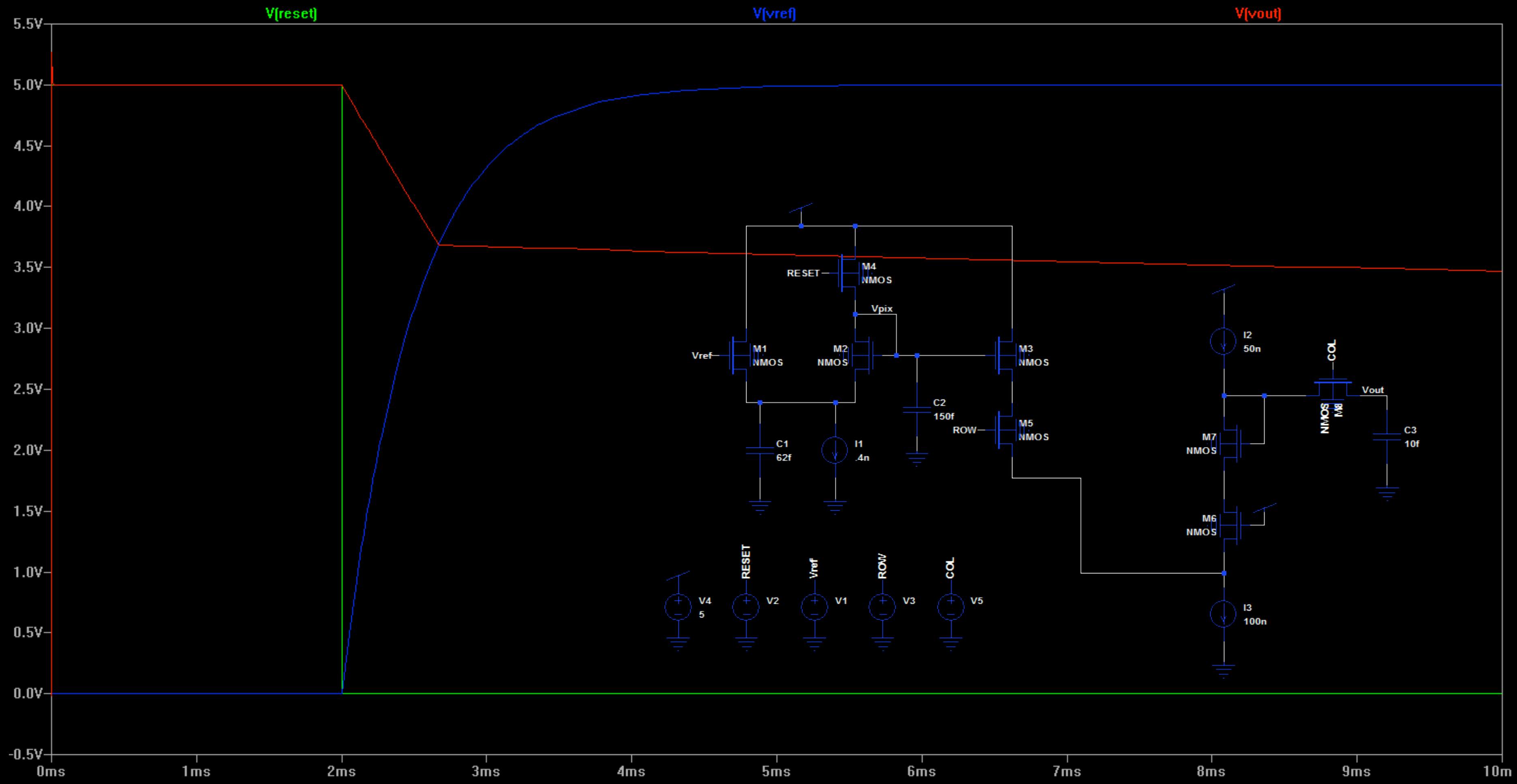
A schematic circuit diagram of the proposed wide dynamic range pixel is shown in Fig. 1. As in the conventional 3T active pixel, the process of forming an image starts when the voltage in the pixel, V_{diode}, is reset. To obtain an increased voltage swing a pMOS device, M_{p1}, is preferred as the reset transistor. This

Literature review

Initial design



Simulation



V(reset)
V(vref)
V(vout)
5.5V
5.0V
4.5V
4.0V
3.5V
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
-0.5V
0ms
1ms
2ms
3ms
4ms
5ms
6ms
7ms
8ms
9ms
10m
RESET
M4
NMOS
Vpix
Vref
M1
NMOS
M2
NMOS
M3
NMOS
C2
150f
ROW
M5
NMOS
C1
62f
I1
.4n
I2
50n
COL
Vout
M8
NMOS
M7
NMOS
C3
10f
M6
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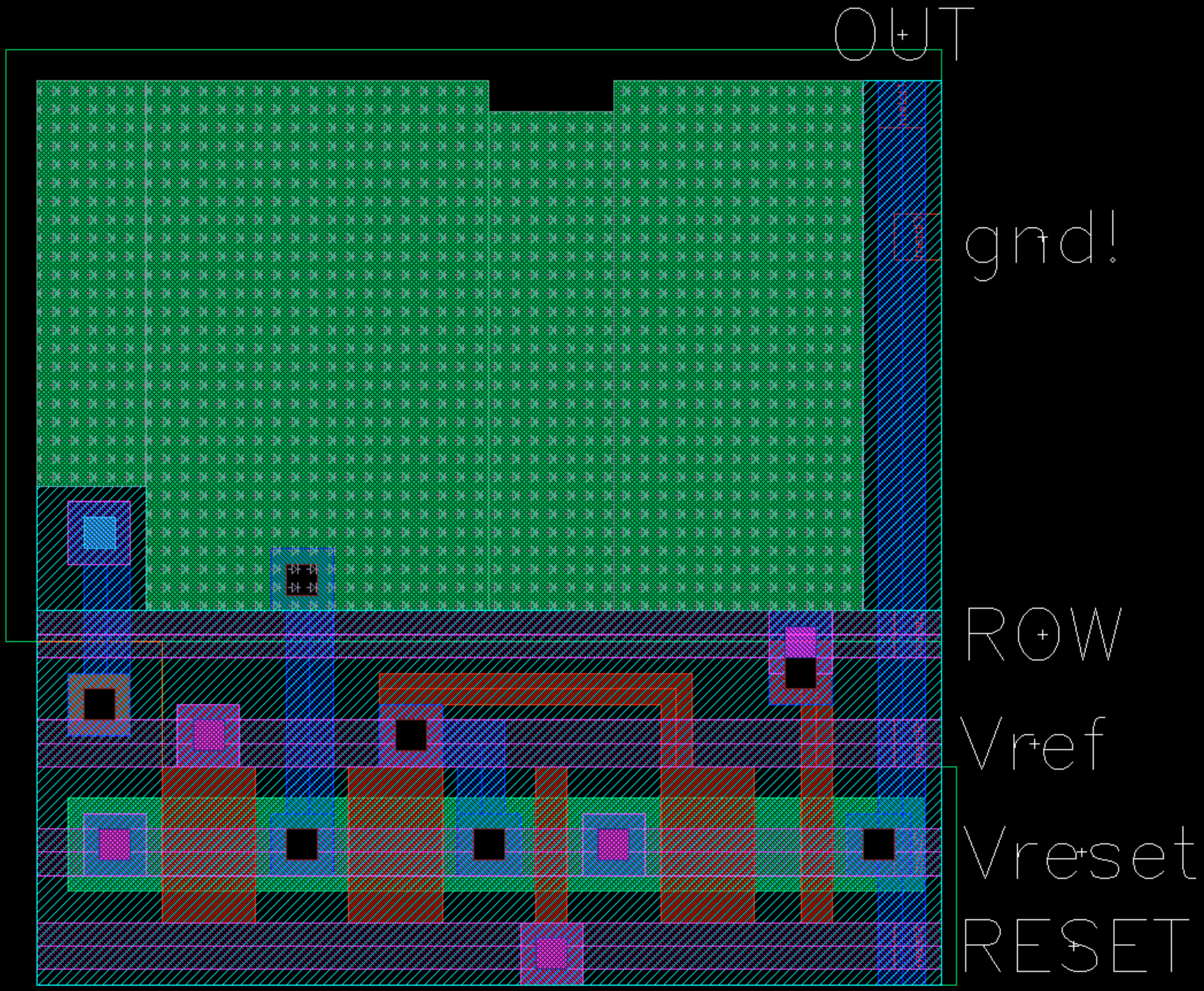
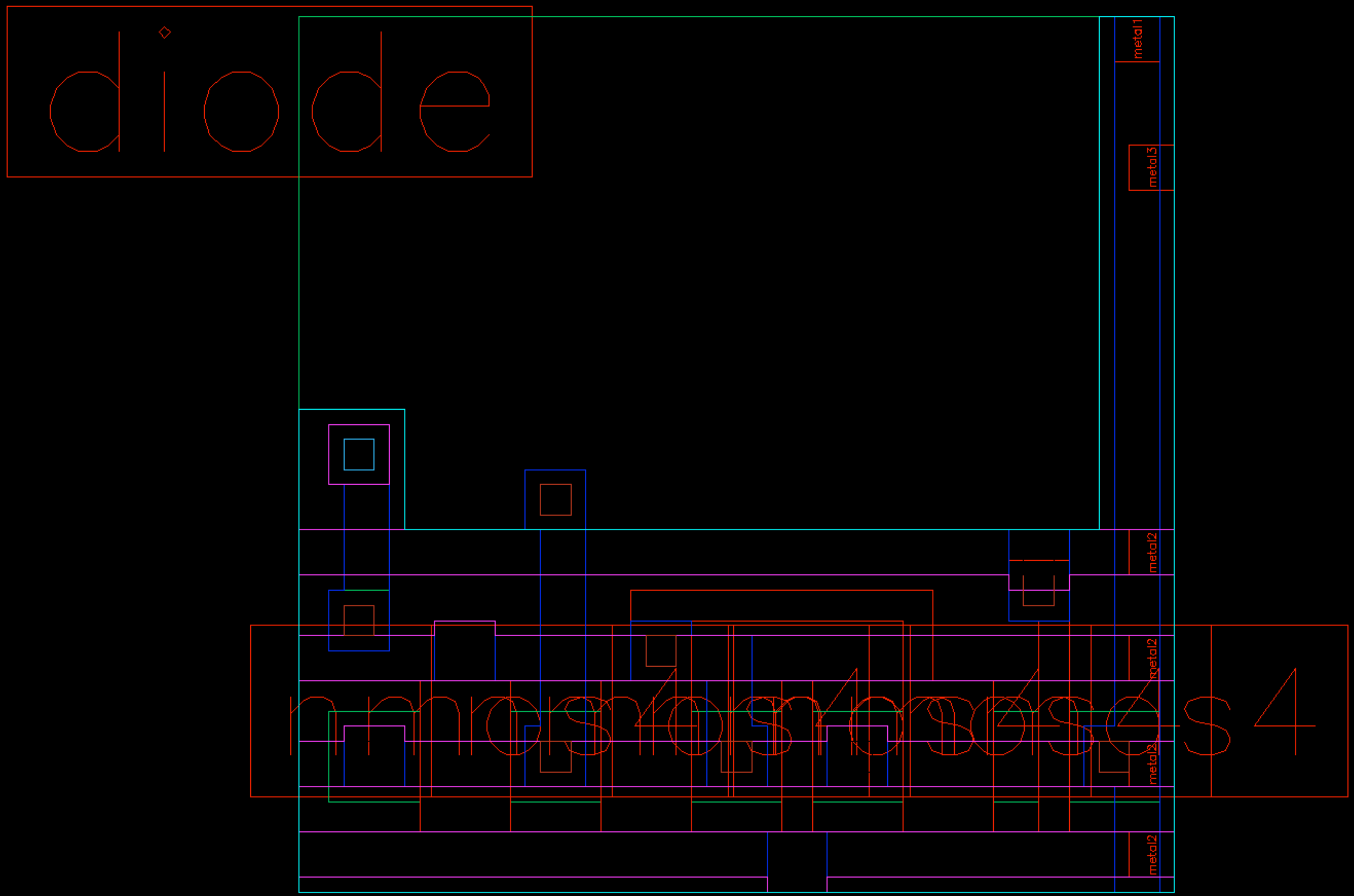
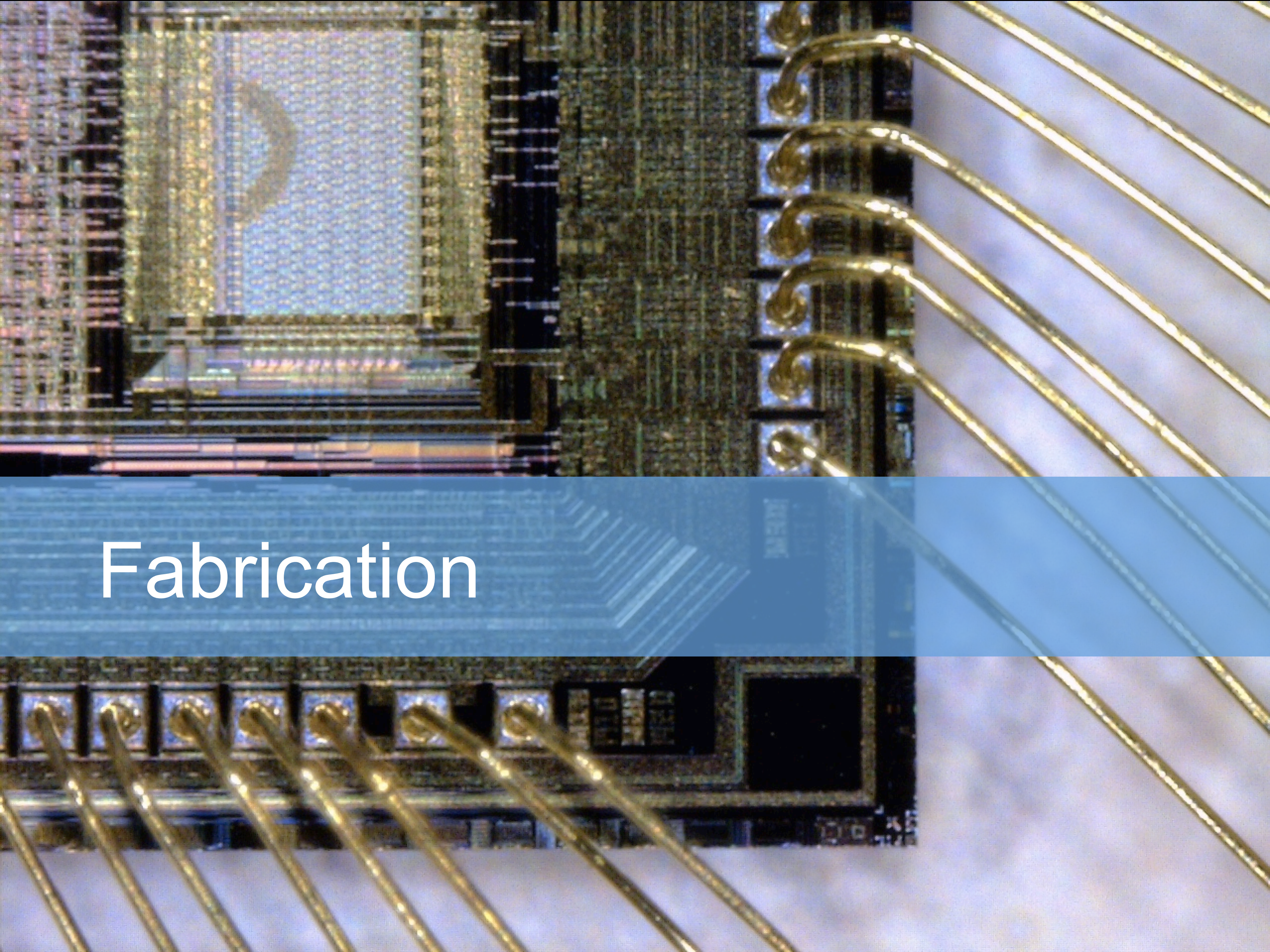
I3
100n
V4
5
RESET
V2
Vref
V1
ROW
V3
COL
V5

Layout

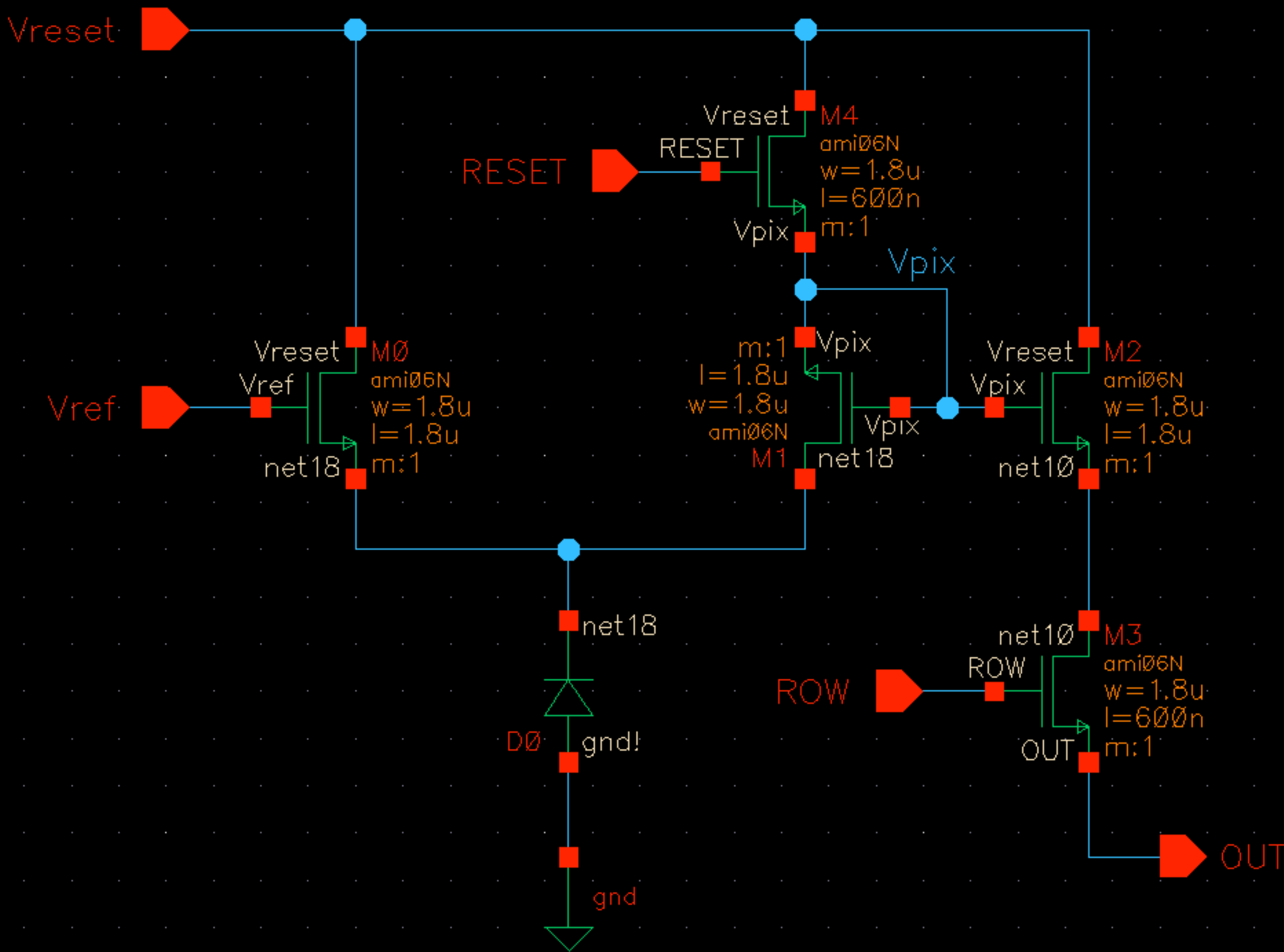


Verification

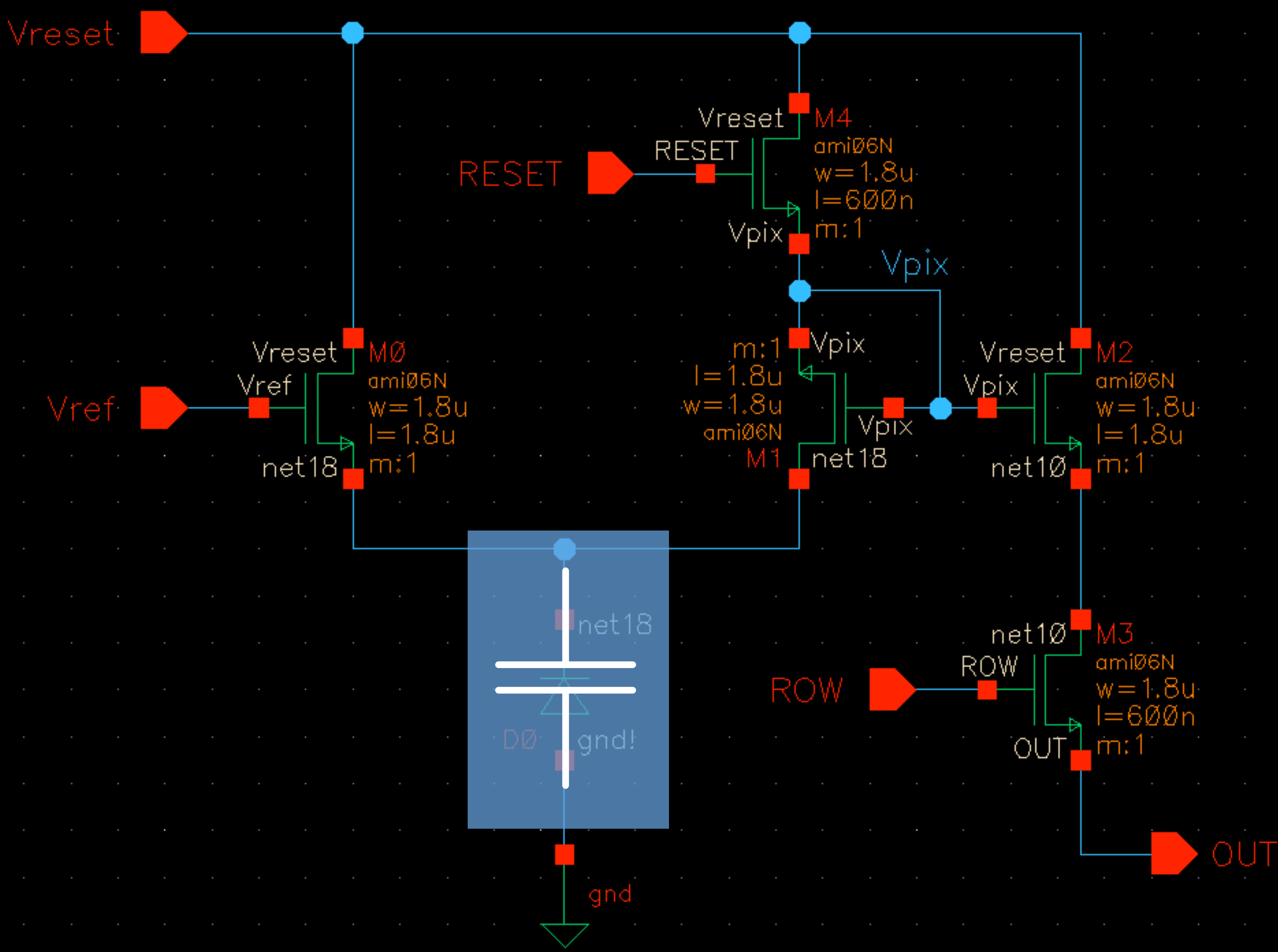


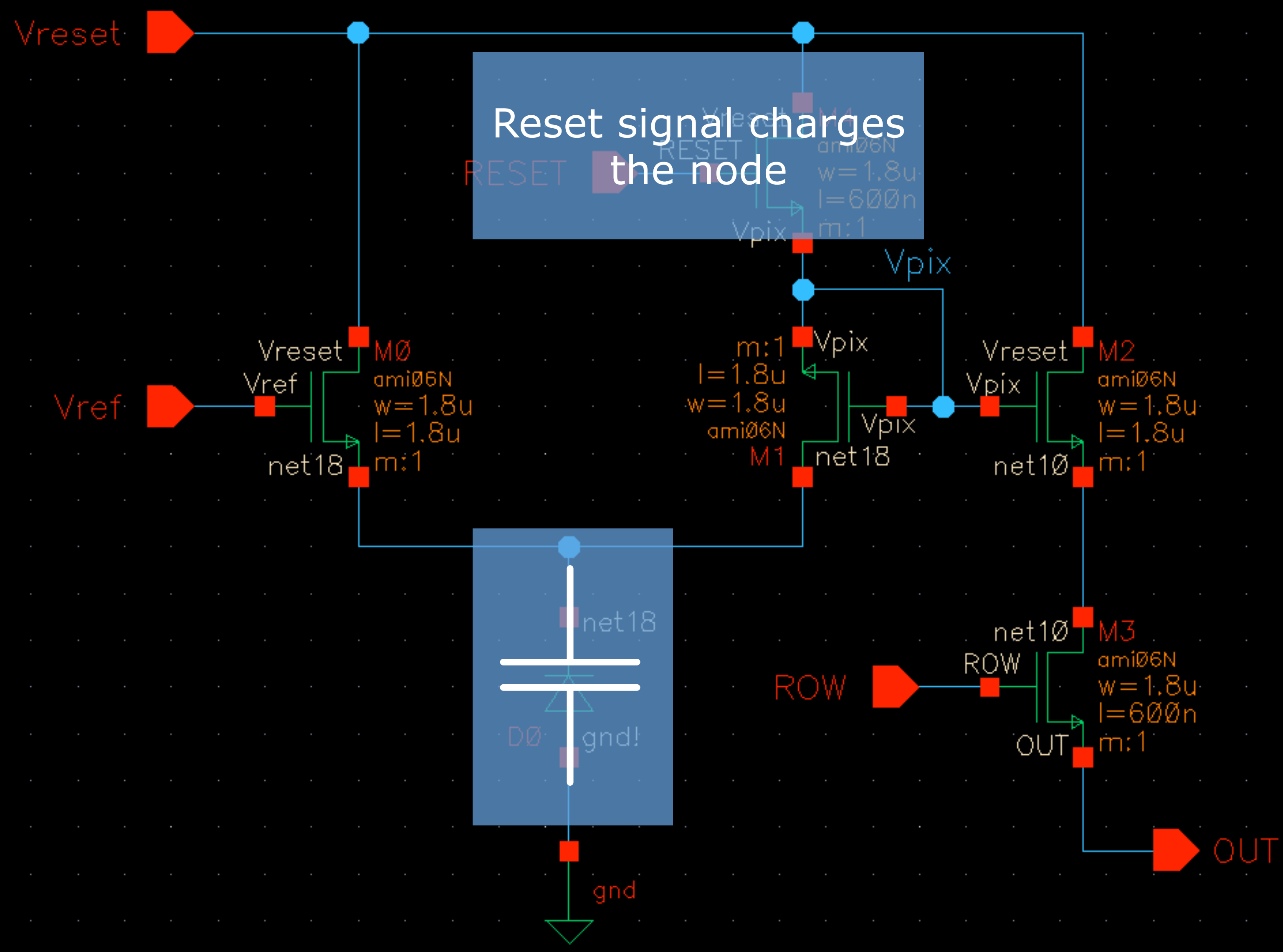

Fabrication

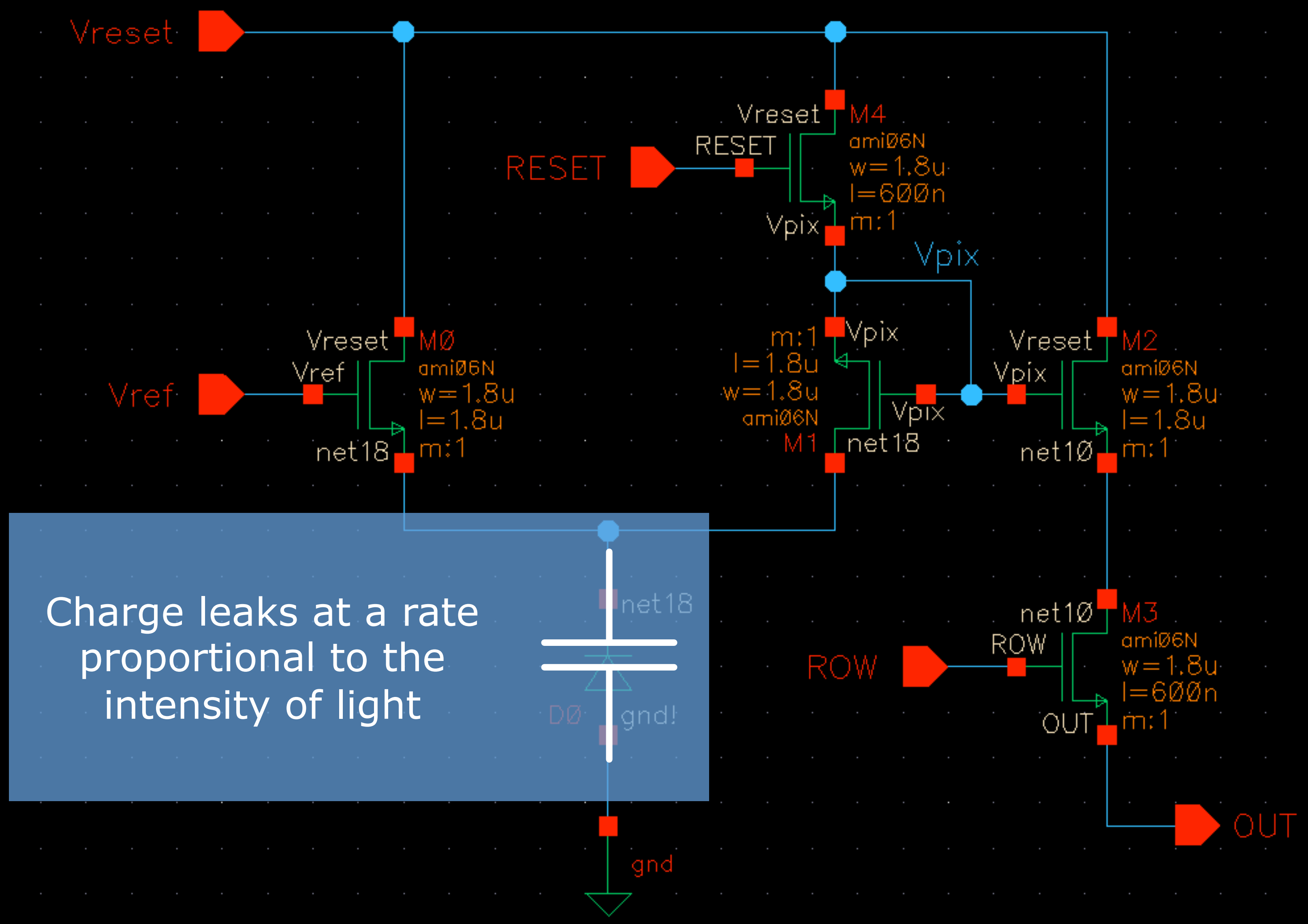
Design

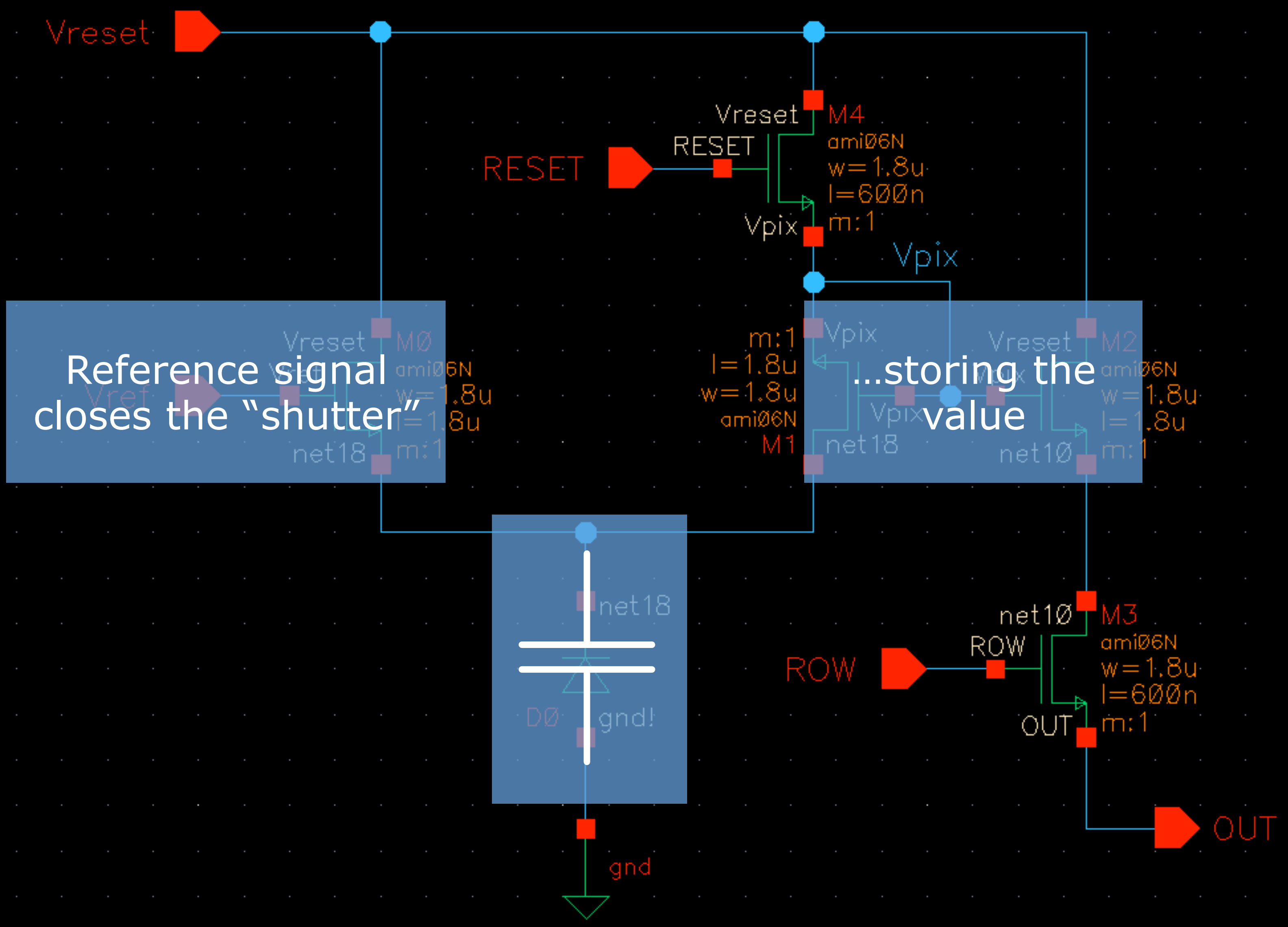


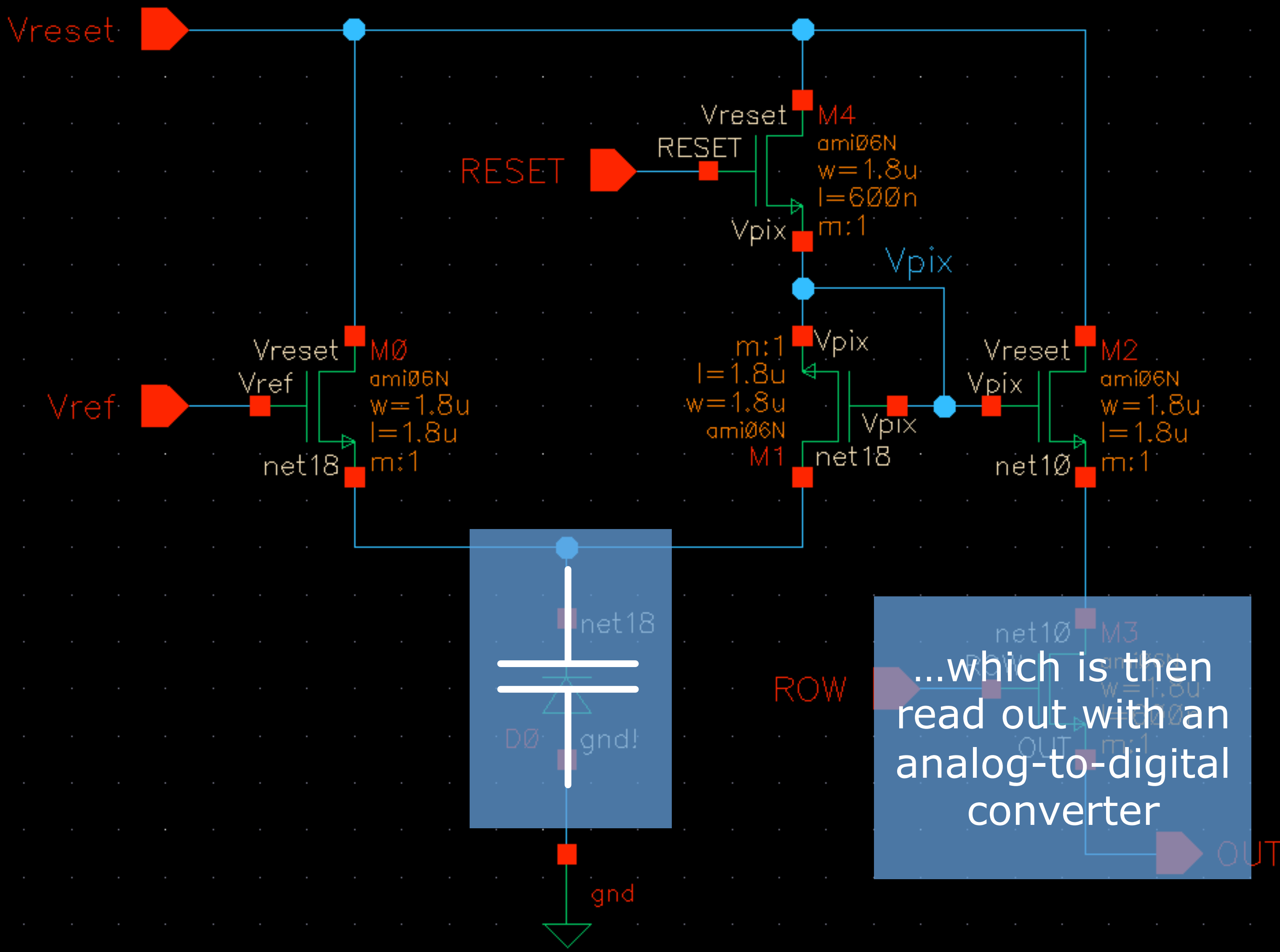
Vreset
RESET
Vreset
M4
RESET
ami06N
w=1.8u
l=600n
Vpix
m:1
Vpix
Vreset
M0
Vref
ami06N
Vref
w=1.8u
l=1.8u
net18
m:1
m:1
Vpix
l=1.8u
w=1.8u
ami06N
M1
Vpix
net18
Vreset
M2
Vpix
ami06N
w=1.8u
l=1.8u
net10
m:1
net18
D0
gnd!
gnd
net10
M3
ami06N
ROW
ROW
w=1.8u
l=600n
OUT
m:1
OUT

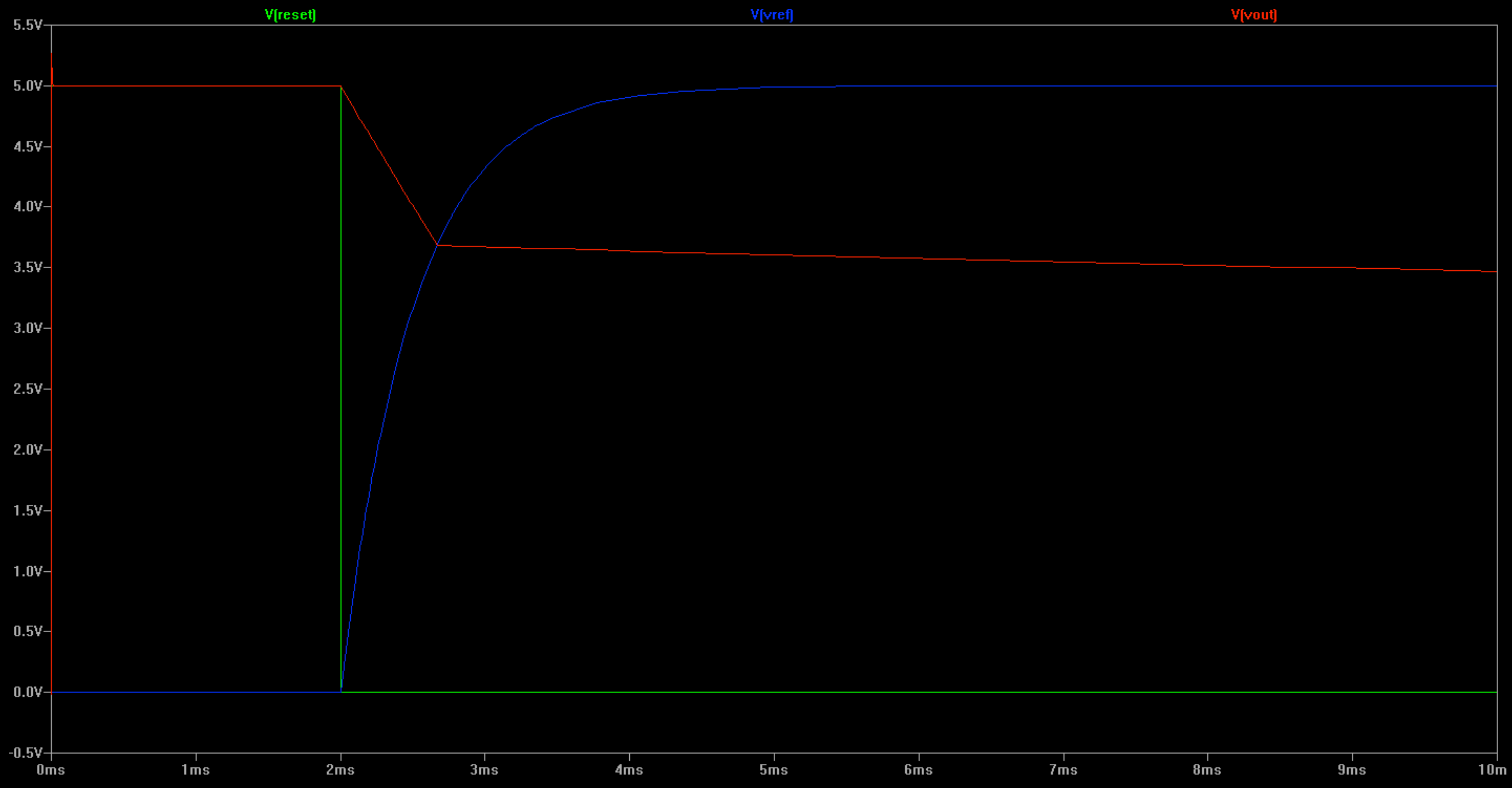

Vreset
RESET
Vref
ROW
OUT
Vpix
Vreset
RESET
Vpix
M4
ami06N
w=1.8u
l=600n
m:1
Vreset
Vref
net18
M0
ami06N
w=1.8u
l=1.8u
m:1
Vpix
m:1
l=1.8u
w=1.8u
ami06N
M1
Vpix
net18
Vreset
Vpix
net10
M2
ami06N
w=1.8u
l=1.8u
m:1
net18
D0
gnd!
gnd
net10
ROW
OUT
M3
ami06N
w=1.8u
l=600n
m:1

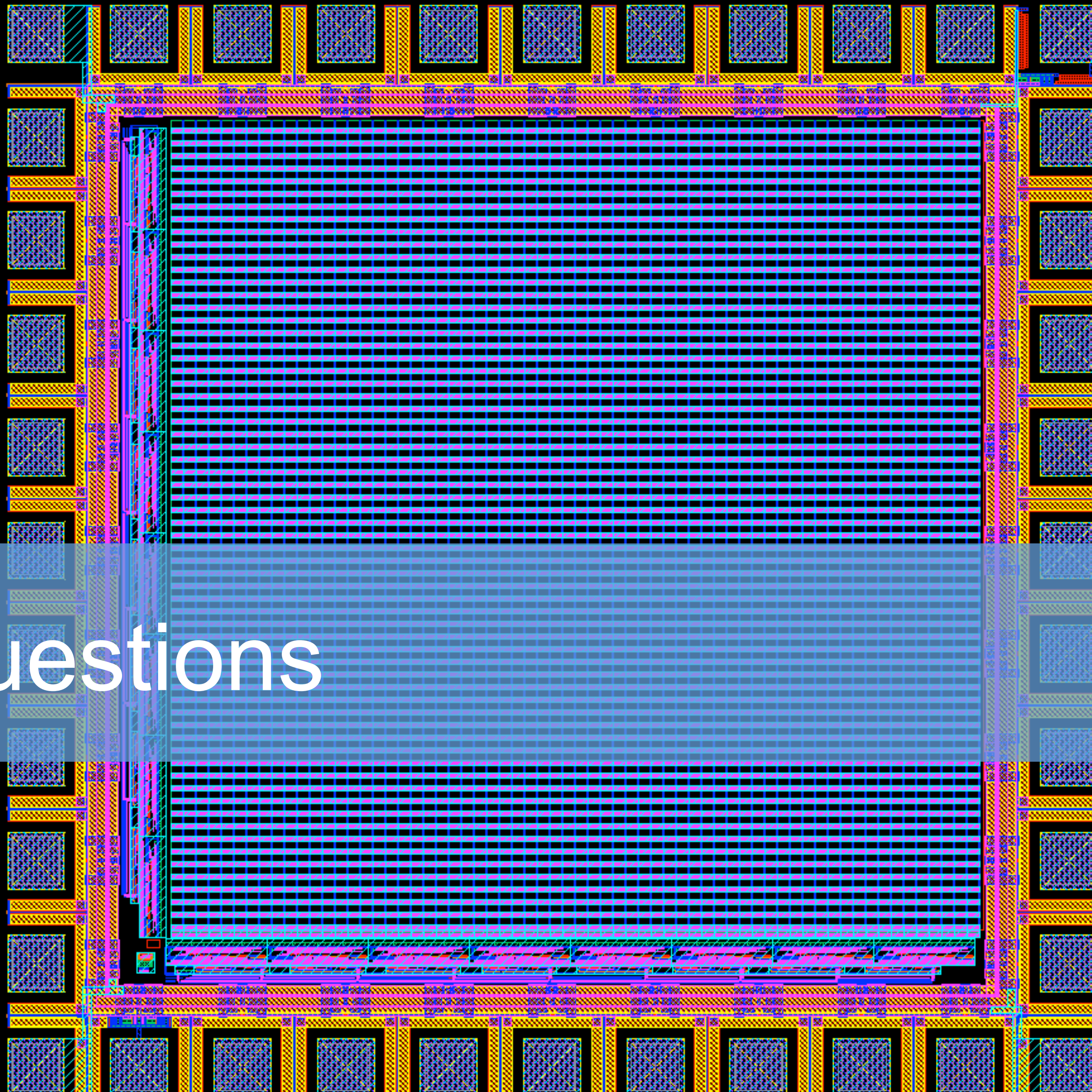

Reset signal charges the node
Vreset
Vref
RESET
Vreset
Vref
M0
ami06N
w=1.8u
l=1.8u
m:1
net18
m:1
l=1.8u
w=1.8u
ami06N
M1
Vpix
Vpix
net18
Vpix
M2
Vreset
Vpix
ami06N
w=1.8u
l=1.8u
m:1
net10
net18
D0
gnd!
gnd
net10
M3
ROW
ROW
ami06N
w=1.8u
l=600n
m:1
OUT
OUT


Vreset
RESET
Vreset
RESET
M4
amiØ6N
w=1.8u
l=6ØØn
Vpix
m:1
Vpix
Vreset
Vref
M0
amiØ6N
w=1.8u
l=1.8u
net18
m:1
Vref
m:1
l=1.8u
w=1.8u
amiØ6N
M1
Vpix
Vpix
net18
Vreset
Vpix
M2
amiØ6N
w=1.8u
l=1.8u
net1Ø
m:1
Charge leaks at a rate proportional to the intensity of light
net18
DØ
gnd!
gnd
net1Ø
M3
ROW
ROW
amiØ6N
w=1.8u
l=6ØØn
OUT
m:1
OUT


Reference signal closes the “shutter”
…storing the value
Vreset
RESET
Vreset
RESET
M4
ami06N
w=1.8u
l=600n
m:1
Vpix
Vpix
Vreset
M0
ami06N
w=1.8u
l=1.8u
m:1
net18
m:1
l=1.8u
w=1.8u
ami06N
M1
Vpix
net18
Vreset
M2
ami06N
w=1.8u
l=1.8u
m:1
net10
net18
D0
gnd!
gnd
net10
M3
ROW
ami06N
w=1.8u
l=600n
m:1
ROW
OUT
OUT


Vreset
RESET
Vreset
M4
RESET
ami06N
w=1.8u
l=600n
Vpix
m:1
Vpix
Vreset
M0
Vref
ami06N
Vref
w=1.8u
l=1.8u
net18
m:1
m:1
Vpix
l=1.8u
w=1.8u
Vpix
ami06N
M1
net18
Vreset
M2
Vpix
ami06N
w=1.8u
l=1.8u
net10
m:1
net18
D0
gnd!
gnd
net10
M3
ROW
OUT
...which is then read out with an analog-to-digital converter


V(reset)
V(vref)
V(vout)
5.5V
5.0V
4.5V
4.0V
3.5V
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
-0.5V
0ms
1ms
2ms
3ms
4ms
5ms
6ms
7ms
8ms
9ms
10m



Questions