PIN Photodiode Based X and γ Ray Detectors

Erhan Emirhan

Cenap S. Ozben

İstanbul Technical University

Faculty of Science and Letters

Department of Physics

34169 Sarıyer

İstanbul Turkey

Outline

- Si-PIN photodiodes
  - Structure
  - Principle of Operation
- Design Considerations?
  - Signal Size
  - Amplification (Transimpedence amplifier)
  - Noise
- Prototype
  - First Signal Measurements
- Future Plans

Si-PIN Photodiode Structure

N-type silicon is the starting material.

A thin P layer is formed on the front surface (ion implementation of boron).

Thickness of P is determined by the wavelength of the radiation to be detected.

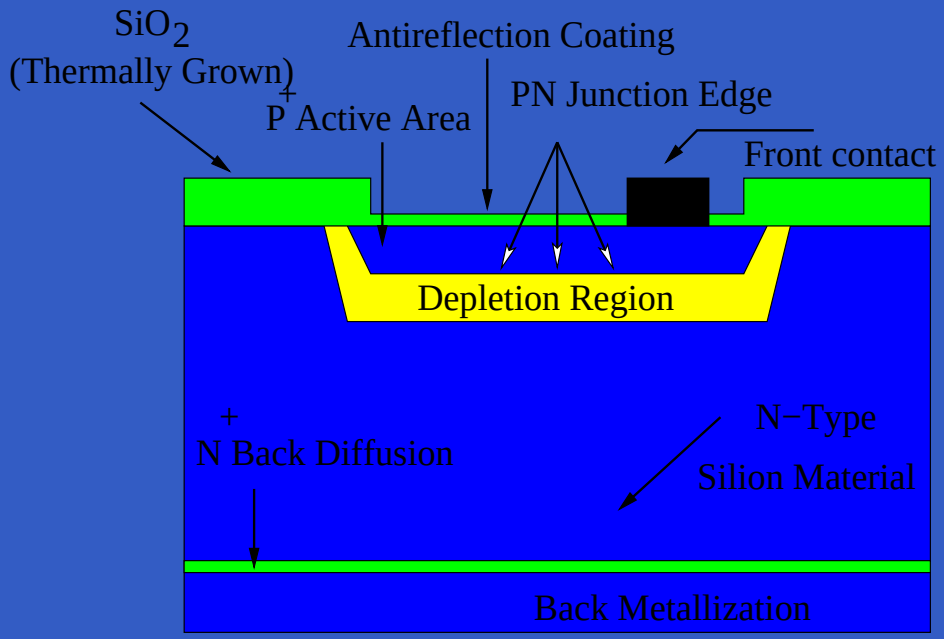
Intirinsic semiconductor is grown between the n and p layers of the junction.

Metal contacts to the front (anode) and entire back surfaces (cathode) are made.

N^+ is needed to improve the ohmic contact.

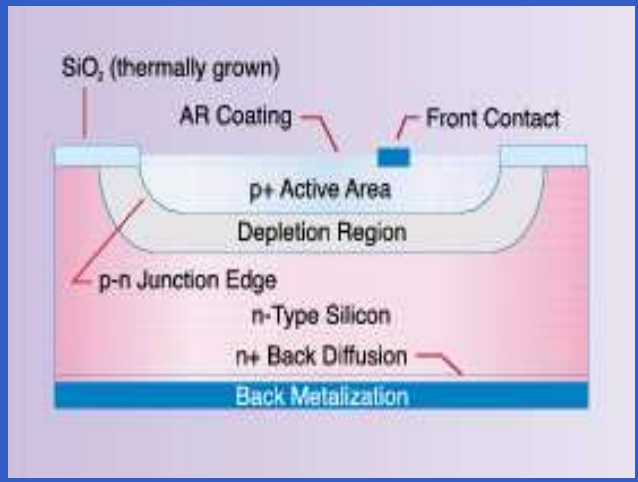
Anti-reflection coating material : Silicon nitride, silicon monoxide/dioxide

Thickness of the coating is optimized for particular wavelength.



Si-PIN Photodiode Signal

Silicon photodiodes absorb light $250nm - 1100nm$.
There are very few charge carriers in the intirinsic region.
The space charge region reaches completely through from the p to the n region.
Light excite electrons and produces charge carriers (e-o).
Charge carriers diffuse across the pn junction driven by a concentration gradient.
This gradient produces an internal electric field across the junction.
This field drives the electrons to N and the holes to the P.
Outside of the depletion region, they move randomly.
The ones in the depletion region are swept rapidly.
The result is having a small photocurrent at the electrodes.



Interaction of photons

They can serve as detectors for X and γ ray photons.

(1) $$Quantum\ Efficiency\ =\ \frac{I_{photo}}{I_{light}}$$

The thicker the silicon wafer is the greater the detection efficiency. Increasing the thickness of the depletion region also helps!

- In production : Vary semiconductor doping levels.
- In usage : Apply external bias voltage.

For 300μm wafer thickness (most photodiodes)

$\rightarrow$ 100% efficiency @ 10 keV

$\rightarrow$ 1% efficiency @ 150 keV

Interaction of γ's : Almost entirely Compton-Scattering for E$>$60 keV

DC-Current Response in Si-PIN Photodiode

Overall detection efficiency is fairly constant above 150 keV.

- A : Area of the diode (cm^2)
- N Gamma Ray flux ($\gamma/(cm^2.s)$)
- ϵ : Detection efficiency (assume 0.01)
- $\overline{E}$: Average energy of recoil electrons (eV).
- s : Ionization constant in Si (3.6 eV in e-o pair).
- q_e : Electronic charge.

(2)
$$I = \frac{N q_e \epsilon \overline{E} A}{s}$$

Simple Calculation

A Cs^{137} = 10 μCi source

Source - Diode distance = 1 cm

Detector Active Area A = 0.13 cm^2 Hamamatsu 1223-01

Flux at detector surface N = $(10 \times 3, 7.10^4)/(4\pi\ 1^2)$=29444 $\gamma/(cm^2 s)$

Wide range of recoil e^- energies are possible in Compton Scattering

Max. $\overline{e}$ energy : $E_{max} = E_\gamma(2E_\gamma/(m_e c^2 + 2E_\gamma))$

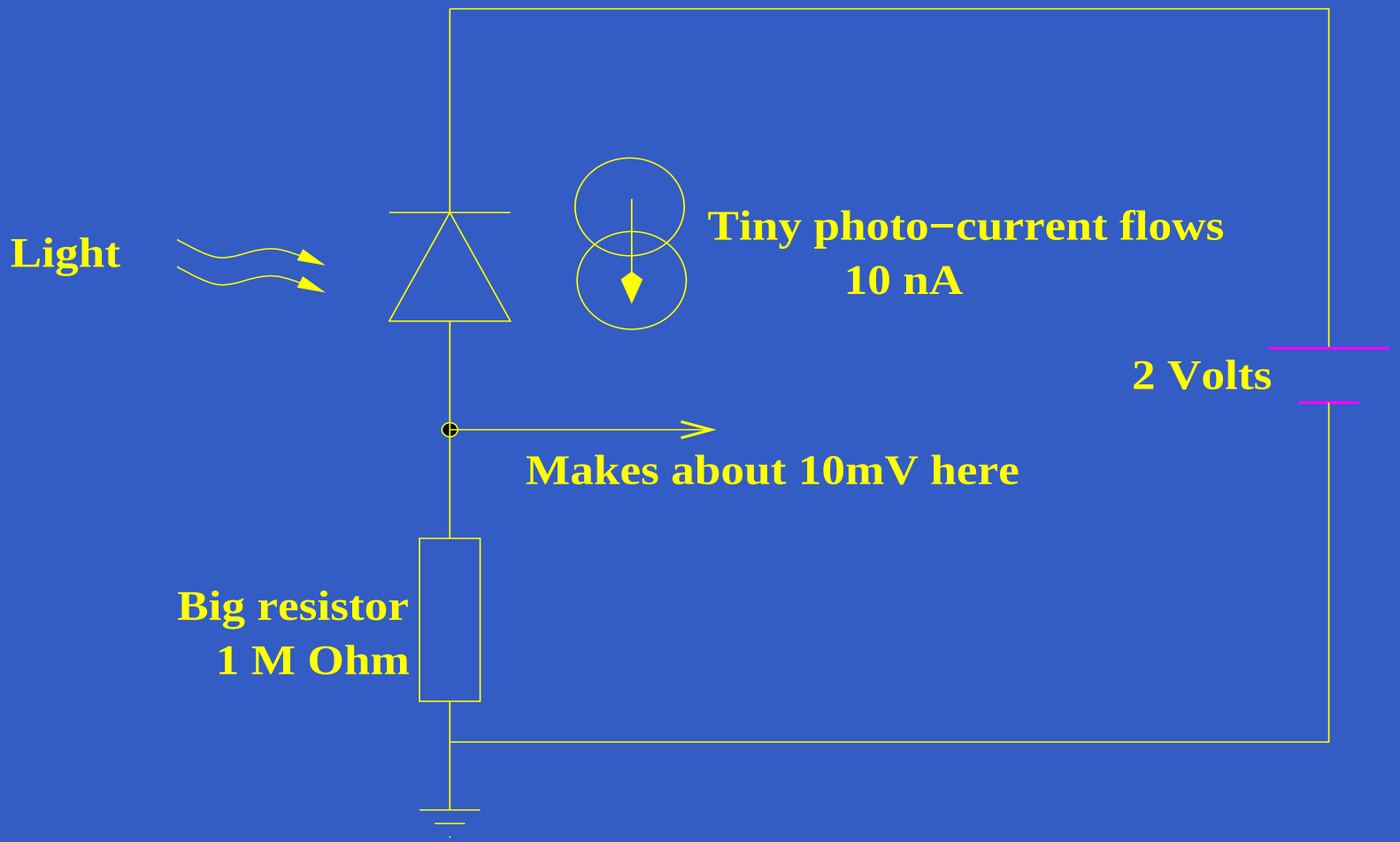
$E_{max} = 2 \times 661^2/(511 + 2 \times 661) = 476\ keV$

$\overline{E} = 238\ keV$ average energy is deposited in the detector.

(3)
$$I = \frac{29444 \quad 1.6\ 10^{-19} \quad 0.01 \quad 238000 \quad 0.13}{3.6} = 0.4pA$$

Not very easy!

How we measure this small current?



Is it that simple?

How we measure this small current?

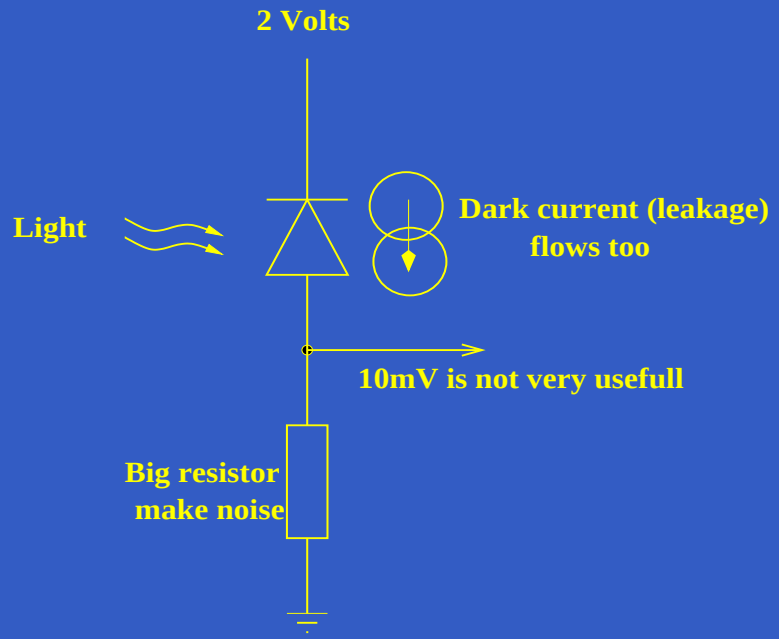
Not that simple!

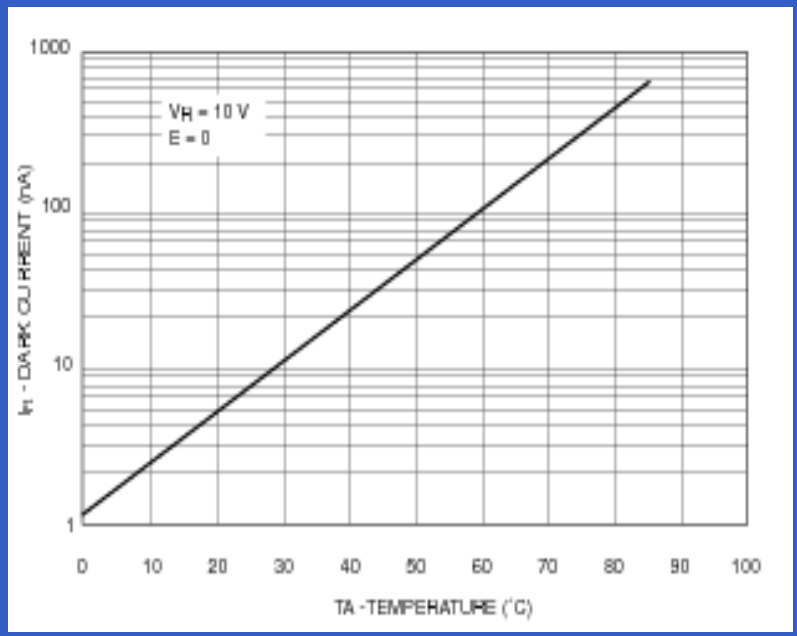
Diodes have intrinsic resistor → leakage current

This leakage current gets worse with the temperature

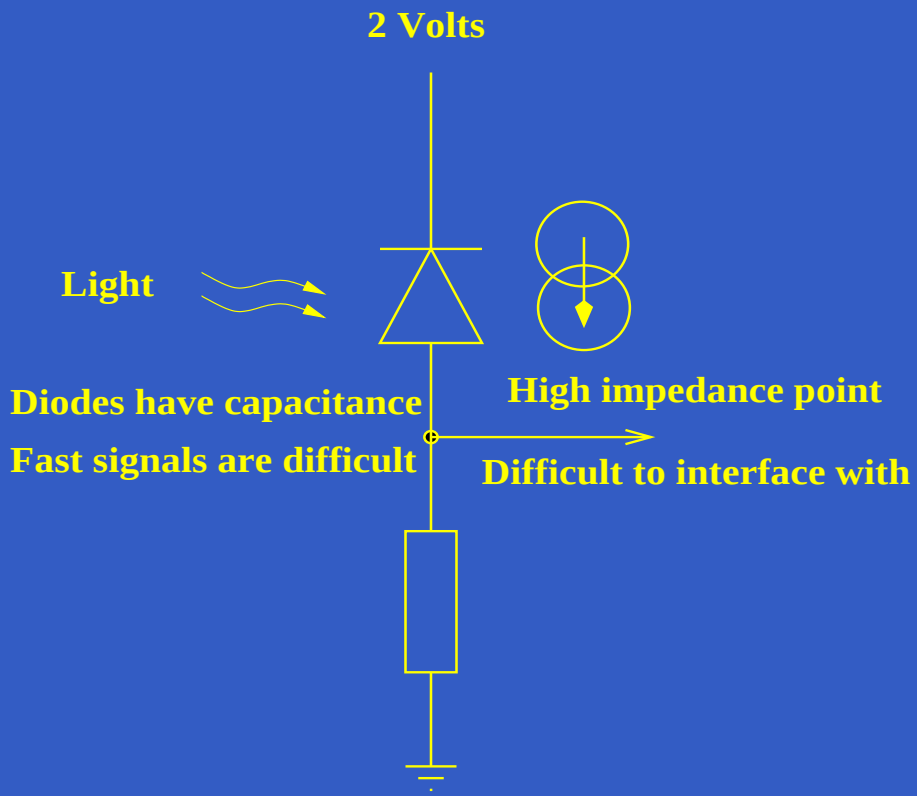
Big resistor creates noise too

To reduce the noise, AC and DC impedance to be lowered AMAP





How we measure this small current?



Capacitance slows the things down.

Typically Fast Photodiode: 2 pF, Large photodiode: 50pF

Larger the active area of the photodiode is better the efficiency.

If the active area of the photodiode is large, it is slower.

1 M ohm resistor and tiny capacitor? Time constant RC !!

How we measure this small current?

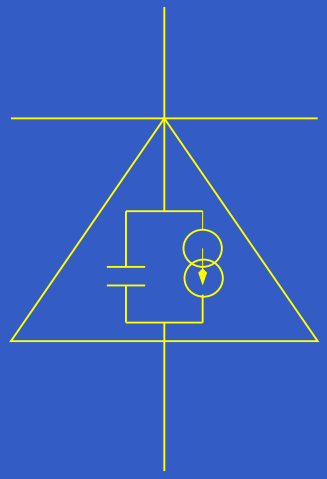
Current source works in reverse.
This reverse bias push P and N apart

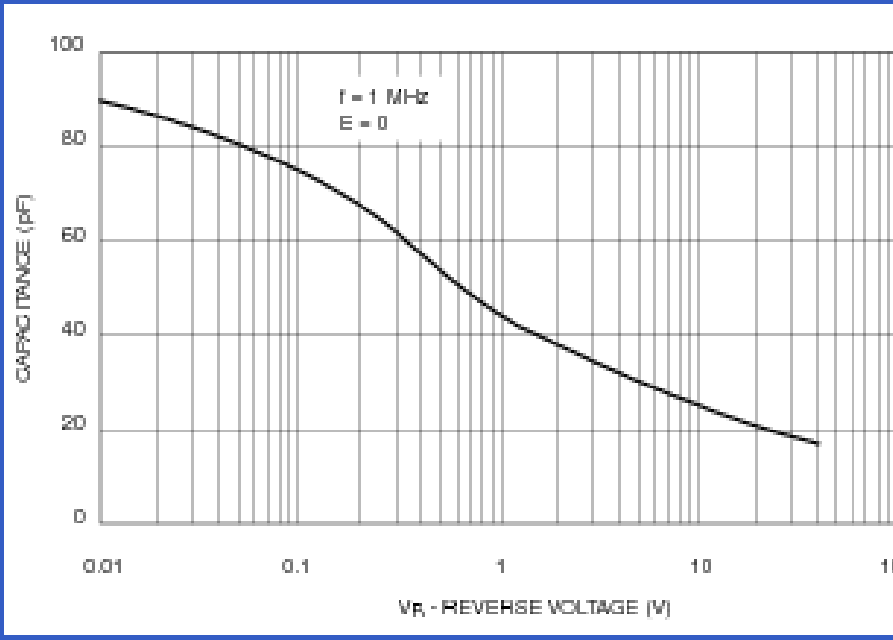
(4) $$C = \frac{K\epsilon_o A}{d}$$

Remember how condenser mic. works

Changing plate distance results voltage.

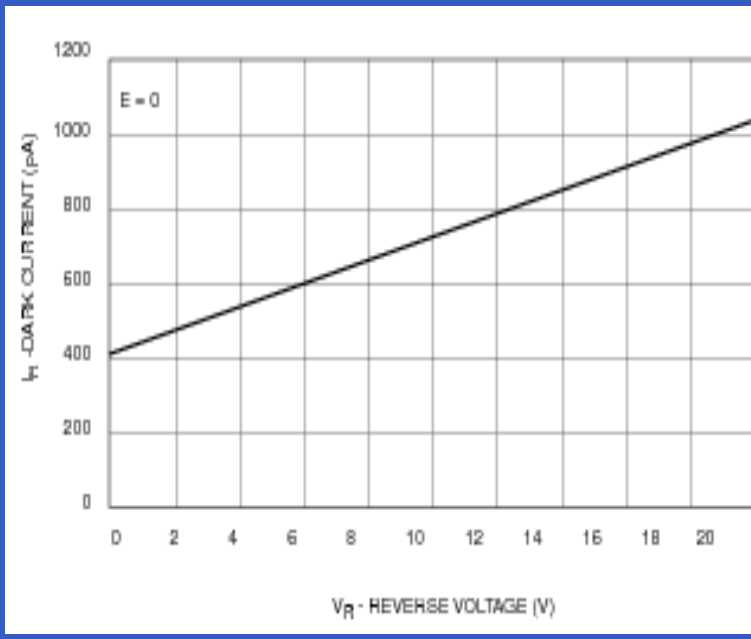
Bias voltage ↑ d ↑ C ↓

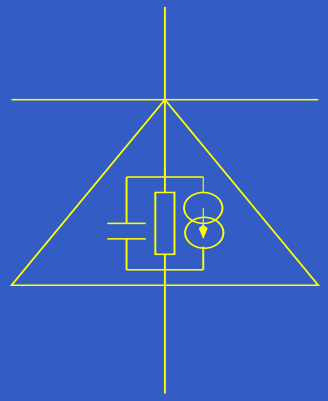




How we measure this small current?

Bulk resistance in diode ; 10 MΩ, 100 MΩ or 1 GΩ
This resistor represents the dark current
No Voltage across the diode means no current flows internally
THAT is GREAT! No dark current!
No voltage means, the capacitance is large!
So it is slower
Fast and more sensitive; How is that possible?





PhotoVoltaic Mode

Do not let any voltage built up across the diode

Grounded from the bottom

In linear mode of OPAMP

+ and - inputs are in the same voltage level

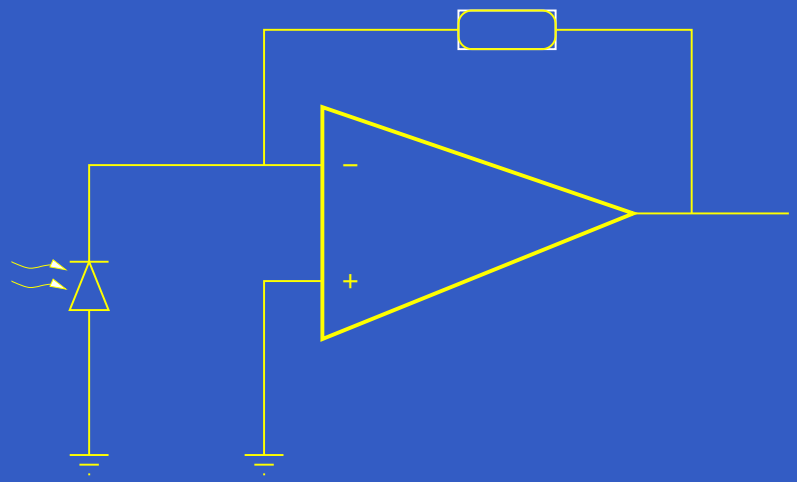


Photo current goes downward,

No current into the OPAMP!

Photocurrent causes reverse bias on the feedback resistor.

Photocurrent on the feedback resistor appears as an out voltage. $V_{out} = I_{pc} \times R_F$

Great Things :

No Dark Current.

Less noise.

High sensitivity.

Output is linear.

PhotoConductive Mode

You want to get data across the amplifier.

Anode of the diode is connected to -10 V.

20 Volts across the diode reduces the C from 20 pF to 2 pF.

Fundamental limitation of the speed is due to the C.

Use photoconductive mode where speed is more important.

Less capacitance maintains stability.

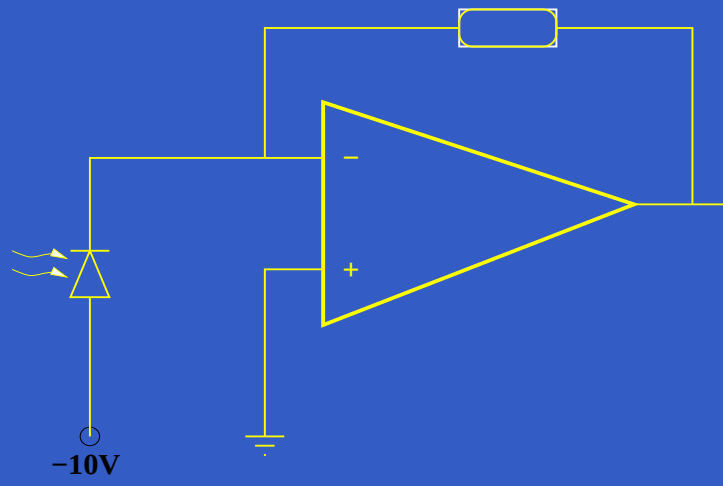
Disadvantages

Non-linear output (Do you really care!)

More noise: dark current exists (current

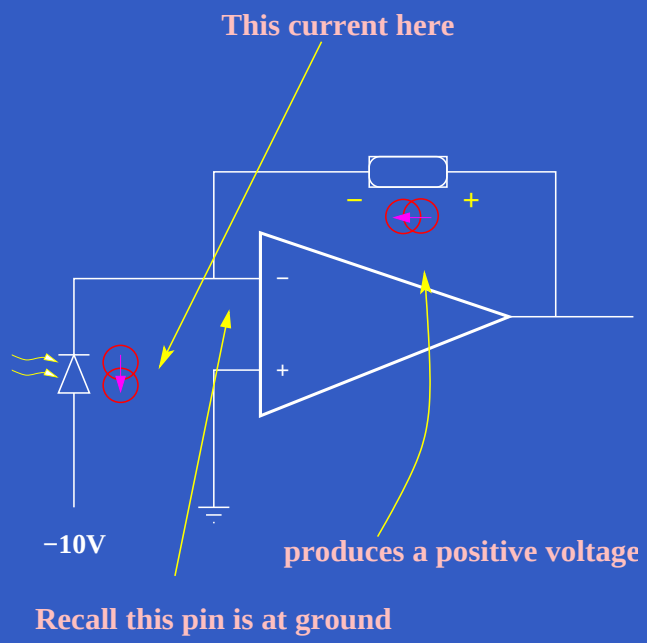
ripping through the internal resistor)

Dark current changes with the temperature



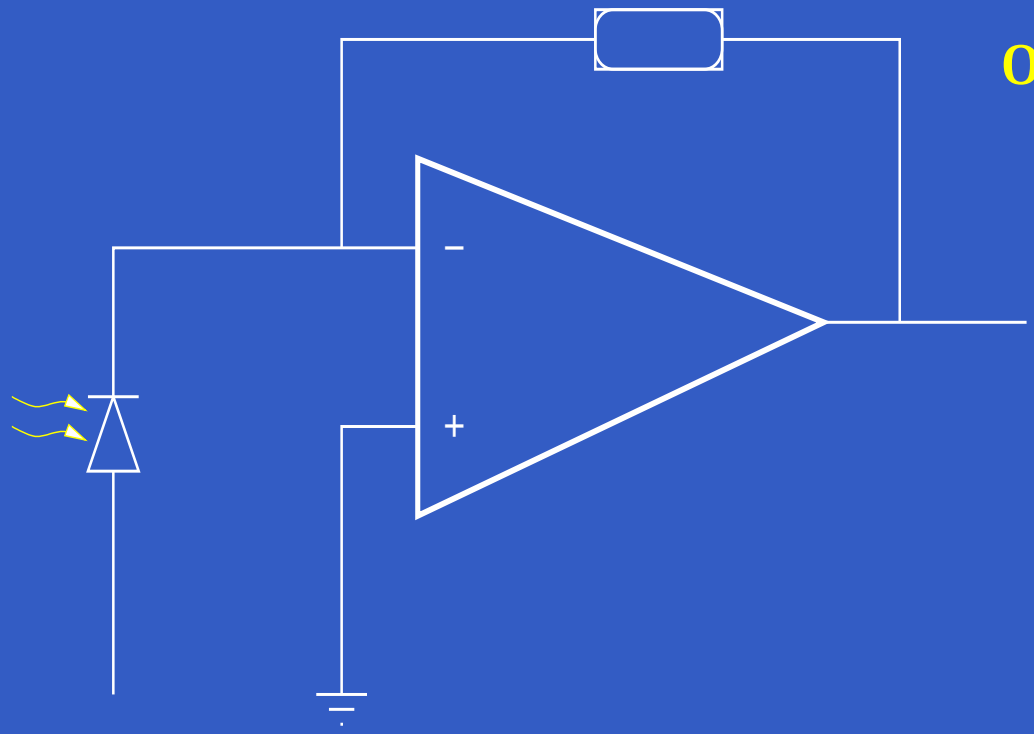
Feedback Resistor

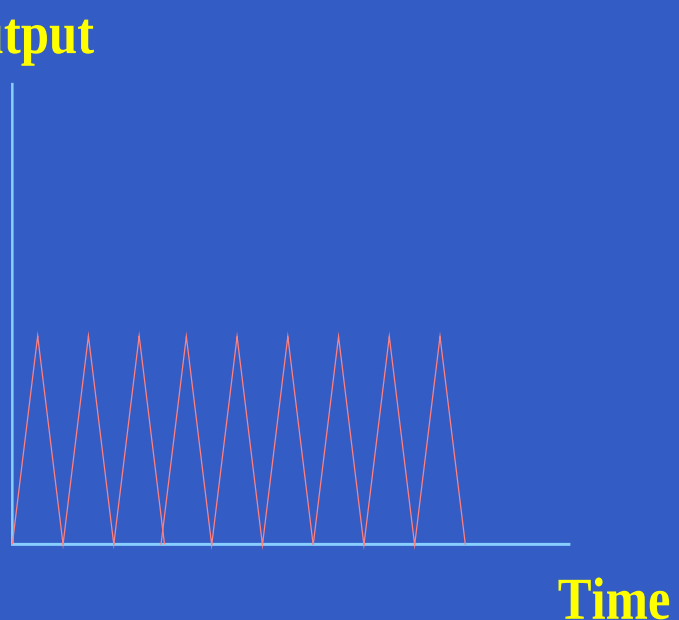
To get signal
Add a feedback resistor
Direction of the Photocurrent in the feedback resistor ;
The rigth side is relatively positive.
Left side of the resistor is nailed to ground.
Therefore the photo current will raise the output of the OPAMP.
The leakage current will going to pick the output (100-300 mV depending on the gain)



If the bias voltage has noise, this noise sneaks in your system
Use reverse voltage as much as diode can stand. Hamamatsu 1223-01

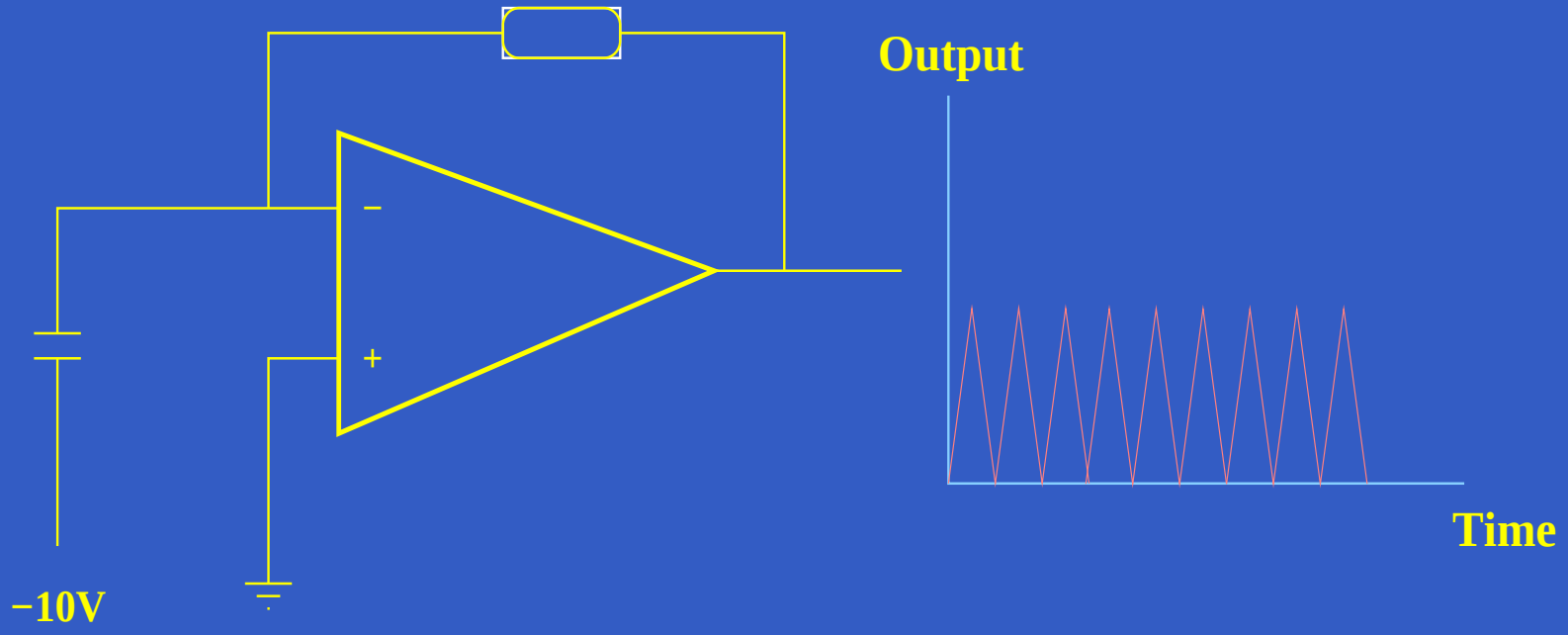
What happens in the Lab.





It oscillates and/or clips, What is wrong?

What is the reason?



This oscillation is caused by the capacitive diode in the input.

AC point of view!

Capacitor in the input slows down the feedback signal.

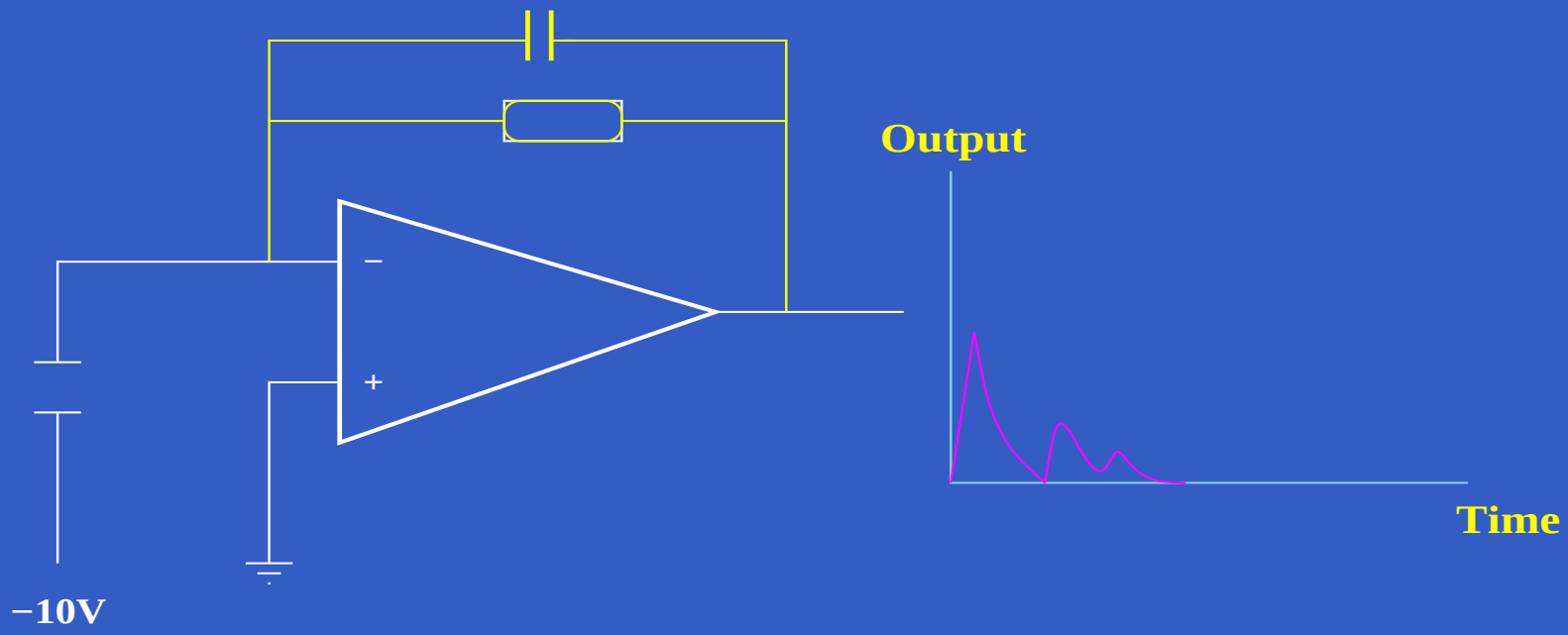
That creates a lag

The lag creates an oscillation. It is a mess!!!

What is the reason?

To compensate it, add a parallel cap. to the feedback

It is a controlled oscillation now (ringing).



A good design requires, an oscillation free amplification.

Bias current of OP-AMP

In reality, a (input) bias current flows through + and - inputs

If bias current comes out of - pin,

Since it can't go into diode, remember diode is a high-impedance current source.

It will go into the feedback resistor

This creates a big -DC offset.

Careful about the bias current!

Could be much larger than photocurrent!

Let's assume bias current coming out is 15 μA (LMH6624)

1 MΩ feedback resistor

The output is at -15 V

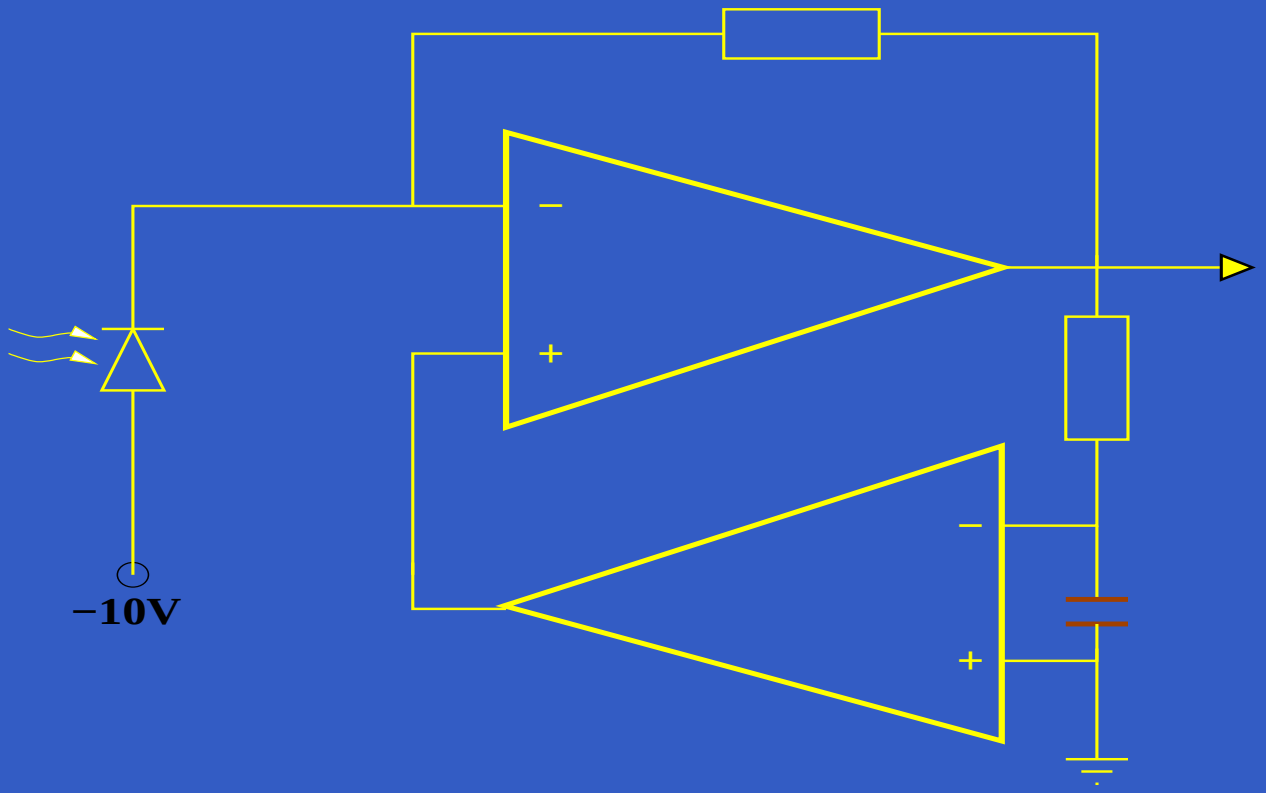
The output just nail down to the bottom rail.

Better IC's ; MAX4475 $\pm$1 (typ)-150(max) pA; negligible...

JFET and CMOS input type OP-AMPs have low input bias current ($\approx$10pA)

But it doubles at every $10^0 C$

Servo out the DC offset



This setup will pass only the AC signals.
Some of the companies have parts build in.

Which OP-AMP ?

Type	$e_n(nV/\sqrt{Hz})$	$i_n(fA/\sqrt{Hz})$	$i_B(pA)$	$c_{in}(pF)$
MAX4475	4.5	.50	1	10
LTC6240	7	.56	.2	3
LTC6241/42/44	7/7/8	.56	.2	3
AD8067	6.6	.60	.6	2.3
LT1769	6	1.0	4.0	1.5
OPA657	4.8	1.3	1.0	2.8
OPA656	7	1.3	1.0	2.8
LMH6622	1.6	1.5	4700	0.9
AD797	0.9	2.0	0.25	5.0
LMV791	5.8	10	0.1	15
LMC6484	37	30	0.02	3
OPA356	5.8	50	3.0	1.5
AD8599	1.15	1500	25000	4.5
LMH6624/26	0.92	2300	$13\ 10^6$	0.9

JFET input amps have low current noise. Bipolar amps have low voltage noise. Finding both in the same device? Dream on it :(

Noise

- Shot noise : Occurs when charges cross a potential barrier (like pn-junction)
  Purely a random event !
  i : Instantaneous current,
  i_D : Average of large number of independent current pulses.
  $q\, i_D$: current power density (A^2/Hz).

(5) $$i_{n_{RMS}} =< i_n^2 >=< i - i_D >^2= \int 2\, q\, i_D\, df$$

  Shot noise have flat spectral density and it is independent of temperature.

- Thermal noise : Caused by thermal agitation of charge carriers in a conductor.
  Present in the passive components.
  Spectral flat/uniform power density. It is independent of current flow.
  It can be modeled as voltage (with a noiseless resistor in series) or current (with a noiseless resistor in parallel)

(6) $$< e^2 >= \int 4kT\ R\, df \qquad < i^2 >= \int \frac{4kT}{R} df$$

$k : 1.38\ 10^{-23} j/K$, T : absolute temperature in K, R : resistor of the semiconductor, 4kTR : voltage density, 4kT/R : current densities.

Noise

- Flicker noise : It is 1/f noise. It present in all active devices and is associated with a DC current.

(7)
$$< \mathbf{e^2} >= \int \frac{\mathbf{K_e^2}}{\mathbf{f}} \mathbf{df} \quad \mathbf{or} \quad < \mathbf{i^2} >= \int \frac{\mathbf{K_i^2}}{\mathbf{f}} \mathbf{df}$$

K_e and K_i are voltage/current related device constants.
Flicker is proportional to dc current in the device.
$K_e^2/f(V^2/Hz)$ and $K_i^2/f(A^2/Hz)$ are related power densities.

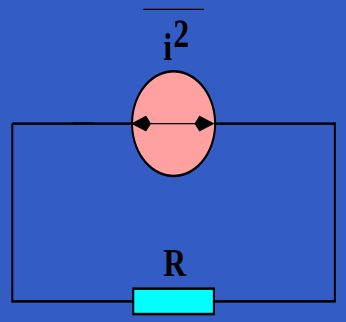
- Burst noise : Related to imperfections in semiconductor material and heavy ion implants. It can be overcomed by using clean device processing.
- Avalanche noise : Is created when a pn junction is operated in reverse breakdown mode.
  Electrons gained large kinetic energy due to the strong electric field in the depletion region.
  They collide with lattice atoms and additional e-hole pairs are formed.
  This is again random process like thermal noise but much more intense.

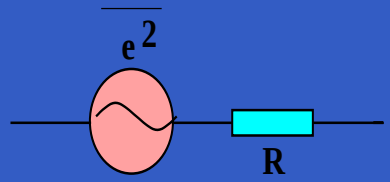
Thermal and shot noise : Gaussian probability density functions. $\overline{N} \pm 3\sigma \rightarrow 99.7\%$

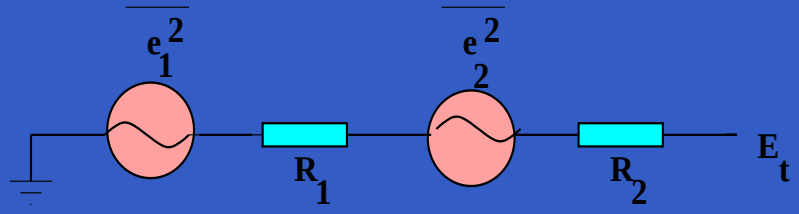
Noise model and adding noise sources

Noise model of a resistor :

Noise in a resistor can be modeled with two equivalent cases : A voltage source connected in series or a current source connected in parallel.





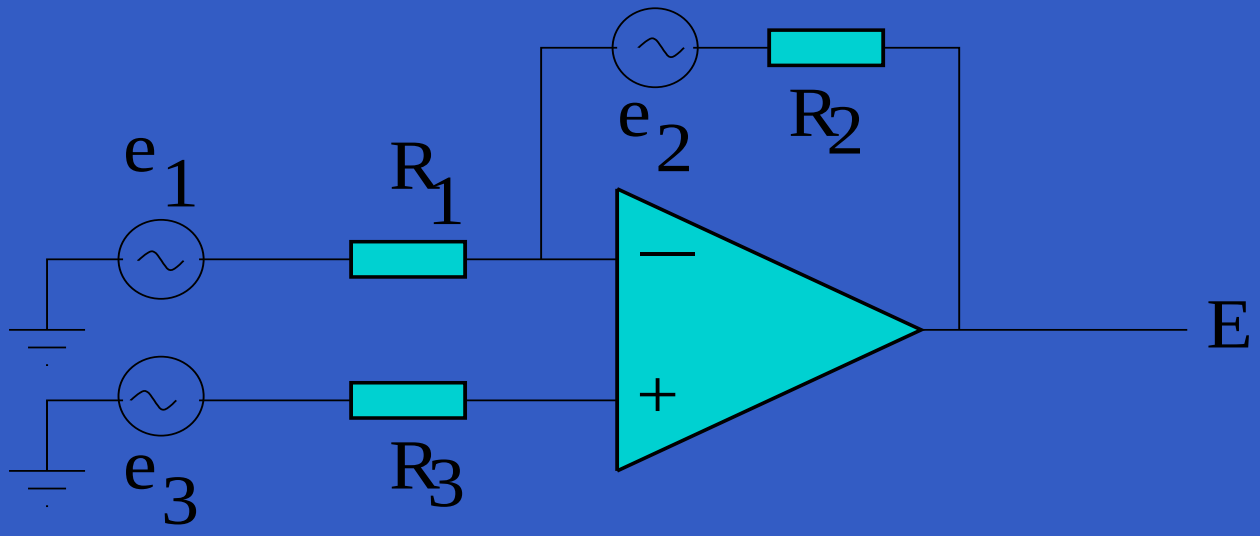


Two resistors, R_1 and R_2, connected in series :

In these models e_x are the noise voltage sources and R_x are noiseless resistors.

(8) $\overline{e_1^2} = \int 4kTR_1 \; df \qquad \overline{e_2^2} = \int 4kTR_2 \; df \qquad \overline{E_t^2} = \overline{e_1^2} + \overline{e_2^2} = \int 4kT(R_1 + R_2) \; df$

Noise due to the peripherals



Noiseless Op Amp

Analyze the noise for each element then superimpose them.

e_2 and e_3 are zero : $\overline{E_1} = \overline{e_1}\frac{R_2}{R_1}$ $\overline{e_1}^2 = \int 4kTR_1df$

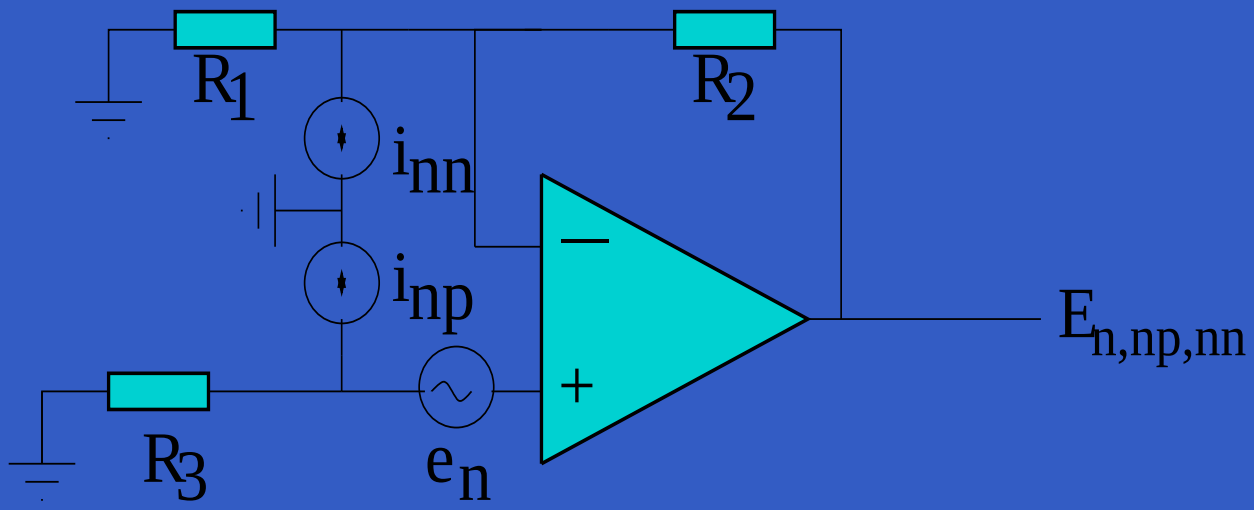
e_1 and e_3 are zero: $\overline{E_2} = \overline{e_2}$ $\overline{e_2}^2 = \int 4kTR_2df$

e_1 and e_2 are zero: $\overline{E_3} = \overline{e_3}\frac{R_1+R_2}{R_1}$ $\overline{e_3}^2 = \int 4kTR_3df$

$E_{Rrms} = \sqrt{\overline{E_1^2} + \overline{E_2^2} + \overline{E_3^2}}$ Gain of the circuit $A_n = \frac{R_1+R_2}{R_1}$

Noise at input $E_{iRrms}^2 = (\frac{E_{Rrms}}{A_n})^2 = \int 4kT[(\frac{R_1R_2}{R_1+R_2} + R_3]df$

Noise equivalent for OPAMP



Noiseless Op Amp

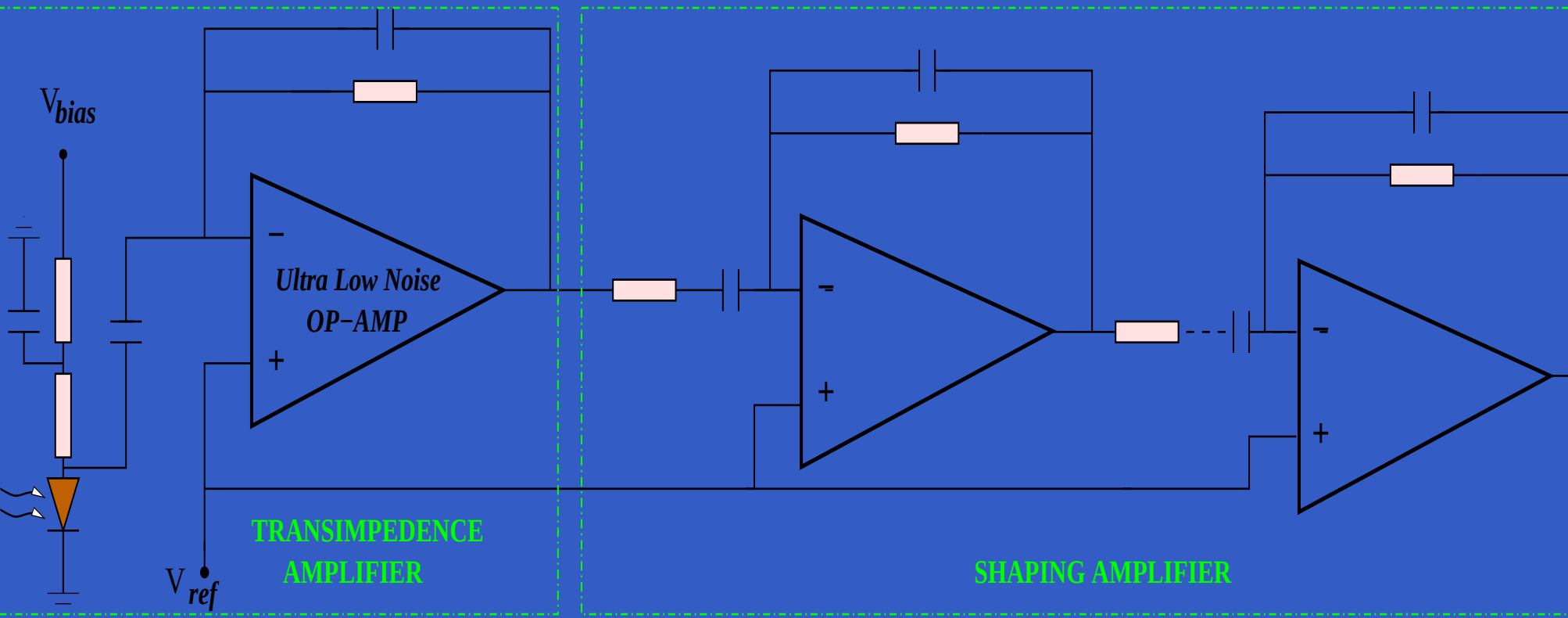
i_{nn} and i_{np} are zero : $\overline{E_n^2} = \int [e_n \frac{R_1+R_2}{R_1}]^2 df$

e_n and i_{nn} are zero : $\overline{E_{np}^2} = \int [i_{np} R_3 \frac{R_1+R_2}{R_1}]^2 df$

e_n and i_{np} are zero : $\overline{E_{nn}^2} = \int [i_{nn} R_2]^2 df$

$$E_{orms} = \sqrt{\overline{E_n^2} + \overline{E_{np}^2} + \overline{E_{nn}^2}}$$

Construction



Noise is dominated by the first stage

Gain is relatively large

A lot of trial and error is required to optimize the output signal

A well done metal cage is required to see the signal.

Photodiode

Hamamatsu 1223-01 Si PIN Photodiode

For optical measurement equipments

High speed : 20 MHz

Active area : 3.6 mm x 3.6 mm,

Max. Reverse Voltage : 30 V

Power dissipation : 100 mW

Photo Sensitivity : 0.45 A/W (660nm), 0.6 A/W (960nm)

Operating temperature : -40^{0}C-100^{0}C

Spectral Response : 320-1100 nm

Dark Current : 0.2 nA

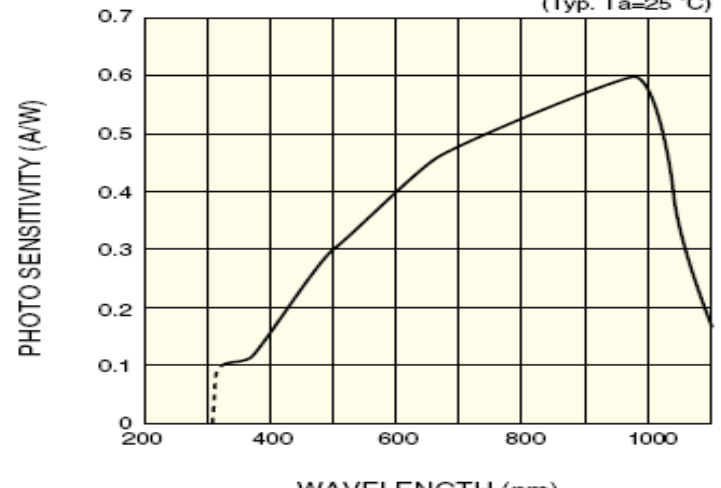
T_{CID} : 1.15 times/^{0}C

Terminal Cap. : 20 pF (V_B=20V)

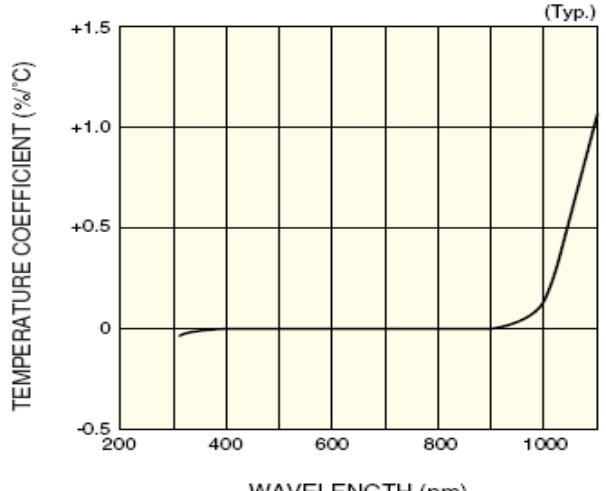
Glass window thickness : 0.2 mm

Hamamatsu 1223-01

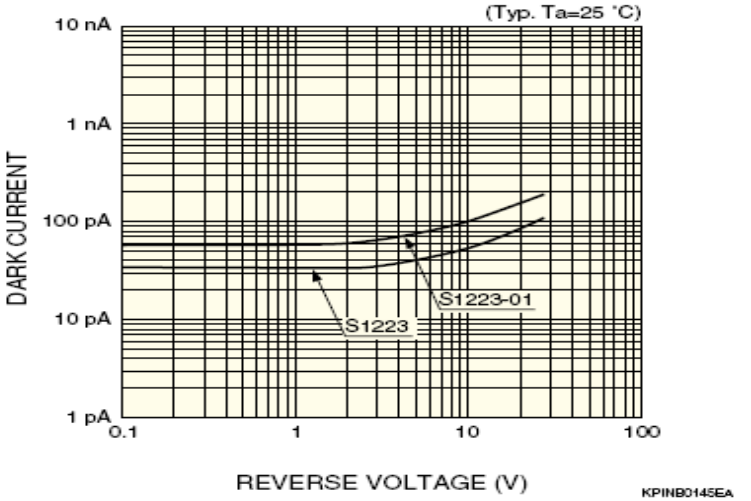
■ Spectral response



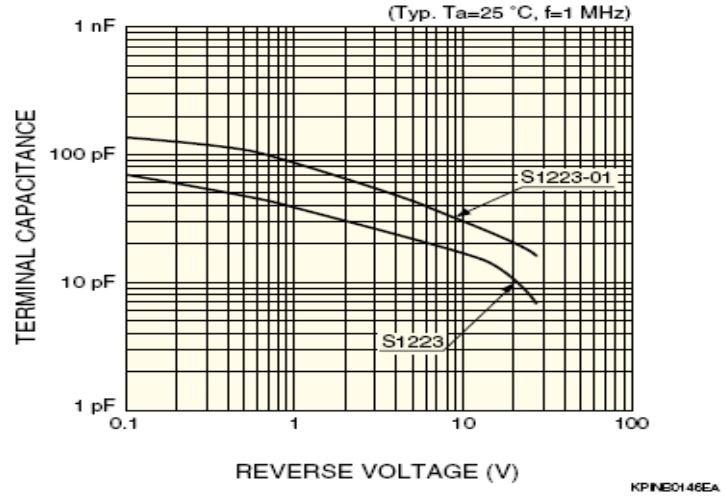
■ Photo sensitivity temperature characteristic



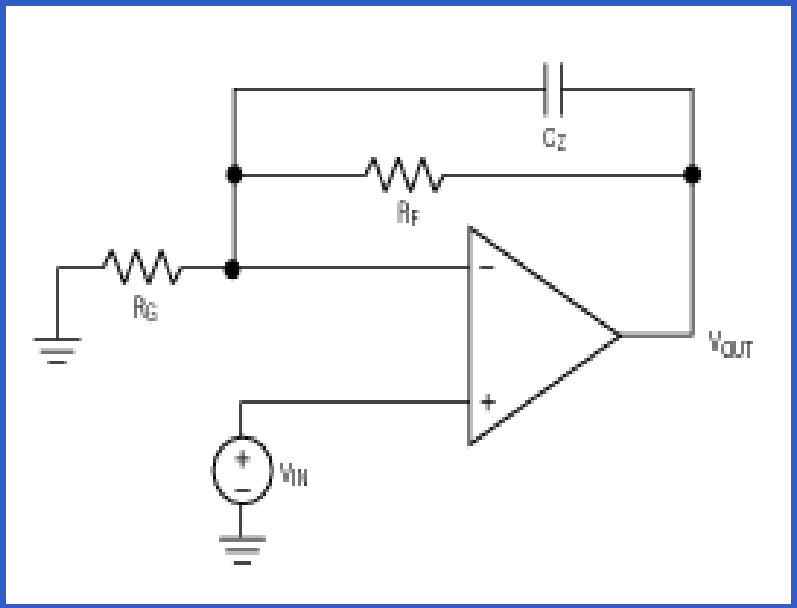
■ Dark current vs. reverse voltage



■ Terminal capacitance vs. reverse voltage



MAXIM 4478



MAXIM 4478 Low Noise OPAMP

For optical measurement equipments

Single Supply Operation : +2.7 V $\longrightarrow$ +5V

4 OP-AMPs in one package

Each Amp. draw 2.5 mA (at 5V)

Ulra Low Distortion : 0.0002% THD + N

Input Voltage-Noise Density : 4.5 nV/$\sqrt{Hz}$

Input Current Noise : 0.5 fA/$\sqrt{Hz}$

Input Bias Current : 1 pA

Bandwidth : 10 MHz

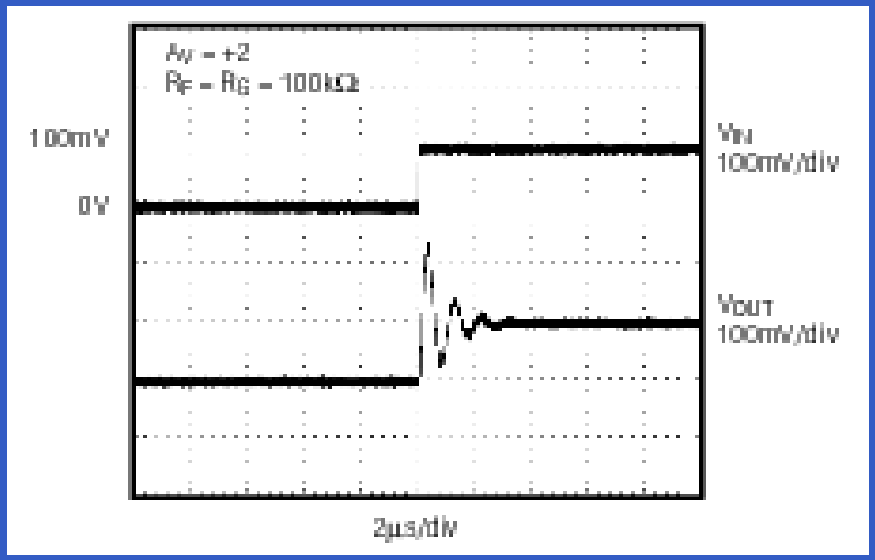
CMRR : 115 dB

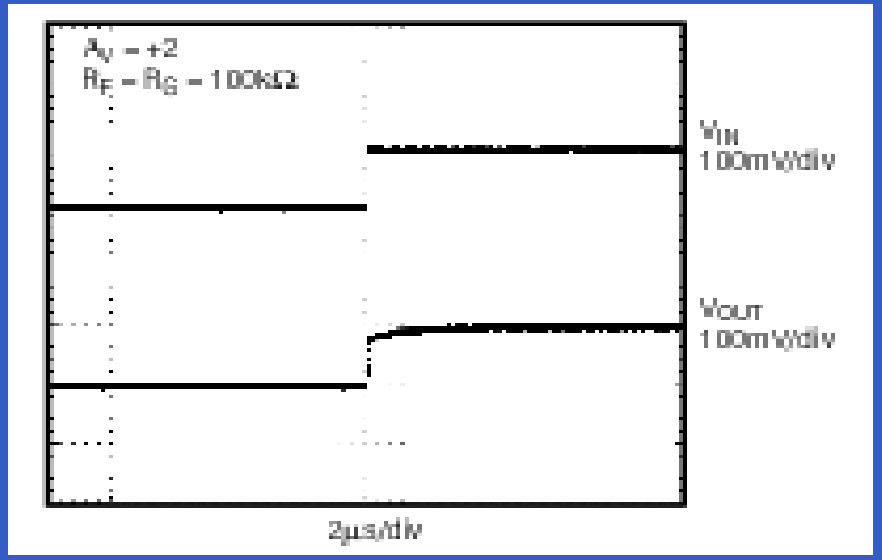
PSRR : 120 dB

Input Resistance : 1000 GΩ

Input Capacitance : 10 pF

Feed Forward Compensation

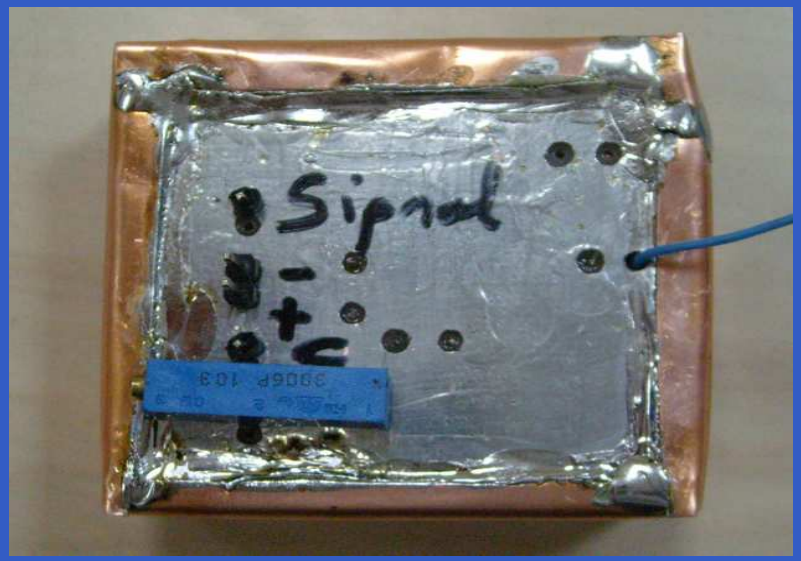




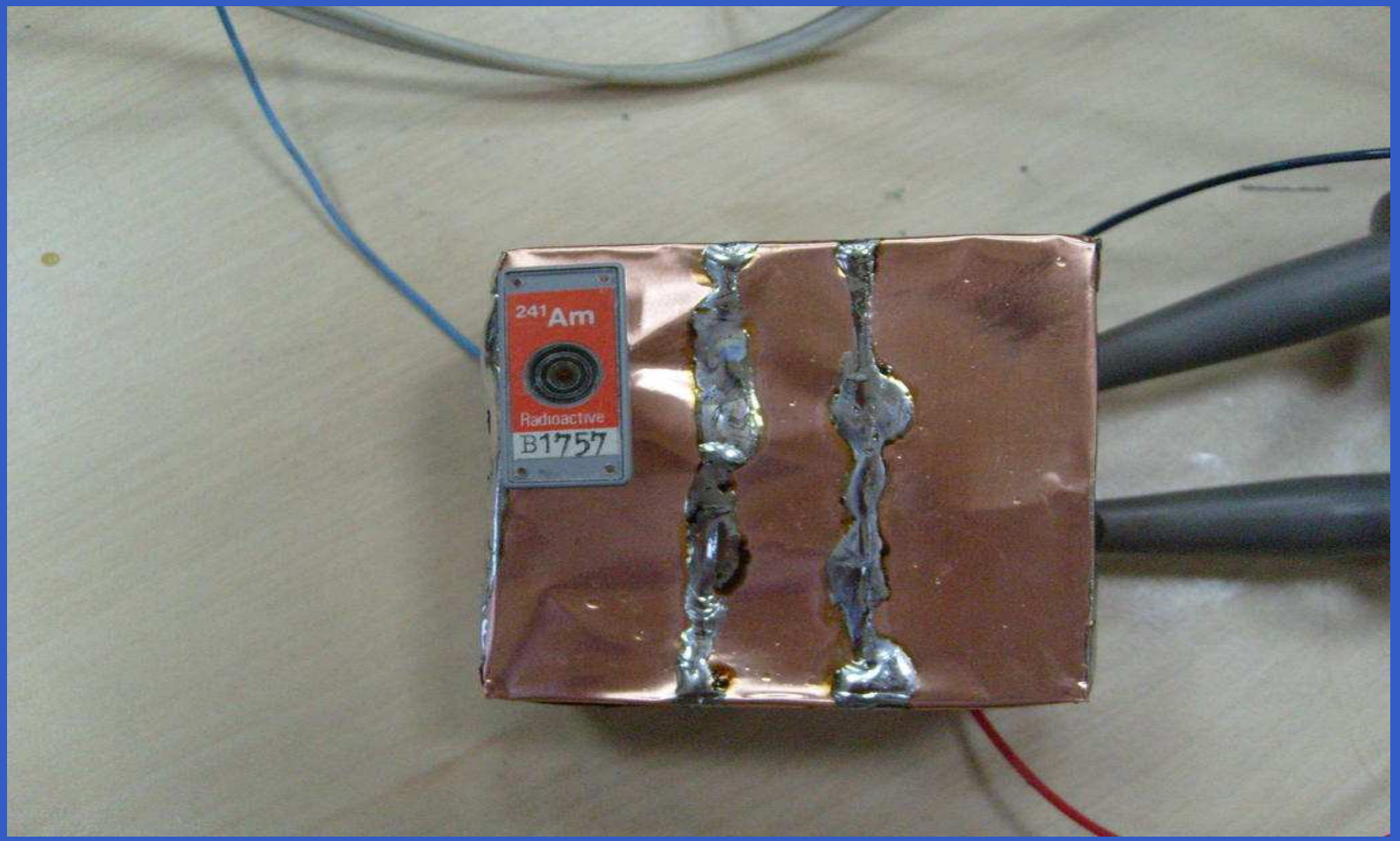
No feedback cap.

With a feedback cap.

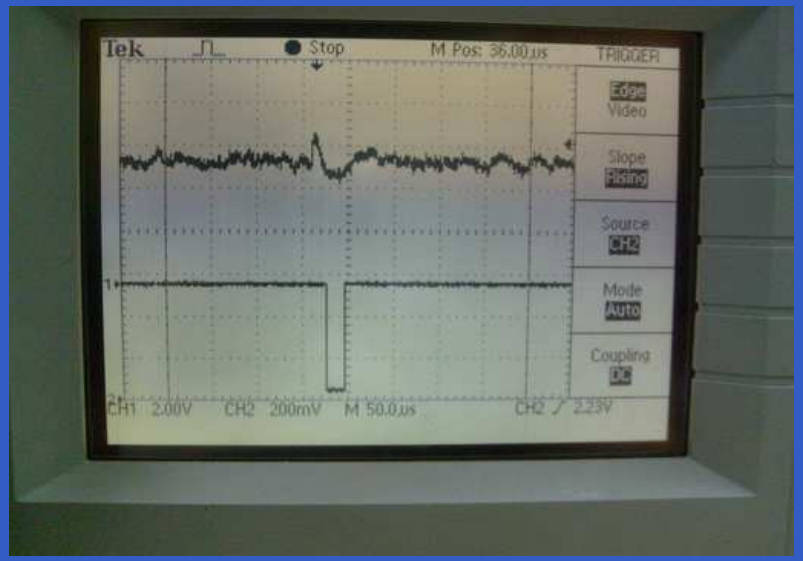
Construction

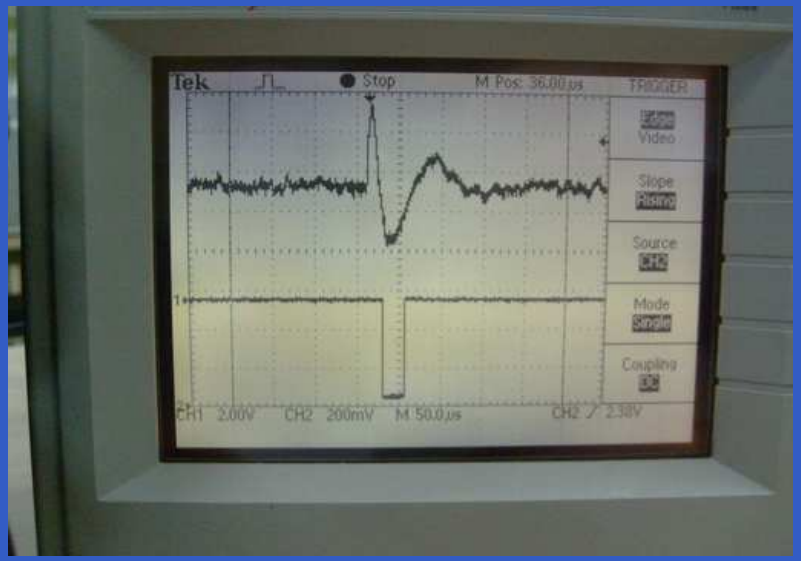


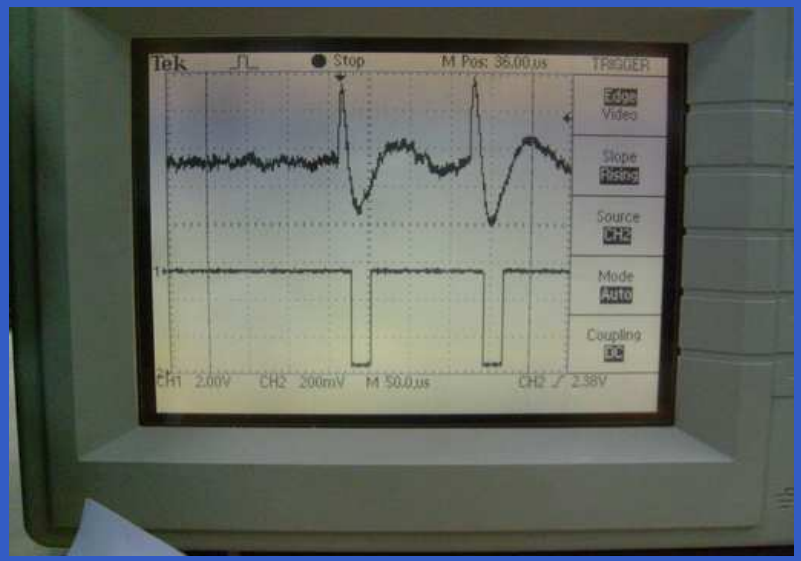
Construction



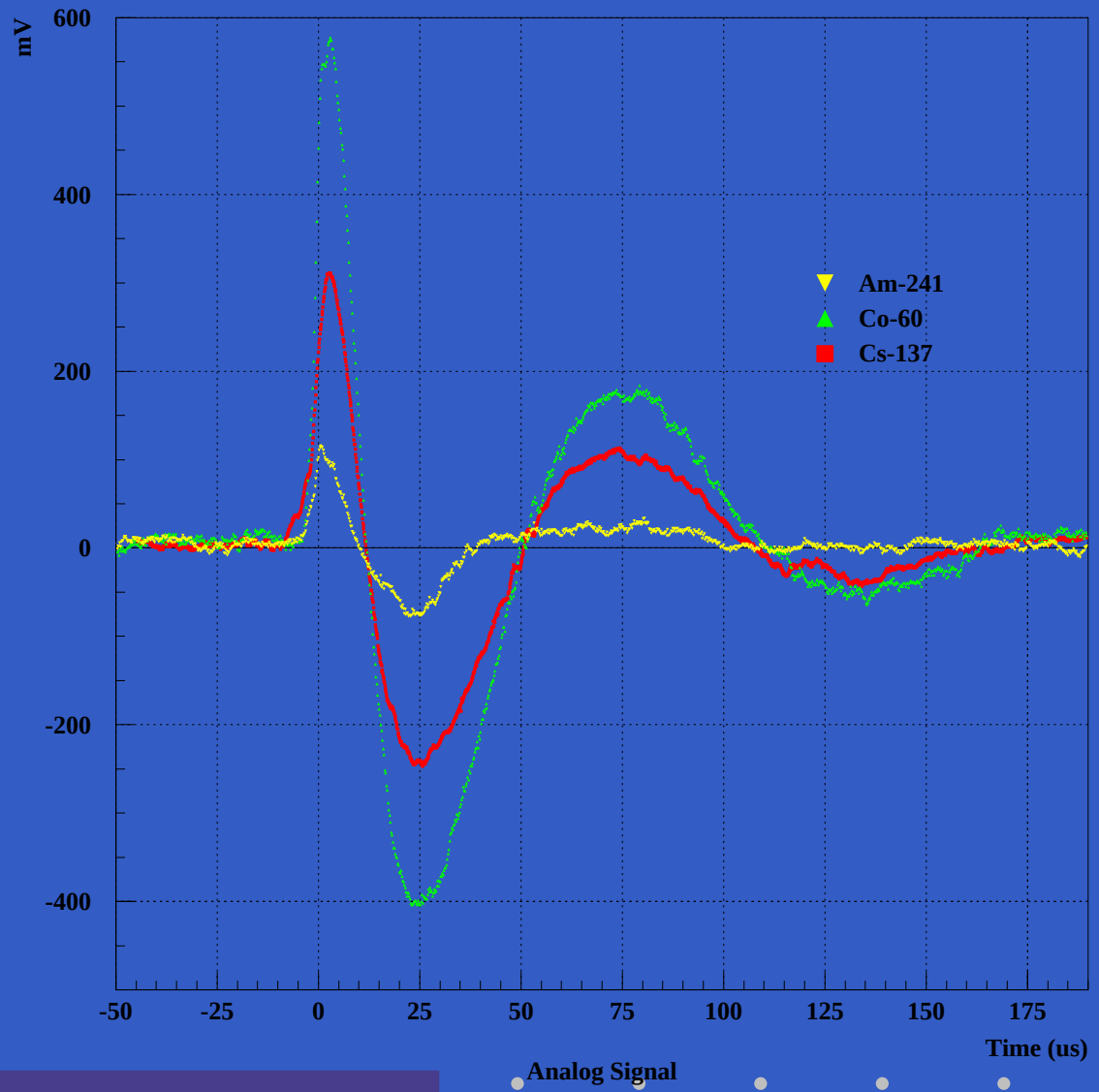
Signals


Tek
Stop
M Pos: 36.00µs
TRIGGER
Edge
Video
Slope
Rising
Source
CH2
Mode
Auto
Coupling
DC
CH1 2.00V
CH2 200mV
M 50.0µs
CH2 2.23V


Tek
Stop
M Pos: 36.00µs
TRIGGER
Video
Slope
Rising
Source
CH2
Mode
Single
Coupling
DC
CH1 2.00V
CH2 200mV
M 50.0µs
CH2 2.38V

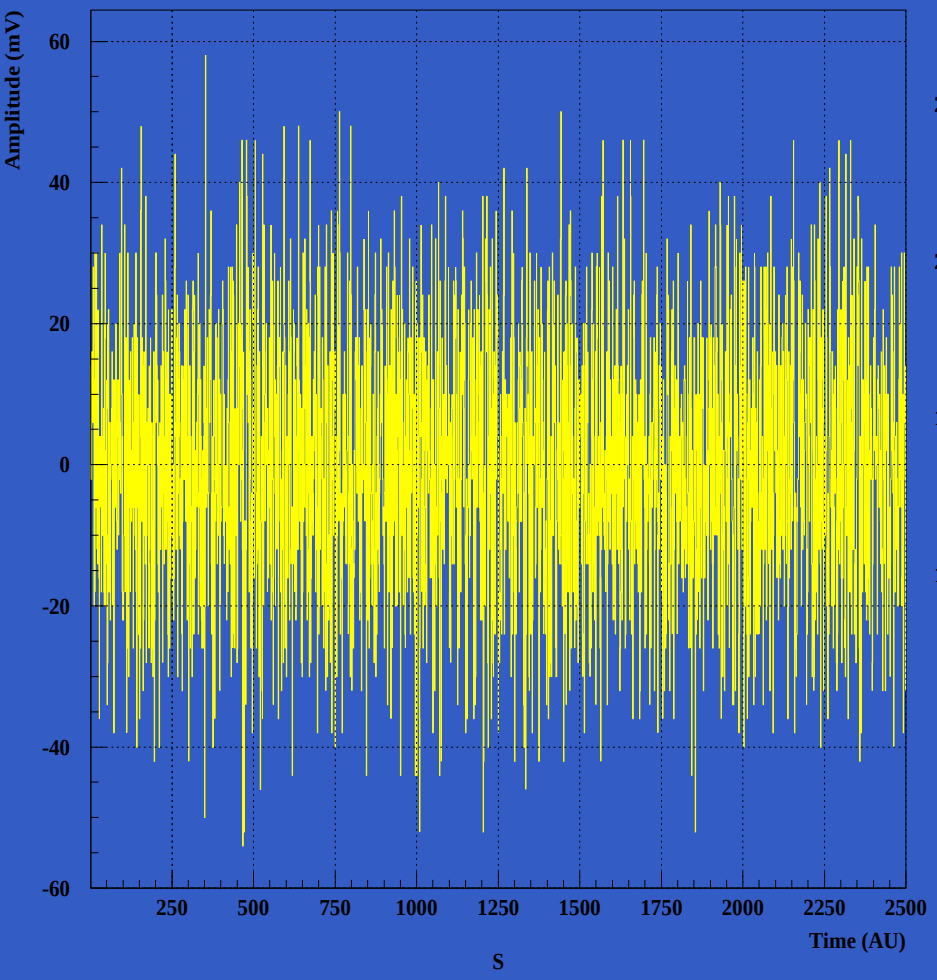

Tek
Stop
M Pos: 36.00µs
TRIGGER
Edge
Video
Slope
Rising
Source
CH2
Mode
Auto
Coupling
DC
CH1 2.00V
CH2 200mV
M 50.0µs
CH2 2.38V

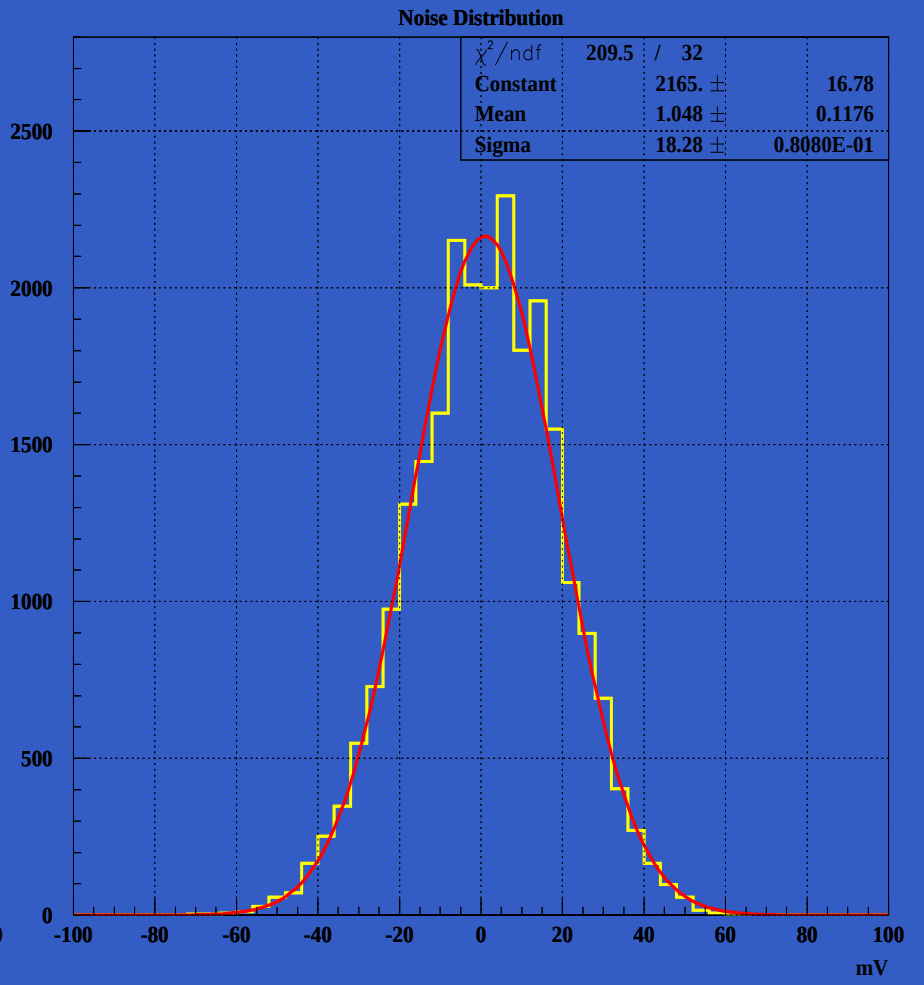
Signals from Sources



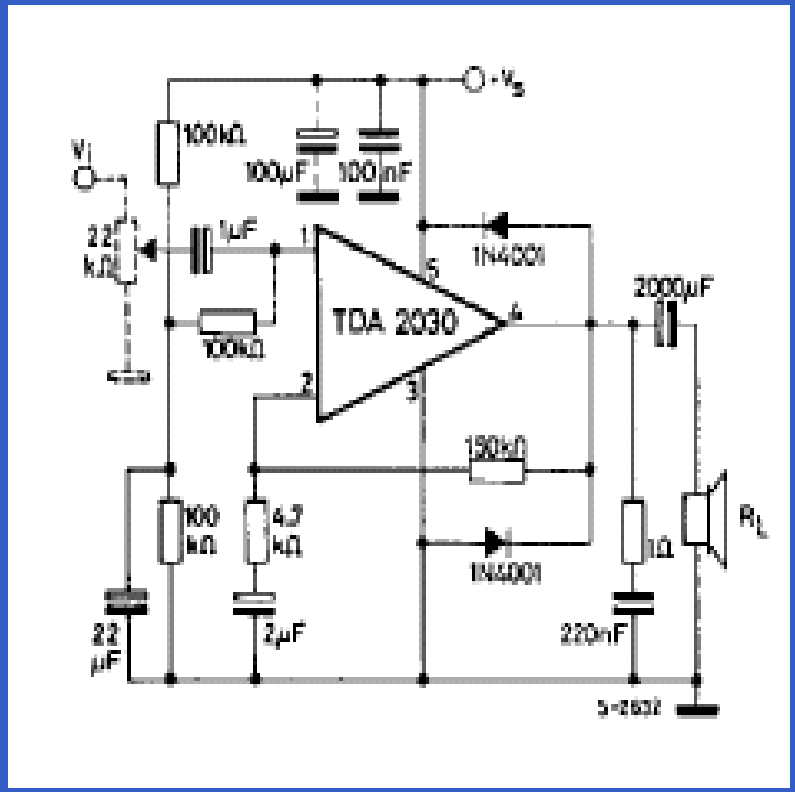
Analog Signal

Signals and Noise





Amplifier TDA2030

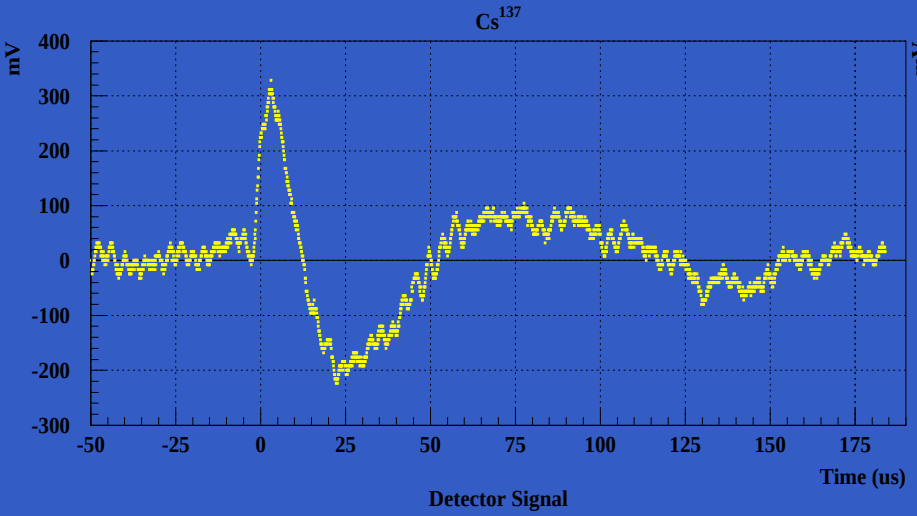


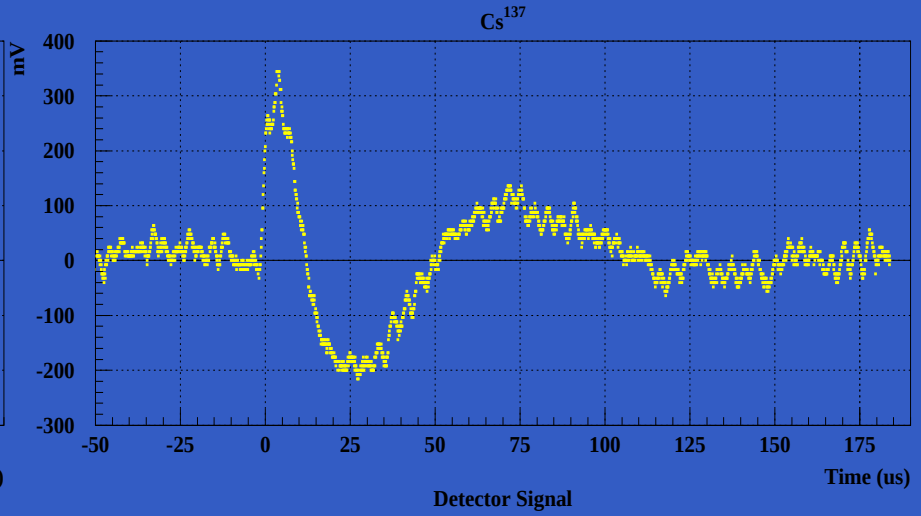
Amplifier TDA2030

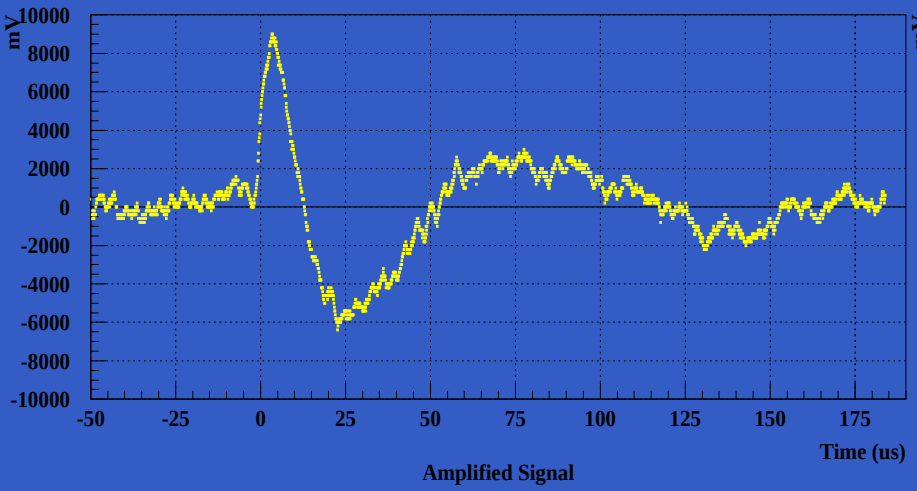
ELECTRICAL CHARACTERISTICS (Refer to the test circuit, $V_s = \pm 14V$, $T_{amb} = 25°C$ unless otherwise specified)

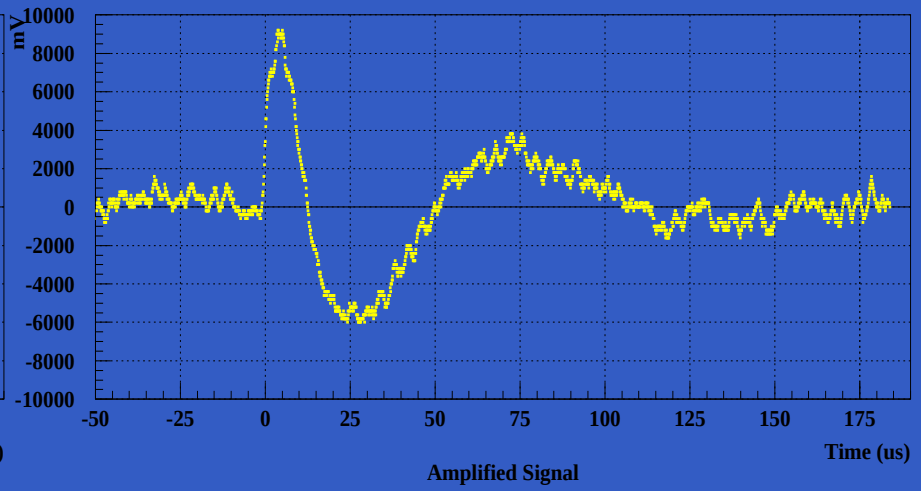
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
V_s	Supply voltage		± 6		± 18	V
I_d	Quiescent drain current	$V_s = \pm 18V$		40	60	mA
I_b	Input bias current			0.2	2	µA
V_{os}	Input offset voltage			± 2	± 20	mV
I_{os}	Input offset current			± 20	± 200	nA
P_o	Output power	d = 0.5% G_v = 30 dB f = 40 to 15,000 Hz $R_L = 4\Omega$ $R_L = 8\Omega$	 12 8	 14 9		 W W
		d = 10% G_v = 30 dB f = 1 KHz $R_L = 4\Omega$ $R_L = 8\Omega$		 18 11		 W W
d	Distortion	P_o = 0.1 to 12W $R_L = 4\Omega$ G_v = 30 dB f = 40 to 15,000 Hz		 0.2	 0.5	 %
		P_o = 0.1 to 8W $R_L = 8\Omega$ G_v = 30 dB f = 40 to 15,000 Hz		 0.1	 0.5	 %
B	Power Bandwidth (-3 dB)	G_v = 30 dB P_o = 12W $R_L = 4\Omega$	10 to 140,000			Hz
R_i	Input resistance (pin 1)		0.5	5		MΩ
G_v	Voltage gain (open loop)			90		dB
G_v	Voltage gain (closed loop)	f = 1 kHz	29.5	30	30.5	dB
e_N	Input noise voltage	B = 22 Hz to 22 KHz		3	10	µV
i_N	Input noise current			80	200	pA
SVR	Supply voltage rejection	$R_L = 4\Omega$ G_v = 30 dB R_g = 22 kΩ V_{ripple} = 0.5 V_{eff} f_{ripple} = 100 Hz	40	50		dB
I_d	Drain current	P_o = 14W $R_L = 4\Omega$ P_o = W $R_L = 8\Omega$		900 500		mA mA
T_j	Thermal shut-down junction temperature			145		°C

TDA2030 : An Audio Amplifier

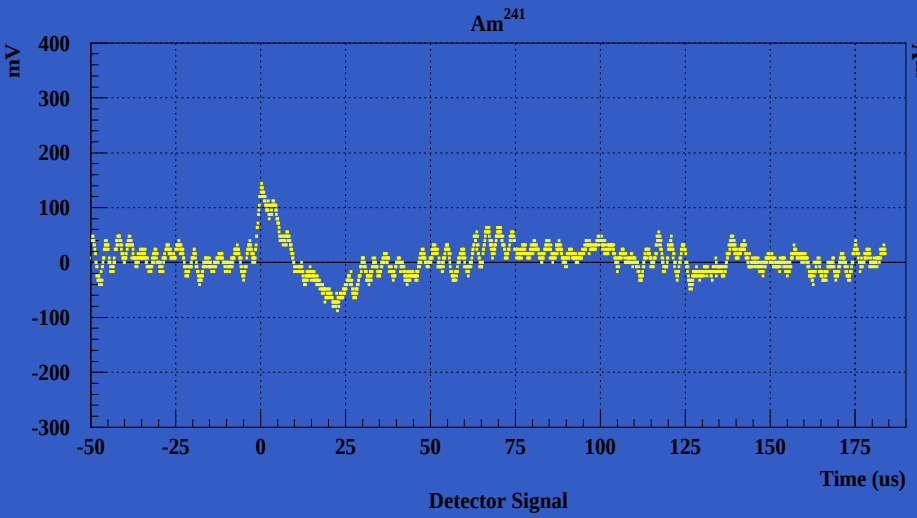


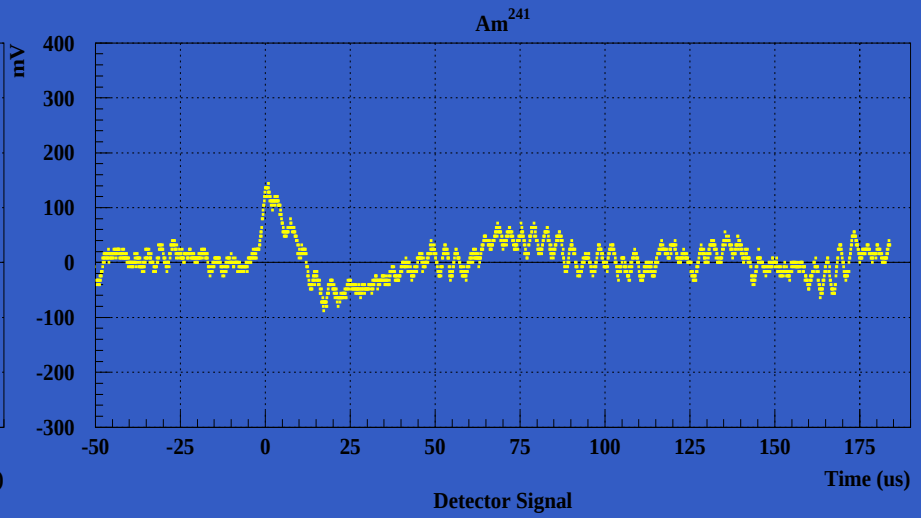


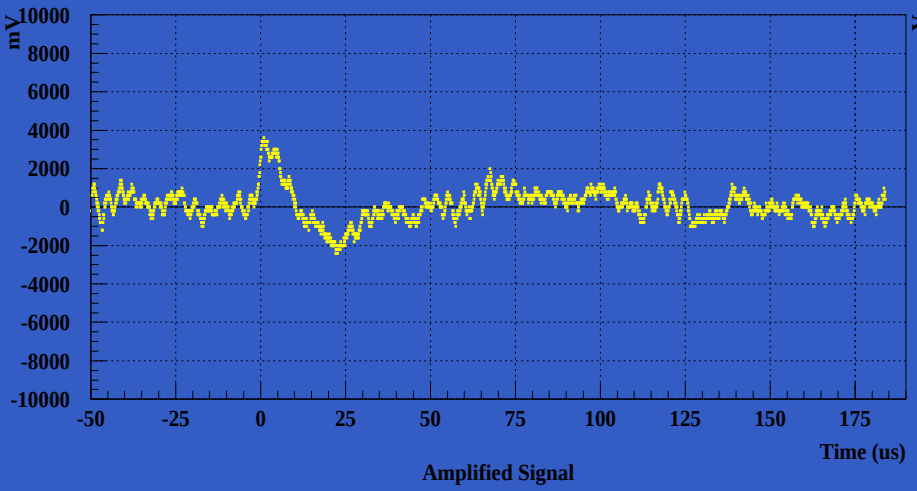


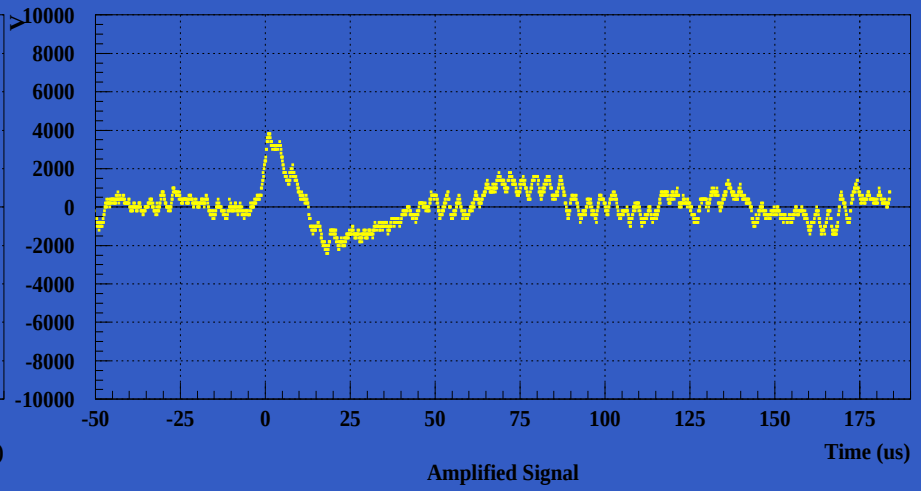


Amplifier TDA2030

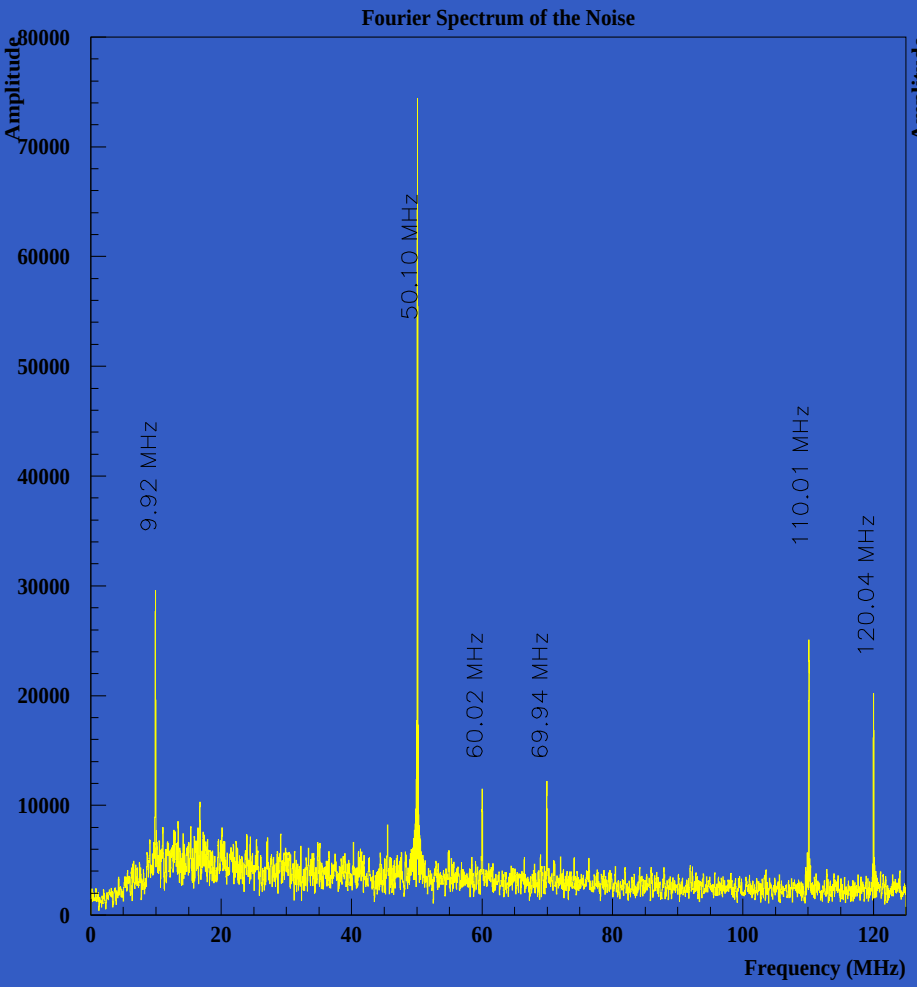


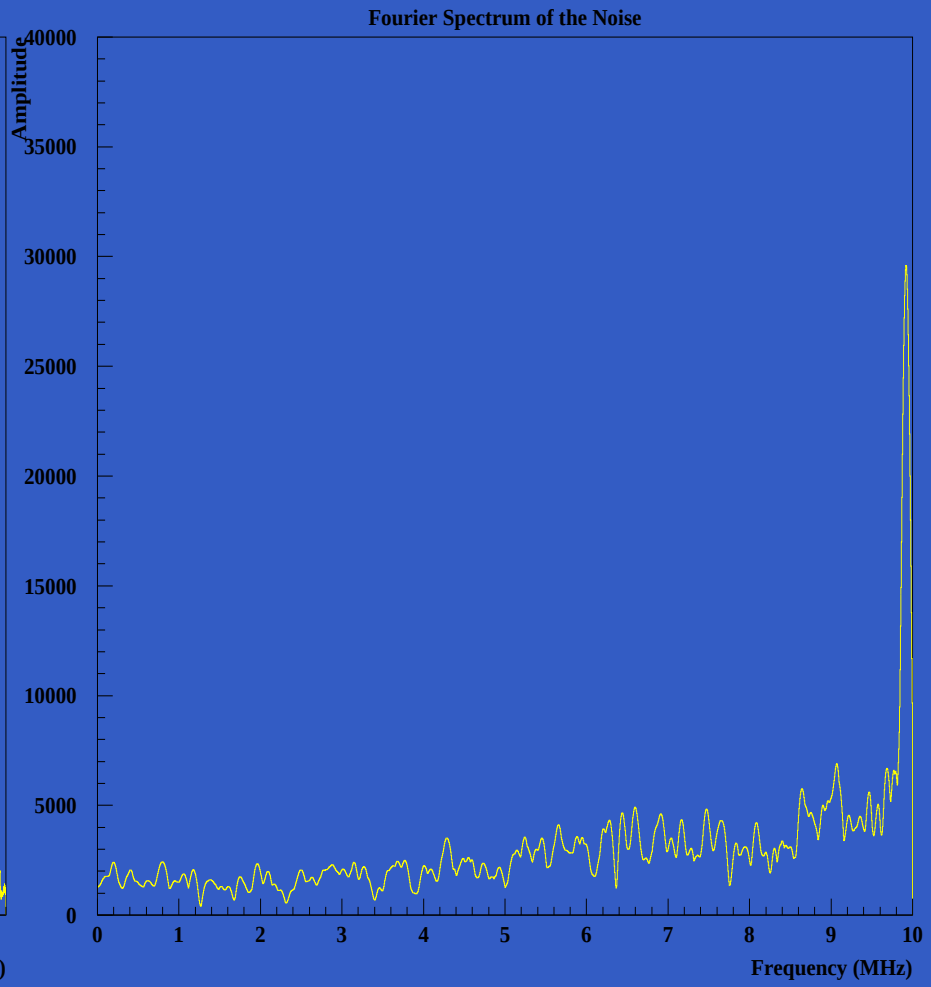






Fourier Analysis of the Noise





Conclusion

Detection of small photocurrent by X and γ radiation is tricky job.
The work requires a lot of trial and error.
We are just in the beginning!

Things to do :
A better PCB design. EMI Software like Ansoft, etc...
Optimization of choice of Photodiode.
Optimization of the shaping time.
Cooling the firts stage : FET input

References

Noise Analysis in Operational Amplifier Circuits, Application Report, Texas Instruments.

Photodiode Amplifiers, Changing Light to Electricity, National Semiconductor, Paul Rako, Application Note.

Characteristics and Use of Charge Amplifiers, Hamamatsu.

Photodiode Amplifiers, Gerald Graeme.

Low Noise Amplifiers for Small and Large Area Photodiodes, Glen Brisebois, Linear Technology.

Operational Amplifiers Handbook, Walt Jung, Analog Devices Inc.

Thanks

THANKS
for
COMMING and LISTENING