AN4451
Application note

Signal conditioning for a UV sensor

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Introduction

This application note describes the analog conditioning circuit used for a high impedance sensor that acts like a current sensor. It explains how to condition a signal coming from the sensor - in this case an ultraviolet (UV) sensor - and how to improve performance.

While sunlight is important for our health, overexposure to it carries significant health risks. For example, sunburn is caused by the UV radiation contained in sunlight. Measurement of UV is important from a medical point of view, but for various other reasons too. The detection of UV rays is important in the industrial domain, particularly to detect flame in a blue flame oil burner or in some fire detectors. Knowing the right levels of UV for plant growth is also important. Low levels of UV light have a positive effect on plant growth and seed germination but, higher levels can be harmful and even toxic. UV is part of our life and if it is not well controlled it can cause damage. Consequently, UV sensors are very important.

Contents

1 How does the UV sensor work

A UV sensor works as a photodiode. When a UV source irradiates the sensor, UV radiation is converted into a small current proportional to the UV radiation. Obviously, the delivered current depends on the UV sensor used. Formula (1) shows a rough estimation of the photocurrent (Ip) given for a particular active chip area (AChip).

$$Ip = \int_{\lambda 1}^{\lambda 2} Achip * Schip(\lambda) * Esource(\lambda)d\lambda \quad (1)$$

where:

Achip is the active chip area in m^2

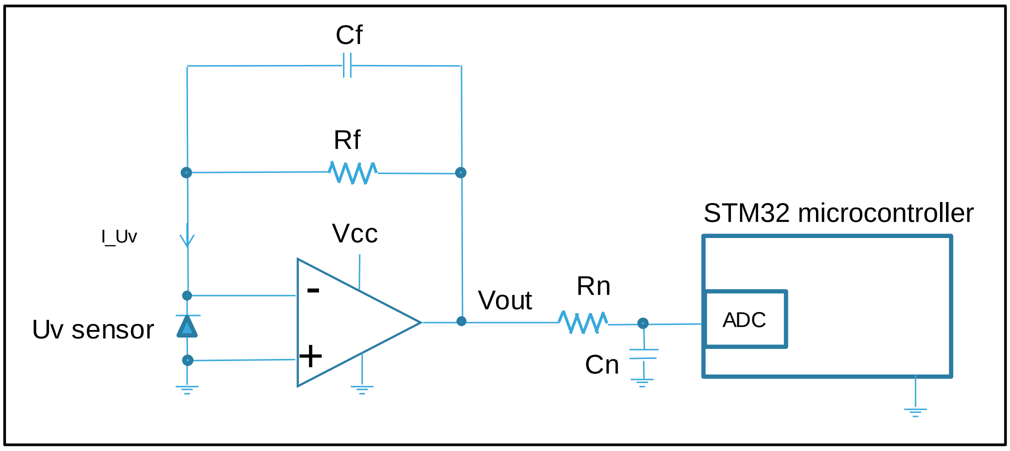
Schip is the chip's spectral sensitivity in AW^{-1}

Eλ is the spectral irradiance of the UV light source which can be measured in $mWcm^{-2}nm^{-1}$

1.1 Signal conditioning of the UV sensor

The UV sensor generates a small current, generally a few nA, which is proportional to the UV insulation. *Figure 1* exhibits a transimpedance amplifier configuration that is used to convert this current into an adequate voltage that can be read by the ADC of the microcontroller.

Figure 1: Transimpedance amplifier



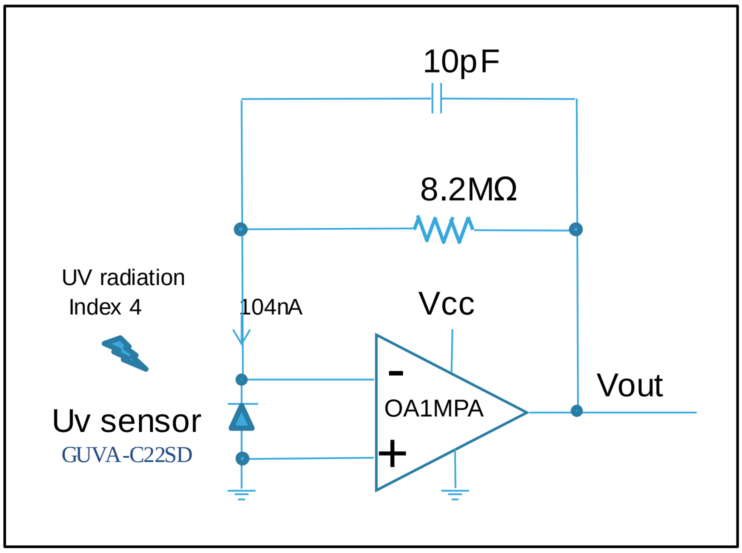
The op-amp converts the current generated by the sensor into a voltage thanks to the Rf resistor. The output voltage sensed by the ADC is theoretically given in formula (2):

$$Vout = I\_Uv * Rf \quad (2)$$

1.2 Application example

The UV sensor under consideration in this application note is the GUVA-C22SD from the Genuv Company (see *Figure 2*).

Figure 2: UV sensor application



The GUVA-C22SD sensor delivers a current of 26 nA/UV index. Rf is set @ 8.2 MΩ. Consequently, this sensor receives UV radiation with an index of 4 (Vout = 26 nA * 4 * 8.2 MΩ = 852.8 mV).

1.3 Input offset voltage (Vio)

As the ideal op-amp does not exist, it must be accepted that the op-amp itself has an impact. For example, an op-amp adds a DC offset on the output which is directly linked to the input voltage offset (see formula (3)).

$$Vout = I\_Uv * Rf \pm Vio \quad (3)$$

Consequently, it is better to choose an op-amp with a low input voltage offset (Vio). The OA1MPA is a good op-amp in this respect as it offers a maximum Vio of 200 µV. By taking the Vio into account, the Vout becomes: Vout = 26 nA * 4 * 8.2 MΩ ± 200 µV. Thus, Vout is in the range [852.6 mV:853 mV] which is an error of 234 ppm!

1.4 Feedback resistance

As the current generated by the UV sensor is extremely small, it is advised to use the largest feedback resistor possible to benefit from the ADC performance. Even though it may seem paradoxical, a large feedback resistor also helps to improve the SNR. Effectively, resistance noise is thermal noise which is defined as: en_Rf = √4*K*T*Rf, where K is the Boltzmann's constant (1.38x10^{-23} J/K) and T is Temperature ºK (T ºC + 273.15). The SNR is expressed in formula (4).

$$SNR = \frac{I\_Uv * Rf}{\sqrt{4 * K * T * Rf}} \quad (4)$$

By using a large feedback resistor, the SNR is improved by √Rf.

1.5 Input bias current (Iib)

By choosing a large feedback resistor while simultaneously trying to achieve a high gain, the input bias current of the op-amp causes another DC offset: Iib * Rf. Consequently, a low bias current op-amp is needed to obtain the highest sensitivity. To achieve this, it is extremely important to choose a CMOS op-amp such as the OA1MPA which offers a very low Iib (10 pA @25 °C). The total output voltage must also be considered (see formula (5)).

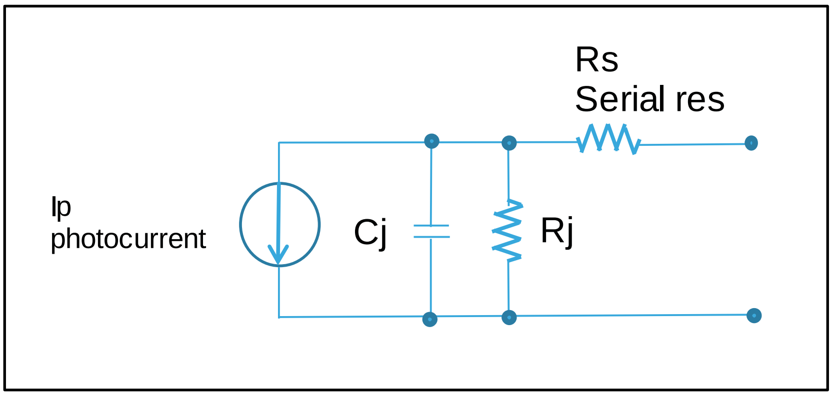
$$\boxed{Vout = I\_Uv * Rf \ \pm Vio \pm Iib * Rf} \quad (5)$$

If we consider the UV sensor application described in this document (see *Figure 2*) and if we use the OA1MPA as the transimpedance amplifier, the total Vout is:
Vout = 26 nA * 4 * 8.2 M Ω ±200 µV ±10 pA * 8.2 MΩ. Consequently, Vout is in the range [852.5 mV:853.1 mV]. This represents an error of 330 ppm compared to the theoretical value.

1.6 UV sensor equivalent circuit

Figure 3 exhibits the equivalent circuit of the photodiode, where Cj and Rj represent respectively the junction capacitor and the shunt resistor of the diode junction.

Figure 3: Equivalent circuit of UV sensor



1.7 Resistors Rs and Rj

The resistance of the output source, Rs, is generally negligible. On the contrary, the diode shunt resistance, Rj, should be as high as possible. For example, regarding the UV sensor GUVA-C22SD, Rj is in the range 100 GΩ. Effectively, without any current in the photodiode, an output of 0 V is theoretically expected. However, in reality Vout is as shown in formula (6).

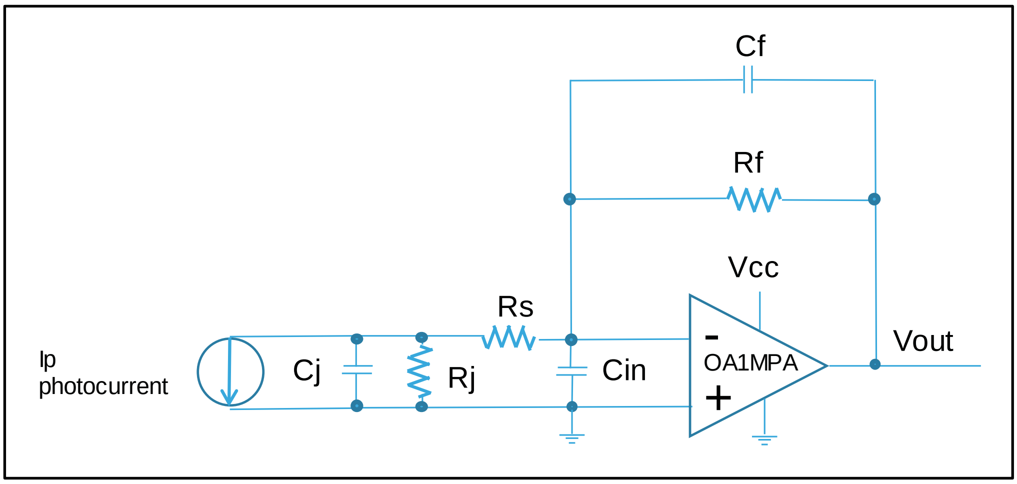
$$Vout = Vio * \left(1 + \frac{Rf}{Rs + Rj}\right) \quad (6)$$

Clearly, it is extremely important to have a low Vio and an UV sensor with a high Rj to limit the offset error on the output.

1.8 Capacitors Cj, Cin, and Cf

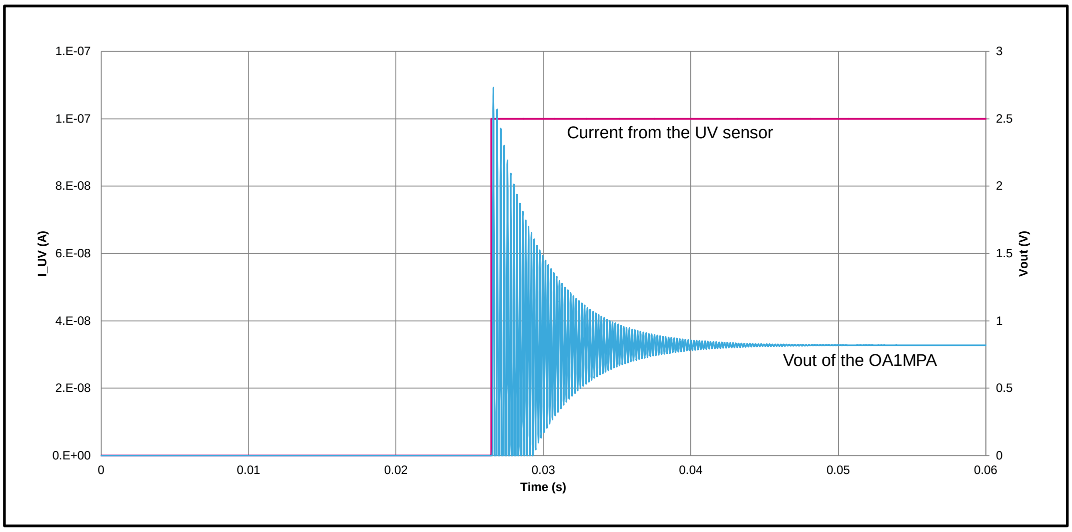
In general, transimpedance amplifiers are prone to oscillate. To understand the stability of this kind of architecture, it is important to take into consideration all components of the amplifier, even parasitic components, as shown in *Figure 4*.

Figure 4: Components that need to be considered in a transimpedance amplifier



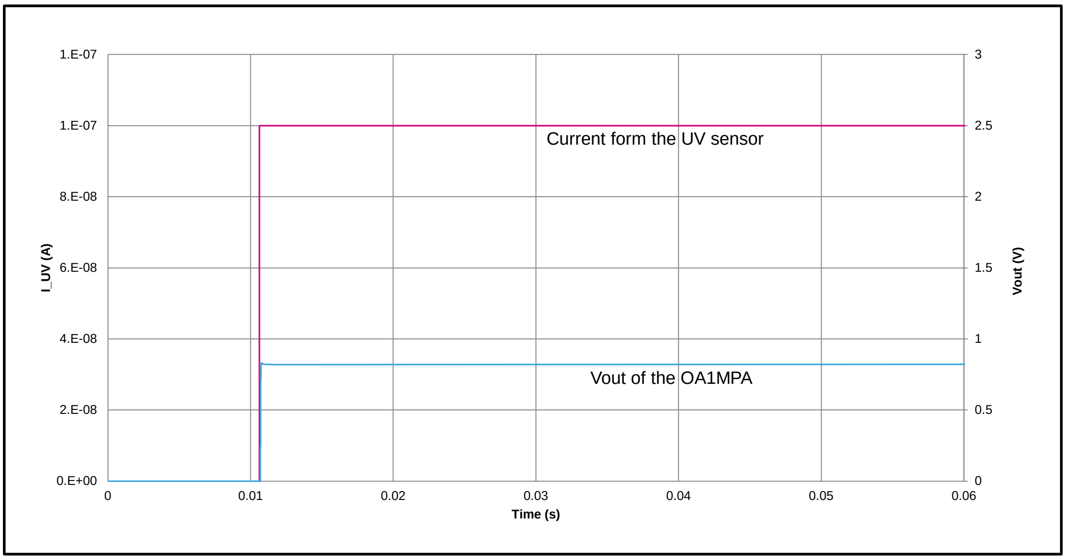
The noise gain of the above configuration determines the stability of the circuit. Generally, Rf is high to provide enough gain to convert the current of the UV sensor into a measureable voltage. However, Rf combined with Cin and Cj creates a pole which ensures instability of the circuit. In *Figure 5*, we can see that for a high value of Rf (8.2 MΩ) and no feedback capacitor (Cf), the output of the OA1MPA is unstable.

Figure 5: OA1MPA output response to a small current signal without feedback capacitance, Rf = 8.2 MΩ



By adding a small capacitor (Cf) across Rf, oscillations or gain peakings are suppressed and the output is stabilized (see *Figure 6*).

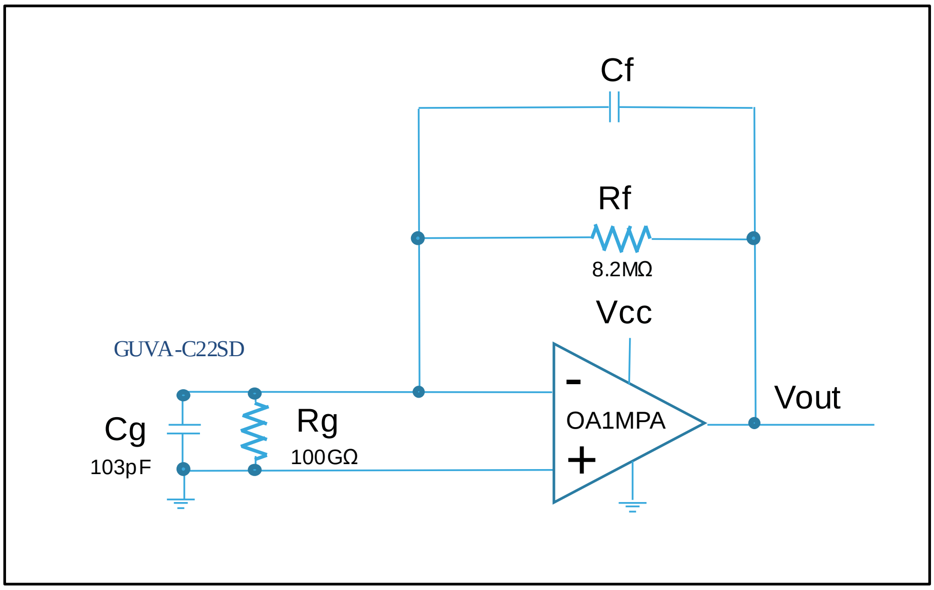
Figure 6: OA1MPA output response to a small current signal with feedback capacitance, Cf = 10 pF and Rf = 8.2 MΩ



2 Stability of the UV sensor

UV sensors are generally very capacitive. For example, the GUVA-C22SD UV sensor has an internal capacitance of 100 pF and the OA1MPA adds an additional input capacitance of 3 pF. Such capacitance has a direct impact on the stability of the system. This section describes how to calculate the minimum value of the Cf capacitor (see *Figure 7*). Cf is a feedback capacitor which is added in parallel with the transimpedance resistor. Its function is to stabilize the system. As Cf limits the bandwidth, it therefore minimizes noise. In the formulas below, Cin and Cj are considered as a unique capacitor, Cg, (see *Figure 7*). The serial resistor, Rs, which has a resistance of about 100 Ω is neglected.

Figure 7: Simplified equivalent circuit



The open loop transfer function of the system is given in formula (7).

$$-A\,\frac{Rg}{Rg+Rf}*\frac{1+j\omega\,(Cf*Rf)}{1+j\omega\left(\dfrac{Rg*Rf}{Rg+Rf}*\,(Cf+Cg)\right)} \qquad (7)$$

where:

A is the open loop transfer function of the op-amp.

However, by using formula (7), a pole appears and must be considered, as shown in formula (8).

$$fp=\frac{1}{2\pi*\dfrac{Rf*Rg}{Rf+Rg}*(Cf+Cg)} \qquad (8)$$

A zero also appears and must be considered, as shown in formula (9).

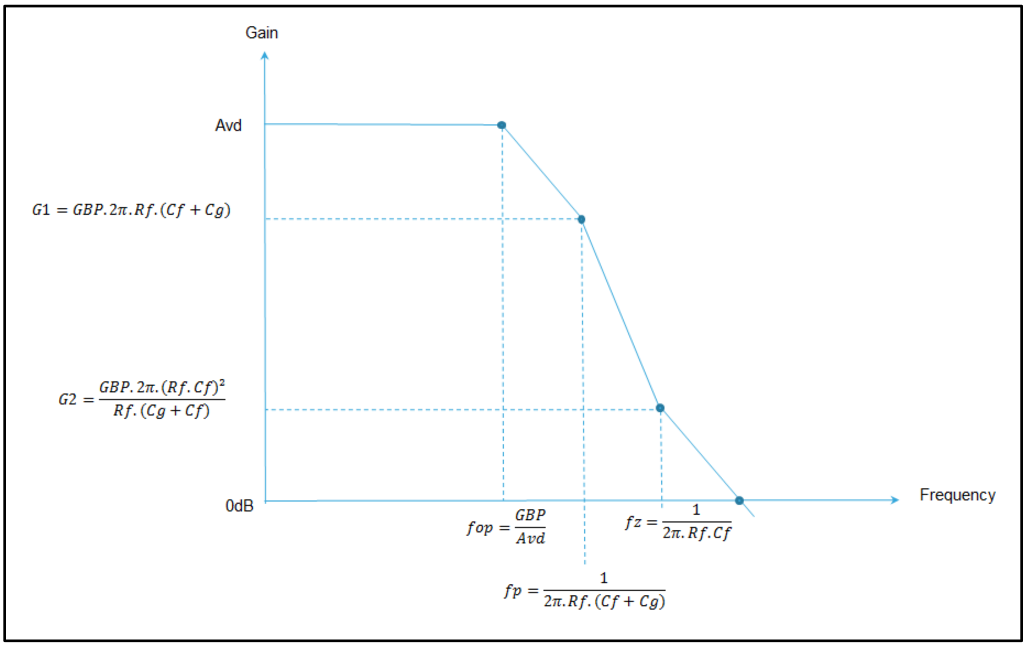
$$fz = \frac{1}{2\pi * Rf * Cf} \qquad (9)$$

In addition, the low-frequency pole of the op-amp's open loop transfer function must be considered, as shown in formula (10).

$$fop = \frac{GBP}{Avd} \qquad (10)$$

Therefore, the bode diagram of this system can be plotted as shown in *Figure 8*.

Figure 8: Bode diagram of the open loop transfer function of an application using a UV sensor



We can consider that Rg (100 GΩ) >> Rf (10 MΩ), so fz > fp.

With these considerations,

$$\frac{Rf * Rg}{Rf + Rg} \sim Rf \text{ and } fp = \frac{1}{2\pi * Rf * (Cf + Cg)}$$

To guaranty stability of the system, the bode diagram must cross the X-axis with a slope of -20 dB/decade. So, considering *Figure 8*, and to ensure stability, the gain at frequency fz must be greater than 1.

Consequently, formula (11) is inferred.

$$\frac{GBP * 2\pi * (Rf * Cf)^2}{Rf * (Cg + Cf)} > 1 \qquad (11)$$

A second order equation can be deduced as shown in formula (12).

$$GBP * 2\pi * Rf * \ Cf^2 - Cf - Cg > 0 \quad (12)$$

So, we can deduce the minimum feedback capacitance of Cf to guaranty stability of the OA1MPA, is shown in formula (13).

$$Cf = \frac{1 + \sqrt{1 + 8\pi * GBP * Rf * Cg}}{4\pi * GBP * Rf} \quad (13)$$

In this application, GBP = 120 kHz, Cg = 103 pF, and Rf = 8.2 MΩ. Using formula (13), we can calculate that the minimum feedback capacitance of Cf is 4.2 pF.

3 Noise reduction

The Cf capacitor added in parallel with the Rf resistor helps to stabilize the transimpedance of the application. It also lowers the bandwidth of the system. The cut off frequency is given by formula (14).

$$fc = \frac{1}{2\pi * Rf * Cf} \qquad (14)$$

If we consider a feedback capacitance of Cf = 10 pF, the bandwidth is limited to 1.9 kHz and noise is also reduced on the output. A simple RC filter may also be added on the output of the OA1MPA to obtain an overall second filter Rn, Cn as shown in *Figure1* and as described in formula (15).

$$fn = \frac{1}{2\pi * Rn * Cn} \qquad (15)$$

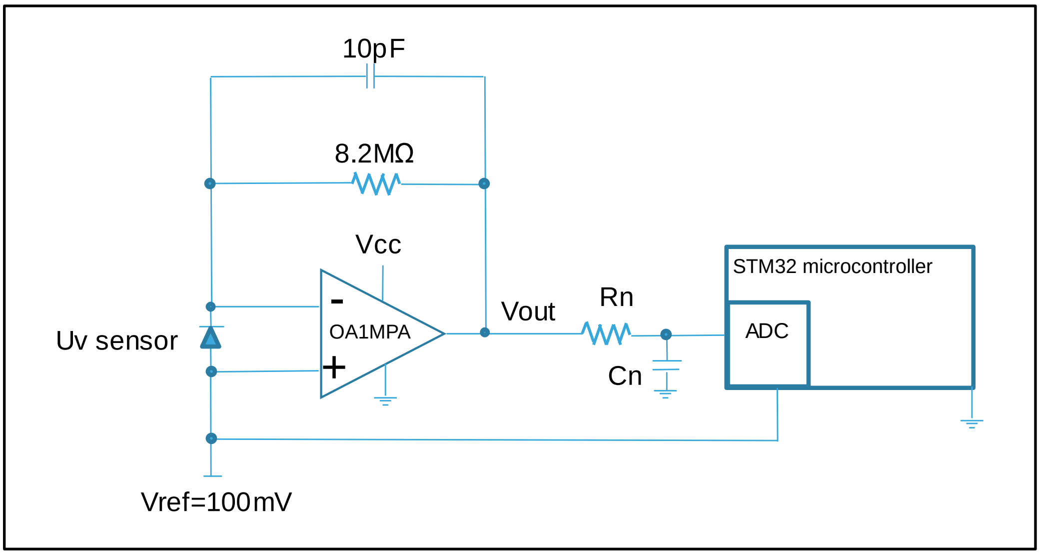
If the bandwidth is a critical requirement, choose an op-amp with a higher bandwidth like the TSV731 (GBP = 900 kHz). In addition, try to reduce the transimpedance gain (Rf) and add a second stage of voltage gain. The drawback is higher noise on the output.

4 Output voltage limitation

To improve the sensitivity of the UV sensor, use it in photovoltaic mode i.e. with a zero bias operation. In this case, the dark current offset is generated by the photodiode leakage. If the op-amp is used in single supply from GND to Vcc (as shown in *Figure1*), the Vol output saturation of the OA1MPA might be a limitation for treating low UV radiation levels.

Despite the fact that the OA1MPA is an output rail-to-rail op-amp, it has a Vol output saturation voltage of 40 mV @ 25 °C. When it is important to know precisely the current delivered by a sensor with a low UV intensity, add a reference to avoid Vol limitation as shown in *Figure 9*.

Figure 9: How to avoid Vol limitation



In the above case, there is an offset of 100 mV at Vout. It is important to connect Vref to the ADC to obtain a precise calculation.

5 Conclusion

UV sensors provide an extremely small current depending of the level of UV radiation. To convert this current to an adequate voltage, a transimpedance amplifier is used. Then, an ADC can convert the signal into the digital domain. For this kind of application, it is important to choose a CMOS rail-to-rail amplifier with a low Vio to avoid inducing big errors on the output. The OA1MPA is a good option for such a UV sensor application. However, stability must be also taken into account and the right components must be chosen, particularly the feedback capacitor Cf which helps to stabilize the system, limit bandwidth, and reduce noise.

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Figure 10: UV sensor evaluation board

6 Revision history

Table 1: Document revision history

Date	Revision	Changes
18-Mar-2014	1	Initial release.

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