SA 20.2: Integrated Ultraviolet Sensor System
with On-Chip 1GΩ Transimpedance Amplifier

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The output current delivered by photo-diodes with enhanced ultraviolet (UV) responsivity is in most cases small, thus requiring an interface circuit with high current gain. Generally, this is achieved using discrete components. This integrated system includes a 1GΩ transimpedance stage and an IC-compatible UV photo-diode on a single chip.

The industrial application motivating this work is flame detection for combustion monitoring. Available flame detectors, that operate inside the furnace, such as thermocouples, microphones and video cameras, provide a low signal-to-noise ratio and easily degrade in the hostile furnace ambient [1]. By contrast, flame monitors based on radiation detection can be placed outside the furnace, in a less harsh and polluted environment, thus increasing significantly long term stability and reliability of the system [2, 3]. Figure 1 shows a comparison between the spectra of combustion flame radiation and black body radiation at 2000K (temperature in the furnace). In the UV region, around 310nm wavelength, emission of the flame is much larger than the background radiation, allowing a large signal-to-noise ratio. For wavelengths longer than 400nm (visible and infrared regions), however, the background radiation is dominant. Therefore, to avoid degradation of detector performance, a special UV sensor that is blind outside the band from 250nm to 400nm is required. These specifications are fulfilled by the integrated UV sensitive photodetection system, whose responsivity is also shown in Figure 1. This system, including sensor and read-out circuit, uses a modified bipolar process [6]. Having a system on one chip allows rejection of electromagnetic interference, a larger signal-to-noise ratio, and cost-effective batch fabrication.

A cross-section of the silicon UV sensor is shown in Figure 2. It consists of very shallow p and n implantsations with high doping gradients, that create a depletion region close to the crystal surface where UV light is absorbed and carriers are generated [4, 5]. Although the depth of the implanted dopants is not standard, a few additional steps with low thermal budget and rapid thermal annealing allow fabrication of sensor and interface circuit on a single chip, without degrading the performance of the analog components [6]. To ensure proper operation of the system, a metallization layer (metal 0) shields the circuitry from stray light. Moreover, an interference filter consisting of aluminum and silicon dioxide is deposited on top of the sensor as a postprocessing step, to improve spectral selectivity.

The electrical equivalent circuit of the sensor is shown in Figure 3. It consists of the desired UV sensitive diode (D₀), a parasitic infrared sensitive diode (D₁) and a large junction capacitor (C). The current generated by the UV diode ranges from 20pA to 1nA and the signal bandwidth is 10Hz. Fortunately, the system does not require accurate control of the current gain and, therefore, the bipolar transistor β is exploited to amplify the signal current and a resistor, to transform it into an output voltage.

The schematic of the bipolar transimpedance amplifier realized for this application is shown in Figure 4. Transistors Q₁ = Q₀ provide a low-impedance input for the photo current (Iᵦ = I₀/R₁) and the proper zero-volt biasing for the UV diode. The anodic photo-current (Iₓ), collected by the emitter of Q₀, is injected into the base of Q₁, multiplied by R₂ and βᵦ, mirrored into Q₀ and, finally, transformed into a voltage by R₁. The infrared dependent cathode current (Iᵦ + Iₓ) is shunted to ground. The voltage Vₒ across the output terminals of the circuit is, therefore, given by

\[ Vₒ = \betaᵦ K (I₁ₚ + I₁ₜ) + \betaᵦ βᵦ K R₁ (I₁ₚ + I₁ₜ) \]

Assuming perfect device matching (Q₀ = Q₀, Q₁ = Q₀, R₁ = R₁, βᵦ = 80K and the mirror factor K = 2), this results in a 1GΩ transresistance. Due to the large transimpedance of the circuit and to satisfy the noise requirements (the white current noise of transistors decreases with the collector current), I₁ₚ has to be very small and well controlled. A biasing section (transistors Q₁ - Q₃) replicates the gain stage (Q₀ - Q₀) and R₁ = R₁ to feeds back the proper bias current. Changing the reference voltage Vₒ accurately, the relationship between Vₒ and I₁ₚ is given by

\[ Aᵦ = \frac{Vₒ}{βᵦ R₁} \]

In view of the large transresistance gain (βᵦ R₁), it is possible to regulate the current from 0 to 15nA with a voltage ranging from 3.5V to 0V. The stability of the feedback loop is ensured by the compensation capacitor C = 12pF.

A micrograph of the transimpedance amplifier integrated together with the UV diode in a modified bipolar process is shown in Figure 5. The die is packaged in a TO5 case with lens cap and filter glass, to focus the UV radiation on the sensor and perform optical band-pass filtering. The 1mm² sensor is octagonal to fit the image of the lens. The total chip area, dominated by the sensor, is 4mm². Figure 6 shows the measured output voltage of the read-out circuit as a function of the UV diode current. The transimpedance is 10KΩ. The step response of the system, obtained by focusing chopped UV light onto the sensor is shown in Figure 7. The response time of less than 100ms is determined by the parasitic load of the sensor. Features of the system are summarized in Table 1.

References:
Figure 1: Spectra of combustion flame radiation, furnace background radiation (2000K) and responsivity of the UV sensor.

Figure 2: Cross-section of silicon UV sensor integrated using a modified bipolar process.

Figure 3: UV sensor electrical equivalent circuit.

Figure 4: Schematic of the proposed transresistance amplifier realized in bipolar technology.

Figure 5: Chip micrograph.

Figure 6: Measured system output voltage vs. UV sensor photo current.

Figure 7: Measured system step response obtained by focusing chopped UV light on sensor.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Modified bipolar</th>
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<tbody>
<tr>
<td>Power supply</td>
<td>5V</td>
</tr>
<tr>
<td>Power consumption</td>
<td>4mW</td>
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<tr>
<td>Input range</td>
<td>20pA-1nA</td>
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<tr>
<td>Transresistance</td>
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<tr>
<td>Bandwidth</td>
<td>20Hz</td>
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<tr>
<td>Input referred noise</td>
<td>&lt;3.68pA/Hz at 1Hz</td>
</tr>
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Table 1: System features.