20.8 A 0.25µm Logarithmic CMOS Imager for Emissivity-Compensated Thermography

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Challenges in the design of solid-state imagers for industrial measurement and control include: high image resolution, wide temperature range, adequate temperature resolution, high measurement speed, thermal stability of the sensor chip, and most importantly, low cost. However, they have the inherent disadvantage that their temperature information is strongly dependent on the emissivity of the probed material. This shortcoming can be eliminated if the ratio of an unfiltered and a filtered response of two photodiodes is considered.

The requirement of fast signal ratioing can be well met if a logarithmic CMOS imager [1] is used, since with the lin-log conversion of each diode signal, the signal ratioing is reduced to a signal subtraction. We recently indicated the potential of this concept by using 2 of the color-filtered pixels in a logarithmic CMOS imager [2]. However, the pixels of this imager are covered by organic filters, which tend to degrade at the high temperatures (\(>70^\circ\text{C}\)) at which the imager is required to operate in industrial applications. To use the circuit in a ratio-pyroelectric camera setup it is essential to have absolutely stable optical filter characteristics. A shift in the cut-off wavelength by thermal-induced degradation would be disastrous for calibration of the chip as a temperature measurement system, and to its long-term stability.

Here, we present a logarithmic CMOS imager for emissivity-compensated thermography, having thermally-stable and optimized inorganic multilayer integrat-ed filters and a pixel cell containing a subthreshold load transistor with optimized device layout, providing VGA resolution, 40fps, a measuring temperature range of 600°C to 3000°C, and a temperature resolution of \(-5^\circ\text{C}\).

The schematic block diagram of this ratio pyro camera chip and the external signal post-processing units is shown in Fig. 20.8.1. The key component of this pixel cell with \(+140\text{dB}\) dynamic range is a load transistor that is forced to operate in the subthreshold regime by short-circuiting the gate-source terminals (Fig. 20.8.2). This load transistor has a special ring-type layout and the photodiode has bevelled corners to minimize the leakage current, thus maximizing the dynamic range of the detectable photo-signal. The degree of leakage-current reduction from this ring-type layout, if compared to a normal transistor layout, is remarkably large (Fig. 20.8.2).

The photo-responses of the unfiltered and filtered diodes are buffered, trans-ferred by means of a multiplier and amplified before being converted to digital signals on the chip, while fixed-pattern noise (FPN) correction and other means of signal post-processing are done in the digital domain off-chip. Also, the ratio-ing of the photo-signal pairs is arranged in the digital domain by subtracting the lin-log and A/D-converted signals of the unfiltered and filtered photodiodes (Fig. 20.8.1).

Ratioing the photo-signals of diodes with different spectral responses according to Planck’s temperature emittance, close proximity and good thermal coupling have several benefits: 1) the signal ratio represents absolute-temperature information; 2) temperature information is independent of the emissivity of the probed material; and 3) the signal ratio is far less affected by the temperature of the imager itself [2]. All these aspects become important advantages when it comes to practical applications. Since such a temperature imager may have to be positioned relatively close to a thermal scene, the sensor may be somewhat heated up itself. In spite of the resulting temperature drift of each diode signal, however, the temperature information remains unaffected thanks to the signal ratioing.

The elevated sensor temperatures during application also require the use of inor-ganic layers for realizing the spectral filter on one of the two diodes. In this work, an optical filter design, based on a 3-layer stack of silicon process-compatible materials (\(\text{Si}_3\text{N}_4, \text{Si}-\text{Si}_3\text{N}_4\)), is employed. The technology process is an add-on to a foundry CMOS imager fabrication process, involving chemical vapour deposition of two 90nm-thick silicon nitride layers in a sandwich structure with a 290nm magnetron sputtered amorphous silicon layer (Fig. 20.8.3). This layer stack provides a long-pass filter characteristic with a cut-off at 650nm (Fig. 20.8.4). The two-dimensional arrangement of the filtered photodiodes is accord-ing to a checkerboard structure (Fig. 20.8.3). The spectral responses of the unfiltered and filtered pixels are measured in a monochromator setup to verify the design. The optical spectrum received by the diodes is tailored by using a glob-al optical filter on the lens of the camera setup [2], into which the imager chip is mounted. The global filtering is done with respect to the lowest measurable tem-perature being related to the red and near-infrared range of the optical spectrum, yielding \(-3\times\) better signal ratio. This increases the detectable temperature span to 2400K (Fig. 20.8.4).

The CMOS part of the imager is fabricated in a 0.25µm foundry technology. The 640×480 camera is calibrated using a radiating grey body, whose temperature is referenced by a prototype single-spot-ratio pyrometer, preliminary within 650 to 1850°C. The design enables this thermal imaging system to have a fixed aperture (f/2.8) throughout the entire temperature range as there is no clipping of the detector to be expected. By means of neutral density filters (OD 0.3, 1.3 and 2.0) the compensation of different emissivity is tested with different temperatures (700°C, 1000°C, 1300°C and 1600°C) and is proven to be reasonable, since there is no evident change of the measured temperatures. The first applications of the chip show macro snapshots from a filament of a tungsten lamp (Fig. 20.8.5). A temperature error of \(-1.5\%\) (related to span) of the measured temperature results from uncertainties in the calibration procedure and the apparent FPN. The exemplary temperature-line contour, shown in Fig. 20.8.5, illustrates the good spatial and temperature resolution of the sensor.

The table of Fig. 20.8.6 provides quantitative and qualitative measures to bench-mark the original thermal imager from this work against three established thermal sensors, e.g. [3]. The comparison clearly shows that the ratio pyro camera fills a gap in the apparent application space, i.e. high-temperature and high-speed thermal measurement with high spatial resolution and last, but not least, compensation for emissivity. There are many industrial applications, such as laser processes, steel moulding, and semiconductor rapid hot-process control, for which this ratio pyro camera appears to be best suited.

References:
Figure 20.8.1: Schematic of the pixel cell, the integrated circuits and the post-processing units. Lin-log conversion of the photo-signals is done directly within the pixel, while division of signals from the unfiltered and filtered photo-signals is done by subtracting the log signals in the digital domain off-chip.

Figure 20.8.2: Schematic of the logarithmic pixel cell with the subthreshold load transistor (top-left), the I_D-V_DS characteristics of that load transistor for normal and ring layouts (right), and the layout of the ring transistor leading to a lin-log conversion range of 7-to-8 decades (bottom-left).

Figure 20.8.3: Schematic cross-section of the filter placement on chip (top), the checkerboard filter arrangement used (bottom-left), and indication of the filter-layer structure (bottom-right and top).

Figure 20.8.4: Design of the long-pass filter with cut-on at 650nm compared to the measured pixel response (left) and relative spectral responses of the unfiltered and filtered photo-signals used for the ratioing, as well as the response of the global filter applied to both signals (right).

Figure 20.8.5: False color table for the thermal image of a tungsten filament 3x7mm² (left) and temperature distribution from a line measurement with a 10-pixel smoothing function (right).

Figure 20.8.6: Benchmarking of 3 established thermal radiation thermometers against the ratio pyro camera from this work.