Ultraviolet and visible spectral imaging of hydrogen flames using an organic photoconductive film CMOS imager

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ABSTRACT

We have developed a real time ultra-violet (UV) imaging system that can visualize invisible hydrogen flame together with a visible (VIS) background scene in outdoor environment. As a UV/VIS image sensor, an organic photoconductive film (OPF) imager is employed. The OPF has intrinsically higher sensitivity in the UV wavelength region than those of conventional consumer CMOS image sensors (CIS) or Charge Coupled Devices (CCD). Imaging of hydrogen flame is realized by subtracting a high level background VIS image from a UV hydrogen flame image overlapped on the background. The system is capable of imaging a weaker hydrogen flame signals by 4 orders of magnitude than that of VIS background. It is applicable not only to future hydrogen supply stations but also to other UV/VIS monitor systems requiring solar blind imaging.

INTRODUCTION

Fuel cells using hydrogen are considered to be a primary candidate for next generation power sources causing no load of environment. Along this roadmap, construction of the hydrogen supply stations has been started in several countries [1]. A major concern in safety issues in these systems lies in the fact that hydrogen becomes extremely flammable due to lowering of the ignition energy when mixed with air in a relative contents range of 10% to 60% [2]. Furthermore, because the emission band head of the hydrogen flame lies in a ultra-violet (UV) region (~310 nm), it is invisible to human eyes. A worst and actually reported scenario is that human beings pass through the invisible hydrogen flame caused by accidentally leaking hydrogen from a high pressure tank ignited near the leaking point [1].

Therefore, in these stations, it is important to immediately and accurately detect hydrogen flames within an ordinary background scene. To this end, an imaging system that visualizes both UV and visible (VIS) light scenes are required. In addition, the light intensity of hydrogen flame is extremely small (typically 1~10 nW/cm^2) against background VIS light (in the case of daytime sunlight, it is about 10^5 lux). In order to visualize hydrogen flame, the imaging system should be able not only to detect hydrogen UV (~310 nm) signals, but also to separate them from high background VIS signals. In this regard, the sensitivity of ordinary Si CMOS image sensor (CIS) in UV region is not sufficiently high except for a specially made CIS in which the quantum efficiency of UV light is enhanced [3]. Although UV sensing material, i.e. AlGaN, based sensors with high sensitivity in a UV range have been reported, they are incapable of imaging VIS light [4].

In this work, we have developed an ultra-violet and visible (UV+VIS) imaging system based on an organic photoconductive film (OPF) imager. The OPF has intrinsically high sensitivity in the entire wavelength region desired, i.e. from UV to VIS regions. Imaging of hydrogen flame is realized by subtracting a high level background VIS image from a UV hydrogen flame image overlapped on the background. This image process is carried out in each frame resulting in a real time monitoring. It is shown that the system is capable of imaging a weak hydrogen flame signals from a 4 orders of magnitude higher VIS background signals.

ADVANTAGE OF OPF IMAGER

Major advantages of the OPF imager as the hydrogen imager are two folds. Firstly, as shown in Fig. 1, the OPF imager has high quantum efficiency both in the VIS and the UV regions as compared with those of ordinary CIS or reported UV sensing materials.

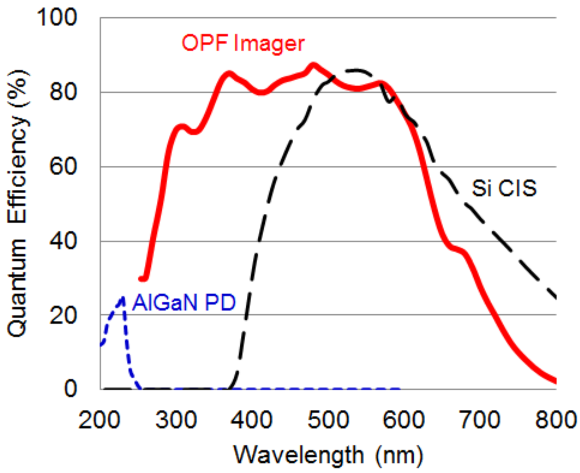

Fig.1: Quantum efficiency spectra of our OPF CMOS imager (red), a Si CIS (black) and an AlGaN photodiode (blue) [4].

The schematic cross sectional view of a typical pixel region of an OPF imager is shown in Fig.2. The device consists of, from the top in order, a protecting film, the top transparent electrode, OPF, the bottom pixel electrode directly connected to CMOS circuits [5, 6]. Since OPF has a high absorption coefficient both for UV light and VIS light, the thickness of OPF could be reduced to 0.5 µm from that of the ordinary photodiodes depth of CIS, i.e. 2~3 µm, while still keeping high sensitivity. Secondly, a high dynamic range of the OPF due to separation of the storage node from the photo-conversion area can be made use of to accommodate the high level VIS background. The pixel circuit is 3-Tr (a reset transistor (Tr1), a selection transistor (Tr2), and a source follower amplification transistor (Tr3)) configuration and in order to extend the saturation level to the highest level possible, a storage capacitance (SC) of large capacity is incorporated as shown in Fig. 3. The SC allows charge accumulation up to the breakdown voltage of the junction, the input of Tr3 can be swung to the level of the input voltage of Tr3 (V_{dd}) giving rise to a much higher saturation level [6]. The specifications of the developed OPF imager are summarized in Table. 1.

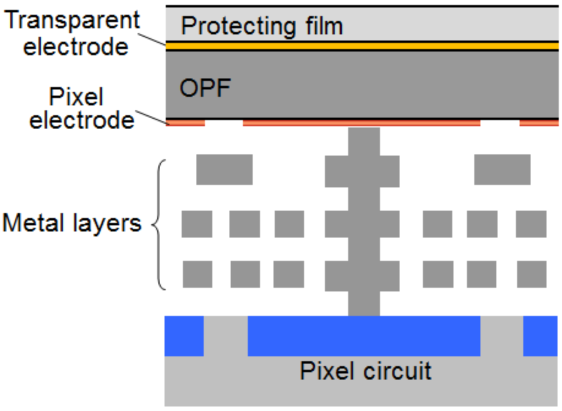

Fig.2: A cross sectional view of an organic photoconductive film (OPF) CMOS imager.

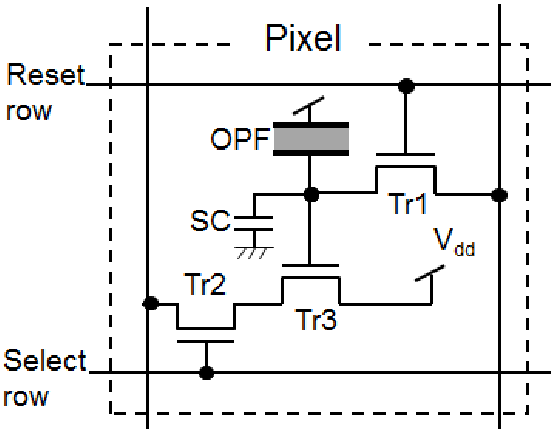

Fig.3: A schematic of the pixel circuit.

Table.1: Specification of the OPF imager used in the present work.

Process Technology	65 nm CMOS (1Poly-3Cu-1Al)
Number of pixels	1880 (H) x 1400 (V)
Pixel size	0.9 µm
Power supply	2.8 V, 10 V
Frame rate	10 fps
Saturation Charge	6500 electrons
Dynamic range	68 dB

PROPOSED IMAGING SYSTEM

A photograph of the developed imaging system (camera) is shown in Fig.4. It consists of 3 boards, i.e. a power supply board, a signal processing (field programmable gate array (FPGA)) board, a sensor head board on which a c-mount lens is attached. Fig.5 shows a signal flow diagram embedded in the FPGA. To explain the flow of signal processing in order, first, the reference visible light (VIS) image data are held in a double-data-rate (DDR) synchronous dynamic random access memory (SDRAM). Secondly, when hydrogen flame is ignited due to the leakage of hydrogen, real-time image data of background visible light and hydrogen flame (VIS + UV) is found. Thirdly, only hydrogen flame image (UV) is extracted by subtracting a VIS reference image stored in the DDR from a UV+VIS image and gain up. Finally, the reference visible image (VIS) is synthesized with the extracted UV image. With this method, it is possible to visualize the hydrogen flames and to determine the leak points in real time and in the real environment (background).

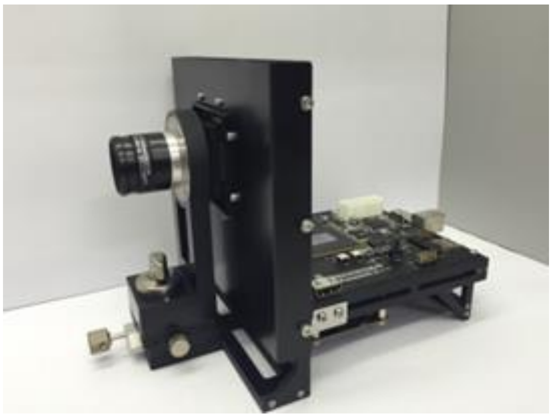

Fig.4: A photograph of the developed imaging system (camera).

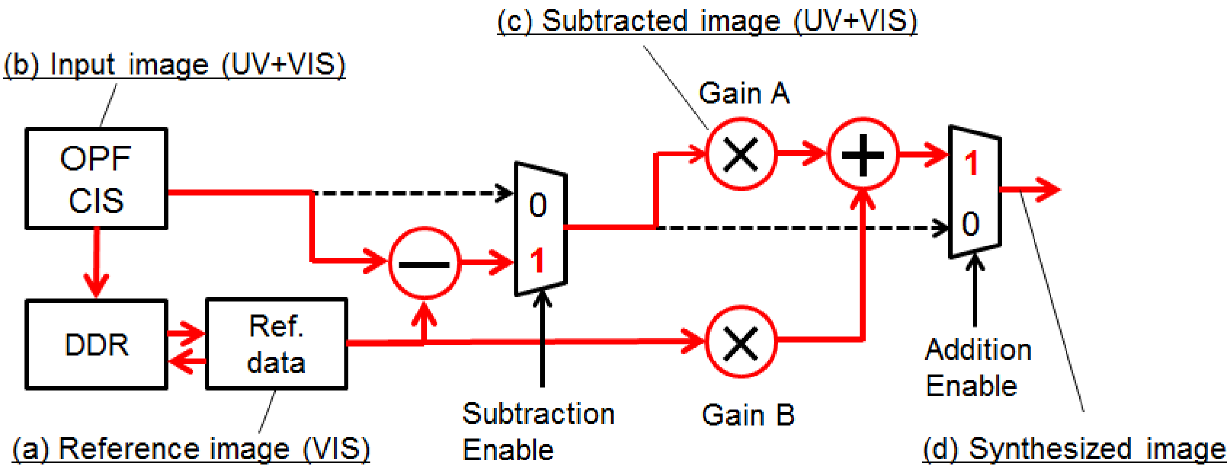

Fig.5: A signal flow diagram of the developed UV imaging system.

RESULTS AND DISCUSSION

In experiments, Bunsen burner systems of hydrogen and propane are used as flame sources. The distance between the camera and hydrogen flame is 8 m. In Fig.6, flames are lit on both burners. The image is taken with a visible CIS. The propane flame (right side) with orange emission is clearly visible while the hydrogen flame (left side) is entirely invisible. A daylight irradiation at about 1000 lux of halogen lamp (color temperature: 2800 K) was measured with an illuminance meter (CL-500A, Konica Minolta). The spectrum of hydrogen flame was measured with a spectrometer (SPG-120UV, Shimadzu) is shown in Fig.7. Intensity of the UV radiation is ~10 nW/cm^2 was calibrated by Si-PD (S12698, Hamamatsu Photonics) and high transmission UV bandpass filter.

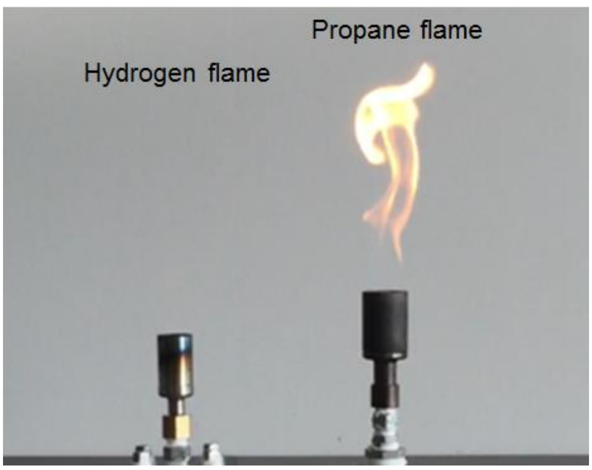

Fig.6: Flame images of hydrogen (left) and propane (right) taken by an ordinary CIS showing entirely invisible characteristics of the hydrogen flame.

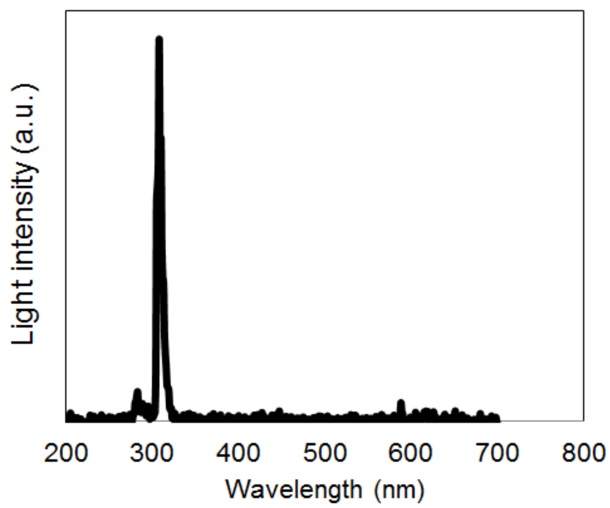

Fig.7: Light intensity spectrum of the hydrogen flame with a peak at around 310 nm.

In Fig.8, obtained images at the specified nodes of the signal flow diagram in Fig.5 are shown. Fig.8 (a) is a reference visible light (VIS) image stored in the DDR. Fig.8 (b) is an image including the UV light of hydrogen flame and background visible light (VIS + UV). Here, hydrogen flame cannot be recognized because the intensity of hydrogen flame is smaller by 4 orders of magnitude with respect to the background VIS light. We have extracted a hydrogen flame image Fig.8 (c) by subtracting Fig.8 (a) VIS image from Fig.8 (b), i.e. UV+VIS image. Finally, the hydrogen flame image of Fig.8 (c) is synthesized with the reference image of Fig.8 (a) resulting in the clear image of Fig.8 (d). The signal to noise ratio (SNR) of image Fig.8 (c) is 3 dB.

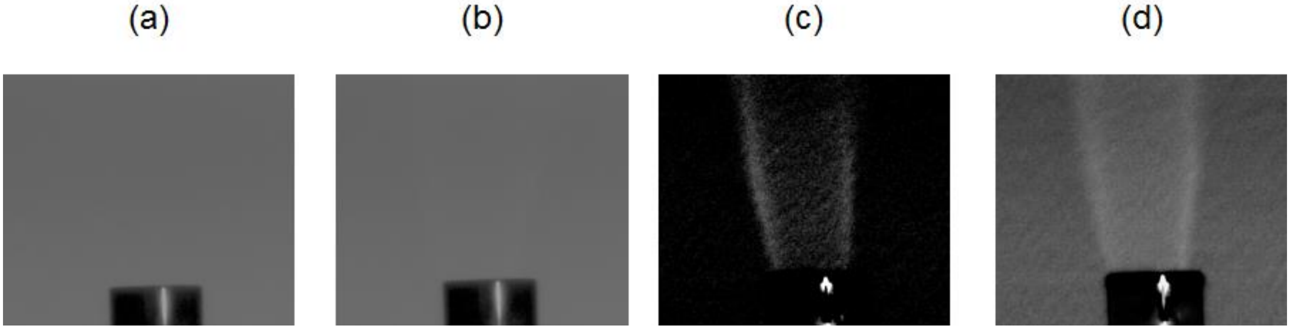

Fig.8: Images of tip of burner: (a) is a reference visible light (VIS) image stored in the DDR. (b) is an image including the UV light of hydrogen flame and background visible light (VIS + UV). (c) is the hydrogen flame image extracted by subtracting (a) VIS image from (b) UV+VIS image. (d) is the hydrogen flame image extracted by synthesizing (c) and (a).

In the case of using the UV transmission filter obtained for comparison, the signal to noise ratio is 12 dB (Fig.9). It is noted that the lower SNR of the present optical-filter-less system is due to shot noise of the VIS image. Finally, in order to investigate a dynamic motion of the hydrogen flame, imaging by a global shutter (GS) operation mode [7] is tested as shown in Fig.10. Compared with an image taken with a rolling shutter mode (left), an image taken with a GS mode (right) exhibits a more resolved signature presumably due to dynamic motion of the flame such as turbulence. It is expected to play a useful role in the investigation of flame dynamics in future.

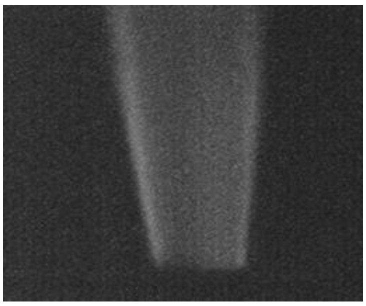

Fig.9: UV image of hydrogen gas extracted by an UV optical filter system.

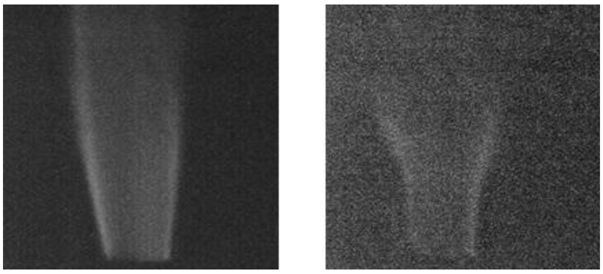

Fig.10: UV images of hydrogen gas generated by a rolling shutter mode (left) and by a global shutter mode (right).

CONCLUSION

We have developed an imaging system using an OPF imager with high sensitivity and wide dynamic range capable of visualizing invisible hydrogen flame. We have employed a real-time monitoring system with a built-in filter function in the FPGA that extracts the UV image of hydrogen flame by subtracting a VIS reference image from image including UV of hydrogen flame and VIS reference image. Invisible hydrogen flames are successfully visualized in real time. This system is expected to be applicable to other UV imaging applications requiring "solar blind" imaging.

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