Color Sensors and Their Applications

Poenar Daniel Puiu

Abstract This chapter intends to provide an introduction to and a very brief summary of the principal categories of color sensors and of their applications, both relatively little known to the general public.

First, an introduction describes the background of the topic(s) and the overall context. The main differences between two major but complementary techniques, colorimetry and spectrometry, will be presented here, as well as a quick summary of the scientific, technical, and industrial applications of color sensing. The second section will summarize the basic operational principles and architectures of color sensors realized in silicon. Although stand-alone detectors will also be described and discussed, the main focus will be on solid-state microsensors which can ideally be monolithically integrated together with signal processing circuits onto the same chip as "smart sensors" or intelligent microsystems. First, sensors realized only in monocrystalline silicon are summarized, followed then by those fabricated in other materials, with amorphous silicon and its alloys as the key players in this latter category.

Finally, the chapter ends with the sections devoted to Conclusions and References.

This chapter presents only a few of the most relevant aspects related to color sensors and examples of their practical applications. It is, in fact, an extensively abbreviated version of a much more detailed and exhaustive review dedicated to both color sensing and microspectrometry, and which is presently in preparation for future submission to Springer Verlag.

Keywords Smart sensors • Color filter array (CFA) • Two-junction color sensors • Triple-junction color sensors • Thin film color sensors

P.D. Puiu (✉)
School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, Republic of Singapore 639798,
e-mail: epdpuiu@ntu.edu.sg

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1 Introduction—The Color Sensor: Necessity or Just a Curiosity?

Color is one of the most important characteristics of light, although we may not always be aware of this fact and of its importance, taking it for granted.

However, even though color plays a unique role of great importance in our daily life and—as we shall soon see—in quite a few industrial and scientific applications, the number of sensors dedicated to color sensing is surprisingly small and—more importantly—the existence or operation principles of such sensors are very little known to the general public. When "microelectronics" is mentioned, most of the people think of mobile phones, computer microprocessors, or other familiar applications such as DVD players, GPS, or game consoles. In general, the media typically focuses its attention on the latest developments in these areas which are very familiar to everybody, such as telecommunications, computers, and new consumer electronic gadgets.

However, another extremely important area deals with sensors and actuators. Sensors can be briefly defined as devices or systems which detect relevant signals from the environment and convert them into an electric signal or data that are further processed into electronic circuits. Without sensors, most of our technological equipment, from complicated machinery to gadgets that we use daily, would be unable to operate. Sensors pick up the signals containing precious information necessary to either correctly operate equipments or control processes by providing vital data for their feedback. Presently, the trend is to no longer realize discrete sensors which can then be combined with various integrated circuits on a printed circuit board in order to perform a certain desired function. Instead, the technological advances in the area of microelectronic fabrication made it possible to integrate a complete microsystem on a single chip both the sensor and its intelligent signal conditioning circuits as well as digital processing blocks which manipulate the obtained data. This high degree of integration is possible due to the progresses in two areas. The first key factor is the miniaturization of integrated circuits which has been going on aggressively in the last decades and which has now reached Ultra-Large Scale Integration (ULSI) levels in which the feature size of the transistors is at submicron scale. For instance, Intel's Atom processors presently integrate features as small as 45 nm using a high-*k* metal gate technology, and this will soon be replaced by a 32-nm silicon process technology [1]. Such advanced fabrication technology allows the realization of extremely complex circuits like microprocessors and Digital Signal Processors (DSPs).

The second factor is the development of Micro-Electro-Mechanical Systems (MEMS) or Micro-Opto-Electro-Mechanical Systems (MOEMS) that can be fabricated in silicon (or other materials) using modified microelectronic processing derived from IC fabrication in order to achieve various structures with different functionalities other than purely electronic ones. This enabled the realization of new and complex structures that can be used as sensors or actuators of various types.

The co-integration of both the sensor(s) and its/their signal processing circuits is demanded by practical considerations such as the reduction of the useful signal magnitude for smaller scale sensors, and the needs to minimize parasitic components and to perform amplification as well as other signal conditioning operations such as scale linearization, filtration, and elimination or minimization of offset and drift. Additional functions can be easily added subsequently using digital circuits of great complexity, and in certain cases, these can process data not only from a single sensor but also from an array of sensors, as is the case in, for example, the "electronic nose," or can control both sensors and actuators embedded in the same microsystem.

Actuators can be defined—in the most general meaning—as devices performing a function complementary to that of sensors; namely, they convert a type of signal (most often electric ones) into another type which is re-introduced back into the environment, either for its feedback control, or by carrying an information/meaning that can be perceived only by the human used. For instance, the computer monitor can be considered as one such actuator since it converts an electrical signal coming from the computer into an optical signal provided into the environment to the human user.

The term "signal" may refer to six different types of measurands: physical/mechanical (e.g., force, acceleration, or displacement), thermal, magnetic, (bio) chemical, radiative, and electric [2].

Yet, despite their importance and ubiquity, sensors and actuators are much less known to the general public, given that, on the one hand, they are usually "hidden" from view, and, on the other hand, the measurement and control field—to which sensors and actuators belong—are not as often and widely popularized as, e.g., consumer electronics.

This introduction may now explain the seeming obscurity of color sensors: they represent just a diminutive group in the family of optical sensors, which is just a small part in the larger category of sensors, which, on its turn, represents only a niche domain in the measurement and control field, in itself a smaller and less known area than, e.g., consumer electronics or microelectronics.

The same situation is also reflected even in the area of scientific papers. A very quick review of the papers published in reputed scientific journals dedicated to the general topic of sensors (e.g., IEEE Sensors; IEEE Journal of MEMS; Sensors and Actuators; Journal of Micro/Nanolithography, MEMS, and MOEMS; or Sensors & Transducers, to name just the more prominent ones) would quickly confirm to the curious reader that the amount of papers dedicated to color sensors represents only a relatively small percentage of the total number of papers published in those journals. Indeed, many—if not the great majority—of the optical sensors detect only the intensity of light, while other science and technology applications have required the detection of other parameters, such as polarization or phase (whose manipulation, or capture and storage are necessary in certain applications, of which holography is the best known to the public).

There is also confusion or a lack of clear understanding among most people regarding the definition of what exactly colorimetry is and how it differs from spectroscopy—its older, more widely spread, and much better known relative. Without going too much into details which are beyond the limited scope and space of this chapter, we can clarify this by providing quick definitions and highlighting the fundamental principles underlying these two measurement techniques. This is necessary because the difference between these two major but complementary approaches, the spectrometric and the colorimetric approach, is a very significant and fundamental one.

Thus, the colorimetric method relies on the decomposition, analysis, and description of incoming light by means of a set of fundamental primary colors, such as red (R), green (G), and blue (B). In contrast, spectrometry decomposes the incident light into a large multitude of extremely narrow passbands by using a dispersion element, such as a prism or a grating. This spectral decomposition is carried out within a certain wavelength range of the incident light, and this fact highlights another major difference between colorimetry and spectrometry: colorimetry always processes only *visible* light, whereas spectrometric analysis is not limited to the visible range alone and can also be carried out in many other spectral ranges of interest, e.g., ultraviolet (UV) or infrared (IR). Moreover, each of these ranges is typically divided in sub-domains, each of which can also constitute the subject of detailed spectrometric investigations. For instance, the IR domain is considered to comprise three such narrower domains: near infrared (NIR; $\lambda \cong 0.7$ μm–3 μm), medium infrared (MIR; $\lambda \cong 3$ μm–8 μm), and far infrared (FIR; $\lambda \cong 10$ μm–100 μm). The ultraviolet (UV) range is “partitioned” in narrower domains as well. The application of spectrometry in such a large number of ranges, domains, and sub-domains, as well as its older age and great importance for a great deal of scientific and technical applications, can all explain the much wider usage of spectrometry and the fact that it is better known even among non-specialists.

Because it splits the operational wavelength range in a large number of very narrow channels and provides a “point-by-point” approximation of the entire spectral information of interest of the analyzed light, spectrometry can be considered to be much more accurate in comparison with colorimetry, which would offer only a more limited, and rather “averaged,” evaluation. However, the spectrometric approach has its own major drawbacks.

First, it requires a much more complicated setup which is considerably more difficult to miniaturize, particularly in a monolithic solid-state solution and/or when high performance is desired, although such microspectrometric solutions can be realized and have indeed been reported. Unfortunately, due to the very limited space of this chapter, we cannot review here the interesting solutions found for the implementation of such microspectrometers. However, it is worth mentioning that many of them do indeed require complicated fabrication and that the requirement to use (monocrystalline) silicon for their fabrication (in order to enable easy integration with signal processing circuits) is not always easily satisfied (in fact, it is very rarely satisfied), particularly for the visible range. This is due to two main reasons. On the one hand, a microspectrometer is not just a simple single device, but it is truly a microsystem of increased complexity and which must include many additional (micro)optical elements (e.g., lenses and gratings) besides photosensors and signal processing circuits in order to perform its function. On the other hand, the usage of silicon is much more convenient for the realization of devices that would operate instead in the IR range.

Second, the very fact that spectrometry offers a dramatically increased amount of information from a large number of output channels makes much more challenging the simultaneous processing of all these data. This further increases the complexity of a spectrometric smart microsystem since it requires the addition of many signal conditioning circuits for all the channels, as well as a complicated digital circuit(s) for subsequent data processing.

Third, one cannot find a single standardized solution for all spectrometric systems. Instead, custom solutions have to be found, depending on each type of operational wavelength domain or sub-domain, and the desired performance requirements for the intended specific task. Even for the visible range, a multitude of solutions and implementations can be found, and the variety is also multiplied by the fact that the number of channels is not fixed and may vary from one application to another.

In contrast, colorimetry is a solution which is not only simpler to implement but is also easier to standardize, making it much cheaper. More importantly, the standard RGB output is directly compatible with the human vision response and thus is immediately applicable for imaging applications. All these factors made colorimetry to become a very valuable analytical tool in its own right. If, for the moment, our attention focuses not on the color sensors but on the real-life applications of color detection and quantification, it will quickly become evident that colorimetry is actually quite a well-established technique with many important applications in a large range of fields or industries. The main areas of such applications can be loosely divided into the following categories: Chemistry, life sciences, food & beverages industry, cosmetics, wood & paper processing as well as the printing and textile industries, and electronics & optoelectronics. Given the fact that the importance of colorimetry for practical applications is relatively little

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