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적외선 영상기법에 의한 CCD 센서의 스펙트럼 응답 특성 분석 기법

(Apparatus and method for analysing spectral response of a CCD optical sensor using an infrared imaging technique)

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요 약

디지털 영상처리를 이용해 CCD 센서의 스펙트럼 응답특성을 직접 측정할 수 있는 적외선 영상기법을 제안하고 있다. 이 방법은 쉽고 경제적인 방법으로 상용 CCD 센서의 스펙트럼 감도를 검출할 수 있도록 한다. 본 장치의 핵심 부품은 단색광원기, CCD 지지대, 디지털 영상처리 시스템이 내장된 컴퓨터이다. 방법의 타당성을 증명하기 위해 상용 CCD 카메라에 대해 시험적으로 행한 실험은 이론적인·모델과 잘 일치함을 보여 주었다.

Abstract

An infrared imaging method is proposed in which direct measurement of the spectral response of CCD sensors can be achieved through digital image processing. This method allows for a simple and economic method to detect the spectral sensitivity of commercialized CCD sensors. The key components of the apparatus are a monochromator, CCD-sample supporter and a personal computer equipped with a digital image processing systems. Tentative experimentation conducted on the commercialized CCD camera has resulted in a fairly consistent agreement with the theoretical model.

Keywords : CCD's spectral sensitivity, monochromator, infrared imaging technique, gray level, spectral resolution

I. Introduction

The quantum efficiency of a charge-coupled device (CCD) is a property of the photovoltaic response defined as the number of electron-hole pairs created and successfully read out by the device for each incoming photon. This property is especially important for low-light imaging applications such as reverse contrast imaging technique which images GaAs whole wafers with light from photon energy just below the bandgap energy(~ Eg-50 meV)[1]. Standard CCDs, which are illuminated through gate electrodes and oxide coatings in the front of the device, are more sensitive to green and red wavelengths in the region between 550 and 900 nanometers.

The spectral response, also called quantum efficiency(QE) or CCD sensitivity, differs from that of a simple silicon photodiode detector because the CCD surface has channels used for charge transfer that are shielded by polysilicon gate electrodes, thin

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films of silicon dioxide, and a silicon nitride passivation layer. These structures, used to transfer the charge from the imaging area and to protect the CCD from humidity and electrostatic discharge, absorb the shorter wavelengths (450 nanometers and lower), reducing the blue sensitivity of the device. Polysilicon transmittance starts to decrease below 600 nanometers and the material becomes essentially opaque to photons at 400 nanometers, but absorption depends upon gate thickness and interference effects of light passing through thin films on the CCD surface[2]. Interline-transfer CCDs have photodiodes that deviate from standard polysilicon gate structure, a factor that reduces interference effects and produces a more ideal and uniform spectral response. These devices are also usually equipped with vertical antibloom drains that provide a reduced response to longer wavelength photons. As photons above 700 nanometers penetrate deep into the silicon substrate close to the buried drain, they have a greater chance of liberating electrons that will diffuse into the drain and be instantly removed. Quantum efficiency is also dependent upon gate voltage, with lower voltages producing small depletion regions and visa versa[3].

A typical spectral sensitivity curve for a standard CCD is illustrated in Figure 1 (standard CCD) where it should be noted that the peak quantum efficiency of 40 percent is markedly below that of a individual silicon photodiode[4]. Ripples in the spectrum occur because of interference effects from thin films on the CCD surface.

Anti-reflection coatings are used in back-thinned CCDs to increase quantum efficiency, but it is not possible to produce coatings that are effective across the entire visible spectrum. Coatings that increase spectral response in the longer wavelengths often produce a corresponding decrease in absorption of lower wavelength photons, thus research is ongoing to produce anti-reflection coatings that are effective across the entire visible light spectrum.

Even though the CCD sensors are non-linear and vary in sensitivity, the fields of application for the device are burgeoning in inspection engineering,

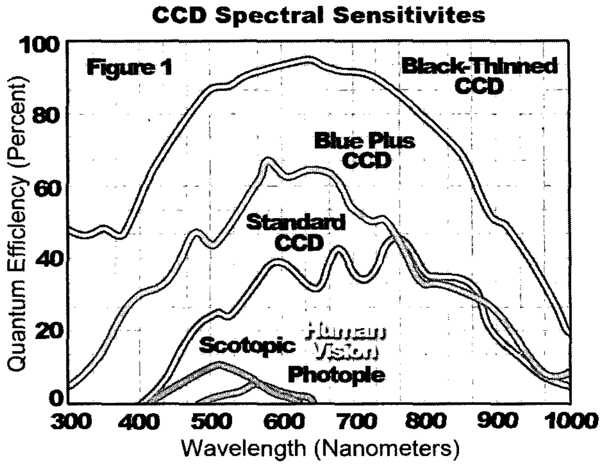


그림 1. 상용 CCD에 대한 일반적인 스펙트럼 감도 특성

Fig. 1. Typical spectral sensitivity curve for a standard CCD.

medical industries and digital camera systems. Specifically, the detailed analysis of commercial CCD sensors is a key issue for machine vision systems requiring a high spectral resolution such as infrared imaging in the semiconductor industry[5,6].

II. Theoretical background of the method

Measurement of the spectral sensitivity of a CCD is usually performed with the aid of complicated laboratory equipment including well calibrated photodiodes. Light at each wavelength is used to illuminate both the CCD and the photodiode, and the ralative difference in two readings is recorded. The final result of such an experiment is an absolute sensitivity curve for the CCD (with respect to the calibrated diode) over the range of all measured wavelengths.

The spectral sensitivity can be derived from simple ratioing between the CCD current and a reference photodiode current. This method is preferred, being more accurate and requiring less hardware. However, this equipment used a number of manually interchangable filter wheels for wavelength selection. It gave unreliable results due possibly to stray light and reflections from inadequately baffled filters. In response to this drawbacks, laboratory based systems for spectral sensitivity measurement are bulky, including computer-controlled-monochromator based ATC system, QE(quantum efficiency) measurement in "diode mode", and QE measurement in "imaging mode".[7,8]

The goal of the method presented in this paper is to achieve a direct measurement of commercial CCD sensitivity using an infrared imaging technique.

Accordingly, the present method provides both a technique and instrumentation for measuring the sensitivity characteristics of a CCD, whereby a given band of infrared is continuously irradiated onto a CCD sensor. The CCD sensor arrays produces an image whose pixel values are proportional to the CCD sensitivity. The images obtained will be displayed on a monitor and applied to a digital image processing algorithm to plot the sensitivities at different wavelengths. This method is based on our patent and includes the following principal aspects:

- Infrared Transmission Imaging Technique(IRT) as previously described [9,10];

- Computer for executing all operations and control functions associated with storing live image and scanning the pixel values along an X-axis of an image;

- Digital image processing algorithm for plotting CCD sensitivity.

Figure 1 illustrates the sensitivity measuring principle used in the present method.

A monochromator produces a certain wavelength light ray ,such as, λp. That wavelength light ray is irradiated onto CCD sensors. The CCD sensors then produce an image in which the gray levels are directly proportional to the CCD sensitivity. The images captured in this manner are then stored for image processing.

Next, the monochromator output wavelength is incremented or decremented to an adjacent value. The increment/decrement value of wavelength △λp will determine the spectral accuracy of the sensitivity curve. The smaller △λp, the more a spectrally detailed curve will result. The minimum value of △λp is dependent on the monochromator's spectral resolution. The procedure is repeated for the whole spectral bandwidth of CCD sensors. Commercial CCD sensors typically have a 300~1,200 nm spectral sensitivity bandwidth.

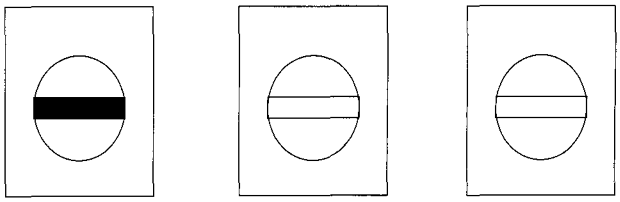


그림 2. 감도변화에 따른 영상의 gray level 변화

Fig. 2. Pictorial representation for relationship between sensitivity and gray level.

If a CCD has a low sensitivity at a certain wavelength λp, the corresponding image appears as a low gray level image, i.e. a blurred image, whereas if it has a high sensitivity at that wavelength, a brighter image will result. Then this sensitivity and gray level relationship could be depicted as Figure 2.

The relative spectral sensitivity curve for CCD sensors is obtained by plotting the gray level of different λp images already stored. Again the amount of △λp will determine the spectral accuracy of the sensitivity curve. Consequently a high-resolution monochromator is strongly recommended for accurate assessment of CCD sensitivity.

Ⅲ. System implementation

The apparatus is composed of an infrared (IR) light source, a monochromator with wavelength controller, an IR sensitive CCD camera, a PC equipped with a video image processing system, and image and computer monitors as shown in Figure 3. The device is illuminated by a halogen light(100W, 12V) through a monochromator.

A monochromator with a focal length of at least 18cm and a minimum spectral resolution better than 1nm is strongly recommended. A CCD sensor is wavelength-consecutively illuminated by a monochromator with a spectral output band of 300nm ~1200nm. This spectral band corresponds to a standard commercial CCD sensors' spectral response. The CCD sensors' spectral response is produced as an image by an image processing board such as PCVISION Frame Grabber. A PC monitor or general-purpose black and white(B/W) monitor could be used as an image monitor. The optical system settlement, i.e. focal adjustment, is, at first, achieved using the image monitor. A personal computer is used for controlling the monochromator and executing image processing operations.

Both the image processing board and CCD sensitivity detecting and displaying algorithms are actually built into the computer. The final CCD sensitivity curve is displayed in all commercially available PC monitors.

Figure 4 shows a flowchart illustrating the CCD spectral sensitivity acquiring process. In step 1, the spectral bandwidth of the monochromator output, scanning start wavelength and increment amount of spectral range are set in monochromator control program. Next, in step 2, we activate the monochromator by the setting value of wavelength. In step 3, the CCD captures the output wavelength of the monochromator and the spectral response of the CCD is stored in a digital image data format.

Then in step 4, the set value of the monochromator's output wavelength is incremented to a new contiguous value. In step 5, the

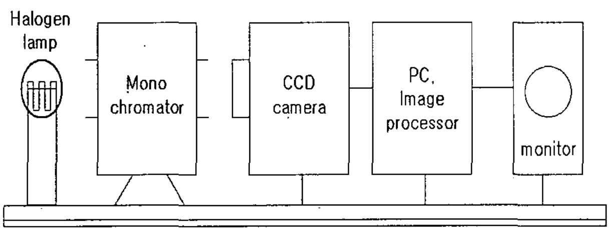


그림 3. 본 방법에서 이용한 실험장치 구성도

Fig. 3. Schematic diagram of equipment used in the present method.

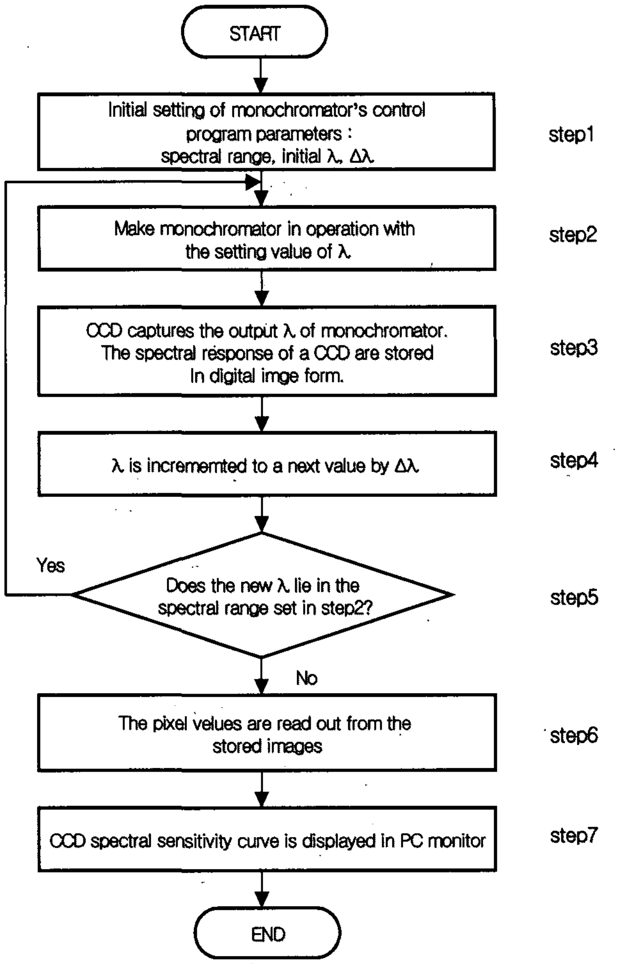


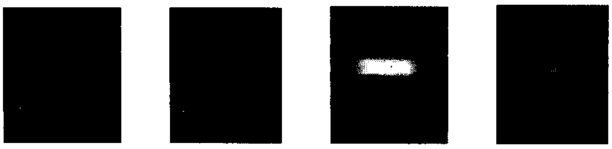
그림 4. CCD 스펙트럼 감도 측정 단계별 흐름도

Fig. 4. Flowchart illustrating the procedure for determining a CCD's spectral response.

incremented wavelength is then tested to see whether this value is in the spectral scanning range, or not. If the value lies in the scanning range, the process goes to step 2 and repeats steps 3,4,5. If the wavelength is out of the spectral range, the process proceeds to step 6, in which the pixel values are extracted from the stored spectral images. Finally, in step 7, the CCD's spectral sensitivity is plotted using the pixel values obtained in the previous step.

Ⅳ. Experimental results and discussion

In order to validate the method and show the spectral sensitivity of commercial CCD sensors, an experiment was performed on Sony CCD Camera (Model XC-55). Figure 5 shows representative images at wavelengths of λ =350 nm, 425 nm, 550



λ = 350nm λ = 425nm λ = 550nm λ = 750nm

그림 5. Sony CCD 카메라(XC-55)에 대한 스펙트럼 응답의 대표적인 영상
Fig. 5. Typical images for spectral response of a Sony CCD(XC-55).

표 1. 감도를 gray level로 나타낸 원시 데이터
Table 1. Raw data of sensitivity in terms of gray level values.

λ (nm)	gray level	λ (nm)	gray level
300	0	775	73
325	0	800	51
350	6	825	48
375	23	850	39
400	29	875	28
425	86	900	21
450	144	925	12
475	199	950	6
500	219	975	5
525	253	1000	3
550	249	1025	0
575	246	1050	0
600	226	1075	0
625	211	1100	0
650	195		

nm and 750 nm respectively. These images reveal exactly the same pattern as that described in the theory(Fig. 2). We have conducted spectral imaging in whole band λ = 300~1,100 nm with a spectral resolution of $\Delta\lambda$ =25 nm. To ensure reliable data, the experiments were repeated three times under the same conditions. The raw data, where sensitivity is given in terms of gray level, is enumerated in Table 1. Using the data given in Table 1, the spectral sensitivity curve for the CCD could be plotted as shown in Figure 6.

Note again that this experiment was completed with a monochromator spectral resolution of $\Delta\lambda$ =25 nm. If the experiment is completed with a finer resolution, for example $\Delta\lambda$ = 1 or 2 nm, Figure 6 will exhibit some ripples in the spectrum because of

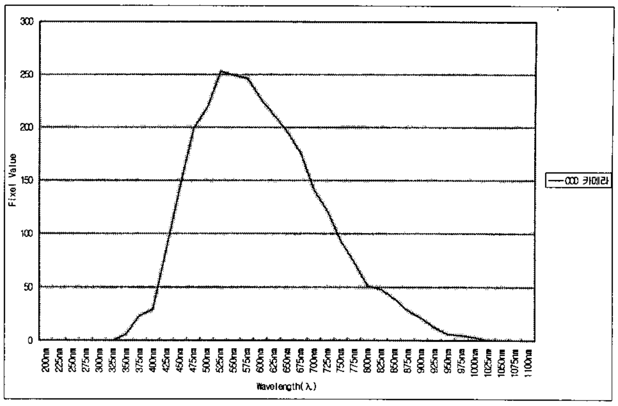


그림 6. 본 방법을 이용해 구한 Sony CCD(XC-55)의 스펙트럼 특성
Fig. 6. Resultant Sony CCD(XC-55) spectral sensitivity.

interference effects from the thin films on the CCD surface. Nevertheless, from this figure, we can easily find that spectral sensitivity has three characteristic regions, i.e. a region in which sensitivity changes smoothly, a region in which sensitivity is relatively constant, and a region in which sensitivity changes drastically. These properties are somewhat different from those given in Figure 1. Though the overall shape of Figure 6 is similar to the CCD's general characteristics, it is more informative and gives spectral details. It is interesting that in the bands of approximately 325~400 nm and 800~1,000 nm the spectral sensitivity is low and changes gradually. It could be considered that these are CCD specific properties but this method clearly delimits the wavelength-dependent sensitivity regions. Again, the results conform the validity of the method as a useful technique for analysing optical sensor's spectral response in a relatively accurate manner.

V. Conclusion

This method shows the possibility of successfully analysing the spectral response of a CCD sensor in detail. The experiment performed for a commercialized CCD camera demonstrates that experimental results and theoretically expected results agree to a great extent. Even though the global patterns of CCD's spectral characteristics are similar, the spectral responses obtained in this manner are more informative and contain spectral details.

This method is of special importance in the technical fields requiring detailed analyses of commercialized CCD sensors, such as in machine vision systems and infrared imaging techniques in the semiconductor industry.

The spectral resolution of this method is limited by the monochromator's spectral resolution but it is relatively simple to implement.

REFERENCES

[1] M.S. Skolnick, M.R. Brozel, "Distribution between near infrared optical absorption and light scattering in semi-insulating GaAs", Appl. Phys. Lett. Vol. 48, No. 5, pp 341-343 Feb. 1986.

[2] M. F. Tompsett. "The Quantitative Effect of Interface States on the Performance of Charge-Coupled Devices", IEEE Trans. Electron. Devices, ED-20, 45 (1973).

[3] D. F. Barbe, "Imaging Devices Using the Charge-Coupled Concept", Proc. IEEE, 63, 38 (1975).

[4] CCD spectral sensitivity, www.retrievertech.com/ Product/ ccd_spectral_sensitivity.

[5] J.P. Fillard, "Infrared Imaging and EL2", Revue Phys. Appl. Vol. 23, pp. 756-777 May, 1988.

[6] S. J. Kang. "New Infrared Imaging Technique for Evaluation of Compound Semiconductor Crystals", Korean Patent, No. 138855, Feb. 23. 1998.

[7] S. Tulloch, "The ATC QE Measurement System", Mar. 1999.

[8] J. C. Mullikin, L. J. van Vliet, H. Netten, "Methods for CCD Camera Characterization", SPIE vol. 2173, pp. 73-84, 1994.

[9] S. J. Kang, B. W. Kim, Y. S. Bae, "Method of and Apparatus for Measuring energy Gap of semiconductor", United States Patent, No. 5,406,505 Apr. 11. 1995.

[10] S. J. Kang, "Method of and Apparatus for Evaluating the Temperature Coefficient of a Semiconductor Energy Gap", Korean Patent, No. 0219761, June 16. 1999.

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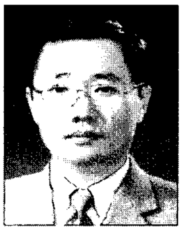

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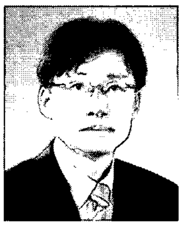

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