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RESEARCH ARTICLE

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# Design of tooth color measurement system based on silicon double P-N junction color sensor



**Abstract** Working principles of silicon double P-N junction color sensor are introduced and a color measurement system to distinguish tooth color difference is designed in this paper. This system consists of silicon double P-N junction, a small optical fiber probe, signal process circuit and an MSP430FG439 single-chip system. Small in size, this system can measure different parts of the tooth in a fast and convenient way with high-accuracy. Thus, this system will be very promising in building prosthodontics and tooth fabrication.

**Keywords** silicon double P-N junction color sensor, color identification, MSP430FG439 single-chip

## 1 Introduction

Various kinds of colors exist in the natural world, which is mainly due to the absorbing selection feature of different objects to light. Optics knowledge tells us that, according to color vision feature, human eyes can respond selectively to the visible light when the wavelength of the light is between 380–780 nm, thereby, people can distinguish different colors. However, the ability of different people identifying various colors is different significantly, so it is hard to reflect all kinds of colors objectively. Research and development of instruments for measuring colors has aroused people's attention. Thus, the semiconductor color sensor has appeared as time requires. The P-N junctions are made on single-silicon or poly-silicon materials and such P-N junctions with different junction deepness are used for identifying different colors, depending on the absorption coefficient difference of different colors. Generally, there are two methods adopted to analyze polychromatic light in recent studies: one is to use tristimulus colorimeter or spectral photometer to confirm the chroma coordinates [1]; the other is only to identify chromatism without reflecting accurate color quantities [2], i.e., chromatism identification.

The technique of color comparison is of great importance in building prosthodontics. Dentists need to measure patients' teeth color to find the same color or the nearest color prosthetic material to achieve the beautification goal. Nowadays, artificial vision measurement is usually adopted in prosthodontics. However, factors such as inaccurate tooth color comparison, inherent quality of prosthetic material, light, environment, and some other objective elements will result in prosthodontics failure. A more accurate measuring method is in great need.

Silicon double P-N junction color sensor instruments are small in size, convenient for use, and low in price. This instrument uses the wavelength-dependence of absorption in silicon to detect the wavelength of incidence light and identifies polychromatic light with different kinds of spectrum, i.e., chromatism identification. The silicon color sensor with double P-N junction has been widely used in many fields such as single color wavelength measurement [3], polychromatic light peak wavelength confirmation, chromatism identification and color temperature measurement. In this paper, by using the chromatism identifying ability of this kind of silicon color sensor with double P-N junction, a kind of color measurement system that can be used in tooth color identification is designed, with the assistance of a well-designed signal process circuit, control software and single-chip management.

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## 2 Working principles of silicon color sensor

The theoretical foundation of color sensor identifying colors is the light absorption characteristic. Figure 1 shows the cross section and equivalent circuit of the silicon color sensor with double P-N junction. It consists of a shallow junction PD1 ($N^+P$) and a deep junction PD2 (P-N), and works on the correlativity between the absorption coefficient of the incident light and the wavelength in silicon. A measurement system for spectral response is used to measure the relative sensitivity of silicon color sensor with double P-N junction as shown in Fig. 2. The curves show that PD1 is more sensitive to light of short wavelength and such light is absorbed near the surface of silicon, while light of long wavelength can go deeper to be absorbed because of the PD2's sensitivity to long wavelength lights. Generally speaking, the designed deepness of the shallow junction is about 1–2 μm and that of the deep junction is about 4–7 μm. When the color sensor instruments are working, those two P-N junctions are both in the condition of short-circuit, and the corresponding short circuit currents of those two P-N junctions are $I_{SC1}$ and $I_{SC2}$. Since the photo-carriers excited by incident light with different wavelength have different distributions, the ratio $I_{SC2}/I_{SC1}$ is closely related to the wavelength. Direct current multiflex galvanometer measurement shows that, for monochromatic light the current ratio monotonously increases as the wavelength of incident light increases in a certain range (as shown in Fig. 3). Thus, the wavelength, or the color of monochromatic light, can be determined by the magnitude of the current ratio. Meanwhile, the current ratio has a dimensionless quantity and does not depend on incident light intensity, which offers a great advantage to practical use [4]. However, for polychromatic light, unlike monochromatic light, the power of incident light is an integral which affects each monochromatic element. Obviously, the short circuit current ratio is related not only to the spectral radiant power of polychromatic light, but also to the spectral responsibility of the sensor instruments [5].

For a certain sensor instrument, the spectral responsibility is fixed, so the current ratio of the instrument is only related to the properties of the polychromatic light source. In a general situation, the polychromatic light source can be viewed as Gaussian distribution with certain full-width at half-maximum (FWHM). In Gaussian distribution, the change of the peak wavelength and FWHM will cause the change of the polychromatic light color and the change of the current ratio. However, the influence of the peak wavelength to the color change is higher by about several

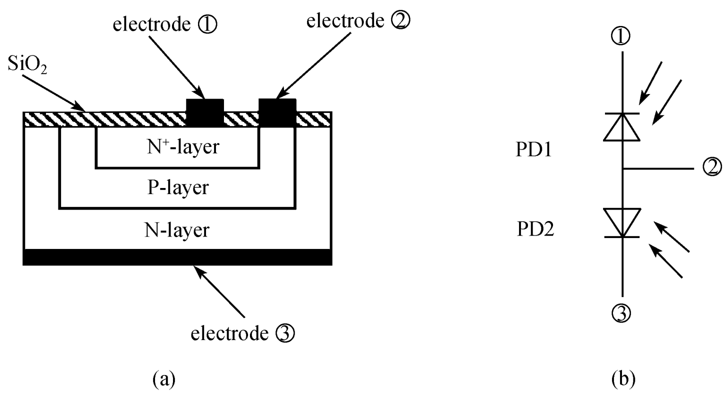


**Fig. 1** Cross section and equivalent circuit of silicon color sensor with double P-N junction. (a) Structure; (b) equivalent circuit

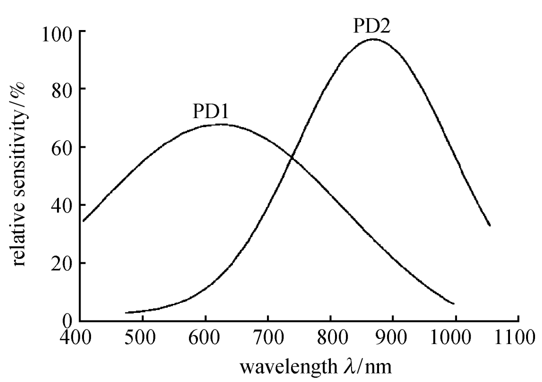


**Fig. 2** Spectral sensitivity of silicon color sensor with double P-N junction

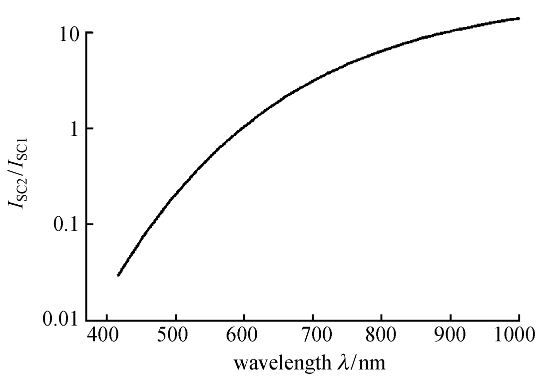


**Fig. 3** Current ratio $I_{SC2}/I_{SC1}$ with different wavelength of incident light

orders of magnitude than that of FWHM [6], and the peak wavelength of those colors are almost the same as the color tone which we can observe in daily life. Therefore, when the polychromatic light testing is carried out, the current ratio of a silicon color sensor with double P-N junction can still be the representative color. When two polychromatic lights cause different current ratios, we can justify that the colors of those two polychromatic lights are different, and then we can carry out the process of color identification.

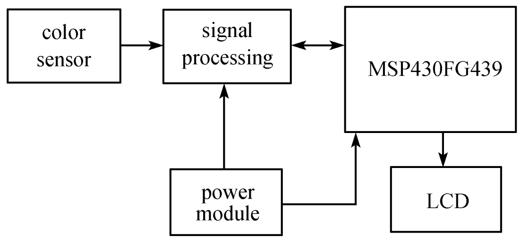


**Fig. 5** Working principle frame of the system

## 3 System design

When the dental color measurement system was designed, we devised a small-sized optical fiber probe with a diameter of less than 4.5 mm to increase the detecting precision. As shown in Fig. 4, this probe consisted of 19 optical fibers, 7 of which were used for illumination, and the other 12 were used for observation. Light from the light source shone on the surface of the teeth by illumination fibers and its reflex light could be detected by the silicon color sensor through detection fibers. Therefore, this design can help the whole system survey all parts of teeth more conveniently in oral cavity.

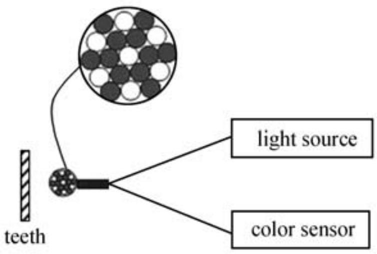


**Fig. 4** Optical fiber probe

Using a silicon color sensor with double P-N junction to realize color identification, the support from a reasonably designed measurement instrument, a control circuit and an application program are necessary. In this system, the high performance MSP430FG439 single-chip was the operating control core, which made up the crucial part of data processing system. With the help of checking and controlling programs, this system used silicon color sensor to detect the color of teeth. Also, the output current signals went through several processes like $I/V$ conversion, A/D conversion, and data processing system before the final measurement results came out. The whole working principle is shown in Fig. 5.

### 3.1 Hardware design

The whole color measurement system consists of signal detection, signal processing, control system and a liquid crystal display (LCD). Since both of the output short circuit currents $I_{SC1}$ and $I_{SC2}$ are weak, the ability of this system to detect and process faint current signals is in high demand.

In this design we adopt a precision switch integrator ACF2101 and a differential amplifier AD602 to form a signal detection and signal processing system. The ACF2101 is a dual switched integrator for precision applications. Each channel can convert an input current to an output voltage by integration, using either an internal or external capacitor. The precision 100 pF integration capacitors, hold and reset switches, and output multiplexers are included on the chip. The integrator ACF2101 has a very high integral conversion rate (about 3 V/μs), a slow signal restoring speed, and a high measuring accuracy. Meanwhile, it can maintain a long valid data cycle which is fit to process the faint current signals. Through four programmed control switches (a hold switch, a reset switch, and two output select switches) of ACF2101, the integrator converts the current signals to voltage signals. After two output voltage signals go through the differential amplifier AD602, we can get the voltage signal $V_o(\lambda)$, which relates to the reflex light signal of teeth. As far as the value of the $V_o(\lambda)$ is obtained, the color wavelength can be determined according to the corresponding principles between $V_o(\lambda)$ and the incident light wavelength, and in this way, the color of the object can be identified. If the color of detecting object changes, the $V_o(\lambda)$ value also changes and the changing range is between 0–2.5 V.

MSP430FG439 single-chip is used as the operational control core of the whole system. From the Texas Instruments MSP430 family of ultralow power microcontrollers, the device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that attribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 6 μs. The MSP430FG43x series has microcontroller configurations with two 16-bit timers, one high performance 12-bit A/D converter, dual 12-bit D/A converters, three configurable operational amplifiers, one universal synchronous/asynchronous communication interface (USART), direct memory access (DMA), 48 I/O pins, and a liquid crystal display (LCD) driver. This single chip can reduce the number of exterior components and enhance system's stability and this system mainly serves the functions such as controlling the selective transit of analog switch, A/D conversion, data processing and display circuit.

Since the output current signals of the color sensor are very weak and easily influenced by outside, the whole system must be put into a metal shield box, which should be connected with the ground of the circuit. In addition, the analog circuit should be connected with the digital circuit.

### 3.2 Software design

The purpose of our design is to distinguish tooth color accurately, so we input 29 colors of the VITA Toothguide 3D-Master as the standard colors into the single-chip memorizer. Thereby, each digital signal obtained by detecting tooth color can be compared with the standard color and the result will be seen on the LCD. Software programs compiled by the assembly language mainly contain: ACF2101 control program, A/D conversion control program, data processing program and display drivers. The main program procedure is shown in Fig. 6. On start, the microcontroller unit (MCU) is operated to initialize program variables such as the location of data memory, the time and the default values, and then start up *I*/*V* converter and A/D converter. The MCU then turns into the main routine loop, judging whether the conversion is finished. After the conversion is finished, the measurement result and the memorized value are compared, from which we can obtain the corresponding color code and display it.

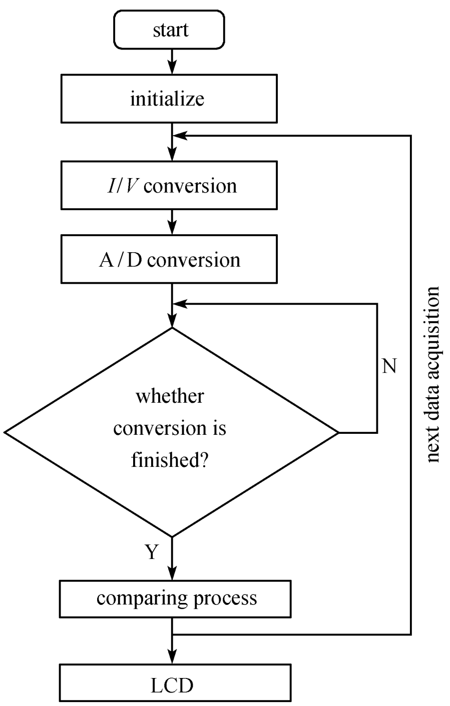


**Fig. 6** Procedure of main system program

## 4 Result and analysis

In the experiment, we chose 20 false teeth as the samples. After detecting those samples repetitiously, we asked five people to observe those samples by their naked eyes. Comparing the results obtained from instrument detection and unaided eyes observation, we found that colors distinguished by instrument were anastomosed to those identified by human vision. As shown in Fig. 7, when the samples were distributed at the distance of 1M and 5M, both the instrument and human eyes could tell the color difference correctly, and the results were the same; when the samples were distributed at the distance of 2M, 3M, and 4M, the repetition detecting results of the instrument were still precise, while the results obtained from human eye observation differed, and 80 percent of those naked eye results were similar to the instruments' results. Therefore, we can draw the conclusion that the precision and repetition properties of the instrument are much better than those of the direct naked eye observation.

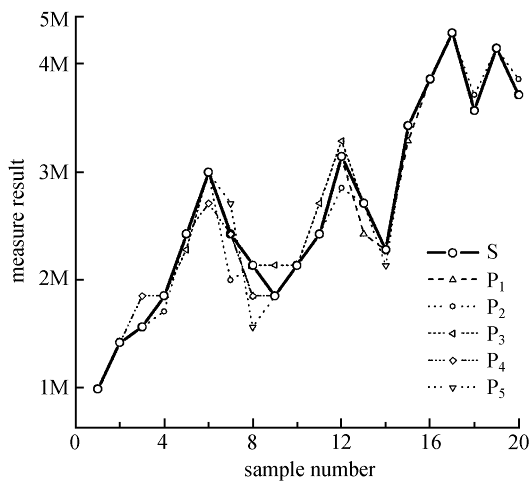


**Fig. 7** Results obtained from instrument (S) detection and unaided eyes ($P_1$, $P_2$, $P_3$, $P_4$, $P_5$) observation

## 5 Conclusions

The tooth color measurement system we designed by using silicon color sensor instrument as the detecting probe and MSP430FG439 single-chip as the operational control core can measure tooth color effectively. This system has the advantages of small size, convenient for use, high reliability and high accuracy, which make it a promising short-cut for tooth color identification, prosthodontics and tooth fabrication. We apply the silicon double P-N junction color sensor in the prosthodontics domain for the first time, thus offering a new way for further research in the field.

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