Research on the enhancement of signal-to-noise ratio of light-addressable potentiometric sensor by optical focusing*

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For enhancing the response of light-addressable potentiometric sensor (LAPS) and further improving its signal-to-noise ratio (*SNR*), an optical focusing method is adopted. Experimental research and theoretical analysis reveal that the magnitude of responsive signal is increased by optical focusing, and the *SNR* is improved remarkably. These research results indicate that the optical focusing is an effective approach for improving *SNR* of LAPS.

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Light-addressable potentiometric sensor (LAPS)[1] is a semi-conductive sensor, which is based on the principle of field-effect in semiconductor structures[2,3]. LAPS can be applied to measure hydrogen ions[4,5], metal ions[6,7], nonmetallic ions[8], etc. Because its flat surface is easy to be settled with protein or cell, LAPS is also applied to biological analysis, such as DNA detection[9] and cell activity monitor[10,11].

However, the responsive signal is too weak (less than 1 μA) and is apt to be disturbed by many factors, so the signal-to-noise ratio (*SNR*) of LAPS is low[12]. Some researchers have presented that the amplitude of photocurrent may be affected by the fluctuation of light, the impedance variation of solution, the flaws in substrate, etc[13,14]. Increasing the amplitude of photocurrent is an effective way to enhance *SNR*. In previous research works, the performances of the methods for increasing the amplitude of photocurrent, which include reducing the thickness of substrate, increasing the wavelength of light, setting proper modulation frequency and increasing the power of light, were studied[15-17], and the research results show that the wavelength and the power of light is closely associated with the *SNR*. For the sake of improving *SNR* of LAPS, in this paper, we research the performance of LAPS for increasing its *SNR* by using optical focusing. All the results are obtained from experiments, and the research results can help to improve the performance of LAPS measure system.

For introducing the principle of LAPS measurement, the structure of LAPS is shown in Fig.1. A direct current (DC) bias voltage is imposed on electrolyte to form depletion region at the interface of insulator-semiconductor. Then a beam of light modulated by alternating current (AC) signal illuminates the bottom of substrate and induces photo-generated carriers, which diffuse towards the depletion region and are separated there by inner electric field. This process induces the formation of AC photocurrent in substrate, and the magnitude of photocurrent is related with the thickness of the depletion region, while the thickness of the depletion region is relative to the surface potential of LAPS. Therefore, any reaction which may affect the surface potential will be measured by LAPS.

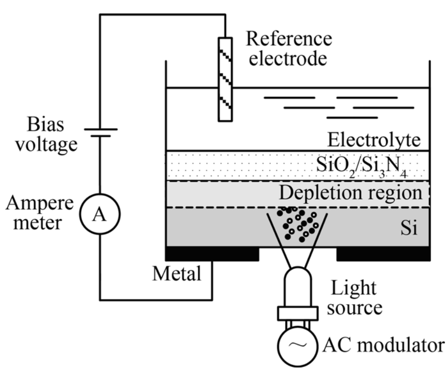

Fig.1 The structure diagram of LAPS

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N-type silicon (Si) with ρ=1—5 Ω·cm, crystal orientation of <100> and thickness of 300 μm was utilized for the manufacture of LAPS chip. The schematic diagram of LAPS measurement system is shown in Fig.2. The center of LAPS was etched to be 50 μm (thickness) by means of wet etching technology. A 100 nm-thick SiO_2 film was formed on Si surface as insulator layer by dry oxidation, and then a 50 nm-thick Si_3N_4 film acting as sensitive layer was deposited on SiO_2 film by low pressure chemical vapor deposition (LPCVD). Finally, a 20 nm-thick Cr acting as adhesion layer and 100 nm Au film were deposited on rear side of LAPS to serve as working electrode. The calomel electrode was used for reference electrode.

The bias voltage and the 4 kHz modulation signal were supplied through analog outputs of NI DAQ card (model PCI-6259, National Instruments). The diverging light emitted from laser diode with wavelength of 680 nm is converted to parallel light by use of collimating lens, and then through convex lens the parallel light is focused to a spot on Si substrate. The trans-impedance amplifier converts the photocurrent to voltage signal and transfers it to an analog input of NI DAQ card, where the voltage signal is converted to digital value by analog-digital converter (ADC). The software of LABVIEW was used to store, process and analyze the data. In experiments, the original data were first processed by band-pass filter, and then the valid signal was extracted by the means of fast Fourier transform (FFT) algorithm. Other instruments used here are an optical power meter (model GL-II, Xi'an Super Photoelectron Equipment Co., Ltd) and a voltage-stabilized source (model WYK-302B2, Shanghai iris Electronic Co., Ltd).

Electrolyte is pH buffer solution, and the range of pH value is from 4.0 to 9.0. The photocurrent-voltage (*I-V*) curves with different pH values are drawn in experiments. The influence of optical focusing on the *SNR* of LAPS is studied by experimental and theoretical analyses.

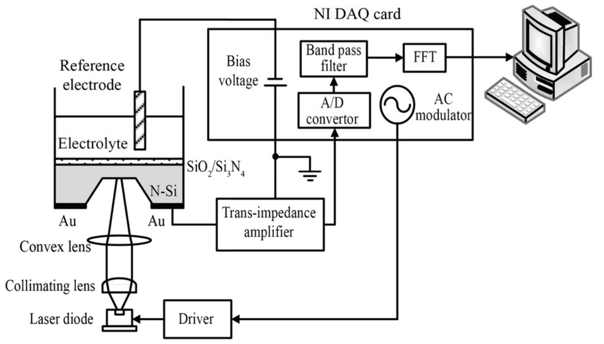

Fig.2 The schematic diagram of LAPS measurement system

Four sizes of light spot obtained by optical focusing, including Φ0.5 mm, Φ1 mm, Φ2 mm, Φ3 mm, were tested in the experiments. The illuminant parameters are luminous power of 0.8 mW, wavelength of 680 nm and modulation frequency of 4 kHz. Fig.3 shows the normalized *I-V* curves of LAPS under different light spot sizes. It can be seen from Fig.3 that with the decrease of light spot size, the *I-V* curves become more and more smooth, which obviously helps to the improve *SNR* of LAPS.

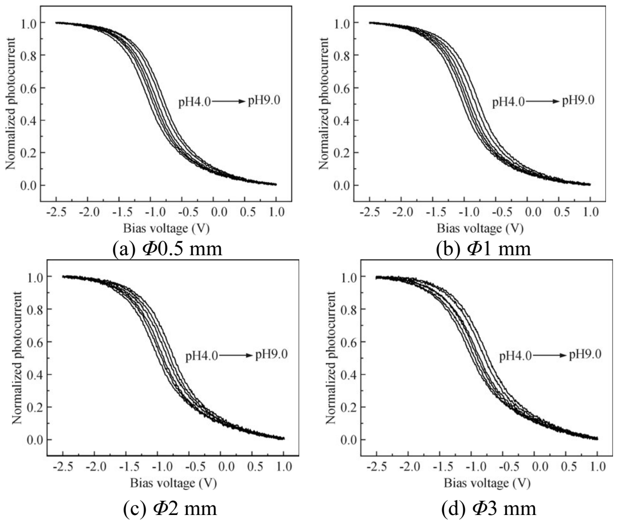

Fig.3 The *I-V* curves of LAPS under different light spot sizes

Fig.4 shows the actual photocurrent under different light spot sizes, where the pH value of solution is 4.0. When the diameter of light spot is larger than Φ2 mm, the magnitudes of photocurrent are almost identical. However, when the diameter of light spot is smaller than Φ1 mm, the magnitude of photocurrent increases drastically with the decrease of light spot size.

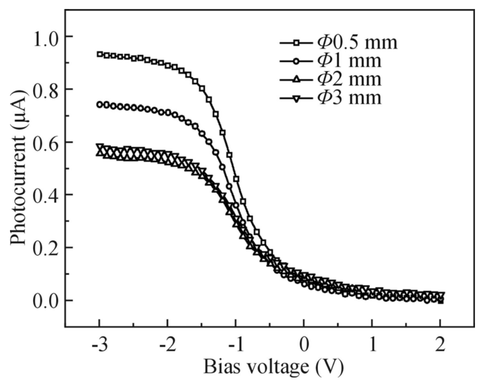

Fig.4 The *I-V* curves under different light spot sizes with pH=4.0

According to the definition of *SNR*[18] expressed as

$$SNR = 10\times\log\left[\frac{\sum_{i=1}^{N} f_i^2}{\sum_{i=1}^{N}(f_i - s_i)^2}\right], \qquad (1)$$

where f_i is the signal without noises, s_i is the original signal, and N is the number of sampling points, the *SNR* of LAPS under different light spot sizes can be calculated as shown in Fig.5. In Fig.5, it can be found that the decrease of light spot size obtained by optical focusing can remarkably improve the *SNR* of LAPS responsive signal.

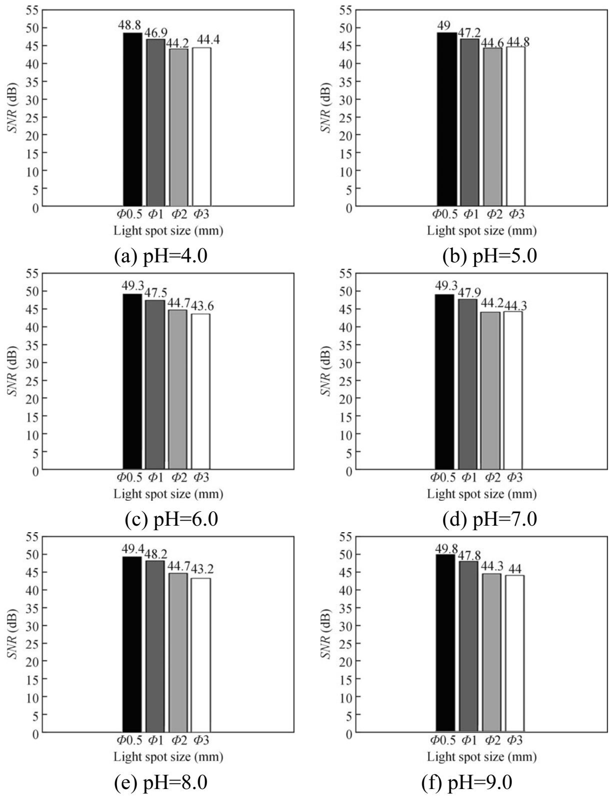

Fig.5 The column diagram of *SNR* of LAPS under different light spot sizes at different pH values

When a beam of light illuminates the backside of LAPS, photons are absorbed and photo-generated carriers are induced in Si substrate. The carrier generation rate is defined as

$$G(x)=\Phi_0\alpha e^{-\alpha x}, \quad (2)$$

where α is the absorption coefficient of substrate, which depends on the wavelength and material characteristics, x is the depth in substrate, Φ_0 is the photon flux at the Si surface generated by a monochromatic optical source and can be further expressed as

$$\Phi_0=\frac{P_{in}}{h\nu}(1-R_f), \quad (3)$$

where P_{in} is the input optical power density (W/cm^2), $h\nu$ is the photon energy, and R_f is the reflection coefficient on the surface of substrate. According to Eqs.(2) and (3), while keeping the magnitude of optical power constant, if light spot is converged by optical focusing, the input optical power density will be increased, so the carrier generation rate $G(x)$ is increased. Therefore, more photo-generated carriers can be induced in deeper substrate and diffused to depletion region, which results in the increase of photocurrent.

In semiconductor photoelectric device, the major noises are thermal noise, shot noise, generation-recombination noise (g-r noise) and 1/*f* noise. When modulation frequency is higher than 1 kHz, the 1/*f* noise can be ignored. The mean square values of noise current of the other three noises are shown in sequence as

$$\overline{i_{nJ}^2}=\frac{4kT\Delta f}{R}, \quad (4)$$

$$\overline{i_n^2}=2e\bar{I}\Delta f, \quad (5)$$

$$\overline{i_{ng\text{-}r}^2}=4e\bar{I}\frac{\tau_0}{\tau_d}\Delta f, \quad (6)$$

where R is the resistance of substrate, k is the boltzmann's constant, T is the absolute temperature, Δf is the operation bandwidth, e is the electron charge, $\bar{I}$ is the average photocurrent, τ_0 is the average life of carriers, and τ_d is the transit time. Comparing Eqs.(4)—(6), it is obvious that the shot noise $\overline{i_n^2}$ and the g-r noise $\overline{i_{ng\text{-}r}^2}$ are both in direct proportion to photocurrent, but the thermal noise i_{nJ}^2 is irrelevant to photocurrent. According to Eqs.(4)—(6), the total noises in LAPS can be expressed as

$$i_n=\sqrt{\overline{i_{nJ}^2}+\overline{i_n^2}+\overline{i_{ng\text{-}r}^2}}. \quad (7)$$

When the photocurrent is increased by optical focusing, the shot noise and the g-r noise can also be increased, but the thermal noise will remain unchanged. It means that the increasing extent of photocurrent is larger than that of noises, so the *SNR* of LAPS can be improved.

In this paper, the *SNR* of LAPS responsive signal is improved by means of optical focusing. Through the optical focusing, remarkable increase of photocurrent and *SNR* are observed in experiments. Through the theoretical analyses of experimental results, it can be determined that optical focusing is an effective method to increase the photocurrent and the *SNR* of LAPS responsive signal.

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