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High Resolution Chemical Image Sensor Using a High-Speed Digital SPV Measurement System

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A high resolution and high-speed two-dimensional surface photovoltage (SPV) sensing system which is based on digital data processing was developed and applied to the ***in-situ*** monitoring of chemical images. The SPV signal generated by a scanning light beam was directly stored in a computer and signal integration of all measurement points was carried out simultaneously in allocated memories by numerical calculation, which made it possible, in principle, to reduce the measurement time to equal the scanning time of the light beam. The light beam was modulated by a haversine (interleaved versed sine) wave in order to separate each measurement point signal and obtain a high resolution image. To form images of 16,384 data points, the proposed system requires about 4.5 min, which is at least two orders of magnitude faster than a conventional analog SPV system.

1. Introduction

The use of a highly integrated chemical sensor such as an image sensor is now of great interest in the fields of biochemistry, environmental monitoring and the food industry.[1, 2] However, a technique which enables high density and high-speed image sensing in, for example, charge-coupled devices for optical image formation has not yet been developed.

Recently, we showed that the surface photovoltage (SPV) technique is promising for the development of a chemical image sensor[3] and we demonstrated the formation of images of 4,000 data point signals using an enzyme sensor.[4] Gas response images using SPV sensors have also been reported by Lundström *et al.*[5]

However, the measurement time of this sensor still poses a serious problem when used for *in-situ* measurement, i.e., the detection of a large number of sensing spots is too time consuming for use in high-speed applications.

This report deals with a new technology which enables high-speed monitoring of chemical images using an SPV image sensor. The proposed system uses digital data processing instead of the analog system of the conventional SPV method. Signal integration, which was responsible for most of the measurement time in conventional SPV sensors, is carried out for each measurement point simultaneously by numerical calculation of the digitized data which ensures high-speed sampling of the two-dimensional signal.

High space resolution of each measurement point is another essential requirement of two-dimensional image sensors for practical applications. An interleaved modulated light beam was used to ensure clear separation of each measurement point by removing cross talk of adjacent measurement points. An SOS substrate was also used to achieve the higher space resolution which is a result of the thinner film and the shorter diffusion length of the silicon layer grown on a sapphire substrate.

2. Measurement Principle

The principle of the proposed numerically processed parallel lock-in amplifier (NPL) system is illustrated in Fig. 1. For comparison, a conventional analog lock-in amplifier is shown in Fig. 2. The conventional SPV method integrates the responses point by point using an analog lock-in amplifier. This process consumes most of the measurement time. In the proposed NPL system, the signal integration is performed by numerical calculation of the sampled digital data which measures all points simultaneously. The system consists of a high precision A/D converter and a CPU unit which correspond to the phase sensitive detector (PSD), analog integrator and DC amplifier used in the conventional SPV method.

Figure 1(b) shows the time sequence for parallel integration. A light beam is modulated in an interleaved haversine with blank time between each excitation period and scanned along the semiconductor surface at a constant speed. The AC photocurrent generated is stored in a FIFO buffer memory after quantization using a high speed A/D converter. Then all of the samples in each period of modulated light beam are integrated numerically after rectification and taken as the correspondent data points, i.e., a certain position signal is made from one cycle of the light beam. The reference signal for rectification is derived by taking into consideration the phase shift of the photoexcitation current. The scanning is repeated several times and the signals of the correspondent position are integrated in the same memory enhancing the signal to noise ratio.

3. Sample Preparation and Measurement

Figure 3 shows the electrode structure and a schematic illustration of a two-dimensional SPV system using NPL. The sample electrode was an n-type silicon-on-sapphire (SOS) substrate of size 15 mm $\times$ 15 mm with 10 Ω cm resistivity. Square patterns (1 mm $\times$ 1 mm)

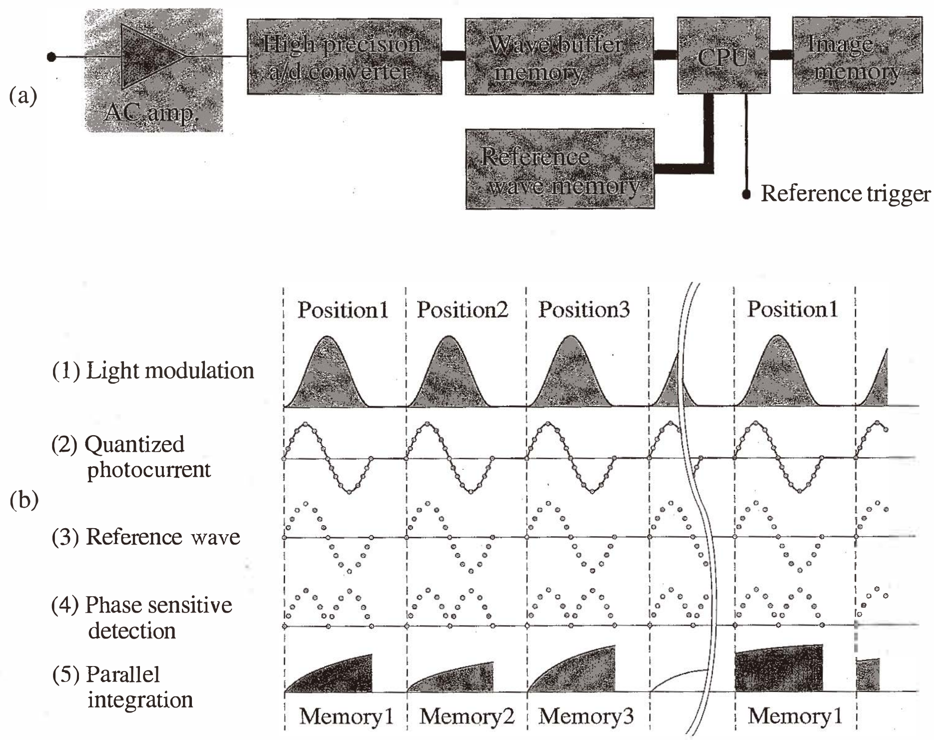


Fig. 1. Block diagram of numerically processed parallel lock-in amplifier (NPL) (a) and the measurement sequence (b).

for evaluation of the system were fabricated on the Si layer onto which SiO_2 and Si_3N_4 films were deposited to a thickness of 50 nm each. The peripheral region of the square patterns was covered with thick SiO_2 film.

A light beam (50 μm diameter), sinusoidally modulated at 1. 4 kHz and interleaved with 0.69 ms blank time, was scanned at a constant speed (9.8 mm/s) and the photo-generated signal was stored in a computer using a 16 bit resolution A/D converter at a sampling frequency of 66 k samples/s. The data for each period were rectified by multiplying the reference wave shown in Fig. 4(2) which corresponds to the theoretical response of the input sine wave (Fig. 4(1)) using the unloaded measurement system. A simplified equivalent circuit of the sensor system shown in Fig. 5 was used to derive the reference signal. The surface potential map of the semiconductor was obtained by scanning with a high precision galvanomirror scanner. The measurement was carried out in a phosphate buffer solution (pH 6.8, 25 mM) at a constant bias voltage (1.2 V vs Ag/AgCl).

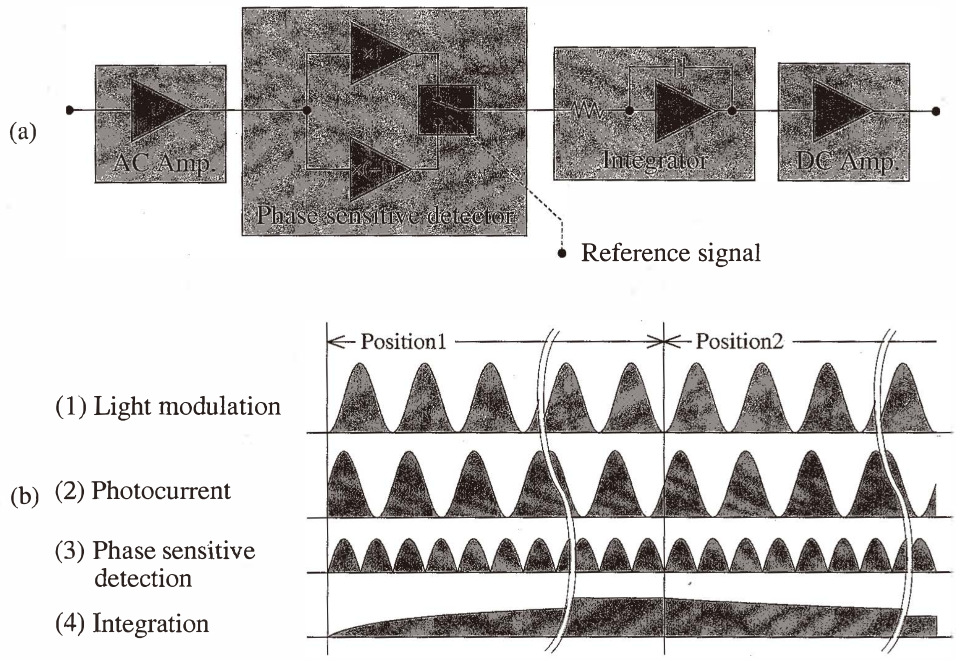


Fig. 2. Block diagram of conventional analog lock-in amplifier (a) and the measurement sequence (b).

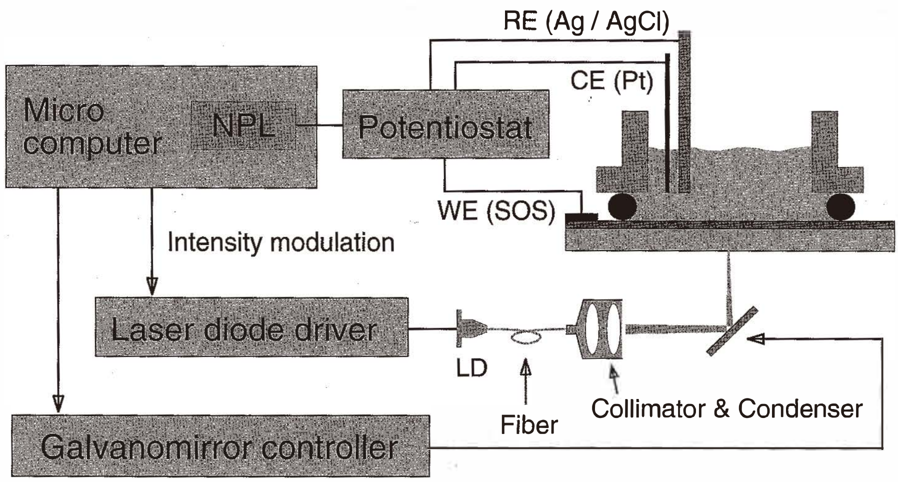


Fig. 3. High speed SPV measurement system using NPL.

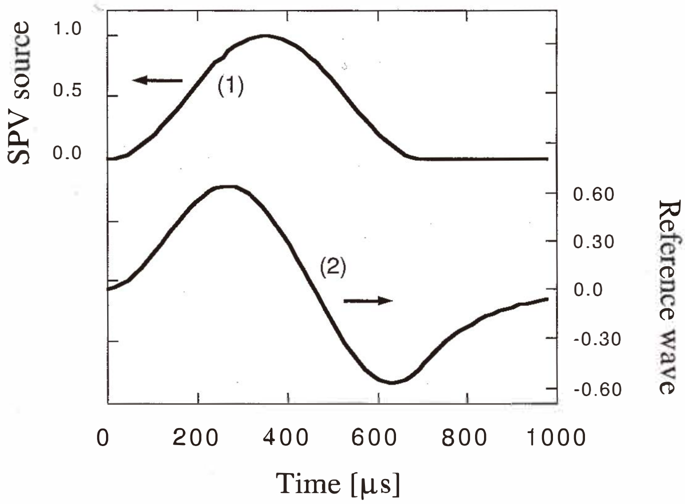


Fig. 4. Haversine photoexcitation wave (1) and reference wave (2).

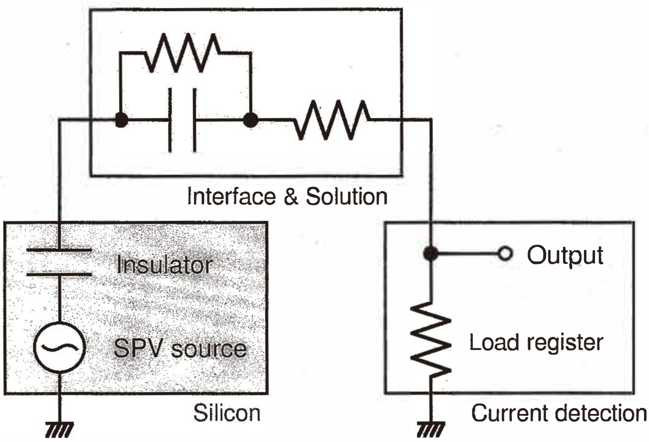


Fig. 5. Equivalent circuit of the SPV measurement system.

4. Experimental Results

Figure 6 shows the memorized response signal which was obtained by scanning the light beam over the border of the square pattern of the SOS electrode. It shows that the border can be clearly seen on the stored samples. Integration of the rectified data leads to

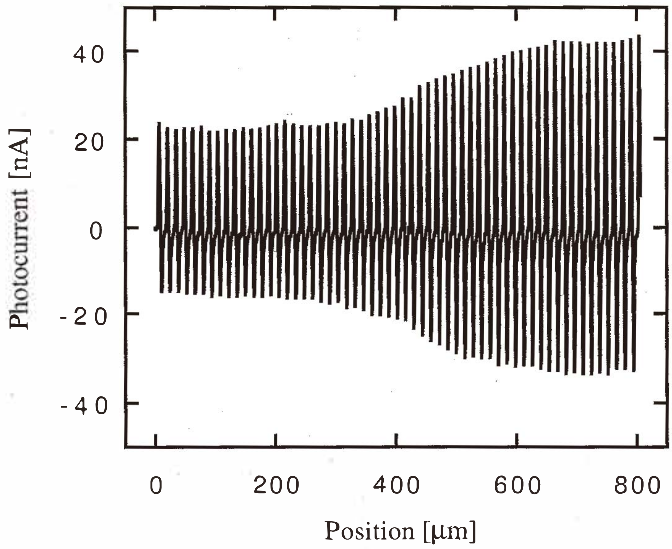


Fig. 6. Memorized response signal of photocurrent measured by scanning light beam.

NPL output. Numerical integration was performed using a simple low pass digital filter which corresponds to the analog RC filter circuit shown in Fig. 7. The recursive equation is expressed as

$$Vout_n = a\ Vout_{n-1} + b\ Vin_n \tag{1}$$

$$a = -\frac{1}{1+\dfrac{\Delta t}{\tau}},\ b = \frac{1}{1+\dfrac{\tau}{\Delta t}}$$

where Δt is sampling time and τ is time constant ($\Delta t << \tau$). Z transformation of eq. (1) results in the IIR filter shown in Fig. 8.

Figure 9 shows the integrated signal response times for various time constants. A longer time constant leads to an improved signal-to-noise ratio, but the total measurement time increases if the time constant exceeds the sampling time. Figure 10 is the NPL output after sample integration with a time constant of 25 ms. In order to reduce system noise, scanning was repeated several times on the same line and the signals of the correspondent position were integrated in the same memories. The plot of Fig. 10 is the iteration result of 5 scans. The total measurement time including the averaging process was 1.0 s which is about one hundred times faster than that of the conventional SPV sensor.

Figure 11 shows a two-dimensional map of the surface photocurrent of the sample in

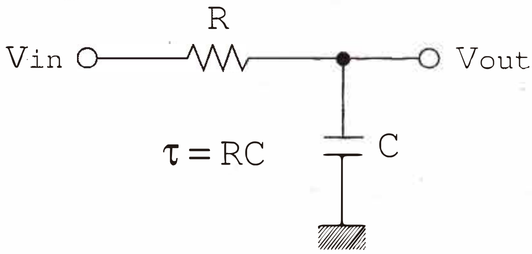


Fig. 7. RC analog filter used as a digital filter model for digital signal processing in NPL.

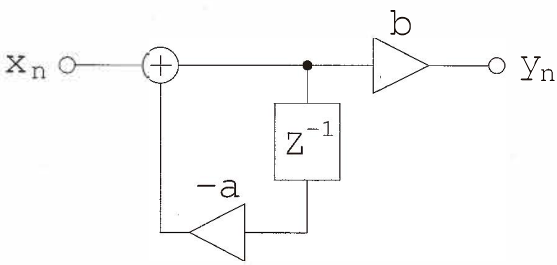


Fig. 8. IIR filter used as a low pass filter for signal integration.

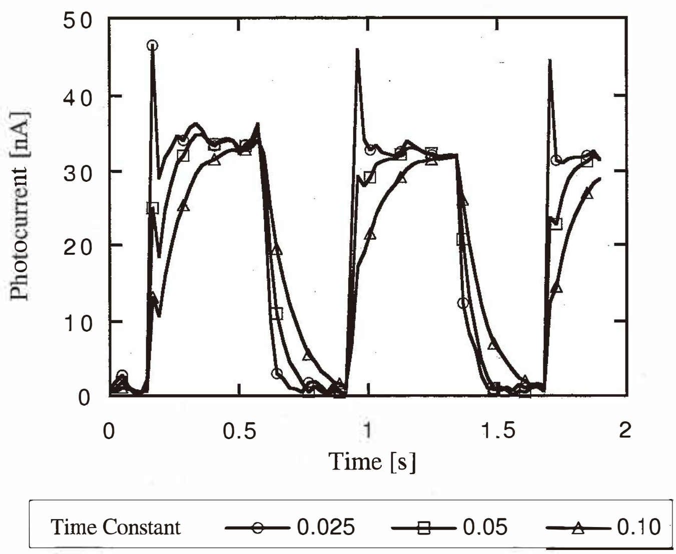


Fig. 9. Response times of integrated SPV signal for various time constants.

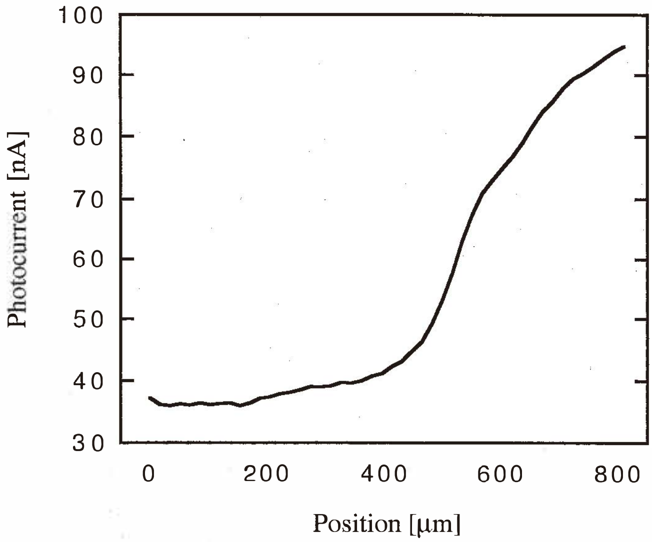


Fig. 10. NPL output after averaging 5 scanning data.

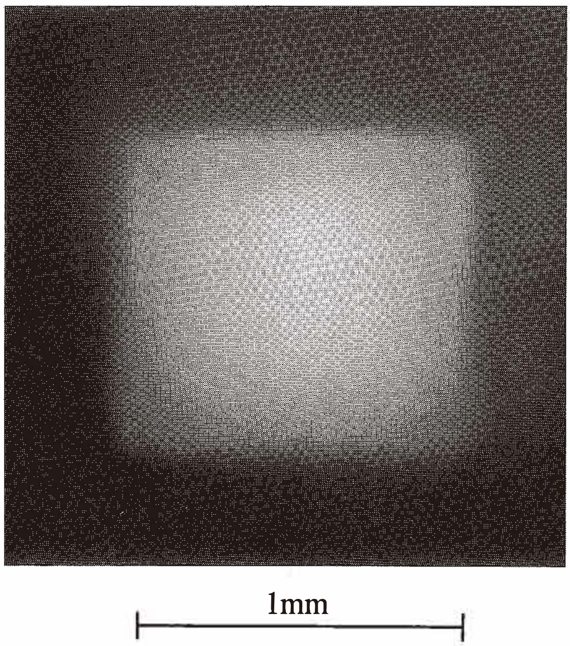


Fig. 11. Two-dimensional photocurrent image of the digital LAPS measurement.

Fig. 10. The x scan took 128 points and the y scan 128 lines, giving a surface potential map of 16,384 measured points. The total time required to produce it was about 4.5 min, while it took about 8 hours using the conventional SPV method with analog lock-in amplifier, i.e., the measurement time became one hundred times faster.

5. Discussion

In the proposed parallel integration method, noise is mixed in a random way at every iterative measurement which enhances the signal-to-noise ratio because each data point is superimposed with a sweeping time interval which is much longer than the light beam period. This is demonstrated in Fig. 12 by periodic noise superimposed on the sinusoidal signal. Figure 12(a) shows the signal averaging procedure of NPL which involves a periodic noise of 50% of the signal magnitude. For comparison, the data averaging effect

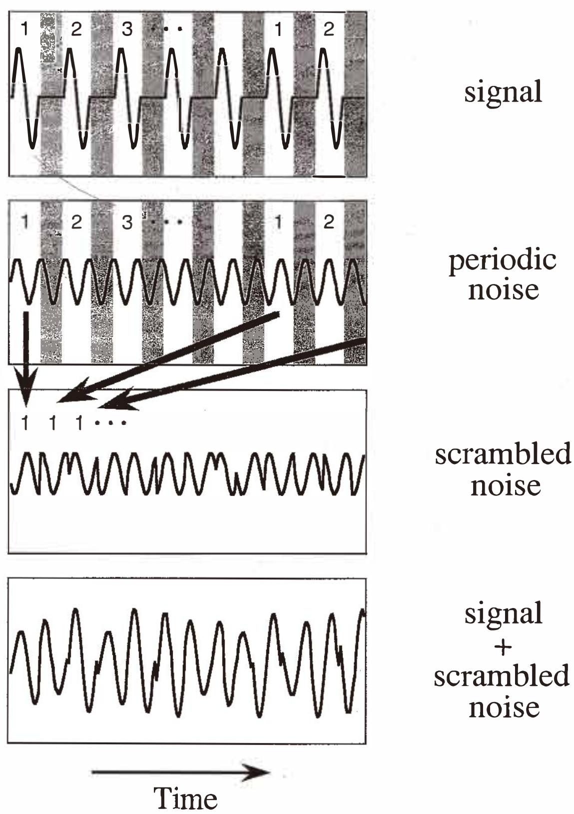


Fig. 12. (a) Signal processing wave forms of parallel lock-in amplifier.

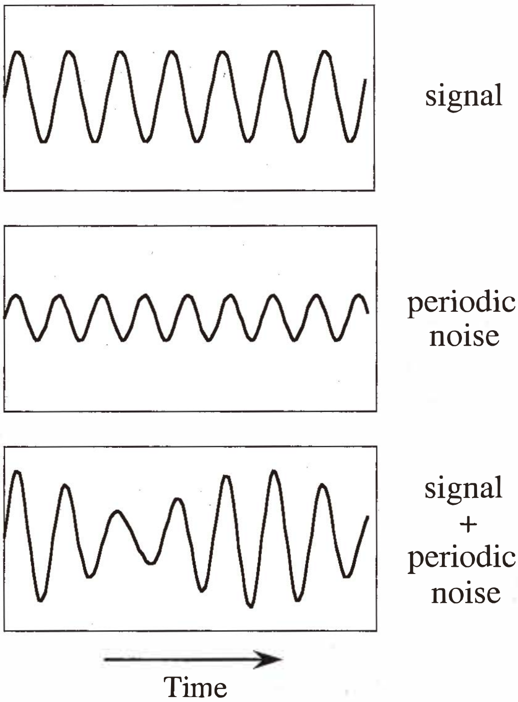


Fig. 12. (b) Signal processing wave forms of conventional analog lock-in amplifier.

of the conventional lock-in amplifier using the same condition is shown in Fig. 12(b). The averaged signal obtained has a low frequency beat and thus an integration time which is longer than the beat period is required for sufficient reduction of periodic noise. On the other hand, the parallel lock-in amplifier superimposes the signals of each point with an interval of sweeping time as shown in Fig. 12(a). Thus the periodic noise is scrambled in the same way as a random noise which suppresses the noise level during the integration procedure. The noise reduction allows a reduction in the number of two-dimensional scanning repetitions required, leading to a shorter measurement time.

A further reduction in measurement time could be achieved using an optimum digital filtering circuit design. For example, a better SN ratio with a shorter averaging time was obtained by controlling the time constant dynamically from small to larger values for every repetition scan. In Fig. 13, the quick response (curve (a)) of the dynamic control method is demonstrated by comparing it with those of fixed time constants (curves (b) and (c)). The time constant of response (a) in Fig. 13 was controlled by the recursive equation

$$\frac{1}{\tau_{n+1}} = (1-\alpha)\frac{1}{\tau_n} + \alpha\frac{1}{\tau_{\text{term}}} \tag{2}$$

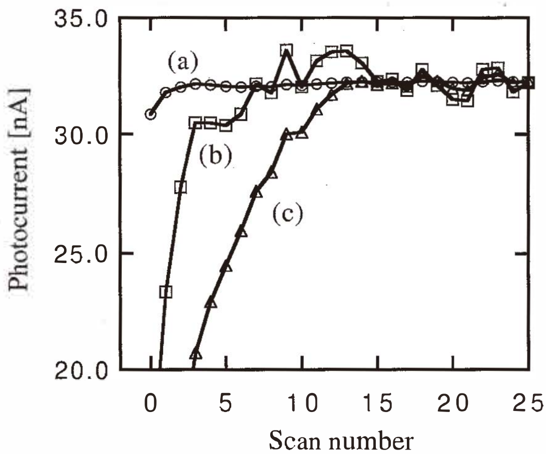


Fig. 13. Comparison of response signals integrated by NPL: (a) dynamic control method, (b) fixed time constant (τ = 0.04), (c) fixed time constant (τ = 0.1).

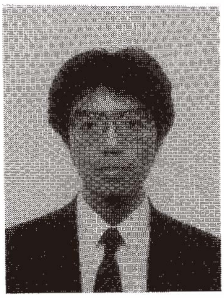
where n is the number of scans, τ_{term} is the convergent time constant and α is the time constant rate of increase. The time response of Fig. 13(a) was obtained using α = 0.75 and τ_{term} = 1.0 s.

6. Conclusion

A new SPV sensor signal processing method is proposed for the high-speed monitoring of two-dimensional high resolution chemical images. The novel system uses digital data processing instead of the analog system of the conventional SPV sensor. This makes it possible to integrate two-dimensional signals by parallel computation through a time sharing process. To form a chemical image of 128 $\times$ 128 points, the measurement time required is about 4.5 min, which is about one hundred times faster than that of the analog system.

References

1 J. Allen, F. Fan Fu-Ren, T. P. David, R. U. Patrick, O. W. David and Z. Feimeng: Science **254** (1990) 68.
2 M. Nakao, T. Yoshinobu and H. Iwasaki: Sensors and Actuators **B20** (1994) 119.
3 Y. Kanai, M. Shimizu, H. Uchida, H. Nakahara, C. G. Zhou, H. Maekawa and T. Katsube: Sensors and Actuators **B20** (1994) 175.
4 M. Shimizu, Y. Kanai, H. Uchida and T. Katsube: Sensors and Actuators **B20** (1994) 187.
5 I. Lundström, R. Erlandsson, U. Frykman, E. Hedborg, A. Spetz, H. Sundgren, S. Welin and F. Winquist: Nature **352** (1991) 47.



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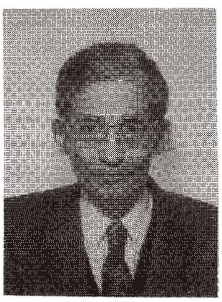

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