# Self Displacement Sensing (SDS) Nano Stage

**Soo Chang Choi[1], Jeong Woo Park[2], Yong Woo Kim[1] and Deug Woo Lee[3,#]**

1 Graduate school, Department of Nano System and Process Engineering, Pusan national University, Busan, South Korea
2 Engineering Research Center (ERC), Pusan National University, Busan, South Korea
3 Corresponding author, Department of Nano System and Process Engineering, Pusan national University, Busan, South Korea
# Corresponding Author / E-mail: dwoolee@pusan.ac.kr, TEL: 82-51-510-3092, FAX: 82-51-514-2982

KEYWORDS : SDS(self displacement sensing), Nano Positioning, Nano stage, PSPD

*This paper describes the development of a nano-positioning system for nanoscale science and engineering. Conventional positioning systems, which can be expensive and complicated, require the use of laser interferometers or capacitive transducers to measure nanoscale displacements of the stage. In this study, a new self-displacement sensing (SDS) nano-stage was developed using mechanical magnification of its displacement signal. The SDS nano-stage measured the displacement of its movement using a position-sensitive photodiode (PSPD), a laser source, and a hinge-connected rotating mirror plate. A beam from a laser diode was focused onto the middle of the plate with the rotating mirror. The position variation of the reflected beam from the mirror rotation was then monitored by the PSPD. Finally, the PSPD measured the amplified displacement as opposed to the actual movement of the stage via an optical lever mechanism, providing the ability to more precisely control the nanoscale stage. The displacement amplification process was modeled by structural analysis. The simulation results of the amplification ratio showed that the distance variation between the PSPD and the mirror plate as well as the length L of the mirror plate could be used as the basic design parameters for a SDS nano-stage. The PSPD was originally designed for a total travel range of 30 to 60 mm, and the SDS nano-stage amplified that range by a factor of 15 to 25. Based on these results, a SDS nano-stage was fabricated using principle of displacement amplification.*

Manuscript received: May 1, 2006 / Accepted: December 22, 2006

## NOMENCLATURE

ΔPSPD = laser spot movement on PSPD
F= vertical force at the end of cantilever
E= young's modulus of cantilever
I= area moment of inertia of cantilever
D= distance between cantilever and PSPD
Zc= displacement
ΔX= displacement of positioning stage
ΔC= intersection of center-line and extended laser trace reflected from mirror plate
L= length of mirror plate
d= distance between mirror plate and PSPD
$\varnothing_M$= angle of mirror plate
$\varnothing_S$= rotation angle induced by stage movement
$\varnothing_P$= reflected angle of laser against center-line

## 1. Introduction

Recently, industrial parts have become smaller, even down to the order of nanometers in length. Therefore, it is important to be able to accurately measure small mechanical parts. It is essential in metrology to be able to make nanoscale measurements in systems such as a STM (scanning tunneling microscope),[1] an AFM (atomic force microscope),[2] and a SNOM (scanning near-field optical microscope).[3]

This paper describes the development of a new nano-positioning stage for use in nano-measurements and manipulation. Conventional positioning systems, which can be expensive and complicated, require the use of laser interferometers or capacitive transducers to measure nanoscale displacements of the stage.[4, 5, 6] In addition, it can be difficult to measure the displacement of the stage with nanometer accuracy because of electrical noise, disturbances, vibrations, and thermal effects. In this study, a new self-displacement sensing (SDS) nano-stage was introduced based on the mechanical magnification of the displacement signal. This is different than that of commercial systems, which electrically amplify the signals. The displacement amplification process was modeled by structural analysis. The simulation results of the amplification ratio showed that the distance between the position-sensitive photodiode (PSPD) and the mirror plate as well as the length of the mirror plate L could be used as the basic design parameters for a SDS nano-stage. In addition, the capability of the self-displacement sensing function was compared with that of a commercial capacitive transducer. The SDS nano-stage resulted in an amplified displacement signal that enabled more precise measurements.

## 2. Amplification Principle for an AFM Cantilever Beam

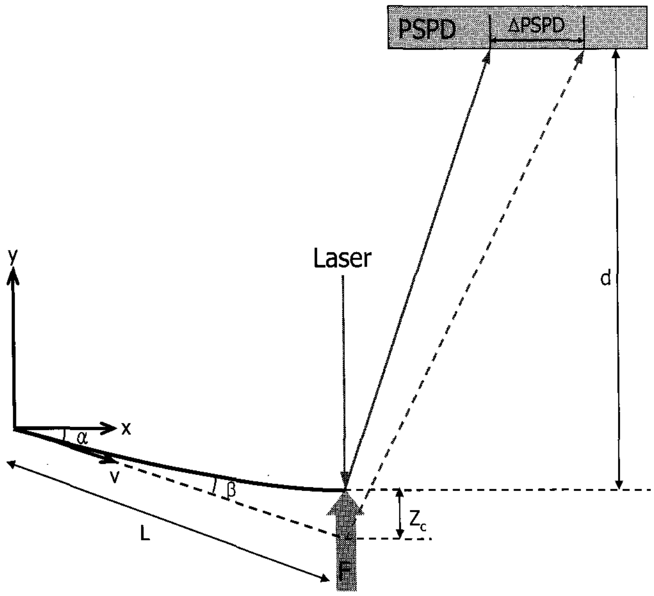


Fig. 1 Schematic of the light lever to detect cantilever deflection

The deflection of an AFM cantilever beam is usually measured using an optical lever technique, as shown in Fig. 1. A beam from a laser diode is focused onto the end of the cantilever and the position of the reflected beam is monitored by a PSPD. When a force is applied to the tip, the cantilever bends and reflects the light beam at an angle twice that of the slope at the end of the beam. If the detector is a distance d away from the cantilever, the laser spot moves on the detector through a distance ΔPSPD where

$$\Delta PSPD \approx 2d\tan\beta = \frac{FL^2 d}{EI} \tag{1}$$

Displacement of cantilever (Zc ) is

$$Z_c = \frac{FL^3}{3EI}\cos^2\alpha \tag{2}$$

According to eq. (1), (2)

$$Z_c = \frac{\Delta(PSPD)L}{3d}\cos^2\alpha \tag{3}$$

Finally, ΔPSPD can be defined as

$$\Delta PSPD = Z_c \times \frac{3d}{L}\cos^2\alpha \tag{4}$$

According to Eq. (4), measured displacement of cantilever ($Z_c$) is amplified by $(3d/L)\cos^2\alpha$.[7,8]

## 3. SDS (Self Displacement Sensing) Nano Stage

### 3.1 Mechanism

Fig. 2 shows a SDS nano-stage with unidirectional movement capability. The SDS nano-stage measures the displacement of its movement using a PSPD, a laser source, and a hinge-connected rotating mirror plate. A beam from the laser diode is focused onto the middle of the plate with the rotating mirror and the position of the reflected beam is monitored by the PSPD. When the positioning stage moves, the mirror rotates, causing the reflected beam to move on the PSPD. The PSPD measures the amplified displacement as opposed to the actual movement of the stage by using the optical lever mechanism, enabling more precise control of the nano-stage.

### 3.2 Principle of Displacement Amplification

Fig. 3 shows a principle of displacement amplification via rotating mirror plate. The angle Øs, Øp are given by

$$\tan\phi_p = \frac{\Delta PSPD}{d + \Delta C} \tag{5}$$

$$\tan\phi_s = \frac{\Delta X}{L} \tag{6}$$

Fig. 4 shows angles definition in our nano stage. The relationship between Øs and Øp can be summarized as

$$180 = 2(90 - \phi_m - \phi_s) + \phi_p + 90$$

$$\phi_p = 2\phi_m + 2\phi_s - 90 \tag{7}$$

If $\phi_M = 45°$

$$\phi_p = 2\phi_s \tag{8}$$

From Eq. (5), (6), (8)

$$\Delta PSPD = \tan\left(2\left(\tan^{-1}\frac{\Delta X}{L}\right)\right)(D + \Delta C) \tag{9}$$

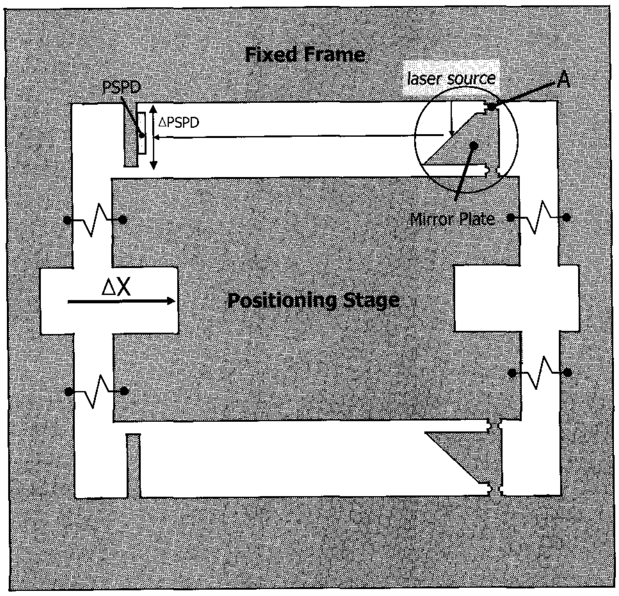


Fig. 2 Mechanism of SDS nano-stage

where,

$$\Delta C = \frac{\Delta X}{2} \tag{10}$$

Finally, ΔPSPD can be defined as

$$\Delta PSPD = \tan\left(2\left(\tan^{-1}\frac{\Delta X}{L}\right)\right)\left(D + \frac{\Delta X}{2}\right) \tag{11}$$

Fig. 5 shows the amplification ratio plotted with respect to d and Fig. 6 shows the amplification ratio plotted with respect to L. It should be noted that d and L are the basic design parameters of the SDS nano-stage. According to Fig. 5 and 6, delta PSPD is linearly proportional to d, but exponentially & inversely proportional to L. The important thing is that size of nano-stage becomes smaller &

smaller, the amplification ratio increases exponentially, which means we can read & control more precisely by miniaturization.

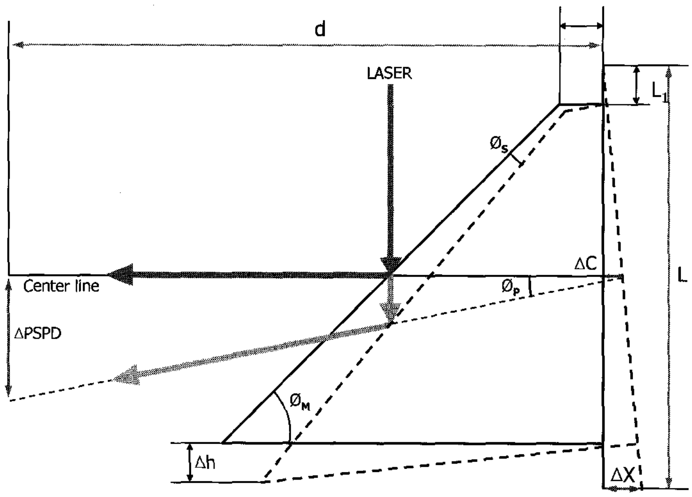


Fig. 3 Principle of displacement amplification via rotating mirror plate

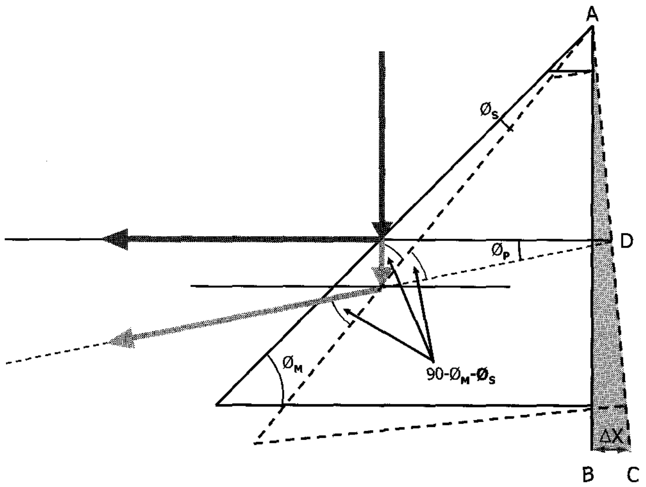


Fig. 4 Angle definition of rotating mirror plate

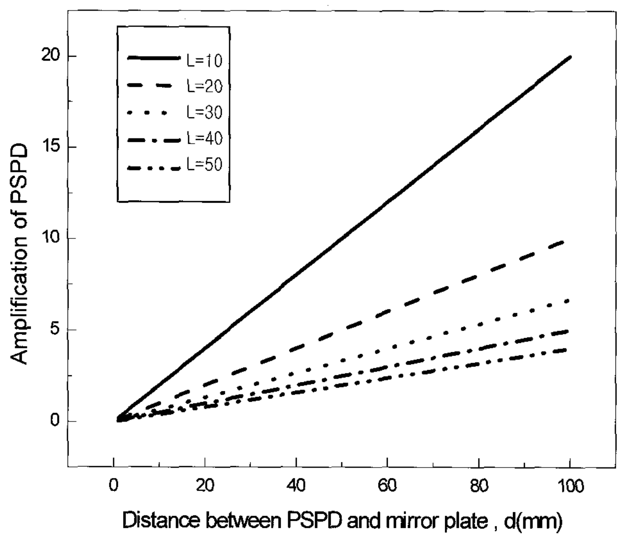


Fig. 5 Amplification ratio plotted according to the distance between PSPD and mirror plate, d (mm)

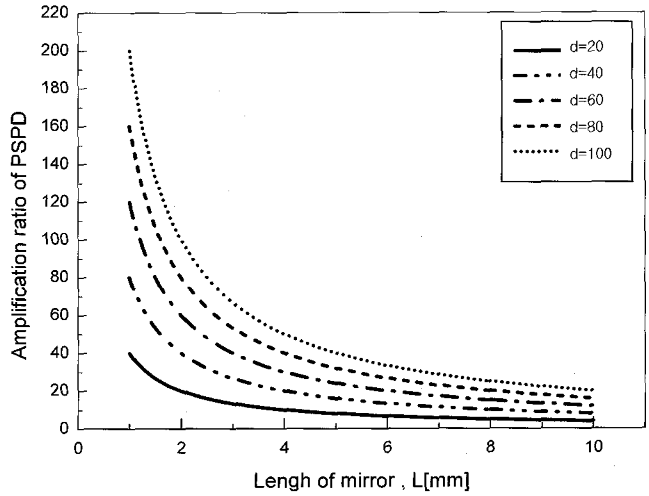


Fig. 6 Amplification ratio plotted according to the length of mirror plate, L (mm)

Hence this SDS nano-stage can be applied to the miniaturized positioning or manipulating system requiring high positioning resolution, for example, micro machine, AFM, STM, SEM (Scanning Electron Microscope), TEM (Transmission Electron Microscope), SIMS (Secondary Ion Mass Spectrometry), and biological manipulating applications. In case that dimensions of d and L are $60 < d < 80$ mm and $4 < L < 6$ mm, an amplification ratio will be within from 20 to 40. Finally, we can fabricate more precise and lower cost nano-stage with self displacement sensing function.

### 3.3 Structural Design of SDS nano Stage

Fig. 7 shows the structural design of the SDS nano-stage with displacement amplification. The PSPD was originally designed for a total travel range of 30 to 60 mm and the SDS nano-stage had an amplification ratio ranging from 15 to 25. Fig. 8 shows a prototype of the nano-stage using the proposed structural design. The nano-stage was fabricated using flexural structures made by wire cutting. The Piezo actuator was a Physik Instruments AE0505D44H40, the PSPD was a Hamamatsu Si PIN photodiode S5980, and the laser diode was a Lanics laser diode module LM-6501EH. The dimensions of L and d were 10 mm and 50 mm, respectively. The SDS nano-stage was able to amplify up to 10 times its movement.

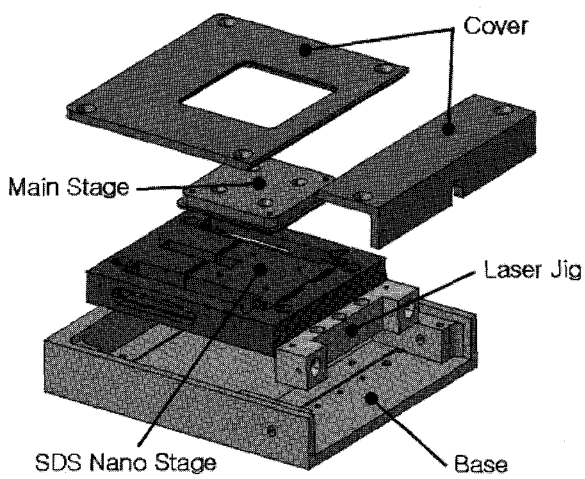


Fig. 7 structural design SDS nano stage

## 4. Experimental test of SDS nano stage

### 4.1 Evaluation of the PSPD

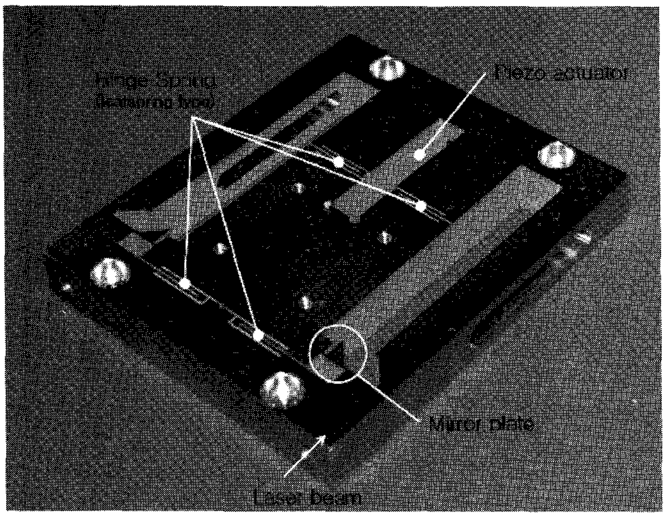


Fig. 8 SDS nano stage

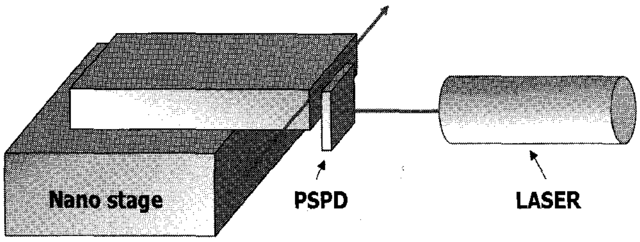


Fig. 9 Test of PSPD using nano stage

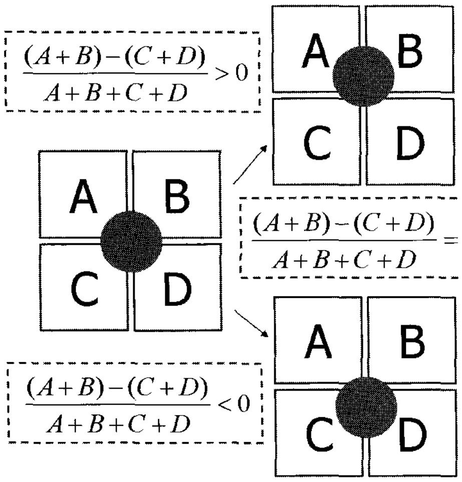


Fig. 10 Detecting of PSPD signal voltage

A schematic of the test for the PSPD is illustrated in Fig. 9. An nPoint, Inc. NPX150Z nano-stage was used to move the PSPD. The beam from the laser diode was focused onto the PSPD, after which the PSPD was moved by the nano-stage. The position of the beam was then monitored by the PSPD.

In general, the output from the PSPD was inversely proportional to the position of the light on the PSPD. The position signal was obtained by normalizing the difference between the four signals from the PSPD using following equation,

$$\frac{(A+B)-(C+D)}{A+B+C+D} = \text{PSPD signal (V)} \qquad (12)$$

where A, B, C and D are voltages from the PSPD. Figure 10 illustrates how the PSPD signal voltage was detected. First, the laser spot was oriented at the center of PSPD to ensure that the PSPD signal voltage was 0 V. Then, the PSPD was moved by the nano-stage, changing the PSPD signal voltage. When the stage was moved, the minimum detected displacement of the PSPD was 3μm. Fig. 11 shows that the voltage at the minimum detected displacement was 0.25 mV. Fig. 12 shows the relatively linear relationship between the PSPD signal voltage and the displacement of the nano-stage. This method proved to be effective at measuring small displacements.

### 4.2 Displacement of the PSPD

A comparison between the theoretical amplified displacement and the actual displacement of the PSPD was made. The schematic of the experimental test is illustrated in Fig. 13. An ADE Technologies 3910 capacitive displacement sensor was used to measure the displacement of the SDS nano-stage. National Instruments PXI Labview was used to obtain the response of the PSPD signal, to obtain the response of the capacitive displacement sensor, to calculate the PSPD signal using Eq. (12), and to compare the displacement of the SDS nano-stage with the displacement of the PSPD. Displacements of the SDS nano-stage and the PSPD were measured according to the input voltage of the piezo actuator, which could range from 10 to 100 V. Fig. 14 shows the calculated PSPD signal from Eq. (12) and the results obtained after applying a 10 Hz low pass filter to the signal.

Fig. 15 shows the results of the PSPD and the capacitive displacement sensor as well as the theoretical displacement data. The SDS nano-stage was designed to amplify 10 times its movement. The data shows good agreement between the experimental and theoretical results

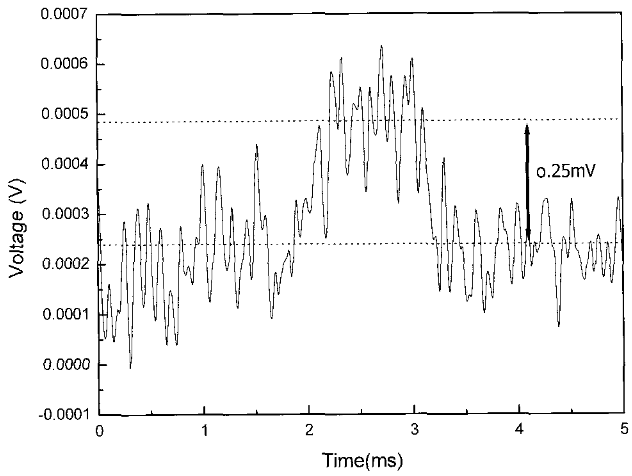


Fig. 11 The voltage of the minimum detected displacement

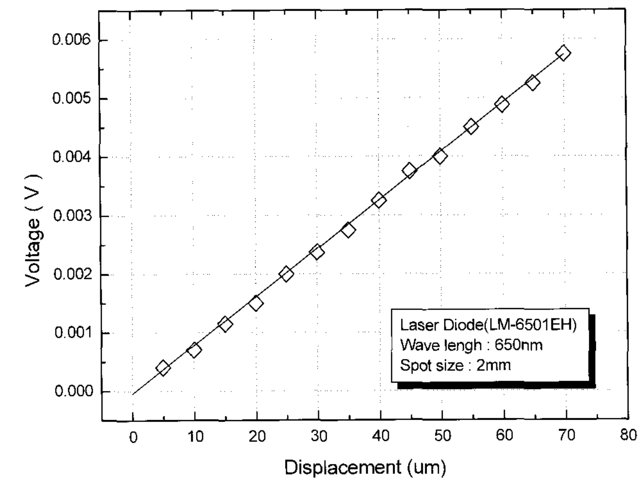


Fig. 12 Schematic diagram of the experimental tests

## 5. Conclusions

A SDS nano-stage was developed for an AFM by applying a

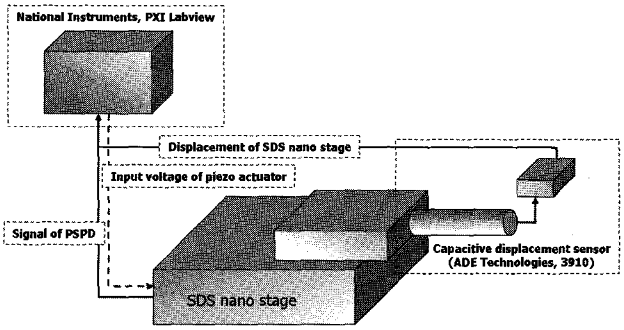


Fig. 13 Schematic diagram of the experimental tests

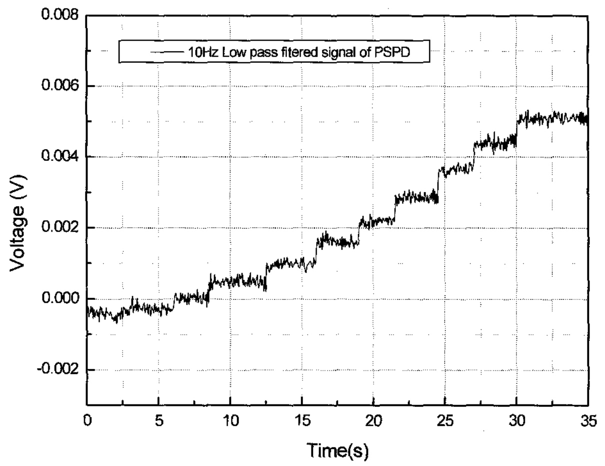


Fig. 14 Signal of PSPD and 10Hz low pass filter on signal of PSPD

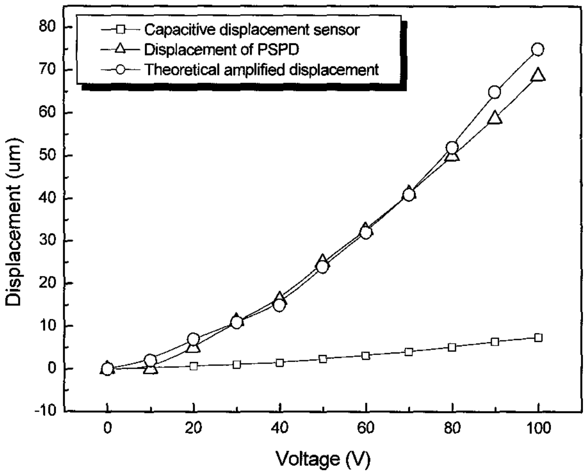


Fig. 15 SDS nano stage's displacement according to input voltage of each piezo actuator

displacement amplification process. The parameters of the nano-stage were designed to amplify the displacement by a factor of 10. A comparison between the theoretical amplified displacements and the actual displacements of the PSPD was made and the two sets of results were in good agreement with each other.

## ACKNOWLEDGEMENT

This work was supported by Micro-Factory Project of the Ministry of Commerce, Industry and Energy (MOCIE).

## REFERENCES

1. Binnig, G, Rohrer, H., Gerber, Ch. and Weibel, E., "Surface studies by scanning tunneling microscopy," Phys. Rev. Lett., Vol.49, No.57, pp.57-61, 1982.

2. Binnig, G., Quate, C. F. and Gerber, Ch., "Atomic force microscope," Phys. Rev. Lett., Vol.56, No.930, pp.930-933, 1986.

3. Pohl, D. W., Denk, W. and Lanz, M., "Optical stethoscopy: Image recording with resolution λ/20," Appl. Phys. Lett., Vol.44, No.7, pp.651-653, 1984.

4. Jäger, G., Hausotte, T., Manske, E., Büchner, H. J., Mastylo, R., Dorozhovets, N., Füßl, R. and Grünwald, R., "Nanometrology-Nanopositioning-and Nanomeasuring Machine with integrated Nanoprobes," Materials Science Forum, Vol. 505-507, pp. 7-12, 2006.

5. Kim, E. Y., Lee, S. J. and Lee, D. W., "A Study of Behavior Characteristics of Nano-Stage According to Hinge Structure," Proceeding of the KSMPE Autumn Conference, pp.75-80, 2005.

6. Fan, K. C. and Chen, M. J., "A 6-degree-of-freedom measurement system for the accuracy of X-Y stages," Precision Engineering, Vol.24, pp.15-23, 2000.

7. Hutter, J. L., "Comment on Tilt of Atomic Force Microscope Cantilevers: Effect on Spring Constant and Adhesion Measurements," Langmuir, Vol. 21, pp.2630-2632, 2005.

8. Butt, H. J., Cappella, B. and Kappl, M., "Force measurements with the atomic force microscope : Technique, interpretation and applications," Surface Science Reports, Vol. 59, pp.1-152. 2005.

9. Vikram, C. S. and Caulfield, H. J., "Position-sensing detector for logical operations using incoherent light," Optical Engineering, Vol.44, pp.115201:1-115201:4, 2005.

10. Huang, M. Z., Shi, L. Z., Wang, Y. X., Ni, Y., Li, Z. Q. and Ding, H. F., "Development of a new signal processor for tetralateral position sensitive detector based on single-chip microcomputer," Review of Science instruments, Vol.77, pp.083301:1-083301:5, 2006.

11. Jywe, W. Y. and Teng, Y. F., "New nano-contouring measurement techniques for a nano-stage," International Journal of Machine Tools & Manufacture, Vol.46, No.7-8, pp.869 -877, 2005.

12. Beaulieu, L. Y., Godin, M., Laroche, O., Tabard-Cossa, V. and Grütter, P., "Calibrating laser beam deflection system for use in atomic force microscopes and cantilever sensors," Applied Physics Letters, Vol.88, pp.083108:1-083108:3, 2005.