Asian Physics Olympiad
2021 TAIPEI

May 20, 2021

The experimental examination lasts for 5 hours and is worth a total of 20 points.

Software for the on-line examination

- For the on-line experiment, one should use PC with WIN10 and 8 Gb RAM.
- The software for the on-line experiment will be uploaded to the 2021APhO website on May 17, 2021. A link will be emailed to the team leaders. Please download the related ZIP file to the examiners' computers.
- Password is required to unzip the software. The password will be announced on the 2021APhO website five minutes before the examination and be sent via email to team leaders. Unzip of the software takes around 1 to 2 minutes. Be patient!
- At the beginning of the examination, find the APHO.exe and double click on the icon to start the experiment.

Before the exam

- You must not open the envelopes containing the problems before the sound signal indicating the beginning of the competition.
- The beginning and end of the examination will be indicated by a sound signal. There will be announcements every hour indicating the elapsed time, as well as fifteen minutes before the end of the examination (before the final sound signal).

During the exam

- Dedicated answer sheets are provided for writing your answers. Write your answers into the appropriate tables, boxes or graphs on the corresponding answer sheet (marked A). For every problem, there are extra blank working sheets for carrying out detailed work (marked W). Be sure to always use the working sheets that belong to the problem you are currently working on (check the problem number in the header). If you have written something on any sheet which you do not want to be graded, cross it out. Only use the front side of every page.
- In your answers, try to be as concise as possible: use equations, logical operators and sketches to illustrate your thoughts whenever possible. Avoid the use of long sentences.
- Estimates of uncertainties are required for all measurements unless explicitly stated otherwise in the question. You should also decide on the appropriate number of data points or measurement repetitions unless specific instructions are given. Please give an appropriate number of significant figures when stating numbers.
- Often, you may be able to solve later parts of a problem without having solved the previous ones.
- A list of physical constants is given on the next page.
- You are not allowed to leave your working place without permission. If you need any assistance, please draw the attention of a team guide by raising one of your flags ("I need water" if you need water, "toilet break" if you need to go to the toilet, "Extra paper, please!" if you need extra working sheets, "equipment/materials" if you have a problem with your equipment or materials or "I need help" in all other cases).

At the end of the exam

- At the end of the examination you must stop writing immediately.

- For every problem, sort the corresponding sheets in the following order: cover sheet (C), questions (Q), answer sheets (A), working sheets (W) and then extra sheets (Z) if you have them.
- Put all the sheets belonging to one problem into the envelope for that question. Also put the general instructions (G) into the remaining separate envelope. Also hand in empty sheets. You are not allowed to take any sheets of paper out of the examination area.
- Leave your writing equipment on the table.
- Wait at your table in silence until your envelopes are collected. Once all envelopes are collected your guide will escort you out of the examination area.

Speed of light in vacuum	c	=	$299\,792\,458\ \mathrm{m\cdot s^{-1}}$
Vacuum permeability	μ_0	=	$4\pi\times10^{-7}\ \mathrm{kg\cdot m\cdot A^{-2}\cdot s^{-2}}$
Vacuum permittivity	ε_0	=	$8.854\,187\,817\ldots\times10^{-12}\ \mathrm{A^2\cdot s^4\cdot kg^{-1}\cdot m^{-3}}$
Elementary charge	e	=	$1.602\,176\,620\,8(98)\times10^{-19}\ \mathrm{A\cdot s}$
Mass of the electron	m_e	=	$9.109\,383\,56(11)\times10^{-31}\ \mathrm{kg}$
Mass of the proton	m_p	=	$1.672\,621\,898(21)\times10^{-27}\ \mathrm{kg}$
Mass of the neutron	m_n	=	$1.674\,927\,471(21)\times10^{-27}\ \mathrm{kg}$
Atomic mass constant	m_u	=	$1.660\,539\,040(20)\times10^{-27}\ \mathrm{kg}$
Rydberg constant	R_∞	=	$10\,973\,731.568\,508(65)\ \mathrm{m^{-1}}$
Universal constant of gravitation	G	=	$6.674\,08(31)\times10^{-11}\ \mathrm{m^3\cdot kg^{-1}\cdot s^{-2}}$
Acceleration due to gravity in Adelaide	g	=	$9.797\ \mathrm{m\cdot s^{-2}}$
Planck's constant	h	=	$6.626\,070\,040\,(81)\times10^{-34}\ \mathrm{kg\cdot m^2\cdot s^{-1}}$
Avogadro number	N_A	=	$6.022\,140\,857\,(74)\times10^{23}\ \mathrm{mol^{-1}}$
Molar gas constant	R	=	$8.314\,4598(48)\ \mathrm{kg\cdot m^2\cdot s^{-2}\cdot mol^{-1}\cdot K^{-1}}$
Molar mass constant	M_u	=	$1\times10^{-3}\ \mathrm{kg\cdot mol^{-1}}$
Boltzmann constant	k_B	=	$1.380\,648\,52(79)\times10^{-23}\ \mathrm{kg\cdot m^2\cdot s^{-2}\cdot K^{-1}}$
Stefan-Boltzmann constant	σ	=	$5.670\,367\,(13)\times10^{-8}\ \mathrm{kg\cdot s^{-3}\cdot K^{-4}}$

Elasticity of cantilever (10 points)

Please read the general instructions in the separate envelope before you start this problem.

I. Introduction

Cantilever beam is one of the common mechanical structures (see Figure 1). It is not only exploited as the main structure to resist shear bending in strucuture design, but also often seen in the field of nano-engineering. To analyze the elasticity response of nanocantilever beam as well as to elucidate the relationship between stress and strain is important in applied physics. However, it is rather difficult to perform direct measurement of nanomaterials to their mechanical properties. It can be only obtained from the indentation test unlike the uniaxial tensile text in macroscale. For nanocantilever beam subjected to a force by employing an atomic force microscope or nanoindentation, the observation of the flexural deformation of the nanocantilever beam to infer its Young's modulus becomes one of the most important tools for measuring the mechanical properties of materials in microscale.

(A)

(B)

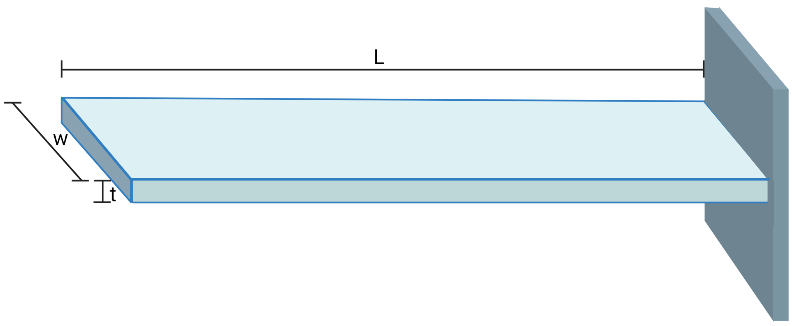
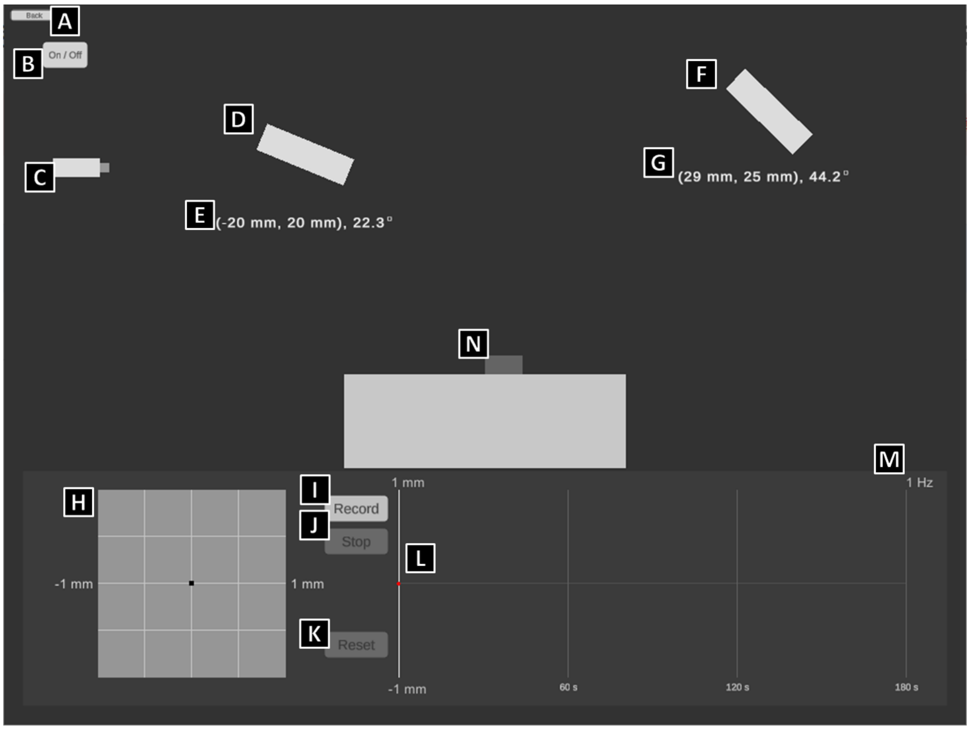


Figure 1(A) SEM image of a nanocantilever beam (B) illustration of nanocantilever beam, with the length *L*, width w and thickness t.

II. Introduction of the equipment

1A

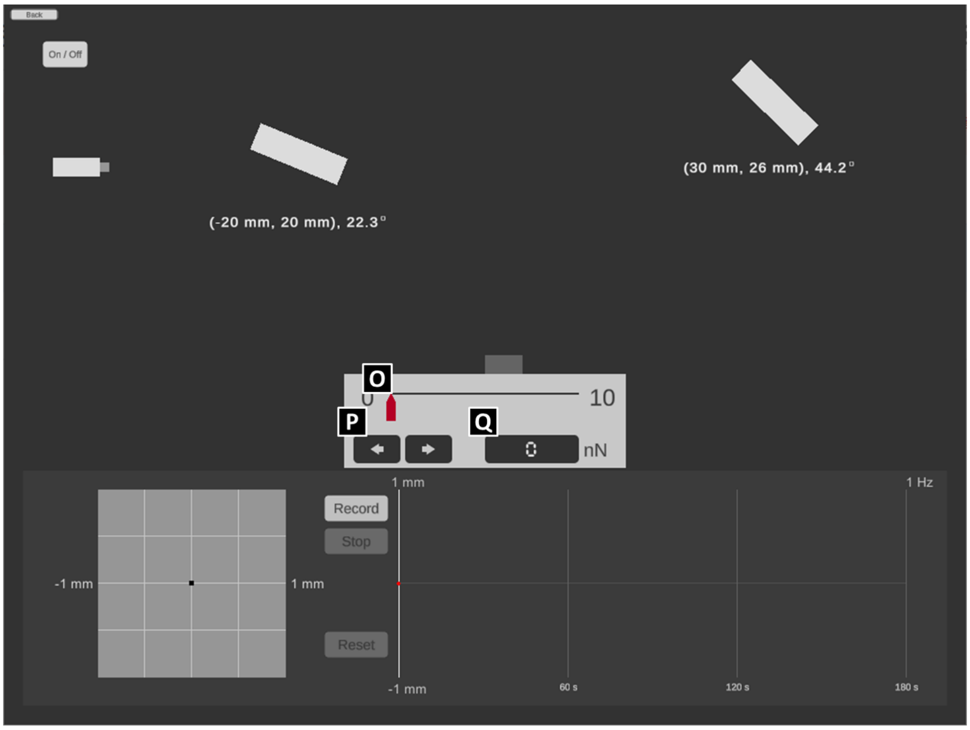


Common

- A. Back to previous page
- B. Laser switch
- C. Laser emiter
- D. Reflector: you can control this device precisely by clicking the arrows next to it, or directly dragging it to move with the left mouse button.
- E. Position of the reflector: the coordinates are accurate to 1×10^{-3}m, and the angle is accurate to 0.1°
- F. Position Sensitive Detection, PSD
- G. Position of the reflector: the coordinates are accurate to 1×10^{-3}m, and the angle is accurate to 0.1°
- H. PSD recording system: you can control this device precisely by clicking the arrows next to it, or directly dragging it to move horizontally with the left mouse botton. The boundaries of this system are within $\pm 1 \times 10^{-3}$m both vertically and horizontally.
- I. PSD recorder: start-recording button
- J. PSD recorder: stop-recording button
- K. PSD recorder: reset-recording button

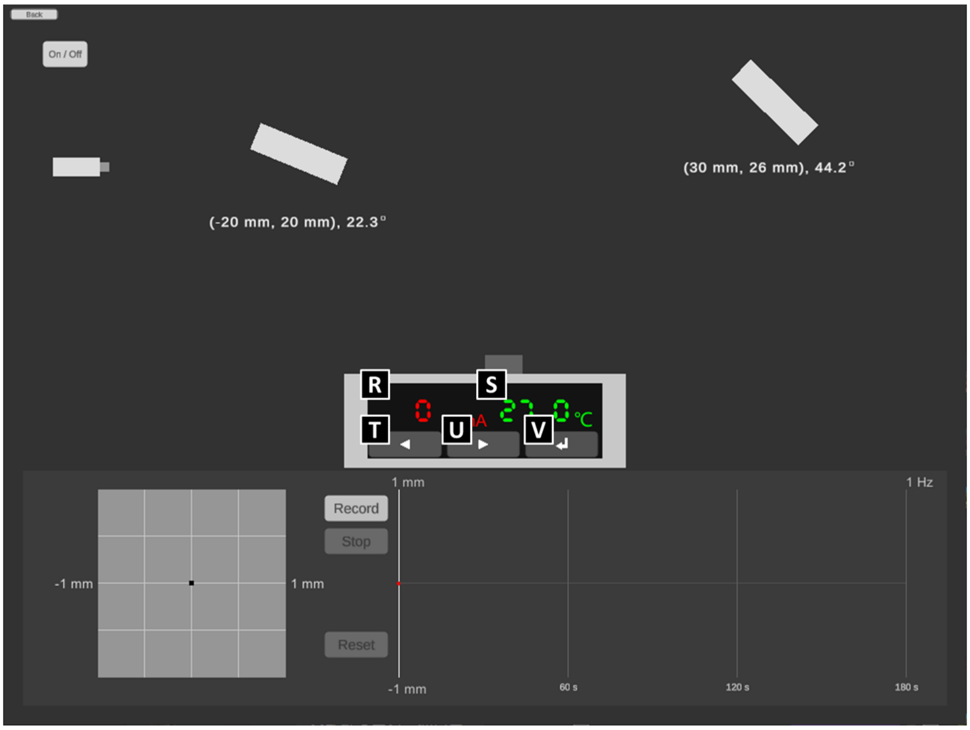
- L. PSD record history: the readings are accurate to 0.0001×10^{-3}m, which can be recorded with the longest duration of 180 sec. You can query the data with the left mouse button on the chart, or by clicking arrow keys on the keyboard.
- M. PSD record frequency: 1 Hz
- N. Nnano-beam carrier: the coordinates at the left-top corner of the carrier are (0, 0), and the nano-beam would be installed on the left edge of the top.

1B



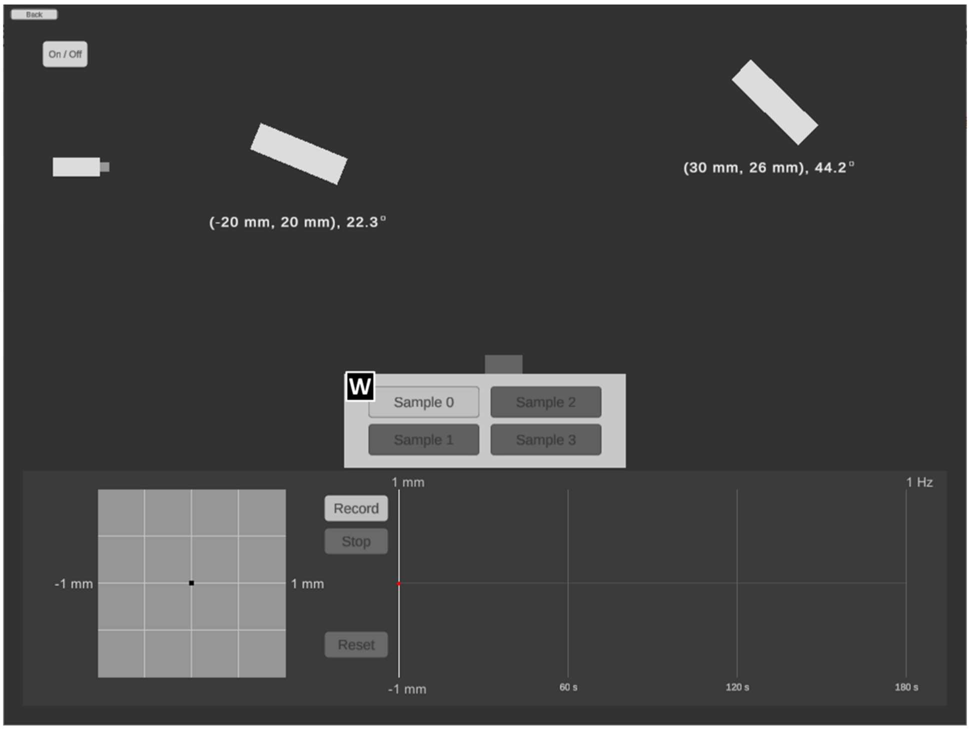
- O. the controller of the point load: you can control the force by dragging the red cursor to move horizontally.
- P. the micro-controller of the point load: you can control the force precisely by clicking the arrow buttons with the left mouse button.
- Q. the monitor of the point load: the precision is up to 0.01×10^{-9} N

1C



- R. the monitor of the electric currenct of the heater with the precision up to 1×10^{-3}A.
- S. the monitor of the temperature of the heater with the precision up to 0.1°C
- T. the button to decrease current of heater: each click for 2×10^{-3}A
- U. the button to increase current of heater: each click for 2×10^{-3}A
- V. the button to set up the change of the electric current: please NOTE that the time to heat or cool down the sample is referring to the authentic experience of the real world and CANNOT be reset arbitrarily, which means the time to let the sample cool down will increase if the sample is over-heated by the excessive electric current.

1D



- W. sample switch: switch the test sample by directly clicking it with the left mouse button.

III. Experiment

Note:Please ensure the data and the answers must be expressed by scientific notation and SI unit. The unit of length should be meter.

Part A. Alignment of light path

It is not an easy task to measure the deflection of nanocantilever beam at microscopic scale by using optical microscope directly. Therefore, by exploiting the straightness and reflection of laser we are able to measure the reflection by a position sensitive detection sensor (PSD). The length L of the nanocantilever used in the present experiment is about 100×10^{-6}m. Please use program 1A and answer question **A.1** to **A.3.**

A.1	Please design a light path so that the laser spot hits the middle of the reflective area of the cantilever beam. Make sure the laser spot can stably appear near the origin of the PSD display screen and draw the relative position (coordinates and angles) of each component on the answer sheet.	0.6pt

A.2	Since the cantilever beam will be disturbed when the device turned on, it may take some time to reach a stable state. After the instrument is turned on, the figure of the position of the light spot on the PSD and time will be displayed at the bottom right of the program. Please record the position d of the light spot on the PSD every 3 seconds under external disturbance after pressing the "Record" button. Please record at least 40 data points, and then press the "Stop" button to stop capturing data.	0.8pt

A.3	Please use the **stable segment** of the data obtained by **A.2** to find the reference value of measurement of this cantilever beam under the fluctuation of the experimental environment. ($\bar{d}$ is the average value of d).	1.0pt

Note : For the convenience of the measurement, we assume the cantilever has reached its stable state under the influence of the environmental perturbation, i.e. the vibration of the optical components will not affect the measured value.

Note:Please ensure the data and the answers must be expressed by scientific notation and SI unit. The unit of length should be meter.

Note:In part B, calculation of the standard deviation in the data analysis is not required.

Part B. Deformation of cantilever beam and deduction of Young's modulus

The Young's modulus of the material of cantilever beam can be obtained by using an atomic force microscope or a nanoindentation tester to apply an external force to the free end of the cantilever beam. Through the measurement of deformation, the magnitude of Young's modulus can be obtained. When a force is applied to a nano cantilever beam, if the amount of deformation does not exceed the elastic limit of the material, then the correlation between the force and the deformation of the free end can be formulated as follows:

$$\delta = \frac{F\,L^3}{3\,E\,I} \tag{1}$$

where F is the force applied at the end point, E is the Young's modulus; I is the area moment of inertia of the cantilever beam section, L is the length of the cantilever beam, and δ is the magnitude of flexural deformation. The area moment of inertia I is a physical quantity that reflects the influence of the cross-section size on the bending deformation of the cross-section of an object subject to bending deformation. The value of the area moment of inertia can be calculated by simple integration. As shown in Figure 2, there is a cantilever beam whose cross-section height is t, the width is w, and its area moment of inertia can be calculated by integral as follows:

$$I = \int_A y^2\,dA = \frac{1}{12} w\,t^3 \tag{2}$$

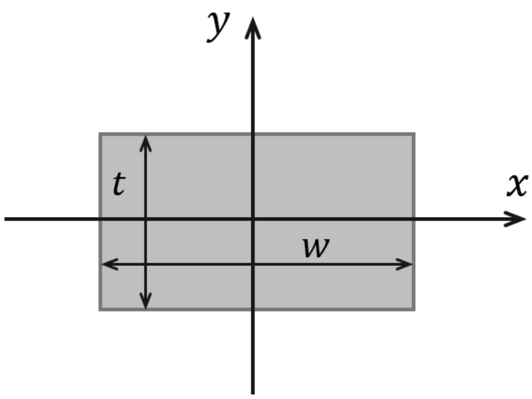


Fig. 2 Schematic illustration of the cantilever beam cross-section.

The cantilever used in this experiment has an L of 100×10^{-6}m, w of 35×10^{-6}m, and t of 0.20×10^{-6}m. Silicon is used as the substrate material, and its standard Young's modulus E is 280×10^{9} Pa.

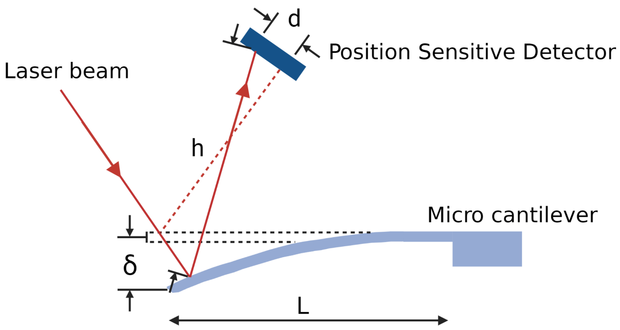


Figure 3. Illustration of the optical leverage setup.

Please use program 1B and answer questions **B.1** to **B.3**.

B.1	Please design the optical path when the external force is 0 N. Let the laser spot hit in the middle of the reflective area of the cantilever, and be sure about that the laser spot can stably appear near the center of the PSD display screen. Record the data on the table to obtain the measurement reference value d_0. The position of the light spot on the PSD at this time is set as the displacement $\Delta d = 0$. Then apply five different magnitudes of external forces on the cantilever, and record the experimental results in the table on the answer sheet.	1.0pt

B.2	Fill in the table. Make a plot by taking the magnitude of flexural deformation δ as the y-axis and $\overline{\Delta d}$ (the average of light spot displacement on the PSD) as the x-axis.	1.0pt

B.3	Please deduce the C_1 value value from the optical leverage relationship $\delta = C_1 \overline{\Delta d}$, as illustrated in Figure 3.	0.4pt

Note : For the convenience of the measurement, we assume the cantilever has reached its stable state under the influence of the environmental perturbation., i.e. the vibration of the optical components will not affect the measured value.

Note:Please ensure the data and the answers must be expressed by scientific notation and SI unit. The unit of length should be meter.

Note : In part C, calculation of the standard deviation in the data analysis is not required.

Part C. Double layer cantilever beam

Double layer cantilever beam is a structure often used in nano engineering application (e.g. IC Printed Circuit Board or nano brake). It consists of two layers of different materials which expand at different rate as they are heated. In Timoshenko beam theory, bending stiffness differences were considered. Figure 4 shows a double layer cantilever beam consists of two layers, with thickness t_1 and t_2 , thermal expansion coefficients α_1 and α_2 , Young's modulus E_1 and E_2.

Figure 4. schematic illustration of the double layer material used as a cantilever.

According to beam theory, the strain for those two layers could be written as

$$\gamma_1 = \alpha_1 \Delta T + \frac{P_1}{w\,t_1\,E_1} + \frac{t_1}{2\,r} \tag{3}$$

$$\gamma_2 = \alpha_2 \Delta T + \frac{P_2}{w\,t_2\,E_2} + \frac{t_2}{2\,r} \tag{4}$$

where P_i is the net force, ΔT is the temperature difference, w is the width, r is the radius of curvature. The net force needs to be balanced as shown in Figure 4. The relation between resultant moment M and net force P_i is written as follows:

$$M = \sum_i P_i \frac{h}{2} \tag{5}$$

The resultant moment M can be written as a function of the bending stiffness E_iI_i and the radius of curvature r, as follows:

$$M = \sum_i \frac{E_i I_i}{r} \tag{6}$$

E_i is Young's modulus and $I_i$is moment of inertia. The boundary condition requires the strain to be continuous, that is $\gamma_1 = \gamma_2$. By this boundary condition, the following equation can be obtained:

$$\kappa = \frac{1}{r} = \frac{(\alpha_1 - \alpha_2)(T-300)}{\frac{2}{hw}\left(\frac{t_1E_1+t_2E_2}{t_1E_1t_2E_2}\right)(E_1I_1+E_2I_2)+0.5h} \tag{7}$$

$$\delta = \kappa L^2 \tag{8}$$

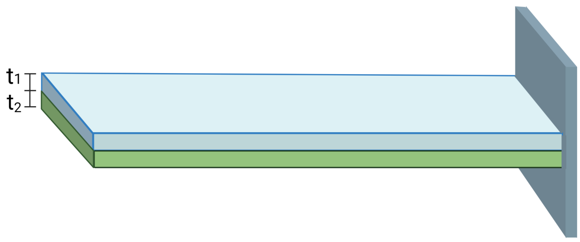


Figure 5: Double layer beam (Upper layer is metal X. Lower layer is silicon.)

The double layer beam structure is shown in Figure 5. Parameters for this experiment are listed as follows: L is 100×10^{-6} m, w is 35×10^{-6} m, t_2 is 0.2×10^{-6} m, t_1 is 0.04×10^{-6} m, thermal expansion coefficients $\alpha_1, \alpha_2$are 14.2×10^{-6}/K and 0.8×10^{-6}/K; the area moment of inertia I_1, I_2 are 1.867×10^{-28} m^4 and 2.333×10^{-26} m^4. The lower layer is silicon base, the Young's modulus E for silicon is 280×10^9 Pa. Please use program 1C and answer question **C.1** to **C.3**.

C.1	Please design a simple experiment diagram with light path. Let the laser beam show near the center of the reflected area. Record the data for room temperature, and find the measurement reference d_0, and used this reference as $\Delta d = 0$. Then, increase the temperature to higher value, wait until the double layer beam stable then record the data. Try to do at least 5 different temperatures and record the data in the table of answer sheet.	1.0pt

C.2	Fill in the table. Make a plot by taking the magnitude of flexural deformation δ as the y-axis and the temperature T as the x-axis. By data analysis, find the slope. You can use the correlation between δ and $\overline{\Delta d}$ in **B.3**.	1.0pt

C.3	Use data from **C.2** to calculate the Young's modulus for the upper layer material.	0.6pt

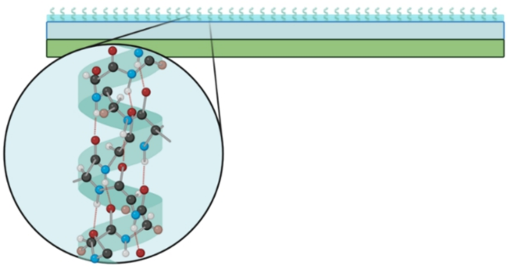
Note : For the convenience of the measurement, we assume the cantilever has reached its stable state under the influence of the environmental perturbation, *i.e.* the vibration of the optical components will not affect the measured value.

Note : Please ensure the data and the answers must be expressed by scientific notation and SI unit. The unit of length should be meter.

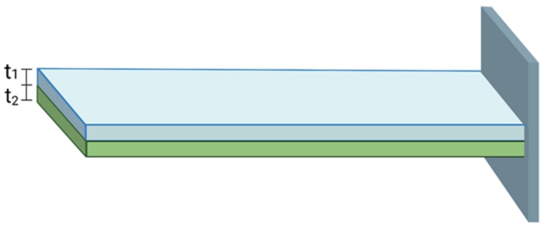
Note : In part D, calculation of the standard deviation in the data analysis is not required.

Part D. Test of molecular-absorption-induced bending of a cantilever beam

A composited cantilever beam can not only be used as a nano-actuators but also a nano-sensor. As an example, Figure 6 shows a nano-protein sensor consisted of a two-layer cantilever beam on which surface is integrated with microfluidic channels and coated with a protein layer. While a different bio-protein is absorbed onto the cantilever, due to the van-der Waal interactions between the molecules the protein attachment can induce a surface stress which distribution is specific to the uniqueness of protein, and consequently a detectable beam bending.



(A)



(B)

Figure 6. (A) A two-layer cantilever beam, used for nano-sensor. The upper layer is coated with a protein layer. (B) a schematic diagram (not in scale) of the cantilever structure, in which the upper layer is made by metal X and the lower layer by Si.

A schematic diagram of the two-layer cantilever beam used in this experiment is illustrated in Figure 6(B). The length L is about $\sim 100\times 10^{-6}$ m , $w\sim 35\times 10^{-6}$ m , $t_2\sim 0.2\times 10^{-6}$ m , and $t_1\sim 0.04\times 10^{-6}$ m . The lower layer is made by Si as substrate. The Young's modulus of Si is 280×10^9 Pa. The coverage ratio (CR) is ~ 0 for Sample 0, ~ 1% for Sample 1. You can ignore the effects of the thickness and Young's modulus of the coated molecules on the cantilever beam because of their tiny amount and small CR. Assume the effective bending stiffness $EI^*\approx 1.84\times 10^{-13}$ N·m^2. Please use program 1D and answer question **D.1** to **D.4.**

D.1	Design an optical path for Sample 0, so that the reflected laser spot locates at the center of the reflection zone, i.e. the laser spot appears stable in the origin of the PSD screen. Record the base value d_0 measured in the tables of the data sheet. The displacement Δd of the laser spot is set zero, $\Delta d=0$ at this position. Then repeat the experiment with Sample 1. Record your answers on the tables of the data sheet. Note that Sample 1 has the highest coverage ratio (CR) in all samples.	0.6pt

D.2	Assume the function form of the magnitude of flexural deformation δ and coverage ratio (CR) can be expressed as : $\delta=C_2\frac{CR}{EI^*}L^4$. Estimate C_2 based on your data obtained in **D.1**. You can use the correlation between δ and $\overline{\Delta d}$ in **B.3**.	0.6pt

D.3	Use Sample 2 and Sample 3, same molecule but different CR. Measure the spot displacement Δd shown on PSD for both samples. Record your answers on the data sheet.	0.8pt

D.4	Please estimate CR of Sample 2 and Sample 3 (expressed in %).	0.6pt

Exploring the spatial structure of the sample with optical methods (10 points)

(Use software 2A to 2E to answer questions)

I. Experimental setup

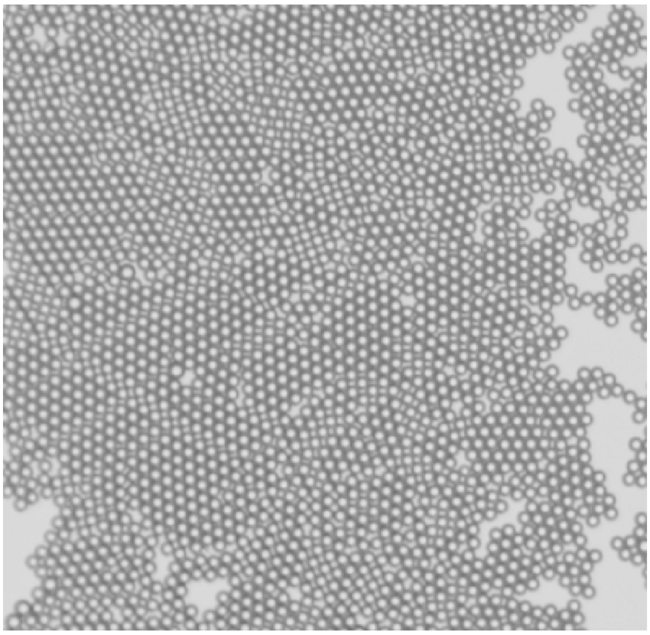


Figure 1 The illustration of the microspheres arrangement

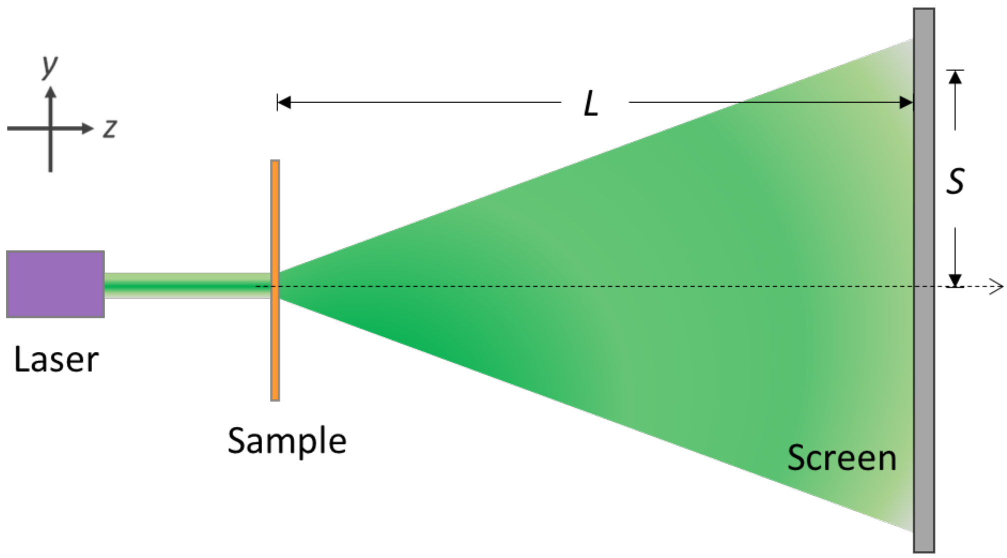


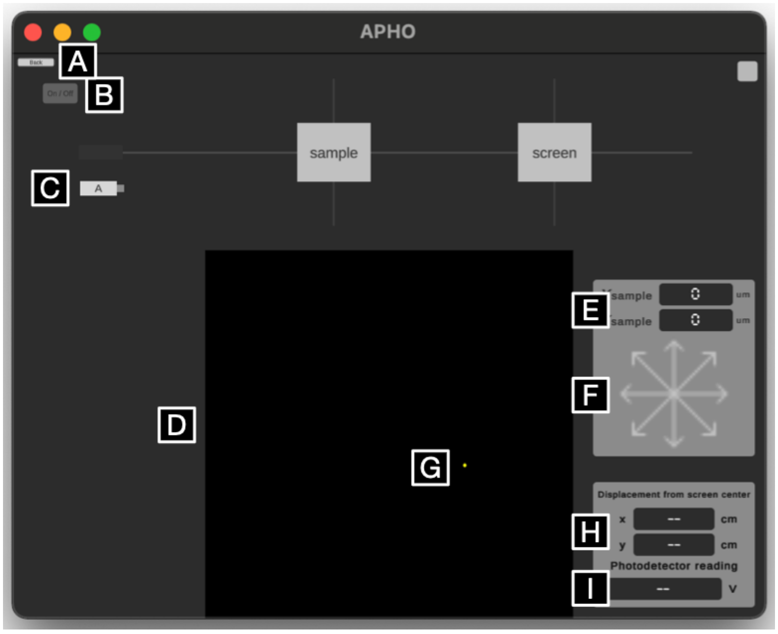
Figure 2 Experimental setup

II. Introduction

Microspheres have many applications in the field of biomedical measurements. The use of a carrier with a structure and pattern design to inject the microspheres can be used to make related photoelectric sensing components. This online experiment aims to simulate the above-mentioned experimental framework, carry out relevant measurements, infer the diameter of the microsphere, the size of the structure pattern, and finally describe the spatial structure of the sample.

There is a sample used for biomedical detecting. This sample is made up of many transparent glass microspheres with the same diameter arranged in a two-dimensional densest packing. The microspheres are closely adjacent to each other, and the arrangement direction is somehow not consistent (as shown in Figure 1). These microspheres are filled into a rectangular array grid which has a size larger than the diameter of the microspheres with a rotation angle. In order to know all the pattern structures of this sample, this experimental design (as shown in Figure 2) uses a laser light source to irradiate the sample to observe the diffraction phenomenon. From the structure analysis of the diffraction pattern, the symmetry and structure size of the sample can be known.

Software Instruction Manual



2A

A. Back to experiment overview

Note that using this button during experiments wipes all experiment states and data.

B. Laser power on/off

Power on/off laser with this button while the laser is on the optical track. When the laser is activated, a light trail is shown on the track.

C. Laser source

Draggable onto or away from the optical track. Note when a new laser source is placed onto the track, “Installing” would be shown to indicate the installation progress.

D. Projection screen

The laser first irradiates the sample, then projects the resulting pattern onto the screen on the right side of the track. In Part A experiment, the screen is fixed at 50 cm from the sample.

E. Sample coordinate display

Shows the coordinates X_{sample} and Y_{sample} for the sample in the middle of the track in 100 μm increments.

F. Sample coordinate adjustment

Click to adjust the coordinates of the sample in 100 μm increments. Long press to move continuously. Diagonal arrows move the sample in both axes in 100 μm increments.

G. Photodetector coordinate adjustment

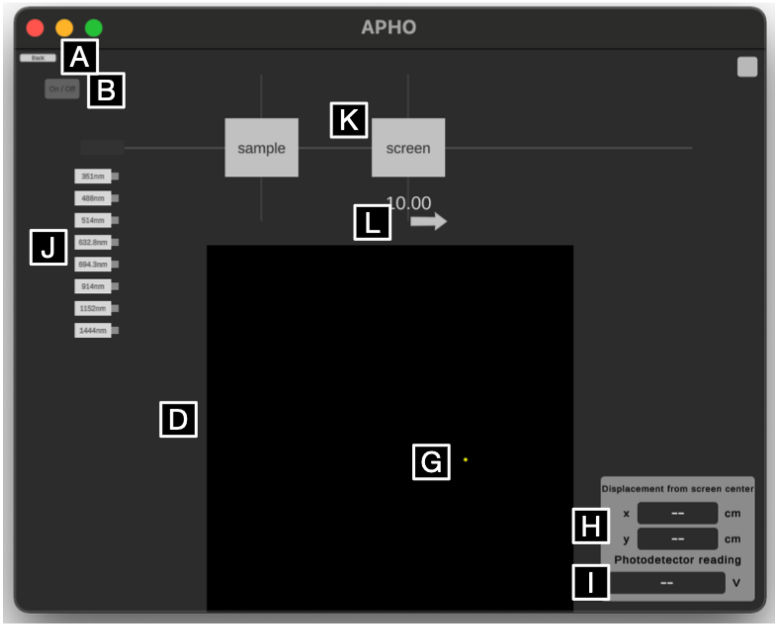
Click on the projection screen to place a photodetector at the spot clicked. Use arrow keys on your keyboard to finetune the location.

H. Photodetector coordinate display

Numerically show the location (x, y) of the photodetector with respect to the origin in 0.01 cm increments.

I. Photodetector voltage display

The voltage readings of the photodetector in 0.01 V increments. Note that the range of the meter cannot be adjusted.



2B - 2E

J. Laser sources of multiple wavelengths

Draggable onto or away from the optical track. Note when a new laser source is placed onto the track, “Installing” would be shown to indicate the installation progress.

K. Projection screen

The laser first irradiates the sample, then projects the resulting pattern onto the screen on the right side of the track. In Part B to Part E experiments, the distance of the projection screen to the sample is adjustable.

L. Projection screen adjustment

Use the mouse to horizontally drag the arrow. This adjusts the distance of the projection screen to the sample at a 1.0 cm increment. Adjustable range is 10.0 cm to 100.0 cm.

III. Experiment

Part A. Collimation of light and sample (1.0 points)

To collimate the laser properly irradiating the sample, a double slit is used as the sample for light calibration. If the laser is properly collimated and irradiated at the center of the double slit, a clear interference fringe can be observed on the screen. The original position of the double slit is (X_{sample}, Y_{sample}) = (0, 0), and the value is displayed on the software interface. The sample has a fixed z position. By sufficiently adjusting the position of the double slit along x-y plane, you would observe the interference fringes displayed on the screen. Please find out the best position (X_{sample}, Y_{sample}) of the double slit that the observer can determine the correct spacing of the interference fringes.

A.1	Please determine the best position value (X_{sample}, Y_{sample}) for the double-slit sample.	0.5pt

A.2	According to the best position value, please draw the observed interference fringes and record the position (*x*, *y*) of the dark fringes of the first and second orders and the distance *S* between the position (*x*, *y*) and origin. Please determine the spacing ΔS between two adjacent dark fringes.	0.5pt

Part B. Exploration of sample structure size (3.0 points)

Assuming that the optical path of the entire system has the optimal setting, the laser position and the sample position are fixed. Just need to change the wavelength of the laser light λ and the position of the screen *L*, and then the corresponding diffraction pattern can be seen on the screen. The corresponding distance between each microsphere *d* can be determined by using the relationship in terms of λ , *L* and *S* (the distance between the position (*x*, *y*) and origin). Please refer to the schematic plot of microsphere arrangement in Figure 1 and use three kinds of laser light sources in the visible light range to estimate the diameter of the microsphere *a*.

B.1	Show the formula for the indicated microsphere distance *d* in terms of λ, *L* and *S*.	0.5pt

B.2	With selecting appropriate position of the screen *L*, please record the coordinates (*x*, *y*) of diffraction pattern on the screen for microsphere, and the estimate distance *S* and $\tan^{-1}(\frac{S}{L})$ (unit: radian) in the selected three laser sources in the visible range. (record five sets on the same ring to obtain the average $\overline{S}$ value)	1.5pt

B.3	Using the formula to estimate the corresponding distance between each microsphere *d*, the diameter of the microsphere *a* and average diameter $\overline{a}$ in the three laser sources.	1.0pt

Part C. Exploration of sample structure size (2.5 points)

This sample has a rectangular grid array with a orientation angle. In each rectangle, there are many transparent glass microspheres arranged in a two-dimensional densest-packed condition. From the pattern on the screen, you can see the crossed diffraction fringe caused by the regular arrangement of the rectangular grid array. Please select a visible laser for experiment, and try to derive the sizes of the rectangular structure and the corresponding orientation angle from the diffraction pattern.

C.1	Please select a visible laser for experiment. Fix the distance between the screen and the sample at L = 90 cm, and observe the diffraction pattern. Please mark the coordinates (x, y) of the 4^{th} to 7^{th} order bright fringes in the two axial directions, calculate the corresponding distance S and estimate the corresponding value of $\tan^{-1}\left(\frac{S}{L}\right)$ (unit: radian).	0.8pt

C.2	Please calculate the distance ΔS_l and ΔS_w between adjacent bright fringes based on the data in the previous question. Please also estimate the length of the long (l) and short (w) sides of a single rectangle.	0.7pt

C.3	Estimate the orientation angle: Draw a line to estimate the angle. Four coordinates (x, y) of the bright patterns should be marked. Estimate the orientation angle ϕ of the long side of a single rectangle with respect to the horizontal axis.	1.0pt

Part D. Exploration of sample structure size (2.5 points)

With the incident light in the visible range as in the previous problems, there are finer diffraction spot patterns within the crossed bright fringes on the screen, which are not easy to identify. Therefore, light of longer wavelength is necessary to acquire clearer diffraction pattern for the sample. Please use infrared lasers to irradiate the samples for generation of fine diffraction spot patterns. Since infrared is invisible, a photodetector is required to find the positions of diffraction spots. Try to determine the sample grid structure by the diffraction spot patterns.

D.1	Please set the screen position at 95 cm, select one infrared laser for the experiment, and use the photodetector to identify the fine diffraction spot patterns on the screen. In the table, please write down the laser wavelength and the center coordinates of a set of 4 × 4 fine diffraction bright spots on the screen. Draw the 4 × 4 spot pattern, denote the distances between adjacent spots, ΔS_x and ΔS_y, in the diagram, and calculate the values.	1.9pt

D.2	Determine the spacings d_x and d_y of the sample grid from the results of the infrared experiments.	0.6pt

Part E. Exploration of sample structure size (1.0 points)

This sample is made up of many transparent glass microspheres arranged in a two-dimensional densest-packed condition (as shown in Figure 1), and is covered in a rectangular array grid with a specific rotation angle. The microspheres are closely adjacent to each other, and the arrangement direction is somehow not consistent. In addition to the regular arrangement of the microspheres, this sample has other rectangular arrays that are larger than the diameter of the microspheres. According to Part C and Part D questions, the structure size and direction information obtained by observing the diffraction fringes, the specific structured pattern of the sample is identified.

E.1	Please draw the periodic arrangement of the sample: Please represent it by a 3x3 rectangular array and mark the sizes (l and w), spacings ($d_x$and d_y) and orientation angle (ϕ) corresponding to the question **Part C** and **Part D** in the pattern with symbols (l, w, d_x, d_y, ϕ).	1.0pt