Physics ATAR – Year 12

Science Inquiry Skills Evaluation and Analysis Test

2016

Name: Solutions

Mark: / 42

= %

Time Allowed: 50 minutes

Notes to Students:

- You must include **all** working to be awarded full marks for a question.
- Marks will be deducted for incorrect or absent units and answers stated to an incorrect number of significant figures.
- **No** graphics calculators are permitted – scientific calculators only.

Atomic Force Microscopy (AFM) is a type of scanning probe microscope which allows the imaging of the topography (surface features) of conducting and insulating surfaces. AFM can demonstrate resolution in the order of fractions of a nanometer.

The basic principle of AFM is that a probe, called the tip, is maintained in close contact with the sample surface by a feedback mechanism as it scans over the surface.

AFM measurements use force vs distance curves to measure the topographical and mechanical properties of a wide variety of surfaces including carbon nanotubes and viruses.

Force – the force between the tip, see figures 1A and 1B, and the sample surface

Distance – the distance between the tip and the sample surface i.e the height of the sample at a given location.

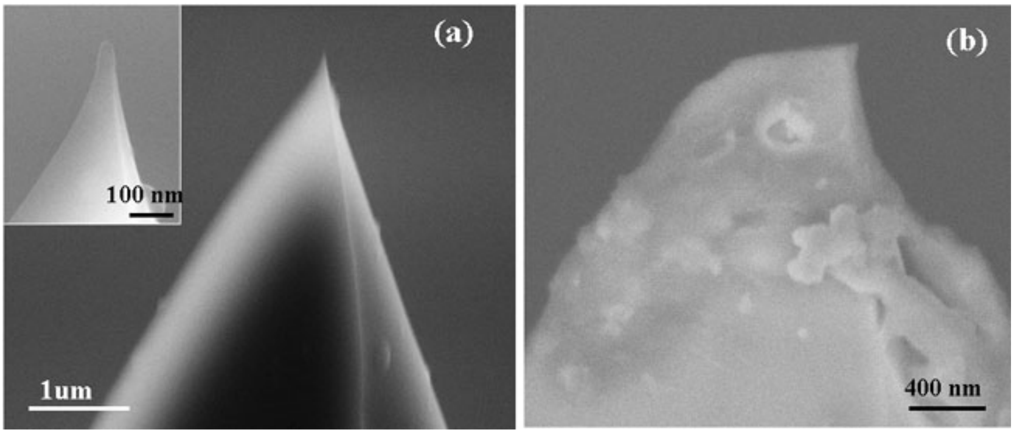


Figure 1A – Images of a tip before and after scanning

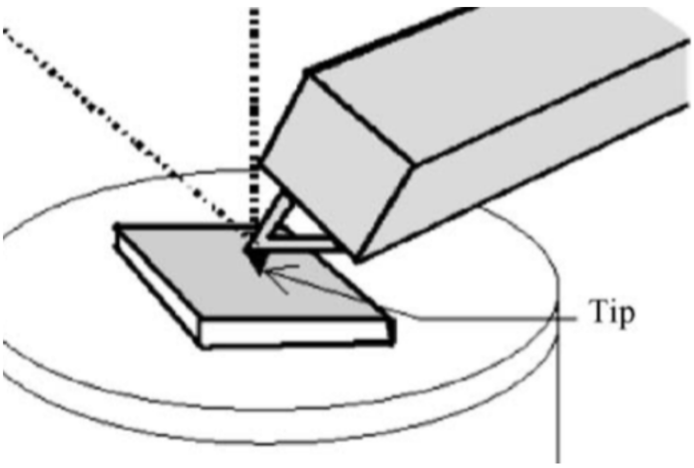


Figure 1B – The tip in contact with the sample surface.

Because the tip is in contact with the surface, strong repulsive forces cause the tip to deflect as it passes over topographical features.

When the tip is close to the surface than an equilibrium distance it experiences a repulsive force. When the tip is further from the surface than an equilibrium distance it experiences an attractive force. Figure 2 shows these forces.

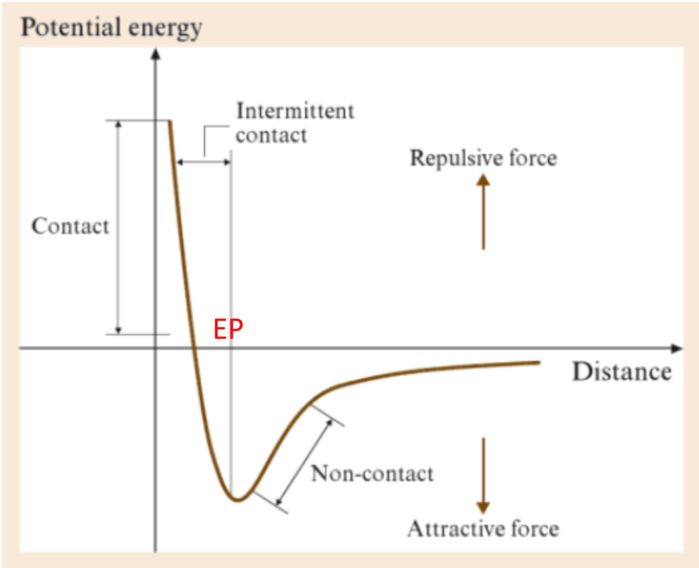


Figure 2 –

(a) Label figure 2 to show the location of the equilibrium position (EP).

(1 mark)

(b) Describe the force between the tip and surface at large distances.

(2 marks)

- There is an attractive force between the tip and the surface
- Which tends to zero.

The tip is attached to a cantilever, as shown in figure 3.

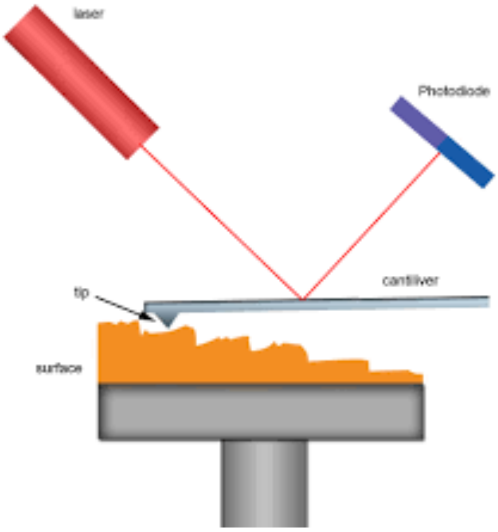


Figure 3 – Schematic of an AFM, showing the cantilever attached to the tip.

While scanning, the force between the tip and the sample is measured by monitoring the vertical deflection of the cantilever as it moves across the surface of a material, as shown in figure 4. A topographic image of the sample is obtained by plotting the deflection of the cantilever versus its position on the sample, as shown in figure 5.

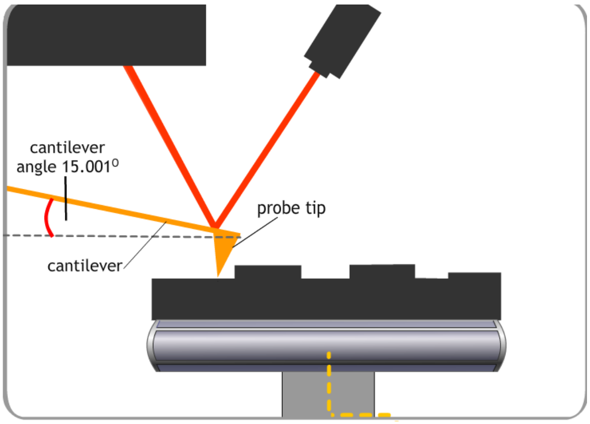


Figure 4 – Deflection of the cantilever

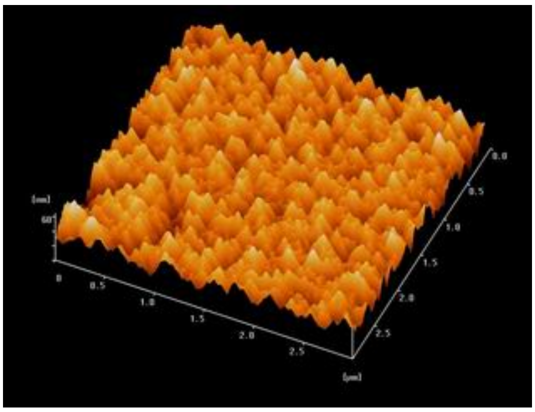


Figure 5 – Force vs Distance plot produced by an AFM.

The deflection of the cantilever is measured using an optical lever technique. 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 position sensitive detector (PSD). When a force is applied to the probe, the cantilever bends and the reflected light beam moves through an angle equal to twice the change of the slope of the cantilever. So the deflection of the cantilever is proportional to the signal.

To keep the tip in contact with the surface the surface is mounted on a piezoelectric translator. During measurement the sample is moved up and down by applying a voltage to the piezoelectric translator.

The force between the tip and the sample cannot be measured directly, instead it is calculated by measuring the deflection of a cantilever. When performing measurements, the cantilever deflection, Z_C, is measured versus the position of the piezo, Z_P, normal to the surface. To obtain a force vs distance curve, Z_C and Z_P have to be converted into force and distance.

The value of Z_P is obtained through scanning a height standard, as shown in figure 6. In this experiment, the cantilever deflection is measured for a known height, the voltage applied to the piezoelectric translator is measured and so it can be known how the relationship between distance piezo. This calibration factor is called the Z-piezo sensitivity (C_Z). The Z-piezo sensitivity is reported in mV^{-1}.

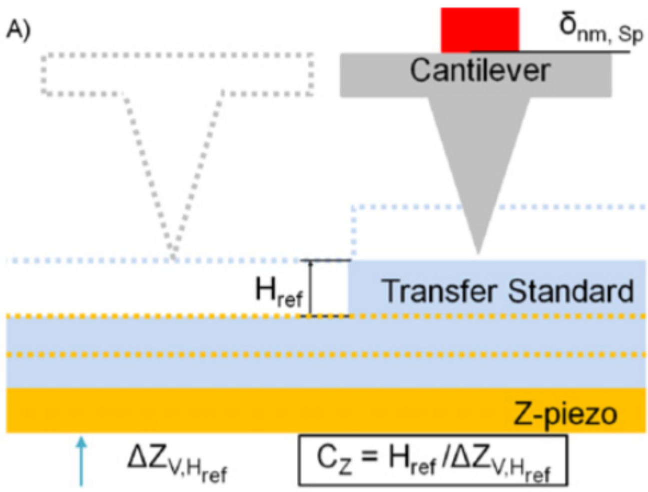


Figure 6 – Using a reference height to determine the calibration factor C_Z.

(c) State the type of error, systematic or random, that is most likely to be introduced through this calibration procedure. Explain your reasoning. (3 marks)

- Systematic
- If there is an error in the given value of the standard/reference height
- This will then be the same for all measurements.

Over time piezoelectric crystals show creep (the tendency of a solid material to deform permanently under the influence of mechanical stresses), which affects the accuracy of distance determination.

(d) State the type of error, systematic or random, that is most likely to be introduced due to the creep. Explain your reasoning.

(3 marks)

- random
- The deformation of the solid will not be in any one direction
- So the amount of error in any one measurement cannot be predicted.

(e) State how you could potentially decrease the error associated with creep.

(1 mark)

- Rescan using the height sample at regular intervals.

Replacing the crystal would still require rescanning with the sample height so was not accepted as a response

The force, F, is obtained by multiplying the deflection of the cantilever with its spring constant, k_c. The spring constant is a measure of the stiffness of a material or the amount of energy required to change its shape.

$$F = k_c Z_c$$

The tip sample separation, D, is calculated by adding the deflection of the cantilever to the position of the piezo. This value is also known as the distance.

$$D = Z_c + Z_P$$

(f) If at one point in measurements, the spring constant for a cantilever is equal to 2.5 ± 0.1 Nm^{-1} and the cantilever deflection 0.815 ± 0.020 nm, calculate the force between the tip and surface.

(4 marks)

$\frac{0.1}{2.5} = 0.04$ (0.5)

$\frac{0.02}{0.815} = 0.0245$ (0.5)

$F = k_c Z_c$

$F = (2.5 \times 0.815 \times 10^{-9})$ (1)

$= 2.0375 \times 10^{-9}\ N$

$2.0 \times (0.04 + 0.0245) = 0.1$ (1)

F = (2.0 ± 0.1) x 10^{-9} N (1)

-1 mark for incorrect number of significant figures in answer
-1 mark if uncertainty is not in the final digit

(g) If at one point in measurements, the Z_P =7.9 ± 1.1 nm and the Z_C the same as in (f), calculate the tip sample separation.

(3 marks)

$D = 0.815 + 7.9$ (1)

$= 8.7 \pm (1.1 + 0.02)$ (1)

$= 8.7 \pm 1.1 nm$ (1)

-1 mark for incorrect number of decimal places in answer
-1 mark if uncertainty is not in the final digit

Being able to measure the tip-sample gap distance directly is currently a challenge for the AFM community.

(h) Explain how being able to measure the distance directly, rather than indirectly, would increase the accuracy of measurements.

(3 marks)

- You would only make one measurement rather than two
- There is only uncertainty in the one measurement
- Rather than having to combine the uncertainty from two processes.

The cantilever is the key element of the AFM and its mechanical properties are mostly responsible for its performance. Cantilevers are typically made of silicon or silicon nitride and both are covered with a native oxide layer of 1 – 2 mm thickness. The mechanical properties of cantilevers are characterised by their spring constant k_c and resonant frequency ν_0.

Both these values can be calculated from the material properties and dimensions of the cantilever. For a cantilever with constant rectangular cross-section the spring constant is given by;

$$k_c = \frac{F}{Z_c} = \frac{Ewt_c^3}{4L^3}$$

where: E is the Young's Modulus
w is the width of the cantilever
t_C is the thickness of the cantilever
L is the length of the cantilever

A good cantilever should have a high sensitivity. High sensitivity in Z_c is achieved with low spring constants or low t_c/L ratio.

(i) Describe the dimensions the shape of the cantilever should have to exhibit a high sensitivity in Z_c. Explain your reasoning.

(3 marks)

- Z_c is inversely proportional to tc/L.
- So needs to be long and thin to make this number as small as possible to
- Reduce the t_c/L ratio

Responses should not be referring to width – the ratio is just between t_c and L

A cantilever is to be constructed from a composite material for which the Young's Modulus (E) has not been measured. A series of measurements are made using cantilevers made of the composite material with different dimensions. The resonant frequency of each of the cantilevers was measured. The resonant frequency of a cantilever is proportional to its spring constant. The results from these measurements are shown in the table on the following page.

w (m) x 10-5	tc (μm)	L (mm)	(k_c ± 0.001) Nm^{-1}	$\frac{wt_C^3}{L^3}$ (pm)
3.00	0.50	0.10	0.009	3.8
3.50	1.0	0.13	0.051	16
4.00	1.5	0.15	0.125	40
4.50	1.8	0.18	0.115	45
5.00	2.0	0.20	0.133	50

(j) State what you should plot to obtain a straight line graph.

(1 mark)

k_c vs wt_c^3/L^3

accept k_c vs $wt_c^3/4L^3$

(k) Process the data in the table above so that you are able to plot your graph from (j).

(4 marks)

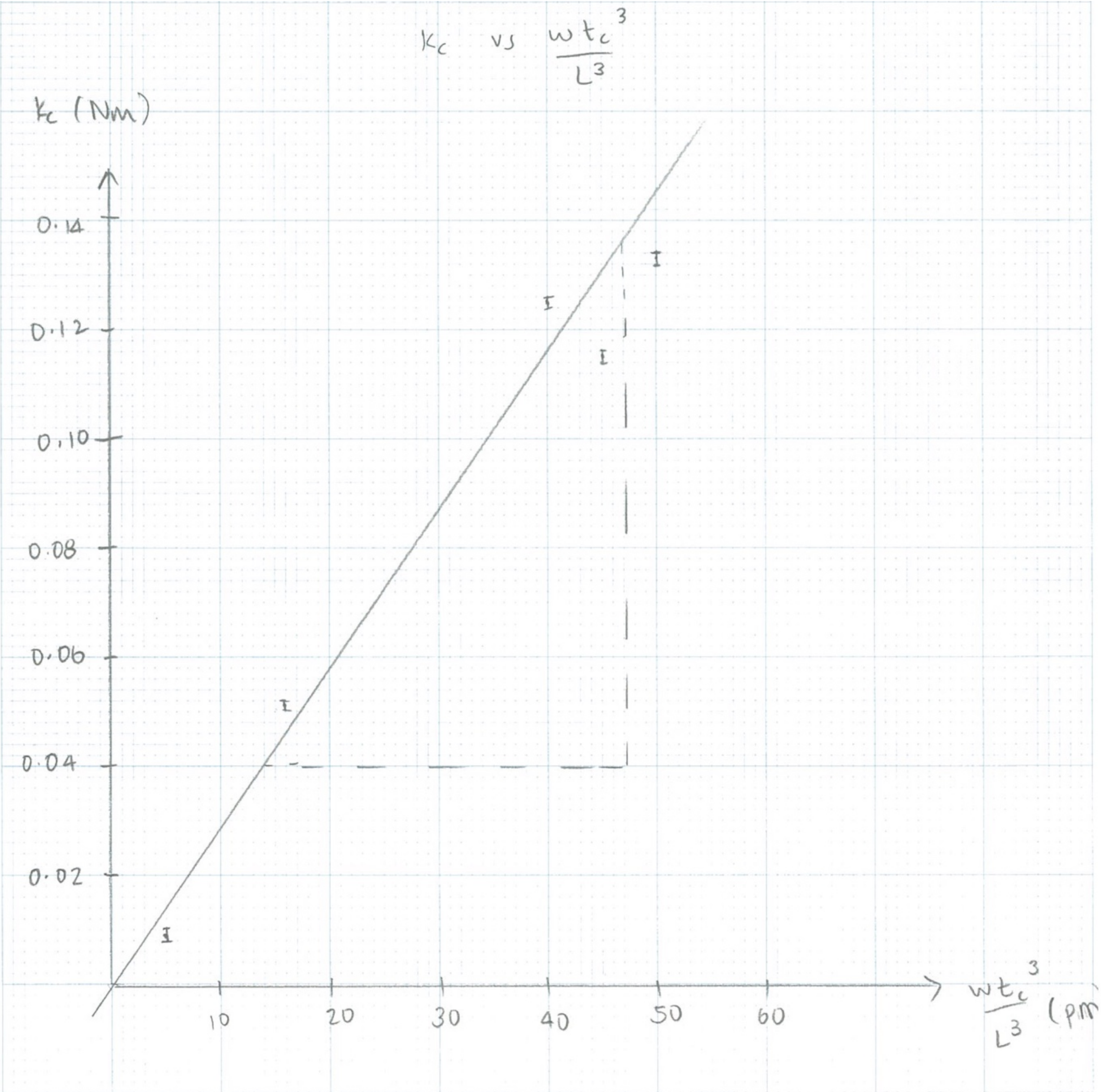
1 mark – correct values
1 mark – correct number of sig figs
1 mark – correct label
1 mark – correct units

(l) Plot your graph on the graph paper provided.

(8 marks)

1 mark – title
1 mark – axes correct way for title
2 marks – axis labels and units
1 mark – linear scales
1 mark – correct points plotted
1 mark – error bars correct
1 mark – line of best fit plotted

NOTE: the y axis should be specified as Nm^{-1} for k_c



(m) Using the graph, calculate the gradient of your line of best fit.

(4 marks)

$$gradient = \frac{rise}{run} = \frac{(0.136-0.04)}{(47-14)\times10^{-12}}$$

$$2.9\times10^{9}Nm^{-2}$$

1 mark – triangle
1 mark – working
1 mark – correct answer to correct number of sig figs
1 mark - units

(n) Calculate, using your gradient, the value of E for the composite material.

(2 marks)

$2.9 \times 10^{9} \times 4 = 11.6 \times 10^{9}\ Nm^{-2}$

END OF TEST