Exam for Nanophysics & -technology (NANPNT-12), term Ib 2014/15

26. 01. 2015

Write your name and student number on each sheet and number the sheets.
Use for each question a different sheet.
You are allowed to use 2 handwritten A4 pages and a calculator.

Name: ____________________

Student number: ____________________

Question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Σ
Points	3	2	2	3	4	2	3	3	2	4	3	3	2	4	5	

1. Scaling laws (3 points)

a) A microcantilever beam 100 μm long and a diving board 5 m long are both deflected and then released simultaneously. Estimate how many oscillations the microcantilever beam completes in the time the diving board completes a single oscillation.

b) The micromirror shown in the figure below is used for redirecting light in an optical communication system. The torque needed to spin it on the y-axis is directly proportional to its mass moment of inertia, I_{yy}:

$$I_{yy} = \frac{1}{12} \rho h t w^3$$

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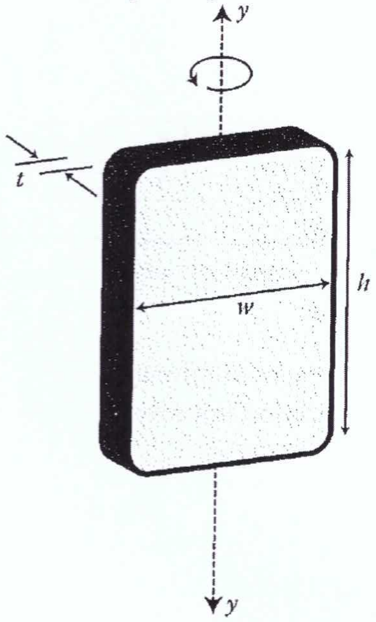
Here, ρ is the density of the mirror material.

(i) Derive the scaling law for I_{yy}.

(ii) If the mirror's dimensions can be reduced to one-third the original size, what is the corresponding percent reduction in the torque required to turn the mirror?



2. Cesium fountain clock (2 points)

If the uncertainty of the cesium fountain atomic clock at NIST (National Institute of Standards and Technology) in Boulder, Colorado is $5*10^{-16}$ s, how many years would it take for the clock to gain or lose 1 s?

3. 1D rectangular potential (2 points)

An electron is in a one-dimensional rectangular potential well with barriers of infinite height. Find the well width if the energy difference between the fifth and fourth quantum states, $E_5 - E_4$, is equal to the electron's average thermal energy at room temperature.

4. Hitachi experiment (2 points)

a) The probability that a quantum particle makes it from a source to a slit is 10% and the probability that it makes it from the slit to the detector is also 10%. What is the probability that the particle makes it from source to detector if there is no other path through the system and the arrival of the particle at the slit is not measured? Explain your answer shortly.

b) If there had been a second slit in the experiment above and the probabilities were the same for the second path, would this be enough information to determine the probability of arrival at the detector? Explain your answer shortly.

5. Orbitals & bonding (4 points)

a) Write out the electron configuration of Argon in the form $1s^2$ …, etc. Which is easier to ionize: Ar or K? And why? (Exam April 2013)

b) Cesium bromide (CsBr) exhibits predominantly ionic bonding. The Cs^+ and Br^- ions have electron structures that are identical to which two inert gases?

c) Briefly cite the main differences between ionic, covalent, and metallic bonding.

d) Offer an explanation as to why covalently bonded materials are generally less dense than ionically or metallically bonded ones.

6. Thermodynamics (2 points)

a) A heater is placed inside a sealed cylinder containing a gas and a fixed amount of heat put into the gas by operating the heater at a fixed current and voltage for a fixed time. In one experiment, the container has a fixed size. In the second experiment, one wall is a free moving piston that maintains the pressure inside the cylinder equal to atmospheric pressure. In which experiment does the gas get hotter? Explain your answer using the first law of thermodynamics.

b) How does the boiling point of water depend on the volume of gas available above the water?

7. Scanning probe microscopy (3 points)

a) Explain the working principle of a scanning tunneling microscope.

b) Why is the spatial resolution of the STM better than that of the AFM?

c) Conducting AFM probes do not usually make a good electrical contact to gold in ambient air unless a significant force is applied. Explain.

8. Cantilever (3 points)

a) Imagine that a silicon cantilever beam (attached at one side to a base) is used as a binary memory element, where an upward deflection represents one state and a downward deflection represents the other state. The beam measures 5 μm long, 250 nm wide and 150 nm thick. The modulus of elasticity, E_M, for silicon is 110 GPa and the density, $\rho = 2330\ kg/m^3$. How quickly can the beam switch states?

b) How does the natural frequency of a cantilever beam change if the width of the beam is tripled?

9. Electron microscopy (2 points)

What is the wavelength of an electron accelerated by a potential of 10 kV in an electron microscope? How is this related to the maximum possible resolution of the microscope? Why do electron microscopes usually not achieve such resolution?

10. Lithography (4 points)

a) Explain why e-beam writing is not competitive as a production process for writing wiring on computer chips.

b) What limits the resolution of e-beam lithography?

c) What is an advantage of e-beam lithography over photolithography?

d) Describe an alternative to photo- and e-beam lithography to produce patterns on the micro-/nanoscale!

11. Nanophotonics (3 points)

The Lorentz Oscillator model for an unbound sea of electrons predicts a negative real dielectric constant ε_m over a range of frequencies:

$$\varepsilon_m(\omega) = 1 - \frac{\omega_P^2}{\omega^2}$$

$$\left(\frac{w_P}{0{,}5w_p}\right)^2 = 4$$

where ω_p is the plasma frequency.

a) Sketch this function for ε_m vs ω. Take care in denoting the axes and the plasma frequency.

b) Using this 'free electron response' we discussed two interesting cases where metals and electromagnetic waves interact. These were small metal nanoparticles and the case of surface plasmon polaritons – both instances relied on what particular aspect of the dielectric response?

   i. The dielectric constant $\varepsilon_m(\omega)$ can be less than zero.
   ii. The dielectric constant $\varepsilon_m(\omega)$ can be greater than zero.
   iii. The dielectric constant $\varepsilon_m(\omega)$ can be zero.

12. Free electron model (3 points)

The density of states for a free electron gas in three dimensions is given by the following equation:

$$\frac{dN}{dE}dE = \frac{V}{2\pi^2}\left(\frac{2m_e}{\hbar^2}\right)^{3/2}E^{1/2}dE$$

Show that the density of states for a free electron gas in one dimension is proportional to $E^{-1/2}$.

13. 2D and 1D structure (2 points)

a) Which experimental technique can be used to study quantum well states? Explain also, how the technique works.

b) With which technique can transport through a 1D structure be studied and how does this technique work?

14. Quantum dot (4 points)

A quantum dot has a capacitance of 2 aF.

a) Explain the term Coulomb blockade.

b) What is the smallest incremental change that can be made to the bias voltage between the dot and the source electrode?

c) When this quantum dot is incorporated into a single electron transistor, it is found that the gate voltage at which single electron tunneling occurs is 110 mV. Over what range of gate voltages can we expect there to be three electrons on the dot?

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15. Nanomagnetism (5 points)

a) What are the most important contributions to magnetic anisotropy in a magnetic material? Why does a ferromagnetic material exhibit hysteresis? Explain its origin! (1.5 points)

b) What are the various contributions to the total energy of a ferromagnetic material and how do they determine the size and shape of domains? (1 point)

c) What is the origin of the different resistance states in a GMR (giant magnetoresistance) device (i.e parallel and antiparallel resistance)? (1 point)

d) Using the simple Mott two-current model, GMR is defined as:

$$GMR = \frac{\Delta R}{R} = \frac{\rho_{AP} - \rho_P}{\rho_P}$$

where ρ_{AP} and ρ_P are the resistivities in the parallel and antiparallel configuration of a GMR stack. If the resistivity of the spin down current with magnetization ↑ is ρ_{HI} and resistivity of the spin up current with magnetization ↓ is ρ_{LO},

then express GMR in terms of α where $\alpha = \frac{\rho_{HI}}{\rho_{LO}}$. (1.5 points)

$\rho_H = \alpha \rho_L$

$GMR = \frac{\Delta R}{R}$ ~~$= \frac{\rho_{AP} - \rho_P}{\rho_P} = \frac{\Delta\rho_P}{\rho_P}$~~ [illegible] $= 2\alpha 2 +$

~~$\rho_{AP} = \rho_H \cdot \rho_I$~~

~~$\rho_P = \frac{2\rho_H\rho_I}{\rho_I^2 + \rho_H^2}$~~

~~$\frac{\rho_H \rho_I - [illegible](+\rho_I^2 + \rho_H^2)}{\rho_I^2 + \rho_H^2}$~~ $=$ ~~$\frac{(\rho_I - \rho_H)^2}{\rho_I^2 + \rho_H^2}$~~

~~$= \frac{\rho_I - \alpha\rho_I}{2\alpha\rho_I^2}$~~ ~~$= \left(\frac{1-\alpha}{2\alpha^2\rho_I}\right)$~~

Constants:

Planck's constant: $h = 6.626*10^{-34}$ Js

Reduced Planck's constant: $\hbar = h/2\pi = 1.055*10^{-34}$ Js

Dielectric permittivity: $\varepsilon_0 = 8.854*10^{-12}$ F/m

Atomic mass unit: $u = 1.66*10^{-27}$ kg

Electron mass: $m_e = 9.109*10^{-31}$ kg

~~$\alpha^2 - \alpha + 1$~~

~~$(\alpha + 1)(\alpha + 1)$~~

[illegible]

~~$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$~~

[illegible]

The Periodic Table of the Elements

3 — Atomic Number
Li — Element Symbol
Lithium — Element Name
6.94 — Average Atomic Mass

1 **H** Hydrogen 1.01																	2 **He** Helium 4.00
3 **Li** Lithium 6.94	4 **Be** Beryllium 9.01											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.91	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.91	56 **Ba** Barium 137.33	57 **La** Lanthanum 138.91	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium 178.49	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (269)	109 **Mt** Meitnerium (268)	110 **Ds** Darmstadtium (281)	111 **Rg** Roentgenium (272)	112 **Cn** Copernicium (285)						

58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.91	60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.96	64 **Gd** Gadolinium 157.25	65 **Tb** Terbium 158.93	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.97
90 **Th** Thorium 232.04	91 **Pa** Protactinium 231.04	92 **U** Uranium 238.03	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium 168.93	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)