Modern Imaging, Spectroscopy and Diffraction Techniques
TIF 030 and FIM 150
October 29th, 2015

Aids: Formula sheets attached to the exam, "Physics Handbook", calculator, and writing tools.

Total marks available from exam: 30
Marks required to pass: 12

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1. OM (4p)

a) Describe image formation theory according to Abbe and Rayleigh. What are the principles behind both theories? What are the differences between them? (2p)

b) What is numerical aperture? Describe in detail why NA is important for image formation. How can NA be greater than 1? Calculate NA of a thin lens with a focal distance f=5cm and diameter D=2cm. (1.5p)

c) What is total internal reflection and how is it useful in microscopy? What should be a minimum NA of an objective to be able to reach TIRF condition provided the sample is located at water/glass interface? Assume n_{water}=1.33, n_{glass}=1.5. (0.5p)

2. OM (3p)

a) Describe in detail what Lorentz model is. How does it explain the two main mechanisms behind contrast formation in optical microscopy? Sketch the wavelength dependence of refractive index of a typical dielectric and mark the regions of normal and anomalous dispersion. Mark the region corresponding to high absorption. What can you say about refractive index at very short wavelength (X-rays) based on this? (2p)

b) What is a "phase" sample and how does phase-contrast microscopy work? (1p)

3. OM (3p)

a) Draw a Jablonski diagram of a typical fluorescent molecule. Mark the following processes: 1) electronic excitation; 2) vibrational relaxation; 3) intersystem crossing; 4) fluorescence; 5) phosphorescence; 6) Raman scattering; 7) infra-red absorption; and 8) FRET (assuming an acceptor molecule around). Specify the typical duration of vibrational relaxation, fluorescence and phosphorescence in seconds. Which is faster and why? What do you think would happen if fluorescence lifetime would be shorter than the vibrational relaxation? (2p)

b) Estimate the quantum yield of a fluorophore whose non-radiative relaxation is 4 times slower than radiative. Assume no other processes involved. (1p)

4. OM (3p)

In super-resolution techniques, such as STED and SIM, one uses highly stable fluorescent molecules.

a) Explain the working principle of STED. Why STED can beat the diffraction limit despite involvement of only conventional diffraction-limited optics? Sketch the principal idea of this microscopy technique. (2p)

b) Explain the idea behind SIM (structured illumination microscopy). Why is it sometimes called inverted STED? What are the two primary advantages of SIM over STED? (1p)

5. SEM (3p)

a) You wish to enhance Z contrast in an image obtained using the SEM. Would you use the backscatter electron (BE) signal or the secondary electron (SE)? Would you expect any difference in the spatial resolution between SE and BSE. Explain your answer (1 p)

b) Explain the importance of objective aperture size on the depth of focus in the SEM. Include a schematic drawing of the beam and the sample. (1p)

c) You wish to reduce the noise in the SE SEM image. Suggest one way to reduce the noise and explain which other effects there will be of the quality of the image as a result of the change in recording parameters? (1p)

6. TEM (3p)

a) Draw a ray diagram to show how bright field (BF) and dark field (DF) operations work. Include the specimen and the objective lens in the diagram. All other lenses can be omitted. Assume parallel illumination onto the specimen (1.5 p)

b) What type of samples can you analyse in the TEM? What are the requirements and limitations? Do these requirements and limitations differ between TEM and SEM? Explain your answer (1.5p)

7. Electron diffraction (3p)

The diffraction pattern shown schematically in Fig. 1 is obtained from an FCC crystal.

a) Index the pattern. Explain how you check the validity of your indices. (1p)

b) Is it possible for the set of atomic planes corresponding to points A, B, C and D to be at the perfect Bragg condition at the same time? Explain your answer. (1p)

c) Draw the Kikuchipattern for the case of the electron beam exactly parallel to the zone axis of the pattern in Fig. 1. (1p)

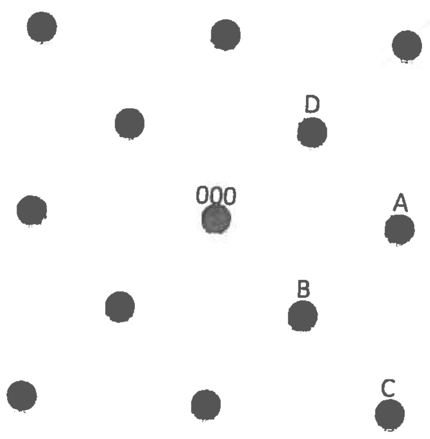

Fig. 1. Diffraction patterns from an FCC crystal.

8. STEM, EDS and EELS (4p)

(a) Describe the principle of HAADF STEM imaging. Where is the detector located with respect to the electron ray path of the TEM? Which electrons are detected? (2p)

(b) Assume that you would like to investigate if there is segregation of an element to a grain boundary using EDX in the TEM. How do you orient your specimen with respect to the electron beam. How does the specimen thickness affect the profile? Draw a schematic illustrating the difference between a thick and a thinner are in the TEM sample. (1p)

(c) Draw a schematic of a typical EDX spectrum in the interval 0-20 keV with peaks from zinc, bismuth and oxygen. (1p)

9. SPM (4p)

(a) How is the vertical movement (surface approach and retraction) of the STM scanner realized? Draw the schematics of the electrodes in the case of a piezoelectric tube scanner and the way to apply a voltage to produce such movement. (1p)

(b) Name one of the AFM's spin-off technologies and describe the operation principle of the chosen technology. By AFM's spin-off technology we mean a technology that uses one (or several) feature of the AFM measuring tool, but uses it slightly differently (as opposed to the direct use of AFM for imaging and force sensing). Note that this does not relate to AFM / SPM imaging modes. (1p)

(c) Give expression for the tunneling conductance, assuming low temperature and known tip density of states (DOS). Give the typical detected tunneling current in a low-temperature STM experiment under applied bias voltage of 10^{-2} V: microampere (μA), picoampere (pA) or nanoampere (nA)? (2p)

Formula sheet

Table

Element (A)	k_{ASi} (1) 100 kV
Na	5.77
Mg	2.07 ± 0.1
Al	1.42 ± 0.1
Si	1.0
P	
S	
Cl	
K	
Ca	1.0 ± 0.07
Ti	1.08 ± 0.07
V	1.13 ± 0.07
Cr	1.17 ± 0.07
Mn	1.22 ± 0.07
Fe	1.27 ± 0.07
Co	
Ni	1.47 ± 0.07
Cu	1.58 ± 0.07
Zn	1.68 ± 0.07
Ge	1.92
Zr	
Nb	
Mo	4.3
Ag	8.49
Cd	10.6
In	
Sn	10.6
Ba	

$$\lambda = h / [2m_0eV(1 + eV/2m_0c^2)]^{1/2}$$

$$d_p = (d_g^2 + d_s^2 + d_d^2 + d_c^2)^{1/2}$$

$$r_{Sch} = 0.66\ C_s^{1/4}\ \lambda^{3/4}$$

$$n > (5/C)^2$$

$$2\ d_{hkl}\ \sin\Theta = n\lambda$$

$$b = 7.21 \times 10^5\ (\rho/A)^{1/2} t^{3/2}\ (Z/E_0)$$

$$I \propto U\rho_s(E,r)e^{-2\frac{\sqrt{2m_e\phi}}{\hbar}d} \quad with\ \phi = \tfrac{1}{2}\left(\phi_{sample} + \phi_{tip}\right)$$