Diagnostic Exam 2014
KOO105 Analysis on the Nanoscale
SOLUTIONS

1. a) The difference between a cold FEG and a thermal FEG is that a cold FEG operates at or near room temperature, while a thermal FEG is heated. The primary reason for heating is to keep the tip clean – it must be very clean for field emission to occur.

If you wrote that a thermal FEG actually gives a combination of FE and thermionic electrons, this was also accepted.

A cold FEG requires UHV to keep the tip clean, which makes it more complicated, more expensive, and less stable. However the lack of thermionic emission means it has a slightly lower energy spread (more monochromatic), slightly smaller crossover size and higher brightness (higher current). A thermal FEG is cheaper, easier to operate and more stable, but slightly worse in the ways listed above.

Common errors:
- Confusing thermionic with thermal FEG – a thermal FEG is still a FEG!
- Thermal FEG still requires (high) vacuum. In fact all electron microscopes operate in vacuum, regardless of the gun type
- A cold FEG is LESS stable, but has HIGHER current (not the opposite)

b) Possible advantages (there are very many possible answers here): higher resolution due to higher wavelength (which in turn gives lower aberrations due to the lenses), higher brightness (current density), less scattering (so samples can be thicker but still transparent), higher resolution for STEM and XEDS which also is due to less scattering, smaller probe size for STEM, less damage due to heating and radiolysis (especially important for lighter elements/softer materials)

Other answers were also possible

Common errors:
- listing two points which are actually the same thing
- confusing TEM and STEM. Your answer could mention both of these, but they are not the same – if you mention probe size for example, you must say STEM

c) For TEM, the main reason would be if we want to increase scattering, but to get full points for this question you need to indicate why we would want to do this. The most common reason is if we have a very thin sample containing light elements. Recall that the mean free path becomes very long for light elements. If we want to look at carbon-based nanostructures (such as carbon nanotubes or graphene), we need kV of not more than 100 or we will not see anything!

This question also did not specify TEM, so answers relevant to SEM were also acceptable. The most common one would be increased resolution for BSE or for XEDS in SEM (not TEM). Less charging in non-conductive samples is another possibility.

There are other possible answers to this question, and you could get full points for listing any one (correct) possibility. "Cheaper" is not a very good answer, but technically correct, so you got full marks for this.

Common errors: Resolution in TEM is NEVER improved by decreasing the accelerating voltage (even for XEDS, STEM etc) so if you mentioned resolution, you had to also mention SEM.

2. a) In normal SEM samples, the yield of BSE does NOT depend on the accelerating voltage (to a first approximation). Higher-energy electrons travel deeper into the sample before scattering, but they can also travel farther on their way back out.

There are a few very subtle effects – for example the yield of elastically scattered electrons increases slightly with accelerating voltage, so this has a small effect on the backscatter yield. But these effects are very small and not covered in this course, so you don't have to know them (but if you gave an answer in this direction, it was of course marked correct).

If a sample is very thin (TEM specimen) so that there is a high probability of transmission, the yield decreases with accelerating voltage since the mean free path increases. This is only relevant if the thickness of the sample is comparable to the mean free path.

Common error: many of you knew that in thin (TEM) samples the yield is affected by transmission. However BSE is actually a SEM technique, so you needed to (correctly) answer what would happen in a SEM sample to get the full marks.

b) We can see strain effects in CTEM. Dark field (DF) TEM is the best way to do this, but you could still get marks for describing BF TEM if your answer was clear and well-motivated. To do DF TEM you tilt your sample into a specific crystal orientation and then put an aperture around a specific diffraction spot, which corresponds to a specific angle for which the Bragg condition is satisfied for a set of planes in the crystal. Then, only parts of the sample where the Bragg condition is satisfied for this specific part of the sample would look bright. If a sample is strained, the interplanar spacing will vary slightly due to the strain, so the Bragg condition will not be quite satisfied in that region. The result will be dark stripes in the bright region.

Common error: confusing HAADF with DF TEM. Check the lecture notes (especially the last few slides from Lecture 5) to clarify.

3. a) To get this question correct, you do not need to write out the structure factor from first principles (although this was acceptable, if you reached the correct answer). The structure factor for zinc blende was given on the data sheet; it is sufficient just to substitute in Ge for both Zn and S.

The result: $F = 0$ if h,k,l mixed (just as for all fcc!)
$F = 4(f_{Ge} +/- if_{Ge})$ if h,k,l all odd
$F = 8f_{Ge}$ if h,k,l all even and $h+k+l = 2N$ where N is even
$F = 0$ if all even and $h+k+l = 2N$ where N is odd

Common errors:

- There is no need to derive the structure factor from first principles! The question only says "write out the structure factor" and F for zinc blende is given on the data sheet. It is not wrong to derive it, so long as you get the correct answer, but a partial derivation does not answer the question
- Trying to simplify the second condition (there is no way to eliminate i!). The only possible simplification is to factor out the f_{Ge}. You cannot simplify it further!

b) The diffraction pattern essentially looks the same as fcc, except that some spots are removed due to the last condition (you don't need to worry about the small intensity difference due to the second and third conditions). The most important result is that spots in the 200 family are forbidden.

To get full points for diffraction questions, you need to label a certain number of DISTINCT spots (e.g. 220 and 400), as well as a few extras (such as -2-20, -400…), which is sufficient to show that you understand the principles. In this case the question stated that you should label 3 distinct spots.

Common error: including forbidden spots (even if you had written F correctly)

c) Looking at the selection rules, the biggest difference between the zinc blende structure and the diamond structure is the last condition (F = 0 if all even and h+k+l = 2N where N is odd). This means that spots such as 200 will be PRESENT for GaAs but ABSENT for Ge. There are also small intensity differences in the present spots, but these are very difficult to quantify.

Common error: you CANNOT distinguish these patterns by measuring the distance to spots with the same index (to calculate a_0). On the data sheet you were given the lattice constants for GaAs and Ge: these differ by only 0.007 Å! Recall that the resolution of the TEM is typically in the range of 1Å – 1 nm. There is NO electron microscopy technique with a resolution better than 0.01 Å.

4. a) Which technique was used to image the wire? Describe the physical principle behind this technique.

STM - should describe quantum mechanical tunneling as the physical principle. If your answer only described the practical procedure for operating STM (such as scanning a sharp tip over a sample), you did not get full marks. It is necessary to mention tunneling.

In theory it is also possible to do this by AFM, although it is extremely difficult to get high resolution by this technique (compared to STM).

Common error: not reading the question! It is stated that the wire is "patterned along the surface of Si(100) in along the <110> direction…" – in other words the wire sits on a surface, and cannot be imaged by any transmission technique. Based on the way the question is worded, only surface techniques are accepted as possible answers. Also, since the wire is only 4 atoms wide, it cannot be imaged by e.g. backscatter.

b) Which technique was used to make the wire?

STM again. In this case, you did not need to motivate your answer further and stating the correct technique was sufficient for full marks.

Here again it was possible to answer AFM, although again, it would in practice be very difficult to achieve compared to STM.

Common error: again, not reading the question, since it says the wire was patterned on the surface. Therefore, it is not fabricated by any technique that does not involve patterning. Since it is only 4 atoms wide, this basically excludes any other technique than STM or, possibly, AFM.

c) The device as seen here is placed in Ultra High Vacuum, what would happen to it if you take it out in air?

The surface would Oxidize and the wire would be destroyed (they actually cover it with Si by in-vacuum evaporation to take it out).

To get full marks for this question you had to give slightly more detail on the fate of the wire than just "oxidize". The wire would in fact completely disappear, given it is only 4 atoms wide.