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Choosing a Beam – Electrons, Protons, Helium or Gallium Ions?

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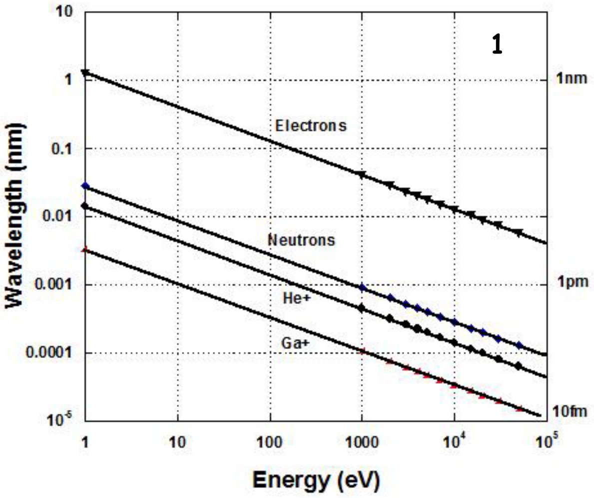
The goal of "Reinventing the SEM" will certainly include replacing electron beams by alternatives such as protons, helium ions, or gallium ions. Each of these options has its own fundamental advantages and drawbacks so a final choice depends on what parameters of the instrument and its applications must be optimized or minimized.

The ultimate **resolution** of a scanning microscope is of the order of $\lambda^{3/4}$ where λ is the wavelength of the beam. As shown in figure (1) for beam energies in the typical SEM energy range of 1-50keV the wavelength varies from a high of 10-50pm for electrons, to a low of 30-100fm for gallium ions, a range of almost 400:1. A switch from electrons to proton or ion beams of some type could therefore result in a significant enhancement in imaging performance. Because scanning microscopes are primarily used for surface imaging the **range** of the incident beam into a sample should also ideally be restricted. For electron beams of energy E the penetration varies as about $E^{1.6}$, while for keV energy proton and ion beams the variation is varying as about $E^{0.7}$ Consequently at low energies (<5keV) the penetration of electron and ions beams are comparable, but at higher energies (30-50keV) the range of electrons in any given material is an order of magnitude higher than that of the heavier particle beams.

Signals in a scanning microscope are produced as a result of the interaction of the beam with the specimen. The strength of these interactions is measured by the **stopping power** - the rate at which the beam gives up its energy as it travels. The stopping power for electrons typically has a maximum value of about 5eV/A which occurs for an energy of about 200eV, above that the stopping power falls as 1/E. For proton and ion beams the maximum stopping power is 50 to 100eV/A and occurs at energies around 1MeV so between 1 and 50keV ion interactions become stronger as the energy rises. Consequently the yield of secondary electrons produced by an electron beam is typically much less than one SE per incident electron, while for protons and ions the yield can be as high as ten SE per incident particle. This divergence in behavior not only results in higher signal levels and enhanced signal to noise ratios but also influences the choice of an optimum **operating energy**. If the aim is for a high resolution surface image then the optimizing the scanning electron microscope requires lowering the beam energy in order to minimize beam penetration and maximize the SE yield. Unfortunately the benefits of these choices are reduced because the low beam energy results in diffraction limiting of the probe size, and the fall in the brightness of the electron gun partially offsets the increase in SE yield. In addition the significant back scatter yield from a sample produces a background of low



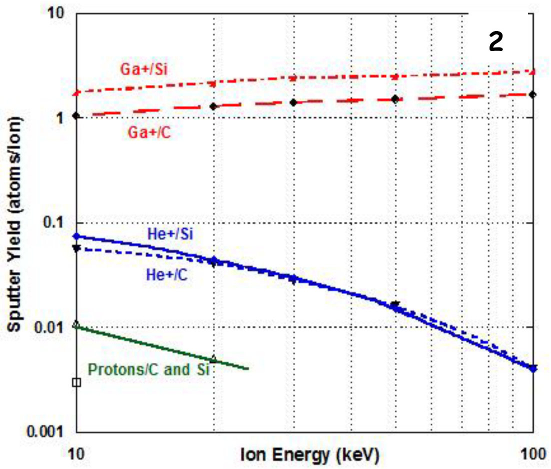


Fig. 1. Wavelength vs energy for electrons, protons, He and Ga ions. Fig. 2 Computed sputter yield from carbon and silicon under Proton, He+ and Ga+ beams of varying energy

resolution (SE2) secondary electrons which degrades image contrast. An energy in the range 3-5keV is typically the best compromise value.

For proton and ion beams the choices and outcomes are different. The SE yield is enhanced by increasing the beam energy, which also has the benefit of increasing the source brightness and still further minimizing the wavelength of the beam. The backscattering of protons and ions is small and produces no significant SE2 contribution to degrade contrast so the increase in beam penetration does not result in a loss in either resolution or contrast. The optimum energy for a proton or ion beam "SEM" is therefore likely to be found above 100keV.

Finally, the effects of **charging** and **beam damage** must be considered. Charging by electron beams can be either positive or negative in polarity and, while unhelpful, can usually be controlled to within acceptable limits by a careful choice of beam energy, beam current, and scan speed. Charging by proton and ion beams, in contrast, is always positive in polarity and, because of the much higher SE yields encountered, leads to large potential build up on the surface which can adversely affect SE yields. Some form of active charge control, such as a low energy flood gun, may therefore be necessary. Electrons of all energies cause severe beam damage to organic materials – such as polymers and biological tissue - and also to many ionic materials so the total beam dose must be strictly controlled. Proton, and ion beams can directly sputter material from a sample. As shown in figure (2) the sputter rate is lowest for protons and highest for Ga+. For He+ the sputter rate falls as beam energy increase but for Ga+ the damage rate rises with energy[1]

References

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