doi: 10.1017/S1431927609092204
Microsc Microanal 15(Suppl 2), 2009

Basic Questions related to Electron-Induced Sputtering

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Radiation damage sets an ultimate spatial resolution for any microscopy or spectroscopy that uses electron beams. Damage takes place by radiolysis in insulating materials but derives from knock-on displacement in conducting solids. Displacement of surface atoms (electron-induced sputtering) occurs for incident energies above a threshold value that often lies below 300 keV; see Table 1. The threshold E_0^{min} depends on the atomic number Z and binding energy E_d of a surface atom:

$$E_0^{min} = [(m_0c^2 - E_d/2)^2 + (1 + m_0/M)^2 Mc^2 E_d/2]^{1/2} - m_0c^2 + E_d/2 \quad (1)$$

where m_0 and M are the rest mass of the electron and the atomic nucleus. E_d is often taken as the sublimation energy E_{sub} per atom but this assumption is questionable since E_{sub} is equal to the binding energy of an atom at a kink site, where there are fewer neighboring atoms. For sputtering from a flat surface, a better approximation may be $E_d \approx (5/3)E_{sub}$, as illustrated in Fig.2.

Taking E_{sub} = 3.8 eV for gold, the surface binding energy is then $E_d \approx 6.3$ eV and Eq.(1) implies that E_0^{min} = 407 keV, not far from the 350keV experimental estimate [1]. We have confirmed the absence of sputtering at 300 keV, which would be *above* the threshold energy (270 keV) if $E_d = E_{sub}$.

Taking E_d = (5/3)(2.95eV) for silver results in E_0^{min} = 202 keV. Braidy *et al*. [2] observed e-beam sputtering of silver particles (6nm to 14nm diameter) at 200 keV but curved surfaces have a greater fraction f of atoms at step sites, approximately $f = 2(h/R)^{1/2}$ for atoms of diameter h on a spherical particle of radius R. Therefore we might expect both E_d and E_0^{min} to be lower for small particles, as represented by the dashed horizontal lines in Fig.3.

Another uncertainty concerns the geometry of the escape potential $E_d(\phi)$, where ϕ is the angle between the momentum transfer and the surface-normal. A spherical potential corresponds to E_d independent of ϕ whereas E_d is proportional to $1/\cos^2\phi$ for a planar surface potential. In the latter case, E_0^{min} increases for non-normal electron incidence (see Fig.3), so sputtering should be slower at the edges of a particle, leading to a flattened particle profile. The form of $E_d(\phi)$ also affects the sputtering rate at perpendicular incidence, introducing an uncertainty factor of about three in the cross section [3]. $E_d(\phi)$ can be estimated from molecular-dynamics calculations, which in the case of a carbon nanotube [4] suggest that the escape potential is intermediate between the planar and spherical cases, as illustrated by Fig.4. [5]

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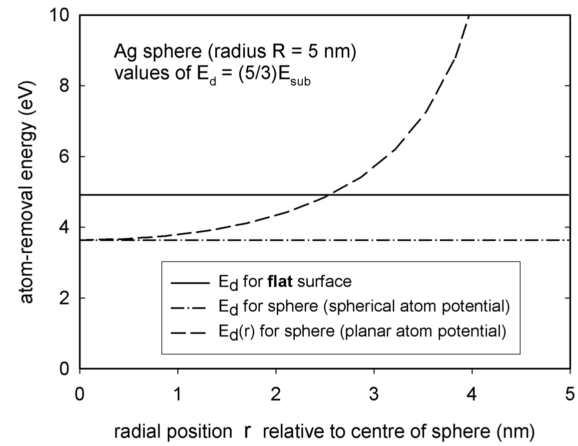
[5] We are grateful to NSERC for financial support of this research.

TABLE 1. Threshold incident energy $E_0^{min}(Z)$ for sputtering from a planar surface, calculated for $E_d = E_{sub}$ and for $E_d = (5/3)E_{sub}$.

Z and element	E_{sub} (eV)	E_0^{min} if E_d=E_{sub}	E_0^{min} for (5/3)E_{sub}
6 C	7.38	39	63
13 Al	3.39	40	65
14 Si	4.63	56	91
22 Ti	4.86	97	154
23 V	5.31	111	175
24 Cr	4.10	89	142
25 Mn	2.93	68	109
26 Fe	4.29	100	158
27 Co	4.47	109	171
28 Ni	4.52	109	172
29 Cu	3.49	93	147
30 Zn	1.35	39	63
32 Ge	3.86	115	181
40 Zr	6.26	215	328
41 Nb	7.50	254	385
42 Mo	6.83	242	366
47 Ag	2.95	129	202
73 Ta	8.12	461	673
74 W	8.80	496	721
78 Pt	5.85	379	560
79 Au	3.80	270	407

FIG.2. Simplified model of a real (vicinal) surface, showing the atoms as cubes that share three faces with neighbors at a kink site (K), five faces in a flat area (F) and two faces at a step site (S).

FIG.3. Predicted sputtering threshold as a function of particle radius R and radial distance r of an incident electron from the centre of the particle.



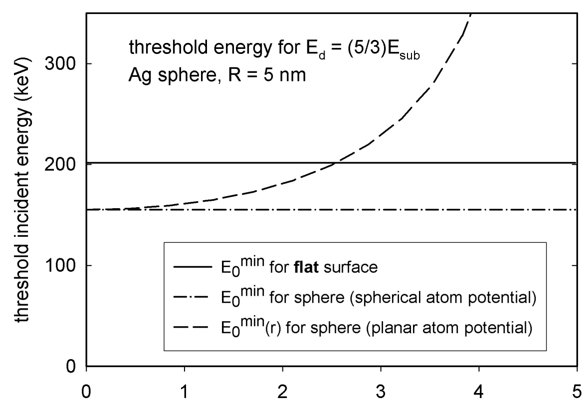


FIG.4. Dependence of surface-removal energy E_d on the angle γ between the e-beam and the surface-normal, as predicted by molecular-dynamics calculations [4] and as predicted by a planar escape potential (small dots) with $E_d(0)$ = 12.4 eV and by a spherical escape potential with E_d = 12.4 eV (dashed line).

https://doi.org/10.1017/S1431927609092204 Published online by Cambridge University Press