Solid State Communications, Vol. 43, No. 10, pp. 727–729, 1982.
Printed in Great Britain.

0038–1098/82/340727–03$03.00/0
Pergamon Press Ltd.

OBSERVATION OF THE IMAGE FORCE FOR FAST ELECTRONS NEAR AN MgO SURFACE

L.D. Marks

Cavendish Laboratory, Madingley Road, Cambridge CB3 OHE

(*Received* 30 *November* 1981 *by C. W. McCombie*)

The image force for fast (80 kV) electrons has been observed using the small electron microprobe available in a scanning transmission electron microscope, and imaging the surface plasmon losses. Preliminary results for the field at grazing incidence to an MgO surface qualitatively agree with the classical theory. The long range decay is found to be exponential.

THE IMAGE FORCE for a charged particle near a solid surface plays a fundamental role in many phenomena; it can, for example, be used to evaluate the van der Walls energy [1]. A more direct application is the inelastic scattering (by the imaginary part of the potential) of electrons travelling just outside a solid, a process normally referred to as the excitation of surface plasmons. These energy loss events may be observed by transmission [2] or by a reflection technique either at low energies [3] or at grazing incidence [4]. Unfortunately, there are problems associated with a theoretical interpretation of these results because of superimposed large bulk plasmon losses, or the complicated series of scattering events by which electrons are reflected from a surface [5]. Consequently, theoretical calculations [6], and experimental results [7] have appeared where a parallel plate condensor arrangement is used to produce electrons with a parabolic non-touching trajectory, eliminating the bulk contribution and simplifying the scattering calculations. A comparable technique, with potentially many more advantages, is to use a small electron microprobe located just outside the surface, as, for example, in the recent observation of surface plasmons around small aluminium spheres [8].

In this letter preliminary results are reported of the direct observation of surface plasmon excitations as a function of the distance from the surface of small (20–200 nm) MgO cubes using an electron microprobe. The results are in good qualitative agreement with the long range behaviour predicted for the image force. For reference, the excitation probability for a classical non-relativistic dielectric can be written [9] as:

$$\frac{d^2P}{d\omega dZ} = \frac{2e^2}{\pi\hbar^2 v^2}\,\mathrm{Im}\left(\frac{-2}{1+\epsilon}\right) K_0\left(\frac{2\omega x}{\hbar v}\right) \qquad x > 0$$

$$= \frac{2e}{\pi\hbar^2 v^2}\left|\,\mathrm{Im}\left(\frac{-1}{\epsilon}\right)\left(\ln\left(\frac{k_c\hbar v}{\omega}\right) - K_0\left(\frac{2\omega x}{\hbar v}\right)\right) + \mathrm{Im}\left(\frac{-2}{1+\epsilon}\right) K_0\left(\frac{2\omega x}{\hbar v}\right)\right| \qquad x < 0$$

where the solid occupies the region $x < 0$; v is the electron velocity; $\hbar\omega$ the energy loss; ϵ the dielectric function of the solid, and k_c the critical cut-off ($\approx 0.1\ \mathrm{mn}^{-1}$). A variety of more sophisticated analyses are available in the literature [10]. The form of the bulk and surface energy loss functions (Im $(-1/\epsilon)$ and Im $(-2/1+\epsilon)$ respectively) for MgO are shown in Fig. 1, calculated from the dielectric function given by Roessler and Walker [11].

The samples used were prepared by collecting the smoke from burning magnesium directly onto freshly cauterised copper microscope grids. These were examined in a VG HB5 scanning transmission electron microscope (STEM) operated at 80 kV with the electron beam focused to a probe of diameter ~ 2 nm. The transmitted electrons were analysed for energy losses with a magnetic sector spectrometer controlled either to scan the electron energy loss spectrum (EELS) with a stationary probe, or form images with a fixed energy loss window. In both cases the spectrometer resolution was 3 eV.

Figure 2 shows typical EELS, taken through the centre of a 30 nm cube; at grazing incidence about 2 nm outside a face, and lastly approximately 2 nm from an edge. The bulk spectra showed a plasmon at 22.5 eV, together with interband transitions at 12, 14 and 16 eV and some evidence of the bulk exciton at about 8 eV. These are in good agreement with the established EELS for MgO [12, 13]. When the probe was outside the particles a surface plasmon at 18 eV was observed, together with strong enhancement of the low frequencies. (The interpretation of the 18 eV loss as a genuine surface resonance is supported by the imaging evidence presented below, and is furthermore consistent with one of the peaks observed in reflection energy loss experiments by Henrich, Dresselhaus and Zeiger [13]. It should be noted that this value is 2 eV less than the 20 eV peak predicted by the data of Roessler and Walker [11], as shown in Fig. 1. An alternative interpretation

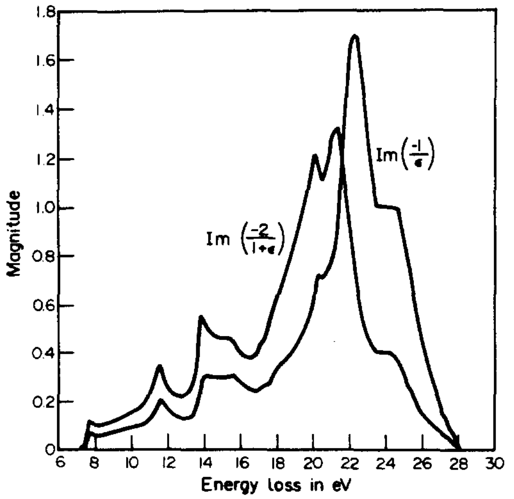

Fig. 1. Plots of the bulk (Im $(-1/\epsilon)$) and surface (Im $(-2/1+\epsilon)$) loss functions for MgO, derived from the dielectric data of Roessler and Walker [11].

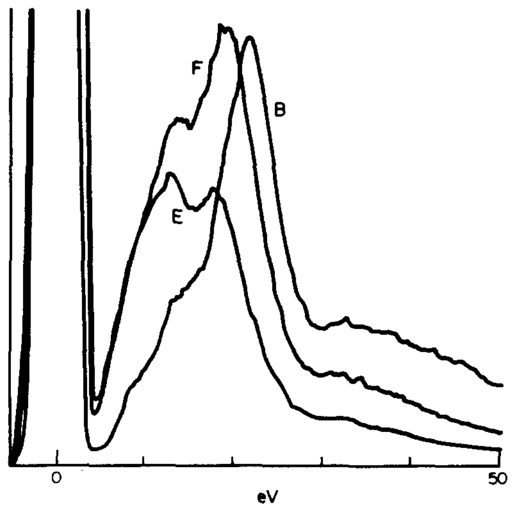

Fig. 2. EELS taken from different positions with a stationary probe: *B*, through the centre of a particle; *F* down a face, and *E*, by an edge. (The latter two are magnified x 4 relative to the bulk spectrum.)

of this peak is due to synchrotron radiation has been suggested by Cowley [14]. However, a relativistic treatment of the image force [15] would suggest that the excitation of radiative surface plasmons, or Cherenkov radiation when $v > c/\sqrt{\epsilon_1}$ would only be of significance in the 0–10 eV loss range. The reinforcement of the lower frequencies correlates with the general form of Im $(-2/1+\epsilon)$, complemented by the frequency weighting away from the surface due to the $K_0(2\omega x/\hbar v)$ term.

Figure 3 shows typical energy filtered line traces as a function of the distance from the surface of a 100 nm particle oriented just off a (100) diffraction pole. One dominant feature of these results is the exponential

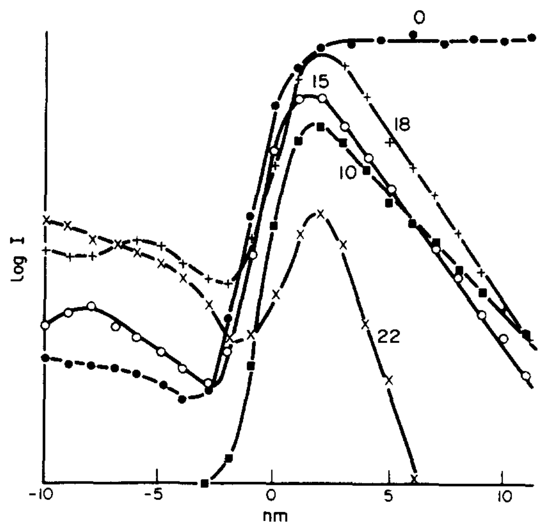

Fig. 3. Line traces from the surface of a 100 nm particle plotted on a log scale. The energy windows used are marked on the figure. The zero loss scan has been reduced by a factor of 30.

decay, which is in fact different from that predicted by the classical theory $(K_0(2\omega x/\hbar v) \sim (\hbar v/\pi\omega x)^{1/2}$ exp $(-2\omega x/\hbar v)$ for large x).

In conclusion, the results presented herein have demonstrated that information can be obtained on the image force for fast electrons using a commercial STEM. The behaviour of the dispersion relationship for surface plasmons as a function of distance can be directly investigated.

Acknowledgements – The author is indebted to Professor R.H. Ritchie for his advice on the theoretical nature of the problem, and would like to thank Dr A. Howie for his extensive advice and the S.R.C. for financial support.

REFERENCES

1. D. Chan & P. Richmond, *J. Phys. C* **9**, 163 (1976).
2. C. Kunz, *Z. Phys.* **196**, 311 (1966).
3. C.J. Powell & J.B. Swan, *Phys. Rev.* **118**, 640 (1960).
4. N. Masud & J.B. Pendry, *J. Phys. C Solid St. Phys.* **9**, 1833 (1976).
5. See the comments in the introduction to [6] (i).
6. B. Gumhalter & D.M. Newns, *Surf. Sci.* **50**, 465 (1975); J.P. Muscat, *Solid State Commun.* **18**, 1089 (1976).
7. J. Lecante, Y. Ballu & D.M. Newns, *Phys. Lett.* **57A**, 159 (1976).
8. P.E. Batson & M.M.J. Treacy, *Proc 38th EMSA Meeting (Reno)* 126 (1980).
9. R.H. Ritchie, private communication.
10. For example, J.P. Muscat & D.M. Newns, *Surf. Sci.* **64**, 641 (1977); J. Mahanty & P. Summerside, *J. Phys. F* **10**, 1013 (1980); A.G. Eguiluz, *Phys. Rev. B* **23**, 1542 (1981); P.M. Echinique, R.H. Ritchie,

N. Barberám & J. Inkson, *Phys. Rev. B* **23**, 6486 (1981).
11. D.M. Roessler & W.C. Walker, *Phys. Rev.* **159**, 733 (1967).
12. H. Venghaus, *Op. Commun.* **2**, 447 (1971).
13. V.E. Henrich, G. Dresselhaus & H.J. Zeiger, *Phys. Rev. B* **22**, 10, 4764 (1980).
14. J.M. Cowley, *Surf. Sci.*, in press.
15. R.H. Ritchie & A. Howie, private communication.