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DISCRETE ELECTRON ENERGY LOSSES AND SECONDARY EMISSION FROM CdO

N. B. GORNYĬ

Leningrad Electrotechnical Communications Institute

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It is shown that the discrete energy losses of the electrons reflected from a CdO surface are determined by the CdO crystal structure. The spectra of the discrete losses in CdO and MgO, which have identical crystal lattices (face-centered cubic), are similar and their differences are due to differences in the lattice constants. The groups of genuine secondary electrons with discrete energies are produced in CdO by a single type of mechanism, which yields the aforementioned discrete electron energy losses. The maximum value of the secondary electron emission coefficient for CdO is only $\delta_{\max} = 1.25$. The small magnitude of this quantity confirms an earlier suggestion regarding the dependence of $\delta_{\max}$ on the relation between the minimum discrete energy loss and the electron work function.

INTRODUCTION

MANY investigations of the discrete electron energy losses lead to the conclusion that these losses are connected with the crystal structure of the given substance.[1-6] Of all the substances investigated, the least definite results were obtained for MgO. As the energy V_p of the primary electrons is increased, the peaks of the discrete electron energy losses in MgO become "smeared" and consequently less and less distinguishable.[6] For MgO with a face-centered cubic lattice the structural factor for the (210) and (211) [also (110)] planes is zero, and no discrete losses with the corresponding energy values should be observed. However, we did observe energies close to these values.[6] It was therefore of interest to investigate the discrete electron energy losses in a substance analogous to MgO and having the same crystal structure. CdO was chosen for this purpose.

It was also deemed interesting to verify with CdO the correctness of the relation, established for several substances, between the ratios of the values of the discrete electron energy losses to the work function, on the one hand, and to the yield of secondary electrons on the other.[7] We investigated therefore the secondary electron emission of CdO.

As far as we know, neither the discrete electron energy losses nor the yield of secondary electrons from the surface of CdO have been investigated heretofore.

EXPERIMENTAL DATA

A round plate was made of a piece* of CdO approximately 0.5 mm thick. After treatment with acid and alkali and subsequent washing in distilled water and pure alcohol, the plate was placed in the instrument. The construction of the vacuum instrument was similar to that used in reference 8. After prolonged training and degassing of the instrument, the pressure (measured with an ionization manometer) prior to the sputtering of the getter and sealing of the instrument was less than 3×10^{-7} mm mercury.

In the measurements of the electron energy distribution, the magnetic field of the earth was compensated for by two coils 1 m in diameter. The corresponding measurements were carried out at night, when the noise level was a minimum.

Electrical differentiation in a spherical-capacitor circuit[1] was employed to investigate the discrete energy losses of the electrons reflected from the surface of the CdO. Figure 1 shows the distribution of inelastically-scattered electrons, at several values of energy of the incident electrons, V_p, and at 250° C. All curves of Fig. 1 show distinct peaks of discrete energy losses. An analysis of the experimental curves displays more clearly the positions of the individual discrete-loss peaks. The dotted curves next to the experimental curves (Fig. 1) characterize the continuous background due to inelastic losses.

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*The CdO was graciously supplied by V. P. Zhuze, to whom we are most grateful.

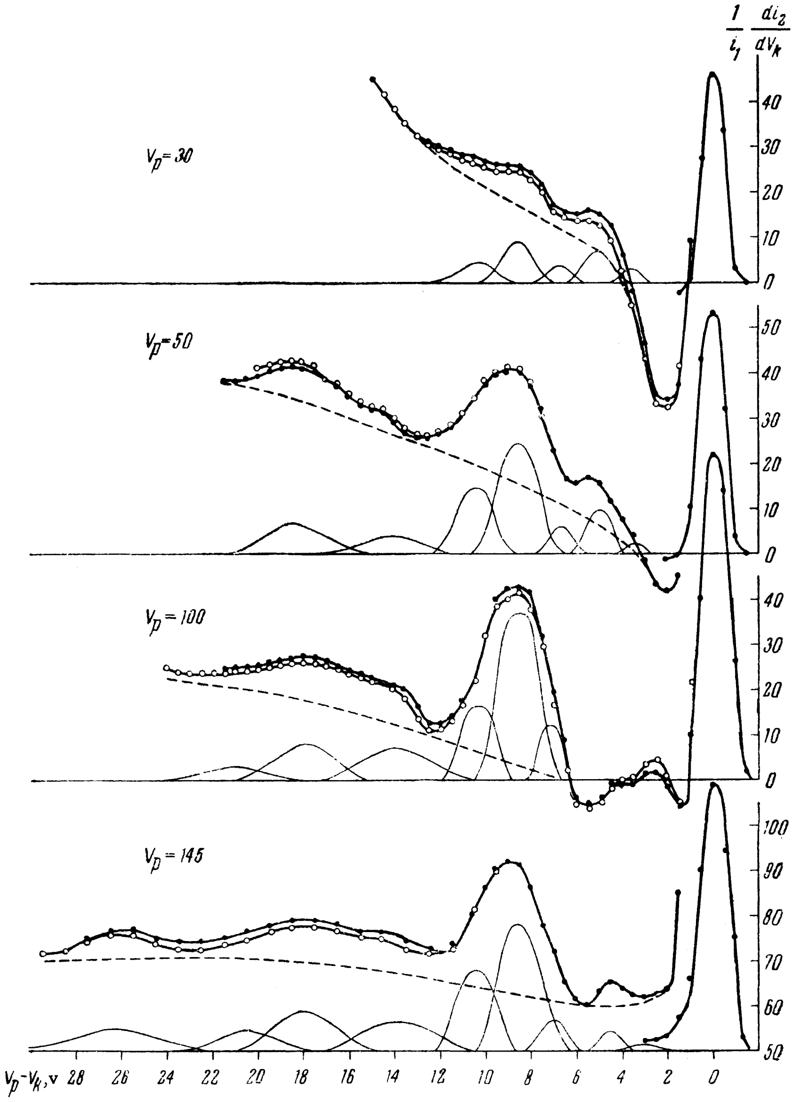

FIG. 1. Energy distribution of inelastically scattered electrons, obtained for CdO at several values of V_p and at t = 250°C. The peaks of elastically-rebounding electrons are drawn on a smaller scale.

The first four rows of the table list the values of the discrete-energy losses, $V_p - V_k$, which we obtained at the corresponding values of V_p. Line 5 shows the Miller indices h, k, and l, for which the values of the energy W were calculated with the following formula[6]

$$W = h^2 (h^2 + k^2 + l^2) / 8ma^2, \tag{1}$$

where m is the electron mass, a is the lattice constant of CdO, and h is Planck's constant. These values are listed in line 6 of the table.

It can be seen from the table that the corresponding experimentally-determined peaks of $V_p - V_k$ are the same, within experimental accuracy, for all energies of the incident electrons investigated. The experimental values of the discrete electron energy losses, $V_p - V_k$, are in good agreement with the values of W, calculated with Eq. (1).

To verify that the discrete losses obtained were due to electron transitions between bands,[1,6] we investigated the energy distribution of the true

Values of discrete energy losses in CdO

No.	V_p, v	$V_p - V_k$, v								
1	30	3.5	5	6.8	8.6	10.3				
2	50	3.5	5	6.6	8.6	10.5	14.2	18.5		
3	100	2.8	4.5	7.0	8.5	10.3	13.8	18	21	
4	145	3	4.6	7.0	8.5	10.4	14	18	20.5	26.5
5	*hkl*	110	111	200	210	211	220	311	222	400
6	*W*	3.4	5.1	6.8	8.6	10.3	13.7	18.8	20.5	27.4
7	$(V_p - V_k)_{MgO}$	4	5.2	6.8	8	10	14.8	20		27.4

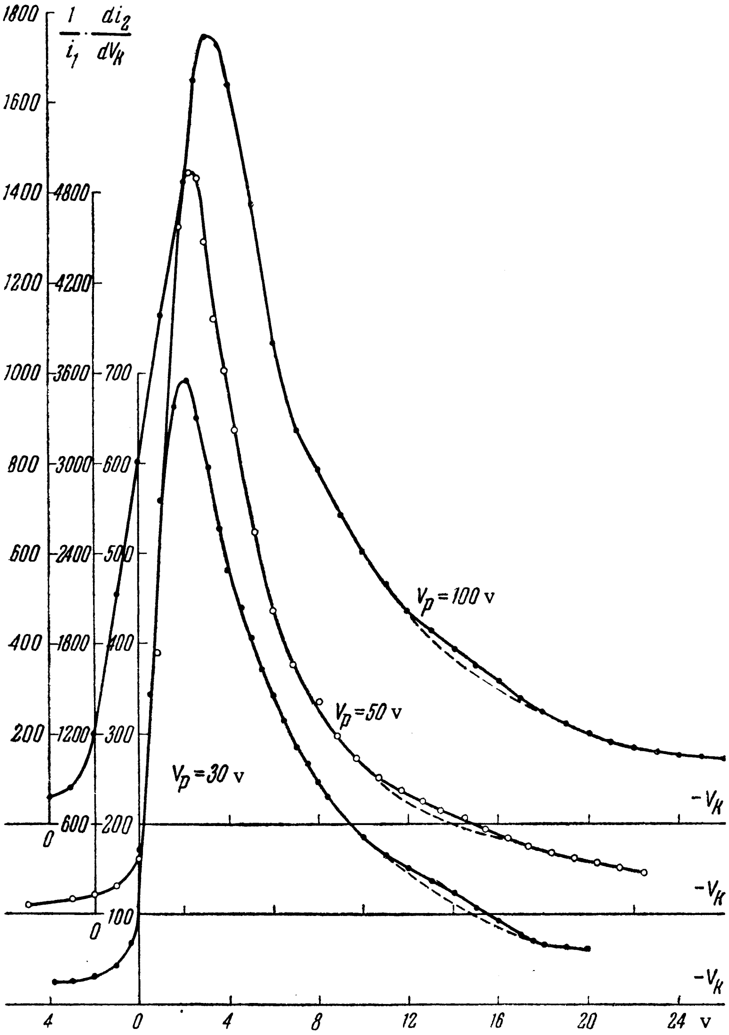

FIG. 2. Curves showing the energy distribution of the genuine secondary electrons, obtained for CdO at several values of V_p and at t = 250°C (lower set of coordinates – for the curve at V_p = 30 v; middle set – for V_p = 50 v; upper set – for V_p = 100 v).

secondary electrons. Figure 2 shows the energy distribution, obtained for the genuine secondary electrons by the method of electric differentiation, at several values of V_p. In all curves of Fig. 2, we see, apart from the principal maximum, also a bend that indicates the presence of a discrete group of genuine secondary electrons with an approximate energy of 14 ev.

The secondary electron emission from CdO was investigated with the same vacuum instrument as used to determine the discrete energy losses.

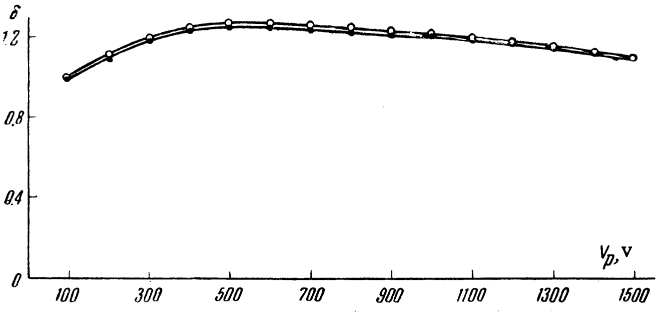

FIG. 3. Curves δ = f(V_p), obtained from the surface of CdO at t = 20°C (open circles) and t = 400°C (full circles).

Since our sample of CdO had a relatively low resistance (ρ = 0.027 ohm-cm at room temperature), the secondary emission was investigated in the static mode.

Figure 3 shows the curves δ = f(V_p), which characterize the dependence of the secondary-emission coefficient δ on the energy of the incident electrons V_p at 20° and 400°C. For CdO, the maximum value of δ was found to be 1.25 at V_p = 500 volts. In the entire measured range of V_p, δ varied very little with the temperature.

To determine the character of the variation of the energy distribution of the secondary electrons with V_p, we plotted delay curves, $I_2/I_1 = f(V_k)$ for several values of V_p, at room temperature and at t = 400°C. The curves obtained for equal values of V_p but different temperatures were found to be identical. Figure 4a shows delay curves obtained for V_p = 150 volts (curve 1) and V_p = 500 volts (curve 2) at 400°C, while Fig. 4b shows the secondary-electron energy distribution curves obtained by numerical differentiation of the delay curves of Fig. 4a.

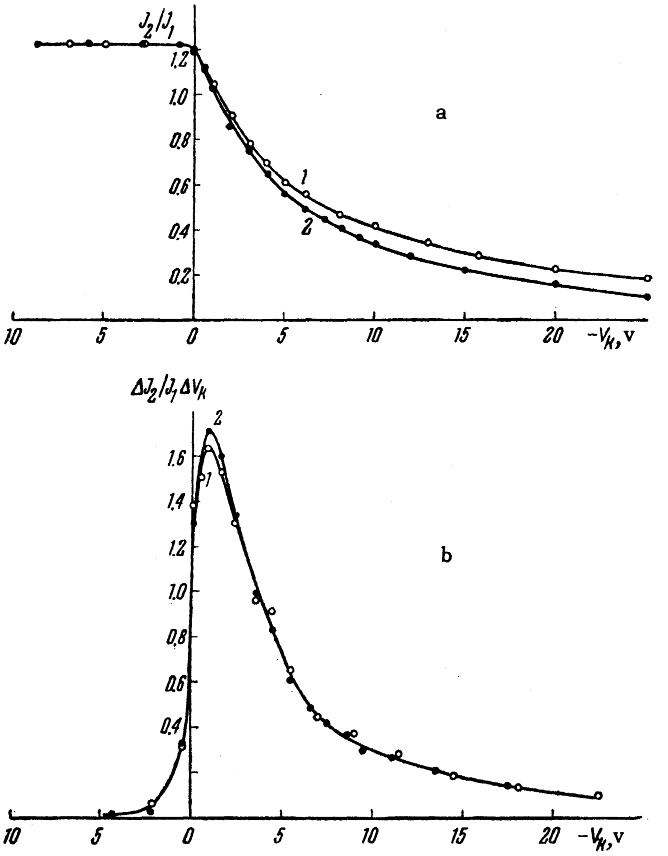

FIG. 4. a – delay curves, b – energy distribution of the secondary electrons (both for t = 400°C). Curves 1 – V_p = 150 v, curves 2 – V_p = 500 v.

Curve 1 (Fig. 4a) is normalized so that its points in the range of positive V_k coincide with the points of curve 2.

It can be seen from Fig. 4b that the distributions obtained at $V_p = 150$ and 500 v are practically the same; the values of the most probable electron energies are also the same.

DISCUSSION OF THE EXPERIMENTAL DATA

The distributions of the inelastically-scattered electrons, obtained for CdO (Fig. 1), are similar in external appearance to the distributions obtained for MgO (reference 6), at lower incident-electron energies (V_p ranging from 30 to 40 v). Only the peaks of discrete losses on the CdO curve are shifted towards the region of lower values of $V_p - V_k$ compared with the MgO curve, because CdO has a greater lattice constant than MgO.

To compare the data obtained for MgO with those obtained for CdO it is necessary to reconcile the values of the discrete losses $V_p - V_k$ for MgO (reference 6) with the lattice constant of CdO. For this purpose, values of $V_p - V_k$ [see Eq. (1)] must be multiplied by $(4.21/4.70)^2$, where 4.21 and 4.70 are the lattice constants of MgO and CdO respectively. All the discrete losses we obtained for MgO (line 7 of the table), reduced in this manner, are in very good agreement with the discrete losses for CdO.

Comparing the Miller indices corresponding to the values of discrete losses W in CdO (see table) with those previously obtained[6] for W in MgO, we note that they are in complete agreement with each other. Furthermore, two peaks were obtained for CdO, exactly as for MgO, corresponding to the indices* (210) and (211), for which the structural factor is zero and the corresponding values, W = 8.6 and 10.3 ev, should not be observed. The only values not noted in reference 6 for MgO are W = 4.3 ev and W = 34.2 ev, corresponding to the indices (110) and (400) respectively. However, the value $V_p - V_k = 5$v, listed in Table 3 of reference 6, does correspond to W = 4.3 ev, and the peak of the discrete losses, W = 34.2 ev, is seen on the curves obtained for V_p values of 50 and 100 v (Fig. 3 of reference 6), although it is not noted in the table. It is possible thus to assume that all the discrete losses obtained for CdO were also obtained for MgO. Leder, Mendlowitz, and Marton[4] established a correspondence between discrete energy losses and crystal structure for several substances. We observed the same correspondence between the discrete losses of GeO_2 and MoO_2, which have an identical crystal structure.[5] Comparison of the data obtained for CdO and MgO confirms the connection between the foregoing discrete electron energy losses and the crystal structure of the given substance.

It must be noted that the smoothing of the peaks of discrete losses with increasing energy of the incident electrons, which we observed for MgO, were not noted for CdO. As V_p increases the peak at $V_p - V_k = 12$ v of the MgO distribution curves becomes smoothed out, but the corresponding CdO peak at 9 volts, to the contrary, becomes even more pronounced. As already pointed out in reference 6, the primary and secondary electrons lose their energy to phonon excitation as they are displaced in MgO. This leads to an ever increasing smoothing of the MgO peaks with increasing energy of incident electrons. The fact that the curves $\delta = f(V_p)$ for CdO do not change with the temperature (Fig. 3) indicates the absence of losses to phonon excitation. Therefore

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*Table 3 of reference 6 contains an erroneous value (411). in column 6 instead of (211).

the peaks of CdO, unlike those of MgO, remain pronounced (unsmeared) with increasing V_p.

We already noted that the energy distribution curves of the genuine secondary electrons (Fig. 2) have, in addition to the principal maximum, also an inflection point due to the peak of the ~ 14-ev genuine secondary electrons. It is natural to assume that groups of genuine secondary electrons with discrete energies appear in the substance during acts of inelastic interaction between the incident electrons and the lattice electrons of the solid, which lead to discrete energy losses of the incident electrons.[1,6] The curves showing the distribution of the inelastically-rebounding electrons (Fig. 1) contain two most intense groups, for which the mean values of the discrete losses are 8.5 — 9 and 18 — 18.5 ev. Apparently the second group of discrete losses causes the appearance of the aforementioned group of 14-ev genuine secondary electrons. The work function for CdO is found here to be approximately 4 — 4.5 ev. The first group of discrete losses (8.5 — 9 ev) should cause the appearance of a group of genuine secondary electrons with energies 4 — 4.5 ev. The peak due to a group of electrons with such energies would be located on the curve (Fig. 2) at the principal maximum, in the steepest portion of the distribution curve, where it is most difficult to detect. From the distribution curves for the inelastically-rebounding electrons (Fig. 1) it is seen that as the energy V_p of the incident electrons increases from 30 to 100 ev, the intensity of the peak at $V_p - V_k = 9$ v increases. Consequently, the peak of the group of genuine secondary electrons, caused by this discrete loss, should also increase with increasing V_p within the indicated limits. This should lead to a corresponding increase in the ordinates of the distribution curves of the genuine secondary electrons with increasing V_p in the region of $V_k = 4 - 4.5$ v. Figure 2 shows the shift of the principal peak of the true secondary electrons towards higher energies as V_p increases from 30 to 100 v, in agreement with the foregoing considerations.

Thus, the presence of a group of genuine secondary electrons with the indicated energy values shows that the discrete losses in CdO are produced by excitation of electron transitions between bands.

Proceeding now to a discussion of the CdO curves of the secondary-electron yield [$\delta = f(V_p)$ (Fig. 3)], the delay curves, and the distribution curves obtained at considerably differing values of V_p (Fig. 4), we note that they differ considerably from the corresponding curves obtained for MgO. Whereas the $\delta = f(V_p)$ curves obtained for CdO (Fig. 3) hardly vary as the temperature changes from 20 to 400°C, the curves for MgO drop considerably with increasing temperature.[9,10] This means that the energy lost by electrons to phonon excitation is quite small in CdO and relatively large in MgO.

The fact that the relative number of low-energy secondary electrons (Fig. 4b) fails to increase with increasing V_p up to $V_p = 500$ v, at which the $\delta = f(V_p)$ curve has a maximum, shows that in practice the energy lost by the secondary electrons does not increase with increasing V_p, in contrast with what takes place for MgO.[11] These two features of CdO, and also the small value of $\delta_{max} = 1.25$ and the negligible variation of δ with V_p, indicate that the secondary electrons are emitted from a smaller effective depth than from MgO, and that this depth varies little with V_p.

It was shown in several investigations that for a given substance the effective depth of emission of secondary electrons is independent of or hardly dependent on the energy of the primary electrons V_p, and remains constant over a wide range of the latter.[12-15] The research of Morgulis and Nakhodkin[14] indicates here that: 1) at a given V_p, δ increases more rapidly with increasing film thickness for a more effective emitter (Sb — Cs, $\delta_{max} = 10$) than for a less effective emitter (Ge, $\delta_{max} = 1.2$), and 2) the effective depth is greater than 100 mμ for Sb — Cs and 70 mμ for Ge.

Let us try and determine the cause of the low value of the coefficient of secondary emission of CdO. It is known that the secondary electron emission is a complicated phenomenon, consisting of several processes. The principal processes are:

1. Displacement of the primary electrons in the solid, accompanied by an energy loss to the excitation of the internal secondary electrons.
2. Energy lost by the secondary electrons as they move in the solid, accompanied by possible formation of tertiary electrons.
3. Emission of the secondary and tertiary electrons from the solid.

Since CdO and MgO have an identical crystal structure and an identical mechanism of discrete losses, and have consequently an identical mechanism of secondary-electron excitation, the first two of the above processes should not differ greatly for these substances. Obviously, the third process is very important in this case. The considerable difference in the coefficients of secondary emission of CdO and MgO is apparently due to the difference in the probability of the emission of secondary and tertiary electrons through the outer surfaces of these substances.

This difference in the electron-emission probabilities can be explained by starting with the criterion that determines the secondary-emission probability as a function of the ratio of the least discrete-energy loss, $(V_p - V_k)_{min}$, to the work function $e\varphi$ of a given substance.[7] The secondary electrons which have energies E greater than $(V_p - V_k)_{min}$ while inside the substance, will expend their energy on phonon excitation as they move (losing an insignificant amount of energy, $\sim kT$, during each act of excitation and on the excitation of the lattice electrons losing thereby an energy not less than $(V_p - V_k)_{min}$ during each such process. The second energy-loss process experienced by the secondary electron will continue until its energy is reduced to a value at which the loss probability becomes close to zero. This occurs when $E \leq (V_p - V_k)_{min}$. Thus, the overwhelming majority of secondary and tertiary electrons that move towards the surface reach it at an energy close to $(V_p - V_k)_{min}$. If $(V_p - V_k)_{min}$ of a given substance is greater than the work function $e\varphi$, then most of the excited electrons of the crystal lattice, moving towards the surface and having an energy $(V_p - V_k)_{min}$, may still have an energy greater than $e\varphi$ as they reach the surface, enough to escape outside. This can be true for electrons which arrive even from a relatively large distance and which have lost a certain portion of their energy to phonon excitation. For such a substance, the effective depth of emission will be comparatively greater, the yield of secondary electrons will be considerable, and phonon losses should cause a noticeable dependence of the yield of electrons on the temperature.

On the other hand, if $(V_p - V_k)_{min}$ of a given substance is less than $e\varphi$, then the overwhelming majority of these electrons with energy close to $(V_p - V_k)_{min}$ cannot escape outside, with the exception of a small group of secondary electrons which are produced on the surface and which do not have a chance to expend their energy to a value close to $(V_p - V_k)_{min}$ as they move on toward the surface. Consequently, the effective depth of emission of secondary electrons for such a substance is small, the yield of secondary electrons is insignificant, and no temperature dependence should be observed for the yield of secondary electrons, owing to the insignificant energy expended for phonon losses at the small emission depth.

For MgO, $(V_p - V_k)_{min} = 5$ ev and exceeds the work function. For CdO, $(V_p - V_k)_{min} = 3 - 3.5$ ev (see table) and is less than $e\varphi$. Therefore MgO belongs to the first group of substances, with a large yield of secondary electrons, while CdO belongs to the second group, with a small yield of secondary electrons.[7]

In conclusion I express my gratitude for M. M. Kozlovskiĭ and A. G. Podgaĭskiĭ for help in the measurements.

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