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INTERPRETATION OF ELECTRON DIFFRACTION PATTERNS FROM THIN PLATELETS

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December 1964

ABSTRACT

Electron diffraction patterns from foils containing planar defects, e.g. precipitates or stacking faults, are considered in terms of relrods normal to the plane of the defect, and/or normal to the specimen surface. The patterns can be regarded as consisting of streaked reciprocal lattices superimposed on the matrix lattice. In the materials examined, faulting did not produce any detectable physical shift of allowed reflections. The observations indicate that faulting is regular rather than random. Stacking faults and HCP precipitates in FCC crystals can not as a rule be distinguished in the early stages of formation of the precipitate. A complete analysis of the spot pattern from foils containing planar defects generally requires an accurate determination of the crystal orientation. For this purpose Kikuchi patterns provide sufficient accuracy and an assessment of this is made.

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1. INTRODUCTION

The correct interpretation of electron diffraction patterns forms an important aspect of the analysis of the data obtainable with the electron microscope. For simple, relatively perfect structures, standard approaches can be employed [1, 2] and no difficulties arise. However, in other situations, varying degrees of sophistication may be required in order to elucidate satisfactorily the diffraction patterns obtained. This paper will be concerned in particular with the analyses of diffraction patterns from faulted FCC-HCP structures and from FCC structures containing thin platelets (e.g. Guinier-Preston zones) but the principles involved apply to all crystal structures. These analyses are similar in that both may involve diffraction effects characterized by relrods (spikes) in the reciprocal lattice [1, 3]. From the transmission image, it is generally possible to tell whether the region being analyzed contains principally faults, GP zones or precipitates. The nature of the image contrasts have been extensively analyzed, and detailed treatises on the subject are available [1, 3-7].

The foil thickness also gives rise to relrods in reciprocal space. Although these are not of great interest here, knowledge of their existence and the effect they produce are of importance in order to guard against possible misinterpretation when analyzing spot patterns. The next section is, therefore, devoted to this topic. The analysis of diffraction patterns is often greatly simplified by the use of a goniometer stage (in the electron microscope) which permits suitable or desirable orienting of the sample. For specimens with structures giving rise to complex or unusual patterns, the use of such a stage may, in fact, be the only method by

which one can obtain diffraction patterns, the analysis of which is tractable or feasible.

An implicit part of the analysis of the spot pattern is the determination of the crystallographic orientation of the foil. Frequently, this is desired information anyway, but of relatively low accuracy [8]. Greater accuracy may be obtained from Kikuchi patterns [8, 9], which can also be of assistance in analyzing the spot patterns. The last section thus emphasizes a number of points in assessing the accuracy of an orientation determination from Kikuchi patterns.

2. RELRODS DUE TO FOIL THICKNESS

For a perfect crystal oriented exactly for diffraction, the intensity of a reflection depends on the product of the geometrical structure factor and the form factor [1, 3]. The latter is determined by the shape of the crystal respective to the incident beam. For thin foils, due to the small thicknesses necessary for electron transmission, relaxation of one of the Laue conditions causes the diffraction maxima, i.e. the reciprocal lattice points (relpoints), to be smeared out in a direction normal to the plane of the foil irrespective of the foil orientation (Fig. 1). The relpoint is thus actually a spike or rod (relrod). Also, the reflecting sphere is essentially planar due to the very short wavelengths of electrons (0.037Å for 100 kV) so that a diffraction pattern which represents the intersection of the reflecting sphere with the relrods, can be obtained over a wide range of angles (±5°), although the intensities fall off the further the deviation from the Bragg condition. In the very thinnest regions of foils (at

the edges), for which the relrods may be quite long, it is possible for the relrods from the second layer of the reciprocal lattice (Fig. 1) to cut the reflecting sphere and so give rise to reflections at or near positions not normally allowed by the structure factor [1], see Figs. 2a,b,c. Although in certain instances this could be confused with superlattice reflections, any such possible confusion is easily resolved by moving to thicker regions of the foil, whereupon the extra spots from relrods due to foil thinness will, of course, disappear (e.g. Fig. 2).

When a specimen is tilted (or bent), the reciprocal lattice can, in general, be considered to be correspondingly tilted (or bent) in exactly the same sense and direction. This is illustrated in Fig. 1. For a crystal oriented exactly at the Bragg condition (Fig. 1a), the relpoint lies exactly on the reflecting sphere so the deviation parameter s is zero [10]. If we now tilt the specimen clockwise about an axis normal to the incident beam, then the reciprocal lattice is also tilted clockwise about a parallel normal through O^* and perpendicular to O^*P^* (Fig. 1). The reflecting angle now becomes $> \theta$, and P^* will move to the outside of the sphere, and the corresponding Kikuchi lines move to the left of the pattern, i.e. in the opposite sense to the Kikuchi pole. Thus, depending on the length of the relrod at P^*, reflections are possible over a range of angles for which $s \neq 0$. The distance between the origin and P^* (projected) measured in the diffraction pattern corresponding to Fig. 1b is obviously not a good measure of $\bar{g}(hk\ell)$ because of the projection. However, the same measurement on a diffraction pattern corresponding to the situation in Fig. 1a gives the exact reciprocal lattice vector $\bar{g}$ (corrected for magnification by the camera constant λL [1]) for the $(hk\ell)$ reflection. In the absence of Kikuchi

patterns the situation corresponding to exact or symmetrical foil orientation (the plane of the reciprocal lattice exactly normal to the incident beam, Fig. 1b) is readily recognized since the spot pattern is symmetrical, with equal numbers of spots on the positive and negative zone directions about the origin, as shown in Fig. 3. In order to obtain many orders of reflection the foil must be very thin so that the relrods cut the reflecting sphere even at large distances from the origin (e.g. Fig. 3).

From Fig. 1 it is seen that tilting of a foil in a clockwise sense makes s negative (by convention) and causes the $hk\ell$ Kikuchi line to move from the $(hk\ell)$ spot towards the origin, i.e. towards the transmitted beam. A counterclockwise tilt makes s positive and the Kikuchi line moves to the outside of the spot. The sense of tilt of the foil is thus apparent from the position of the Kikuchi pattern with respect to the spot pattern. In order to obtain the unique foil orientation, solely from the diffraction pattern, two Kikuchi poles will be required [8]. In special cases, single pole solutions are sufficient.

3. RELRODS DUE TO PLATELETS AND FAULTS

According to the same principles discussed in the preceding section, sufficiently thin planar defects (twins, stacking faults or second phases) will give rise to relrods in the reciprocal lattice. The direction of the relrods is normal to the platelet since this is the direction along which the Laue condition is relaxed and, in the case of precipitation, in the early stages the relrods will pass through the matrix relpoints, i.e. the form factor dominates the diffraction pattern.

Since in electron diffraction it is possible to consider diffraction from a narrow column of crystal, then even for a single intrinsic stacking fault,

where four layers are in HCP stacking: ABCAB | CACA | BCA, there may be a sufficient volume of HCP material present so that the layers can be regarded as a thin platelet of HCP structure. The intensity diffracted by a plate is determined (as for the perfect crystal) by the product of its geometrical structure factor and the form factor. One can then consider the diffraction pattern from a foil containing a fault in terms of two reciprocal lattices, viz., one "normal" pattern corresponding to the matrix and the other consisting of the streaked HCP reciprocal lattice, corresponding to the thin fault, superimposed. Since the fault plane is one of the four {111} in FCC and because of the unique crystallographic relations between FCC and HCP lattices, the relrods will lie along <0001> parallel to and coincident with <111> continuously throughout reciprocal space. These streaks which can be considered to originate from HCP reciprocal lattice points will thus pass through all matrix reflections contained in the particular [111] and parallel zones. In support of this view consider a diffraction pattern taken from a single fault lying parallel to the incident beam. Figure 4a illustrates such a case for growth faults in silicon. The foil is oriented with [110] parallel to the incident beam and the "edge-on" faults on $(1\bar{1}1)$ and $(\bar{1}11)$ are joined by a fault on $(11\bar{1})$ or (111) inclined at 35° to the beam. By placing a small field limiting aperture over the edge-on fault at A the diffraction pattern in Fig. 4b was obtained. It can be seen that streaks are visible along [111] and pass through (000) and the other relpoints. These streaks can be attributed to the stacking fault acting as a thin (HCP) platelet; the structure is indeterminate in the direction of streaking, as no maxima are visible along [111]. If a larger fraction of edge-on faults were to contribute to the pattern or if there

were regular faulting on alternate (111) planes over a sufficient volume of crystal, then the [110] pattern would contain resolvable HCP maxima as sketched in Fig. 5a. Some examples of this case are shown in Figs. 5b and 6. The possible twin positions shown in Fig. 5(a) can easily be calculated [11].

Figure 4c is a diffraction pattern taken across the inclined fault shown in Fig. 4a after the foil was tilted into a strong $\bar{2}20$ beam case (i.e. the reflecting sphere passed exactly through the $\bar{2}20$ relpoint). Doublets can be resolved in the pattern. These doublets are due to both the effects of foil thickness and fault relrods [7]. By Kikuchi pattern analysis the orientation of Fig. 4c was determined to be almost exactly $[33\bar{1}]$ and this may also be taken as the normal to the foil surface. There are two possible streaking directions depending on whether the fault is on (111) or $(11\bar{1})$. By suitable projection it can easily be shown that the spots to the inside of the doublets can only arise from streaks due to a $(11\bar{1})$ fault. The positions of these inner spots are exactly where the $[11\bar{1}]$ streaks are expected to cut the reflecting sphere for this orientation. The outer spots of the doublets arise from foil thickness relrods and their distance from the inner spots corresponds to that calculated for relrods along $[33\bar{1}]$. It is instructive to observe that if the orientation is taken as "approximately [110]," a choice readily made on the basis of the diffraction pattern alone, the separation of the doublets may also be calculated, assuming thickness relrods along [110]. If this is done, it is found that the calculated separation of the doublets is an order of magnitude smaller than that observed, even though the angle between [110] and $[33\bar{1}]$ is only 13.3°. This example serves to emphasize the importance of precise orientation determinations for explaining fine detail in diffraction patterns. A

similar pattern to Fig. 4c was examined by Whelan and Hirsch [7], but since no Kikuchi patterns were obtained, a detailed analysis could not be made. The separation of the doublets in their case is also an order of magnitude too large for an "approximate [100]" orientation.

No examples from faulted structures were ever obtained in which the shift of the matrix spots from their normal positions, as predicted by random fault theory, could be measured. Examination of heavily faulted, deformed FCC metals indicated that in many regions the faults tended to be so spaced that the HCP rather than the twin FCC structure was produced, e.g. in Fig. 5(b) the appearance of the $(10\bar{1}0)$ peak proves that many faulted regions are actually thin platelets of HCP structure.

Because of the fact that streaks through all spots are observed in the presence of stacking faults, it is not possible from the diffraction pattern alone to distinguish between stacking faults and thin plates of HCP precipitates. In both cases, if all four {111} habit planes operate, and if all affected regions diffract, all relpoints will have four relrods through them, i.e. the diffraction pattern can be regarded as consisting of five superposed reciprocal lattices. In a sense there is no difference between a thin layer of HCP precipitate and a stacking fault formed by deformation or growth mistakes. (In contrast, for X-ray diffraction from a randomly faulted crystal certain relpoints, e.g. {111}, would have only three relrods through them [12]). If the change in c/a from non-ideal is due to a change in the (0001) interplanar spacing, then the [0001] streaks will still pass exactly through the centers of the matrix relpoints; if due to changes in the (HKIO) interplanar spacings this will no longer be true (e.g. compare Figs. 6b, 10 with that from faulted Co, Fig. 6a, in

which the streaks pass through the FCC reflections of Co).

Figure 7 summarizes the situations for thin platelets on {111} FCC. Figure 7a shows the disposition of the relrods for foils in [001], [$\bar{1}$01] and [111] orientations, Fig. 7b shows the diffraction patterns for exact foil orientations and Fig. 7c shows the diffraction pattern for a tilted foil (only one hkℓ spot is shown). The change from Figs. 7b to 7c is readily understood by considering the tilting of a reciprocal lattice, containing both thickness and defect relrods (along <111>), with respect to the fixed reflecting sphere (plane). It follows that the diffraction pattern is extremely sensitive to the tilt of the foil. However, the spacing and asymmetry of the extra spots (with respect to the hkℓ reflections) produced as the reflecting sphere cuts the relrods is an indication of the sense and amount of foil tilt. The effects of streaks on diffraction patterns can sometimes be followed more easily with models of streaked reciprocal lattices [13]. It may also be essential to tilt the foil and to observe how the pattern changes in order to avoid possible misinterpretations.

Figure 7b emphasizes that no extra spots or streaks are ever obtained from thin platelets for foils in exact orientation, except for the higher order reflections when the sphere curves away from the relpoints, and except when the habit plane of the platelet is (nearly) parallel to the incident beam (see Fig. 4b). In FCC crystals containing stacking faults these orientations are those that contain a <111> zone, e.g. <110> and <112>, and in no orientation can more than two sets of streaks lie completely in the plane of the diffraction pattern. Figure 7b is, of course, exaggerated because the reflecting sphere is actually curved and because of this curvature continuous streaks will only be observed through the low

order reflections. As shown in Fig. 1b even in the exact (symmetrical) orientation, because of the slight curvature, it is difficult in practice to obtain streaks of uniform intensity. Consequently, in order to investigate in detail possible modulations of intensity along a streak, it is necessary to tilt the gun so as to translate the streak along the reflecting sphere.

Necessary additional information can generally be obtained by tilting the foil and by examining the bright and dark field images. Also, by tilting to obtain only one strong reflection, one can eliminate, for example, possible complications in both the image and the diffraction pattern that can arise from multiple diffraction. Frequently, it is known beforehand whether effects predominantly due to platelets or due to stacking faults are to be expected. This applies to the examples which follow.

4. EXAMPLES OF SPOT PATTERNS FROM THIN PLATELETS

If the platelets are perpendicular to the foil surfaces, the streaks will lie in the plane of the diffraction pattern when the foil is in exact orientation (s negative, Fig. 1b). Figure 8 shows the diffraction pattern for a specimen from an Al-4% Cu age hardening alloy containing GP (1) zones on {100} [14]. The foil is in exact [011] orientation so that only the 200 streaks are visible. In the [100] orientation the 020 and 002 streaks can be made to appear. Figure 9 illustrates this, though the foil is not exactly in [001]; hence, the streaks are not continuous throughout the entire pattern. However, streaks are actually continuous from one spot to the next, suggesting that the platelets or zones may be only one or two atoms thick. Such diffraction patterns can indicate the presence of GP

zones that are not readily resolved in the image [14]. At intermediate orientations, spots or short streaks will be obtained corresponding to the intersection of the reflecting plane with the relrods (streaks). As the foil is tilted, these spots will move continuously to new positions, unlike the discontinuous appearance and disappearance of spots from unfaulted structures so that tilting experiments can be used to identify possible streaks. As the precipitates grow, they thicken, and the streaks in the diffraction pattern shorten. Eventually, the streaks become discrete reflections at positions given by the structure factor for the new phase. If n orientations of precipitates are present, then there will be n spot patterns in addition to the matrix pattern.

The diffraction pattern in Fig. 10 shows several interesting features. It was obtained from an Al-20% Ag alloy aged to produce thin platelets of the hexagonal γ' phase on {111} [14,15]. The orientation of the foil is [112] tilting toward [334]. The streaks in this pattern are not very long and stop short of the FCC spots. Although the length of the streaks may be somewhat abridged due to the non-exact orientation of the crystal, their main shortening is unquestionably due to the thickening of the platelet. This has had the further effect of defining the hexagonal structure of the platelets sufficiently to show that the streaks originated from the positions corresponding to the new structure. This would not be so apparent if the lattice constants of the new structure were such as to make its spots superimpose on the matrix spots, as e.g. in faulted structures where c/a is ideal.

5. EXAMPLES OF SPOT PATTERNS FROM FAULTED FCC-HCP STRUCTURES

Several examples of spot patterns and Kikuchi patterns from faulted

FCC-HCP structures were analyzed in a recent paper by Otte et al. [8]. One of the aims of that paper was to evaluate the accuracy with which the orientation of the crystal could be determined from the patterns. For that purpose two cases were distinguished. Case I, in which the pattern was produced by the intersection of the reflecting "plane" with the relrods due to stacking faults, and Case II, where the intersection was with relrods due to the thinness of the foil. All patterns were generally indexed as FCC even though some actually were HCP. It was shown that all patterns could be conveniently analyzed by considering them as representing the projections of "tilted" (111) planes. It was pointed out that interpretations could equally well have been made in terms of tilted (110), say, though the corresponding analysis would generally have been more complicated.

The accuracy of the orientation determinable from situations representing Case I were regarded to be generally higher than those of Case II, provided the angle of "tilt", θ, was large (>10°). The main source of error arose from the inaccuracies in placing a straight line along the principal directions in the diffraction pattern. These inaccuracies were attributable to (i) the large size, in general, of the diffraction spots, (ii) the distortion of the spot pattern by the electron optics of the microscope and (iii) the distortion of the spot pattern due to the geometrical aspects of diffraction when not in the exact foil orientation (Figure 1b). For the cases analysed [8], the accuracy of the determination of the angle between the principal directions was reported as being ±1/4°, corresponding to an error in θ of ± 6.2°. This must be regarded as a rather optimistic value, so that the good agreement with the orientations determined from Kikuchi patterns, as reported for some of the cases treated in [8]

may be fortuitous. In particular this may apply to Fig. 6c of [8], a drawing of which is reproduced in Fig. 11. It is likely that the reported values of β and γ are in error by more than $\pm 1/4°$, since the pattern is only 1.4° off exact $[1\bar{2}13]_{HCP} \equiv [\bar{1}\ 4\ \bar{7}]_{FCC}$ orientation as determined from the Kikuchi pattern [8] so that β and γ should be almost exactly equal to β_o and γ_o (Fig. 11). Inspection of the actual photograph shows that the errors could indeed be larger than estimated and that this illustration is actually an example of Case II, particularly as the pattern shows no doubling of spots and is from a HCP structure. This example again emphasizes the dangers in attempting to make accurate measurements on spot patterns.

6. ON THE ACCURACY OF AN ORIENTATION DETERMINATION USING KIKUCHI PATTERNS

As was shown in reference 8, the accuracy of an orientation obtained from an electron diffraction pattern is, in general, relatively low, i.e. a direction can at best be determined to within a cone of semi-angle 1/2°. The accuracy that can be obtained from a Kikuchi pattern is at least a factor of two or better. If a tilting stage is available in the electron microscope, it may be possible to establish an orientation with an accuracy that is better still, depending primarily on the sensitivity of the tilting stage. If necessary, the tilting stage can be calibrated [9] by measuring the displacement of Kikuchi lines when the sample is tilted through a small angle. However, a tilting stage may often not be in operation, especially if the sample is being deformed and/or heat treated in the microscope. An orientation from the diffraction or Kikuchi pattern may, nevertheless, still be desired; every effort should then be made to obtain a Kikuchi pattern, clearly because of its greater accuracy.

The method of determining the orientation from the Kikuchi pattern has been discussed in the earlier papers [8,9] and an exact formula was given for the normal to the photograph in terms of measurements on it [8]. The formula given, and equivalent forms of it [16], are simple to use, but the computations are tedious if not performed on an electronic computer. Because of the nature of the problem, no useful shortcuts or simplifications of such formulae are possible.

Obtaining a unique foil orientation from a pattern containing only one Kikuchi pole can sometimes be done provided the correct indexing of the spots is made. Due to the ambiguity in choice of plus or minus diffraction vectors, it can be determined that the indexing is correct, either if a second Kikuchi pole is available, or if the sense of slope of a particular plane can be determined, e.g. by taking dark field images of fault or slip traces [17,18]. In general, the second pole is indispensable to the orientation solution if only one diffraction pattern is available and there are no known traces in the images. Once the correct indexing is obtained the exact orientation can be solved using equation 15 of reference 8 for just one Kikuchi pole, the correct answer of the two possibilities will frequently be obvious from the vector character of the solution. It should be emphasized that most attempts at shortcuts or simplifications result in formulae with accuracy that is difficult to assess, except for special values or that produces vectors which should be, but are not, exactly unity. The only useful alternative (though of lower accuracy) to the analytical approach is the graphical method, employing a stereographic net. This has two serious limitations: (1) the accuracy of the net is not the same in all regions, and (2) the accuracy is limited by the pencil line thickness and the

relative positions of the vectors, represented by points on the net, involved in the manipulation.

SUMMARY

A planar defect such as a fault or a thin platelet of second phase gives rise to streaks or extra spots in its electron diffraction pattern depending on the orientation of the crystal with respect to the defect and the beam. These patterns can be interpreted in terms of the super-position of a streaked reciprocal lattice, due to the defect, on the matrix reciprocal lattice. The streaks will be normal to the plane of the thin defect. As the latter thickens and the structure becomes well defined in three dimensions the corresponding reciprocal lattice will assume the spot pattern appropriate to the new structure, and will be different from, but usually oriented with, the matrix pattern. Examples have been given for stacking faults, zones and thin precipitates. The complete interpretation of many spot patterns requires frequently an accurate orientation determination. It is recommended that for the highest accuracy in foil orientation determination, an analytical solution of two Kikuchi poles (minimum) be carried out.

ACKNOWLEDGMENTS

This work was supported in part by the Office of the Naval Research (H.M.O.), and by the United States Atomic Energy Commission through the Inorganic Materials Research Division, Lawrence Radiation Laboratory, University of California, Berkeley, California (W.B. and G.T.).

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FIGURE CAPTIONS

Figure 1. Scheme showing relationship between a) two beam exact Bragg reflection (+g, s = 0) condition and b) exact or symmetrical foil orientation (+ an -g, s < 0). Notice that in (b) the Kikuchi lines move to the left for a clockwise tilt. In the symmetrical case they are situated half-way between +g and -g, i.e. the centers of symmetry of spot and Kikuchi patterns coincide. If the foil is very thin the relrods from the second layer may cut the sphere (e.g. at A), giving rise to extra reflections.

Figure 2. (a) Diffraction pattern from thick region in (c).

(b) Diffraction pattern from thin edge within first extinction distance in (c). Notice extra spots and due to large condenser aperture the area illuminated is revealed by the shape of the spots. In (a), the extra reflections present in (b) have disappeared.

(c) Edge of silicon foil.

Figure 3. Exact foil orientation [0001] for a mica foil. The relrods are sufficiently long to give many orders of reflection.

Figure 4. (a) Silicon foil in [110] showing connected stacking faults on three intersecting planes.

(b) Diffraction pattern from the edge-on fault in the thin region A of Fig. 4a; notice streaks in [111]. Since the foil is not in precise [110], the streaks are not continuous throughout the entire pattern.

(c) Diffraction pattern from the 35° fault shown in Fig. 4a after tilting into [33$\bar{1}$] orientation. Notice doubling (arrowed in enlarged pattern). See text for discussion.

Figure 5. (a) Calculated diffraction pattern for heavily faulted FCC crystal in [$\bar{1}$01] orientation, with fault plane (111). The intensities redistribute from FCC (circles) to HCP (triangles) or to twin (crosses) positions, as the fault density increases.

(b) Electron diffraction pattern from the structure shown in Fig. 5c. Orientation about 2.5° off exact [101], fault plane (111). Streaks lie parallel to <111>; compare to Fig. 4b. The streaks due to faults appear to maximize at HCP positions; there is no measurable shift of the FCC spots. Compare to circles and triangles in Fig. 5a, which is drawn in the same orientation.

(c) Electron micrograph of Cu-8% Al alloy (FCC solid solution) tensile deformed 20% showing a high fault density on (111) planes parallel to electron beam.

Figure 6 (a) Diffraction pattern from heavily faulted FCC cobalt. Orientation tilted off [110] about the [112] axis. The extra spots are streaked in projected <111> and maximize at HCP positions. There is no measurable shift in position of FCC relpoints.

(b) Diffraction pattern of martensite in quenched Cu-12% Al showing streaks and extra spots due to transformation faulting. Notice that the streaks do not appear through

the centers of the matrix spots, due to a change in spacing of the planes with normals perpendicular to the streaks.

Figure 7. Scheme showing effect of relrods due to foil thickness and due to faults one or two planes thick on {111} in FCC crystals for three low index orientations. (a) section through reciprocal lattice (b) diffraction patterns for exact (symmetrical) orientation (c) diffraction pattern for tilted foil - notice extra spots. The relrods only coincide with FCC spots when c/a for matrix and faulted regions are the same.

Figure 8. Streaks along [200] due to GP zones in Al-4% Cu aged 12 hrs. at 190°C. Orientation almost exactly [110].

Figure 9. Same as Fig. 8, but foil is close to [001] showing appearance of [200] and [020] streaks.

Figure 10. Al-20% Ag aged to form HCP γ' plates on {111}. The streaks emanate from the HCP relpoints and do not coincide with FCC spots because of the difference in c/a; orientation [112] tilted towards [334]. There is no measurable shift of the FCC reflections.

Figure 11. Drawing of the diffraction pattern of Fig. 6c in Reference [8]. The direction $D = [\bar{1}101]_{HCP} \equiv [\bar{7}75]_{FCC}$, $E = [\bar{1}010]_{HCP} \equiv [121]_{FCC}$ and $F = [0\bar{1}1\bar{1}]_{HCP} \equiv [11\,1\,\bar{1}]_{FCC}$; the normal to the paper is $[1\bar{2}13] \equiv [\bar{1}4\bar{7}]$. $\beta_o = D\hat{}E = 63.79°$, $\gamma_o = D\hat{}F$ $2\beta_o = 127.58°$. β and γ are the actual angles measured on the photograph, and were given as 62.10° and 128.07° respectively in Reference [8].

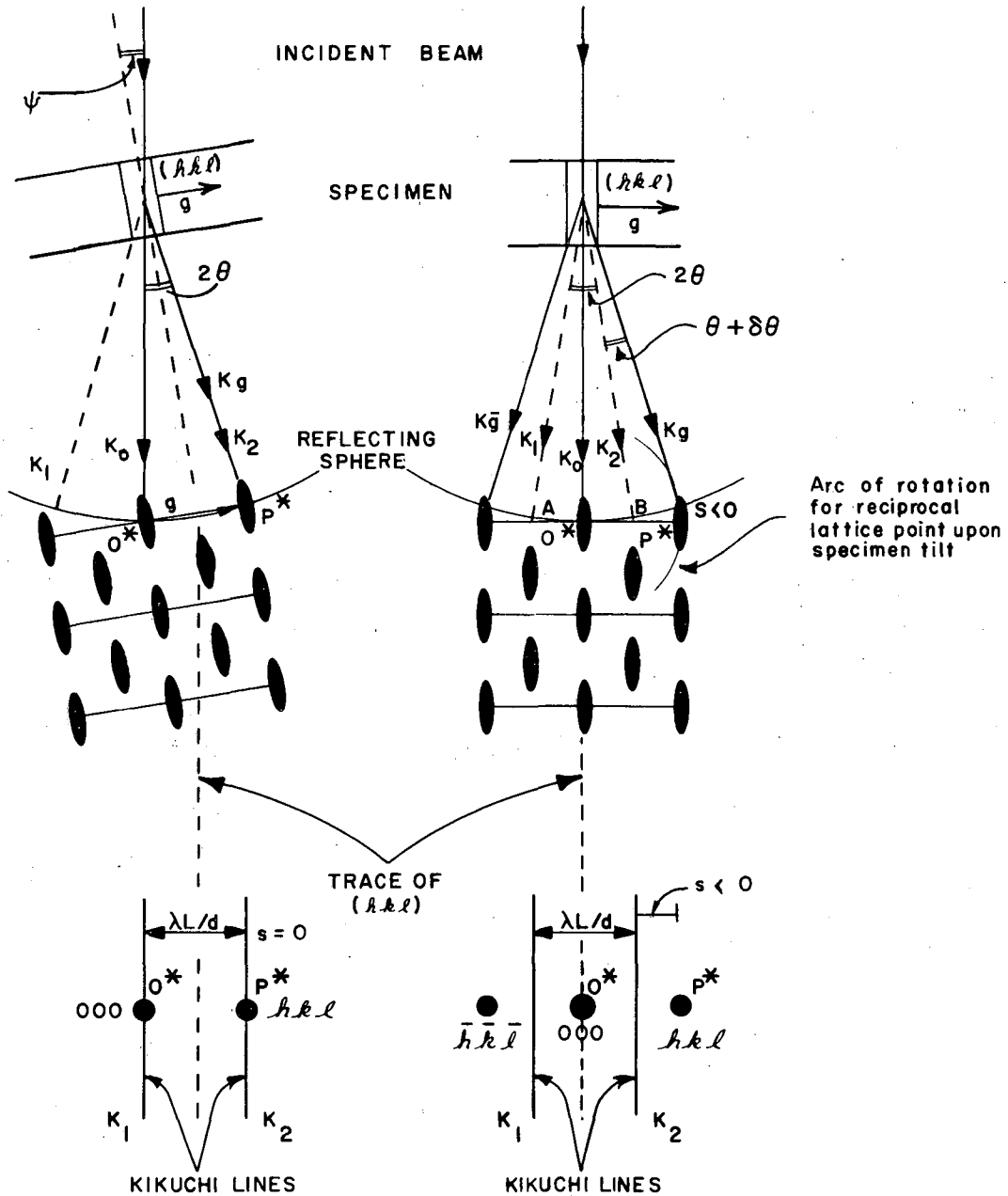

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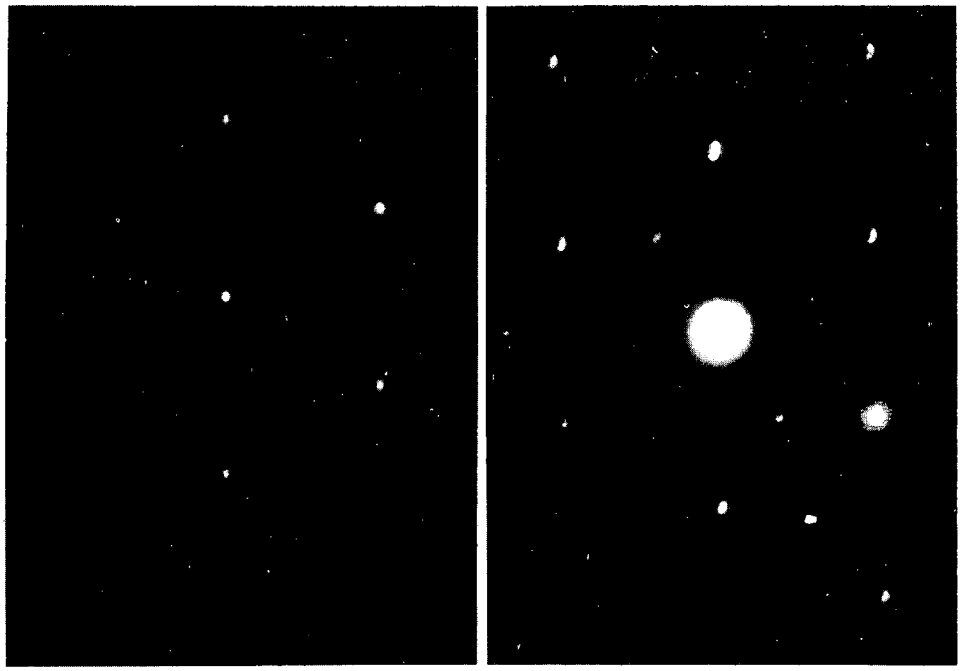
Fig. 1



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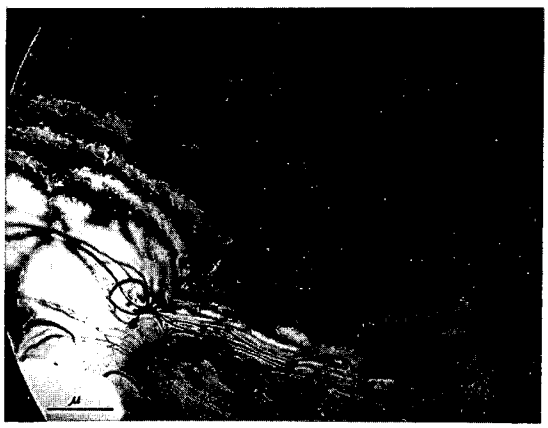

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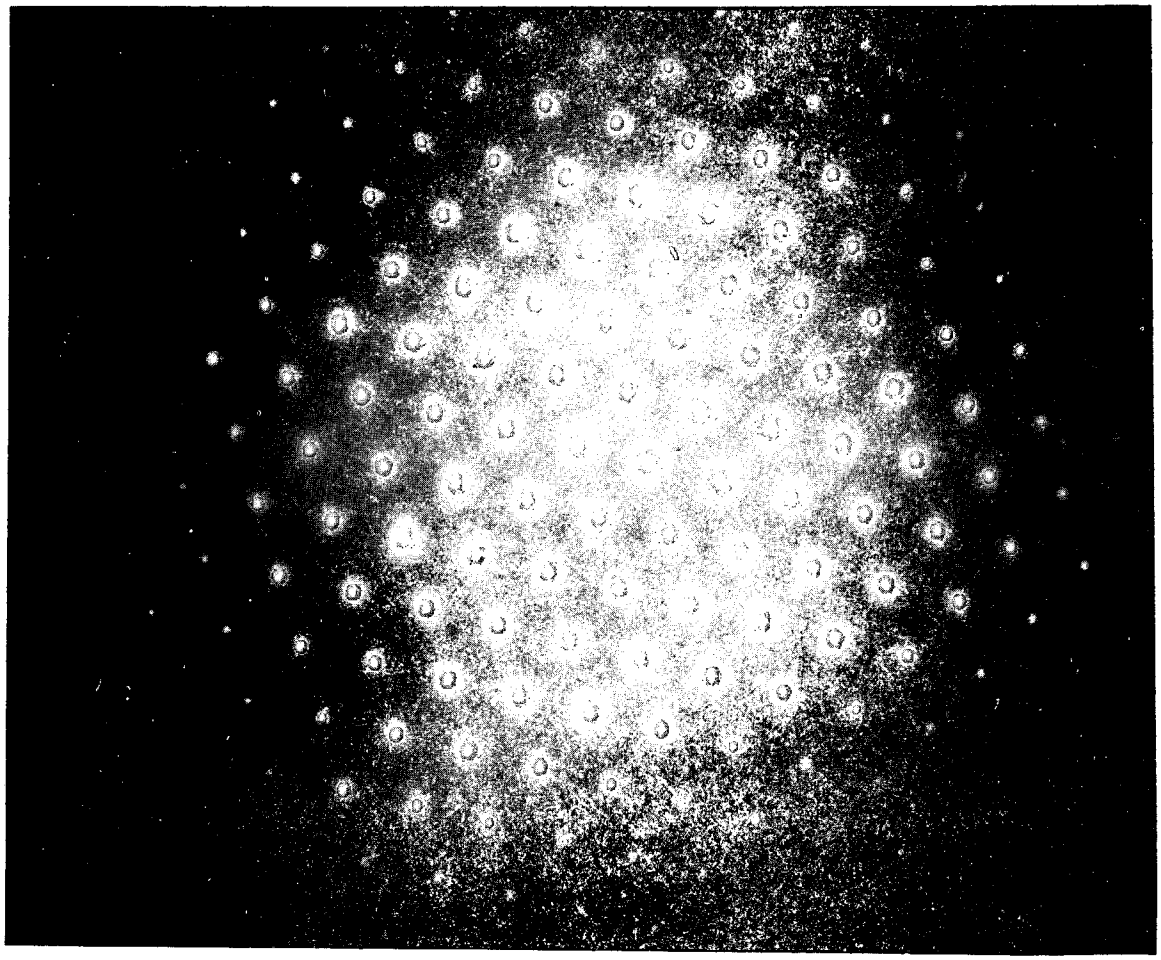
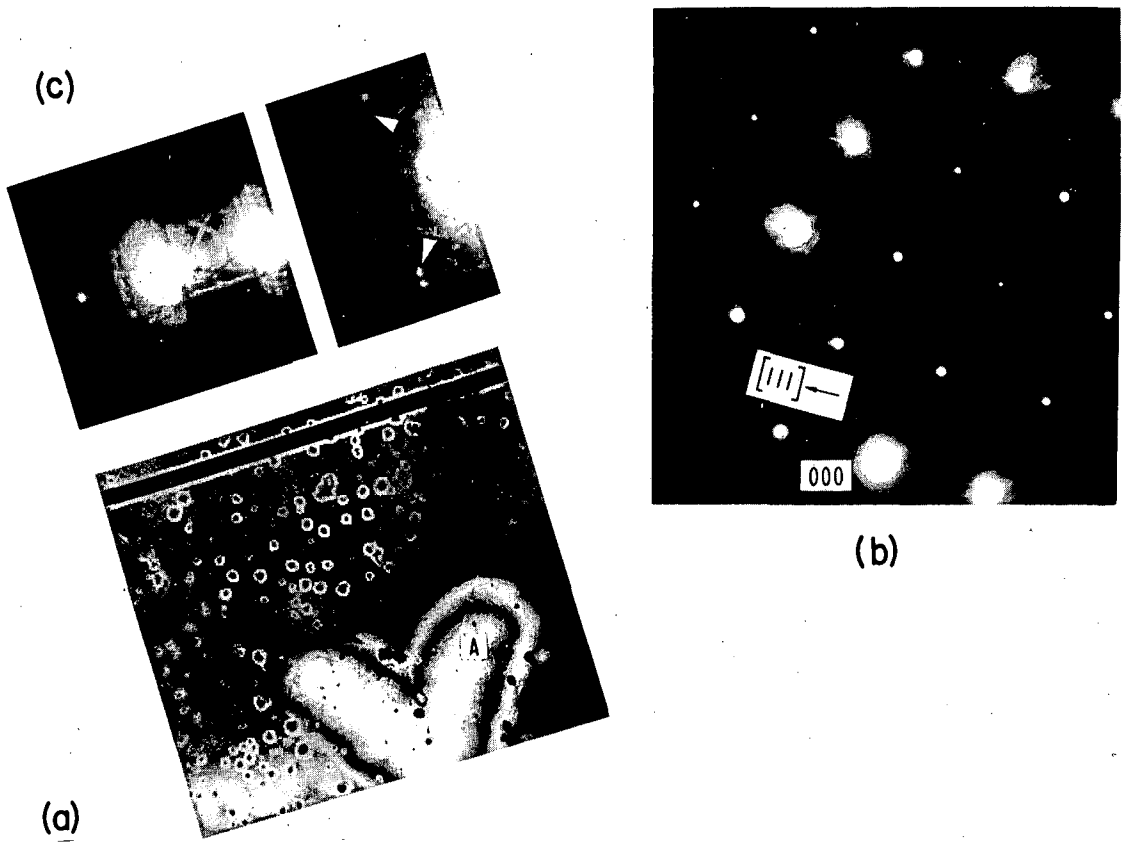
ZN-4691

Fig. 2



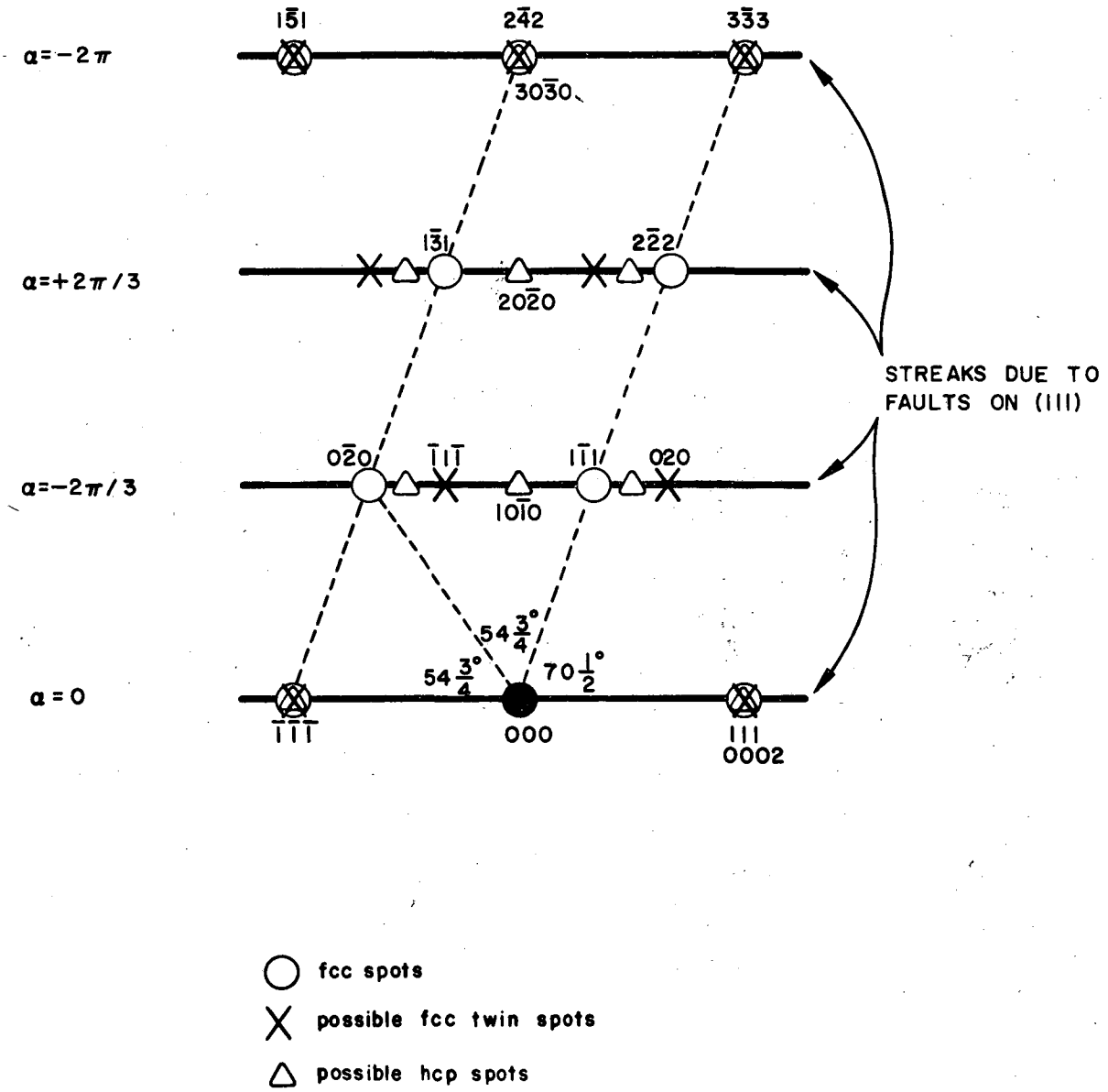
ZN-4749

Fig. 3



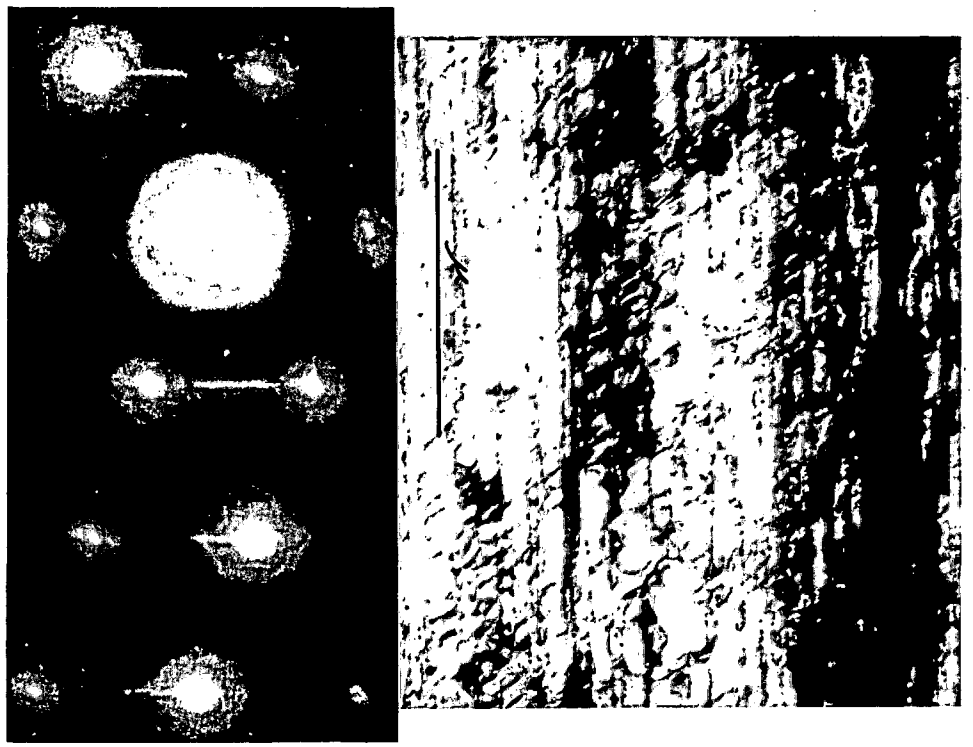
ZN-5255

Fig. 4



MUB-8568

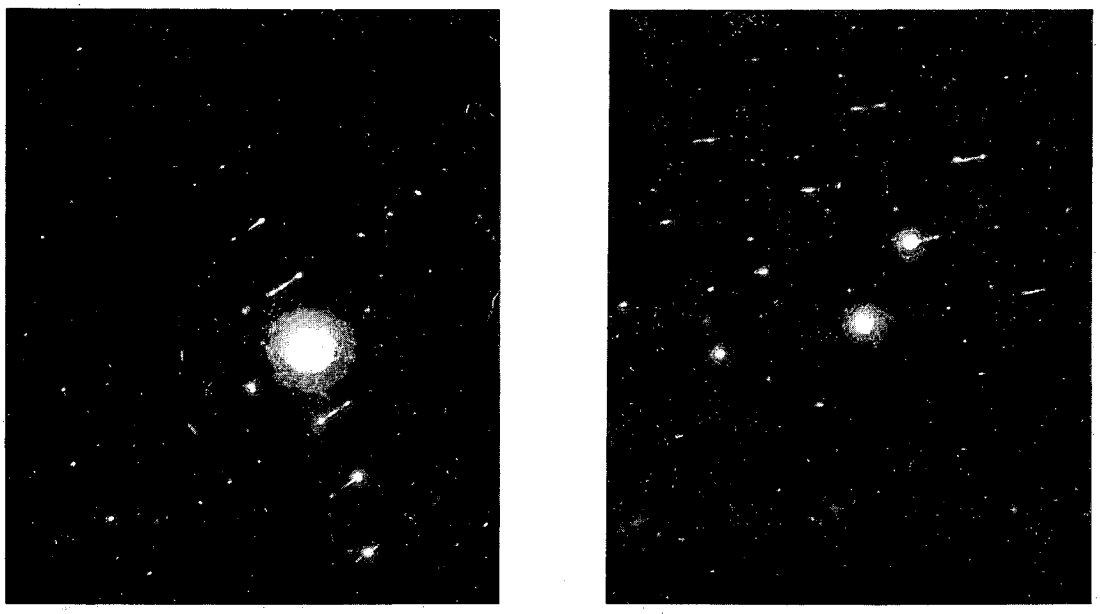
Fig. 5a



(b) (c)

ZN-5256

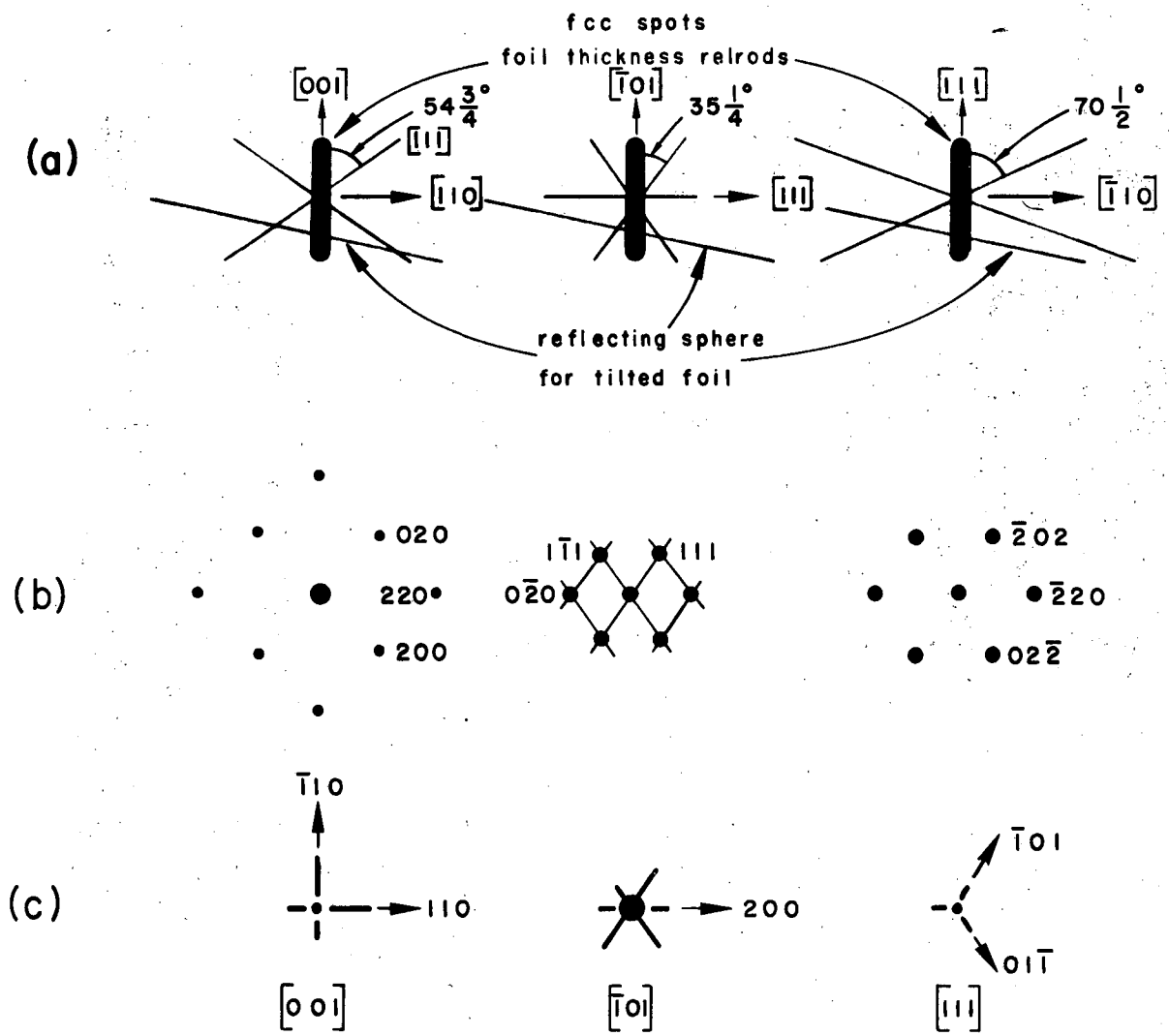
Fig. 5b ç



(A) (B)

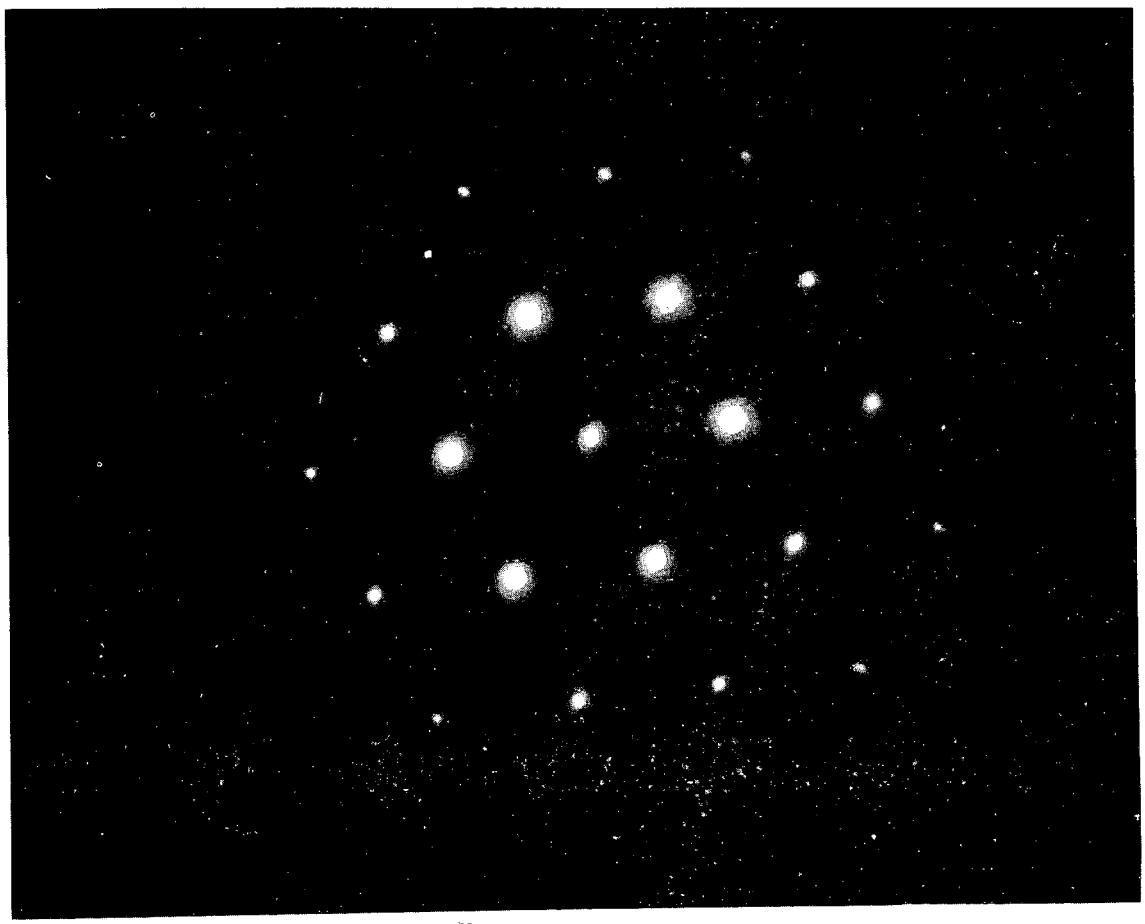
ZN-5262

Fig. 6



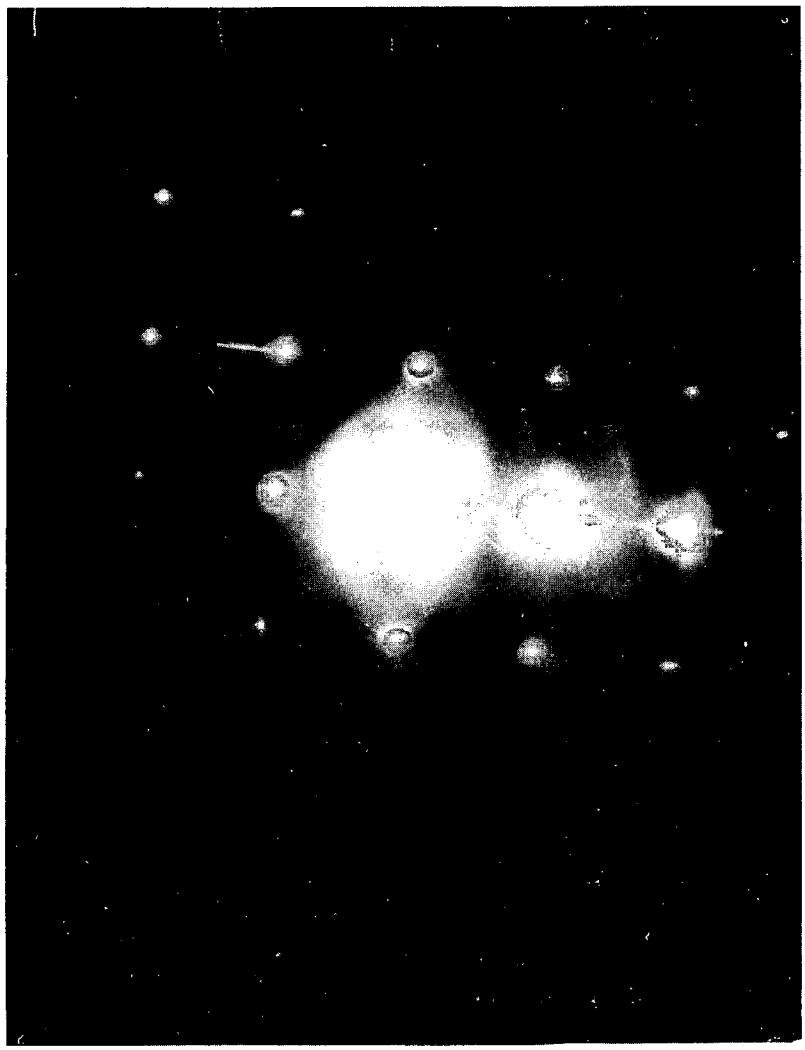
MUB-8569

Fig. 7



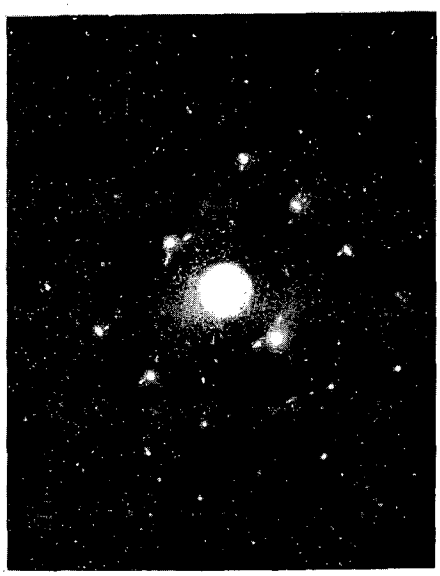
ZN-5263

Fig. 8

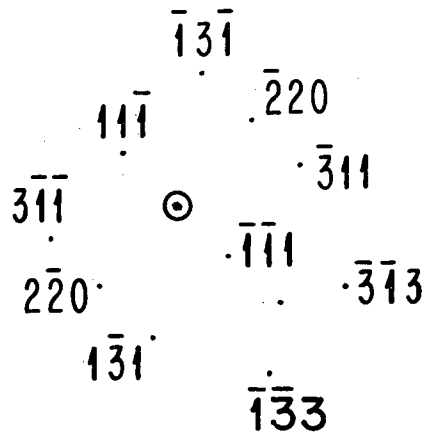


ZN-5257

Fig. 9



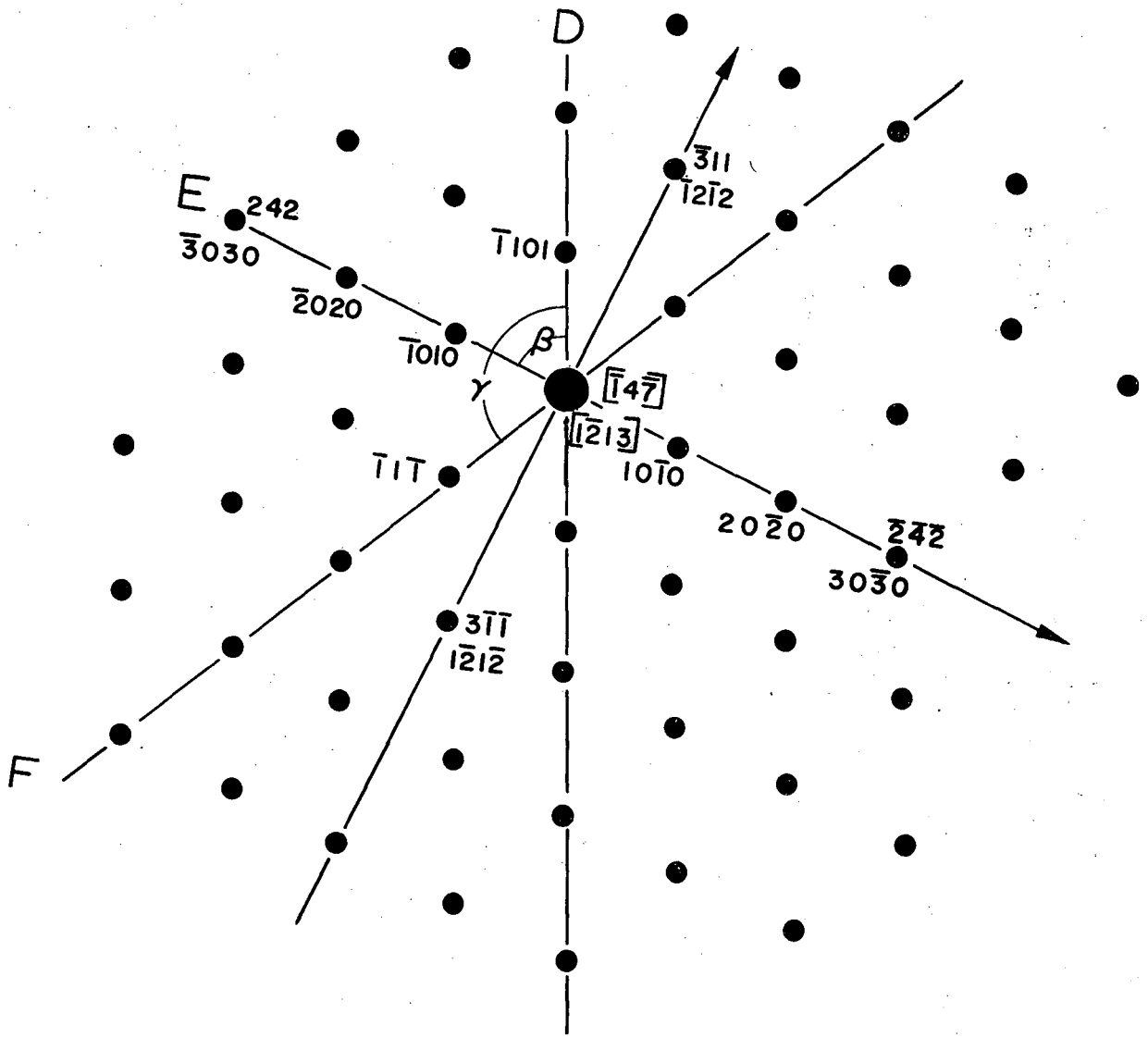
(a)



(b)

ZN-4686

Fig. 10



MUB-8570

Fig. 11

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