MINERALOGICAL MAGAZINE

JOURNAL OF THE MINERALOGICAL SOCIETY

Vol. 33 March 1964 No. 264

# *A new incident illuminator for polarizing microscopes*

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[Communicated by Dr. A. F. Hallimond; taken as read 28 March 1963]

*Summary.* The customary illumination by a 'coverglass' inclined at 45 degrees is replaced by a double reflection. The beam from the horizontal collimating tube is first reflected from a highly reflecting mirror at the back of the unit, then downward from a coverglass placed at the top of the unit. With this arrangement the coverglass is inclined at less than $22\frac{1}{2}$ degrees to the axis of the microscope, with a similar reduction of the angle of incidence. The correction ratio for rotation by upward passage of light through the coverglass is now reduced from 6:5 to the almost negligible value 21:20. There is a corresponding improvement in the homogeneity of extinction over the microscope field.

WHEN incident illuminators of the conventional thin-glass type are used for the microscopical examination of specularly reflecting objects with polarized light the homogeneity of polarization is impaired. This familiar effect results from rotation of the vibration directions of rays whose planes of incidence at the thin-glass reflector are not orthogonally related to the incident vibration direction of the illuminating beam. The two mutually perpendicular plane-polarized components arising from this condition have different amplitudes by virtue of partial polarization by reflection in the illuminator and their resultant is, therefore, inclined to the original vibration direction.

Conventional coverglass illuminators having only a collimating lens in the side-tube fail to give homogeneous polarization over the back of the objective. Rays from a point in the field iris are focused on a point in the object but, especially with short-tube microscopes, they are not parallel at the coverglass, since the object is not at the principal focus of the objective (being conjugate with the focal plane of the eyepiece). This condition was partially remedied by inserting collimating lenses below and above the reflector, so that the rays were strictly parallel in the region of the coverglass (compare the collimating lenses on a Nicol analyser);[1] these lenses collimated also the rays returning from the object to the eyepiece. Thus they provided homogeneity of aperture, but unfortunately there still remained the field effect due to inclined incidence on the coverglass of rays from the sides of the field, and extinction was therefore confined to a dark band across the centre of the field.[2] Even with a coated thin-glass reflector there are rotations as great as 0·5° at the sides of the field.

In the form of thin-glass incident illuminator here described the degree of polarization associated with conventional illuminators of this type is greatly reduced by changing the angle of incidence on the thin-glass reflector from 45° to 22·5° or less. As is shown in fig. 1, this reduction is achieved by the introduction of a first surface mirror, *M*, which reflects the horizontal illuminating beam on to the thin-glass reflector, *G*, whose normal is inclined at about 22·5° to the optical axis of the microscope objective lens, *O*. Whatever the angle of inclination of the thin glass, *G*, it must make an angle of 45° with the mirror *M*, for the usual case where the illuminating and emerging beams are mutually perpendicular. *M* and *G* are, in fact, geometrically equivalent to the two adjacent reflecting faces of a pentagonal prism.

In a practical realization of this arrangement *M* is a first-surface mirror consisting of an opaque layer of aluminium on a glass plate, and *G* is a glass plate whose lower and upper surfaces are coated with quarter-wave layers of sputtered bismuth oxide and of evaporated magnesium fluoride respectively.

The degree of polarization of the illuminator for the axial principal ray will be obtained by calculating $T$, the effective transmission of the illuminator as a whole, for the two plane-polarized components, $s$ and $p$, that vibrate in directions respectively perpendicular and parallel to the plane of incidence on the reflecting surfaces. These calculations will yield two transmission coefficients, $T_s$ and $T_p$, from which the degree of polarization can be obtained from the formula quoted by Heavens:[3] $P = (T_p - T_s)/(T_p + T_s)$.

From the sequence of reflections and transmissions it is easily seen that for an isotropic object with $R = 100\ \%$, $T = R_m R_g\,(1 - R_g)$, where $R_m$ and $R_g$ are the intensity reflection coefficients of *M* and *G* respectively. The bracketed term expresses the single upward transmission through *G*

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[1] A. F. Hallimond and E. W. Taylor, Min. Mag., 1953, vol. 30, p. 49.

[2] A. F. Hallimond, Manual of the polarizing microscope, 2nd edn, 1956, p. 99.

[3] O. S. Heavens, Optical properties of thin solid films, 1955, p. 240.

and the absorption is considered negligible. The contribution of multiple internal reflections will be regarded as too small to be significant when calculating $R_g$.

The procedure for the calculation may be followed from the diagrammatic section through the thin-glass, $G$, shown in fig. 2. The numerals 1, 2, 3, and 4 refer respectively to the interfaces between air and bismuth oxide, bismuth oxide and glass, glass and magnesium fluoride, and magnesium fluoride and air. The amplitude reflection coefficients of these four interfaces are obtained from the Fresnel reflection formulae:

$$r_s = \sin(\theta_l - \theta_{l+1})/\sin(\theta_l + \theta_{l+1}), \qquad r_p = \tan(\theta_l - \theta_{l+1})/\tan(\theta_l + \theta_{l+1}),$$

where $\theta_l$ and $\theta_{l+1}$ are the angles of incidence and refraction respectively at the interface between successive layers $l$ and $l+1$.

Holland[1] quotes the refractive index of sputtered bismuth oxide as 2·45. A characteristic value for glass is 1·52, while the most frequently quoted value for evaporated magnesium fluoride is 1·38. Assuming an initial angle of incidence in air $\theta_1$ 22·5° and these refractive indices one obtains the following amplitude reflection coefficients: $r_{1,s}$ 0·447, $r_{2,s}$ 0·244, $r_{3,s}$ 0·052, $r_{4,s}$ 0·179; and for the $p$-component: $r_{1,p}$ 0·392, $r_{2,p}$ 0·224, $r_{3,p}$ 0·045, $r_{4,p}$ 0·140. The amplitude reflection coefficient, $A_1$, for the two surfaces 1, 2 on the bismuth-oxide coated side of $G$ will be (neglecting multiple reflections): $A_1 = r_1 + r_2(1-r_1)^2$, where the reflected beams are to be added since the thickness of the coating is adjusted to give reinforcement of the beams. The corresponding expression for the magnesium-fluoride-coated side of $G$ is: $A_2 = r_4(1-r_3)^2 - r_3$, the negative sign being due to the adjustment of the coating to give destructive interference.

Substituting the values of the reflection coefficients, found above: $A_{1,s} = 0{\cdot}522$, $A_{1,p} = 0{\cdot}475$, $A_{2,s} = 0{\cdot}109$, and $A_{2,p} = 0{\cdot}084$. Under all practical conditions $A_1$ will be incoherent with $A_2$ owing to the relatively large separation of the two coated surfaces. Consequently the expression for the total intensity reflection coefficient for $G$ will be: $R_g = A_1^2 + A_2^2(1-A_1^2)^2$, where the bracketed term represents the intensity transmission coefficient of the bismuth-oxide-coated surface of $G$. Taking the values of $A$ calculated above for the two components $s$ and $p$, one obtains $R_{g,s} = 0{\cdot}278$ and $R_{g,p} = 0{\cdot}230$. These are the reflection coefficients of the inclined coverglass for vibrations respectively perpendicular and parallel to the plane of incidence.

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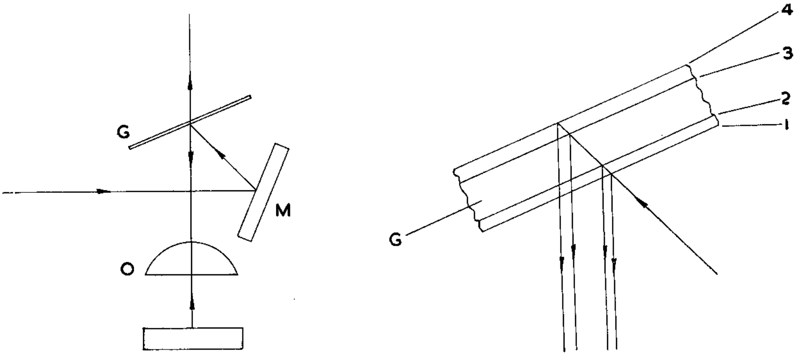
[1] L. Holland, Vacuum deposition of thin films, 1956, p. 512.

It remains to estimate $R_{m,s}$ and $R_{m,p}$, the intensity reflection coefficients of the aluminium mirror, $M$, using the familiar formulae:

$$R_s = \{(n-\cos\theta)^2+n^2k^2\}/\{(n+\cos\theta)^2+n^2k^2\}$$

and $$R_p = \{(n\cos\theta-1)^2+n^2k^2\cos^2\theta\}/\{(n\cos\theta+1)^2+n^2k^2\cos^2\theta\},$$

where $\theta$ is the angle of incidence and $n$, $k$ are respectively the equivalent refractive index and absorption coefficient of the metal. For aluminium Heavens (*loc. cit.*, p. 200) quotes $n$ 0·76 and $k$ 5·32 at a wavelength of 550 m$\mu$. In the present instance $\theta = 22{\cdot}5°$, and substituting for $\theta$, $n$, and $k$ one obtains $R_{m,s}$ 0·854 and $R_{m,p} = 0{\cdot}840$.



FIGS. 1 and 2: FIG. 1 (left). Diagrammatic cross-section of the new incident illuminator. FIG. 2 (right). Diagrammatic section of a coated thin-glass reflector.

Substitution of the values of $R_{g,s}$ and $R_{m,s}$ in the expression for $T$ yields $T_s = 0{\cdot}172$, and similarly $T_p = 0{\cdot}149$. The degree of polarization can now be calculated, and is found to be $\mathbf{P} = \mathbf{0{\cdot}072}$.

The effective light transmission of the whole illuminator with the analyser crossed can now be calculated on the assumption that the beam incident on the mirror, $M$, vibrates in the $s$-direction and that the upward beam that would be transmitted by the analyser vibrates in the $p$-direction. For this condition the effective transmission

$$T_o = R_{m,s}\, R_{g,s}(1-R_{g,p})$$

is, using the above values of $R$, $\mathbf{T_o} = \mathbf{0{\cdot}183}$.

The corresponding performance parameters for the conventional 45° thin-glass reflector can be calculated using the same general procedure, except that the omission of the mirror simplifies the expression for the component transmission to: $T = R_g\,(1-R_g)$.

Assuming that the coatings on the thin-glass reflector are equivalent to those stipulated for the new illuminator, but with the values required for incidence at 45°, $R_{g,s} = 0{\cdot}371$ and $R_{g,p} = 0{\cdot}160$, leading to $T_s = 0{\cdot}233$ and $T_p = 0{\cdot}134$. With these transmission coefficients the degree of polarization is $\mathbf{P = 0{\cdot}27}$. And to obtain the effective light-transmission $T_o$ with the analyser crossed $T_o = R_{g,s}(1-R_{g,p})$, which with the above values of $R_{g,s}$ and $R_{g,p}$ (at 45° incidence) gives $\mathbf{T_o = 0{\cdot}312}$.

An incident illuminator based on the system here described has been made and found greatly to reduce the extinction gradient in the orthoscopic field. Further, the collimating system in the vicinity of the thin-glass reflector is no longer necessary.

*Acknowledgements.* The writer gratefully acknowledges much friendly encouragement from Dr. A. F. Hallimond and permission to publish this communication, granted by courtesy of the Directors of Vickers Instruments Ltd.