2. The synthesis of an optimum system to search an image and best determine the presence or absence of a particular configuration.
3. The reproduction of a picture with optimum discrimination in favor of a configuration sought, and against background "noise."
4. The equalization of a picture, as, for example, to remove blur due to object motion, or to remove aberrations of an image-forming lens.

These problems will be treated in later papers in this series.

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The Infrared Properties of Gold Smoke Deposits*

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An interpretation of the infrared optical properties of gold smoke deposits is presented together with new experimental results. This interpretation is based on an application of classical electromagnetic theory. The gold smoke deposits are assumed to interact with infrared radiation as if they were sheets of an essentially uniform material which is characterized by an average electrical conductivity small compared to that of ordinary metals. The electrical conductivity of gold black deposits is found to be $\sim 10^{-5}$ times that of bulk gold, and the volume percent of gold in a gold black deposit is found to be ~ 0.2 percent.

INTRODUCTION

GOLD smoke deposits are very porous structures of colloidal gold particles. They are prepared by evaporating gold in an inert atmosphere, such as nitrogen, at a pressure of about 2–3 mm of mercury. The evaporated gold atoms condense to form particles about 100A in diameter; these particles adhere to one another to form chains and aggregates which deposit on any cool, solid surface. Figure 1, taken from a previous publication,[1] is an electron microscope photograph of a gold smoke deposit weighing about 15×10^{-6} g/cm^2; it shows the grouping of the individual particles into chains and aggregates.

Gold smoke deposits may be divided into two distinct classes: gold black deposits and gold smoke filters. The two types of deposits are similar in their physical structure, both in particle size and in degree of aggregation of those particles. Both types absorb strongly and manifest very small reflectance in the visible and near infrared regions; however, they are quite different in their absorption characteristics at longer wavelengths. Gold black deposits, even in thin layers, absorb a considerable fraction of the incident infrared radiation, and their absorption is practically independent of wavelength, at least to 15μ. Gold smoke filters absorb very little beyond about 2 or 3μ.[2]

Gold smoke filters are obtained when gold is evaporated from a tungsten filament in a nitrogen atmosphere containing about one percent or more oxygen. Under such conditions, tungsten oxides are formed at the evaporating filament and are deposited along with the gold. Gold black deposits, on the other hand, are obtained when the residual oxygen in the nitrogen atmosphere is first removed; such deposits consist almost entirely of pure gold.

The two types of deposits may be further distinguished by differences in their electrical conductivity. The conductivity of gold smoke filters is lower than that of gold black deposits by a factor of 10^4 to 10^5.

The preparation and optical properties of gold smoke deposits have been described in some detail in a previous publication[2] from this laboratory. New experimental results are presented here which are representative of deposits made under more carefully controlled conditions; the measurements are more extensive and precise than those reported previously.

A detailed treatment of the optical properties of gold smoke deposits by the quantum theory is impractical. The electrical conductance of the deposits suggests a treatment in terms of "free" and "bound" electrons. Gold smoke filters contain comparatively few "free" electrons and are thus nearly transparent to radiation of wavelength greater than 3μ. Gold black deposits contain much larger concentrations of "free" electrons and are therefore good absorbers of infrared radiation. A sufficiently good approximation of the infrared optical properties of these deposits may be obtained in terms of classical electromagnetic theory at sufficiently long wavelengths. The data are fitted here for wavelengths as short as 7μ.

The classical treatment here is not based on the Mie

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† Presented in partial fulfillment of the requirements for the degree of Ph.D. in the Department of Chemistry at the Massachusetts Institute of Technology.

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[1] Harris, Jeffries, and Siegel, J. Appl. Phys. 19, 791 (1948).

[2] Harris, McGinnies, and Siegel, J. Opt. Soc. Am. 38, 582 (1948).

theory of scattering from small particles.[3] The Mie theory is applicable only to completely independent particles; the particles of a gold smoke deposit which actually touch one another and can conduct an electric current cannot be considered to be independent.

THEORETICAL

In the first approximation gold black deposits may be assumed to interact with infrared radiation as if they were sheets of a homogeneous medium having a characteristic electrical conductivity. Then the infrared properties of the deposits may be calculated by using classical electromagnetic theory for a conducting medium. The following development is based primarily on the equations and nomenclature of Stratton.[4]

The electric vector of a plane electromagnetic wave propagated in the "x" direction through a homogeneous medium may be written as follows:

$$\begin{aligned} E &= E_0 \exp[i2\pi\nu t] \exp[i2\pi/\lambda(n+ik)x] \\ &= E_0 \exp[i2\pi\nu t] \exp[i\alpha x] \exp[-\beta x], \end{aligned} \tag{1}$$

where E_0 is the amplitude of the wave at $x=0$, ν is the frequency of the radiation ($\omega=2\pi\nu$), t is the time, and λ the wavelength. The factor $(n+ik)$ may be called the complex index of refraction of the medium. This quantity may be expressed as two parts, the phase factor, $\alpha=(2\pi/\lambda)n$, and the attenuation factor, $\beta=(2\pi/\lambda)k$.

By applying classical electromagnetic theory, Stratton[4] obtains the following expressions for α and β:

$$\alpha=\omega\{(\boldsymbol{\mu}\boldsymbol{\varepsilon}/2)[(1+\eta^2)^{\frac{1}{2}}+1]\}^{\frac{1}{2}} \tag{2}$$

$$\beta=\omega\{(\boldsymbol{\mu}\boldsymbol{\varepsilon}/2)[(1+\eta^2)^{\frac{1}{2}}-1]\}^{\frac{1}{2}}, \tag{3}$$

where $\boldsymbol{\varepsilon}$ is the electric permittivity of the medium and $\boldsymbol{\mu}$ is the magnetic permeability of the medium. $\eta=\sigma/\boldsymbol{\varepsilon}\omega$, where σ is the electrical conductivity of the medium.

The gold smoke deposits are very porous structures consisting primarily of air. Therefore, to a first approximation, the electric permittivity and the magnetic permeability of the deposits may be set equal to those of free space, $\boldsymbol{\varepsilon}_0$ and $\boldsymbol{\mu}_0$. Under these conditions

$$\eta=(376.7/2\pi)\sigma\lambda, \tag{4}$$

where σ is given in $\text{ohm}^{-1}\text{cm}^{-1}$ and the wavelength λ, in cm.

The velocity of light, c, is given by

$$c=[1/(\boldsymbol{\mu}_0\boldsymbol{\varepsilon}_0)^{\frac{1}{2}}]=\nu\lambda=(\omega/2\pi)\lambda. \tag{5}$$

The conductivity of gold smoke deposits is sufficiently small so that $\eta^2\ll1$ for wavelengths less than 15μ. Substitution of Eq. (4) into (2) and (3) and expansion in terms of η^2 gives:

$$\alpha=(2\pi/\lambda)[1+\tfrac{1}{8}\eta^2+\cdots], \tag{6}$$

$$\beta=(2\pi/\lambda)[\tfrac{1}{2}\eta(1-\tfrac{1}{8}\eta^2+\cdots)]. \tag{7}$$

The reflection from gold black deposits is less than one percent of the incident radiation for wavelengths shorter than 15μ. If this small reflection is neglected, then the transmission coefficient (T) of a gold black deposit may be calculated directly from Eq. (1). If the distance between the two surfaces of a gold black deposit is d, and the radiation is normally incident on the surface at $x=0$, then

$$T\cong|E(x=d)/E(x=0)|^2\cong\exp[-2\beta d]. \tag{8}$$

After substituting values from Eqs. (4) and (7),

$$\log_e(1/T)\cong2\beta d\cong376.7\sigma\times d[1-450(\sigma\lambda)^2+\cdots]. \tag{9}$$

To a first approximation, the transmission depends only on the product of the electrical conductivity and the thickness of the deposit and is independent of wavelength. However, Eq. (9) shows that the transmission increases slightly at longer wavelengths.

The reflection coefficient (R) of a very thick gold black deposit (such that T approaches zero) may be calculated from the usual formula for the reflection from a plane separating two different media.[5] If one medium is air or vacuum ($n=1$, $\alpha=2\pi/\lambda$), and the other medium is a gold black deposit, then for normal incidence:

$$R=\frac{(n-1)^2+k^2}{(n+1)^2+k^2}=\frac{[\alpha-(2\pi/\lambda)]^2+\beta^2}{[\alpha+(2\pi/\lambda)]^2+\beta^2}. \tag{10}$$

After substituting values of α and β from (6) and (7) and the value of η from (4):

$$R\cong\eta^2/16 \text{ to the first power of } \eta^2, \tag{11}$$

$$R\cong225\sigma^2\lambda^2. \tag{12}$$

The above equations can be used only for those wavelength regions where $\eta^2\ll1$. Measurements show that the equations are valid for the infrared region, at least out to 15μ. At much longer infrared wavelengths and in the microwave region, the value of η is not small compared to unity and the above expansions are not valid.

EXPERIMENTAL

The gold smoke deposits were prepared in a vacuum system having a volume of about 30 liters and a leak rate of less than 0.003 mm of mercury per hour. A low leak rate is very important in order to exclude oxygen. The gold back deposits were prepared in an atmosphere of dry nitrogen at 3 mm of mercury pressure; the small amount of oxygen in the nitrogen was removed by heating a shielded tungsten filament for two minutes immediately before the gold evaporation. The gold smoke filters were prepared in an atmosphere of 2 mm of nitrogen plus 0.08 mm of air. This atmosphere was renewed for every 45 sec of gold evaporation.

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[3] G. Mie, Ann. Physik 25, 377 (1908).

[4] J. A. Stratton, *Electromagnetic Theory* (McGraw-Hill Book Company, Inc., New York, 1941), pp. 268–278.

[5] Reference 4, p. 512.

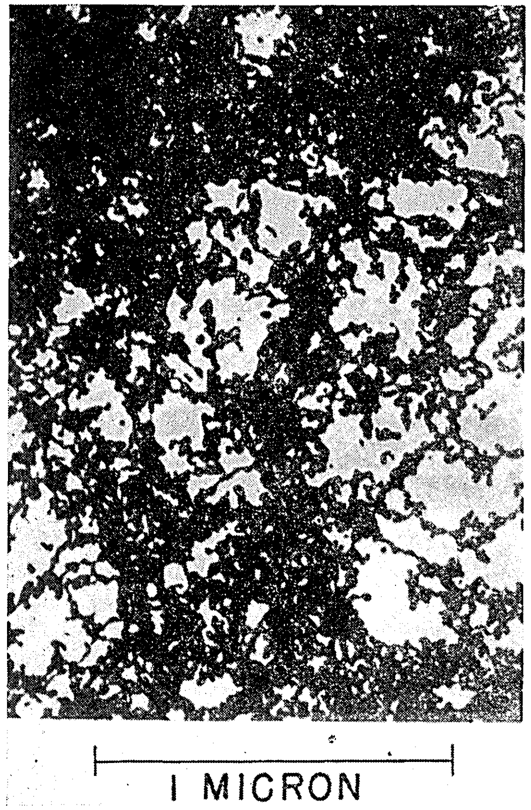

Fig. 1. Electron microscope photograph of a gold black deposit.

The gold used had a purity of 99.99+ percent. About 0.2 g of this gold was melted in a high vacuum on a tungsten filament so that a drop of gold was suspended from the bottom of a V bend in the filament. During the preparation of a deposit, the gold was evaporated by passing a current of 25 amp through the filament which had a diameter of 0.030 in. This resulted in a deposition rate of about 0.5×10^{-6} g/cm²-sec. A metal shield protected the deposit from most of the radiation from the filament. The sample plate to be coated was mounted vertically at a horizontal distance of 3½ in. from the filament with the center of the plate opposite the suspended gold drop.

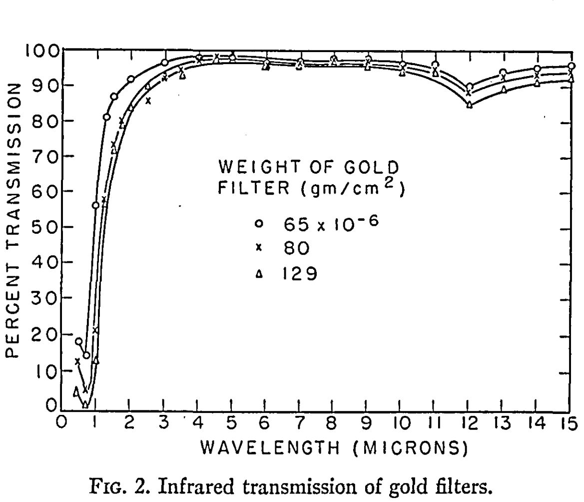

Fig. 2. Infrared transmission of gold filters.

Most of the deposits were made on cellulose nitrate films about 500A thick, which were mounted on a 2 in.×2 in. glass plate having a central circular hole 1⅜ in. in diameter.[6] During deposition of a gold smoke deposit, the glass plate supporting the film was mounted on a special brass holder so that a backing plate protruded through the central hole to within 0.008 in. of the back of the cellulose nitrate film. The function of this backing plate was to keep the film sufficiently cool so that a uniform deposit could be obtained. A few samples of gold black deposits were made on NaCl plates $\frac{1}{16}$ in. thick in order to study the influence of the substrate.

Resistance measurements were made with a Wheatstone bridge. Electrical contact was made through evaporated bright gold electrodes deposited on the sample plate before deposition of the gold smoke deposit.

Before making the final electrical resistance and infrared measurements, the gold black deposits were heated for 24 hours at 69°C, a treatment known as thermal stabilization. The electrical conductance of a freshly prepared deposit may change slowly, even at room temperature. During thermal stabilization, the conductance increases to a constant value and does not change further at room temperature. This process has been described in detail in a previous publication.[7]

Infrared transmission measurements were obtained at specific wavelengths, from 2 to 15μ, with a Perkin-Elmer Model 12-B infrared spectrometer with a precision of about 1 percent for the individual measurements. Reflection measurements were made with the same instrument using a modification similar to that described by Burstein.[8] Transmission measurements were also made in the 0.4 to 2.5μ region with a Leiss quartz monochromator provided with a lead sulfide receiver.

The infrared transmission measurements of deposits on NaCl plates were corrected for the transmission of the substrate to obtain the corrected transmission coefficient (T) of the deposit itself. No correction was necessary for the cellulose nitrate films for wavelengths longer than about 2μ, since the film transmits practically 100 percent. However, a small correction was necessary at wavelengths shorter than 2μ because of losses due to the reflection of the film.

The weight of a deposit was obtained by weighing a known area of the cellulose nitrate film together with the deposit on an Ainsworth microbalance. Correction was made for the previously known weight of the film. The over-all error in the determination of the weight of the deposit was probably less than $\pm2\times10^{-6}$ g/cm². The weight of a gold black deposit on a NaCl plate was

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[6] The preparation of the cellulose nitrate films and the calibration of their weights in terms of optical reflection measurements will be described in a later publication.

[7] Harris, Jeffries, and Siegel, J. Chem. Phys. 18, 261 (1950).

[8] Burstein, Oberly, and Plyler, Proc. Indian Acad. Sci. 28, 388 (1948).

determined from infrared transmission measurements and the transmission-weight curve for gold black deposits on cellulose nitrate. This determination assumes that the transmission of a given mass per unit area is identical for both substrates.

DISCUSSION AND RESULTS

A. The Infrared Transmission and Electrical Conductivity of Gold Smoke Deposits

Figure 2 shows the experimental measurements of the infrared transmission of a series of gold smoke *filters*. These deposits absorb strongly in the visible and near infrared; however, they absorb practically no radiation beyond two or three μ. The absorption band which appears near 12μ is due to the presence of tungsten oxides in the gold smoke filter. Deposits of tungsten oxides prepared in a manner similar to that of gold smoke filters, but without any gold, also show this absorption band. The tungsten oxide content of gold smoke filters is not accurately known, but it is estimated to be about 10 percent of the total weight of the deposit. Except for the absorption bands due to the tungsten oxides, the gold smoke filters are nearly 100 percent transparent for wavelengths greater than 3μ, in agreement with the low electrical conductivity of the deposits. The absorption of the filters for wavelengths shorter than 2μ is ascribed to the "bound" electrons.

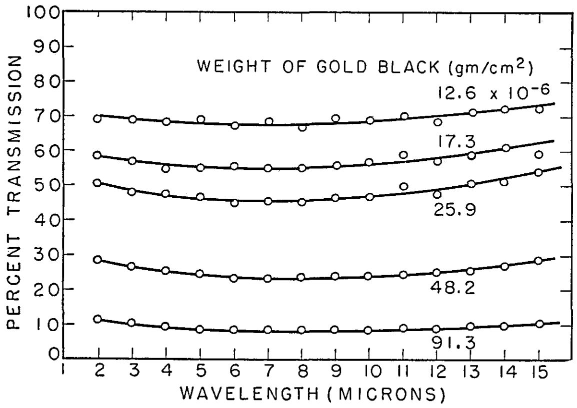


FIG. 3. Infrared transmission of gold blacks.

Figure 3 shows the experimental measurements of the infrared transmission of a series of gold black deposits. These deposits absorb strongly throughout the 2–15μ range as well as in the visible and near infrared regions. The transmission is almost constant with wavelength but increases slightly at longer wavelengths in accordance with Eq. (9). A further analysis of the change of transmission with wavelength will be presented in a later paper.

A more detailed comparison of the data of Fig. 3 with the theoretical Eq. (9) is shown in Fig. 4. The optical density of gold black deposits is plotted as a function of the weight of the deposit and the straight lines were determined by least squares. If it is assumed that the thickness of a deposit is directly proportional to the weight of the deposit, then the straight lines should pass through the origin and with decreasing slope at longer wavelengths, Eq. (9). The precision of the data is not sufficient to show the small decrease in slope with increasing wavelength. The straight lines in Fig. 4 do not pass exactly through the origin. The assumption that the thickness is directly proportional to the weight probably does not hold exactly, especially at small weights. Figure 1 shows an electron microscope photograph of a deposit weighing 15×10^{-6} g/cm²; at this weight the area is not completely covered. Obviously, the "thickness" to be used in Eq. (9) must be some kind of average, and this average thickness may not be exactly proportional to the weight of the deposit. Except for these small deviations, Eq. (9) is a good fit of the infrared transmission of gold black deposits, if the value of the conductivity at infrared frequencies is used.

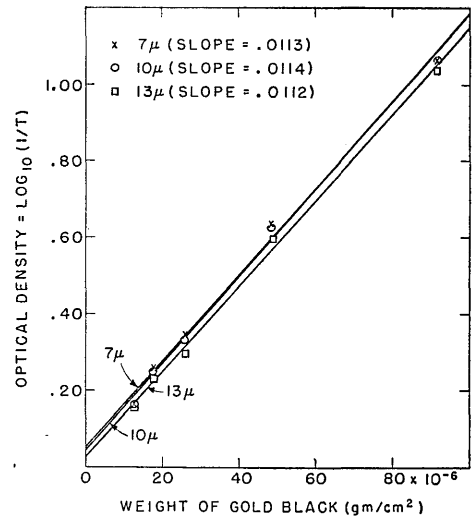


FIG. 4. Optical density of gold black deposits on cellulose nitrate.

The value of the $\sigma\times d$ product at zero frequency may

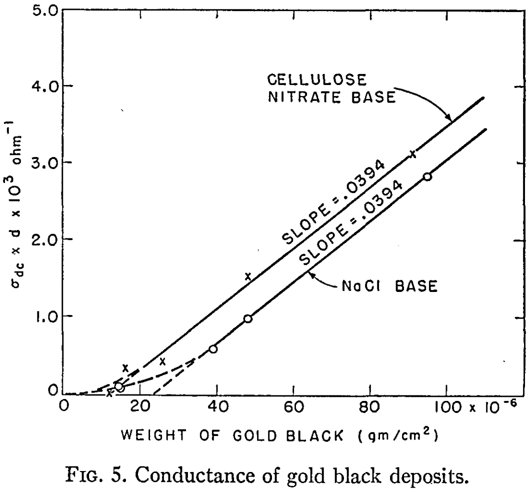
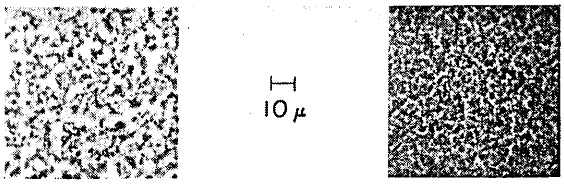
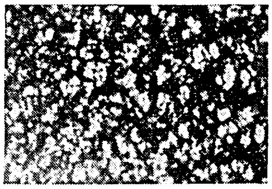


FIG. 5. Conductance of gold black deposits.



(A) (B)

Gold black deposits



(C)

Gold black deposit collapsed by acetone

FIG. 6. Optical microscope photographs of gold black deposits.

be calculated from electrical resistance measurements. For a deposit of thickness d, separation between electrodes l, width w, and resistivity ρ, or conductivity σ_{dc}, the resistance is:

$$\text{resistance} = \rho(l/wd) = (1/\sigma_{dc})(l/wd), \tag{13}$$

or

$$\sigma_{dc}\times d = (l/w)(1/\text{resistance}). \tag{14}$$

Figure 5 shows the values of the $\sigma_{dc}\times d$ product calculated from resistance measurements, both for cellulose nitrate and NaCl substrates for different amounts of gold black. Least squaring of the data gave a slope of 0.0391 for the cellulose nitrate substrate and 0.0397 for the NaCl substrate. The straight lines were drawn with an average slope of 0.0394. (All slopes are given in terms of the units appearing on the ordinate and abscissa.)

A gold black deposit is made up of agglomerates of crystallites. A minimum amount of deposit is required to build up conducting paths from one electrode to the other. The intercept on the weight axis of Fig. 5 represents the minimum amount of material necessary to give conducting paths. (Figure 1 shows a deposit on cellulose nitrate which happens to have a weight corresponding to the intercept.) The NaCl plates were unpolished and were therefore rougher than the cellulose nitrate films; more material was required to build up complete conducting paths on the NaCl substrate. The slope represents the change in the $\sigma_{dc}\times d$ product with weight, per unit area, and it is independent of surface effects, for both types of substrate. Therefore, the slope is representative of the "bulk" value of the $\sigma_{dc}\times d$ product.

Any correlation of the infrared transmission data with electrical conductivity data should be made in terms of this slope since infrared radiation is absorbed by *all* the material in the deposit. The experimental data may be compared with the theoretical equations by using the average slopes in Figs. 4 and 5.

$$\log_{10}(1/T) = 0.0113\times\text{wt. }(\text{g/cm}^2\times10^{-6})\ (\text{Fig. 4}), \tag{15}$$

$$\sigma_{dc}\times d\times10^3 = 0.0394\times\text{wt. }(\text{g/cm}^2\times10^{-6})\ (\text{Fig. 5}). \tag{16}$$

Therefore

$$\log_e(1/T) = 660\sigma_{dc}\times d \qquad \text{(experimental)} \tag{17}$$

$$\log_e(1/T) = 367.7\sigma_{IR}\times d \qquad \text{(theoretical)} \tag{9}$$

where the $\sigma\times d$ product is in ohm^{-1}.

The form of Eq. (9) fits the experimental data very well, but the experimentally determined constant is 1.75 times greater than the theoretical one. This difference may be attributed to a lower value of the conductivity for zero frequency than for infrared frequencies. There are several reasons for this lower value at zero frequency. The interaction of infrared radiation with a gold black deposit is determined by the conductivity of the deposit within a small region comparable in size to the wavelength of the radiation. The conductivity in Eq. (9) may be considered to be the average of the conductivities of all these small regions. On the other hand, resistance measurements involve conducting paths which must extend from one electrode to the other and which include a large number of the small conducting regions involved in interaction with infrared radiation. If a few of these small conducting regions in the conducting paths have a considerably lower conductance than most of the others, then the zero frequency conductivity would be affected more and would be lower than the infrared conductivity.

However, even if all the small conducting regions have the same conductivity, then the zero frequency conductivity must still be lower than the infrared conductivity. In the calculation of the zero frequency conductivity from Eq. (14) it was assumed that the length, l, was simply the shortest distance between electrodes. Optical microscope photographs of two gold black deposits are shown in Fig. 6. On the scale of infrared wavelengths, these deposits are not uniform. Any complete conducting path which extends from one electrode to the other must zigzag through the deposit and consequently is longer, in terms of the small conducting regions, than the shortest distance between electrodes. Since the actual path length is longer than that used in Eq. (14), then the zero frequency conductivity calculated from Eq. (14) is too low. If the average conducting path were 1.75 times as long as the straight line distance between electrodes, then the spatial nonuniformity on the scale of infrared wavelengths would be sufficient to account for all the difference between Eq. (17) and Eq. (9).

During thermal stabilization of a gold black deposit most of the vacant sites in the crystalline lattice of the gold particles are "removed" by becoming filled with atoms. Both the electrical conductance and the optical density (wavelengths greater than 5μ) increase as a result of stabilization.[7] However, the increase in $\sigma_{dc}\times d$ is severalfold greater than the increase in $\sigma_{IR}\times d$ at 10μ. The observations suggest that the presence of vacant sites in the crystallites has a relatively large influence in decreasing the value of σ_{dc} in addition to the spatial effects described above, but the vacant sites have only a small influence on the value of σ_{IR}.

B. Evaluation of σ_{IR} and d

According to Eq. (12), σ_{IR} might be evaluated from the measurement of reflectance at a known wavelength. We have not been able to obtain an exact measure of the infrared (3 to 15μ) reflectance of gold black deposits because of the predominant scattered radiation. For example, no difference in the combined reflected and scattered radiation was obtained from a heavy gold black deposit, when the sample was rotated as much as 15° to either side of the position which would give specular reflection. The combined reflected and scattered radiation that came from a heavy (transmittance less than one percent) gold black deposit, over a small angular field at the specular angle (angle of incidence ten degrees from the normal) varied from 0.2 percent at 8μ to 0.6 percent at 12μ, in approximate agreement with the change indicated by Eq. (12). The results show, in agreement with the results of the optical microscope, that the surface of a gold black deposit is "rough" to these wavelengths. If a reflectance even as high as 0.5 percent at 10μ is assumed, then from Eq. (12), $\sigma<5$ ohm cm^{-1}.

We have measured the thickness and volume content of gold of a number of heavy gold black deposits by several independent measurements.

(a) A gold black deposit was made on a glass plate in such a way that it covered only part of the top surface of the plate. A glass microscope slide was supported at one end by the gold black deposit and at the other end by the glass substrate so that an air-wedge was formed between the two glass pieces. By counting the interference fringes of monochromatic light formed by this air-wedge, a value for the thickness, d, of the deposit was determined. Some compression of the deposit resulted from the weight of the glass slide.

(b) A second method involved a density determination of a gold black deposit by weighting the deposit and its substrate in air and in water. The gold black was deposited on a weighed sample of thin bright sheet gold. The sheet was blackened and then the weight of the blackened sheet was determined while it was immersed in air and then in water. (Gold black deposits, on clean glass, become disengaged from the glass surface upon immersion in water, so that it was necessary to use sheet gold, to which the gold black adheres better, as the substrate.) There is some penetration of water into the gold black during the measurement, so that the measured volume percent of gold is greater than the true value.

(c) A third method involved the measurement of the interval between the top and the bottom surface of a gold black deposit on a glass plate. The interval was determined with the aid of a microscope (magnification 430×) having a calibrated focusing screw.

The weight of gold black per unit area for methods (a) and (c) were obtained from a calibration of the transmission coefficient (in the visible spectrum) of gold black deposits *vs* weight per unit area of the deposits.

The results of the determination of volume percent of solid gold, assuming that the gold particles in the gold black have the same density as bulk gold, 19.3 g/cm^3, are listed in Table I.

The agreement among the results of the different methods is as good as might be expected.

Methods (a) and (b) each give results with too *high* a gold content. Method (c) requires thick deposits for the best accuracy but even then precise values for the volume percent cannot be obtained because the "upper surface" of the deposit is not well defined. Despite the drawbacks, method (c) gives the most reliable results.

Assuming that the same volume percentage prevails for the thinner gold black deposits, the thickness, d, for the deposit of Figure 3 which weighed 91.3×10^{-6} g/cm^2 is 23.6×10^{-4} cm. Since $\log_{10}(1/T)$ for this sample is 1.09 at 10μ, the value of σ_{IR}, the conductivity, is 2.8 ohm^{-1}cm^{-1}.

C. Properties of Gold Black Deposits at Long Wavelengths

These measurements were made in other laboratories on deposits prepared here. (The deposits were not the same ones discussed above and might have minor differences in their properties.)

Plyler[9] measured the transmittance and reflectance from 1 to 39μ for gold black deposited on KRS5. His results are in substantial agreement with the results given above for wavelengths as long as 15μ. He found little change in the reflectance and transmittance from 15 to 39μ. The samples were measured before the effect of stabilization was known. It will be interesting to repeat the measurements in the 15 to 39μ region on stabilized deposits.

Dr. W. W. Sinton, of Johns Hopkins University, measured the transmittance and reflectance of stabilized gold black deposits on cellulose nitrate in the 100 to 455μ region. Both the transmittance and reflectance increase with increasing wavelength. A sample that absorbed 96 percent of the incident radiation at 10μ absorbed slightly less than 60 percent at 455μ. Since η^2

TABLE I. Volume percent of solid gold in gold black deposits.

Method of determination	Gold content by volume
(a) Counting interference fringes in an air-wedge between glass plates	0.32 %
(b) Density determination by weighing under water	0.31 %
(c) Focusing a microscope on top and bottom surfaces	0.20 %

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[9] E. K. Plyler and J. J. Ball, J. Opt. Soc. Am. 38, 988 (1948).

is not $\ll 1$ at these long wavelengths, Eqs. (6)–(12) are not applicable here. Equations based on optical interference in thin films must be used for these long wavelengths.[10]

A few measurements have been made on gold black deposits with microwaves having a wavelength of 3.5 cm by Mr. L. D. Smullin of the M.I.T. Radiation Laboratory. Gold black deposits on mica were inserted in a wave guide and the standing wave ratios for incident and reflected waves were measured. From such measurements an effective resistance of an area of equal length and width could be calculated and compared with corresponding values obtained from dc resistance measurements. It was found that the gold black deposits behave like thin metal films having the same electrical resistance. The values obtained for the effective resistance of gold black deposits by microwave measurements agree with the dc resistance measurements within the precision of the method; furthermore they agree whether or not the deposits have been previously thermally stabilized. Naturally the spatial effects discussed earlier cannot be resolved by microwaves.

VALIDITY OF ASSUMPTIONS IN DEVELOPING EQUATIONS USED

The gold content per unit volume of a gold black deposit and the numerical value of the conductivity, σ, may be used to check the assumptions involved in deriving the equations of the theoretical section above. The small gold content per unit volume, 0.2 percent, certainly corresponds to a porous structure and permits the assumption that the magnetic permeability, μ, and the electric permittivity ε of the gold black deposits may be set equal to those of free space, μ_0, ε_0. The value for the infrared conductivity, σ_{IR}, is sufficiently small so that η^2 is small compared to unity, at least for wave lengths shorter than 15μ. The expansions, depending on this condition are thus valid.

The validity of the assumption that the gold black deposits behave like sheets of a homogeneous medium is sufficient for the approximations used here, but the deposits are not perfectly uniform, as can be observed with a high power microscope or as can be deduced from the fact that infrared radiation is scattered, in small amounts to be sure, by the gold black deposits.

ACKNOWLEDGMENTS

We are grateful to Mrs. A. Goode, Miss J. Lamie, Mr. R. W. Hartley, and Mr. W. E. Krag of this laboratory for their assistance; to Dr. E. K. Plyler of the Bureau of Standards for the measurements to 39μ, to Dr. W. W. Sinton and Professor John Strong of Johns Hopkins University for the long wavelength measurements, and to Mr. L. D. Smullin of the M.I.T. Radiation Laboratory for the microwave measurements.

APPENDIX. COLLAPSE OF THE GOLD BLACK STRUCTURE

Gold black deposits are very porous structures; the gold particles comprising a deposit occupy approximately 1/500 of the total volume of the deposit, but each particle touches adjacent neighbors, as demonstrated by the measurements of electrical resistance. Binding forces between particles manifest themselves by the fact that a gold black deposit can be floated off a clean glass surface by immersion in water; the binding forces are strong enough to hold the gold black deposit together. However, a gold black deposit adheres to a gold substrate strongly enough so that it is not floated off. The type of bonding is probably electronic.

When a small quantity of a liquid (acetone, alcohol, benzene, carbon tetrachloride, or an aqueous solution of a detergent) capable of wetting a gold black deposit is poured on such a deposit, the deposit takes on a brownish appearance after the liquid has evaporated. The infrared reflectance (for wavelengths $>10\mu$), of a thick gold black deposit on glass which was originally less than 1 percent, was found to increase to more than 80 percent and the electrical resistance decreased by a factor 10 after such treatment. When viewed under the high powered microscope, the focusing position for the top of the metal deposit could not be distinguished from that of the substrate. There had thus been a nearly complete collapse of the gold black structure. The increased infrared reflection and loss of absorption observed when gold black deposits are heated to over 150°C, may also be the result of a collapsing process.

The merit of gold black deposits as absorbers of radiation depends in part on their low reflectance and low infrared conductivity which in turn are attributed to the large ratio of total volume to gold volume in the deposits. A very important conclusion to be drawn from these observations is that any metal smoke deposit must have a large ratio of total volume to metal volume if it is to be a good absorber of infrared radiation. Collapsed deposits do not have the large volume ratio and are therefore not suitable as absorbers of radiation.

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[10] Reference 4, pp. 511–516.