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enough that mere chance agreement is virtually out of the question, and we must conclude that the nearequivalence is significant. This fact, together with the similar temperature dependence for the two processes, constitutes a very strong confirmation of the proposed mechanism for final trapping of photoelectrons in silver bromide microcrystals. The initial trap is shallow, and the center is stabilized by the electrical attraction of a mobile silver ion to an electron temporarily bound to a trap.

The details of the trapping mechanism are undoubtedly complex, and the two alternatives discussed here are merely first-order, simplified models. Nevertheless, they do embody these two essential differences, which are distinguished by the measurements reported: (1) the initial traps are shallow so that an electron captured there has a far greater chance of escaping than of being stabilized, and (2) the stabilization step involves the *motion* of a silver ion to the center, under the influence of an electrostatic force.

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Vacuum Evaporation of β Ag₂Te^{*}

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The evaporation of β Ag₂Te in vacuum has been studied. It is concluded that β Ag₂Te dissociates on heating and that deposits of this compound produced by evaporation are formed by diffusion and reaction on the substrate.

HE compound silver telluride, Ag₂Te, exists in three stable polymorphs.¹ The polymorph stable below about 140°C is called β Ag₂Te and has a monoclinic structure. This polymorph, also referred to as "hessite," has been reported to be a small ($\sim 0.06 \text{ eV}$ at 0° K) band gap semiconductor^{2,3} with a melting point of approximately 950°C.4 An additional silver tellurium compound with the composition $Ag_{(5-x)}Te_3$, where $0 \le x \le 0.50$, has been reported⁵ as having a hexagonal structure. This silver-deficient modification is known as "empressite." As part of a study of β Ag₂Te, an investigation of its evaporation characteristics was undertaken. Gottlieb *et al.*² report that the dissociation pressure of Te at the melting point is less than 10⁻⁶ Torr and state that no problems of dissociation were encountered. Paparoditis⁶ reports that the compound remains practically undissociated during evaporation and that stoichiometric composition is maintained. The purpose of this paper is to report that our results indicate that, on heating, β Ag₂Te does dissociate. However, under certain conditions, the dissociation products can recombine on the substrate to form β Ag₂Te.

⁵G. Donnay, F. C. Kracek, and W. R. Rowland, Jr., Am. Mineralogist 41, 722 (1956).

The experimental data consist of compositional information on a series of layers deposited by evaporation of β Ag₂Te in vacuum. The experimental conditions used are described below and in Table I. The layers were analyzed by taking an x-ray powder pattern of a portion of the material and determining the phases present. The β Ag₂Te used was prepared in this laboratory by direct reaction of the pure elements in vacuum at approximately 1000°C. Material from two different samples was used for evaporation; x-ray powder patterns of portions of both lots showed the presence of only monoclinic β Ag₂Te. The material used for evaporation was carefully crushed under clean conditions; the particle size used ranged from about 0.05 cm to 0.08 cm. The evaporations were carried out in a vacuum of about 10⁻⁵ Torr using resistance heated "boats" described below. No reaction of these boats with β Ag₂Te was noted. In all but three (samples 13, 17, 28) cases, the substrate temperature was 20°C. In several cases in which the starting material was not completely evaporated, the residue remaining in the boat was analyzed by x-ray diffraction to determine the phases present. The thicknesses of the films, determined approximately by depth microscopy, were less than one micron.

The experimental results can be divided into several groups. The first (samples 2 to 7) consists of evaporations of β Ag₂Te from either alumina-coated platinum wire boats or from a heated molybdenum tube. In each case, the evaporation temperature was below 1100°C and the substrate was fused quartz. It was found that, for both types of boat, evaporation between 750°C and 1080°C produced deposits which were mixtures of free

^{*} The research reported in this paper was sponsored by the Advanced Research Projects Agency through the U. S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia.

¹A. J. Frueh, Jr., Z. Krist. 112, 44 (1959).

² G. E. Gottlieb *et al.*, J. Phys. Chem. Solids **15**, 183 (1960); C. Wood, V. Harrap, and W. H. Kane, Phys. Rev. **121**, 978 (1961).

³ R. Dalven and R. Gill, Bull. Am. Phys. Soc. 10, 594 (1965). ⁴ W. D. Lawson and S. Nielsen, *Preparation of Single Crystals* (Academic Press, Inc., New York, 1958), p. 243.

⁶ C. Paparoditis, J. Phys. Radium 23, 411 (1962).

	Sample	Substrate	Evaporation temperature	Composition	Evaporation time	Residue composition
Group 1	2 3 4 6,7	Q Q Q Q	1080°C 920°C 750°C 500°C	$\begin{array}{c} \operatorname{Te} + E \\ \operatorname{Te} + E \\ \operatorname{Te} + E \\ \operatorname{Te} + E \\ \cdots \end{array}$	15 min 15 min 60 min	Ag
Group 2	8 10 11 12 13 14 16 18 19 21	$ \begin{array}{c} Q\\ Q\\ Q\\ S\\ S\\ P\\ Q\\ Q\\ Q\\ Q\\ Q\\ Q \end{array} $	~1350°C ~1450°C 1350°C 1450°C 1425°C 1425°C 1410°C 1340°C 1400°C 1380°C 1440°C	Te+E H $H+E$ $E+H$ $H+E$ H E E H $E+H$	3 min 90 sec 30 sec 30 sec 40 sec 20 sec 30 sec 15 sec 30 sec	Ag+H Ag+H Ag+H
Group 3	22 23 25 26 27 28 17 19A	$\begin{array}{c} Q\\ S\\ KBr\\ Q\\ Q\\ Q\\ Q\\ C(T=75^{\circ}C)\\ S(T=75^{\circ}C)\\ Q(T=35^{\circ}C)\\ Pyrex \end{array}$	1600°C 1600°C 1600°C 1600°C 1600°C 1600°C 1600°C 1600°C 950; 1410°C 	H H H H H H H H H H H H H H H H H H	F F F F F F F T 11 min	

TABLE I. Vacuum evaporation of β Ag₂Te. Q = fused quartz, E = empressite, S = Al₂O₃ (single crystal), $H = \beta$ Ag₂Te, KBr = single crystal, F = "flash" evaporation.

tellurium and the hexagonal empressite modification of silver telluride. Two evaporations from a molybdenum tube at 500°C produced no observable deposit in 60 min. Analysis of the residue after evaporation of β Ag₂Te at 920°C showed the presence of silver only.

The second group (samples 8 to 16, 18, 19, and 21) consists of evaporations of β Ag₂Te from molybdenum wire coil boats at temperatures from 1300°C to 1450°C. The evaporation times ranged from 15 sec to 90 sec; most of these evaporations completely exhausted the charge of starting material. Both fused quartz and single crystal alumina substrates were used. Analysis of the residues remaining after three (8,10,16) experiments showed the presence of β Ag₂Te plus silver. X-ray analysis of the layers produced by this group of evaporations showed either β Ag₂Te alone, empressite alone, or mixtures of the two.

The third group of experiments (samples 22 to 28) employed a different technique. Individual pieces (0.05 cm to 0.08 cm in diameter) of β Ag₂Te were dropped onto a flat tantalum surface at a temperature of 1600°C. This "flash" evaporation technique produced (except in a single case) layers of pure β Ag₂Te on substrates of single-crystal alumina, fused quartz, or single-crystal KBr. Two other observations are of interest. In an experiment (17), using a molybdenum wire boat, a sample of β Ag₂Te was completely evaporated by heating at 950°C for 10 min and then at 1400°C for one min. The object of this experiment was to determine whether sequential evaporation of the tellurium from β Ag₂Te (suggested by the results of the first group of experiments) followed by complete evaporation of the residue (presumably silver or silver and β Ag₂Te) would result in silver-tellurium compound formation in the deposited layer. The resulting deposit on fused quartz was pure β Ag₂Te. In a similar experiment⁷ (sample 19A), pure silver and pure tellurium were evaporated alternately from separate sources. It was found that deposition of tellurium on a layer of silver *increased* the resistance of the layer, indicating combination of the reactants. X-ray analysis of the final deposit after four alternations of the reactants showed the presence of both β Ag₂Te and hexagonal empressite. The temperature of the Pyrex substrate was 20°C during this experiment. It may also be noted that the observation (samples 16, 18) of hexagonal empressite with the composition (determined by chemical analysis) $Ag_{0.7}$ Te suggests that it may exist over a wider range of composition than previously reported.

Based on these data, the following picture of the evaporation of β Ag₂Te is proposed. The compound dissociates appreciably at temperatures as low as 750°C. This proposal is supported by the presence of free tellurium in several of the deposited layers. This conclusion is not inconsistent with the reported² low dissociation pressure p_{Te} of Te at the melting point. A small value of p_{Te} implies nothing, a priori, about the values of the dissociation pressures p_{Ag} of silver and p_H of β Ag₂Te. It is believed that the values of the latter two pressures are considerably smaller than p_{Te} . Hence, using

⁷ A. H. Sommer (private communication).

the Langmuir equation,⁸ it is proposed that the evaporation rate R_{Te} of tellurium atoms is greater than the evaporation rates R_{Ag} of silver atoms or R_H of β Ag₂Te molecules. Thus, tellurium is preferentially evaporated from the starting material and an incomplete evaporation leaves a residue of silver or a mixture of silver and β Ag₂Te. As the temperature of the evaporation is increased, the rates R_{Te} and R_{Ag} both increase. Examination of the vapor pressure data for pure silver and pure tellurium suggests that p_{Ag} increases faster with temperature than does p_{Te} . At temperatures higher than about 1100°C, the evaporation rates of both silver and tellurium are such that *complete* evaporation of the charge can take place rapidly. The experiments at 1600°C on "flash" evaporation give an even more rapid

⁸ S. Glasstone, *Textbook of Physical Chemistry* (D. Van Nostrand Company, Inc., Princeton, N. J., 1946), 2nd ed., p. 449.

complete evaporation because of the higher temperature and small mass of the individual β -Ag₂Te particles. With complete transfer of the starting material to the substrate, it is believed, as is suggested by experiments 17 and 19A, that diffusion on the substrate, at room temperature or slightly above, is rapid enough, with the small diffusion distances involved in the thin film, to form the compounds observed.

In summary, it is concluded that β Ag₂Te dissociates on heating and that deposits of this compound produced by evaporation are formed by diffusion and reaction on the substrate.

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Determination of the Particle Velocity in Detonating Gases by a Magnetohydrodynamic Principle

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A technique for experimentally determining the hydrodynamic particle velocity in gaseous detonations is described. The technique is based on the magnetohydrodynamic interaction of the ionized reactants and products with an externally applied magnetic field. Particle velocities in $2H_2+O_2$ and $2H_2+2O_2$ detonations were found to be 1.3 mm/ μ sec and 0.96 mm/ μ sec, which are in good agreement with those calculated from detonation rate and pressure.

I. INTRODUCTION

THE hydrodynamic theory of detonation¹ shows that the flow velocity of the products of detonation in the Chapman-Jouget plane is given by

$$u = (p_1 - p_0) / \rho_0 D, \qquad (1)$$

where ρ_0 and p_0 are the density and pressure ahead of the detonation, and p_1 and D are the pressure in the detonation and the velocity of detonation. A measurement of the flow velocity independent of the parameters involved in Eq. (1) would thus be a valuable test of this theory.

Such measurements have been made using the principles of the magnetohydrodynamic generator.

II. THEORY OF MEASUREMENTS

When an electrically conductive gas (e.g., the products of a detonation) flow through a magnetic field transverse to the flow and electrodes are placed in the walls of the detonation tube, then the emf in volts gen-

¹ J. Taylor, Detonation in Condensed Explosives (Clarendon Press, Oxford, England, 1952), pp. 65-67.

erated between the electrodes is given by

$$e = Bul$$
 (2)

if the path between the electrodes is mutually perpendicular to the flow and the magnetic field direction.^{2,3} In Eq. (2), *B* represents the magnetic field intensity in Wb/m², *u* the flow velocity in m/sec of the gaseous products, and *l* the separation in meters between the electrodes.

In practice the emf is not measured directly but rather the terminal potential difference between the electrodes with current flowing through an external resistive load. Since the partially ionized detonation products have finite electrical resistance, a correction must be made for the internal resistance of the gas. Thus, it is necessary to determine the resistivity of the product's gases by a direct measurement of the current-voltage characteristic (with no magnetic field).

III. EXPERIMENTAL

The arrangement used for measuring particle velocities is shown diagrammatically in Fig. 1. The detona-

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² H. J. Pain and P. R. Smy, J. Fluid Mech. **10**, 51 (1961). ⁸ E. H. Beckner, Phys. Fluids **7**, 586 (1964).