

Electrical Conductivity of Thin Metallic Films with Unlike Surfaces*

HELLMUT J. JURETSCHKE†

Laboratoire d'Electrostatique et de Physique du Métal, Grenoble, France
(Received 14 June 1965; in final form 18 August 1965)

THE influence of two surfaces with different probabilities of specular scattering, P and Q , on the conductivity of thin films has been discussed recently by Lucas.¹ His tables will be useful for estimating the effects of the differing boundary conditions on the two surfaces which one may expect in most thin films prepared by deposition on a substrate.

A more extensive examination of these effects is actually possible since the conductivity for the case $P \neq Q$ is related to that for $P = Q$ in a simple manner.² If we write the result of Sondheimer³ for the case of identical surfaces

$$\sigma/\sigma_0 = \Phi(K, P), \tag{1}$$

where K = thickness/bulk mean free path, σ_0 = bulk conductivity, then the film conductivity in the presence of two surfaces of differing reflectivity is given by

$$\sigma/\sigma_0 = \frac{(1-P)(1-Q)}{(1-(PQ)^2)^2} \Phi[K, (PQ)^2] + \left\{ 1 - \frac{(1-P)(1-Q)}{(1-(PQ)^2)^2} \right\} \Phi(2K, PQ). \tag{2}$$

While Eq. (2) is essentially equivalent to that obtained by Lucas,¹ the latter form² is more convenient and permits extending the numerical tables using only the tabulated function $\Phi(K, P)$. In addition, it can be used with facility for making qualitative comparisons with Eq. (1). As an example, we discuss the asymptotic form of Eq. (2) for both extreme values of K .

As is anticipated from the similarity of Eqs. (1) and (2), their asymptotic forms are closely related. The limiting forms of Φ are

$$K \gg 1 \quad \Phi(K, P) = 1 - \frac{3}{8} \frac{1}{K} (1-P), \tag{3a}$$

$$K \ll 1 \quad \Phi(K, P) = \frac{3}{4} \frac{(1+P)^2}{1-P^2} K \ln \frac{1}{K}, \tag{3b}$$

and their substitution in Eq. (2) gives for $P \neq Q$

$$K \gg 1 \quad \sigma/\sigma_0 = 1 - \frac{3}{8} \frac{1}{K} \left(1 - \frac{P+Q}{2} \right), \tag{4a}$$

$$K \ll 1 \quad \sigma/\sigma_0 = \frac{3}{4} \frac{(1+P)(1+Q)}{1-PQ} K \ln \frac{1}{K}. \tag{4b}$$

Equations (3) and (4) indicate that a film with two surfaces characterized by P and Q can always be described, at a given K , by a single surface scattering parameter P_{eff} lying within the limits

$$\frac{P+Q}{2} - \frac{[(P-Q)/2]^2}{1+(P+Q)/2} \leq P_{eff} \leq \frac{P+Q}{2}. \tag{5}$$

P_{eff} is now a slowly varying function of K , and will become smaller for smaller K . Thus thin films which have two differing surfaces, and whose behavior follows the Sondheimer model, show a tendency towards lower P_{eff} as they become thinner. This effect can contribute to such a trend often found experimentally; in practice, however, P_{eff} for the thinner films normally trespasses the lower limit set by Eq. (5), so that P and Q must also change.

The small differences existing between some of the values of σ_0/σ listed in the tables of Ref. 1 and those of Ref. 2 are apparently due to errors in the tabulation of Φ in Ref. 3. This tabulation formed the basis for evaluating Eq. (2) in Ref. 2.

* Supported in part by the National Aeronautics and Space Administration.

† NSF Science Faculty Fellow. Permanent address: Polytechnic Institute of Brooklyn, Brooklyn, New York.

¹ M. S. P. Lucas, *J. Appl. Phys.* **36**, 1632 (1965).

² H. J. Juretschke, *Surface Sci.* **2**, 40 (1964).

³ E. H. Sondheimer, *Advan. Phys.* **1**, 1 (1952).

Metastable Amorphous Ferromagnetic Phases in Palladium-Base Alloys*

C. C. TSUEI AND POL DUWEZ

W. M. Keck Laboratory of Engineering Materials, California Institute of Technology, Pasadena, California
(Received 13 May 1965; in final form 15 July 1965)

THE existence of an amorphous phase obtained by rapid quenching from the liquid state, has been recently reported in palladium alloys containing from 16 to 22 at. % silicon.¹ Since the ferromagnetic elements iron, cobalt, and nickel, form complete series of solid solutions with palladium, it was anticipated that the amorphous structure could be retained if these elements were substituted for palladium up to a certain concentration. It was found that this was actually the case. Ternary alloys in which the atomic concentration of silicon was kept constant (20 at. %) were studied, and amorphous structures were obtained in alloys containing 5 at. % Fe (Pd₇₅-Fe₅-Si₂₀), 12 at. % Co (Pd₆₈-Co₁₂-Si₂₀) and 15 at. % Ni (Pd₆₅-Ni₁₅-Si₂₀). Quenching from the liquid state was achieved by the "piston and anvil" technique used in the study of binary Pd-Si alloys.¹ The structure of the quenched alloys was considered to be amorphous when the x-ray and electron diffraction patterns showed only diffused rings typical of a liquid structure. In addition, no structure was observed by transmission electron microscopy. As in the case of the Pd₈₀-Si₂₀ amorphous alloys described in Ref. 1 a sudden heat release of about 1000 cal/g mole was measured around 420°C when the ternary alloys were heated at rates greater than about 20°C/min. Below this temperature range, the alloys transform by a process of nucleation and growth. Preliminary kinetics data indicate that, at room temperature the time required for reaching half of the transformation would be about 10³ years.

Remanent magnetization and coercive force measurements were performed on some of the amorphous magnetic alloys. The sample (about 1 cm in diameter and 25 μ thick) was magnetized in a field of 10 kOe in a direction parallel to its plane. A torque balance of the type described in Ref. 2 was used. The preliminary results were as follows: Pd₆₈Co₁₂Si₂₀; remanence about 0.1 ± 0.005 G, coercive force 466 Oe; Pd₇₅Fe₅Si₂₀; remanence 0.01 ± 0.004 G, coercive force 160 Oe.

The existence of ferromagnetism in amorphous structures has been theoretically predicted by Gubanov.³ The model used by Gubanov does not require any periodic arrangement of the atoms in a lattice and takes into consideration only the exchange integral of neighboring ferromagnetic atoms and the radial distribution function of the structure. On the basis of this model a reduction in magnetization is predicted when a crystalline ferromagnetic alloy undergoes a crystalline to amorphous transition. This conclusion is in qualitative agreement with the findings of this investigation.

It should be pointed out that small concentrations of ferromagnetic precipitates in a nonmagnetic matrix can give rise to weak ferromagnetic properties (remanence and coercive force) of the same order of magnitude as those measured in the present investigation.⁴

It is experimentally found that palladium solid solutions containing less than 10 at. % of either Co or Fe, are not ferromagnetic at room temperature.^{5,6} In some of the ternary alloys studied in this investigation for which the concentration of the ferromagnetic element relative to Pd (excluding Si) is less than 10 at. % (case of Pd₇₅Fe₅Si₂₀) precipitates of a PdFe ferromagnetic solid solution would require the simultaneous presence of palladium silicide precipitates. It is recognized that this possible source of ferromagnetism in the amorphous alloys cannot be eliminated until it has been definitely established that the alloys are absolutely free from crystalline precipitates.

* Work sponsored by the U. S. Atomic Energy Commission.

¹ Pol Duwez, R. H. Willens, and R. C. Crewdson, *J. Appl. Phys.* **36**, 2267 (1965).

² F. B. Humphrey and A. R. Johnston, *Rev. Sci. Instr.* **34**, 348 (1963).

³ A. I. Gubanov, *Fiz. Tver. Tela* **2**, 502 (1960).

⁴ F. W. Constant and J. M. Formwalt, *Phys. Rev.* **56**, 373 (1939).

⁵ R. M. Bozorth, P. A. Wolff, D. D. Davis, V. B. Compton, and J. H. Wernick, *Phys. Rev.* **122**, 1157 (1961).

⁶ J. Crangle and W. R. Scott, *J. Appl. Phys.* **36**, 921 (1965).