

Properties of AuIn_2 Resistors for Josephson Integrated Circuits

The influences of film thickness and composition on the resistivity and microstructure of AuIn_2 films, which are used as resistors in Josephson integrated circuits, have been investigated. The films were prepared by evaporating Au and In layers onto SiO_2 -coated Si wafers held at 348 K. The resistivity at 4.2 K was found to be $\approx 5 \mu\Omega\text{-cm}$ for 40-nm-thick films and to vary as $\approx d^{-0.76}$ over the thickness range 30–250 nm. Corresponding sheet resistances ranged from 0.05 to 2 $\Omega/\square$. Resistivity changes were also observed as the composition was altered. A decrease of $\approx 10\%$ in the In/Au thickness ratio from that of AuIn_2 produced an increase of $\approx 50\%$ in resistivity. A similar increase in In/Au ratio produced $\leq 10\%$ decrease in resistivity. Electron microscopy analysis revealed that the grain size of AuIn_2 films increases with film thickness, and is approximately two times smaller for the low In/Au ratio films than for those of nominal or larger In/Au ratios. The factors governing the resistivity of AuIn_2 films were analyzed using the Fuchs surface scattering and Mayadas-Shatzkes (M-S) grain boundary scattering theories. It was found that the M-S theory can be used to explain the resistivity data for a range of choices of r and p , the grain-boundary-reflection and surface-reflection coefficients, respectively. Reasonable agreement was obtained for parameter values between $r = 0.31$, $p = 0$, $\rho l = 3 \times 10^{-11} \Omega\text{-cm}^2$ and $r = 0.74$, $p = 1$, $\rho l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$. The available evidence is interpreted as favoring grain boundary scattering as the dominant scattering mechanism.

Introduction

Thin film resistors are needed for Josephson integrated circuits for use as load resistors [1] and for damping resonances [2]. It has been shown that AuIn_2 films can be used to form stable resistors that are compatible with a superconducting Pb-In-Au alloy interconnection metallurgy [3]. Such resistors have been used successfully in a variety of experimental logic and memory circuits [4]. In the fabrication of such circuits, it is desirable to have good process control for close resistor tolerances to be maintained. In addition, future devices and circuits made with smaller dimensions will probably require higher resistance values. To maintain high device packaging densities it would be desirable to achieve this increase in resistance by using a resistor film with a higher sheet resistance. Thus, it is of interest to understand the range of sheet resistances obtainable with AuIn_2 films and the factors that govern the resistivity of such films.

In our work, the range of sheet resistances obtainable with AuIn_2 films of various thicknesses has been investi-

gated and the effect on resistivity of varying the composition about the nominal AuIn_2 composition has been determined. In addition, because previous work indicated that the resistivity of AuIn_2 films may be due to electron scattering from grain boundaries or other defects in the films [3], representative Au-In alloy films were investigated by transmission electron microscopy (TEM) to characterize their microstructures. Results of these experiments have been used to analyze the factors that govern the film resistivities.

Experimental procedure

Films of AuIn_2 were prepared in vacuum by evaporating a layer of Au followed by a layer of In. For AuIn_2 the thickness ratio is $\text{In}/\text{Au} = 3.074$. Substrates were SiO_2 -coated Si wafers that were cleaned *in situ* by using an oxygen discharge and held at 348 K during film deposition. Pressures in the deposition chamber during evaporation were $\leq 6 \times 10^{-5}$ Pa. Evaporation rates of 0.1 and 0.5 nm/s were used for Au and In, respectively. The films were main-

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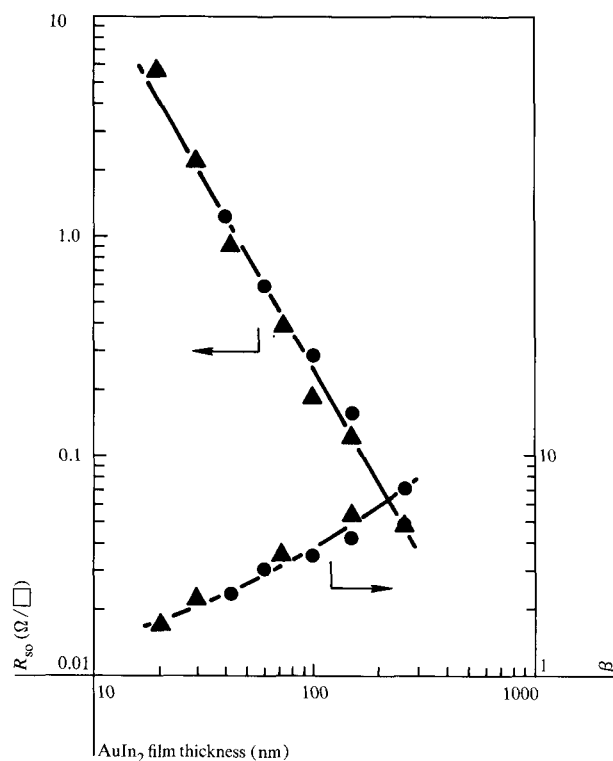


Figure 1 Values of R_{so} and β for AuIn_2 films as a function of film thickness. The $\bullet$ samples were prepared with companions for TEM analysis.

tained at 348 K for one hour after deposition of the layers to allow the In and Au to interdiffuse to form the AuIn_2 intermetallic compound before removal from the vacuum. Film thicknesses were determined with a quartz crystal deposition monitor calibrated by means of optical interferometry. The AuIn_2 thickness was taken to be the sum of the In and Au thicknesses; this procedure is expected to introduce a thickness error of $<1.5\%$ from the values obtained in calculations made with the bulk densities of the film materials.

The AuIn_2 films were patterned using a photoresist stencil lift-off method [5] to form 5–25- μm -wide resistors of various lengths with measurement leads. Resistances R were measured using the four-terminal method at ambient temperature (≈ 297 K), and at 4.2 K by immersing the film in liquid He. Sheet resistances ($R_s \equiv RW/L$) were obtained with lengths L and widths W measured by optical microscopy. Films to be examined by transmission electron microscopy (TEM) were prepared on Si wafers coated with a layer of photoresist followed by a 50-nm-thick layer of evaporated SiO. The amorphous SiO provided the same surface for film nucleation as that used for the resistor samples without interfering with the TEM

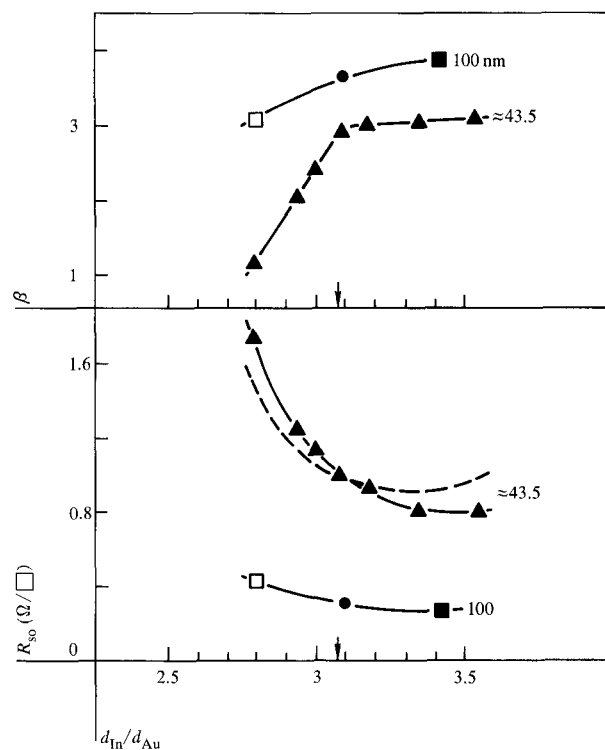


Figure 2 Values of R_{so} and β for Au-In films with compositions in the vicinity of that for AuIn_2 (indicated by arrows). The 100-nm samples were prepared with companions for TEM analysis.

analysis. The photoresist is soluble in acetone and allowed the $\text{AuIn}_2 + \text{SiO}$ composite to be transferred to a grid-type film support for TEM analysis.

Results

• Sheet resistance

The sheet resistances at 4.2 K, R_{so} , obtained for AuIn_2 films of various thicknesses d , are shown in Fig. 1. The corresponding values of the resistance ratio $\beta \equiv R_s(297 \text{ K})/R_{so}$ are also shown. The values of R_{so} are observed to increase from 0.05 to 5 $\Omega/\square$ as the thickness is reduced from 250 to 20 nm, following the empirical relation $R_{so} \propto 844 d^{-1.76}$ (d in nm). This thickness dependence is stronger than $R_{so} \propto d^{-1}$, indicating that the resistivity ρ of the AuIn_2 film material is increasing with decreasing film thickness. In addition, the magnitude of R_{so} over the range investigated is large compared to the value expected from the bulk resistivity of AuIn_2 . Such high and thickness-dependent resistivities are common for thin films because the film thicknesses, grain sizes, and defect-to-defect spacings can be small enough to limit the electron mean free paths in the films. The relative importance of these factors in determining the ρ of the AuIn_2 films is

discussed later. A useful consequence of this behavior is that the range of R_{so} values obtainable is considerably extended.

The dependence on composition of R_{so} for Au-In films has been obtained for compositions near that of $AuIn_2$ (In/Au thickness ratio $d_{In}/d_{Au} = 3.074$). The data for R_{so} and for β are shown in Fig. 2 for films 100 nm and ≈ 43.5 nm thick. The composition variation in the latter case was obtained by using incremental changes in d_{In} to allow precise relative compositions to be obtained. (This was done, e.g., by depositing $d_{Au} = 10.5$ nm and $d_{In} = 30$ nm on a group of four samples. A mask was then used to cover one sample and an increment of ≈ 2.5 nm In was then deposited on the three remaining samples. A second sample was then masked and an additional increment of ≈ 2.5 nm In was deposited on the two remaining samples, etc.) This procedure resulted in composite film thicknesses of 40–48 nm as d_{In}/d_{Au} was varied from 2.8–3.6. The contribution of this thickness change to R_{so} (d_{In}/d_{Au}) has been estimated using the data of Fig. 1. The R_{so} (d_{In}/d_{Au}) behavior after adjusting for the effect of these thickness changes is shown by the dashed curve in Fig. 2.

The effect of changing composition on R_{so} is seen to be much more pronounced for d_{In}/d_{Au} ratios < 3.074 ($AuIn_2$). As seen in Fig. 2, an R_{so} increase of $\approx 50\%$ is obtained for both $AuIn_2$ thicknesses as d_{In}/d_{Au} is reduced by $\approx 10\%$ from that of $AuIn_2$ (corrected 43.5-nm curve), while changes in R_{so} are $\leq 10\%$ for an $\approx 10\%$ increase in d_{In}/d_{Au} . Similar differences in the change in β are observed for films with d_{In}/d_{Au} above and below the nominal $AuIn_2$ composition, particularly for the thinner films. These results indicate significant differences in the distribution of the second-phase material and/or the film microstructure between films with d_{In}/d_{Au} above and below that of $AuIn_2$. The phase diagram for In-Au binary alloys [6a] indicates that $AuIn_2$ has a very narrow composition range. Thus, for In concentrations above that of $AuIn_2$, a second phase of pure In should develop. For In concentrations below that of $AuIn_2$, a second phase of the AuIn intermetallic compound is expected.

One factor contributing to the smaller R_{so} and β changes for In concentrations above that of $AuIn_2$ can be seen in Fig. 3(a), an SEM of the 100-nm-thick, high-In-concentration film of Fig. 2. Globules of metal are formed on this film that are not observed for $AuIn_2$ films. The In/Au x-ray fluorescence intensity ratios obtained from such globules using an electron microprobe are $\approx 3\times$ higher than those from the surrounding matrix, indicating that the excess amount of In has primarily collected in local regions on the surface. Thus, most of this film is similar in thickness and composition (and hence R_{so}) to the $AuIn_2$

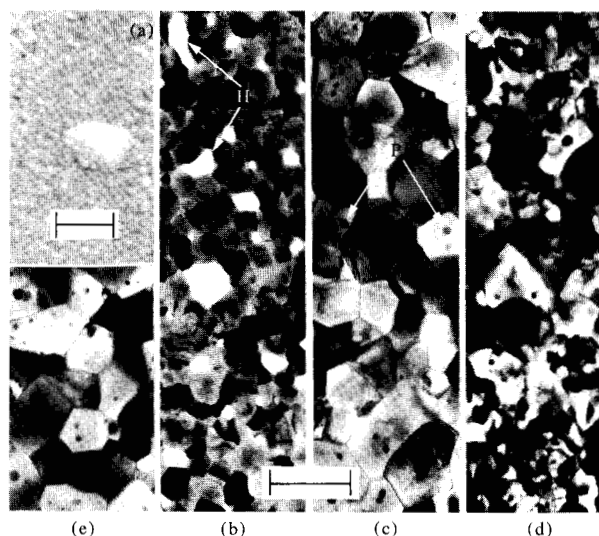


Figure 3 (a) SEM of 100-nm $AuIn_2 + In$ film showing In globule; length mark is $2\mu m$. (b) 20-nm and (c) 100-nm $AuIn_2$ films showing holes (H) and "particles" (P). TEMs of 100-nm Au-In films with compositions of (d) $AuIn_2 + Au$ and (e) $AuIn_2 + In$; length mark for (b)–(e) is 200 nm.

film. For In concentrations lower than $AuIn_2$, such globules are not observed, and thus the AuIn phase appears to be distributed in a more uniform manner in the $AuIn_2$ matrix.

• Electron microscopy

Resistor samples of several thicknesses of $AuIn_2$ (shown as $\bullet$ in Fig. 1) and of several compositions (shown as $\square$ and $\blacksquare$ in Fig. 2) were prepared with companion samples for TEM analysis to allow the effect on resistivity of grain size and second-phase particles to be evaluated. Representative electron micrographs from these two sample groups are shown in Figs. 3(b–e). They exhibit several interesting features. Holes are evident in the thinnest (20-nm) $AuIn_2$ sample [Fig. 3(b)] and are probably the reason the measured R_{so} values for samples of this thickness are higher than expected from the $R_{so} \propto d^{-1.76}$ dependence.

In addition, the grain sizes of the films vary with film thickness [Figs. 3(b, c)] and composition [Figs. 3(d, e)]. Values of the average grain size g (computed using the area method) are plotted in Fig. 4. For $AuIn_2$ films, g varies linearly with d , increasing from 60 to 220 nm as d is increased from 20 to 260 nm. The value of g for the 100-nm-thick sample with In concentration above that of $AuIn_2$ ($\blacksquare$) is about equal to that of the $AuIn_2$ sample. However, g for the 100-nm-thick low-In-concentration sample ($\square$) is only about one-half that of the $AuIn_2$ sample. Thus, changes in grain size are observed for In-

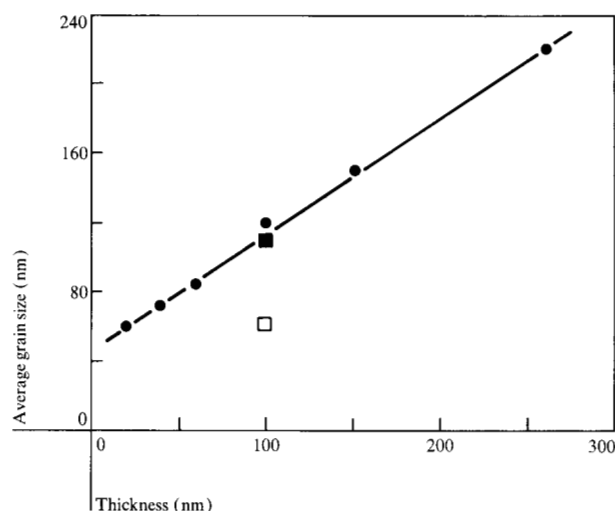


Figure 4 Average grain size of Au-In films as a function of film thickness. Symbols correspond to those in Figs. 1 and 2.

Table 1 Interplanar spacings (nm) calculated from diffraction patterns or obtained from the ASTM file. Spacings set in **bold type** correspond to the highest-intensity diffraction rings; spacings set in *italics* are weak rings of AuIn₂, as discussed in the text.

Diffraction patterns				ASTM file	
AuIn	AuIn ₂ + AuIn	AuIn ₂	AuIn ₂ + In	In	AuIn ₂
0.526					
0.431					
	0.372	0.376	0.372		0.376
0.334	<i>0.321</i>	<i>0.322</i>	<i>0.318</i>		
			<i>0.267</i>	0.271	
0.265	0.263				
0.246				0.247	
0.225	0.227	0.230	0.226	0.230	0.230
0.215	0.215				
0.204					
0.198					
	0.195	0.195	0.194		0.197
	0.186	0.189	0.186		0.188
0.180	0.182				
0.166	0.165		0.168		
0.162	0.161	0.162	0.161	0.162	0.163
	0.148	0.149	0.147	0.146	0.150
	<i>0.145</i>	<i>0.145</i>	<i>0.143</i>		
				0.140	
0.138	0.137			0.136	
0.131	0.131	0.132	0.131		0.133
0.125	0.124	0.125	0.124	0.124	0.125
		0.114	0.114	0.115	0.115
		0.109	0.109	0.109	0.110
	<i>0.107</i>	<i>0.108</i>	<i>0.107</i>	0.106	
		0.103	0.101	0.102	0.103

Au films as both thickness and composition are varied. These changes are consistent with the R_{so} changes observed on companion samples.

Small regions of darker contrast on or within the grains (referred to here as "particles") were observed by TEM in all of the AuIn₂-containing samples. The volume fraction of these particles was estimated from the bright-field TEM pictures [cf. Figs. 3(b-e)] to be <1%. The volume fraction is approximately independent of film thickness; however, particle size decreases with film thickness.

We do not understand the origin of the particles. They do not appear to be due to a departure from exact stoichiometry (AuIn₂) since samples intentionally prepared with low- or high-In content relative to that of AuIn₂ contained particles of similar size and concentration [Figs. 3(d, e)]. The particles do not appear to be an artifact of the preparation procedure since a film of the AuIn intermetallic compound prepared at the same time did not exhibit the particles. Neither have other films prepared using this procedure shown evidence of these particles. Thus, the particles appear to be characteristic of the films containing AuIn₂.

Transmission electron diffraction patterns were obtained for Au-In films of several compositions by using a relatively large-diameter aperture. The interplanar distances d obtained are summarized in Table 1. For the nominal AuIn₂ samples, only d values corresponding to AuIn₂ were observed. (The d values of 0.32, 0.145, and 0.107 nm, corresponding to the {200}, {420}, and {600} planes of AuIn₂, are not reported on the ASTM data card. Reflections from these planes are expected to be greatly reduced in intensity because the corresponding structure factors are small.) Diffraction patterns from the low- and high-In-content samples show additional diffraction rings due *only* to AuIn or In phases, respectively, expected from the binary equilibrium phase diagram [6a]. Thus, there is no evidence from the electron diffraction patterns of any unexpected crystalline phase.

A possible explanation for the particles is that they are associated with native oxide formed nonuniformly on the surface of the AuIn₂ films. Such islands of thicker oxide have been reported for Pb [6b] and could produce features (labeled P) observed in Figs. 3(b-e). Although the diffraction patterns showed no evidence of indium oxide, this is not surprising since the volume fraction of the oxide is small.

Analysis

The values of ρ_{f0} , the film electrical resistivity at 4.2 K, have been determined for the AuIn₂ films from the $R_{so}(d)$

data of Fig. 1 and are shown in Fig. 5. The film resistivity is seen to vary strongly with film thickness, increasing from 1.3–7 $\mu\Omega\text{-cm}$ as d is decreased from 250–30 nm. These ρ_{f0} values are much larger than the value of 0.15 $\mu\Omega\text{-cm}$ reported for the resistivity of bulk single crystals of AuIn₂ at 4.2 K, ρ_{b0} [7]. We now consider the factors that determine ρ_{f0} .

The influence of the particles observed in the AuIn₂ films [Figs. 3(b–c)] on the film resistivity is considered first. The effect would be greatest if the particles were distributed inside the AuIn₂ grains; this situation has been analyzed by Kirkpatrick and Mayadas [8]. Their analysis indicated that 1 vol% of randomly distributed, highly resistive particles would increase ρ_{b0} by $\leq 2\%$, i.e., $\Delta\rho < 0.003 \mu\Omega\text{-cm}$. Thus, in our case, the effect of the particles on the film resistivity should be negligible.

• Theory

In contrast to the effect of particles, the influence of film surfaces and grain boundaries on ρ_{f0} can be large. Fuchs and Sondheimer [9] have developed a theory (F-S) for the effect on ρ_f of electron scattering from film surfaces. Their result is

$$\frac{\rho_f}{\rho_i} = \left[1 - 3 \frac{(1-p)}{2k} \int_1^\infty \left(\frac{1}{t^3} - \frac{1}{t^5} \right) \frac{1 - e^{-kt}}{1 - pe^{-kt}} dt \right]^{-1} \\ = [1 - A(p, k)]^{-1}, \quad (1)$$

where $k = d/l_i$, ρ_i and l_i are the intrinsic resistivity and electron mean free path of the material (i.e., in the absence of surfaces and grain boundaries), and p is a phenomenological parameter, the probability that an electron will be specularly reflected from a film surface. Values of p may be selected from 0 to 1 to fit experimental data. A value of $p = 0$ corresponds to diffuse scattering and produces the maximum obtainable value of ρ_f for a given k . A value of $p = 1$ corresponds to perfect specular (elastic) electron scattering that causes no increase in ρ_f . Values of $p = 0$ –0.5 have given the best fits to single-crystal and large-grain-polycrystalline films [10].

A theory for the effect of grain-boundary scattering on ρ_{f0} has been developed by Mayadas and Shatzkes (M-S) [11]. Their result is

$$\frac{\rho_f}{\rho_i} = [1 - (3\alpha/2) + 3\alpha^2 - 3\alpha^3 \ln(1 + 1/\alpha)]^{-1} \\ = [F(\alpha)]^{-1}, \quad (2)$$

where

$$\alpha = (l_i/g)[r/(1-r)] \quad (3)$$

and r is the grain-boundary-reflection coefficient. The more complex case for which grain-boundary and surface

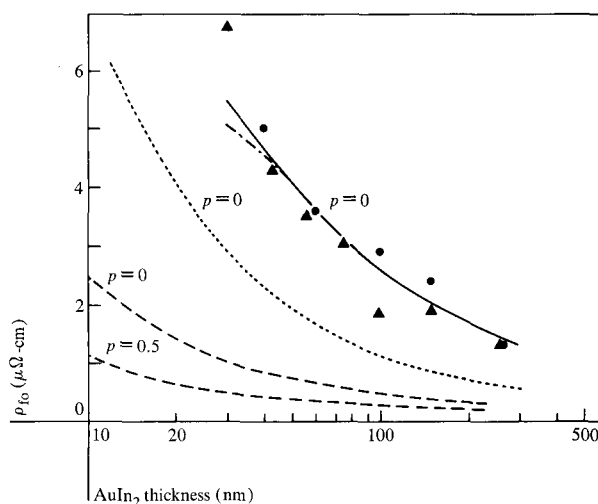


Figure 5 Resistivity of AuIn₂ films at 4.2 K as a function of film thickness. Data points are experimental values. Calculated resistivities obtained using F-S theory are shown as dashed lines ($\rho l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$) and the dotted line ($\rho l = 3 \times 10^{-11} \Omega\text{-cm}^2$, $p = 0$). Data points obtained using M-S theory are shown as a solid line ($\rho l = 3 \times 10^{-11} \Omega\text{-cm}^2$, $r = 0.31$, $p = 0$) and a dashed-dotted line ($\rho l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$, $r = 0.71$, $p = 0$).

scattering are both important has also been treated by Mayadas and Shatzkes. Tellier [12] has developed an analytical approximation for the M-S theory that agrees well with M-S over most of the range of interest in this paper ($k \geq 0.02$). His result is

$$\rho_f/\rho_i = [1 - A(p, k)]^{-1}[F(B)]^{-1}, \quad (4)$$

where

$$B(r, p, k) = \alpha[1 - A(p, k)] \quad (5)$$

and A , F , and α are defined in Eqs. (1)–(3).

• Estimation of $\rho_i l_i$

The theoretical models express ρ_f in terms of intrinsic ρ_i and l_i values. In practice it is found that the interpretation of ρ_{f0} data is more sensitive to the $\rho_i l_i$ product than to the values of ρ_i and l_i ; ρl is a constant for a given material, given by

$$\rho l = 6\pi^2 h/e^2 S_f, \quad (6)$$

where S_f is the area of the Fermi surface. In the free electron approximation [13]

$$S_f = 4\pi(3\pi^2 n)^{2/3}, \quad (7)$$

where n is the carrier concentration. Thus,

$$\rho l = (3/8\pi)^{1/3} (h/e^2) n^{-2/3}. \quad (8)$$

The carrier concentration for AuIn₂ is not known precisely; however, assuming that conduction is due to a

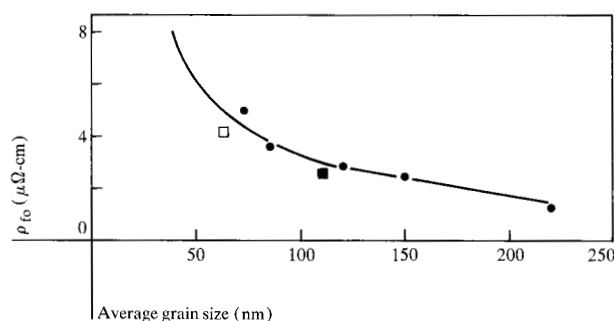


Figure 6 Resistivity of AuIn₂ films at 4.2 K as a function of average grain size observed by TEM. Data points are experimental values. Calculated resistivities obtained using M-S theory ($\rho_l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$, $r = 0.74$, $p = 1$) are shown as a solid line.

Table 2 Parameter values for which reasonable agreement was obtained between M-S theory and experiment for AuIn₂ resistivity at 4.2 K. Values of $l_i = 0.53$ and $2 \mu\text{m}$ are most likely for $\rho_l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$ and $3 \times 10^{-11} \Omega\text{-cm}^2$, respectively, as discussed in the text.

ρ_l ($10^{-11} \Omega\text{-cm}^2$)	l_i (μm)	p	r
0.8	0.53	1	0.74
0.8	0.53	0	0.71
0.8	0.3	0	0.68
3.0	2	1	0.43
3.0	2	0.5	0.38
3.0	2	0	0.31
3.0	1	0	0.25

single carrier type, a maximum value for n can be estimated [3] from the value of the Hall coefficient R_H reported for bulk single-crystalline AuIn₂ [7]. For $R_H = 9.3 \times 10^{-5} \text{ cm}^3/\text{C}$, $n = 6.7 \times 10^{22}/\text{cm}^3$, giving an estimated minimum ρ_l of $0.8 \times 10^{-11} \Omega\text{-cm}^2$, a value in the range observed for most metals [10, 14]. However, the positive value of R_H indicates that hole conduction dominates and that conduction by both electrons and holes may be important. If so, the actual carrier concentration would be smaller and ρ_l would be correspondingly larger. The range of ρ_l values observed for a wide variety of metals [10, 14] extends to only $\rho_l \approx 3 \times 10^{-11} \Omega\text{-cm}^2$. Taking this as an upper limit, ρ_l for AuIn₂ should be $0.8\text{--}3 \times 10^{-11} \Omega\text{-cm}^2$.

The values of ρ_i and l_i can now be estimated. As discussed earlier, the effect of the particles observed in the AuIn₂ films was judged to be negligible. The vacancy con-

centration should be small due to the high atomic mobility of Au and In in AuIn₂ at 348 K and to the close proximity of surfaces and grain boundaries that serve as vacancy sinks. Other physical defects, such as dislocations or twins, were relatively rare in the films; thus their effect on the intrinsic resistivity is expected to be negligible. We therefore take $\rho_i \approx \rho_{b0} = 0.15 \mu\Omega\text{-cm}$. For the ρ_l range estimated above, $l_i = l_{b0}$ would then be in the range $0.53\text{--}2 \mu\text{m}$.

• Interpretation of resistivity data

The interpretation of the $\rho_{fo}(d, g)$ data using Eqs. (1), (2), and (4) is sensitive to the value of ρ_l . For this reason, and because the ρ_l value is not known very well for AuIn₂, it is instructive to consider both ends of the ρ_l range previously identified. The case where $\rho_l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$ is considered first.

The effect of surface scattering on ρ_{fo} has been calculated using Eq. (1) for the cases $p = 0$ (maximum surface scattering) and $p = 0.5$ (a commonly observed value) [10]. The results are plotted as the dashed curves in Fig. 5. The calculated ρ_{fo} values are seen to be much smaller than the experimental ones: $\approx 5\times$ smaller for the $p = 0$ case. Thus, for $\rho_l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$, surface scattering is not the major factor in determining ρ_{fo} .

The grain-boundary-scattering theory is now considered for the case $p = 1$, i.e., surface scattering is assumed to be negligible, thereby simplifying the analysis. The $\rho_{fo}(g)$ data for the samples of Figs. 1 and 4 are plotted in Fig. 6, together with ρ_{fo} values (solid curve) calculated from Eq. (2). The data can be fitted by using a value of $r = 0.74$. The data points for the 100-nm-thick samples of high (■) and low (□) In concentration are also included; these also fall near the $r = 0.74$ curve for ρ_{fo} . Thus, the $\rho_{fo}(g)$ data can be explained using a hypothesis that scattering from grain boundaries is the dominant electron-scattering mechanism.

The value of r required to fit the data, however, is $\approx 3\times$ higher than the values used to fit ρ_i data on other metal films evaporated in high vacuum [11, 15]. The use of smaller l_i values (at constant $\rho_i l_i$) has little effect on the r required (Table 2). Combining surface and grain boundary scattering [Eq. (4)] allows r to be reduced only to ≈ 0.71 , as shown in Fig. 5. Thus, for $\rho_l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$, the large ρ_{fo} values and the observed dependence of ρ_{fo} on d can be explained using the theories only by assuming a larger than typical value of the grain-boundary-reflection coefficient.

The case $\rho_l = 3 \times 10^{-11} \Omega\text{-cm}^2$ is now considered. The combined grain-boundary- and surface-scattering case

[Eq. (4)] is used to allow smaller r values to be obtained. Calculated values of ρ_{f0} for $p = 0$ and $r = 0.31$ are shown as the solid curve in Fig. 5. Good agreement is observed between the calculated and measured values. The growing disparity, apparent at $d \lesssim 35$ nm, is primarily a consequence of Eq. (4) no longer being a sufficiently good approximation to the full M-S theory. For example, Teller [12] shows that M-S would give $\rho_f(30 \text{ nm}) \approx 1.2 \times$ higher, in good agreement with the measured values. Thus, the ρ_{f0} data can be explained by a combination of surface and grain-boundary scattering, with r values close to the range observed for other films. The shape of $\rho_{f0}(d)$ and the value of r needed to obtain agreement with the data are again only weakly dependent upon the choice of l_i ; however, reasonable agreement can also be obtained for other choices of r and p . Several such sets of parameters are listed in Table 2. Agreement could not be obtained for the pure surface-scattering case ($p = 0, r = 0$); the calculated values of ρ_{f0} remained $\geq 2 \times$ smaller than the data under all conditions investigated. This is illustrated in Fig. 5 for the $l_i = 2 \mu\text{m}$ case (dotted line).

In summary, we found that comparably good agreement between theory and experiment could be obtained for $r \approx 0.31$ – 0.74 for reasonable values of p and ρl . This is due to the fact that the shapes of the theoretically calculated $\rho_f(d)$ curves for the different combinations of r, p , and ρl (Table 2) are not significantly different from one another compared to the scatter in the data. Thus, the relative contributions to $\rho_{f0}(d)$ of surface and grain-boundary scattering cannot be determined very well by applying these theories to our data.

Discussion

There are several factors which suggest that grain-boundary scattering may be the dominant electron-scattering mechanism in AuIn_2 films. If surface scattering were dominant, the temperature-dependent portion of the AuIn_2 film resistivity at 300 K, $\rho_T = (\beta - 1)\rho_{f0}$, would be smaller than the bulk resistivity [3, 10]. The value of ρ_T previously observed for 280-nm-thick AuIn_2 films [3] and those values observed for the AuIn_2 films in our investigation are found to be comparable to the bulk value of $\approx 7.5 \mu\Omega\text{-cm}$ [7], indicating that surface scattering is not the main factor that determines ρ_{f0} .

The available ρl data for metals suggest that ρl for AuIn_2 is likely to be closer to $0.8 \times 10^{-11} \Omega\text{-cm}^2$ than to $3 \times 10^{-11} \Omega\text{-cm}^2$. Of the approximately twenty metals for which we have ρl data, only Cs and K have ρl values that exceed $2.2 \times 10^{-11} \Omega\text{-cm}^2$. Values of 0.7 – $1.5 \times 10^{-11} \Omega\text{-cm}^2$ are most common. In and Au have values of 1.5×10^{-11} and $0.92 \times 10^{-11} \Omega\text{-cm}^2$, respectively. From Fig. 5 it is evident that the contributions to ρ_f of surface scattering

(dotted curve) and grain-boundary scattering (the difference between the solid and dotted curves) are comparable for $\rho l \approx 3 \times 10^{-11} \Omega\text{-cm}^2$, even assuming maximum surface scattering. Thus, for $\rho l < 3 \times 10^{-11} \Omega\text{-cm}^2$, as is likely for our AuIn_2 films, grain-boundary scattering would be dominant.

Thus, the evidence suggests that grain-boundary scattering may be more important in AuIn_2 films than in other pure metal films. Why this would be the case is not clear. Although incorporation of impurities from the residual gas background present during film deposition has been reported to cause such increased grain-boundary scattering in Mo films [15], this effect does not seem to be important in our work. When the deposition rates of Au and In were increased by $\approx 5 \times$ to reduce the concentration of gaseous impurities, the ρ_{f0} values for AuIn_2 films increased $\approx 20\%$ for Au and remained essentially unchanged for In. This result is probably due to decreasing grain size with increasing deposition rate, and is contrary to what would be expected if incorporation of gaseous impurities were important. Another possibility is that the more complex grain-boundary structure expected for intermetallic compound films results in greater electron scattering than is observed for pure metals.

Summary

The influences of film thickness and composition on the resistivity and microstructure of AuIn_2 films have been investigated. The resistivity at 4.2 K was found to be $\approx 5 \mu\Omega\text{-cm}$ for 40-nm-thick films and to vary as $\rho_{f0} \propto d^{-0.76}$ over the thickness range 30–250 nm. Resistivity changes were also observed as the composition was altered. A decrease of $\approx 10\%$ in the In/Au thickness ratio from that of AuIn_2 produced an increase of $\approx 50\%$ in ρ_{f0} . A similar increase in In/Au ratio produced a $\leq 10\%$ decrease in resistivity. Electron microscopic analysis revealed that the grain size of AuIn_2 films increases with film thickness, and is $\approx 2 \times$ smaller for the films with In/Au < 3.074 than for those ≥ 3.074 . Small regions of darker contrast ("particles") were also observed on or within all films having compositions near that of AuIn_2 ; however, their effect on the film resistivity was judged to be negligible.

The factors governing the resistivity of AuIn_2 films have been analyzed using Fuchs surface-scattering and Mayadas-Shatzkes grain-boundary-scattering theories. It is found that M-S theory can be used to explain the ρ_{f0} data for a range of r and p values. Reasonable agreement was obtained for parameter values between $r = 0.31, p = 0, \rho l = 3 \times 10^{-11} \Omega\text{-cm}^2$ and $r = 0.74, p = 1, \rho l = 0.8 \times 10^{-11} \Omega\text{-cm}^2$. The available evidence is interpreted as favoring grain-boundary scattering as the dominant scattering mechanism.

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