Ageing of Thin Gold Films

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Thin gold metallizations are used in microelectronic devices when high reliability is required. Experience has shown that the operating lives of transistors and monolithic integrated circuits with high power dissipation, and of ultra-high-frequency devices such as microwave integrated hybrid circuits, are longest when gold is used in the manufacture of their interconnections. With gold, the probability of zero-hour failures and of degradation under thermal and electrical load, and in corrosive environments, is very low. The reasons for the high reliability of thin gold metallizations are to be found in the chemical stability of the metal, in the fact that it is not very sensitive to diffusion from other metallizations and in the ease with which connections can be made to it by microwelding (1, 2, 3).

The limits of stability of polycrystalline thin gold films are imposed by their sensitivity to defect reactions. Faraday showed over a century ago, during his experiments on the transmission of light through flash-evaporated thin gold films, that 'the metal appears to run up into globules' (4). This effect is caused by a slight temperature increase of the adherent thin film/substrate system. Recently, many studies have been made of interdiffusion in multilayer metallizations with gold as a component. The aspects of such interdiffusion which affect phenomena discussed in this article include low-temperature interactions (5), diffusion with phase formation (6) and grain boundary diffusion (2, 7).

Interdiffusion and electrotransport (8) are phenomena resulting from the high driving forces (gradients of the chemical potential, and electric field and current, respectively) to which metallizations may be submitted in service. Because they contain lattice defects such as vacancies, dislocations and grain boundaries in much higher concentrations than do metallizations in thermal equilibrium, as-deposited thin metal films are highly susceptible to these phenomena and to their effects which are undesirable from an engineering point of view. However, at temperatures above absolute zero, such imperfect structures tend to transform into more stable ones. They display low-

Table I
Deposition Data for Thin Gold Film Systems Referred to in This Article

Type	Adhesion layer				Gold film				
	deposit	deposition method	residual gas pressure, Pa	growth rate, nm/s	thickness, nm	deposition method	residual gas pressure, Pa	temperature, K	growth rate, nm/s
I	10 nm NiCr	evaporated	$<10^{-3}$	0.2	10^2	evaporated	$<10^{-3}$	330	~0.6
	50 nm NiCr				5×10^2				
	10 nm Mo				10^2				
	50 nm Mo				5×10^2				
	50 nm Ti				5×10^2				
II	10 nm NiCr	sputtered	1.2 (Ar)	0.5	6×10^2	sputtered	1.0 (Ar)	350	~1.0
	20 nm Mo		0.7 (Ar)	0.5	6×10^2				
III					370 to 1 100	evaporated	$<5 \times 10^{-7}$	296	1.2 to 1.8
IV	10 nm Mo	sputtered	0.7 (Ar)	0.5	100	sputtered	0.6 (Ar)	330	0.8
V	10 nm Mo	sputtered	0.7 (Ar)	0.5	50	sputtered	0.6	330	0.8
VI	50 nm Ti	sputtered	1.3 (Ar)	0.6	500	sputtered	0.8 (Ar)	330	1.4
VII	10 nm Ti	sputtered	1.3 (Ar)	0.5	500	sputtered	0.8 (Ar)	330	0.8

rate ageing effects which are very sensitive to temperature, time and, of course, to features of the initial as-deposited structure. Increasing knowledge of these effects has shown that they may, in fact, be exploited to the advantage of the designer of electronic devices.

The purpose of this article is to review previous work and to discuss results obtained from recent research carried out by the authors on:

- (1) How different defect reactions dominate at the various stages of ageing of thin gold films
- (2) The effect of ageing on important physical properties of gold metallizations
- (3) Which aged metallization structures are desirable for optimum long-term stability of thin gold films.

Sample Preparation

The substrates for the deposition of thin gold films were *p*-doped silicon single crystals of $\langle 111 \rangle$ orientation. They had the same thickness, 0.24 mm, as that used in semiconductor applications. The silicon single crystals had been polished and then oxidized in a water vapour-containing atmosphere to form a silicon oxide layer 600 nm thick and of composition between $\text{SiO}_{1.5}$ and $\text{SiO}_{1.8}$. The oxide was amorphous and showed no surface irregularities visible by light interference microscopy or in transmission electron microscopy (TEM) of replicas. These techniques would have revealed a surface roughness greater than the thickness of the following adhesion layer.

Adhesion layers were deposited on the samples for recovery experiments. The thickness of these layers was such that the heat treatments did not cause loss of adhesion of the thin gold films under investigation (9, 10). The gold films for the recrystallization experiments were evaporated without adhesion layers in order to avoid, at a later stage, anchoring of grain boundaries in them by species which diffused from the adhesion layer (11). Table I shows the deposition conditions for the metallizations discussed in this article.

The purity of the sputter targets and of the ingots for electron beam evaporation was better than 99.998 weight per cent. The residual gas pressures and the growth rates reported in Table I were selected to ensure that the gold deposits had a concentration of impurities of less than 20 ppm. The sputtered layers contained a small amount of sputter gas (argon) trapped in grain boundaries and pores in the metallization. The films used for the recrystallization experiments were evaporated in ultra-high vacuum and had an impurity level of less than 10 ppm.

Figure 1 shows schematically the cross-section of the samples. After chemical dissolution of the adhesion layers and thinning by ion etching, the gold had a grain size of about 100 to 150 nm (Figure 2). Ion-etching of both sides of

Fig. 1 Schematic cross-section of the metallizations used for this study

the thin gold films revealed that the grain sizes on both their bottom and top surfaces were similar.

Mechanical wiping and scratching affect the behaviour of freshly deposited metallizations during subsequent heat treatment (9). Therefore, only thin films with undamaged surfaces were used for the ageing experiments.

Recovery

Fine-grained thin films contain higher concentrations of lattice defects than does metal in bulk form. They are in a thermodynamically unstable state and, upon increasing their temperature to just below the melting point of the metal, their free energy can be lowered by the annihilation and rearrangement of lattice defects in various ways.

Fig. 2 Transmission electron micrograph of an evaporated thin gold film removed from the silicon substrate by chemical dissolution of the adhesion layer and thinned by ion etching from the side of the adhesion layer

Fig. 3 Temperature, T , against time, t , relationship for samples submitted to (a) isochronal and (b) isothermal heat treatments. The resistance measurements were all made at a reference temperature (78 or 309.2 K) at times marked by an asterisk

The fundamental structural processes which may be involved during annealing of materials containing defects fall into five categories. These are (12):

- (i) Reactions of point defects and of clusters of them; in particular the annihilation of interstitials and vacancies
- (ii) The annihilation of dislocations of opposite sign and the shrinking of dislocation loops
- (iii) The rearrangement of dislocations from high energy configurations to lower energy configurations
- (iv) The absorption of point defects and dislocations by grain boundaries migrating through the metal
- (v) The reduction of the total grain boundary area.

Generally, a polycrystalline metal does not attain thermodynamic stability by a single process. In fact, all the reactions mentioned above contribute to the process either singly or simultaneously.

The defect structures in condensed thin films are comparable to those in polycrystalline bulk metals quenched

from high temperatures, or to those in irradiated materials. Processes (i) and (ii) are observed upon annealing of such structures. When considered together, processes (i) and (ii) are termed recovery. Processes (iv) and (v), which involve migration of large-angle grain boundaries, are termed recrystallization. The intermediate process (iii) contributes to the formation of small-, as well as large-angle grain boundaries, and is regarded as a part of recrystallization.

A useful tool for investigating defect reactions is the measurement of DC electrical resistance. The reasons for this are the ease of achieving high accuracies and the possibility of comparing readily the behaviour of different samples. An essential condition is that the DC resistance should continually increase with the duration of the ageing treatment. Another is that the resolution of the measuring equipment should be high compared to the changes in resistance during ageing.

In the measurement of DC resistances for this investigation, 16 different values of DC current were used. When fitting the slope of the measured voltages, an accuracy of 1.65×10^{-3} was reached for resistance values from 0.1 ohm upwards. The resistances of the samples were compared to that of a standard measured simultaneously. The resulting plots show the deviations of the resistance of each sample, after each heat treatment step, from its initial resistance before ageing.

Figure 3 schematically shows the sequence of measurements and of heat treatments. Both isochronal and isothermal treatments are used to determine the thermal activation energy Q of the ageing process (13). If only one of the ageing mechanisms, numbered (i) to (v) above, is active, the change in the average concentration C of the reacting defects is given by:

$$\Delta C = -\alpha C^{\gamma} \exp(-Q/T)$$

where:

α is the reaction rate

γ is the reaction order

k is the Boltzmann constant

Q is a sensitive indicator of the kind of atomistic reaction occurring and is the physically interesting parameter in this relationship.

Figure 4 shows the changes in the DC resistances during isochronal heat treatments of different evaporated gold/adhesion layer combinations. In the system gold/nickel-chromium, alloying of the gold by diffusion of the nickel and chromium occurs. The relative changes in the DC resistance during ageing are higher for the thinner film combinations at lower temperatures. In the system gold/molybdenum, recovery occurs independently of the

layer thickness. This was confirmed by tests on gold/molybdenum metallizations prepared under various conditions of residual gas pressure, growth rate and heat source — electron beam gun or resistance heating.

The temperature against time correlations shown in Figure 5 are obtained from the values of these two parameters yielding equal changes in resistance during isochronal and isothermal heat treatments. The gold/molybdenum combination, in which no interdiffusion occurs, yields a thermal activation energy for ageing between that for the migration of vacancies in gold, 0.93 eV (14), and that for self-diffusion in gold, 1.7 eV (15). The recovery of the gold/nickel-chromium system has a thermal activation energy near that for grain boundary interdiffusion, about 0.5 eV (2).

The holding time during the isochronal heat treatments (1 hour) covers the initial stage of recovery. This is also true for the gold/nickel-chromium system in which diffusion takes place. Figure 6 shows the changes in resistance of various thin film combinations, measured with an accuracy of 1.6×10^{-5} . The resolution of the recovery effect is improved by using heat treatments of short duration.

Recovery is defined as continuing until a resistance minimum occurs, and up to this point no change was observed in the grain size of gold films and, using TEM, no marked grain growth was found. Upon completion of recovery, the resistance increases, due to the diffusion of nickel and chromium into the gold. Figure 7 shows concentration against depth profiles measured by secondary ion mass spectrometry before and after isochronal ageing of a gold/nickel-chromium sample. The high surface concentrations of chromium and nickel are caused by grain boundary diffusion, and surface sinking results from the oxidation of these metals at the free surface of the gold.

Thin gold films with titanium adhesion layers show an identical recovery process followed by interdiffusion. However, here the first steps of phase formation have been observed (16). The formation of the Au_4Ti phase — after 10 minutes at 573 K — was rather faster than indicated by other experiments (6).

Recrystallization

The behaviour of high-angle grain boundaries is sensitive to the presence of impurities, so our recrystallization study was made on gold films evaporated directly onto oxidized silicon in ultra-high vacuum (Type III of Table I).

The time and temperature ranges for the heat treatments were from 1 to 384 h and 370 to 570 K, respectively. The lower limits were set to ensure that the recovery process was completed, while the upper limits coincided with the start of crystallization effects on the surface of the gold (see below).

Gold-coated substrates without adhesion layers were

Fig. 4 Changes in resistance during 1 h anneals of evaporated gold films on various adhesion layers (Type I, Table I)

Fig. 5 Temperature-time correlations for the ageing of thin gold film combinations — from data giving equal changes in resistance during both types of heat treatment

A = 500 nm gold on 50 nm molybdenum, $Q = 1.5 \pm 0.04$ eV
 B = 500 nm gold on 50 nm nickel-chromium, $Q = 0.68 \pm 0.03$ eV
 C = 100 nm gold on 10 nm molybdenum, here two different kinetics are visible, $Q \approx 0.97$ eV and $Q > 1.8$ eV

scratched and broken into pieces, each with an area of approximately 25 mm^2 . The specimens were then subjected to heat treatment in air or ultra-high vacuum (less than 10^{-8} Pa residual gas pressure). The samples for TEM were prepared by detaching the thin gold films from the substrate. The films did not curl up on separation, which indicated that

they were stress-free. After fixing portions of the films to a grid support, thinning was carried out by ion etching with the accompanying temperature increase being limited to 5 K.

The films were studied in a microscope in beams of 80 and 100 kV electrons. Bright-field images were used for the determination of the average grain diameters (calculated from the number of large-angle grain boundaries intercepted by cross-lines). Dark-field images were used to establish the orientation of individual grains. The indexing of the diffraction patterns was carried out using the ratio method (17).

Grain Orientation

Comparison of TEM micrographs of gold films which had been thinned from either the free surface or from the interface with the substrate, with micrographs of as-deposited films which were sufficiently thin for direct observation in the microscope, showed no marked differences in the grain structures. This indicates that continuous nucleation and columnar grain growth occur during deposition. In several areas of the gold layers, the orientations of the as-deposited grains were not distributed statistically; there were local

Fig. 8 Dark-field transmission electron micrographs of a 90 nm thick gold film deposited in ultra-high vacuum (Type III of Table I)

(a) Beam tilt for illumination with a $\{200\}$ reflexion; $\langle 100 \rangle$ grains are bright

(b) Beam tilt for illumination with a $\{220\}$ reflexion; $\langle 110 \rangle$ grains are bright

Both micrographs show the same section of the film at a magnification of $\times 4\,000$

accumulations of certain crystal types. For example, a concentration of $\langle 100 \rangle$ grains can be seen in the upper part of Figure 8 (a), while $\langle 110 \rangle$ grains predominate in the middle part of Figure 8 (b). Results such as these indicate that many TEM observations are necessary if reliable conclusions are to be drawn on the recrystallization structures of, and grain growth in, thin films. From numerous observations it has been estimated that more than 80 per cent of the recrystallized gold film areas had even distributions of $\langle 100 \rangle$, $\langle 110 \rangle$, $\langle 111 \rangle$, $\langle 311 \rangle$, $\langle 331 \rangle$ and $\langle 210 \rangle$ grains.

Grain Size

The average grain size $\bar{D}_0$ measured on the free surface of as-deposited gold films somewhat increases with the film thickness d . For instance, when d increases from 90 to 370 nm, $\bar{D}_0$ increases slightly from 50 to 60 nm, and when d reaches 670 nm, $\bar{D}_0$ rises to 250 nm.

During heat treatment in air or in vacuum, the thin films show marked, but uneven, grain growth. Figure 9 shows the structure of a 370 nm thick gold film before and after heat treatment in ultra-high vacuum. The large grains present after annealing have a $\langle 100 \rangle$ orientation (11).

In order to produce elongated grains of up to 1 500 nm, thicker gold films (670 or 1 100 nm) had to be heat-treated,

Fig. 9 Bright-field micrographs of a 370 nm thick gold film before (inset) and after a heat treatment in ultra-high vacuum at 480 K for 40 h $\times 42\,000$

Fig. 10 (a) Bright-field micrograph of a $\langle 100 \rangle$ grain with twins $\times 13\,200$
 (b) Selected-area diffraction pattern of (a)
 (c) SEM secondary electron image of a larger $\langle 100 \rangle$ grain also with twins $\times 10\,000$

but only for a short time (1 to 5 h at 480 to 580 K). Grain growth in the 1 100 nm thick films was always inhomogeneous, large elongated grains being found adjacent to fine-grained areas.

From the observation of numerous TEM micrographs, the conclusion can be drawn that a well-defined and simple distribution of grain sizes in the as-deposited condition results in the growth of uniformly sized grains during recrystallization and conversely (11). Table II illustrates this conclusion with some typical results.

Scanning electron microscope (SEM) observations confirm the phenomena detected in the TEM micrographs. The bright-field TEM micrograph of Figure 10 (a) shows twins in a $\langle 100 \rangle$ grain as small, contrasted rectangles. The coherent twin boundaries are long and straight, whereas the incoherent boundaries are short and jagged. The twin planes have $\{ 111 \}$ indices and the corresponding diffractions are found in all the patterns obtained from discontinuously grown $\langle 100 \rangle$ grains (Figure 10 (b)).

In the SEM secondary electron image, the different grain orientations lead to different image intensities. The elongated grains and the twins are clearly distinguishable (Figure 10 (c)).

Driving Forces and Growth Limits

The recrystallization of bulk metals by nucleation of new grains and their growth requires nuclei with a minimum size of about 1 000 nm. These have low defect densities and may

form as a result of grain boundary migration into grains with high defect densities (18). The thin gold films discussed here had initial grain sizes which were much smaller (Table II).

Nucleation of new grains is not required for recrystallization which may also occur by grain growth alone. This is indeed what we observed in thin gold films. However, the mechanism of grain growth has not yet been modelled quantitatively (19) and only qualitative experimental data are available concerning the dependence of grain boundary mobility on the driving forces produced by different kinds of lattice defects.

The forces driving or retarding grain boundary movement in thin gold films are listed in Table III. The annihilation of dislocations and the reduction of the grain boundary area per unit volume are the most effective driving forces. The maximum recrystallization grain size $\bar{D}_{lim}$ is determined by the equilibrium between these two driving forces and the retarding force due to surface grooving (Table III) yielding:

$$\bar{D}_{lim} = 12d$$

Table IV shows the maximum grain sizes observed by us to be comparable with this estimated value.

Crystal Ripening

Heat treatment of thin gold films at elevated temperatures and for several days leads to the formation of gold crystallites on their surfaces. Figure 11 shows how this phenomenon characteristically begins with local thickening and pore formation in a gold/molybdenum metallization. The material which is necessary for the local thickening migrates

Table II
Typical Grain Sizes of Thin Gold Films
(Type III of Table I) after Heat Treatments

Film thickness, nm	Heat treatment temperature, K	Heat treatment time, h	Grain size, nm		
			min.	ave.	max.
90	—	—	60	25	250
	480	1	130	50	800
	570	1	170	50	800
	370	5	75	25	250
	470	5	110	25	600
	570	5	110	50	900
	370	168	130	50	900
	450	168	130	50	900
	570	384	190	80	1 400
	—	—	—	110	~ 1 100
	370	—	—	120	~ 800
	480	1	—	200	> 1 500
670	570	—	—	790	> 1 500
	370	—	—	170	~ 1 000
	480	5	—	—	> 5 000
	570	—	—	880	~ 5 000
	370	168	—	240	~ 25 000
	480	180	—	1 010	~ 6 500
	570	168	—	1 610	~ 6 500
	—	—	—	—	—
	—	—	—	—	—
	—	—	—	—	—

Table III
Forces Driving or Retarding the Motion of a Grain Boundary

Cause of the force	Formula	Parameter values for gold thin films	Driving forces, N/m ²	Retarding force, N/m ²
1. deformation energy	$p \approx \rho G b^2$	$\rho = 10^{11}$ to $10^{12}/\text{cm}^2$	10^7 to 10^8	10^6 to 10^5
2. GB energy	$p \approx \frac{3\gamma_{GB}}{\bar{D}}$	$\bar{D} = 50$ to 170 nm	10^7 to 10^8	
3. difference in surface energy of adjacent grains	$p \approx \frac{2\Delta\gamma_s}{d}$	$d = 90$ to 1100 nm $\Delta\gamma_s \geq 0.1$ J/m ²	10^8 to 10^5	
4. thermally induced mechanical stress	$\mu = \frac{1}{2} \frac{\tau^2}{E}$	$\Delta\alpha = 7 \times 10^{-6}/\text{K}$ $\Delta T \approx 200$ K	10^5 to 10^6	
5. surface grooving	$p \approx \frac{\gamma_{GB}^2}{2d\gamma_s}$	$d = 90$ to 1100 nm		

p = driving/retarding force, ρ = density, τ = mechanical stress, E = elasticity modulus, d = film thickness

Fig. 11 Local thickening and pore formation during extended heat treatments of gold thin films

- (a) Type IV metallization of Table I, heat treated by linearly increasing temperature from 323 to 526 K over 41 h in laboratory air $\times 8\ 000$
 (b) Type V metallization, heat treated at 684 K for 169 h in helium $\times 2\ 300$

from the thin film sites adjacent to the growing area. The thicker parts are connected to the residual thinned gold film, so that local thickening is different from the classical process of ripening of a separated crystal on a carrier, or in a transport medium.

If the gold film is sufficiently thick, and there is a relatively thin adhesion layer of titanium or molybdenum, faceted single crystals of gold are formed in an inert gas atmosphere (Figure 12). These crystals have the shape of truncated octahedra which is that with minimum surface energy for fcc single crystals (20). The crystals have a $\{111\}$ axis perpendicular to the thin film plane, which has been found to be the preferred orientation of dendrites of gold growing on amorphous substrates (21). The time required for producing ripened crystals with a size of 1 000 nm or more is 65 hours at 523 K or 20 hours at 673 K. These crystals are chemically pure, containing less than 0.1 weight per cent of the adhesion layer metal (for example, titanium) — the residual gold layer contains the diffused species (22).

The thin gold films are not subjected to a temperature gradient, an electric current or a chemical potential gradient during heat treatment. Possible transport mechanisms are therefore surface diffusion and/or bulk diffusion and/or diffusion along defect paths such as grain boundaries and dislocations. Evaporation and re-condensation can be excluded, because the cold spots in the furnaces used for our experiments would have acted as sinks for any vapour which was present, and on account of the low vapour pressure of gold at the temperatures employed.

At low temperatures, transport phenomena with low thermal activation energies are more effective than those with high thermal activation energies. Thus, surface self-diffusion of gold with an activation energy of 0.23 eV (23) and grain boundary diffusion with an activation energy of about 0.5 eV (9, 24) are more effective than other transport phenomena at these temperatures. The relaxation of stresses in the thin gold film could provide the necessary driving force.

Table IV
The Limit of Grain Growth Given by Equating Causes 2 and 5 of Table III

d , nm	Observed $D_{\max}$
90	2d to 15d
370	1d to 4d
670	4d to 10d
1100	20d to >30d

The recovery of lattice defects, recrystallization and the growth of crystals with low specific energy are made at the expense of crystals with high specific energy. This effect is called Ostwald ripening and has been treated theoretically by Wagner (25). By consideration of the changes in specific energy, it can be shown that the relaxation of mechanical stresses yields a greater driving force than the recovery of defects (22).

Assuming that a gold film is stress-free at the deposition temperature, the positive difference between the thermal expansion coefficient of gold and that of its silicon substrate ($\alpha_{Au} - \alpha_{Si}$) introduces a compressive stress at elevated temperatures. This can be lowered by partially reducing the volume per area F :

$$\Delta V = 2d \Delta F (\alpha_{Au} - \alpha_{Si}) \Delta T$$

With the experimental data $d = 600$ nm, $\Delta T = 100$ to 250 K, $(\alpha_{Au} - \alpha_{Si}) = 6.7 \times 10^{-6}/K$ one finds $\Delta V / \Delta F = 0.8$ to 2 nm³ per nm², this being much lower than the observed volume of the faceted crystals (20 to 200 nm³ per nm²). The crystal growth must then be governed by the Ostwald ripening.

Indeed, using the results of Wagner (25) and equating the diffusion flow of gold at the surface of the thin films with the volume growth of the faceted crystals, it is possible to predict for ageing temperatures of 523 to 633 K and times of 10 to 200 h, average crystal radii of 500 to 800 nm, which agrees well with experimental observations.

Fig. 12 Examples of crystal ripening on different gold thin film/adhesion layer combinations aged in helium

- (a) Type VI metallization of Table I, heat treated at 664 K for 166 h $\times 10\ 600$
- (b) Type VII metallization of Table I, heat treated at 664 K for 166 h $\times 9\ 000$
- (c) Type V metallization of Table I, heat treated at 684 K for 169 h $\times 12\ 200$

Stability of Thin Gold Films

Thin metal films are susceptible to ageing. This is due to the high density in them of lattice defects and to stresses arising from the composite nature of the gold/substrate system.

Ageing affects the reliability of components and circuits which incorporate thin films of metals (including gold) and its results can be used to characterize thin film technology (26). To establish reliability, it is necessary to predict property changes for a given batch of devices from ageing experiments on samples from that batch.

Two fundamental problems are attached to obtaining meaningful data from ageing investigations. First, the extrapolation of changes in physical properties observed in accelerated experiments under high loads in order to predict the changes which will occur in long-term use under smaller operating loads is difficult in practice. Secondly, it is not always possible to distinguish between failures which develop gradually and those which occur catastrophically through a variety of causes. Both problems have been solved in only a few relatively simple cases. The operating behaviour of components can be forecast only if the dominant ageing process which governs changes in their technical specifications can be related to point defect reactions (recovery and diffusion) within ranges shorter than the minimum grain

size, to chemical reactions and phase formation, for example diffusion of the adhesion layer to the free surface, or to changes in structure with interaction distances longer than the grain size and film thickness. This is an approximate classification of partially overlapping phenomena such as recovery, recrystallization, grain boundary migration and interdiffusion.

Summarizing the evidence collected from Faraday onwards, one might conclude that 'thin film metallizations are not stable' (27). However, thin gold films can be, and are, made very stable, particularly when the technical reliability of professional electronic equipment is required. It can be concluded, from the ageing experiments described above, that the probability of reliable functioning of devices containing thin gold films will be increased if the following conditions are satisfied:

- (1) The grain size is uniform with a maximum grain diameter approximately 4 times the film thickness (11)
- (2) Interdiffusion via grain boundaries is minimized by stabilization of the adhesion layer (26)
- (3) Any mechanical disturbance of the metallization, except microwelding, should be avoided (22)
- (4) Thermal cycling due to heat-sink soldering, photo-resist baking and other necessary production steps is reduced to a minimum (10).

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