GOLD-ALUMINIUM INTERMETALLIC COMPOUND FORMATION

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During investigations of failure mechanisms and failure avoidance we have studied the kinetics and the mechanisms responsible for the growth of the Au-Al compounds. Au_4Al , Au_5Al_2 , Au_2Al , $AuAl$, $AuAl_2$ have been observed and the growth kinetics of the Au_2Al , $AuAl$, $AuAl_2$ follow a $(\text{time})^{1/2}$ dependence. The activation energy for the growth of Au_2Al is 1 eV and 1.2 eV was found for $AuAl$ and $AuAl_2$. The kind of compound formed depends on the samples preparation and the results indicate that the kinetics of the mixing is the main mechanism responsible for the sequence of formation of the various compounds.

1. INTRODUCTION

Au-Al thermocompression bonds are generally used for *monolithic* and hybrid integrated circuits as well as for discrete devices. Their break-down is caused in most cases by the failure of the Au-Al bonds. Degradation of the bonds appears in their increased resistance or total rupture. It has been observed that in certain cases loose, voided phases appear at the failed Au-Al bond, which are described in the literature as Au_mAl_n intermetallic phases.^{1,2,3} These phases do not cause failure by themselves but certain types of the failures, i.e. broken metallization around the bond, lifted bonds, cracks are related to the formation of these phases.^{4,5,6}

The purpose of the present paper is to show, in the form of an investigation into the failure mechanisms and the possibility of avoidance of them, a) the kinetics of the compound formation and b) the mechanisms responsible for the growth.

2. EXPERIMENTAL METHOD

On thermally oxidized Si single crystal, Au and Al films were deposited in a high vacuum oil-free system by e-gun. To minimize interface effects, mainly due to oxygen contaminations, gold was deposited first followed by Al, without breaking the vacuum. The thicknesses of Au and Al range between 1000 Å and 3000 Å. Thermal annealing was carried out in a 10^{-7} torr furnace in 50°C to 500°C temperature range. The different compounds were identified by X-ray diffraction and MeV $^4\text{He}^+$ Rutherford backscattering was used to measure the thicknesses of the compound layers with a resolution of about 200 Å. Both the techniques are widely described in the literature.^{7,8}

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FIGURE 1 Schematic diagrams showing the compound formation in Au-Al system. It seems that initially Au_5Al_2 is formed by reaction at room temperature. Depending on the relative thickness of Au and Al films, different compounds can be formed.

TABLE I
End phases in the Au–Al thin films interactions

Sample	End phase		Thickness (Å)		Compound
	500°C 10 ^h	Al evaporated	Au evaporated	Compound	
1	AuAl ₂	5700	1100	3400	
2	AuAl	1400	1500	3000	
3	Au ₂ Al	850	1800	2600	
4	Au ₅ Al ₂	900	2500	3350	
5	Au ₄ Al	600	2400	2400	

In Figure 1 the phase diagram of the system Au–Al is shown. Five different compounds are predicted: AuAl₂, AuAl, Au₂Al, Au₅Al₂, Au₄Al. The sequence of formation for the various compounds is resumed in the same figure. The first phase formed at low temperature is Au₅Al₂ in competition with Au₂Al. The question mark near Au₅Al₂ indicates that we are not sure if Au₅Al₂ is formed before Au₂Al or not. By pushing the heat treatment Au₂Al is formed. Now depending upon the relative quantity of Au and Al three different sequences can be constructed. The end phases are AuAl₂ in the case $Au \ll Al$, AuAl in the case $Au = Al$ and Au₄Al for $Au \gg Al$. These sequences follow a precise scheme: AuAl₂ starts to form only when all Au is consumed, Au₄Al only when all Al is consumed and AuAl starts to develop only when both Al and Au are consumed. Au₂Al and Au₅Al₂ are end phases only when the thicknesses of Au and Al films were chosen in such a way that the Au/Al atomic ratios were made 2/1 and 5/2 respectively. The end phases have been found to be stable up to 500°C. The list of the samples made is given in Table I, together with thicknesses of Au, Al and resulting compound formed after heat treatment. These data have been obtained by a backscattering technique.

The growth rate proportional to $\sqrt{t}$ and controlled by a single activation energy E_T for different times and temperatures has been determined for Au₂Al,⁹ AuAl₂ and AuAl.

Figure 2 shows the typical backscattering spectra of the sample as evaporated and after heat treatment at 247°C for different times. The Au and Al thicknesses are 1500 Å and 1400 Å respectively. The formation of the compound occurs at room temperature and the high ratio between Au unreacted and Au in the compound indicates the presence of Au₅Al₂ in agreement with X-ray diffraction analysis. After heat treatment at 247°C for 5 min only the compounds Au₂Al and AuAl₂ have been observed as confirmed by X-ray diffraction data. These compounds constitute two layers, not mixed, Au₂Al

FIGURE 2 ⁴He⁺ MeV backscattering spectra of the samples as evaporated and after annealing at 247°C for 5 min, 15 min, 120 min..

near the substrate and AuAl₂ on top of it. By further heating at the same temperature for 15 min a step at energies around 1.55 MeV starts to develop. This step corresponds to the formation of a layer of AuAl between the two previous ones. The AuAl layer grows utilizing material either from Au₂Al or from AuAl₂. By increasing the annealing time, AuAl grows and after 120 min Au₂Al and AuAl₂ are almost completely converted into about 3000 Å of AuAl.

Figure 3 reports at two different temperatures, 217°C and 247°C, the dependence of the square of the thicknesses of AuAl upon the annealing time. The experimental data are fitted by a straight line indicating that diffusion through AuAl is the limiting process for the growth of the compound. The data show the presence of a delay in AuAl formation, a delay which is attributed to the time necessary to consume all the Al to form AuAl₂. Also, in the same figure, the kinetic growth of AuAl₂ at 217°C

FIGURE 3 Square of AuAl and AuAl₂ thickness as a function of time. t_D corresponds to time necessary for the formation of about 1500 Å of AuAl₂.

obtained by backscattering data, is reported. This phase has been identified by X-ray diffraction data.

The growth rate of AuAl and AuAl₂ as a function of $1/T$ is shown in Figure 4 compared with the data obtained for AuAl₂ and Au₂Al compounds by Campisano et al.⁹ AuAl has a growth rate controlled by a single activation energy $E_T = 1.2 \pm 0.1$ eV, the same has been obtained from AuAl₂. The growth rate of AuAl₂ measured here is in agreement with the data of Campisano et al.⁹ The growth rates of Au₄Al and Au₅Al₂ are not measured yet.

Moreover, although quantitative data are not available yet, the impurities play a fundamental role in the kinetics and/or nucleation of intermetallic compound formation. In the Au-Al system, for instance, the hydrogen inhibits the phases formation, the presence of Si accelerates the formation of some phases and the oxygen decomposes the AuAl₂ compound.

FIGURE 4 Arrhenius plot of AuAl, AuAl₂ and Au₂Al formation compound.

3. DISCUSSION AND CONCLUSION

All the phases predicted by the phase diagram of Au-Al system were obtained with a low temperature process by thin film interactions. The sequence and the kind of compounds formed strongly depend upon the thickness of deposited material: samples made differently give different compounds, even if the same heat treatment is performed. This indicates that the kinetics of compound formation and, above all, the end phases, are not controlled by the stability of the compound itself but by the quality and kind of the material available for the reaction. In other words the nucleation of a compound seems to be controlled by the boundary conditions. Also the delay in AuAl formation shown in Figure 3 is due to a nucleation phenomenon inhibited by the presence of Au or Al more than to a different growth rate of AuAl compared to AuAl₂ or Au₂Al. The growth kinetic of Au₂Al,⁹ AuAl, AuAl₂ phases is proportional to $\sqrt{t}$ indicating that the transport across the compound layer is the limiting step in the process. In the temperature range considered one single activation energy E_T is found. Marker experiments are necessary in order to identify the moving species.

In conclusion we have shown that the sample preparation plays a fundamental role in the Au-Al phases which are mainly responsible for the failure observed when Al and Au are used.

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