Effect of Chromium-Gold and Titanium- Titanium Nitride-Platinum-Gold Metallization on Wire/Ribbon Bondability

[1]Jianbiao Pan, [2]Robert M. Pafchek, [2]Frank F. Judd, [2]Jason Baxter
[1]California Polytechnic State University
Department of Industrial & Manufacturing Engineering
1 Grand Ave.
San Luis Obispo, CA 93407
Phone: (805) 756-2540 Fax: (805) 756-1420
Email: pan@calpoly.edu
[2]Agere Systems, Allentown, PA

Abstract

Gold metallization on wafer substrates for wire/ribbon bond applications require good bond strength to the substrate without weakening the wire/ribbon. This paper compares the ribbon bondability of Cr/Au and Ti/TiN/Pt/Au metallization systems. Both Chromium and Titanium are used to promote adhesion between substrates and sputtered gold films. Both can diffuse to the gold surface after annealing and degrade the wire/ribbon bondability. Restoring bondability by ceric ammonium nitrate (CAN) etch was investigated.

Experiments were conducted to investigate the effect of Cr/Au and Ti/TiN/Pt/Au, annealing, and CAN etch processes on 25.4 x 254 μm (1 x 10 mil) ribbon bonding. All bonds were evaluated by noting pull strengths and examining specific failure modes. The results show that there is no significant difference in bondability between Cr/Au and Ti/TiN/Pt/Au before the annealing process. At this point excellent bond strength can be achieved. However, wire/ribbon bondability of Cr/Au degraded after the wafers were annealed. The experimental results also show that a CAN etch can remove Cr oxide. Improvement of wire/ribbon bondability of Cr/Au depends on the CAN etch time. The annealing process does not have significant effect on bondability of Ti/TiN/Pt/Au metallization. Auger Electron Spectroscopy was used to investigate what caused the difference in bondability between the two metallizations.

Introduction

Future developments in silicon waveguide devices such as thermo-optics require multilevel metallization in addition to the deposition of doped silica layers. There are several available metallization schemes under consideration that could meet the requirements for resistance and stability. The specific metallization systems tested were Cr/Au and Ti/TiN/Pt/Au.

Both Chromium (Cr) and Titanium (Ti) are used to promote adhesion between substrates and sputtered gold films. Both can diffuse up to the gold surface after annealing and then oxidize [3]. Thus they will degrade the wire/ribbon bondability. For example, thermocompression bondability of 3 μm thick Au films degraded after heating Cr/Au films for 2 hours at 250°C [1]. Higher temperature can increase Cr diffusion speed and decrease the diffusion times to Au surface significantly [2]. It has been shown that these bonding problems can be eliminated either by etching the gold surface using KI + I2 so that the attached oxide is removed, or by etching with ceric ammonium nitrate (CAN) to remove the oxide without affecting the gold [1, 3].

Titanium diffuses very slowly and should not reach the surface of the gold film without exposure to temperature higher than 300°C. But it is unknown whether titanium can diffuse to gold surface through grain boundaries then causes a bondability problem if annealing process takes long time at higher temperature than 300°C.

The purpose of this study was to determine which metallization is better for wire/ribbon bonding: Cr/Au or Ti/TiN/Pt/Au.

Design of Experiment

Two experiments were designed to examine the effects of metallization scheme on ribbon bondability. The first experiment focuses on metallization without annealing. The second experiment includes effects of the annealing and the CAN etch. Samples for both experiments were prepared by dicing wafers and mounting them on a suitable metal package with epoxy so that the wafers were clamped well during bonding.

The bondability was based on evaluations using gold ribbon 25.4 μm (1 mil) thick and 254 μm (10 mil) wide. Bondability of wide gold ribbon was judged to be more sensitive to the metallization structures under study here than a round wire. Ribbon samples were tested destructively on a Dage pull tester. Pull strengths and failure modes were recorded. The ribbon bonds were made using an automated Palomar 2470V bonder using row bond mode.

Experiment 1

The first experiment consisted only of wafers without annealing. A 2 factor 2 level factorial design was selected in this experiment. The samples were split into four cells: Cr/Au, one with 10 minutes of UV ozone cleaning and one without, Ti/TiN/Pt/Au, one with 10 minutes of UV ozone cleaning and one without. The purpose of UV ozone cleaning is to remove the contamination from wafer surfaces.

To achieve the highest pull strength, bonding process parameters were optimized and are shown in Table 1. Loop profile parameters are listed in Table 2. Each package was bonded with 100 ribbons. Thermal cycling was used to evaluate the reliability of ribbon bonds. After thermal cycling (0 ~ 85°C, 4 cycles), all ribbons were pulled. Pull strengths and failure modes were documented in Table 3.

Table 1. Process parameters

	1^{st} bond	2^{nd} bond
Force (grams)	120	130
Time (msec.)	500	500
U/S Power	60	60
U/S Mode	voltage	voltage
U/S Type	ramp	ramp
Delay time (msec.)	250	250
Workholder temp.	150°C	

Table 2. Loop profile

Loop mode	2
Loop parameter A	160
Loop parameter B	55
Loop parameter C	70
Loop parameter D	85
Loop height	140

Bond pull strength testing was accomplished in accordance with MIL-STD-883E, method 2011.7. Per MIL-STD-883E, the minimum bond pull strength for the 25.4 μm x 254 μm (1 x 10 mil) gold ribbon bonds is 20 grams. Note that pull strength is loop dependent. In this study, measured loop height was 203 μm (8 mil) and measured loop length was 508 μm (20 mil) with the loop profile parameters listed in Table 2. The two bonds were at the same level on wafer surface and the pull hook was at the center of the loop as shown in Figure 1. The tensile strength in the 1^{st} bond and the 2^{nd} bond can be calculated according the following equation [3].

$$F_1 = F_2 = \frac{F}{2}\sqrt{1+(\frac{d}{2h})^2}$$

The loop profile in this study results in both the break strength at the 1^{st} bond and at the 2^{nd} bond were the same and about 0.8 times of the pull strength at the hook.

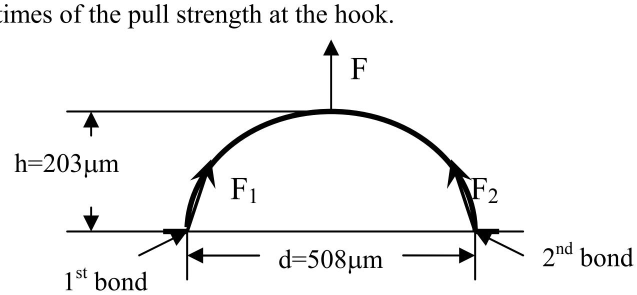

Figure 1. Ribbon bonds pull test geometry

Table 3 shows that there is no statistically significant difference in ribbon bondability between the Cr/Au and the Ti/TiN/Pt/Au metallization systems without annealing. Both metallization systems without annealing provide excellent bondability. The average pull strength is more than 18 sigma above the minimum bond pull strength defined by MIL-STD-883E. Note that the difference between foot lift and non-stick in failure mode is that foot lift means the whole bond foot is lifted after the destructive pull test while non-stick means ribbon won't stick to the substrate during ribbon bonding. Although Table 3 shows that there were 2% and 1% foot lifts on Cr/Au metallization without UV Ozone cleaning, and UV Ozone cleaning for 10 minutes, respectively, the bonding process could be adjusted to eliminate the undesired failure mode. Generally speaking, there is a correlation between bond strength and wire/ribbon deformation [4]. Increasing bonding ultrasonic power and/or bonding time can deform wire/ribbon more, which will make stronger bond between bond foot and the substrate but weaken the heel. The UV ozone clean did not improve bonding performance indicating that there might not have been much contamination on the wafer surface in this experiment.

Experiment 2

From the result of the previous experiment, it seems clear that both Cr/Au and Ti/TiN/Pt/Au metallization systems are accepted for 1 x 10 mil ribbon bonding process. The purpose of the second experiment is to determine whether an additional wafer annealing process has a detrimental effect on ribbon bonding performance. The purpose of the annealing process is to stabilize the metallization system. In this experiment, the annealing process added during wafer fabrication was a 400°C air bake for 30 minutes to pronounce the effect.

The second experiment was split into 16 cells as illustrated in Figure 2. The two metallizations each had one annealed and one no-annealed sample with each of these being with or without CAN etch. After ribbon bonding, half of the bonds were pulled right away and half were pulled after temperature cycling of 0 ~ 85 °C for 4 cycles.

The CAN etch was 1 minute. The solution for CAN etch consists of 65-75% water, 20-30% ceric ammonium nitride, and 1-5% acetic acid. All of the samples received the 10 minutes UV ozone cleaning after the CAN etch.

All bonding parameters and loop parameters were the same as in Experiment 1 except the ultrasonic power increased from 60 to 65. The purpose of the change was to eliminate the foot-lift failure mode. Some gold peel-off was observed on annealed wafer with Cr/Au metallization during dicing.

The pull strengths and failure modes are summarized in Table 4. The data show that all bonds were foot lift or non-stick on annealed Cr/Au metallization. Although different bonding parameter combinations were tried, foot lift and non-stick still were dominant failure modes on annealed Cr/Au metallization. Even maximum ultrasonic power was unable to eliminate the foot lift and non-stick bonds.

CAN etch improved bondability and switched the failure mode from non-stick to foot lift. Undesired failure modes disappeared on all other wafer samples after adjusting the process parameter settings.

The data were analyzed using Analysis of Variance (ANOVA). The ANOVA Table for the average pull strength is shown in Table 5. It shows that metallization and annealing have statistically significant effects on the mean pull strength and strong interaction exists between metallization and annealing. The interaction plot of metallization and annealing in Figure 3 shows that annealing has significant effect on Cr/Au metallization, but not for Ti/TiN/Pt/Au metallization. The bondability of Cr/Au degraded dramatically after the wafers were annealed.

The ANOVA analysis in Table 5 also shows that CAN etch and temperature cycles do not have statistically significant effect on mean pull strength. There is interaction between annealing and CAN etch at 90% confidence level. The interaction plot of annealed and CAN etch is shown in Figure 4. Table 4 shows that CAN etch improved the ribbon bond pull strength on annealed Cr/Au metallization. However, the failure mode is 80% foot-lift and 20% non-stick, which is not acceptable for good wire/ribbon bondability. The investigation of the experimental phenomena is described in the next section. ANOVA analysis shows that temperature cycling does not significantly degrade Au-Au ribbon bonds.

Table 3. Failure modes and pull strengths from Experiment 1

		Failure mode for 100 ribbons				**Pull strength for 100 ribbons**	
		Heel break	Foot lift	Non-stick	Ribbon break	Average (grams)	Stdev
Without UV cleaning	Cr/Au	93%	2%	0	5%	211.5	7.6
	Ti/TiN/Pt/Au	97%	0	0	3%	210.3	6.6
UV cleaning 10 min.	Cr/Au	98%	1%	0	1%	206.8	9.9
	Ti/TiN/Pt/Au	96%	0	0	4%	214.6	6.2

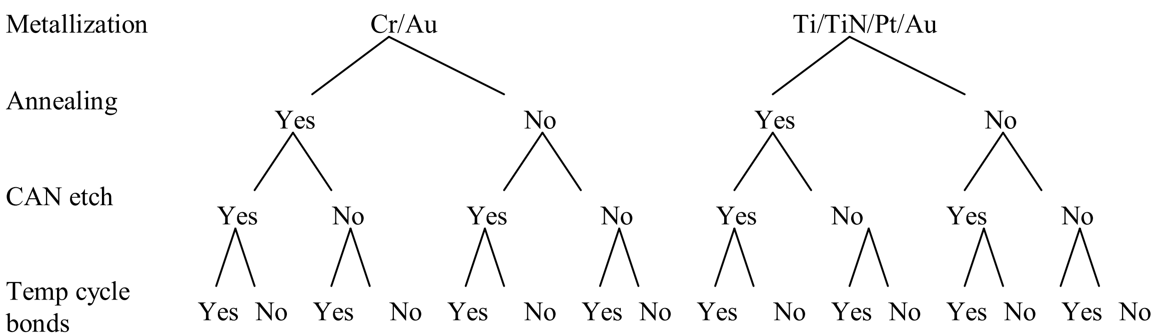

Figure 2. Experiment 2 design

Table 4. Failure modes and pull strengths of Experiment 2

				Failure mode				**Pull strength**	
	Metallization	Annealed	C.A.N.	Heel break	Foot lift	Non-stick	Ribbon break	Average (grams)	Stdev
Before Temp. Cycle	Cr/Au	No	No	100%	0	0	0	170.5	6.4
	Cr/Au	No	Yes	100%	0	0	0	137.7	3.9
	Cr/Au	Yes	No	0	0	100%	0	0	0
	Cr/Au	Yes	Yes	0	80%	20%	0	127.5	33.5
	Ti/TiN/Pt/Au	No	No	100%	0	0	0	191.8	6.5
	Ti/TiN/Pt/Au	No	Yes	84%	16%	0	0	181.6	11.8
	Ti/TiN/Pt/Au	Yes	No	100%	0	0	0	180.4	3.9
	Ti/TiN/Pt/Au	Yes	Yes	100%	0	0	0	179.9	5.6
After Temp. Cycle	Cr/Au	No	No	100%	0	0	0	155.7	8.3
	Cr/Au	No	Yes	100%	0	0	0	147.4	7.4
	Cr/Au	Yes	No	0	0	100%	0	0	0
	Cr/Au	Yes	Yes	0	80%	20%	0	79.5	48.8
	Ti/TiN/Pt/Au	No	No	76%	6%	0	18%	190.2	7.2
	Ti/TiN/Pt/Au	No	Yes	78%	10%	0	12%	185.2	7.4
	Ti/TiN/Pt/Au	Yes	No	97%	3%	0	0	191.8	6.5
	Ti/TiN/Pt/Au	Yes	Yes	97%	0	0	3%	182.9	11.1

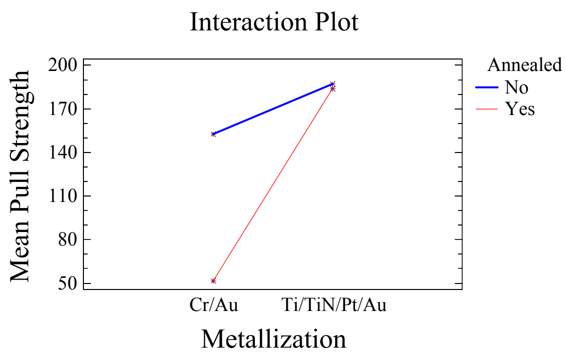

Figure 3. Interaction plot of annealing and metallization.

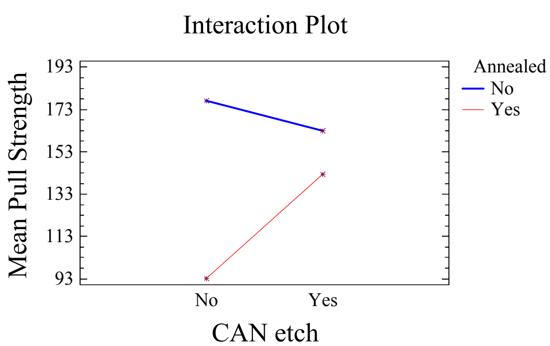

Figure 4. Interaction plot of annealing and CAN etch

Table 5. ANOVA Table for Mean Pull Strength

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-value
Main effect					
A: Metallization	27680.6	1	27680.	30.31	0.002
B: Annealing	10925.5	1	10925.	11.96	0.018
C: CAN etch	1247.86	1	1247.8	1.37	0.30
D: Temp-cycling	84.18	1	84.18	0.09	0.77
Interactions					
AB	9530.6	1	9530.6	10.44	0.02
AC	2268.1	1	2268.1	2.48	0.18
AD	301.89	1	301.89	0.33	0.59
BC	40229.1	1	4029.1	4.41	0.09
BD	58.14	1	58.14	0.06	0.81
CD	44.56	1	44.56	0.05	0.83
Residual	4566.37	5	913.27		
Total (Corrected)	60737.0	15			

Auger analysis

To further investigate what caused the bondability difference between two metallizations, Auger Electron Spectroscopy (AES) was used to analyze all wafer surfaces. The AES surface analysis results are summarized in Table 6. Chromium was detected on annealed Cr/Au metallization, and the chromium-gold ratio decreased from 3.7 to 0.3 after CAN etch for 1 minute. Panousis and Bonham [1] reported that no chromium was detected after CAN etch for 10 minutes. It implies that the CAN etch time in this experiment was not long enough and increasing etch time may remove all chromium and chromium oxide on the gold surface. It was expected that the amount of chromium diffusing on the gold surface would increase with higher annealing temperature, longer annealing time, and thinner gold thickness. Therefore, a proper CAN etch time should be determined according to the annealing process (annealing temperature and annealing time) and the gold thickness. The AES surface survey for annealed, no CAN etch, Cr/Au wafer is illustrated in Figure 5 and that for annealed, CAN etched, Cr/Au wafer is illustrated in Figure 6.

The C/Au ratio is one of the ways to determine the organic contamination level on Au surface. The higher the C/Au ratio means more organic contamination on gold surface. Table 6 shows that the no-annealed Ti/TiN/Pt/Au wafers have higher C/Au ratio than that with annealed. This could explain why the no-annealed Ti/TiN/Pt/Au wafers have more foot lift bonds than the annealed ones.

To determine why Au peeled off from annealed Cr/Au wafers during dicing, AES was used to do ion sputtered depth profiles, which is an analytical technique capable of identifying elemental concentration profiles. Ion sputtered depth profile of annealed, no CAN etch, Cr/Au wafer is shown in Figure 7 and that of annealed, CAN etched, Cr/Au wafer is shown in Figure 8. Au was found in Cr layer of annealed Cr/Au metallization. For comparison, ion sputtered depth profiles of no anneal, no CAN etch, Cr/Au and that of annealed, no CAN etch, Ti/TiN/Pt/Au are shown in Figure 9 and 10. Figure 9 shows that no Au was in Cr layer. Chromium's function is to promote adhesion between substrates and sputtered gold films. That Au diffused to Cr layer may be the reason that Au peeled off during dicing.

Table 6. Auger Surface Analysis Results

Metallization	Annealed	CAN etched	Elements detected except C, O, N, Au	Cr/Au ratio	C/Au ratio
Cr/Au	No	No	None	--	1.3
Cr/Au	No	Yes	None	--	2.5
Cr/Au	Yes	No	Cr	3.7	7.8
Cr/Au	Yes	Yes	Cr	0.3	2.8
Ti/TiN/Pt/Au	No	No	None	--	3.2
Ti/TiN/Pt/Au	No	Yes	None	--	4.0
Ti/TiN/Pt/Au	Yes	No	None	--	1.2
Ti/TiN/Pt/Au	Yes	Yes	None	--	1.1

Conclusions

The following conclusions can be drawn based on this study:

1. Without annealing, both Cr/Au and Ti/TiN/Pt/Au metallization systems have good wire/ribbon bondability.
2. The ribbon bonding performance degraded dramatically on Cr/Au wafers after they were annealed. CAN etch for 1 minute partially removed Cr oxide on Au surfaces. A

longer time could restore the bondability for Cr/Au metallization.

3. Annealing does not degrade ribbon bondability of Ti/TiN/Pt/Au metallization.
4. Temperature cycling does not degrade Au wire/ribbon to Au metallization bonds.
5. Au peeled off from annealed Cr/Au metallization during dicing seems due to Au diffusing to Cr layer.

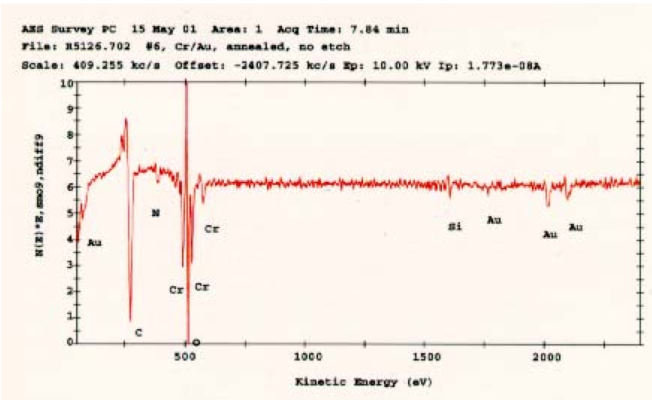

Figure 5. AES surface surveys for annealed, no CAN etch, Cr/Au wafer

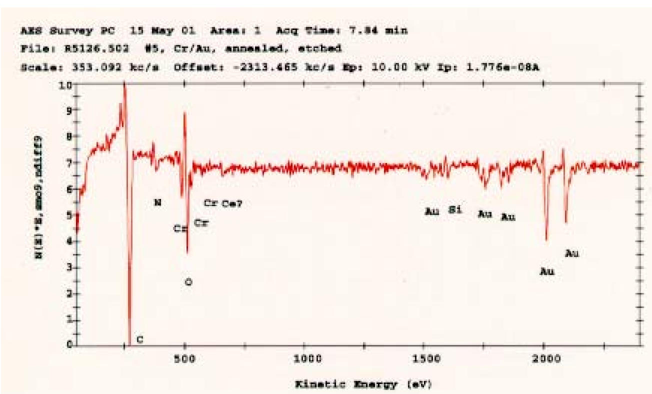

Figure 6. AES surface surveys for annealed, CAN etched, Cr/Au wafer

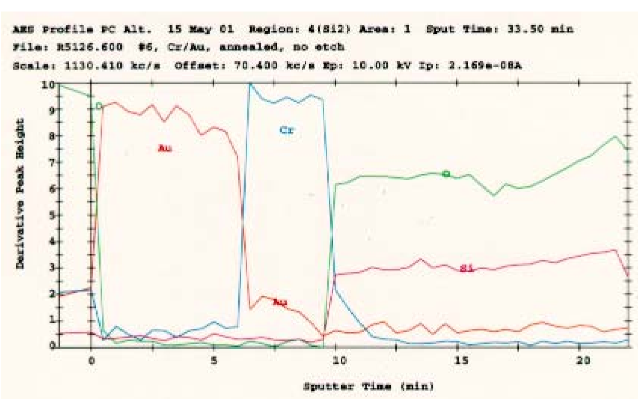

Figure 7. AES profile for annealed, no CAN etch, Cr/Au

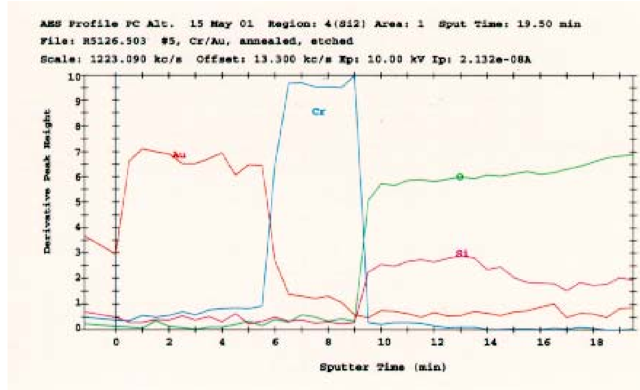

Figure 8. AES profile for annealed, CAN etched, Cr/Au

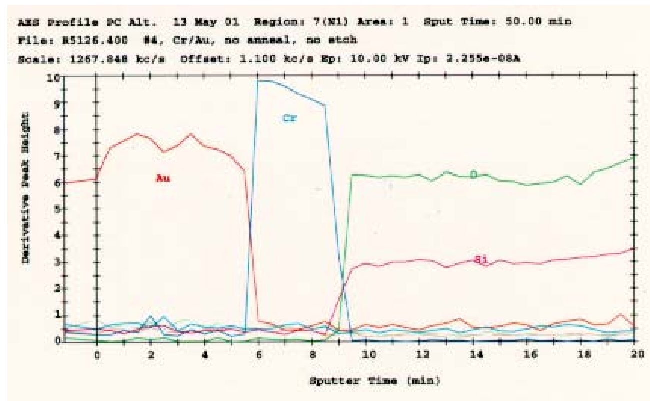

Figure 9. AES profile for no annealed, no CAN etch, Cr/Au

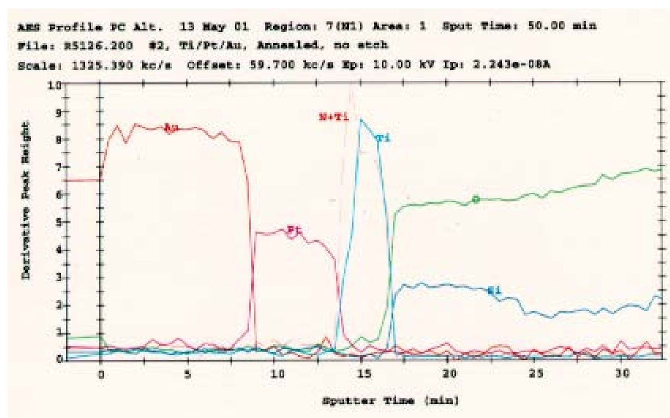

Figure 10. AES profile for annealed, no CAN etch, Ti/TiN/Pt/Au

Acknowledgments

The author gratefully acknowledge the contributions of the following individuals: Jeff Shearer for the Auger analysis, Lou Gomez and Jim Bailey for preparing the matallized samples, Rob Liddick and Brain Hayes for ribbon bonding and pull testing, and Rick Kershner for valuable discussions.

References

1. Panousis, N. T. and Bonham, H. B., "Bonding Degradation in the Tantalum Nitride-Chromium-Gold Metallization System," *Proceedings of the 11th Annual Reliability Physics Conference*, Las Vegas, NV, USA, 1973, pp. 21-25.
2. Holloway, P. H. and Long, R. L., "On Chemical Cleaning for Thermocompression Bonding," *IEEE Transactions on Parts, Hybrids, and Packaging*, Vol. PHP-11, No. 2, (June 1975), pp. 83-88.
3. Harman, George, Wire Bonding in Microelectronics: Material, Processes, Reliability and Yield, McGraw-Hill, 2nd edition, New York, 1997.
4. Rodwell, R. and Worrall, D.A., "Quality Control in Ultrasonic Wire Bonding," *International Journal for Hybrid Microelectronics*, Vol. 8, No. 2, June 1985, pp.1-8.