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Procurement of Reliable Semiconductor Devices for Military Space Applications	A. G. Stanley
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LINCOLN LABORATORY

PROCUREMENT OF RELIABLE SEMICONDUCTOR DEVICES
FOR MILITARY SPACE APPLICATIONS

A. G. STANLEY

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ABSTRACT

A study was undertaken to determine the feasibility of obtaining high reliability devices for long term space missions and military applications by imposing and monitoring additional process quality controls and screening procedures on standard commercial production lines. A survey of more than a dozen semiconductor manufacturers indicated that the following reliability areas are not adequately controlled: metallization, wire bonding, loose conductive particles and ceramic packages sealed by low melting point glasses. Wide variations were found in the manner in which the bond strength test is carried out. Methods were studied to institute SEM inspection and a more rigorous bond strength test on the production lines, coupled with wafer and bonder traceability. This report surveys reliability problems caused by defects in semiconductor devices and their control.

PROCUREMENT OF RELIABLE SEMICONDUCTOR DEVICES
FOR MILITARY SPACE APPLICATIONS

I. INTRODUCTION

Semiconductor devices employed in long term space missions, e.g., in communication satellites, must possess the highest possible reliability, since repairs are impossible to carry out and there are limits to the degree of redundancy that can be achieved. Moreover, component reliability plays a crucial role in hardening electronic circuits against catastrophic failures in a weapons environment.

The following methods can be used to ensure device reliability (Ref. 1):

in-process quality controls

line qualification

captive assembly lines

preseal visual inspection

burn-in and other screening procedures

environmental and life tests

reliability physics studies

Space communications systems impose additional constraints, in that the systems are very complex and employ a large number of different types of components, whereas the total number of components of a given type is quite small. This makes it economically prohibitive to run special captive lines or to institute line qualification procedures where none exist.

The study described in this report was undertaken to determine the feasibility of obtaining high reliability devices from standard commercial lines by imposing and monitoring additional process quality controls and screening procedures. Many of these are based on existing military or NASA specifications. More than a dozen semiconductor manufacturers were surveyed to examine their existing quality controls and the problems arising from the imposition of supplementary process controls and screens. Visits were also paid to a number of organizations engaged in the construction of military or space electronic systems to study their reliability procurement methods.

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II. FAILURE MODES

Table I shows the predominant failure modes, their origin in the fabrication process and applicable screening methods. A basic understanding of the failure mechanism is required to gain an understanding of the mean time to failure and of the applicability of accelerating stresses.

It may be seen from the table that many failure modes follow an Arrhenius type relation of the form

$$R(T) = A \exp(-E/kT)$$

which expresses the time rate of degradation, $R(T)$, of some device parameter as a function of operating temperature, T (Ref. 2,3). E is the activation energy of the process. An elevated temperature stress is an effective method of screening out Arrhenius type failure modes as long as E is sufficiently high and as long as no new failure modes are thereby introduced. (Ref. 4) has shown that the activation energy for junction failure modes is 1.1 eV. In practice this means a temperature below 370°C, the gold-silicon eutectic point. Failure modes that also depend on nonthermal stresses cannot be eliminated by this method.

The importance of different failure modes is indicated by their frequency of occurrence, which has been derived from several recent publications (Ref. 1, 5-9). This report is primarily concerned with standard bipolar integrated circuit technology and does not discuss the special problems arising in MOS technology or multilayer metallization systems.

III. METALLIZATION DEFECTS

Metallization and bonding defects represent the most important reliability problems in integrated circuits. The metallization defects may be classified as follows:

microcracks - cracked or thin metallization around periphery of contact windows

overalloying - lack of adhesion, flaking and voids

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TABLE I

FAILURE MODES

Processing Stage	Failure Mode	Failure Mechanism	Time Dependence Ref. 2	Accelerating Stress		Frequency of Occurrence (Per Cent)					Detection and Screening
				Thermal Ref. 2	Non-Thermal	Gott & Soltau Ref. 5 Fig. 7	Myers Ref. 6	Brown Ref. 7	Hollingworth Ref. 8	Minuteman Handbook Ref. 9	
Diffusion & Oxidation						12	25	12	29	44	visual
	diffusion pipes							1		2.4	power burn-in
	dislocations & stacking faults							2			
	surface effects	contamination, inversion: diffusion	yes	Arrhenius		2	7	6	9	2.4	high temp reverse bias burn-in
	photolitho-graphic defects	pinholes: diffusion	yes	yes	voltage	10	18	3	14	2.4	burn-in
Metallization						39	26	11	12	22	visual
	thin metal at oxide steps, microcracks	current density, melting	unknown	indirectly	current density			5			SEM, power cycling, thermal cycling
	voids	adherence	none		thermo-mech.					2.4	visual
	corrosion	chem. reaction diffusion	yes	yes				2		19.5	stabilization bake
	Mo-Au metalliza-tion defects	metal particles, entrapment of etch residue									SEM
Bonding						38	33	52	22	17	centrifuge
die bond	cracks in chip	strain relaxation	unknown	no	mechanical			6	8		visual
	adhesion, voids										thermal resis-tance, push test, current pulse
	alloy slag										visual, vibra-tion-shock or acoustic

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				Accelerating Stress		Frequency of Occurrence (Per Cent)					
Processing Stage	Failure Mode	Failure Mechanism	Time Dependence Ref. 2	Thermal Ref. 2	Non-Thermal	Gott & Soltau Ref. 5 Fig. 7	Myers Ref. 6	Brown Ref. 7	Holling-worth Ref. 8	Minute-man Handbook Ref. 9	Detection and Screening
wire bond	intermetallic formation	Kirkendall effect: chem. reaction & diffusion	yes	Arrhenius				46	14	2.4	bond strength test
	short to substrate	mech. deformation	no	no	freq. mech.						visual, centrifuge
	lead short or open	mech. deformation or pressure	no	no						14.6	
Handling	metal scratches	current density, melt	no		current density			3			visual
scribe & break	cracks	mech. fracture	no	no	mechanical			2	7	12.2	thermal shock, temperature cycling
	foreign material					2		6		4.9	vibration shock or acoustic
Sealing						8	10	11	11	3	
	hermeticity	contamination: diffusion	yes	Arrhenius		6		5		2.4	leak tests, thermal shock
	package					2		6			visual

TABLE 1 (Cont'd.)

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Processing Stage	Failure Mode	Failure Mechanism	Time Dependence	Accelerating Stress		Frequency of Occurrence (Per Cent)					Detection and Screening
				Thermal	Non-Thermal	Ref. 5 Fig. 7	Ref. 6	Ref. 7	Ref. 8	Ref. 9	
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	lead short or or open	mech. deformation or pressure	no	no						14.6	
Handling	metal scratches	current density, melt	no		current density			3			visual
scribe & break	cracks	mech. fracture	no	no	mechanical			2	7	12.2	thermal shock, temperature cycling
	foreign material					2		6		4.9	vibration shock or acoustic
Sealing						8	10	11	11	3	
	hermeticity	contamination: diffusion	yes	Arrhenius		6		5		2.4	leak tests, thermal shock
	package					2		6			visual

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> photolithographic defects - pinholes and misalignment, inadequate
>   contact cut areas
>
> general handling problems - scratches, contamination, cracks and
>   corrosion

Metallization defects produce opens, high resistance regions, and shorts as well as long term effects due to electromigration. The latter is a potential wearout mechanism that takes place at current densities in excess of 10^5 A/cm^2 particularly in aluminum layers in the silicon contact region (Ref. 10). In good quality devices such current levels occur only as the result of design error or misuse, but they can also be induced by any of the metallization defects listed above. Electromigration obeys the Arrhenius relation with an activation energy depending on the film structure.

Microcracks

Microcracks were first described in a paper by Goldberg and Adolphsen (Ref. 11), who attributed their cause to photoetching problems and who demonstrated the effectiveness of the scanning electron microscope in their detection. A recent review of this phenomenon by Blech et al. (Ref. 12) states that microcracks form during metal deposition, but their formation depends both on the profile of the oxide step and on the evaporation geometry. The most serious cracks occur over the phosphosilicate glass steps, where etching produces an overhang on the phosphosilicate glass portion of the step (see Fig. 1). The phosphosilicate glass etches much faster than the thermally grown silicon dioxide. The cracks can be eliminated by tapering or thinning the phosphosilicate glass portion or by heating the substrate during the metal deposition, but thinning anomalies at the steep step cannot be eliminated by substrate heating.

The formation of microcracks may be avoided by the following procedure (Ref. 13). The window ledge should possess a smooth contour. This may be achieved by partial removal of the phosphosilicate glass and by careful control of the temperature, concentration and duration of the etch. The vapor deposition should be carried out on a hot substrate at 250 to 275°C, so as to produce large grains that tend to be more stable. A planetary system
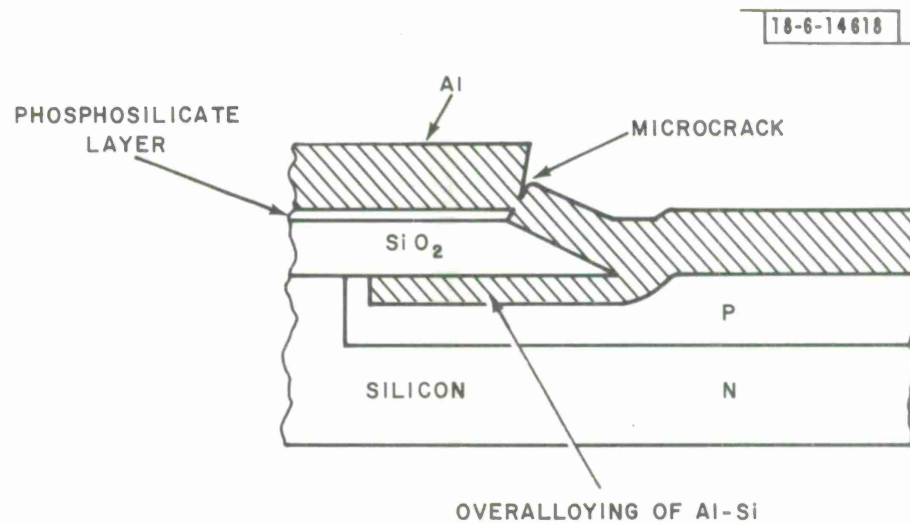
Fig. 1. Microcrack at contact cut and overalloying of Al-Si under oxide.

should be used for greater uniformity. The aluminum thickness should be at least 1 μm. The metal should be deposited slowly. The subsequent metal etch is a critical operation. Impurities should be avoided throughout the process.

Overalloying

Aluminum reacts with silicon and also with silicon dioxide at higher temperatures (Ref. 14) and this can lead to the following types of defects (Ref. 2):

a. The solid-state dissolution of silicon in aluminum at the edges of the contact cut produces a discontinuity between the aluminum over the oxide and the aluminum at the edge of the contact region, which results in a con-striction of the cross-sectional area (see Fig. 1). This phenomenon was described by Anstead and Floyd (Ref. 15).

b. Diffusion of silicon along grain boundaries produces embittlement and flaking (Ref. 16).

c. Aluminum penetration due to overalloying of aluminum and silicon under the oxide produces shorts, particularly in shallow diffusion regions (Ref. 1).

d. Aluminum migrates under bias at the interface of thermal silicon dioxide and the glassivation layer. Bart (Ref. 17) observed this effect on applying 250 mW of current at 150°C for 96 hours. Aluminum diffuses without applied bias when heated at temperatures near the Al-Si eutectic.

Overheating is readily detected by the characteristic mottled appearance of the metal in the silicon contact areas.

Defects of the Mo-Au Metallization System

Gold metallization possesses certain advantages over aluminum, in that the formation of Au-Al compounds during bonding is avoided and also electro-migration effects are at least an order of magnitude smaller. On the other hand, gold metallization requires a multiple layer system, since gold diffuses into silicon and does not adhere to silicon dioxide.

Molybdenum has been in use for some time as an intermediate layer.
Molybdenum itself forms three intermetallic compounds with silicon and is
subject to oxidation. The latter results in variable and unreliable contacts
(Ref. 18). For this reason the multilayer system shown in Fig. 2 has been
developed (Ref. 19). A very thin layer of aluminum is applied before the
deposition of the molybdenum to improve the ohmic contact. The sputtered
molybdenum layer is coated with a thin layer of gold containing 10% platinum.
The latter is soluble in both molybdenum and gold and thus prevents lifting
of the top gold layer.

The most important defects of the Au-Mo system are related to the under-
cutting of the molybdenum barrier layer during etching which can produce the
following effects:

a. The unsupported gold flakes off producing a constriction in the
conductive path or an open circuit.

b. The gold flecks create a contamination problem that may lead to
shorting.

c. Entrapment of residual phosphoric acid etchant below the gold
surface causes galvanic corrosion and the dendritic growth of molybdenum
salts containing oxygen and silicon (Ref. 20).

d. Gold diffuses into the silicon due to the localized formation of
Au-Si eutectic (m.p. 370°C) during subsequent processing, where the moly-
bdenum layer is not continuous (Ref. 20).

e. Silicon penetrates into the gold film. This produces flaking of the
gold due to precipitation of the silicon at the grain boundaries (Ref. 16).

The gold metallization cannot be glassivated without adding yet another
layer, since the glass will not adhere to gold. The Mo-Au system corrodes
in a humid atmosphere. Microcracks have been observed at contact windows with
Mo-Au metallization (Ref. 2). Structural changes occur in the Mo-Au system
during high temperature storage which may result in lack of adhesion and
peeling of gold (Ref. 17, 21, 22). The same conditions may be brought about by
electrical stress.

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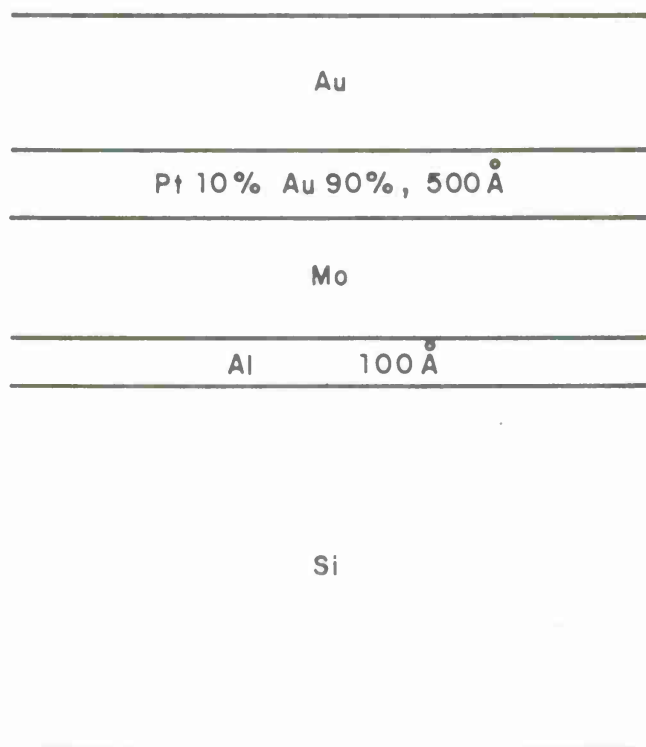| |
| --- |
| Au |
| Pt 10% Au 90%, 500 Å |
| Mo |
| Al   100 Å |

Si

Fig. 2.   Mo-Au metallization system.

Recently a more stable system has been developed in which molybdenum is replaced by titanium.

Detection of Metallization Defects

All metallization defects except the microcracks can be easily seen under a microscope and should, therefore, be screened during the visual die or precap inspections. A metallurgical microscope is required for further analysis of defects. Voltage contrast scanning electron microscopy is the best method for the detection of microcracks.

Some of the logistics problems in channeling the output of a production line through SEM inspection are described in Section 8. Additional problems are created by the glassivation layer that most manufacturers apply over the aluminum metallization. Samples to be subjected to SEM inspection must be removed before this layer is applied, since results obtained from samples with an etched glassivation layer are difficult to evaluate. This requires the use of separate wafers or parts of wafers that will not be subjected to further processing for the SEM inspection. Hence individual dice cannot be used for SEM inspection.

A rigorous study of undercutting in the Mo-Au system requires the removal of the gold film. This complicates the procedure, but in this case individual dice can be selected.

A detailed NASA specification (Ref. 23) for SEM inspection is now available, though a corresponding military specification has not yet been formulated. The acceptance and rejection criteria are of necessity presented in pictorial form, which complicates the interpretation of marginal cases. Further experience with the method should lead to the development of a more quantitative specification. A detailed specification for SEM inspection of the Mo-Au metallization system has been developed by Jet Propulsion Laboratory (Ref. 24). It includes a provision for stripping off the gold layer to permit examination of the underlying molybdenum.

Attempts have been made to screen out devices containing microcracks by means of thermal cycling between -26 and $74°C$. Power should be applied during the temperature stress, which should be terminated at the cold

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temperature. The test is followed by d.c. and a.c. electrical tests. The effectiveness of this screen depends on the work hardening of aluminum. Burn-in screens based on similar principles have also been proposed.

IV. DIE MOUNTING

The die mounting operation is commonly performed by means of a Au-Si alloy preform at 370°C and is subject to the following problems (Ref. 1, 18):

> voids underneath the die
> lack of adhesion
> alloy slag formation
> cracked dice

Smaller dice usually have the Au applied to the underside during wafer fabrication and do not require separate preforms.

Voids are produced by irregular soldering and nonuniform wetting. They may be detected by visual inspection of the solder fillet, x-ray scanning, infrared scanning and measurement of the thermal resistance. In one effective method a heavy current is passed through the device for a short period of time followed by a temperature measurement. There are dangers in using a high current density screen.

The best way of detecting lack of adhesion is a push test on the die to be carried out on a sample basis as a process control. In this way corrective action can be taken on the assembly line. Devices with poor die adhesion may be screened by centrifuging followed by electrical tests.

The formation of lose slag during the scrubbing operation may result in particle contamination (see Section VI) or in direct shorts to the active circuit. The internal visual (precap) inspection should screen out devices that show alloy slag problems or cracked dice.

Glass should not be used for die mounting.

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V. WIRE BONDING

The wire bonding operation presents one of the greatest reliability prob-
lems in integrated circuits and other semiconductor devices. The two most
common bonding techniques are thermocompression bonding with gold wire and
ultrasonic bonding with aluminum wire. The thermocompression bonds take the
form of ball, wedge or stitch bonds and are made to aluminum or gold substrates.
Ultrasonic bonds are normally made to aluminum. The same techniques are used
to bond to the package, where the substrate is most often in the form of a gold
plated post or pad. Aluminum pads can only be employed in those ceramic
packages that use low melting point glasses as sealant. Other techniques, e.g.,
beam leads, are not yet in large scale production and will, therefore, not be
considered here. Recent reviews of failure modes in wire bonding have been
given by Lesk and Black (Ref. 25) and by Schnable and Keen (Ref. 16, 1).

Au-Al Thermocompression Bonds

Thermocompression diffusion bonding was originally developed at the Bell
Telephone Laboratories in 1957 (Ref. 26). It requires close control of the
temperature, time and pressure in order to avoid damage to the device, weak
bonds or the formation of brittle intermetallic compounds (Ref. 27).

Au-Al bonds have long been known to degrade during storage at elevated
temperatures, while at the same time forming a dark or purple phase referred
to as the "purple plague". It was subsequently shown that the bond itself
degrades by Kirkendall diffusion, i.e., the gold diffuses faster then the
aluminum and hence leaves a void (Ref. 14, 18, 28-31). There appear to be in
fact two failure modes both of which are Kirkendall voids (Ref. 30, 31):

a. Interface voiding, leading to brittle fracture of the bond (Selikson
and Longo, Ref. 28). This mechanism possesses an activation energy of 0.2 eV
and takes place only if the aluminum film thickness is at least 5000A.

b. Peripheral or annular voiding (Blech and Sello, Ref. 29), resulting
in an increase in the electrical resistance. This mechanism predominates at
high temperatures and in thin aluminum films.

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Rossiter (Ref. 31) found that interface voiding tends to be produced in a hermetically sealed package, whereas annular voiding is produced in air. Oxygen and water vapor limit the surface diffusion of aluminum and thus exercise a retarding effect on interface voiding which is catastrophic. The latter is catalyzed by the presence of silicon (Selikson, Ref. 18).

From the point of view of a system that must function reliably for up to a decade in space it is extremely important to determine the time-temperature dependence of the bond degradation. Table II shows that very varied estimates have been given by different authors. If the degradation process possesses a well defined activation energy it is best to subject all devices to an extreme temperature stress, so that the process may go to completion and then eliminate the defective devices by some suitable screening procedure. This technqiue has been adopted by Bell Telephone Laboratories using a constant acceleration screen (Ref. 4, 33). It assumes that all defective devices are screenable and that no additional failure modes are introduced by the high temperature stress.

A recent review on the "purple plague" by Philofsky (Ref. 34) states that the kinetics of intermetallic formation are given by a rate constant

$$k = 5.2 \times 10^{-4} \exp\left(-15,900/RT\right) \text{ cm}^2/\text{sec}$$

corresponding to an activation energy of 0.7 eV. The bond strength does not depend on the formation of intermetallics, as long as these do not contain a near continuous line of Kirkendall voids. Moreover, intermittent aging is more effective in producing these than continuous aging at a higher temperature. Workman (Ref. 3) states that the activation energy for the formation of Kirkendall voids is about 1 eV. A similar value was obtained by Zierdt (Ref. 4) for Al-Au bond failures under temperature stress.

Al-Al Ultrasonic Bonding

The bond strength of Al-Al ultrasonic bonds is affected by a large number of variables including the surface conditions, the ultrasonic power, the

TABLE II			
ESTIMATES OF HIGH TEMPERATURE STORAGE RESULTING IN BOND FAILURE IN Au-Al SYSTEM			
Reference	Temp.	Time	Effect
Selikson & Longo 28	300°C	18 hours	loss in bond strength, bond failures
Cunningham 32	300°C	48 to 216 hrs	bond failures
Blech & Sello 29	300°C	100 hours	no bond failures in thick Al filmes
Peck, 33 Zierdt 4	300°C	16 hours	bond failure after centrifuging
Schnable & Keen 16	< 150°C	extended periods	reliable
Cunningham & Harper 14	85°C	20 years	time to failure
Anderson & Cox 30	125°C	1 year	time to failure
Philofsky 34	< 300°C	intermittent	results in bond failure
	300°C	100 hours	no failure

rigidity of the parts and chuck relative to the tool, the resonance of the system and temperature variations (Ref. 35-38). The ultrasonic power setting is very important, since too low a value causes bond lifting, whereas too high a value causes the bonds to break. For this reason the power should be frequently monitored by means of a suitable transducer (Ref. 39). Many bonders are not adequately protected from vibrations that produce random failures due to weak bonds and pinched-off leads.

The majority of semiconductor devices use aluminum wire containing 1% silicon, which segregates in the form of silicon crystallites at the grain boundaries. Work hardening may be induced by temperature or power cycling. The substitution of Mg results in a mechanically superior bond, but may result in degradation of the electrical characteristics (Ref. 35, 38).

Grain growth at high temperatures during manufacture may result in the formation of single crystal aluminum, which will break at a very small load. The tensile strength of the wire decreases on annealing (Ref. 35). Al-Al bonds usually fail at the heel of the bond, where the wire has been deformed by the bonding tool, but is not bonded to the aluminum film. For this reason a visual check of the deformation is important. Metal fatigue caused by power cycling at a low repetition rate can break the wire at this point (Ref. 25, 40).

The aluminum wire is usually bonded to the pad or post of the package by ultrasonic bonding. A thin, soft gold plating of 50 to 100 microinches produces the best results. Aluminum plating can only be applied to packages that do not experience high temperatures during the sealing operation. Even then contaminants may cause bond degradation (Ref. 41). Bond failure of aluminum wire to gold plated posts can occur if excessive temperatures are applied during bonding (Ref. 1), but this does not apply to ultrasonic bonding.

Bonding Process Controls

It is difficult to achieve reliable screening methods for bond strength. Nondestructive tensile tests have often been proposed (Ref. 42), but the risk of introducing hidden damage has restricted their use on production lines. On one line a force of 0.5 gm is applied by nitrogen pressure while the device is viewed through a microscope. Devices with zero pull strength are

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thus removed from the line. On another line a force of 1.5 gm is applied. Both production lines employ Al-Al ultrasonic bonds. Constant acceleration tests up to 30,000 G after thermal stress appear to have achieved some measure of success for gold wires (Ref. 4, 16, 33).

Visual inspection criteria for bond formation are shown in Table V, Section IX. A microscopic inspection will eliminate grossly defective bonds, but there is no correlation between bond strength and visual appearance. In ball bonds the diameter is the most important measure; it should be about 2 to 4 times the wire diameter. In other bonds the compression indentation should be between 20 and 75%, resulting in a width equal to 1.2 to 2 times the wire diameter. Any evidence of lifting or partial separation should be cause for rejection, also lateral bond pulling across the bonding pad.

The main control of the bonding operation is in the form of a destructive bond strength test, whose results should provide the necessary feedback loop for corrective action and elimination of substandard devices. A survey of the industry, whose results are shown in Table III, has indicated an extra-ordinary diversity in the manner in which this process control operation is carried out.

The pull test is performed by placing a rounded metal hook centrally under the span of a wire between the die bond and post bond, and by pulling vertically at a constant rate not to exceed two grams per second. The angles that the wire makes with the hook are critical and should not be varied. The general method, illustrated in Fig. 3, is described in MIL-STD 883, Methods 5005 and 2011. A general description of the equipment is given in MHB 5300.4 (3D), Methods 6090A and B (Ref. 43).

Fracture may occur at the following locations shown in Fig. 4:

a. at the die bond. The adhesion failure occurs either between the bond and the metallization, between the metallization and the oxide, or between the oxide and the silicon.

b. in the neckdown region at the heel of the die bond

c. in the wire

TABLE III
BOND TESTS

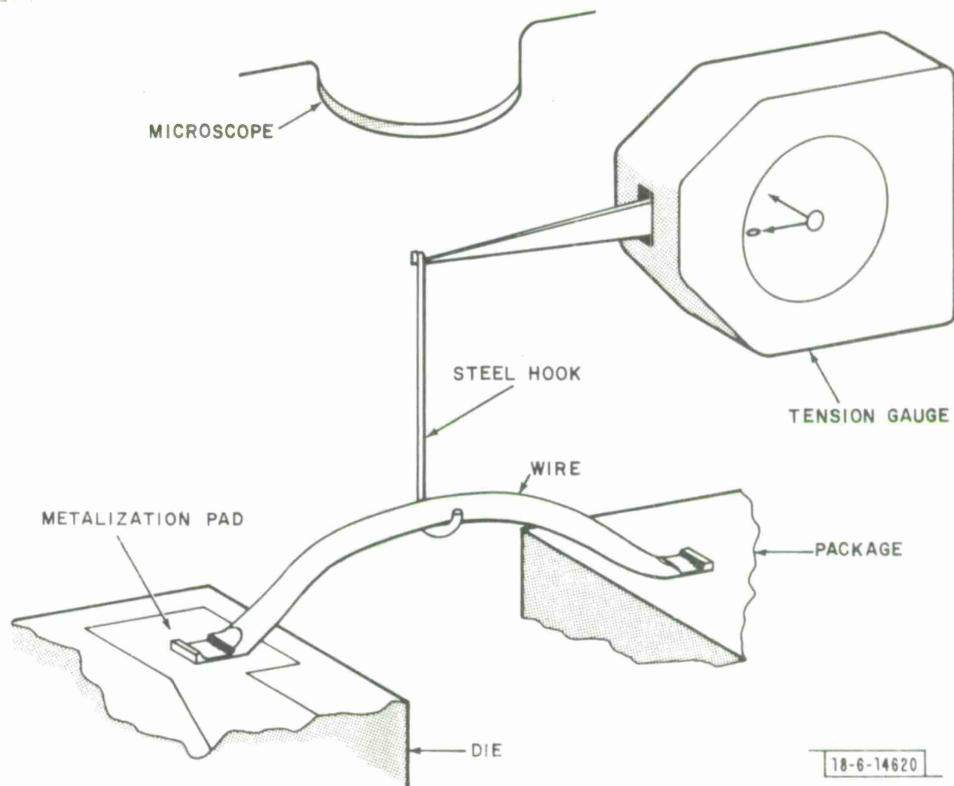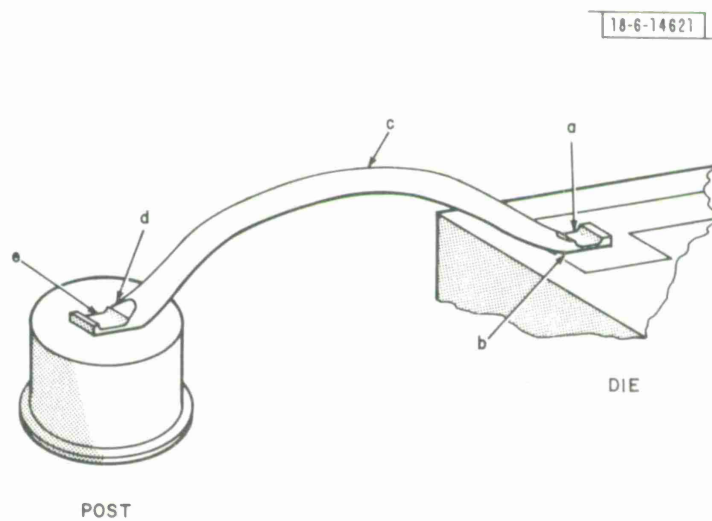| Manufac-turer	Type of Bond					Bond Screen Test	Bond Strength Test							Rebonds	Remarks
	Pad Die	Metallization Package	Wire	Bond			Test Frequency	Sample Size	Rejection Criteria		Documentation	Corrective Action	Post Anneal Pull Test		
				Die	Package				Fracture Mode (Fig. 4)	Strength of Other Modes					
1	Mo-Au	Au	1 mil Au	ball	stitch		1 per shift		any mode permitted		monthly data $\bar{X}$ = 5 gm	machine shut down, no lot rejection	no		
2	Mo-Au	Au	1 mil Au	ball	stitch		1 per hour	10	any mode permitted	2.5 gm	$\bar{X}$ - R chart	lot rejection	yes		stitch bond is weakest
3	Al	Al	1 mil Al	U/S	U/S		1 per 2 hrs	15	a and e		$\bar{X}$ - R chart	lot rejection	yes		
4	Al	Au	1 mil Al	U/S	U/S		2 per shift		any mode permitted			machine shut down only	no		
5	Al / Al	Al / Au	1 mil Al / 1 mil Au	U/S / ball	U/S / wedge	no regular tests, but could be instituted								5%	
6	Al	Al	1 mil Al	U/S	U/S	1.5 gm	1 per 2 hrs	5	a and e		$\bar{X}$ - R chart $\bar{X}$ = 2.8 gm, R = 2.6 gm	machine shut down	yes		bonder traceability
7	Al	Al	1 mil Al	U/S	U/S		2 per shift	10	a and e < 4 gm	2.5 gm	$\bar{X}$ = 6 gm on die, 4 gm on package				
8	Al	Au	1 mil Al	U/S	U/S		unannounced checks							on package only	operators set machines
9	Al	Au	1 mil Al	U/S	U/S	0.5 gm	4 per day			2.0 gm			yes		
10	Al	Au	1 mil Al	U/S	U/S		1 per hour			3.0 gm		machine shut down	yes		
11	Al	Au	1 mil Al	U/S	U/S		1 per 4 hrs			1 or 2 gm	$\bar{X}$ = 4.8 gm				
12	Al	Al	1 mil Al	U/S	U/S	20 psi	1 per day	4	any mode permitted	2.0 gm	yes	machine shut down		depends on cust. specs.	bonder traceability
13	Al	Au	1 mil Al	U/S	U/S		2 per shift	5	a and e < 3 gm	2.0 gm		< 3 gm adjust machine < 2 gm lot rejection	yes	permitted if not in same place	
							Microwave Devices								
14	Ti-Au	Au	0.5 mil Au	wedge	wedge				no tests		1-1.2 gm typical				bonder without pressure control
15	Au	Au	0.7 mil Au	ball & wedge	ball				no tests					on package	
16	Al	Au	0.8 mil Au	wedge					no tests						

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Fig. 3. Bond pull strength test.

Fig. 4. Failure modes in bond pull strength test.

d. in the neckdown region at the heel of the post bond

e. at the post bond. The adhesion failure occurs either between the bond and the plating or between the plating and the substrate.

In a strong bond the wire should always break first. In many cases it is the post bond that is the weakest bond. One of the two stitch bonds to the post will fail first.

Destructive bond tests should be carried out at frequent intervals, e.g., every two hours for each operator machine combination. The first test should be performed immediately following the machine setup operation, and also prior to resuming normal operation, whenever a machine has been shut down for maintenance or readjustment.

About 10 sample bonds constitute an adequate sample size. The data obtained in the pull test should be arranged in the form of control charts giving the average bond strength $(\overline{X})$, the range R and the failure mode. An out-of-control condition shall be considered to exist when the average parameter exceeds the following lower control limits:

a. any bond that separates below two grams pull strength

b. any gold wire that breaks below two grams pull strength

c. any aluminum wire that breaks below one gram pull strength

If any sample contains one or more rejects, the machine from which the sample is taken should not be allowed to continue operation until an acceptable sample has been submitted to process control. Also all devices manufactured on the machine since the last successful check should be rejected. A survey of the industry showed that this last rule was most often violated, although some manufacturers would divert such devices to commercial use.

An additional shear bond strength test is required for bonds made to Mo-Au metallization (Ref. 21, 22). This test should be carried out as a quality control before encapsulation but after heating the samples. This test provides the only adequate screening against peeling of the metallization under the bond, which is induced by undercutting of the gold layer by depletion of molybdenum and by lack of adhesion between the molybdenum and the gold.

Other Process Controls

The bonders require a carefully planned maintenance schedule as well as checks of all temperatures and pressures. All piece parts including the header or package, wire and plated surfaces must undergo rigorous checks at incoming inspection. The die surface must be thoroughly cleaned before bonding. The glassivation process has introduced new surface problems on the bonding pads, since it is difficult to remove without overetching the aluminum and can also form reaction products with the latter.

The process lines should be organized so that any device can be traced back to a given bonding machine and operator. This is done in relatively few assembly lines. The results of the bond strength test should also be correlated with each bonding machine and operator. This procedure not only ensures reliable devices, but should also increase the yield of the bonding operation substantially.

Post Anneal Bond Strength Test

Both gold and aluminum wires anneal during storage at elevated temperatures. Initially, thermocompression gold bonds are stronger than ultrasonic aluminum bonds, but after extended storage at 300° C aluminum bonds are somewhat superior to gold bonds in strength (Ref. 16). Also, substantial degradation may be caused by the sealing process, which takes place at considerably higher temperatures. An additional quality control check is, therefore, required, which should be carried out after burn-in.

A bond strength acceptance test forms part of the qualification and quality conformance procedures specified in Method 5005 of MIL-STD 883. The sealed devices must be opened up in order to carry out this test. Traceability back to the bonder and metallization lot is desirable. Any failures should be cause for rejection of the lot that is being sampled.

Rebonding

MIL-STD 883 permits up to 10 percent of rebonds in a microcircuit, if the initial bonding attempt has been unsuccessful, provided that the metallization

has not been disturbed. Overbonds are not permitted. Rebonds present a potential reliability hazard on two counts:

a. The first unsuccessful attempt indicates an out-of-control situation that may not be further investigated and rectified.

b. The first attempt degrades the metallization in a manner not immediately visible under low power magnification.

Discussions with the manufacturers suggest that they do not object to a no rebonding rule for die bonds, since this carries a low yield penalty, but that no rebonds on pads or header posts carry a much higher yield penalty. This implies a lack of uniformity and quality control of the package, which is in itself a reliability hazard. Rebonds must not be performed in the area where the first bond was attempted.

VI. CONDUCTIVE PARTICLES

The presence of small conductive particles constitutes an important reliability hazard in the weightless space environment. The particles may be attracted by electrostatic charges or by charges in dielectric materials and cause shorts by bridging metallization paths. The particles are produced by flaking of the metallization, particularly in the Mo-Au system, by slag from the die bonding operation, bits of wire from the wire bonding operation, and by the sealing process.

A glass passivation layer of about 50 microns affords a high degree of protection against shorts produced by small conductive particles in the aluminum metallization system. The Au-Mo system cannot be passivated in the same manner, since the glass will not adhere to gold. Consequently, screening against particle contamination is particularly important in this case.

Radiographic tests are not able to pick up particles below 10 mil in size. Special monitored vibration-shock or acoustic tests had to be developed for this purpose. These are described in Section X.

VII. PACKAGE

Transistors and integrated circuits for high reliability space applications are packaged either in Kovar headers and cans or in flatpacks.

Different types of flatpack construction are listed in Table IV (Ref. 9). In all cases the lead frame is made of Kovar or a similar alloy, which is sealed into the package by means of borosilicate glass. The second seal, which is made after the visual precap inspection, is made in a number of different ways depending on the package construction.

All packages suffer from leakage problems caused by defective seals or by meniscus cracks in the glass around the leads. There are considerable differences in the quality of the glass used by different package vendors. All devices must be screened by hermeticity tests for gross and fine leaks.

Care must be taken not to introduce leaks in screened devices by applying undue stresses to the leads. The leak rate introduced by lead bending may be as high as 3 percent (Ref. 8). The Jet Propulsion Laboratory (Ref. 44) has instituted a second hermeticity check after lead bending followed by electrical tests to overcome this problem.

Ceramic Package

Flatpacks with the low melting point glass seals suffer from additional reliability problems. The glass contains lead oxide and alkali salts, which may be distributed over the entire package during the sealing operation. This conductive contamination may produce leakage paths both in the package and across the surface of the die.

The application of excessive glass may cause shorting of the wires to the die, package or to one another. Many packages are found to be almost entirely filled by the glass after sealing. For this reason glass preforms should be restricted to the periphery of the package, and the quantity of glass should be minimized. The glass should not be painted around the edge, and strict quality controls should be applied to the glass thickness on incoming inspection.

All ceramic packages possess a weak mechanical structure. The lid may become detached during thermal stress, so that a thermal shock test is required followed by centrifuging. Voids in the seal cause hermeticity problems. Larger ceramic packages cannot support a pressure of 90 psi applied during the fluorocarbon hermeticity test for gross leaks, which has to be modified (see Section X). They also do not stand up well to vacuum exposure.

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		TABLE IV			
		FLATPACK CONSTRUCTION (REF. 9)			
Type	Construction	Base	Sealing Flange	Cover	Seal
I	Kovar	Kovar	Kovar body	Kovar	stitch weld
II	borosilicate glass	glass	glass	glass coated metal	low temp. glass
III	Kovar-glass	(a) glass	Kovar	Kovar	braze
		(b) Kovar	Kovar	Kovar	braze
IV	glass-ceramic	(a) ceramic	Kovar	Kovar	braze
		(b) ceramic	metallized ceramic	Kovar	braze
V	ceramic	ceramic	none	ceramic	low temp. glass

Package Size	Type Construction	No. of Leads	TO Outline
1/4" × 1/8"	I, III	6	
		10	TO-89
		14	TO-84
1/4" × 1/4"	II, III, IV	6	
		10	
		14	TO-86
1/4" × 3/8"	II, III, IV, V	14	TO-87
		16	
		24	

Quality Assurance

The packages should be subjected to a visual inspection at 30 — 50X magnification at three stages in the fabrication process: during incoming inspection, visual precap inspection and during external visual inspection after screening. The inspection criteria should include the following:

dimensional	out of tolerance conditions, misalignment of package elements, warpage, lead burr on inside of sealing ring frames
voids, bubbles, undercutting	
package damage	cracks, microcracks along leads, chips, delamination, scratches
plating defects	flaking, peeling, stains
foreign material	unattached and attached

The visual precap inspection concentrates on inspection of the sealing region for contamination, damage and other irregularities.

The quality and alignment of the seal is checked during external visual inspection.

The rejection rate during incoming inspection may be as high as 30%.

VIII. PROCESS QUALITY CONTROLS

It is in the interest of each manufacturer to maximize his yield. Consequently, process quality controls are instituted on every production line, and some manufacturers have developed elaborate quality assurance programs for this purpose. Military and NASA line qualification procedures have been applied to many semiconductor products, and are now being introduced into some integrated circuit lines. Nonetheless, many reliability problems remain as indicated by a survey of recent NASA and GIDEP Alerts (Ref. 45). It is therefore desirable for the user to ensure that adequate process controls are in force, since not all reliability problems can be screened out.

The process controls in the wafer fabrication stage primarily determine the yield, since all devices undergo electrical multiprobe inspection at the

end of that stage. Any reliability problems in dies that pass the electrical test can usually be eliminated by visual inspection during the assembly stage. Since many additional reliability problems are introduced in assembly the quality controls during this phase are the most critical. A process flow diagram is shown in Fig. 5.

Certain quality control operations must be carried out in the form of sample checks because of their potentially destructive nature, i.e., SEM analysis, die mount control and bond strength tests. For these operations the line flow and wafer traceability become critical. Ideally, some devices should be sampled from each wafer. This is rarely done for economic reasons, and the dice are segregated by diffusion lot or by metallization lot. Some firms assemble devices from several different diffusion runs in one metallization lot.

The following examples illustrate the inadequacy of such procedures: One of the prime purposes of the SEM wafer check is to detect microcracks. These depend on the metallization, but also on the phosphorus diffusion and subsequent etching steps. The latter are usually carried out by means of manual operations depending on the time of immersion and the chemical condition of the etchant. The metallization process itself frequently depends on the position of the wafer. Similarly, the bonding operation depends on the quality of the metallization and on the absence of contaminants.

Some of the assembly operations use preforms, wire, package and lids that require careful screening and quality control procedures in their procurement, preparation and use. This applies particularly to types of packages that contain many defects.

Some customers prefer to carry out certain quality control inspections on their own, particularly SEM wafer check and visual precap. There are strong reasons for such a procedure, since the reject criteria are very complex and in the case of the SEM inspection not defined with any precision. The inspections should be carried out in close collaboration with the vendor, so that the right kind of corrective action may be taken.

The customer may also exercise some control over the wafer traceability by purchasing wafers, carrying out SEM and visual inspections and then
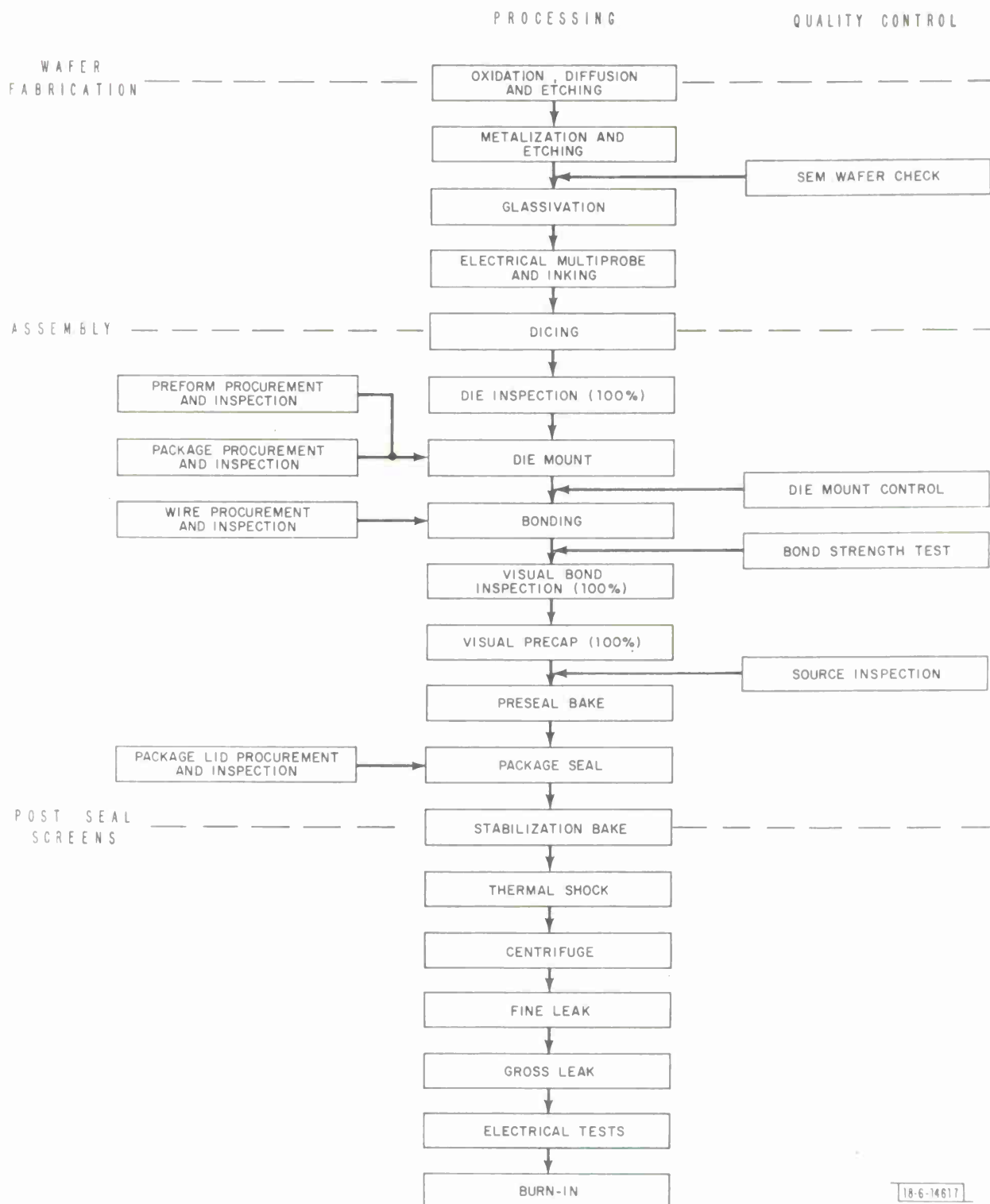
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Fig. 5. Process flow diagram.

resubmitting the wafer to the vendor for die assembly. The chief objection to this procedure is surface deterioration produced by excessive handling apart from the time delay involved. On the other hand, this method looks economically attractive, since no defective wafers receive further processing in the expensive assembly stage. Some vendors keep inventories at the wafer level that make such a system easy to operate.

IX.   INTERNAL VISUAL INSPECTION

The most comprehensive screening out of defective devices is carried out by means of detailed microscopic inspections. MIL-STD 883 provides for such an examination in three stages:

a. Dice inspection at 100X magnification for metallization, oxide and diffusion, scribing and die defects. The inspection is carried out immediately after die sorting.

b. Inspection at 40X magnification for die mounting, bonding, internal lead wire and package defects. The inspection is carried out after bonding.

c. Repeat of inspection (a) immediately before sealing.

The 100X inspection after die sorting is designed to remove defective devices before they undergo further processing. The final 100X inspection is to ensure absence of scratches, foreign matter and other defects at the last opportunity before sealing. A survey of the industry has shown that many manufacturers do not carry out the second inspection as a 100% screen, but only on a sampling basis by quality control. However, the customer is invited to carry out his own source inspection at this point in manufacture. Some firms impose a charge for permission to carry out a source inspection.

The internal visual inspection requires a high quality stereomicroscope with vertical illumination, a good field of view for inspection (b) at 40X magnification and firm location of the die surface in the focal plane of the microscope. A metallurgical microscope should be available for further analysis of some defects, particularly those that reveal shortcomings in certain processing steps. Some manufacturers provide very marginal equipment for the internal visual inspection, thus placing greater strain on the operator.

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Table V lists defects to be looked for during the internal visual inspection. MIL-STD 883 provides for an inspection under test condition A for applications requiring the highest reliability and under test condition B for applications that can tolerate a somewhat lower level. A survey of the industry has shown that most manufacturers apply test condition B routinely and have little experience with test condition A.

There is some correlation between certain types of metallization oxide and diffusion defects and electrical parameters, but electrical screening eliminates such defects far more expeditiously. No correlation has been established between inspection for visual defects under test conditions A and B and long term reliability failures. The rejection criteria had to be drawn up on a sufficiently broad scale, so as to encompass all possible potential failure modes, even though this will eliminate some perfectly good devices. The resulting specifications represent compromises at different levels.

As an illustration, let us consider scratches in the metallization. All scratches are potential failure hazards and should be rejected. If the scratch appears to terminate halfway across the metallization path, microscope examination at higher power may reveal disturbed metal further across the metallization. Long term failure by electromigration is a function of the current density, which depends on the detailed circuit design, the application, the overall width and depth of the metallization stripe and the operating temperature. Rejection criteria depending on leaving 50% or 75% of the metal path undisturbed do not possess any significance.

For this reason it has been suggested that level A inspection is not tight enough, but should be strengthened. Tighter specifications have been developed by NASA and Jet Propulsion Laboratory and are shown in the Table. Also, MIL-STD 883 does not deal with certain types of defects, e.g., the glass passivation layer, the Mo-Au system and package defects that can be examined by internal visual inspection. Some of these areas will be added in future revisions.

		MIL STD 883		
Defect	NASA or JPL Specifications	Test Condition A	Test Condition B	Minuteman (Ref. 9)
TABLE V VISUAL INSPECTION CRITERIA				
Metallization Defects:	100 X min	100 X min	75 X min	80 X min
scratches: undisturbed metal width	50%	50%	50%	50%
undisturbed metal width over oxide step	100%	75%	75%	
voids: undisturbed metal width	75%	75%	50%	0.6 mil, 50%
undisturbed metal width over oxide step	75%	75%	75%	0.75 mil
undisturbed metal width over emitter area	100%	75%	75%	0.75 mil
corrosion	none	none	none	
discoloration or stains	none			
adherence: lifting, peeling, blistering	none	none	none	
probe marks: not on pads	none	like scratches & voids	like scratches & voids	
on pads	do not expose underlying surface	more lenient spec.	—	
bridging: minimum separation	50% of normal	50% of normal	0.1 mil	
alignment: contact window	100%	75%	50%	
other	0.25 mil	0.25 mil	0.1 mil	
Moly-Gold silver grey eutectic	none	—	—	
moly undercutting	< 1/4 width	—	—	
moly exposure	50%	—	—	

The table title "TABLE V / VISUAL INSPECTION CRITERIA" appears above the column headers.

Table V (Cont'd.)

| Defects | NASA or JPL Specifications | MIL STD 883 | | Minuteman (Ref. 9) |
		Test Con-dition A	Test Con-dition B	
Oxide and Diffusion Defects:	100 X min	100 X min	75 X min	150 X min
bridging: between diffusion areas and metallization stripes	0.25 mil separation	contact	contact	
narrow diffusion area: minimum	50%	25%	25%	
apparent short: between metal & underlying material	none	none	none	
active junction: not covered by oxide	none*	none	none	none
contact cut across junction	none	none	none	
contact window: undersized, enlarged, incorrect location	none	—	—	
adherence: flaking, lifting, crazing, cracking	none*	—	—	
nonuniform thickness or color	none*	—	—	
dislocations or stacking faults	none			
Scribing and Die Defects:	100 X min	100 X min	75 X min	80 X min
edge separation: oxide between edge and active area	1 mil	0.25 mil	0.1 mil	1.5 mil
chipouts or cracks: in active circuit area	none	none	none	
cracks: longest length	5 mil	5 mil	5 mil	
closest distance to active area	1 mil	0.25 mil	0.1 mil	none within
pointing to active area	1 mil	1 mil	1 mil	1 mil
attached portions of adjacent die containing active metallization	none	none	—	
cracks delineating pieces of Si	none	—	—	

* Applies also to glass passivation layer

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Table V (Cont'd.)

| Defects | NASA or JPL Specifications | MIL STD 883 | | Minuteman (Ref. 9) |
		Test Condition A	Test Condition B	
Bonding Inspection:	30X — 50X	30X — 50X	30X — 50X	30X — 50X
ball bonds: diameter	2-4X wire dia.	2-6X wire dia.	2-6X wire dia.	2-6X wire dia.
location within unpassivated bond pad	90%	75%	50%	> 50%
location on post	completely	completely	completely	
exit wire: symmetrical	yes	yes	yes	
vertical	for 1 wire dia.	—	—	
other bonds: width	1.2 — 2.0X wire dia.	1.2 — 3.0X wire dia.	1.2 — 3.0X wire dia.	< 2 wire dia.
length	> 2.0X wire dia.	1.5 — 5.0X wire dia.	1.5 — 5.0X wire dia.	
location of wedge bonds in passivated bond pad	90%	75%	50%	
wire angle at bond	10 — 30°	—	—	
bond compression indentation	10 — 75%	—	—	
general: wire distance of nearest approach	2 wire dia.	2 wire dia.	contact	
cross over	no	no	no	
bond separation	0.25 mil	0.25 mil	0.1 mil	
bond placement in fillet area				
wire tails at bond pad	< 2 wire dia.	< 2 wire dia.	< 2 wire dia.	
wire tails at post	< 4 wire dia.	< 4 wire dia.	< 4 wire dia.	
missing tails	no	—	—	
tearing bonds	no evidence of lifting or partial separation	50% of bond impression remains attached	—	
rebonding	none on pad one on post	no evidence on pad	—	
lateral pond-pulling across pad	no evidence	—	—	

Table V (Cont'd.)

Defects	NASA or JPL Specifications	MIL STD 883		Minuteman (Ref. 9)
		Test Con-dition A	Test Con-dition B	
Internal Lead Wires:	30X — 50X	30X — 50X	30X — 50X	30X min.
loop or sag: to wires, pad, post, die, lid, no crossing	5 wire dia.	2 wire dia.	touch	touch, 2 mil for wires yes
no sagging below top surface of die	yes	—	—	
max. horizontal displacement	3 wire dia.	—	—	
diameter reduction: nicks, cuts, crimps, neckdown, scoring	25%	25%	25%	50%
tearing at bond junction	none	none	none	
bends or kinks: max. bend radius	2X wire dia.	—	—	
taut wire: minimum displacement	1 wire dia.			
Die Mounting:	30X — 50X	30X — 50X	30X — 50X	30X min.
die mounting build up: height	< 75% die height	die height	—	—
must not touch top surface	yes	yes	yes	
die-to-header melt: percentage of total perimeter	> 75%	> 75%	> 50%	> 80% preform > 50% eutectic bond
material: balling, cracking, crumbling, chipping, flaking, slag	none	none	none	
location: flat	within 10°	level	level	
Foreign Material:	30X — 50X	30X — 50X	30X — 50X	30X min.
unattached	none	none	none	
attached: bridging distance between conductors on die, wire, posts	50% of distance none	distance 0.5 mil	distance —	50% of shortest distance < 0.5 mil
ink, photoresist or chemical processing material	none	none	—	

X. SCREENING

The general screening sequence as prescribed by MIL-STD 883 is shown in Table VI which also indicates the major failure modes to be screened out as well as different screening levels. A recent review of screening methods has been given by Myers (Ref. 6).

The stabilization bake is primarily designed for stabilization of the electrical characteristics and to screen out metallization and bulk silicon defects. MIL-STD 883, method 5004, prescribes a stabilization bake before the visual inspection for gold-gold metallurgical systems. This appears to be related to Mo-Au adhesion problems described in Section 3. Peck (Ref. 33) and (Ref. 4) advocate a 16 hour bake at 300°C to eliminate not only devices with bulk defects but also weak bonds. They have achieved failure rates of 0.001%/1000 hours in devices with aluminum metallization and Au-Al thermocompression bonds.

Thermal shock and thermal cycling tests serve the same purpose, but the former is more rigorous. Thermal cycling has been used to screen out weak Al-Al ultrasonic bonds, taut Al wires, and Au-Au ball bonds. In the latter case 100 cycles were applied between − 65 and 150°C and the failure mode appears to be Au-Mo delamination. 2500 cycles between − 55 and + 150°C have been used to screen microcracks.

The mechanical shock test is considered inferior to constant acceleration. However, the pneupactor shock test is more effective (Ref. 6). Autonetics (Ref. 46) have developed a monitored vibration-shock test that is very effective in detecting small conducting particles in ceramic packages. The test consists of a conventional monitored vibration with a mechanical shock pulse superimposed every seven seconds. The shock pulse is intended to overcome electrostatic charges that build up after four or five impacts during vibration and cause the particles to become attached to the package or chip. An acoustic particle tester has been developed by Lockheed (Ref. 47), but it works well only on metal cans. X-ray tests are not capable of detecting small particles that may produce shorts.

TABLE VI

SCREENING METHODS

Sequence	Screen	Method	MIL STD 883 Class A	MIL STD 883 Class B	Minuteman (Ref. 6, 9, 20)	Jet Propulsion Lab. (Ref. 44)	Failure Modes
1	internal visual (precap)	2010	s e e S e c t i o n I X				
2	stabilization bake	1008	> 24 hours*, > 150°C	same as Class A	96 hours at 150°C	48 hrs at 150°C	electrical stability, bulk silicon and metallization defects, corrosion
3	thermal shock	1011	0-100°C, 15 cycles	—	10 cycles, 0-100°C	-65 to 100°C, 10 cycles	metallization defects, microcracks, cracked dice, weak die and wire bonds, package and seals (ceramic)
4	temperature cycling	1010	-65 to 150°C, > 10 cycles	same as Class A	-55 to +125°C, 15 cycles, +50°C to 175°C, 20 cycles	same as Class A	
5	mechanical shock	2002	1 pulse at 20,000 G or 5 pulses at 1,500 G in Y_1 plane (axial)	—	1,500 G/5 ms/ shock, 6 axes	5 pulses at 1,500 G in Y_1 plane (axial)	wire bond, die bond, cracked dice
6	centrifuge	2001	30,000 G in Y_2 plane, then Y_1 plane	30,000 G, Y_1 plane only	30,000 G, Y_1 plane only	30,000 G Y_1 axis then Z_1 axis	wire to case shorts, lead dress, loose dice, wire bonds (not satisfactory for Al bonds)
7	hermeticity fine	1014	5×10^{-7} cc/sec He, 5×10^{-8} cc/sec Kr	same as Class A	1×10^{-8} cc/sec He or radio-isotope	1×10^{-8} cc/sec He or radioisotope	
	gross		fluorocarbon	same as Class A	same as Class A	same as Class A	faulty package, cracked seals, improper lid alignment
8	intermediate electrical parameters						
9	burn-in	1015	240 hrs at 125°C	168 hrs at 125°C	250 & 500 hrs at 125°C	168 hrs at 125°C	parameter drift, inversion and channeling, surface contamination and corrosion, metallization defects, oxide pinhole shorts and breakdown
10	intermediate electrical parameters						
11	reverse bias burn-in	1015	72 hrs at 150°C	—			

* 48 hours typical

Table VI (Cont'd.)		MIL STD 883					
Sequence	Screen	Method	Class A	Class B	Minuteman (Ref. 6, 9, 20)	Jet Propulsion Lab. (Ref. 44)	Failure Modes
12	final electrical test						
13	radiographic inspection	2012	yes	—	method 209, MIL-STD 202	method 2012 & JPL Doc. EP 50583	die void, conducting particles, lead dress (Au), gross manufacturing errors, seal, package
14	external visual	2009	yes	yes	yes	Doc. EP50582	improper sealing, cracked packages, poor lead plating and lead contamination
15	additional tests					threshhold test, high voltage test, insulation resistance, vibration	

Constant acceleration tests do not screen weak Al-Al bonds. Gill et al. (Ref. 21, 22) have shown that constant acceleration tests at 100,000 G are very effective in screening die delamination and ball bond separation. Such tests cannot be carried out in practice, since constant acceleration tests in excess of 20,000 G produce permanent device damage (Ref. 48).

It is claimed that the constant acceleration test aids in dressing the leads. This is questionable if the acceleration in the Y_1 plane is applied after the acceleration in the Y_2 plane as specified by MIL STD 883. The stress is applied only in the Y_1 plane, and the dressing is done by accelerating in the Y_2 plane.

The bomb pressures prescribed in the hermeticity fluorocarbon leak tests, method 1014, test condition C exceed the package capability of soft glass packages. Alternate pressure and time conditions must be used, but the pressure should be at least 30 psig.

Burn-in is one of the most effective screening tests, since it provides sufficient energy to cause a change in an unstable device and allows time for the change to proceed to a detectable failure (Ref. 49). 95% of all failures occur within 168 hours. Additional failures in the most complex devices occur beyond this period. The fallout is very dependent on the operation of the production line. Variations by two orders of magnitude have been observed for the same type of device manufactured by different vendors. The burn-in screen improves the failure rate by a factor 10 on the average.

Different burn-in techniques have recently been reviewed by Brown et al (Ref. 7). Burn-in is most effective for passivation, metallization and silicon bulk defects. Unless the devices are extensively characterized, the burn-in stresses should be limited to the manufacturer's maximum ratings. Operating d.c. is the preferred burn-in mode, since a.c. burn-in is not as effective against metallization failures.

Reverse bias burn-in is needed for surface sensitive devices, e.g., MOS and linear microcircuits. This method is particularly effective against inversion layers, corrosion or oxide breakdown. Cooldown under bias is required after completion of the burn-in. This also applies to the operating d.c.

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burn-in for microcircuits, since part of the circuit is always under reverse bias.

Radiographic inspection is important primarily for voids under the die bond, seal or package defects, lead dressing in gold wire and large particle contamination. A detailed specification for radiographic inspection of microcircuits has recently been issued by NASA (Ref. 50).

XI. DEVICES WITH SPECIAL CONSTRUCTION

Microwave Devices

The fabrication of microwave devices is characterized by a small scale laboratory type of operation. Very careful work is done by skilled operators and there is excellent wafer lot control. At the same time there is a complete absence of quality assurance and screening procedures other than electrical. The devices themselves are typically of epitaxial planar construction with glass passivation in some instances.

The metallization is critical in view of the small dimensions that require visual inspection at 400X magnification. Under these conditions gold metallization is more satisfactory than aluminum. It is very important to ensure the absence of microcracks, but SEM inspection is not currently employed on any of the lines inspected. Many of the evaporators are of the laboratory type without a planetary system, but with a heated substrate.

There is a complete absence of any bonding controls or pull tests despite the critical nature of the bonds (see Table III, Section V). Wedge bonds are normally made on 0.5 to 0.8 mil gold wire. Some devices will not pass 20,000 G constant acceleration.

The ceramic strip line package with a Kovar lid presents hermeticity problems that are in part caused by lack of quality control on the part of the package manufacturer. Porosity in some of the packages causes leak rates in excess of 10^{-7} cc/sec resulting in humidity problems. Glass seals cause leakages on bending the leads. This could be eliminated by replacing the glass by ceramic. The cylindrical microcoaxial package is considerably more reliable.

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Some of the manufacturers do not possess in house screening capabilities, and not all the screens listed in Table VI are performed. The sealing operation may cause build-up of metallic particles inside the lid. This should be screened by radiographic methods or by a monitored vibration-shock test. Thermal shock, centrifuge and hermeticity screens should be imposed on all devices.

Special problems arise in the use of semiconductor materials other than silicon or germanium. Compound semiconductors like GaAs can show long term bulk degradation phenomena and may create unusual bonding problems. The mechanical stability of some of the structures needs to be investigated.

Integrated Circuits with Thin Film Resistors

Nichrome thin film resistors are typically only 200 $\overset{\circ}{\mathrm{A}}$ thick. They are degraded by moisture and other contamination. The moisture may be introduced during processing or sealing, as well as afterwards if the package is not hermetically sealed. The nichrome filmes are protected by an oxide passivation layer which should be free from pinholes and other imperfections. Stress related problems may also occur after passivation.

The standard burn-in test is not effective in screening nichrome resistors against degradation by moisture or contamination. RADC have developed a high temperature bake (125°C) followed by a low temperature cycle with applied bias. There is also a freeze-out test in which the devices are kept at $-10°C$ for 24 hours. These tests are effective also for thin film resistors other than nichrome.

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13. ABSTRACT

A study was undertaken to determine the feasibility of obtaining high reliability devices for long term space missions and military applications by imposing and monitoring additional process quality controls and screening procedures on standard commercial production lines. A survey of more than a dozen semiconductor manufacturers indicated that the following reliability areas are not adequately controlled: metallization, wire bonding, loose conductive particles and ceramic packages sealed by low melting point glasses. Wide variations were found in the manner in which the bond strength test is carried out. Methods were studied to institute SEM inspection and a more rigorous bond strength test on the production lines, coupled with wafer and bonder traceability. This report surveys reliability problems caused by defects in semiconductor devices and their control.

14. KEY WORDS

semiconductor devices	space applications	communication satellites