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# EFFECTS OF SUBSTRATE TEMPERATURE ON SILICON NITRIDE CRACKING OF BEAM LEAD DEVICES DURING THERMOCOMPRESSION WOBBLE BONDING

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# EFFECTS OF SUBSTRATE TEMPERATURE ON SILICON NITRIDE CRACKING OF BEAM LEAD DEVICES DURING THERMOCOMPRESSION WOBBLE BONDING

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## ABSTRACT

Recent failures in several completed Sandia Laboratories' electronic systems have traced to specific format 25 beam lead transistors and diodes. More extensive failure analysis on the devices showed them to exceed their respective specifications in electrical leakage. All of the failed devices were observed to have one thing in common: cracked silicon nitride over the beams. These observations triggered several investigations to determine if cracked silicon nitride causes electrical failures, where (processing, assembly, etc.) nitride cracking occurs, and when nitride cracking can be reduced or eliminated.

This report describes the work done to determine the effects of changes in substrate temperature and force upon nitride cracking during bonding. Devices were bonded at 150°C, 200°C, and 250°C, and at 250 gms and 525 gms of force, and the amount of nitride damage in the bonding operation was determined. Neither parameter had large effects in cracking. The pulled strength and failure modes were recorded. The results showed that approximately 22% of the devices developed silicon nitride cracks over the beams. Total production handling and processing result in 80-90% of the devices having cracked nitride. Although the sample size is small (63 devices), it does not appear that the cracking is dependent on the substrate temperature over the range used in this evaluation. The high level of nitride cracking in production must be caused by other production processes or by a difference in the bonding conditions for production as compared to the bonding done for this evaluation.

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## INTRODUCTION

One of the primary concerns for the reliability of beam lead devices bonded on substrates is to develop a schedule of bonding parameters that will assure good adherence of each beam to the substrate. It has been found that a wide range of temperature, time and force will result in adequate bond strengths.[1] A typical pull off test[2] strength of a format 25 beam lead device with Sandia Laboratories bonding techniques is 25 to 30 grams.

Several latent failures in completed systems have been traced to excessive leakage in format 25 (Figure 1) beam lead devices. A visual inspection at 240X revealed that the failed devices had cracked silicon nitride over at least one of the gold beams.

The cross section of a typical format 25 device is shown in Figure 2. The bulk silicon chip is one of the electrodes of the device. It is isolated from the gold beam lead by 20,000 Å or 2μn of silicon dioxide ($SiO_2$) and approximately 1500 Å of silicon nitride ($Si_3N_4$). The silicon dioxide is formed as a natural result of the process steps in building the device.[3] The silicon nitride is added as an effective impurity barrier to provide a sealed junction device. The $Si_3N_4$ may extend beyond the $SiO_2$ depending on the etching process for each wafer.[3] Cracks in the silicon nitride, particularly over the gold beams would increase the possibility of a low resistance path from the silicon die to the beam. This is especially true if there is moisture or organic contaminants present.

Eighty percent of the format 25 beam lead devices in Sandia-designed systems have cracked nitride, therefore, it is not unexpected that the devices found to be out of specification or leakage have cracked nitride.[4] It is not certain at this time that the cracked nitride was the controlling factor in causing the device to fail. There are several evaluations in progress that may establish a

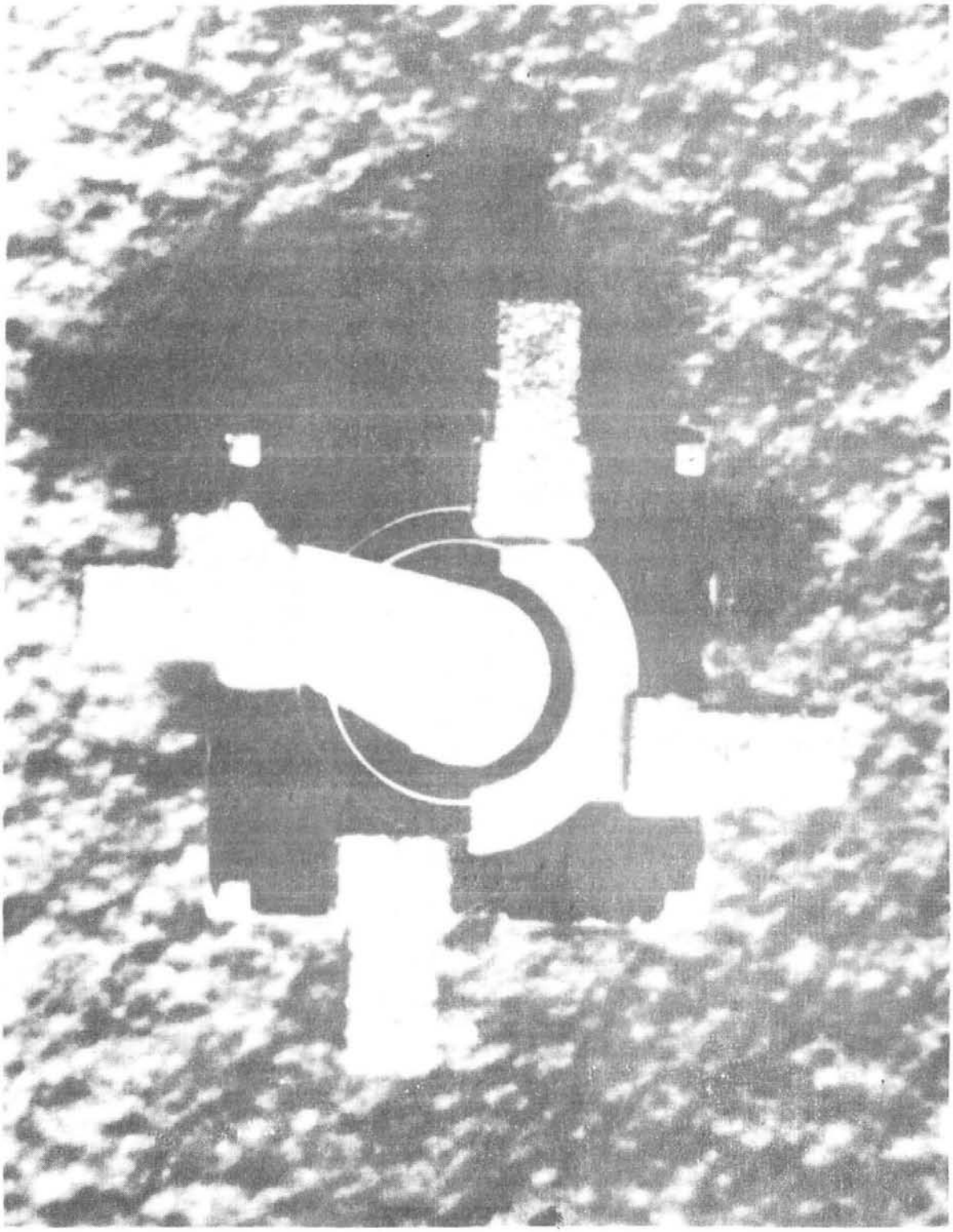


Fig. 1. Format 25 Beam Lead Device

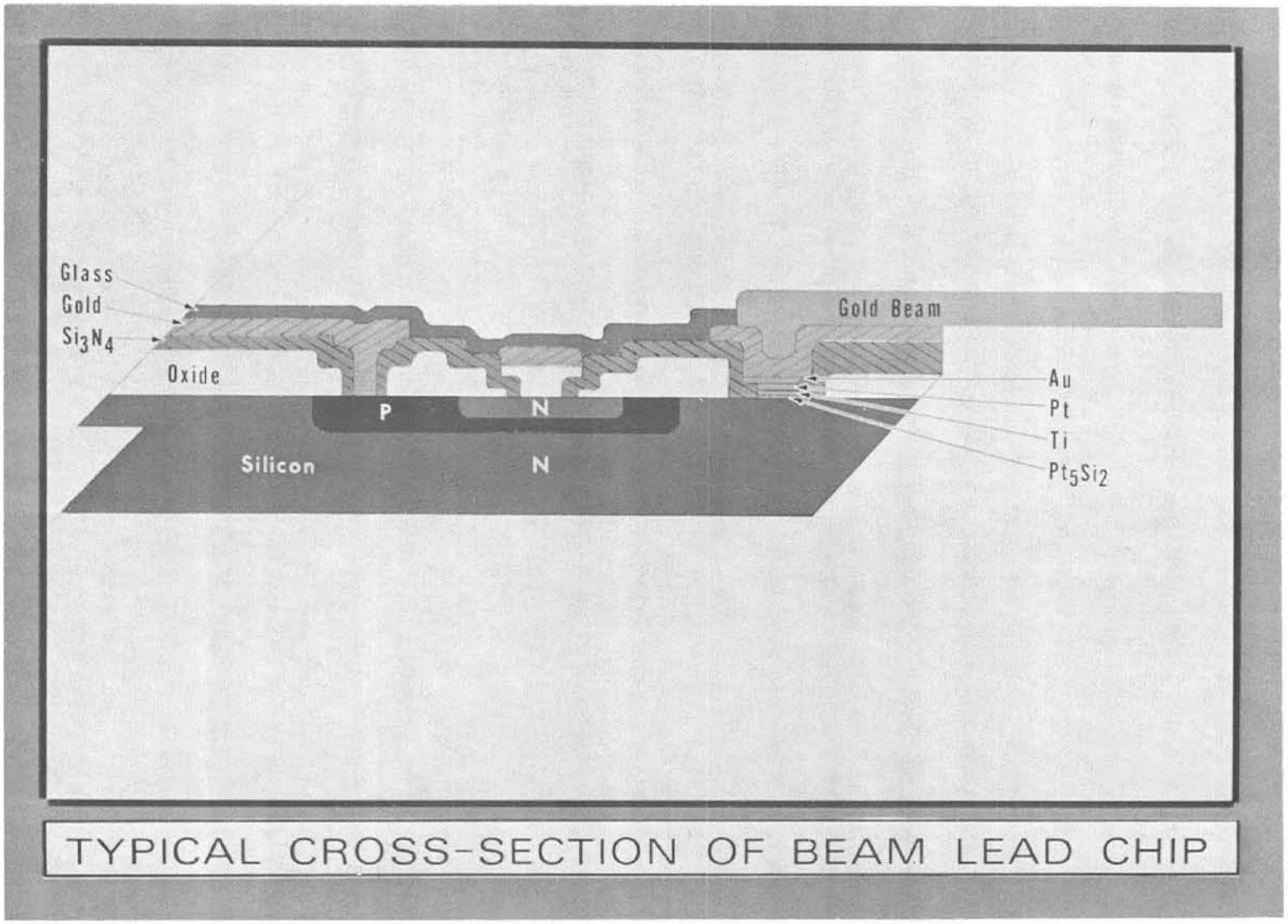

Glass
Gold
$Si_3N_4$
Oxide
P
N
Silicon
N
Gold Beam
Au
Pt
Ti
$Pt_5Si_2$
TYPICAL CROSS-SECTION OF BEAM LEAD CHIP

Fig. 2

relationship between cracked nitride and device failure.[5] Obviously, since the silicon nitride is deposited in the device to act as an insulator and barrier to impurities, it would be preferred that the nitride be free of cracks.

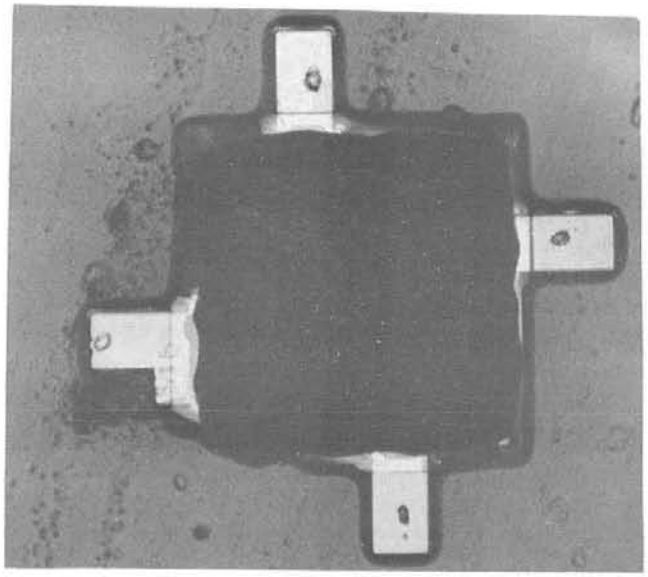
Preliminary investigations into the handling and processing of beam lead devices indicate that any physical contact with the devices after the separation etch causes some degree of nitride damage.[4] Cracked nitride has been found on some devices just after electrical probing and before expansion of the wafer.[6] It has also been shown that wobble bonding increases the presence of cracked silicon nitride when using the bond parameters developed during the first phase of HMC technology development.

## DETERMINATION OF INITIAL SILICON NITRIDE CONDITON

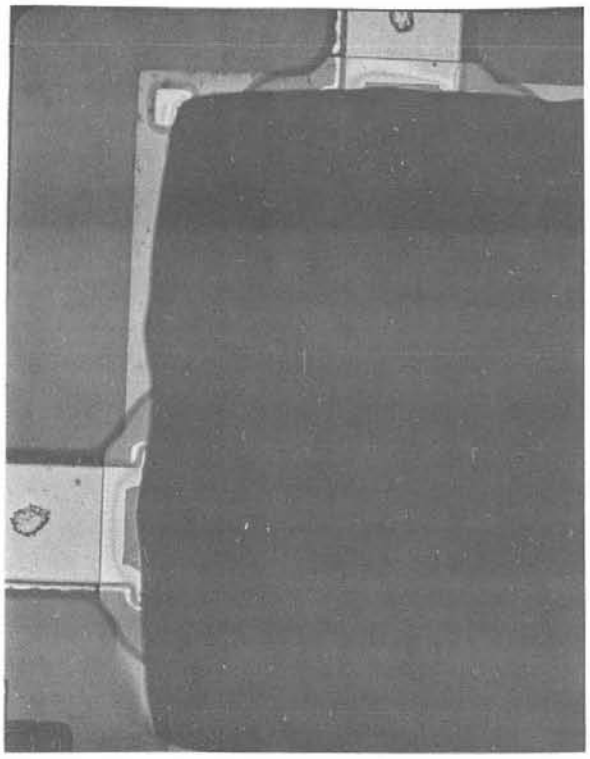
Devices could not be found that did not have silicon nitride cracks before bonding. Therefore, it was decided to take pictures prior to bonding of each device on both the Raytheon and Texas Instruments devices in order to categorize the condition of the nitride.[7] A magnification of 240X was used, showing only two leads in each photograph (Figure 3). This magnification was chosen because nitride cracks did not appear on lesser magnification. Figure 3 shows a device photographed at 100X and 240X before bond then 240X after bonding. In taking photographs of each device, it was seen that most of the devices had cracks in them prior to bonding.

## BONDING PROCEDURES

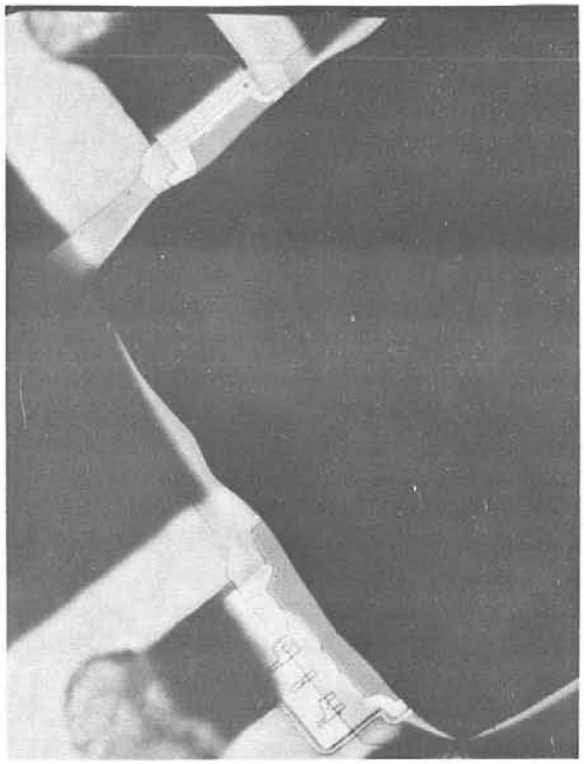
The bonding equipment used for these tests consisted of a Kulicke and Soffa Model 576 beam lead wobble bonder. Temperature and bond force were applied to the bond areas through a heated work stage holder and a heated bonding tool. The wobble mechanism rotated for two complete revolutions in a time period of



100X Not Adequate for Visual Examination



Before



After

240X Shows Existing Nitride Cracks

Fig. 3 Nitride Condition Catagoration

approximately 2 seconds to 2½ seconds. A Format 25 bonding tool provided by Micro-Swiss, Inc., was used to bond all of the beam devices. The bonding tool dimensions were 0.625 mm square with a bonding face (width) of 0.125 mm. The bonding surface was a test pattern consisting of a chrome-gold metallization overlay (approximately 6 μm thick) on a glass substrate (Figure 4). The glass substrate was used to facilitate visual inspection of the bonded devices with the aid of microscope backlighting. The test temperature was set at 390°C for both Raytheon and Texas Instruments devices. Three different substrate temperatures (150°C, 200°C, 250°C) were used with ten samples bonded at each substrate temperature. The bonding force for these devices was adjusted to 255 grams.

## POSTBONDING EVALUATION

Following the bonding, the devices were photographed once again at 240X and the postbonding condition of the nitride was compared to the photographs taken of the respective devices prior to bonding. Color film had been used before bonding, but a color film shortage required the use of black-and-white after bonding. It was discovered that black-and-white film was better than color film because it showed the cracks in the $Si_3N_4$ better than the color film. Bugging of the devices as a result of bonding caused some difficulty in photography because of light shadowing (Figure 5).

The Texas Instruments devices showed cracking at all substrate temperatures, whereas, Raytheon devices showed cracking at 150°C and 250°C but not at 200°C (see Table I). With the small sample size for each substrate temperature, there appeared to be a trend for the devices bonded at 200°C substrate temperature to show less cracks than those bonded at 150°C for both Texas Instruments and Raytheon. Results of this bonding are shown in Table I.

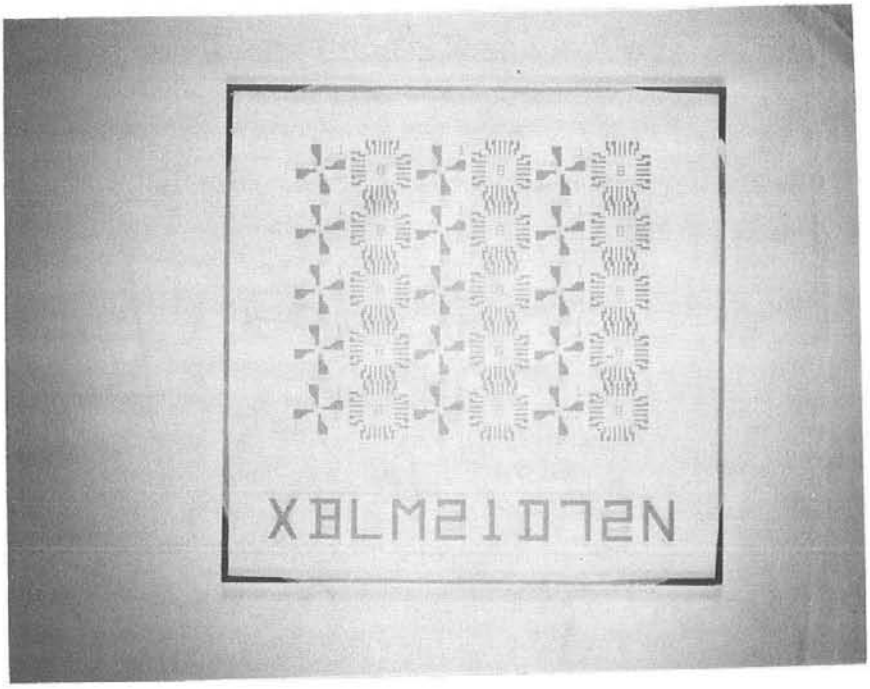



Fig. 4

Test Pattern Used for Bonding

shadow prevents a meaningful visual analysis

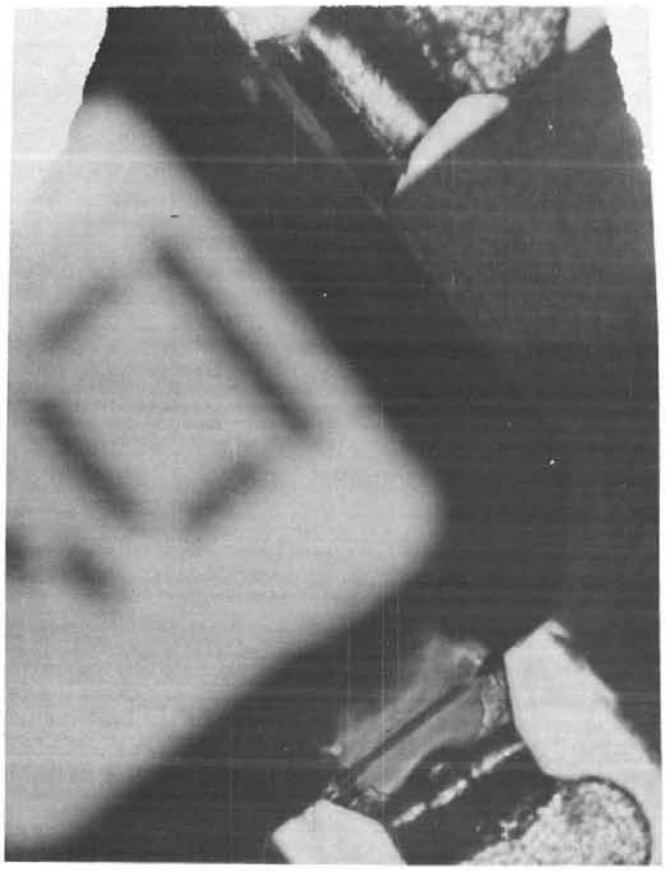


Fig. 5. Device at 240X After Bonding

Table I

| Supplier | Number of Cracks at Substrate Temp. 150°C | 200°C | 250°C |
|---|---|---|---|
| Raytheon | 3 of 10 | 0 of 10 | 3 of 10 |
| Texas Instruments | 3 of 10 | 2 of 10 | 3 of 10 |

Following the visual examination, half of the devices bonded were pull-tested to destruction.[2] A comparison of beam failure modes were made to determine the effects of substrate temperature on bond integrity. Figure 6 shows the locations and nomenclatures of the various failure modes. A bond separation (D failure) is indicative of a poor bond. A low strength bond heel failure (F failure) is not desirable and is caused by over deformation of the beam by the bonding tool. The remaining failure modes are usually device-related rather than bonding-related and are not significant in this evaluation. Table II shows the failure modes at each temperature.

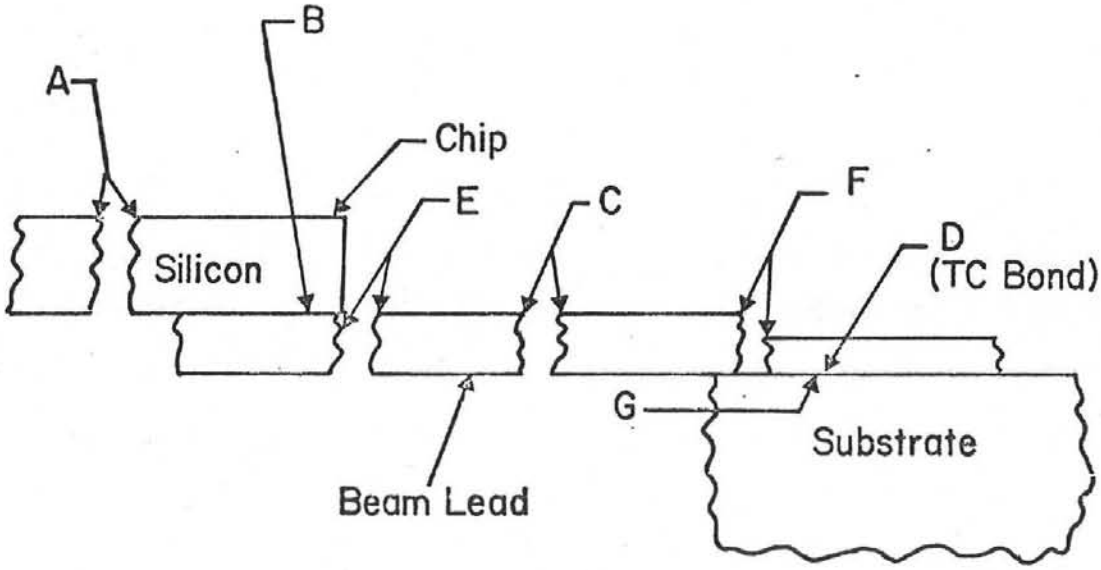
Table II

Beam Lead Failure Modes

| Bond Force | Temperature of Substrate | Bond Strength $\bar{X}$ | Type/Number of Failure Mode |
|---|---|---|---|
| | | Raytheon Devices | |
| 255 gr | 250°C | 13.6 gr | E/15, B/2, F/3 |
| 255 gr | 200°C | 11.4 gr | E/14, B/2, F/4 |
| 255 gr | 150°C | 16.6 gr | E/10, B/4, F/3, C/3 |
| | | Texas Instrument Devices | |
| 255 gr | 250°C | 28.6 gr | E/13, C/3, F/4 |
| 255 gr | 200°C | 30.6 gr | E/12, F/8 |
| 255 gr | 150°C | 29.2 gr | E/9, D/1, F/6, C/4 |

It is significant from the above table of the absence of type D failures (lifting

(Beam Lead Silicon Interface)



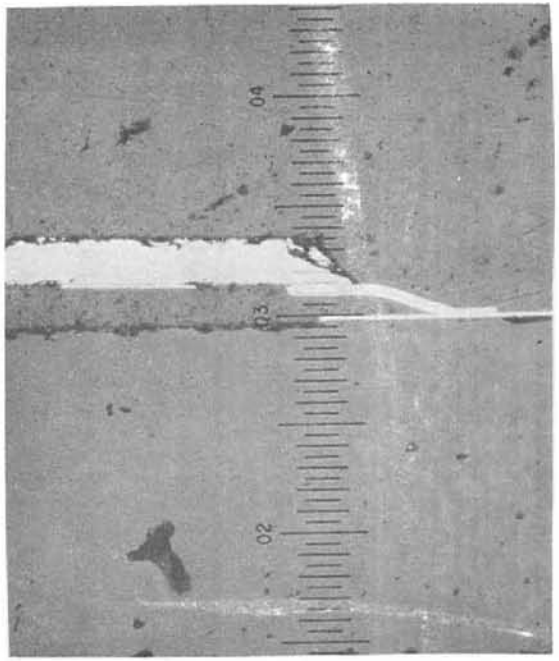

A = Silicon Broken
B = Silicon to Beam
C = Beam Broken
D = TC Bond Broken
E = Beam Broken (Edge of Silicon)
F = Beam Broken at Heel
G = Metallization Failure

Fig. 6 -- Beam Lead Failure Modes

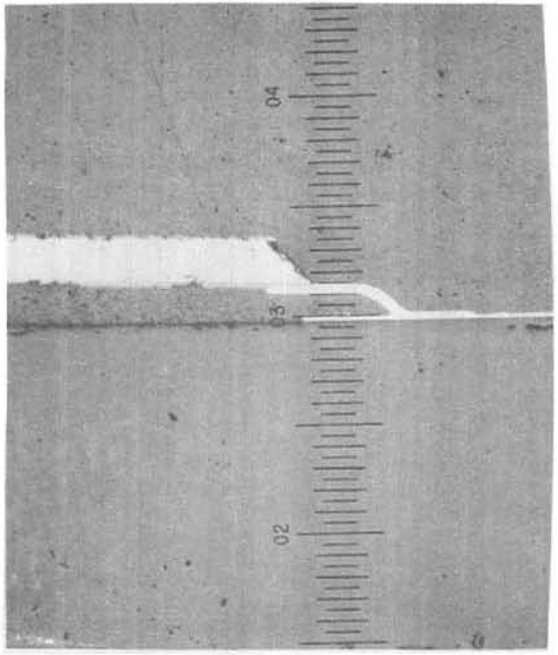
of the bonds) from the substrate metallization except in one instance which occurred at the 150°C temperature level. This would indicate that adequate mechanical bonds can be made at the bond forces and substrate temperatures used in this evaluation.

In an effort to make a rough check on the effects of bond force on nitride cracking, three devices were bonded using a substrate temperature of 200°C and a bond force of 520 grams. The tool temperature, as in the earlier evaluation, was set at 390°C. The results were surprising. None of the three devices showed cracked nitride due to bonding. This result could lead one to believe that there is at least one other variable effecting nitride cracking during bonding that has not been taken into consideration.

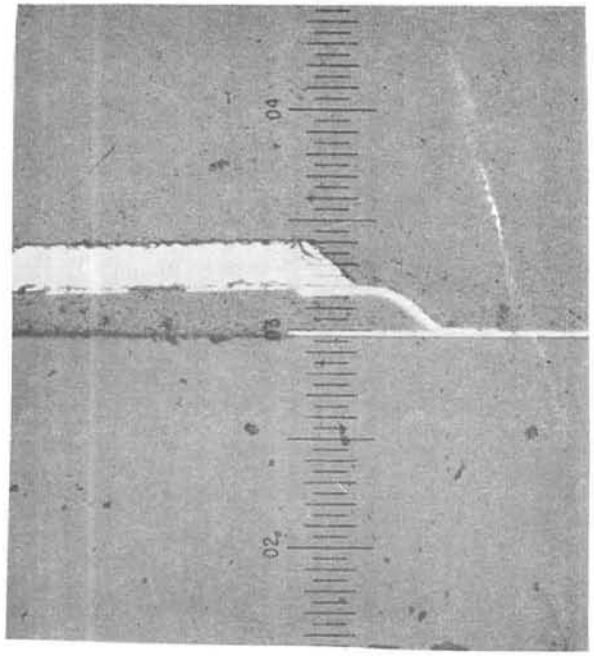
Three bonded beam lead devices were encapsulated and sectioned in order to examine the bugging characteristics. All three devices were bonded using a force of 255 grams. One device was bonded at 150°C, one at 200°C and one at 250°C. Figure 7 shows the cross section of each device. The photos show the expected increased bugging height with increasing substrate temperature. However, more significant than the bugging height is the difference in the shape of the beam bonded at each temperature. Since the object of this evaluation was to determine the effect of bonding on the silicon nitride, special attention should be given to the possible stresses on the silicon at the point where the beam leaves the chip. The most ideal shape of the beam (tangent to the chip) for low nitride stresses appears to exist in the picture of the device bonded at 200°C substrate temperature; therefore, one might conclude this temperature is the most desirable for bonding. A closer look at Figure 7 shows that the beam thickness from one device to the other is considerably different. It has been shown that the perturbing of a straight beam due to stresses is



150°C Substrate



200°C Substrate



250°C Substrate

Fig. 7. Bonded Device Cross Section

directly related to the third power of the beam thickness.[8] Other factors such as beam length and hardness also have effected beam shaping, but not to the degree as beam thickness. Therefore, the beam thickness may be the cause of the 200°C sample to have more desirable beam bugging rather than the temperature.

## RECOMMENDATIONS

It is important to determine if the cracked silicon nitride is the cause of the latent failures in the finished production assemblies. The answer to this question would establish the priority for any additional work on eliminating or reducing the cracked nitride.

It would be desirable to reduce the amount of nitride cracking where possible. This could be accomplished in part by the following activities.

1. Expedite the availability of the beam lead devices with the channeled beams.[9] This channel reduces the beam thickness at one point and influences the shape of the beam during bugging.
2. Consider a redesign of the beam lead device to reduce the amount of the $Si_3N_4$ apron. This would allow more freedom for the beam to flex without causing damage to unsupported $Si_3N_4$. This design change is under consideration at the present time.[10]
3. An additional evaluation of the effects of bond forces and substrate temperatures using a more respectable sample size could show that it would be beneficial to bond at different forces and temperatures in order to reduce beam flexture.
4. Wobble bonding with one revolution rather than two should be considered. If one revolution is adequate to give a good mechanical bond, perhaps the

elimination of the second revolution would reduce the damage to device nitride.

5. A closer look should be taken at the physical position of the bonding tool during the bonding operation. It is possible that transverse movement (skating) of the tool during the wobble could be stressing the device nitride. If this is the case, the machine operation should be adjusted to reduce the skating.
6. Additional evaluation of compliant bonding should be considered.[11] This bonding technique is considered to be more forgiving in device beam variations and perhaps would cause less damage to the $Si_3N_4$.

## CONCLUSIONS

The results of this limited evaluation shows that nitride cracking can be caused over a range of substrate temperatures using a minimum acceptable force. The bonding was performed on the same bonding machine by the same operator, therefore, it is unlikely that variations in the bonding conditions could be a major cause of variations in nitride cracking. Since 22% of the devices were nitride-cracked during bonding, it is obvious that some devices are affected differently than others. Variations in beam thicknesses could be a major factor in cracking the nitride. The amount of bugging during bonding influences the possibilities of nitride cracking, however, the shape the beam takes during the bugging appears to be determined for the most part by the beam thickness and it is this shape that may be affecting the silicon nitride.

Silicon nitride cracks have been found in all stages of processing and assembly. They have been found before and after the bonding operation. The bonding operation appears to cause approximately 22% of the devices to develop

cracked nitride, but 80% of the devices in the finished assemblies have cracked silicon nitride. It appears unlikely that the beam lead bonding operation is the major cause for nitride cracking. Although some additional bonding evaluations are continuing a reduction of the cracking due to changes of bonding parameters does not seem likely with the present equipment because of the inconsistency of beam thickness.

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