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Accelerated hermeticity testing of a glass–silicon package formed by rapid thermal processing aluminum-to-silicon nitride bonding☆

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Abstract

A hermetic, glass–silicon package formed by rapid thermal processing (RTP) aluminum-to-silicon nitride bonding has been demonstrated and characterized by means of accelerated hermeticity testing. Surface-micromachined comb-drive resonators have been hermetically packaged and tested in an autoclave chamber (130 °C, 2.7 atm and 100% RH). In order to determine the reliability of the package, the life time data are first fitted with Lognormal model and analyzed using *maximum likelihood estimato*r. The results show that for packages with sealing ring width of 200 μm and average sealing area of $1000 \times 1000\ \mu m^2$, the lower bound of the 90% confidence interval of mean time to failure (MTTF) is estimated as 270 years under jungle condition (35 °C, 1 atm and 95% RH). Thermal shock and temperature cycling tests between −195 and 200 °C for 20 cycles have also been performed, and only 2 out of 59 packages were found failed after the test. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Hermetic wafer bonding; Packaging reliability; MEMS packaging; Aluminum-to-silicon nitride bonding

1. Introduction

Wafer-level hermetic sealing process provides first level MEMS device protection that may drastically reduce the expensive post-packaging cost. The common approach is to use bonding process to the topmost layer on the MEMS chip and various bonding mechanisms have been demonstrated for direct bonding with silicon, silicon dioxide or metal layers [1]. Silicon nitride has been widely used as the passivation layer in either MEMS or IC [2] but little work has been done in silicon nitride bonding because the requirements of very high bonding temperature and long processing time [3]. On the other hand, reliability and long-term stability of sealed packages are very important characteristics of hermetic sealing and there is little published work in the area of MEMS. Both issues are to be addressed in this paper.

Previously, rapid thermal processing (RTP) bonding has been demonstrated to be capable of providing low thermal budget, wafer-level processing and insensitive to surface topography to achieve excellent bonding strength [4]. In this paper, RTP bonding is applied as an foundry-compatible packaging process to bond silicon nitride with a glass cap using Al as the bonding material. The sealed packages are tested in autoclave chamber [5] to accelerate the aging and corrosion process and to predict the reliability and life time of devices under normal usage.

2. Experimental procedure and results

Fig. 1 shows the schematic illustration of Al-to-nitride RTP bonding for MEMS packaging applications. A surface-micromachined MEMS structure [2] is surrounded by an integrated sealing ring with LPCVD silicon nitride as the topmost layer. The thickness of the LPCVD silicon nitride layer is 5000 Å, and the typical sealing area ranges from 300×300 to $600 \times 600\ \mu m^2$. A Pyrex (Corning 7740) glass wafer is deposited and patterned with aluminum of 4 μm thick and 100–200 μm wide as sealing rings. The assembled pair is put into RTP chamber. Within a process time of 10 s at 750 °C by radiative heating, a stable bond is formed at the Al–nitride interface. Fig. 2 shows the packaged comb-drive resonator that is resonating at 17.0 kHz when immersed in DI water as seen under an optical microscope. The Al-to-nitride seal has successfully blocked water from entering the package. A rare void on the sealing ring is identified in this

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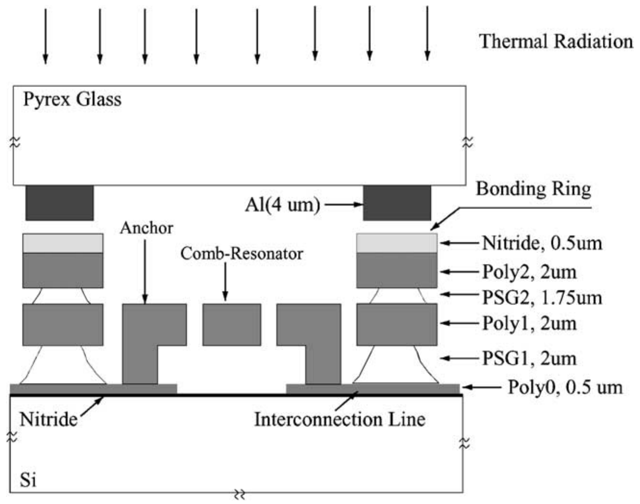

Fig. 1. The schematic diagram of the MEMS packaging process using Al-to-silicon nitride RTP bonding.

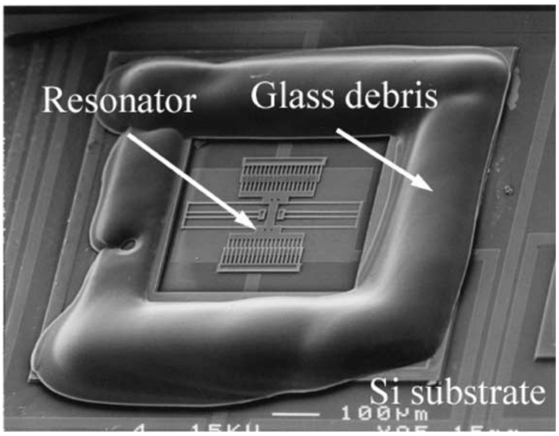

Fig. 3. SEM microphoto of silicon substrate after the Al-to-silicon nitride bond is forcefully broken. Bulk glass is found on the silicon substrate.

figure and it is probably formed due to the poor wetting of liquid aluminum over glass during the bonding process. This phenomenon has been minimized by adding a thin chromium layer between glass and aluminum to promote adhesion. In order to examine the bond, the package is forcefully broken as shown in Fig. 3. The glass debris is now attached to the sealing ring surrounding the comb-drive resonator on the silicon substrate. This shows that Al-to-nitride bonding strength is greater than the pyrex glass fracture strength that is estimated around 270 MPa [6].

3. Accelerated test and reliability analysis

In order to evaluate the reliability of the MEMS package fabricated by RTP Al-to-nitride bonding, packaged dies with or without comb-resonators are put into the autoclave chamber filled with high temperature and pressurized steam (130 °C, 2.7 atm and 100% RH) for accelerated testing. The pressurized steam can penetrate small crevasses caused by bonding defects. Moreover, the elevated temperature and humid environment can raise corrosion against the bonding interface [7].

The statistical data gathered from accelerated tests in this paper is catagorized as *right-censored* data. The devices under testing are subjected to optical examination in every 24 h until a prescribed time of 864 h when new failure is seldom observed (therefore, right-censored in time axis). In practice, this method is easier and more economical to implement than other methods [8]. Owing to the robustness of the sample, it is difficult to conduct the tests all the way when all the packages may fail. The cumulative failure function $F(t)$ is defined as

$$F(t) = \frac{\text{number of cumulative failure}}{N} \tag{1}$$

where N is the sample size at the beginning of the test. A package is considered as failure if water is condensed inside or diffused into the package. For example, water was found to diffuse into the cavity after 240 h of testing time as shown

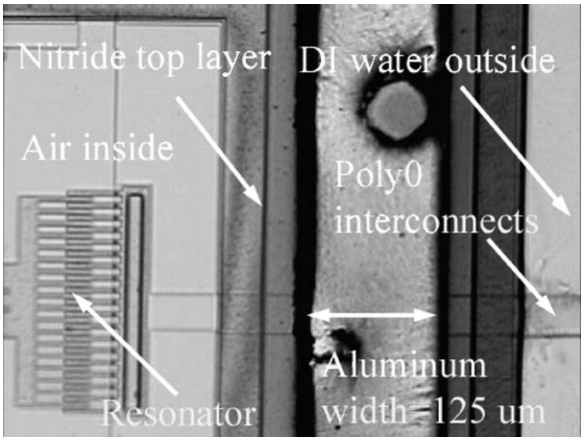

Fig. 2. After RTP bonding, comb-drive resonator is resonating at 17.0 kHz under glass package immersed in DI water.

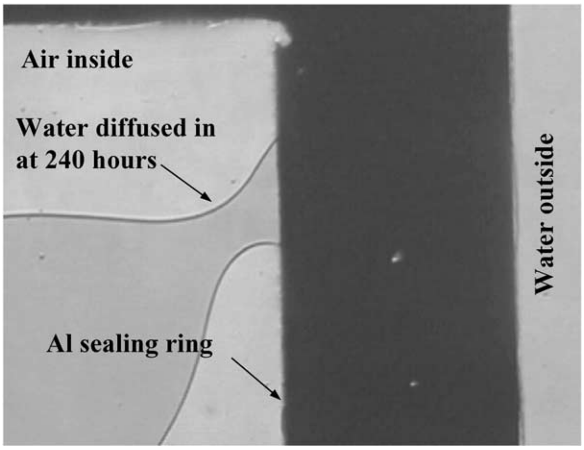

Fig. 4. Optical photograph taken at the end of 240 h of testing time in the autoclave chamber. Water is diffused into the cavity.

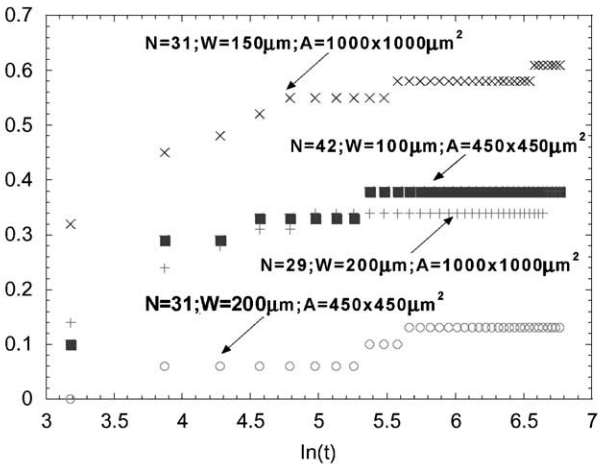

Fig. 5. Cumulative failure function $F(t)$ vs. logarithm time t (in h). N is the sample size, W is the Al bonding ring width and A is the sealing area.

in Fig. 4, but no leakage path can be identified under the optical microscope.

Fig. 5 shows that the $F(t)$ (in %) is plotted versus logarithm of time. In general, most of the failures occurred in the first 96 h ($\ln(t) \simeq 4.56$), such high early failure reflects the yielding issue of the packaging process. Moreover, packages with smaller bonding width and larger bonding areas have higher percentages of failure. Weibull and Lognormal models [8] are compared to predict the life time of packaged devices and the least-square-fit method is used to determine the best fitting model. It is found that R^2, *the coefficient of determination* [8], values are generally in the range of 0.8 by using the Lognormal model as compared with the values of 0.5 by using the Weibull model. Therefore, the Lognormal model is used to predict the life time of packages (Fig. 6).

$F(t)$ can be transformed by the *inverse standard normal distribution function* (Φ^{-1}) using a statistical software package and plotted versus $\ln(t)$ as shown in Fig. 5. Maximum likelihood estimator (MLE) is then used to predict the mean, standard deviation and MTTF of a life distribution from right-censored data [9]. As shown in Table 1, the upper bound and lower bound of 90% confidence interval of MTTF for the packages with larger bonding width and smaller bonding areas have larger values. The wide interval of confidence level comes from the fact that only a small number of samples failed at the end of the test. However, the lower bound of the MTTF provides the worst case scenario. For example, only 4 out 31 samples failed when tests stopped in the case of ring width of 200 µm and sealing area of 450×450 µm^2. The MTTF predicts, in the worst case scenario, that there is 90% chance that a package will fail in 0.57 years in the testing environment.

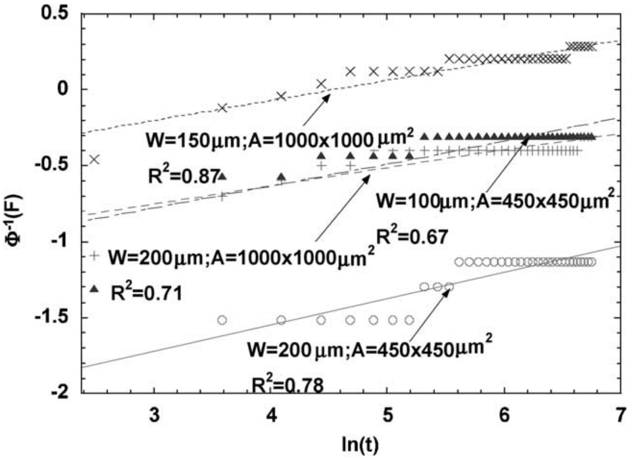

Fig. 6. Life data fitted by Lognormal distribution. R^2 is the coefficient of determination.

Table 1
MLE calculation results of MTTF[a]

Bonding width, W (µm)	Area, A (µm^2)	MTTF		Worst cases in jungle condition (years)
		UB (years)	LB (years)	
200	450 × 450	1.8E7	0.57	1700
100	450 × 450	5.3	0.10	300
200	1000 × 1000	6.5E3	0.09	270
150	1000 × 1000	0.50	0.017	50

[a] UB is the upper bound and LB is the lower bound of the 90% confidence interval, respectively. The MTTF LB times AF is the worst case MTTF used in jungle condition.

It is widely accepted that the acceleration factor (AF) for autoclave tests follows the Arrhenius equation [7] and can be modeled as [5]

$$\mathrm{AF} = \frac{(\mathrm{RH}^{-n}\,\mathrm{e}^{\Delta E_\mathrm{a}/kT})_\mathrm{normal}}{(\mathrm{RH}^{-n}\,\mathrm{e}^{\Delta E_\mathrm{a}/kT})_\mathrm{accelerated}} \quad (2)$$

where RH is the relative humidity (85%, RH = 85), k the Boltzmann constant and T the absolute temperature. The recommended value for n, an empirical constant, is 3.0 [5] and ΔE_a, the activation energy, is 0.9 eV for plastic dip packages [5] and 0.997 eV for anodically bonded glass-to-silicon packages [7]. If $\Delta E_\mathrm{a} = 0.9$ is used to estimate the AF for the testing condition as compared with the jungle condition (35 °C/1 atm, 95% RH), AF is about 3000. Based on this AF, the worst cases in jungle condition are listed in Table 1. The high values of the estimated MTTF in jungle condition as listed in Table 1 could be a result of over-estimation of AF because plastic dip package may have faster AFs than those of glass packages.

Fig. 7 shows spectrums of two reliability tests of comb-resonators: (1) a 12.2 kHz resonator before and after the RTP bonding process, and (2) a packaged 17.0 kHz resonator before and after a 24 h autoclave test. In both cases, no observable change is found. However, these testing results are not conclusive because the changes may only be observed under high quality factor in vacuum. Further investigation in this area are required to understand the packaging effects to micro resonators.

Thermal shock tests are also performed. Packaged devices are first immersed into boiling liquid nitrogen (−195 °C at

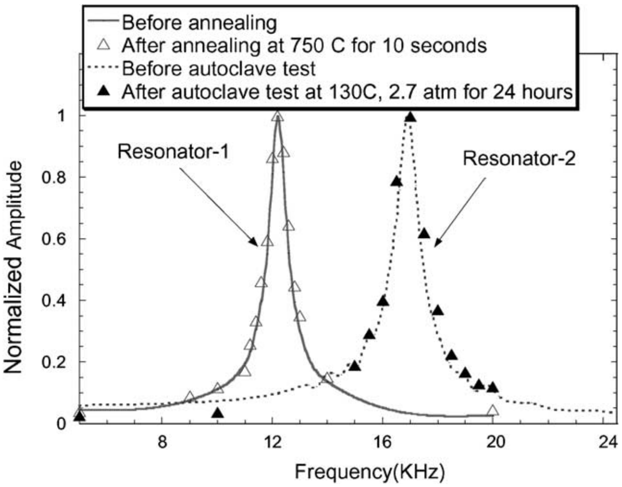

Fig. 7. Reliability tests showing frequency responses of two comb-drive resonators. Resonator-1: before and after annealing. Resonator-2: before and after autoclave test.

1 atm) and are moved immediately onto a hot plate set to 200 °C. After 20 cycles, the devices are immersed into isopropanol alcohol (IPA) to examine leakage and only 2 out 59 devices were found failed. Under a preliminary examination, the leaking passage is at the Al–nitride interface, however, more work needs to be done in order to determine the failure mechanism.

4. Bonding mechanism

It has been reported that aluminum can react with silicon nitride at 800 °C for 5 h and form crystalline β'-sialon [3]. For RTP bonding process, X-ray diffraction (XRD) technique was used to investigate the bonding interface and it is concluded that no new crystalline structure can be detected after bonding (Fig. 8). The short pulse annealing time in RTP bonding process may be insufficient of forming any Al–N–Si crystalline compounds. Therefore, the bonding process could be dominated by volume diffusion of aluminum into silicon nitride. In order to verify the hypothesis, Al-to-silicon nitride RTP bonding process was fitted by Arrhenius equation. Fig. 9 shows successful bonding results at various bonding temperature and time. The slope of the straight line is the activation energy of RTP bonding and is found as 2.5 eV, which is close to the activation energy of aluminum diffusion into silicon nitride (2.0 ± 0.3 eV) reported by other researchers [10].

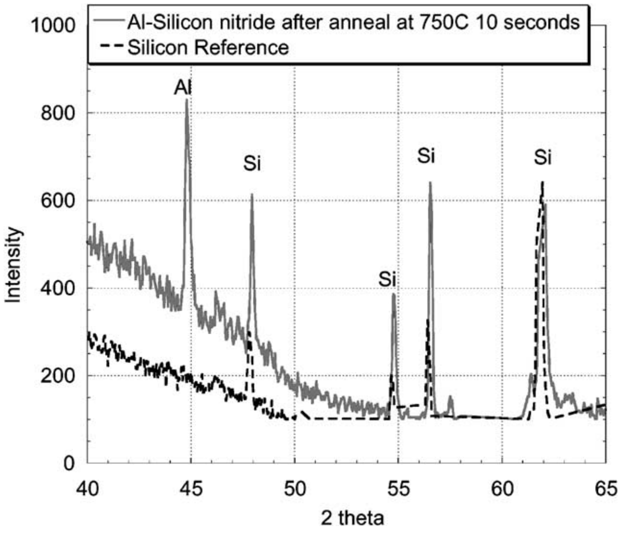

Fig. 8. XRD spectra of aluminum–silicon nitride bonding interface compared with silicon reference. No other compound was detected.

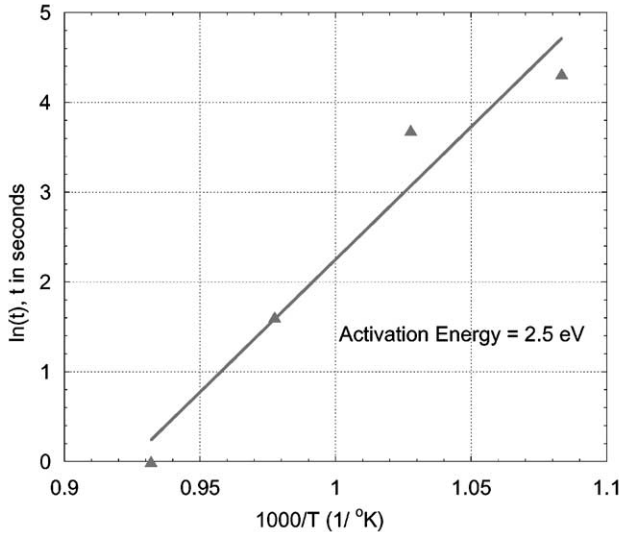

Fig. 9. Experimental result of Al-to-silicon nitride RTP bonding temperature vs. time. The activation energy of the RTP bonding process is extracted as 2.5 eV.

5. Conclusion

In this paper, MEMS packages formed by Al-to-nitride bonding using RTP have been demonstrated and accelerated hermeticity testing has been conducted and analyzed. The worst case of MTTF is estimated between 50 and 1700 years with 90% confidence under the jungle condition. The MTTF increases with increasing sealing ring width and decreasing bonding area. Moreover, the Al-to-nitride bonding mechanism was identified as diffusion bonding by using XRD technique and the activation energy was measured as 2.5 eV which is close to the activation energy of Al–nitride diffusion reported by other researchers.

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Biographies

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