Effects of humidity on non-hermetically packaged III-V structures and devices.

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ABSTRACT

High humidity and temperature tests (known as 85/85 tests) were performed on various III-V devices and structures to determine environmental effects in non-hermetically packaged GaAs membrane mixer diodes. Results are shown for conventional recessed Au/Ge/Ni/Ag/Au ohmic contact test structures, thin films of AlGaAs and for anode-less and operational 2.5 Terahertz mixer diodes. Performance and morphological degradation were determined by using four point probe measurements (transmission line method) for ohmic contacts, by Scanning Electron Microscopy examination and by measuring the DC Current-Voltage (I-V) characteristics in the membrane diodes. The 85/85 humidity test caused a slight degradation in the contact resistance of the ohmic contact test structures and an increase in the scatter in measurements between similar test contact structures. Blistering in various regions of the GaAs membrane diodes and complete consumption of epitaxial AlGaAs test films were also found. However, the I-V characteristics of the 2.5 THz membrane-diode mixers did not degrade after 500 hours at 85°C and 85% relative humidity.

Introduction

The performance of devices in nonhermetic applications is of interest for various applications. High reliability of 1.3 micron InP lasers in broad-band multimedia communication could provide a significant cost reduction. Reliable optical transmitters in plastic packages might also be suitable in future information networks. In space applications, some of the far infrared sensing applications for III-V devices are incompatible with hermetic enclosure of the sensing device due to the unavailability of non-absorbing window materials. The effects of humidity on semiconductor devices have shown detrimental effects in the past, from failures due to large increases in threshold current in InP-based lasers [1-4] to mechanical stresses due to polymeric layers' volume expansion in micro-mechanical devices [5]. Humidity in Ag based metallization in microelectronic interconnects has caused metal corrosion and dendrites due to migration [6].

This study was undertaken with the 2.5 THz GaAs monolithic membrane-diode mixers (fabricated at the Jet Propulsion Laboratory) to be used on the Earth Observing System Microwave Limb Sounder instrument [7-9]. These devices will be used to measure and differentiate the emission from O_2 at 2502 GHz and OH at 2510 and 2514 GHz (119.820, 119.438 and 119.248 microns respectively). The 2.5 THz GaAs monolithic membrane-diode mixers are by their nature non-hermetic since hermetic of the sensing device is not possible due to the unavailability of non-absorbing window materials.

The tests were done to assess any possible effects from moisture during the pre-launch time period (approximately two years). All tests were performed in a constant temperature and humidity chamber, at 85ºC and 85% relative humidity (known in short as 85/85 tests). Exposure to 85/85 conditions was for either for 1000 hours, or at increments of 100, 500, and 1000 hours [10]. No bias was used since none was needed to simulate use conditions. The expected failure mechanism will be corrosion from exposure of the device to humid air. This exposure would occur if the normal hermetic chamber was compromised during shipping or storage. It is assumed the devices will be exposed to the ambient with no packaging to insulate it from ambient conditions.

For temperature and humidity (T/H) testing the unbiased Peck model for accelerated combined temperature-humidity effects [11,12] sometimes is used:

$$t_f = (RH)^n \exp\left(\frac{\Delta H}{kT}\right)$$

where RH is the relative humidity and the other parameters hold usual significance. If the failure mechanism is corrosion of metallic components, then n = 3 and ΔH is assumed to be 0.7 eV. If the failure mechanism is bond failure, then n = 1 and ΔH is closer to 0.3 eV.

A more specific expression for acceleration factors was determined for InP planar PIN diodes in an extensive study were devices were aged at different temperatures and humidities. Such accelerating factor was found to be:

$AF = \exp^{(\Delta H/kT)}\exp^{[A(RH)2]}\exp^{[B(V)]}$, which at zero bias simplifies to:

$AF = AF = \exp^{(\Delta H/kT)}\exp^{[A(RH)2]}$

And the experimentally determined constants were:

$\Delta H = -0.42$ eV, $A = -4.6 \times 10^{-4}$, and $B = -6.7 \times 10^{-2}$/V

In this present study, GaAs devices were assumed to follow similar relationships. Using the parameters obtained for the cited InP study (1), 1000 hours in 85/85 conditions would be equivalent to:

3.2 years at 80 % RH and 45ºC (113 F), or 14 years at 50 % RH and 45ºC

Relevance to NASA projects:

This study was undertaken primarily in support of the micro limb sounder (MLS) instrument of Earth observing System (EOS). The study of ohmic contact changes with humidity was designed to test both the 640 GHz and 2.5 THz mixer diodes. The test of capped AlGaAs films was done to evaluate the reliability of bare AlGaAs membranes in humid conditions, since better performance is expected from Schottky diodes in that material, and making the membrane in AlGaAs might have improved the mixer diodes. Tests on operating 2.5 THz diodes were done since the complex fabrication process involved in these devices did not allow passivation of the back membrane surface. Figure 1 shows a scanning electron micrograph of one of the membrane diode structures before exposure to moisture.

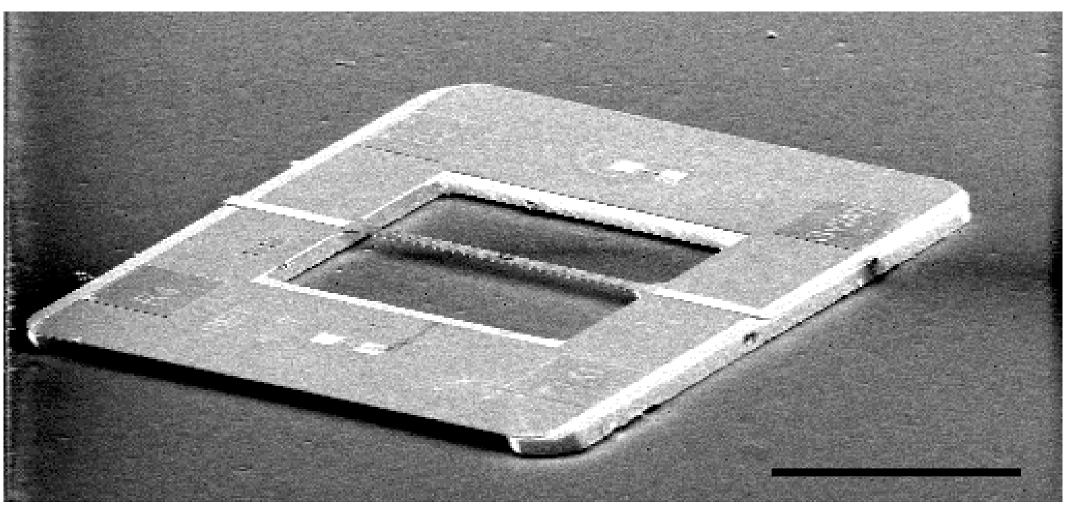


Figure 1. Scanning electron micrograph of 2.5 THz GaAs membrane diodes and frame prior to humidity testing. Membranes are 3 microns thick. Bar is 500 microns long.

Changes in contact resistance in Au/Ge/Ni/Ag/Au GaAs ohmic contacts

Au/Ge/Ni/Ag/Au ohmic contacts are used in JPL's 640 GHz and 2.5 THz mixer diodes, and will be used in the formation of ohmic contacts to several GaAs devices in future devices made at JPL for NASA projects. Possible failure of the passivating layer was a concern, as well as the know formation of intermetallic compounds of gold and silver [13,14], which can degrade the ohmic contacts by increasing the contact resistance (Rc)

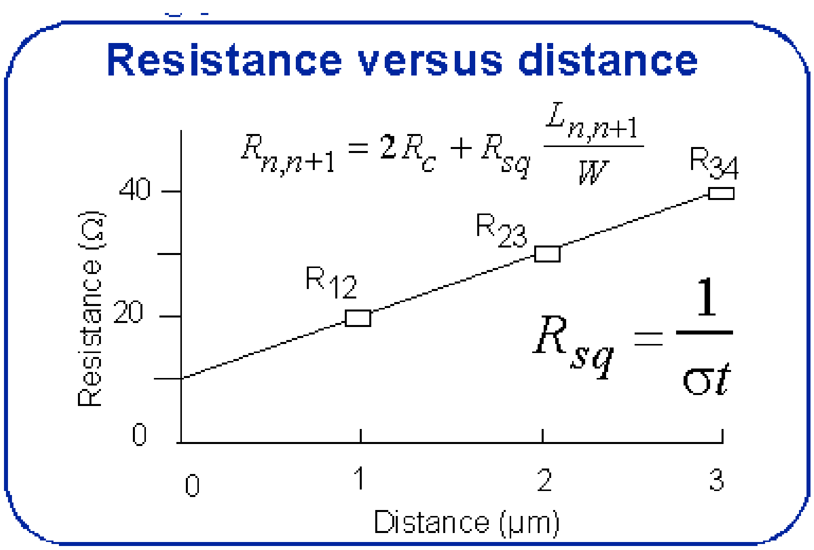


Figure 2. Contact resistance extrapolation for the transmission line method.

Because the current distribution across a contact area is usually not homogeneous, Rc cannot be directly measured, but must be extracted with special test structures. By employing the commonly used transmission line method (TLM) [15] illustrated in figure 2, one determines the resistance between two rectangular contact pads of length *l* and width *W* on an insulation mesa of width *W* + 2d with respect to the spacing d between the contacts. The total resistance *R T* between two contacts comprises the resistance of the contacts and a contribution related to the sheet resistance. To separate these two contributions, a series of resistance measurements with different contact spacings can be performed. The resulting plot of R_T versus d yields the resistivity r_s in the slope of the linear relationship, while $2R_c$ is obtained from the intercept on the y axis. Shockley analysis of a TLM contact shows, that the plot of R_T vs d intersects the x axis at $2L_T$. Therefore, r_s, L_T, and R_c can be extracted and the specific contact resistivity r_c can be calculated.

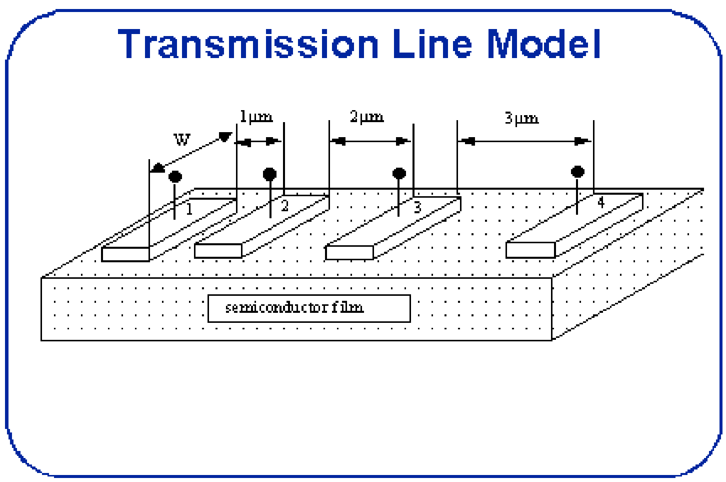


Figure 3. Transmission Line method geometry.

As shown in Fig. 3, the test structures consisted of a pad of equal area with varying separation between metallization in GaAs ohmic contacts. An example of the raw data (before humidity testing and after 100 hours) is shown in Fig. 4, which shows degradation in contact resistance after 100 hours in an 85% humidity environment and 85 degrees.

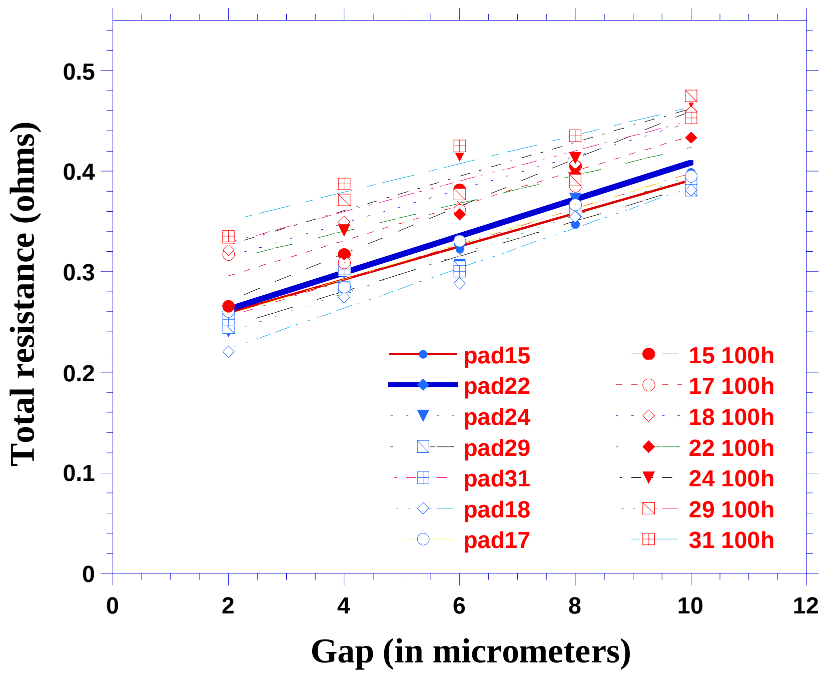


Figure 4. Degradation in contact resistance after 100 hours in an 85% humidity environment and 85 degrees. The test structures consisted of a pad of equal area with varying separation between metallization in GaAs ohmic contacts.

As seen in Table 1, The contact resistance for these structures degraded 22.9%, 10.4%, and 3.9% after 100, 500, and 1000 hours respectively. The total degradation after 1000 hours is small, however, the scatter in the data or standard deviation in values for contact resistance between pads becomes larger, mainly after 1000 hours. The standard deviation in values for contact resistance starts at 9.1 x 10 –7 before humidity testing, and this value increases by 17.1%, 19.4% and 47.4% after 100, 500, and 1000 hours respectively, as compared to the initial values.

As some difficulties were encountered in the measurements, this study suggests the need for better ohmic contact test structures. The transmission line method structures have several advantages, but the structure design should include contact pads that are not directly above the ohmic contact area. In order to eliminate measurement artifacts and gain more confidence in the data, at least one alternate test structure should be used for testing ohmic contacts. The cross-Kelvin resistor [16,17] is another commonly used structure which provides a more direct measurement of interfacial contact resistance and which should be included in a test pattern.

Table 1. Changes in contact resistance (in ohms) after 100, 500 and 1000 hours in 85/85 humidity test. Test pads distributed among 4 GaAs wafer pieces (1 and 3), (4, 5 and 6), (10, 12, 13 and 14) and (15, 16, 17, 18, 19, 22, 24, 26, 29, 30 and 31). Piece containing 10, 12, 13 and 14 showed some very high contact resistance from some of the pads (not used in test) and other anomalous behavior.

Pad#	**initial Rs**	**after 100h**	**% dif**	**after 500h**	**% dif**	**after 1000h**	**% dif**
1.	6.4000e-06	7.4050e-06	15.703	8.3000e-06	29.687	6.3900e-06	-0.15626
3.	8.1350e-06	9.6750e-06	18.931	7.6500e-06	-5.9619	6.2200e-06	-23.540
4.	6.4218e-06	8.7135e-06	35.687	4.8800e-06	-24.008	4.0100e-06	-37.556
5.	6.4750e-06	8.1075e-06	25.212	5.6200e-06	-13.205	8.8700e-06	36.988
6.	6.5250e-06	8.0000e-06	22.605	6.0200e-06	-7.7395	8.1030e-06	24.184
10.	6.4425e-06	5.5400e-06	-14.009	5.8300e-06	-9.5072	3.3400e-07	-94.816
12.	7.2400e-06	8.2500e-06	13.950	7.1600e-06	-1.1050	7.5000e-06	3.5912
13.	7.2750e-06	7.5550e-06	3.8488	6.5700e-06	-9.6907	6.8125e-06	-6.3574
14.	7.4000e-06	8.2000e-06	10.811	6.5550e-06	-11.419	6.7500e-06	-8.7838
15.	5.6500e-06	5.6000e-06	-0.8849	7.0000e-06	23.894	0.0000	-100.00
16.	6.6250e-06	7.8850e-06	19.019	8.8500e-06	33.585	1.0166e-05	53.449
17.	5.5500e-06	6.5275e-06	17.613	7.1300e-06	28.468	8.6500e-06	55.856
18.	4.5900e-06	7.0500e-06	53.595	6.5100e-06	41.830	7.7400e-06	68.627
22.	5.6500e-06	7.1000e-06	25.664	7.5150e-06	33.009	8.4000e-06	48.673
24.	5.0300e-06	7.3250e-06	45.626	6.3800e-06	26.839	6.8200e-06	35.586
29.	5.2605e-06	7.4650e-06	41.907	6.4700e-06	22.992	7.0800e-06	34.588
31.	5.4910e-06	8.0540e-06	46.676	6.2550e-06	13.914	7.5600e-06	37.680
33.	5.3350e-06	6.1393e-06	15.075	5.7900e-06	8.5286	6.4660e-06	21.200
26.	5.3500e-06	6.4357e-06	20.294	6.1200e-06	14.393	3.6400e-06	-31.963
19.	4.7925e-06	6.7350e-06	40.532	5.4200e-06	13.093	2.8960e-06	-39.572
Means	**6.08e-6**	**7.39e-6**	**22.9%**	**6.6e-6**	**10.4%**	**6.22e-6**	**3.9%**
St. Dev	**9.1e-7**	**1.04e-6**	**17.1**	**9.72e-7**	**19.4**	**2.7e-6**	**47.4**

Effect of humidity on capped (passivated) AlGaAs thin films:

Humidity testing with no bias was also done on high Al content AlGaAs films. The objective of the test was to determine the potential reliability of THz membrane diodes with AlGaAs used as the membrane layer and no passivation (other than the GaAs cap). Figure 5 shows a "crater" formed in 1.5 micrometers $Al_{0.98}Ga_{0.02}As$ film capped with a 30 nm GaAs film. Severe film deterioration occurred after 1000 hours in ambient conditions (25 C, ~ 50% relative humidity). The films that were subjected to the 85/85 testing for 1000 hours were totally detached from the GaAs substrates and consumed by the resulting oxidation. This indicates that high Aluminum content AlGaAs cannot be used in non-hermetic conditions even with a GaAs cap.

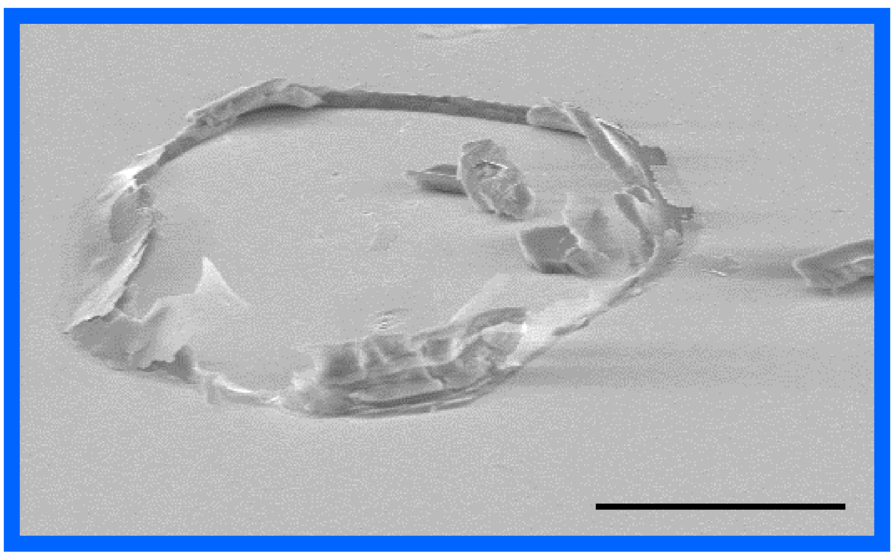
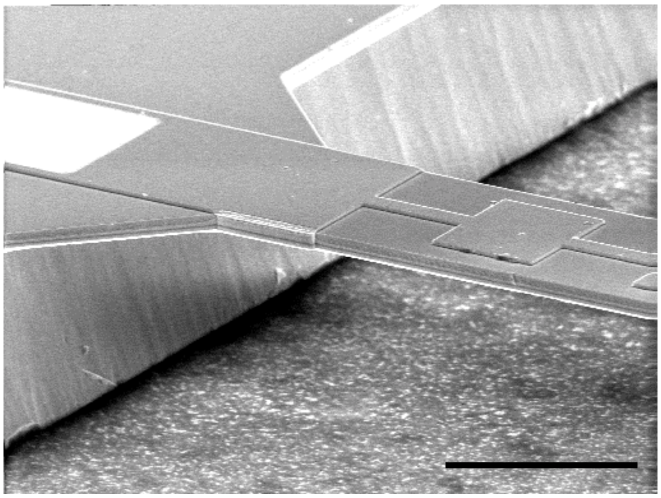


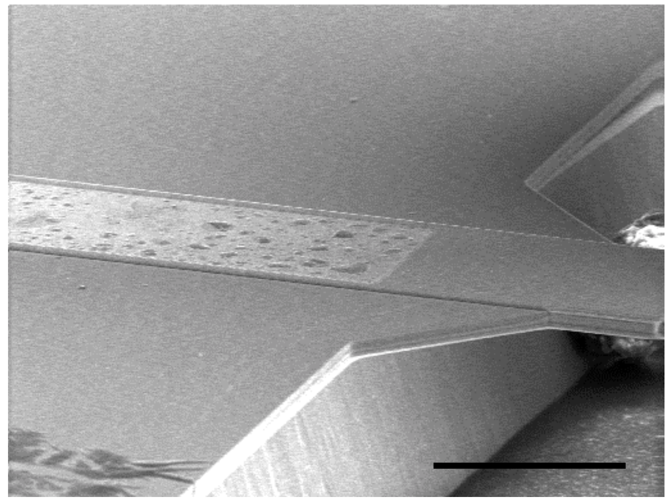
Figure 5. SEM micrograph shows "crater" formed in 1.5 micrometers $Al_{0.98}Ga_{0.02}As$ film capped with a 30 nm GaAs film. Severe film deterioration occurred after 1000 hours in ambient conditions (25 C, ~ 50% relative humidity). Bar is 20 microns.

Effects of humidity on 2.5 THz GaAs membrane diode mixers:

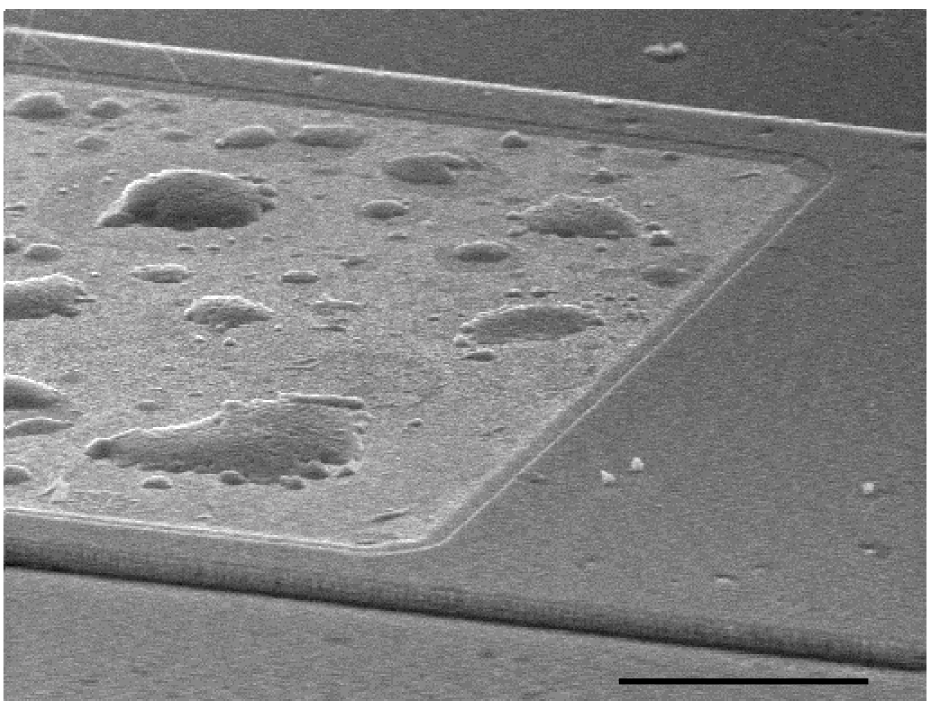
The 2.5 THz GaAs membrane diodes cannot be enclosed in a hermetic package and processing difficulties did not allow passivation of the back membrane (the 3 micron thick and 500 micron long GaAs membrane that contains the anode or active device). It was therefore necessary to conduct humidity testing to evaluate the effects of device torage in ambient conditions before launch. The effects of humidity were tested by scanning electron microscopy imaging and by IV measurements before and after exposure to the 85/85 test.



(a)



(b)



(c)

Figure 6. (a) Enlarged view of membrane without humidity testing. Bar is 30 microns. (b) “Blistering” in unprotected metallization in GaAs mixer diodes after 1000 hours at 85 C and 85 % RH. Bar is 30 microns. (c) Enlarged view of blistered area. Bar is 6 microns.

The tests were done for two groups of devices. The first set did not have the active part of the device, and the test was done to examine morphological changes alone. Figure 6 (a) shows an enlarged view of the membrane showing some of the gold metallization prior to testing. Figure 6 (b) shows the same area after 1000 hours at 85/85, and enlarged view is shown in Fig. 6(c). Functioning devices were also later tested, and no blistering was observed even after 1000 hours in 85/85 conditions. These results suggest that process residues can cause morphological changes (“blistering”) in exposed areas of GaAs devices subject to humidity testing, but no blistering is observed if all the residues are totally cleaned from the device surface. Electrical testing indicated that the DC I-V characteristics of the 2.5 THz GaAs membrane mixer diodes (with unpassivated membrane backs) did not degrade after 500 hours of 85/85 testing. Figure 7 shows two pre and post 85/85 exposure IV curves.

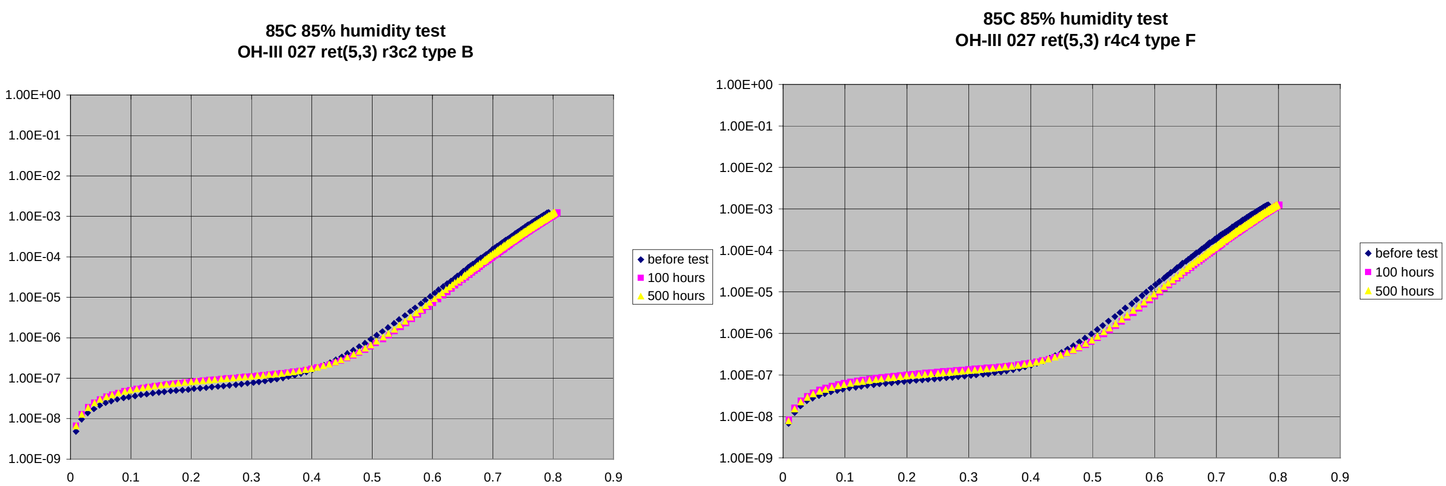


Figure 7. Pre- and post-testing current voltage characteristics for two of the membrane diode GaAs devices after 100 hours and 500 hours 85/85 exposure.

Table 2: DC I-V characteristics of the 2.5 THz GaAs membrane mixer diodes (with unpassivated membrane backs) after 100 hours and 500 hours of 85/85 exposure.

Device		Pre-testing IV data	After 100 hours at 85°C and 85% relative humidity	After 500 hours 85°C and 85% relative humidity
Ret 2,5 R1c3 lh test type E	I_s η R_s	6.7×10^{-12} (Amps) 1.61 25.1 (ohms)	1.5×10^{-12} 1.47 18.5	2.2×10^{-12} 1.49 19.1
Ret 2,5 R1c3 rh test type E	I_s η R_s			5.4×10^{-12} 1.47 14.0
Ret 5,3 R3c2 type B	I_s η R_s	2.7×10^{-12} 1.54 8.50	1.3×10^{-12} 1.51 8.84	1.6×10^{-12} 1.52 9.97
Ret 5,3 R3c2 lh test type B	I_s η R_s	2.9×10^{-12} 1.56 18.2	3.1×10^{-12} 1.52 17.7	2.7×10^{-12} 1.51 17.4
Ret 5,3 r4c4 type F	I_s η R_s	2.5×10^{-12} 1.51 10.9	1.1×10^{-12} 1.49 9.60	1.3×10^{-12} 1.49 10.1
Ret 5,3 r4c4 lh test type F	I_s η R_s	NA	3.6×10^{-12} 1.54 24.9	4.9×10^{-12} 1.54 29.9
Ret 5,4 R3c1 type B	I_s η R_s	7.3×10^{-12} 1.61 13.3	6.0×10^{-12} 1.55 11.6	2.3×10^{-12} 1.48 10.4
Ret 5,4 R3c1 lh test type B	I_s η R_s			2.1×10^{-12} 1.49 15.7
Ret 5,5 R4c3 Type A	I_s η R_s	8.1×10^{-12} 1.58 11.17	4.8×10^{-12} 1.53 8.97	3.8×10^{-12} 1.51 8.52
Ret 5,5 R4c3 lh test Type A	I_s η R_s		2.1×10^{-12} 1.47 12.7	1.7×10^{-12} 1.47 12.5
Ret 6,3 R2c2 type C	I_s η R_s	7.0×10^{-12} 1.59 16.3 frame cracked	NA Frame broke so can no longer probe	
Ret 6,3 R2c2 lh test type C	I_s η R_s	1.5×10^{-12} 1.71 12.5	4.6×10^{-12} 1.60 14.1	4.5×10^{-12} 1.60 14.2
Ret 6,3 R2c2 rh test type C	I_s η R_s			1.9×10^{-12} 1.51 16.6

Diode parameters extracted from these and similar IV curves for all the tested devices are summarized in table 2. SEM examination of the device, including areas where blistering was observed under the metal pads showed no changes in these devices, this confirms that blistering is only present after humidity exposure when process residues are not completely eliminated in the device fabrication.

Effects of nonhermeticity on the reliability of InP devices:

As was mentioned in the introduction, acceleration factors have already been determined for InP planar PIN diodes in an extensive study were devices were aged at different temperatures and humidities [refs]. These studies found that failure occurred as a sudden increase in dark current in all cases. The failure model proposed [ref] involved reduction of the p-contact at the InP surface with the emission of hydrogen gas. Hydrogen then reacts with In and P under bias, forming gaseous IH and PH3, leading to semiconductor erosion. This study estimated an increase in one order of magnitude in FIT over a 20 year period as compared to the hermetically packaged InP counterparts.

Recommendations for use of III-V devices in non-hermetic conditions:

- High Al content AlGaAs based devices are unsuitable for nonhermetic device applications even with a GaAs cap. The effectiveness of other passivation schemes for AlGaAs based devices remains to be investigated
- These results show that 2.5 THz membrane diodes with unpassivated GaAs back membranes can tolerate non-hermetic conditions during the pre-launch wait.

Recommendations for further studies and testing:

- Acceleration factor expressions with appropriate experimental parameters are well known for InP [refs] but not for GaAs devices, therefore, these should be determined for GaAs since there are several NASA flight projects which intend to use GaAs in standard and non-hermetic applications.
- A comparative study utilizing ohmic and Schottky test structures in GaAs should be made in sufficient quantities to gather significant statistics. Such sample set and

study would provide the needed acceleration factors for GaAs device degradation in humid environments in the materials used in JPL devices.

Conclusions

- AlGaAs is unsuitable for nonhermetic device applications even with a GaAs cap. The effectiveness of other standard passivating films still remains to be investigated.
- 2.5 THz GaAs membrane mixer diodes (with unpassivated membrane backs) do not show degradation in their DC I-V characteristics after 500 hours of 85/85 testing.
- Process residues can cause morphological changes ("blistering") in exposed areas of GaAs devices subject to humidity testing.
- Unpassivated standard recessed Au/Ge/Ni/Ag/Au ohmic contacts on GaAs suffer a slight degradation in contact resitance (R_s).
- Values for R_s from different test pads show much greater variance after the 85/85 tests. Identifying the cause for this variance will require more detailed structural characterization like transmission electron microscopy or scanning probe microscopy analysis.

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