Lifetimes of NbN Hot Electron Bolometer mixers.

M. Hajenius, Z.Q. Yang, J.J.A. Baselmans and J.R. Gao.

***Abstract*— Superconducting NbN hot electron bolometer mixers have become the only sensitive heterodyne detectors operating at frequencies far above 1 THz. Since their application will be mainly in space, the reliability of such mixers becomes a key issue. In this paper we report measurements of the resistance and the superconducting critical current as a function of time under normal laboratory conditions for a period of one year as well as the resistance versus time under a harsh condition (85 ^oC/ 85 % relative humidity). The devices studied are small volume twin slot antenna coupled NbN HEB mixers. By defining the lifetime during which the room temperature resistance increases by 15 %, we find that the lifetime of standard devices is only half a year in normal atmosphere, which is insufficient for space applications. However, by introducing an additional passivation on the standard devices, the lifetime becomes longer than one year. The advantage of applying the passivation layer is further confirmed by the 85/85 accelerated tests.**

***Index Terms*— Superconducting, NbN, HEB mixers, Lifetime, Space Qualification, Passivation layer, SiO_2.**

I. Introduction

NBN HEB detectors currently demonstrate the best characteristics for heterodyne astronomical observations at frequencies above 1.5 THz [1], [2]. Since the earth's atmosphere is largely opaque in this range the mixers will primarily be used from space (e.g. HIFI on HERSCHEL space telescope [3]) or from high elevations. Obviously, reliable detector operation of the NbN based HEBs is crucial to the success of such missions. However, in contrast to standard semiconductor devices, very few is known about the lifetime of mixer structures based on extremely thin (NbN) superconducting films.

According to the American Society for Testing and Materials (ASTM), the service lifetime of materials, devices, or systems is the exposure time at which degradation occurs below a prescribed or required value, i.e. a total failure or a failure to perform at a preassigned value. Still, no such criteria have been established for NbN HEB mixers yet. It is clear that deterioration of superconducting properties eventually imposes questionable device operation and even failure. The increase in room temperature resistance (R_{300K}) is found as a good indicator for this deterioration. We choose a 15 % increase in R_{300K} as prescribed limit.

The (required) lifetime is in general coupled to the precise conditions under which the device is kept or treated. Two conditions are of special interest: Firstly under normal atmosphere at room temperature and secondly under vacuum at 85 ^oC. For space applications, the mixers should be able to survive many integration, transport and storage steps. The total duration of exposure to normal atmosphere can be between one to five years [4]. The resistance to more extreme conditions, i.e. baking at 85 ^oC for at least 72 hours [4] under vacuum is required as a standard method to assure vacuum hardness of the system. We note that several other conditions (e.g. thermal cycling) remain undiscussed here since they proved to be unproblematic.

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II. Devices

The HEB devices under consideration are based on sputtered NbN thin films on a pure Si substrate with an intended thickness of 3.5 nm prepared at MSPU, Moscow. The unprocessed NbN has a critical temperature (T_c) between 8.6 - 9.3 K depending on the film and precise location on the wafer, a sheet resistance ($R_{sheet,300K}$) of 600 Ω at 300 K, and a resistance ratio RRR ($R_{sheet,300K}/R_{sheet,16K}$) of 0.8. After processing the bulk film degrades marginally: The $R_{sheet,300K}$ of the film, of a large structure is slightly higher; 650 Ω, the T_c is reduced $<$ 0.5 K, and a critical current (I_c) of 900 μA for an 8 μm wide structure is measured.

Below we discuss the fabrication process of the devices as lifetime may depend on its details.

The NbN films are contacted to the antenna structure by the contact pads. The contact pads are defined by E-beam lithography using a double layer PMMA resist system, which requires in total 10 minutes baking at 120 ^oC. After development, an Oxygen plasma clean is performed, just long enough to remove resist remnants. Next, a short physical Ar^+ etch is performed followed by in situ deposition of 10 nm of $NbTiN$ and 40 nm Au. We note that the exact contacting procedure is crucial [6], [7] to device performance. See Fig. 2

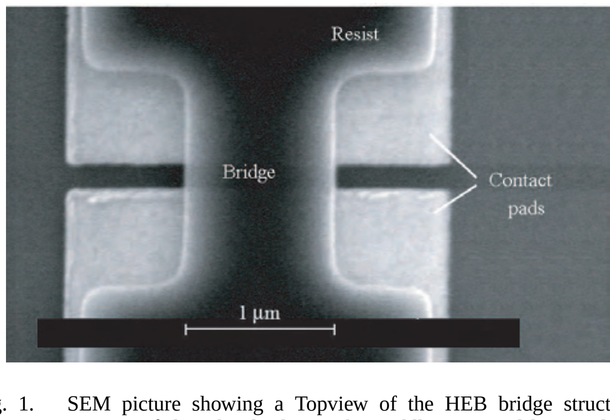

Fig. 1. SEM picture showing a Topview of the HEB bridge structure. The HEB consists of the NbN bridge in the middle contacted by two large contactpads on either side. The HEB bridge is protected by negative resist on top.

for a cross-section of the contactpads. To define the twinslot antenna, a single layer Negative resist is spun, requiring 3 minutes baking at 90 ^oC and after E-beam exposure a 3 minutes 110 ^oC postbake. After development with MF322 for 9 minutes and Oxygen plasma clean we evaporate 5 nm Ti for adhesion and 150 nm Au to constitute the antenna. Liftoff is done in PRS3000 at 90 ^oC for two minutes in combination with ultrasonic agitation, followed by 5 minutes ultrasonic agitation in Acetone. Finally, the bridge is defined by E-beam lithography using a 500 nm thick SAL601 negative resist etch mask. After 7 minutes development in MF322 we perform an Oxygen plasma clean to remove resist remnants. The final etch is performed by RIE using CF_4 + O_2, with a 20 % overetch. After RIE etching, a short Oxygen etch is performed to oxidize any remaining material on the surface. After the final etch, the remaining SAL601 etch mask is about 300 nm thick and is left on the device. The completed bridge measures 150 nm in length and 1.0 um to 2.0 um in width, see Fig. 1. This concludes fabrication for ”standard” devices.

To reduce the aging effect, to be discussed shortly, we introduce a passivation layer on top of the active region of the HEB. This layer consists of 500 nm thick SiO_x ($1.5 < x < 2.0$). The Devices *with* passivation layer experience only one additional fabrication step which consists of SiO_x sputter deposition using a SiO_2 target. Note that the sample is pumped down 24 hours before deposition. An elevated mask is used to cover only a 200 μm x 200 μm region around the bridge *with* SiO_x. The SAL601 resist remains on the bridge in order to avoid chemical reactions between SiO_x and NbN. Care is taken to avoid heating of the substrate during the SiO_x deposition.

Shortly after fabrication, such devices (1 μm wide) have a $R_{sheet,300K}$ around 800 to 900 Ω and (I_c) around 70 μA. These values are found for both devices *with* and *without* passivation layer. Note that this is higher and lower respectively than values for a big film after processing. The reason for this is not clear to us. Note however that devices are typical and are taken from several batches with mixer performance > 10 % from the best.

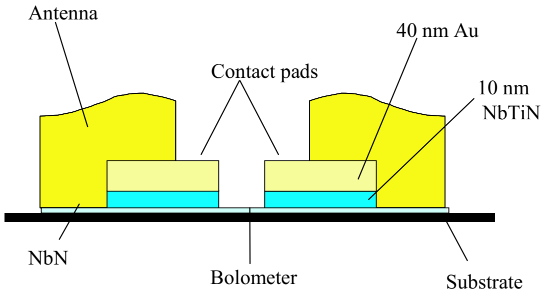

Fig. 2. Cross-sectional drawing of the HEB structure as shown from the top in Fig. 1. The cross-section reveals the composition of the contactpads, consisting of the NbN with 10 nm NbTiN on top followed in situ by 40 nm Au. Note that the resist protecting the NbN bridge is not shown.

III. Lifetime in Laboratory Conditions

Lifetime measurements of NbN HEBs are performed in standard laboratory conditions, 20 ^oC and 65 % relative humidity (RH). The R_{300K} as well as the superconducting properties are measured at certain intervals in time. Fig. 3 shows the typical resistance versus temperature (RT) and Fig. 4 the current versus voltage (IV) measurements for a device *without* passivation layer. It becomes clear from Fig. 5 how the resistance increases while T_c and I_c decrease for longer exposure. To show this trend for more devices, the R_{300K} and I_c of several devices *without* passivation layer versus exposure time is shown in Fig. 5. Note that the readily measured R_{300K} reliably indicates the degradation of superconducting properties. Specifically, the standard devices (*without* passivation layer) show an increase in resistance of about 0.1-0.3 Ω per day. Over a period of one year the R_{300K} is expected to increase about 7-30 % (10-50 Ω). The average lifetime of the devices *without* passivation layer is thus about half a year, well below the required one year. The 15 % increase in R_{300K} matches with a substantial 30 % average reduction in I_c.

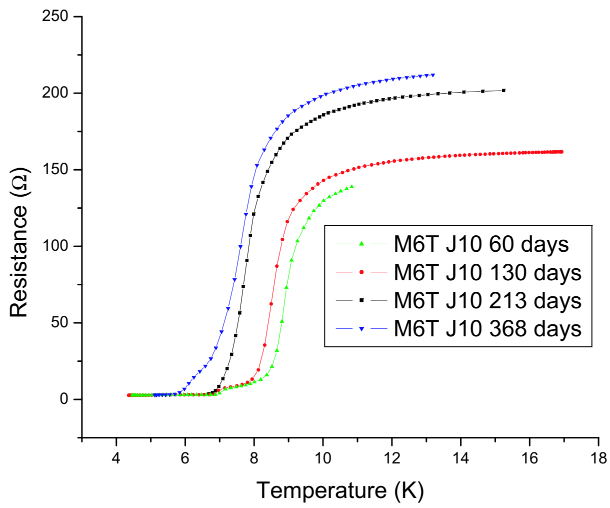

Fig. 3. Resistance versus Voltage plot of device J10 of batch M6T measured at several intervals, indicated in days after fabrication.

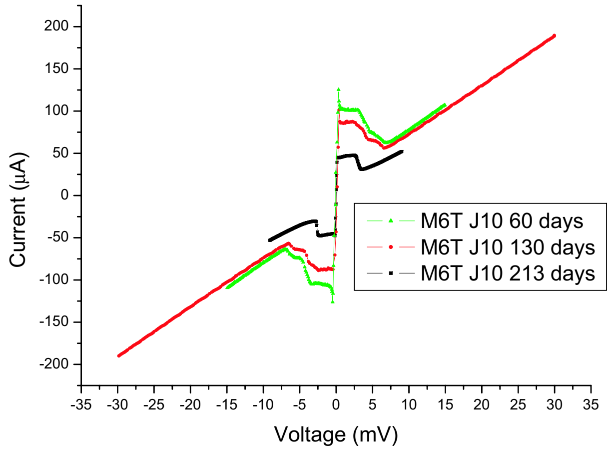

Fig. 4. Current versus Voltage plots of device J10 of batch M6T measured at several intervals, indicated in days after fabrication.

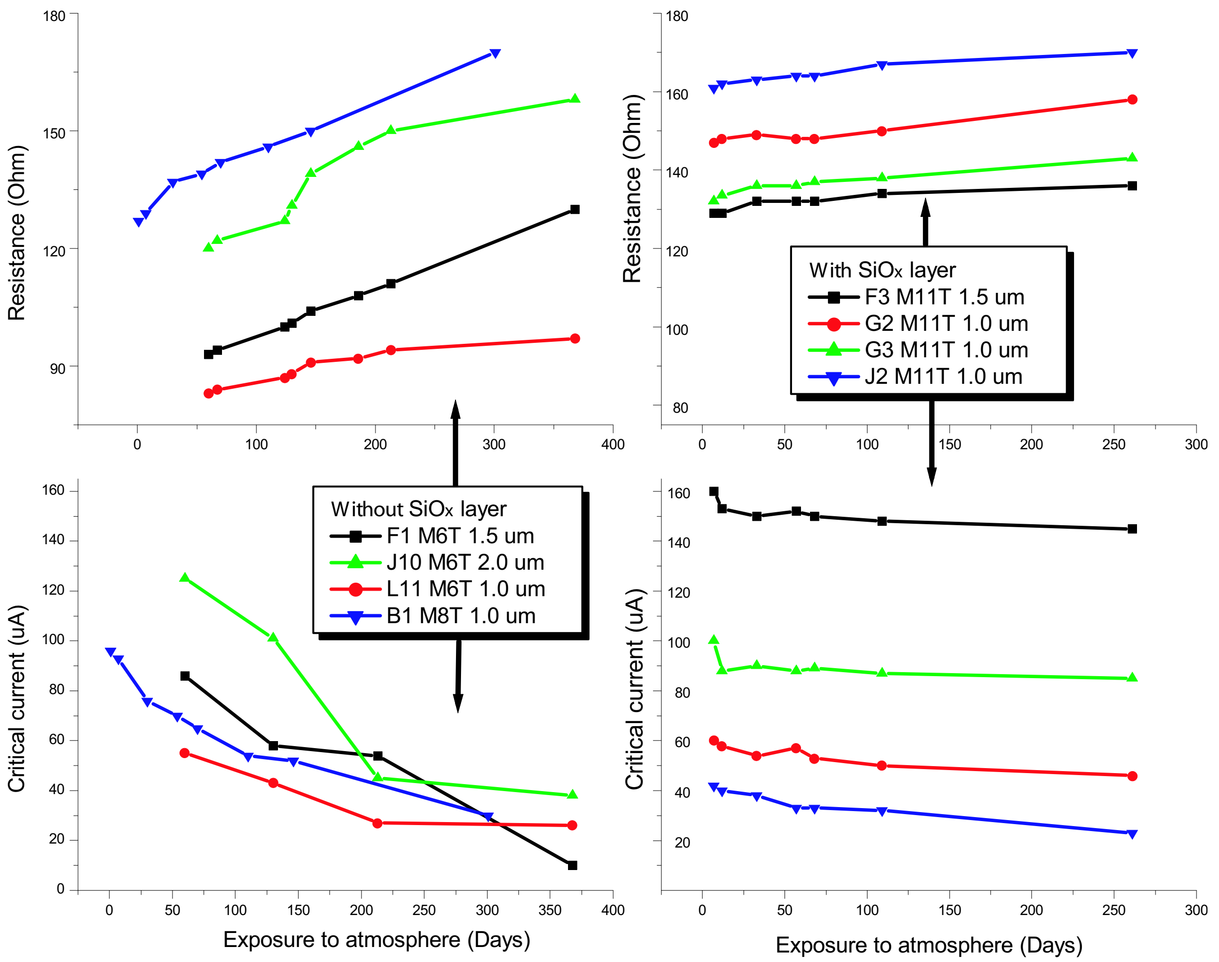

Fig. 5. Normal state resistance at 300 K (top panels) and critical current at 4.2 K (lower panels) versus exposure time in atmosphere at 300 K and 65 % RH. Left panels are for devices *without* passivation layer, right panels for devices *with* SiO_x passivation layer.

By storing devices in vacuum, we found that the aging effect is reduced considerably. This indicates that O_2 and H_2O in normal atmosphere are likely ingredients of the aging. However, during integration of HEB mixers into the instrument, applying vacuum is impractical. This motivates the introduction of a capping layer to reduce the aging effects, similar to the SiO passivation layer proposed by Kawamura et al. for Nb HEBs [8]. Fig. 5 shows the dramatic improvement in lifetime by using SiO_x passivation layer, in which the resistance increases less than 10 % during approximately one year storage in the laboratory. This is also reflected by no more than 10-15 % decrease of I_c for the same storage time.

IV. Accelerated lifetime tests.

A standard method to determine the lifetime of semiconductor devices is the "accelerated test" at 85 ^oC and 85 % relative humidity (RH). Then, applying a well established model to predict the lifetime under normal conditions. This method can not apply to NbN HEB mixers since such model is lacking. We merely make use of the accelerated lifetime test to compare the devices *with* and *without* passivation layer. We performed accelerated lifetime tests at 85 % RH and 85 ^oC. The R_{300K} as function of exposure time is shown in Fig. 7. The R_{300K} in Fig. 7 increases exponential-like over time for both devices *with* as well as *without* passivation layer. The 15 % increase in R_{300K} of devices *without* passivation layer is reached on average after 29 hours and only after an average of 60 hours

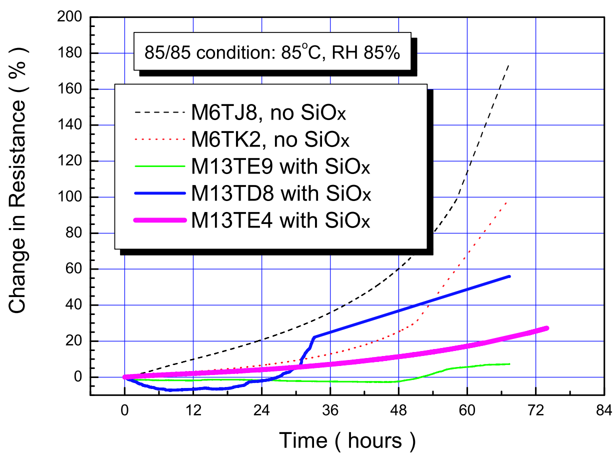

Fig. 7. Accelerated aging test by monitoring the device resistance under a harsh 85 ^oC - 85 % relative humidity environment as a function of time. The R_{300k} of the devices is close to 150 Ω, except for device J8 which has a R_{300k} of 100 Ω.

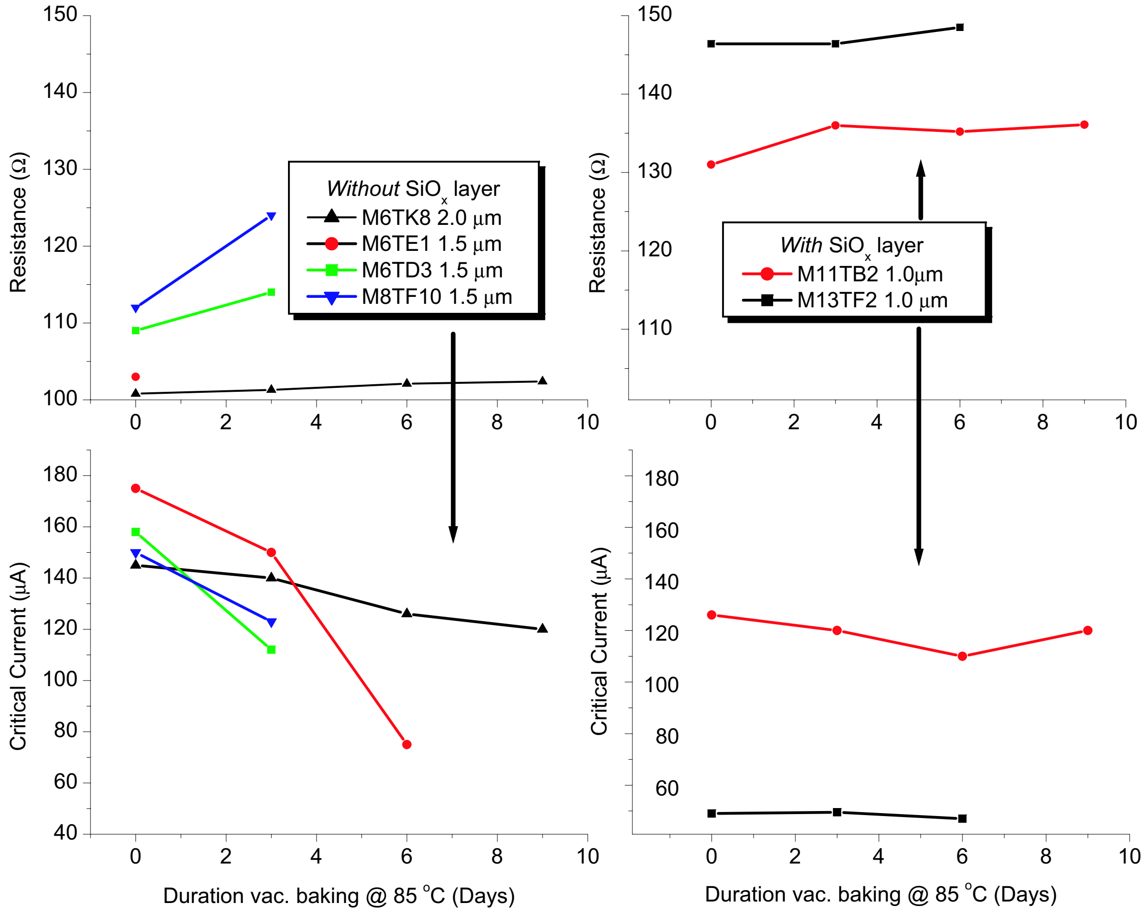

Fig. 6. Normal state resistance at 300 K (top panels) and critical current at 4.2 K (Lower panels) versus baking time in days at 85 ^oC and $6 \cdot 10^{-5}$ mB. Left panels are for devices *without* passivation layer, right panels for devices *with* SiO_x passivation layer.

for devices *with* passivation layer. This confirms the advantage of using the SiO_x passivation layer.

V. Lifetime under bake-out conditions.

Devices were baked at 85 ^oC under vacuum conditions ($6 \cdot 10^{-5}$ mB) using a rotary pump. The baking was interupted for characterisation of R_{300K} and I_c. Fig. 6 shows R_{300K} and I_c as a function of baking time. For devices *without* passivation layer, R_{300K} increases between 5 % and 20 % for a duration of 9 days. Critical current decreases from 10 % to 60 % after 9 days baking. Although some devices *without* passivation layer hardly change, the limit of 15 % R_{300K} increase is exceeded for others. Moreover, the atmospheric pressure during bake-out may be much higher than used in this baking test. Consequently the deterioration of the device performance of devices *without* passivation layer may be even more severe. Again, devices *with* passivation layer show reduced deterioration as can be seen in Fig. 6. R_{300K} increases less than 10 % and I_c decreases less than 20 % for 9 days of baking at 85 ^oC. It is interesting to note that a device with low critical current density (J_c) *with* passivation layer shows almost unchanged I_c after a maximum of 6 days baking. We note that pumping down the oven 24 hours before starting the heater is advantageous in reducing device degradation. Baking has been performed to a maximum of 9 days.

As part of the baking tests we also measure the influence on RF performance. Fig. 8 shows the mixer noise temperature

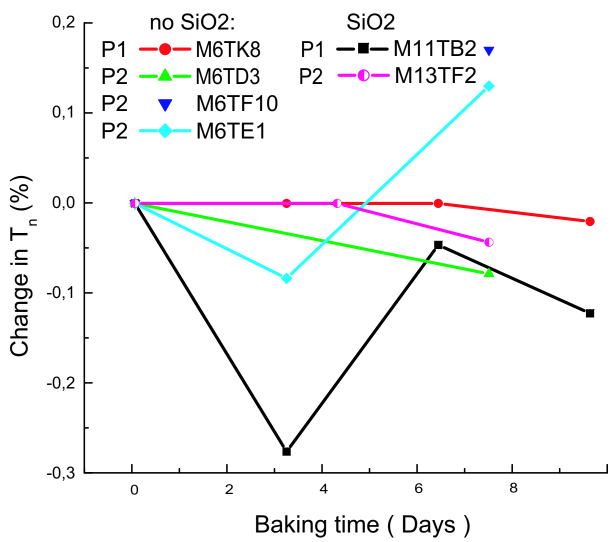

Fig. 8. Relative changes of the noise temperature with baking time in days for devices *with* and *without* passivation layer. P1 indicates the procedure that the heating was switched on 24 hours after the pumpdown was started. P2 indicates that the heater was started several hours after the pumpdown was started. In both cases the pressure during baking was about $6 \cdot 10^{-5}$ mB

(T_n) for different durations of baking. Also here we compare between devices *with* and *without* passivation layer. We find that T_n can either decrease or remain unchanged after short baking times of 2-3 days. When baking is resumed, after a total of 6 days of baking the T_n will increase again. Devices *with* passivation layer generally show largest decrease of T_n after 3 days while after 6 days the increase in T_n is small compared to before baking. The exact reason for this is not clear. However, DC characterization suggests an improvement of the contacts by short baking (e.g. 3 days) in competition with film degradation for longer baking times [9].

VI. Conclusions.

The resistance and superconducting critical current of standard NbN HEB devices in normal atmosphere *without* passivation layer show a severe deterioration over a period of about one year. Based on this data, a practical definition for the lifetime is established which equals the duration at which the R_{300K} has increased by 15 $\%$. Using this definition we find that standard devices *without* passivation layer have a lifetime of about half a year, which is insufficient for (space) applications. In contrast, devices with a 500 nm thick SiO_x passivation layer have prolonged lifetime in atmosphere to more than one year. The advantage of introducing the passivation is further confirmed by accelerated lifetime tests. The devices *with* the passivation layer show lifetimes at least a factor of two longer than those *without*.

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