Investigation for Condensation Test Condition of HVIGBT Modules

Kenji HATORI*, Keiichi NAKAMURA*, Wakana NOBORU*
Nils SOLTAU**, Eugen WIESNER**
*Mitsubishi Electric Corporation, 1-1-1 Imajukuhigashi, Nishi-Ku, Fukuoka, Japan
**Mitsubishi Electric Europe B.V., Germany
Tel.: +81-92-805-3406
Fax: +81-92-805-3676
E-Mail: Hatori.Kenji@dx.MitsubishiElectric.co.jp
URL: https://www.mitsubishielectric.com/semiconductors/products/powermod/index.html

Keywords

«IGBT», «Humidity», and «Reliability» of the official keywords list.

Abstract

Humidity robustness is one of the main concerns of IGBT modules since the modules are not hermetically sealed. IGBT modules are generally filled with silicone gel which has a filter effect. Condensation amount at various condensation test conditions is described in this paper based on silicone gel humidity absorption behavior investigation. At first, the humidification condition impact is investigated. As a result, it is confirmed that condensation amount depends on dissolved humidity in silicone gel, not on the absolute humidity of ambient air. Secondly, cooling speed impact is investigated, and it is confirmed that humidification at lower temperature is effective to obtain stable results independently from cooling speed. Thirdly, it is confirmed that humidification at higher temperature is effective to shorten test time. Next, it is confirmed that humidification at lower temperature is effective to obtain stable results independently from gel thickness of the module. Finally, the calculation result is verified with the experiment.

Introduction

The power modules for today's modern HVIGBTs are not hermetically encapsulated, resulting in condensation occurring inside or around the power semiconductor in some cases. Therefore, HVIGBTs are required to have excellent performance and high reliability even under such conditions. Hence, the SCC (Surface Charge Control) technology [1], [2] and other unique technologies [3], [4], [5] are proposed to improve the robustness against humidity. Also, the humidity acceleration model [6] or humidity lifetime model [7] are proposed. However, previous studies are based on static tests with stable operational and environmental conditions. Whereas, in the field, conditions are usually not stable. In addition to humid condition, condensation is considered as one of the harshest environments as well. In order to confirm the robustness against condensation, the condensation tests of HVIGBT modules are proposed [8], [9]. However, it has not been clarified how frequently condensation occurs around IGBT chips during field operation.

IGBT modules are generally filled with silicone gel which has a filter effect against vapor diffusion. Therefore, it takes time to transfer the ambient environment to the local environment around semiconductor chips. This transfer function is very important to understand condensation amount during condensation test, which is related with severity of the test.

Considering previous works, reference [10], regarding the humidity absorption behavior of the whole IGBT module, has contributed to this issue. Moreover, the humidity absorption behavior of silicone gel has been analyzed in [11]. Based on the previous work about silicone gel humidity absorption behavior, this paper evaluates the condensation amount at various condensation test conditions.

Humidity absorption behavior of silicone gel

Generally, IGBT modules are filled with silicone gel. Polymer resin-like silicone gel absorbs humidity depending on the ambient environment. This humidity absorption takes time and then it also takes time for humidity to reach IGBT chips. Humidity absorption behavior of polymer resin can be explained by diffusion and dissolution of vapor [12], [13].

The correlation between vapor concentration c and diffusion coefficient D is defined with the following equation of Fick's laws of diffusion. The below equation is simplified with one dimension: location parameter is x here. The diffusion coefficient D follows the Arrhenius equation: $D0$ is the pre-exponential factor, E_D is activation energy and R is the universal gas constant (8.314 J/K·mol). The previous study confirms the activation energy E_D = 20.8 kJ/mol and pre-exponential factor D_0 = 40.3 mm^2/s [11].

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \qquad (1)$$

$$D = D_0 \exp\left(-\frac{E_D}{RT}\right) \qquad (2)$$

The correlation between vapor concentration c and solubility coefficient S is defined with the following equation: P_v is defined as vapor pressure. The solubility coefficient S also follows the Arrhenius equation: S_0 is the pre-exponential factor, ΔH_S is enthalpy and R is the universal gas constant (8.314 J/(K·mol)). The previous study confirms the enthalpy ΔH_S = -26.8 kJ/mol and pre-exponential factor $S_0 = 4.12 \times 10^{-12}$ mg/(mm^3·Pa) [11].

$$c_{(t=\infty)} = S \cdot P_v \qquad (3)$$

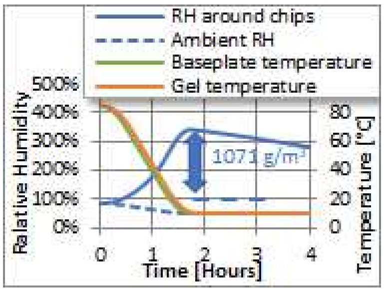
$$S = S_0 \exp\left(-\frac{\Delta H_S}{RT}\right) \qquad (4)$$

Condensation is considered as the most severe humid condition. In order to confirm the robustness against condensation, a condensation test is proposed [8][9]. In the condensation test, firstly, rapid cooling is applied after humidification. Subsequently, DC voltage is applied. Rapid cooling causes condensation in the silicone gel. The amount of condensate in silicone gel affects the condensation test result. Thus, it should be investigated how much condensation occurs in silicone gel depending on the test condition.

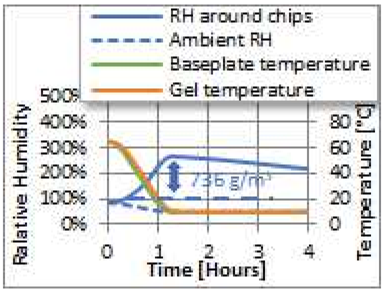
Humidification condition impact on the condensation test

Condensation test result strongly depends on the pre-humidification condition that is applied as pretreatment. Then relative humidity during humidification is one of the biggest factors. Based on equations (1), (2), (3) and (4), condensation amount during the condensation test is calculated with various humidification conditions as shown in Fig. 1 and Fig. 2.

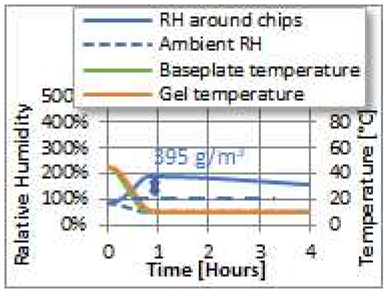
As shown in Fig. 2, condensation amount is well related to humidification condition. Humidification condition of 75°C40%RH and 35°C80%RH brings same condensation amount of 200 g/m^3. These two humidification conditions of 75°C40%RH and 35°C80%RH shows the same dissolved humidity (SH) of 644g/m^3 as shown in Fig. 3 which is calculated by equation (4) [11]. Therefore, the humidification condition dependency on condensation amount can be described with dissolved humidity, not with absolute humidity of ambient air.



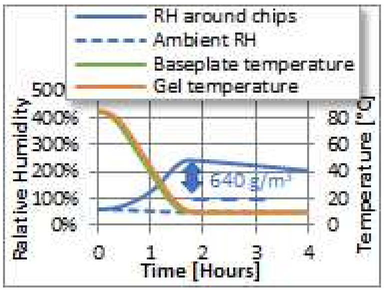
(A) Humidification condition of 85°C85%RH



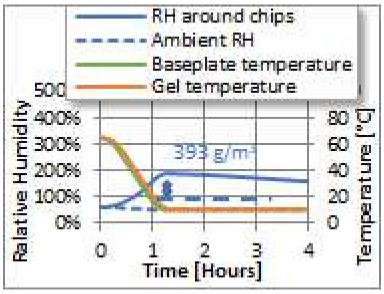
(B) Humidification condition of 65°C85%RH



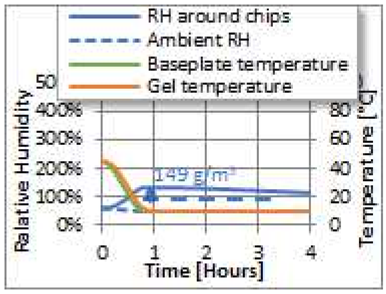
(C) Humidification condition of 45°C85%RH



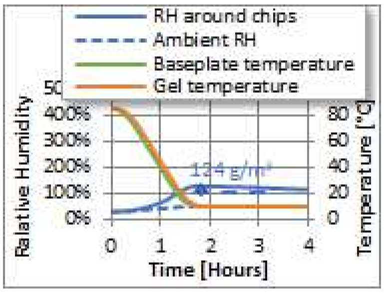
(D) Humidification condition of 85°C60%RH



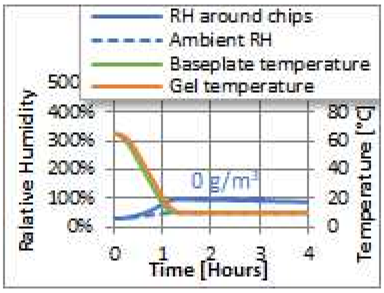
(E) Humidification condition of 65°C60%RH



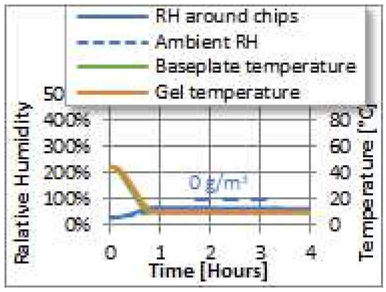
(F) Humidification condition of 45°C60%RH



(G) Humidification condition of 85°C30%RH



(H) Humidification condition of 65°C30%RH



(I) Humidification condition of 45°C30%RH

Fig. 1: Calculation result of condensation amount during condensation test in the condition with cooling to 10°C50%RH, dT/dt=-1K/min, saturated humidification duration, silicone gel thickness=20 mm, time constant of gel temperature=5min

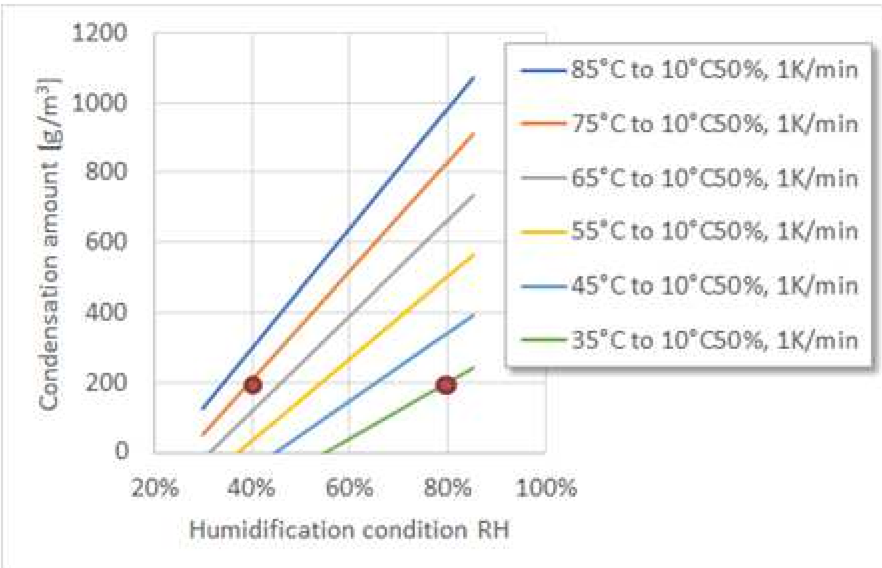


Fig. 2: Humidification condition impact

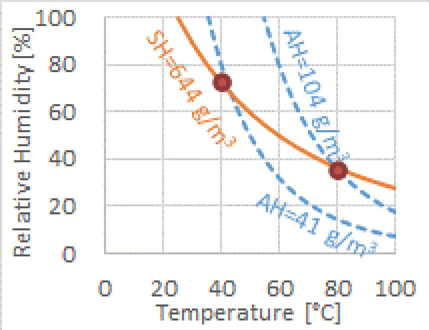
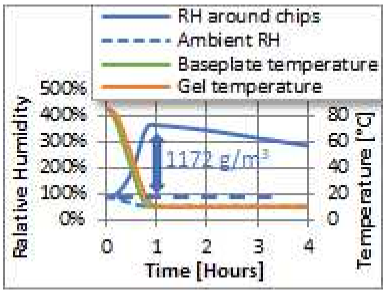


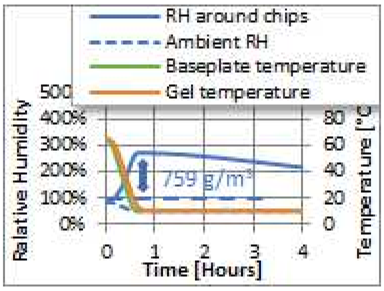
Fig. 3: Dissolved humidity (SH) & Absolute humidity (AH)

Cooling speed impact on the condensation test

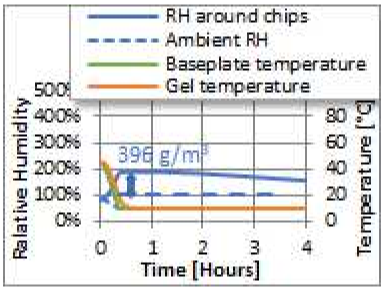
Cooling speed is also important to decide condensation amount. Condensation amount at the condensation test is calculated with various cooling speeds and various temperatures at humidification as shown in Fig. 4 and Fig. 5.



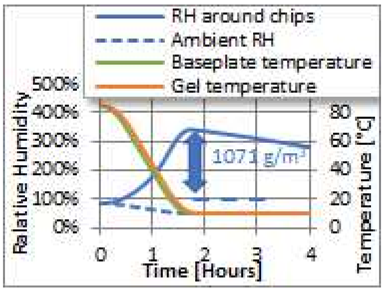
(A) Cooling from 85°C85%RH by 2K/min



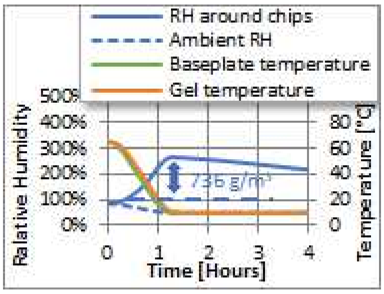
(B) Cooling from 65°C85%RH by 2K/min



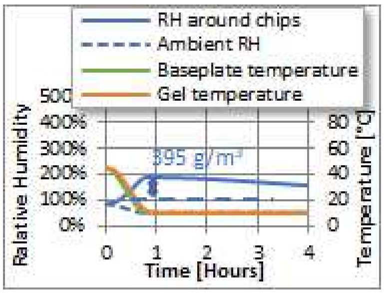
(C) Cooling from 45°C85%RH by 2K/min



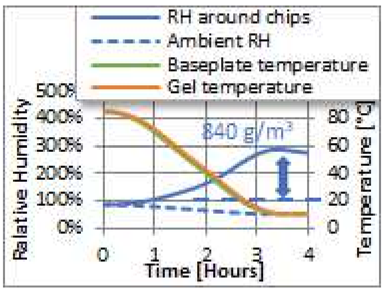
(D) Cooling from 85°C85%RH by 1K/min



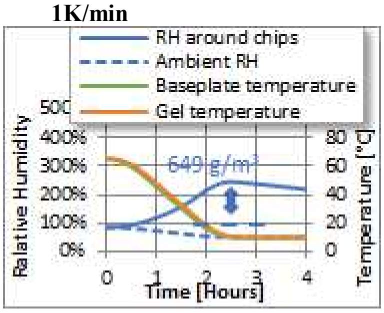
(E) Cooling from 65°C85%RH by 1K/min



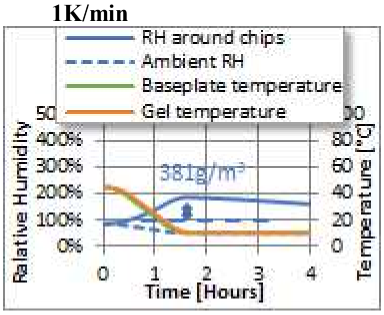
(F) Cooling from 45°C85%RH by 1K/min



(G) Cooling from 85°C85%RH by 0.5K/min



(H) Cooling from 65°C85%RH by 0.5K/min



(I) Cooling from 45°C85%RH by 0.5K/min

Fig. 4: Calculation result of condensation amount during condensation test in the condition with cooling to 10°C50%RH, saturated humidification duration, silicone gel thickness=20mm, time constant of 5min for gel temperature

Diffusion coefficient is larger at higher temperature according to equation (2). Hence, vapor is diffused out faster. As a result, vapor in silicone gel is dried out during ramping down phase. Thus, as shown in Fig. 5, cooling speed influences on condensation amount at higher temperature, but does not influence at lower temperature. It is shown that humidification at lower temperature is effective to obtain stable result independently from cooling speed.

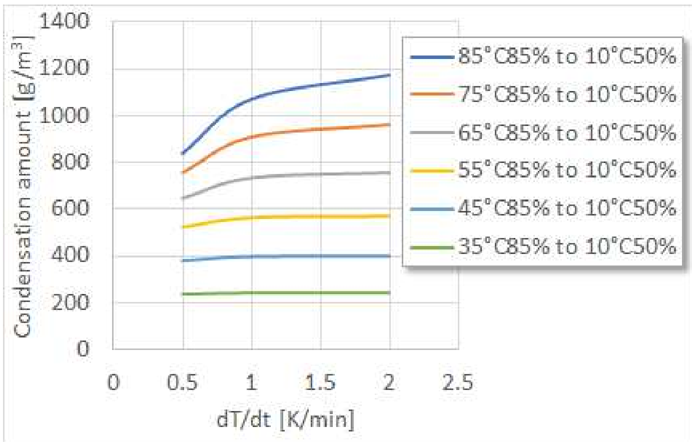
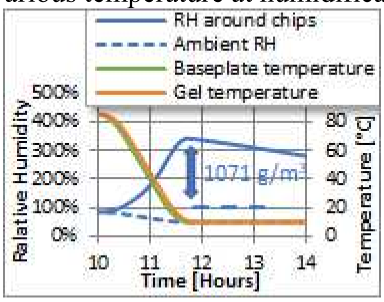


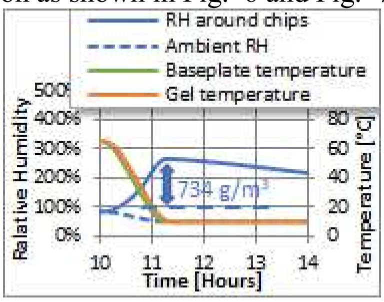
Fig. 5: Cooling speed impact

Humidification duration impact on the condensation test

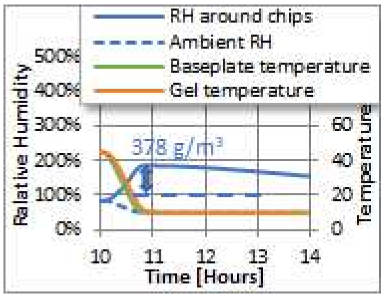
Condensation amount at the condensation test is calculated with various humidification duration and various temperature at humidification as shown in Fig. 6 and Fig. 7.



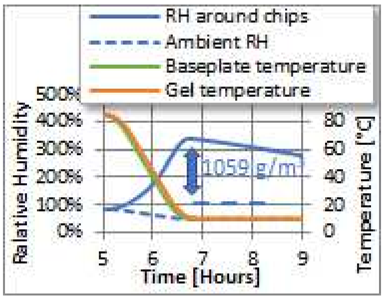
(A) Humidification condition of 85°C85%RH 10h



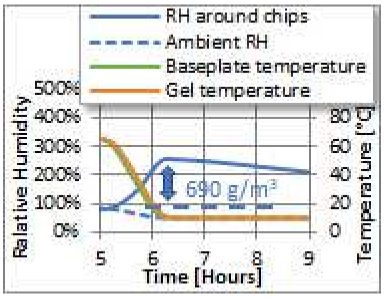
(B) Humidification condition of 65°C85%RH 10h



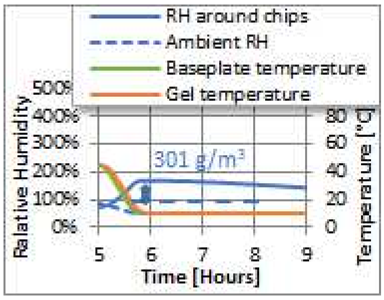
(C) Humidification condition of 45°C85%RH 10h



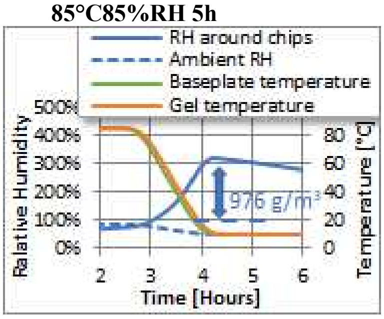
(D) Humidification condition of 85°C85%RH 5h



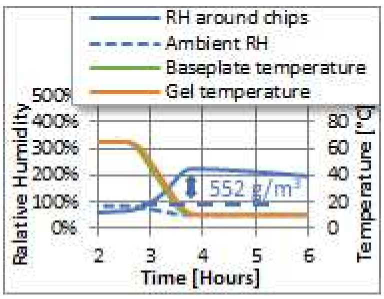
(E) Humidification condition of 65°C85%RH 5h



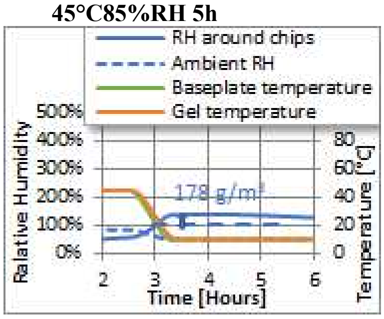
(F) Humidification condition of 45°C85%RH 5h



(G) Humidification condition of 85°C85%RH 2.5h



(H) Humidification condition of 65°C85%RH 2.5h



(I) Humidification condition of 45°C85%RH 2.5h

Fig. 6: Calculation result of condensation amount during condensation test in the condition with cooling to 10°C50%RH, dT/dt=-1K/min, silicone gel thickness=20mm, time constant of 5min for gel temperature

Humidification speed becomes higher at higher temperature because diffusion coefficient is larger according to equation (2). As a result, humidification becomes saturated faster at higher temperature but slower at lower temperature. Then, as shown in Fig. 7, humidification duration difference does not have impact on condensation amount with range of more than 5 hours humidification at higher temperature. On the other hand, humidification duration should be cared at lower temperature. It is shown that humidification at higher temperature is effective to shorten test time.

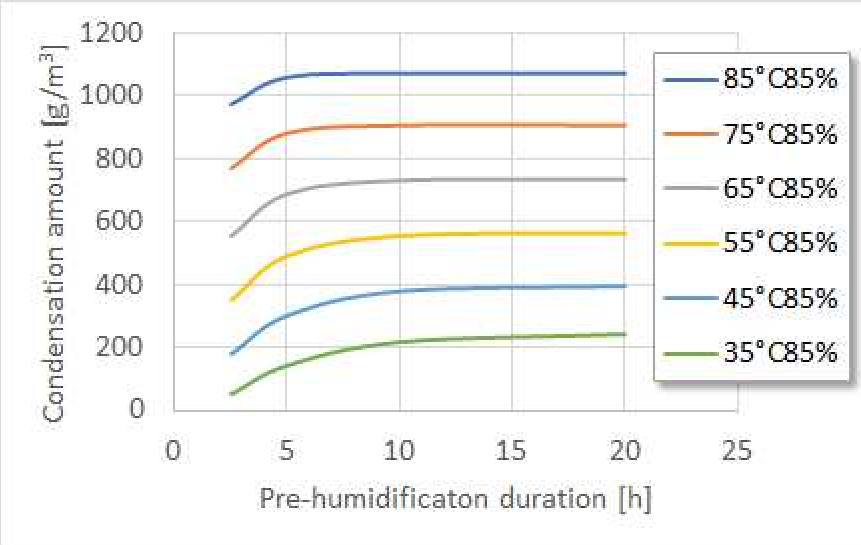


Fig. 7: Humidification duration impact

Gel thickness impact on the condensation test

Condensation amount at the condensation test is calculated with various gel thickness, various temperature, and various humidity as shown in Fig. 8 and Fig. 9. In this calculation, sufficient humidification duration is defined to obtain saturated vapor absorption.
Vapor is diffused into the air through gel during cooling phase. In case of thinner gel, the vapor is diffused into the air more quickly. As a result, thicker gel brings larger amount of condensation than thinner gel. This diffusion effect is stronger at higher temperature according to equation (2). Thus, gel thickness dependency is bigger at higher temperature. In contrast, gel thickness dependency is negligible at lower temperature. Also, relative humidity does not influence on the gel thickness dependency on condensation amount. Then, it is shown that humidification at lower temperature is effective to obtain stable results independently from gel thickness of the module.

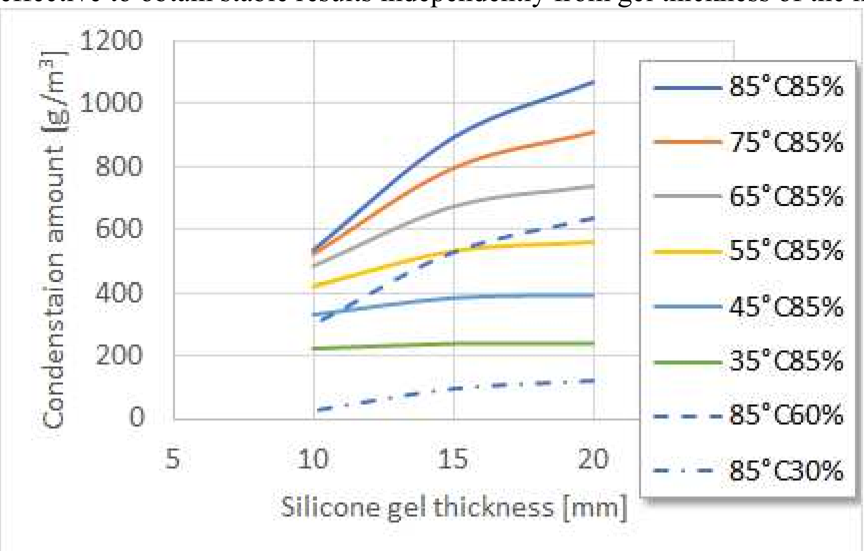
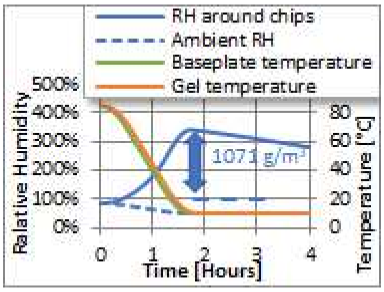
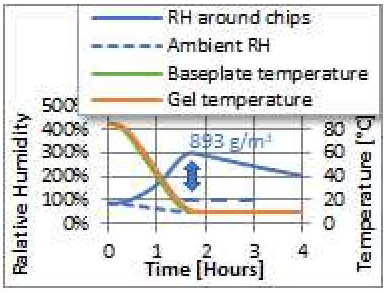


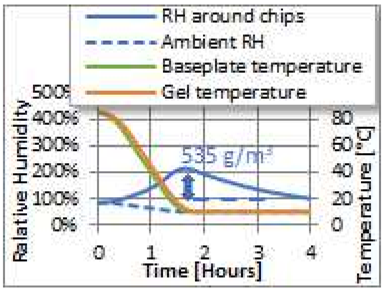
Fig. 8: Gel thickness impact



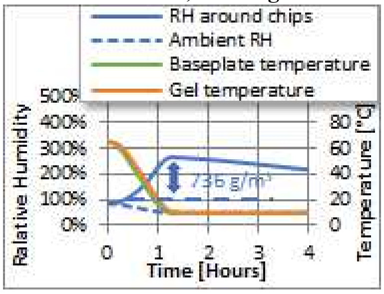
(A) Humidification condition of 85°C85%RH, 20mm gel



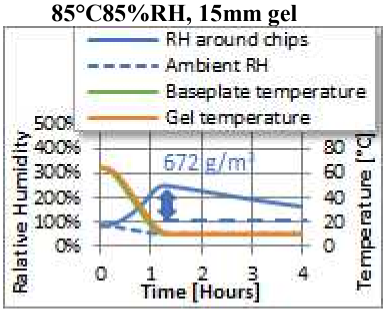
(B) Humidification condition of 85°C85%RH, 15mm gel



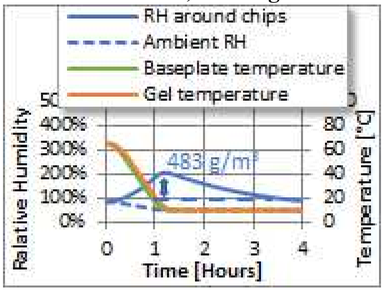
(C) Humidification condition of 85°C85%RH, 10mm gel



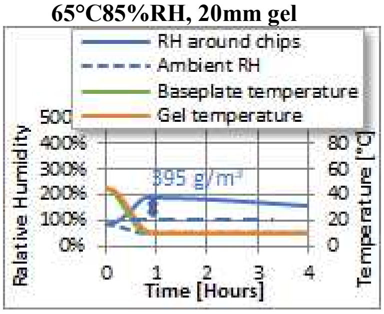
(D) Humidification condition of 65°C85%RH, 20mm gel



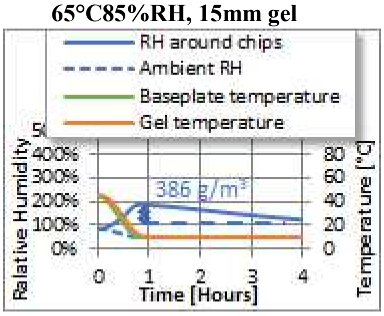
(E) Humidification condition of 65°C85%RH, 15mm gel



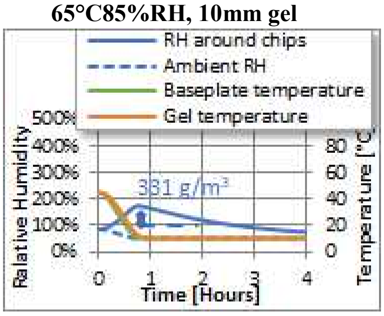
(F) Humidification condition of 65°C85%RH, 10mm gel



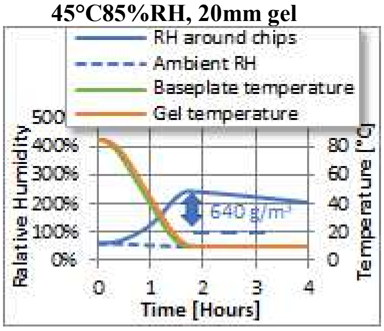
(G) Humidification condition of 45°C85%RH, 20mm gel



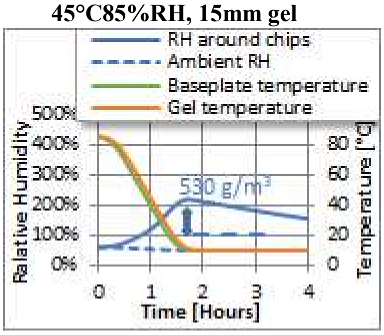
(H) Humidification condition of 45°C85%RH, 15mm gel



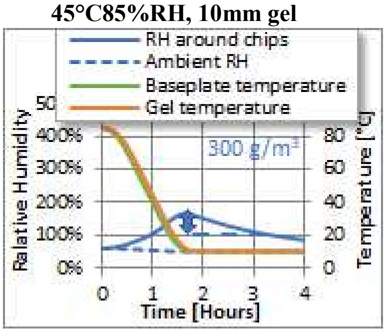
(I) Humidification condition of 45°C85%RH, 10mm gel



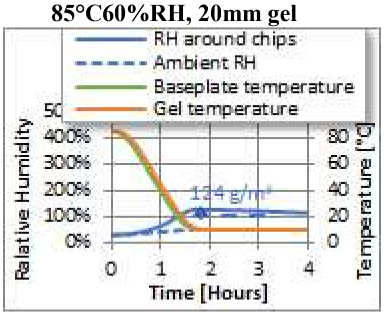
(J) Humidification condition of 85°C60%RH, 20mm gel



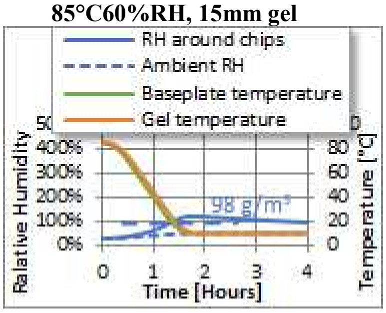
(K) Humidification condition of 85°C60%RH, 15mm gel



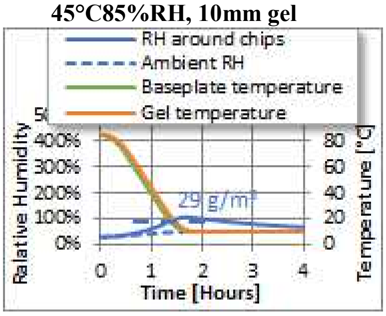
(L) Humidification condition of 45°C85%RH, 10mm gel



(M) Humidification condition of 85°C30%RH, 20mm gel



(N) Humidification condition of 85°C30%RH, 15mm gel

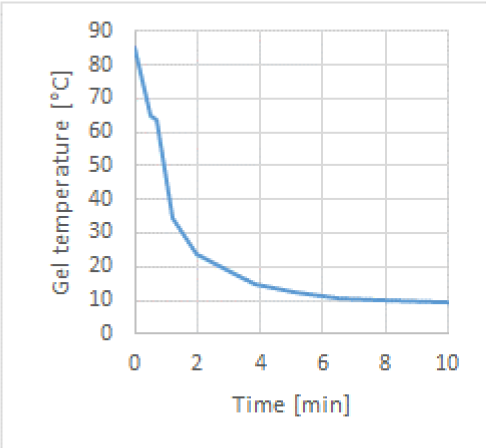


(O) Humidification condition of 85°C30%RH, 10mm gel

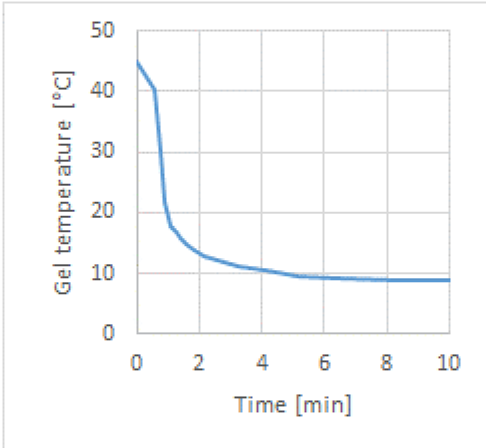
Fig. 9: Calculation result of condensation amount during condensation test in the condition with cooling to 10°C50%RH, dT/dt=-1K/min, time constant of 5min for gel temperature

Verification by experiment

The calculation result was verified by the experiment. The gel was filled in the glass cylinder with 30 mm diameter and the gel thickness is 10 mm. These gel samples were humidified with two conditions of 85°C85%RH and 45°C85%RH. The humidification duration varied from 40 min to 60 min for 85°C85%RH experiment and 155 min to 170 min for 45°C85%RH experiment. The cooling profile is shown in Fig. 10. As shown in Fig. 10, cooling speed is around 40 K/min for 85°C85%RH experiment and 20 K/min for 45°C85%RH experiment in early phase. Temperature sensor was located on the bottom of the cylinder. If condensation duration is too short, enough vapor does not reach the bottom of the cylinder. As a result, condensation appears only on the upper side of the gel in the cooling phase. The border between condensation area and the non-condensation area is marked in the experiment as shown in Fig. 11 and Fig. 12.

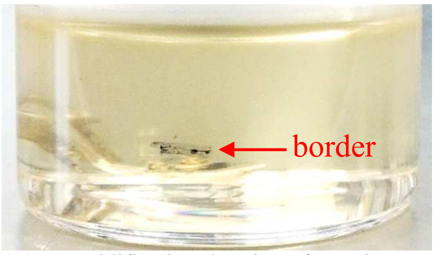


(A) Humidification condition of 85°C85%RH

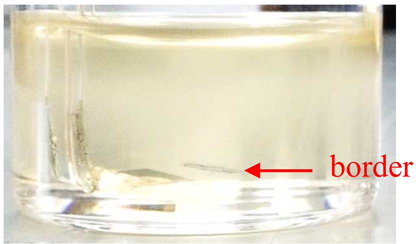


(B) **Humidification condition of 45°C85%RH**

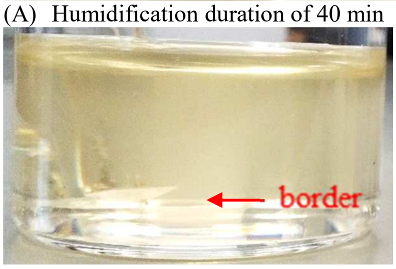
Fig. 10: The cooling profile of the experiment



(A) Humidification duration of 40 min



(B) Humidification duration of 51 min



(C) Humidification duration of 55 min

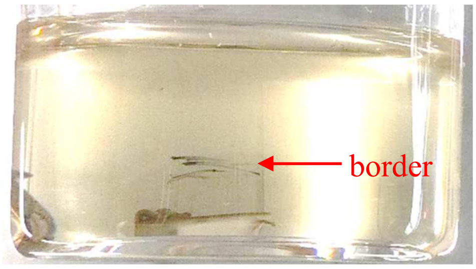
(D) Humidification duration of 60 min

Fig. 11: The experiment result with 85°C85%RH humidification condition

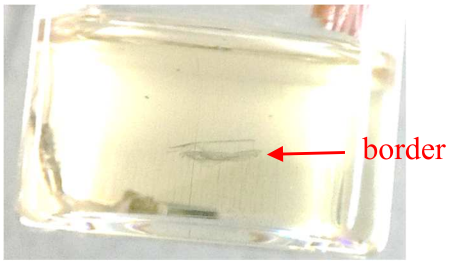
As shown in Fig. 11, the border between condensation area and non-condensation area was observed if 85°C85%RH humidification is less than 55 min. On the other hand, condensation reached the bottom of the cylinder in the case of longer humidification than 60 min with the condition of 85°C85%RH.

In the case of 45°C85%RH humidification, the border between condensation and non-condensation was observed if humidification is less than 165 min. In the case of longer humidification than 170 min, condensation reached the bottom of the cylinder.

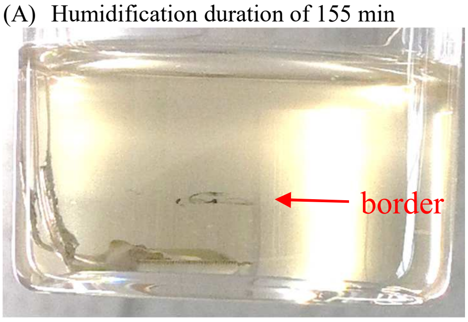
Then, 45°C85%RH humidification condition requires longer humidification to have condensation on the bottom of cylinder compared to the 85°C85%RH humidification condition. This result verified the calculation result which indicated higher temperature condition helped to reduce humidification duration for creating condensation on the bottom of the gel.



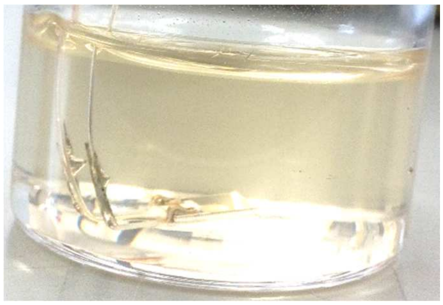
(A) Humidification duration of 155 min



(B) Humidification duration of 160 min



(C) Humidification duration of 165 min



(D) Humidification duration of 170 min

Fig. 12: The experiment result with 45°C85%RH humidification condition

Summary

As discussed above, humidification condition influences the condensation event. In order to establish the condensation test method, humidification condition is one of the most important parameters. Table 1 summarizes the findings of this work.

As described here, high temperature humidification condition is good to shorten test duration. However, it increases risk of cooling speed deviation and dependency on gel thickness. On the other hand, more stable condensation can be expected with humidification at lower temperature, since dependency on cooling speed and gel thickness is reduced. However, longer test duration is required.

Table 1: Humidification temperature impact on the condensation test

	Cooling speed dependency	Pre-humidification duration	Gel thickness dependency
High temperature humidification	Dependent	Enough with short time	Dependent
Low temperature humidification	Independent	Long time is required	Independent

Conclusion

Based on the humidity absorption model of silicone gel, condensation amount is calculated at various condensation-test conditions. At first, it is confirmed that condensation amount depends on dissolved humidity in silicone gel, not on absolute humidity of ambient air. Also, it is confirmed that humidification at lower temperature is effective to obtain stable results independently from cooling speed. Thirdly, it is confirmed that humidification at higher temperature is effective to shorten test time. Next, it is confirmed that humidification at lower temperature is effective to obtain stable results independently from gel thickness of the module.

Finally, the calculation result is verified by experiment.

It can be concluded that high temperature humidification condition is good to shorten test time, but low temperature humidification condition is good to obtain stable test results on the other hand.

Therefore, humidification temperature should be carefully chosen to meet condensation test requirement.
More research is required on the experiment in terms of quantification of condensation amount. This is desired to further reconfirm today's working results.

References

[1] S. Honda et al, "High Voltage Device Edge Termination for Wide Temperature Range plus Humidity with Surface Charge Control (SCC) Technology," *28th International Symposium on Power Semiconductor Devices and ICs (ISPSD)*, 2016, pp. 291-294.

[2] N. Tanaka et al, "Durable Design of the New HVIGBT Module," *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2016, pp. 1-7.

[3] S. Kremp, et al, "Humidity robustness for high voltage power modules: Limiting mechanisms and improvement of lifetime," Microelectronics Reliability, vol. 88–90, Sep. 2018, pp. 447-452.

[4] C. Papadopoulos, et al, "The influence of humidity on the high voltage blocking reliability of power IGBT modules and means of protection," Microelectronics Reliability, vol. 88–90, Sep. 2018, pp. 470-475.

[5] C. Papadopoulos, et al, "Humidity Robustness of IGBT Guard Ring Termination," *PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2019, pp. 1-8.

[6] Christian Zorn, Nando Kaminski, "Acceleration of Temperature Humidity Bias (THB) Testing on IGBT Modules by High Bias Levels," *2015 IEEE 27th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, 2015, pp. 385-388.

[7] Y. Kitajima et al, "Lifetime estimation model of HVIGBT considering humidity," *PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2017, pp. 1-6.

[8] N. Tanaka et al, "Robust HVIGBT module design against high humidity," *PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2015, pp. 368-373.

[9] K. Nakamura et al, "The test method to confirm robustness against condensation", *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*, 2019, pp. P.1-P.8.

[10] S. Kremp et al, "Realistic climatic profiles and their effect on condensation in encapsulated test structures representing power modules," Microelectronics Reliability, vol. 76–77, Sep. 2017, pp. 409-414

[11] K. Hatori et al, "Humidity Absorption Behavior of Silicone Gel in HVIGBT Modules," *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*, 2021, pp. 1-8.

[12] T. Mizutani, "Warpage Analysis in LCD Panel under Moisture Diffusion and Hygroscopic Swelling," Journal of Japan Institute of Electronics Packaging, Vol. 12, 2009, pp. 144-153

[13] K. Nagai, "Barrier Technology," 62-63, Kyoritsu Shuppan Co., Ltd. 2014 Print