Experimental characterization and simulation of water vapor diffusion through various encapsulants used in PV modules

Namsu Kim*, Changwoon Han

Components and Materials Physics Research Center, Korea Electronics Technology Institute, #68 Yatop-dong, Bundang-gu, Gyeonggi province 463-816, Republic of Korea

ABSTRACT

Water vapor ingress significantly impacts the performance and the long-term reliability of copper indium gallium selenide photovoltaic modules. A cost effective packaging method that can protect photovoltaic modules from the operating environment is critical to their widespread commercialization. Due to the sensitivity of both the copper indium gallium selenide cells and the electrodes to water vapor, they need an encapsulant with low water vapor permeation as well as side sealing materials, resulting in a high cost of manufacturing. Hence, a packaging strategy without sealing materials is proposed with new encapsulant materials. In this study, the overall amount of permeated water vapor through ionomer and polyvinyl butyral encapsulants was investigated and compared with widely used encapsulants such as ethylene vinyl acetate. The diffusion and solubility coefficients were calculated from the experimentally determined water vapor transmission rate in both transient and steady state transport regimes. To understand the permeation mechanism of water vapor through the encapsulant, the temperature dependence of the diffusion and solubility coefficients was investigated. Based on experimentally determined permeation properties, the amount of water vapor absorption and the ingress speed into the PV module under a continuously varying environment were investigated. Ethylene vinyl acetate shows its excellence among encapsulants, when simply considering ingress speed of water vapor (slower permeation), while ionomer dominantly outperforms other materials, when focusing on the total amount of water absorption (less permeation).

1. Introduction

As a result of advancements in material synthesis, fabrication and module processing, thin-film photovoltaic (PV) modules are moving rapidly toward commercialization. In spite of the significant advantages of thin-film PV modules such as light weight, low cost and applicability of flexible applications, their long-term reliability remains one of the greatest challenges. In particular, it has been reported that water vapor ingress significantly impacts the lifetime of copper indium gallium selenide (CIGS) PV cells [1–3]. Coyle et al. developed a life model for CIGS modules based on a moisture degradation failure model [4]. They reported that higher humidity levels can accelerate the degradation of PMMA-coated CIGS cells under both high and low temperatures. Hence, package design to minimize water vapor ingress into and within the module is critical to the improvement in performance and long-term reliability.

Encapsulant materials are widely used in PV modules for mechanical support, electrical isolation, protection against corrosion, and degradation of the electrical performance of thin-film layer [5]. Hence, one of the main requirements for an encapsulant is to suppress water vapor ingress into and within the module. To investigate the resistance against the ingress of water vapor, the water vapor transmission rate (WVTR) was measured and compared. However, the measured value of WVTR simply means how much water vapor can permeate material from one side of the encapsulant to the other side. It cannot evaluate how much water vapor can be absorbed in the encapsulant or how fast water vapor can diffuse through it. Hence, to evaluate the performance of an encapsulant as a water vapor ingress limiting layer in the PV module, the diffusion and solubility coefficients should be investigated separately. Based on both the values, it can be determined how well an encapsulant performs as a moisture ingress limiting layer.

Many types of encapsulants with different materials have been developed and used in laminating PV modules. Polydimethyl siloxane (PDMS) was the dominant material when PV panels were first developed in the 1960s [6,7]. However, the paradigm shift to low cost module manufacturing, especially in crystalline silicon PV modules, leads to the development of an ethylene vinyl acetate (EVA)-based encapsulant as the dominant PV encapsulant [6]. EVA is relatively inexpensive and known to be adequate for most

* Corresponding author. Tel./fax: +82 31 789 7053.
E-mail addresses: nkim@keti.re.kr, knamsu7@gmail.com (N. Kim).

crystalline silicon PV modules. Recently, there has been renewed interest in finding an improved water vapor limiting encapsulant which can outperform EVA, due to the relatively high susceptibility of thin-film PV modules to water vapor. The common candidates, ionomer and PVB, offer higher protection from environmental exposure for thin-film modules than EVA. The performance of these candidates and EVA as a water vapor ingress limiting layer should be evaluated to provide design guidelines for the long-term reliability of PV modules.

The structure of a PV module can consist of an impermeable front and back sheet (generally glass), or a permeable sheet. The latter, generally called a "breathable structure", is the typical structure for crystalline silicon PV modules, and this breathable structure is reported to be more desirable [5,8]. The former, called a glass-to-glass structure, is the general structure for thin-film technology. In both the cases, the amount of permeated water vapor and the time for ingress of water vapor into and within the module should be determined, to design PV modules for long-term reliability. However, these parameters cannot be measured experimentally because the PV module operates under a continuously varying environment. Hence, in this study, a two-dimensional (2-D) finite element method was employed to model water vapor ingress with time varying boundary conditions, and the simulation was carried out based on an experimentally determined diffusion and solubility coefficients, including their temperature dependence. This analysis can be a valuable design guideline for manufacturers to choose an adequate encapsulant and to determine the structure of modules according to the external environment.

2. Experimental details

2.1. WVTR measurement

The WVTRs of EVA and the EVA replacement, ionomer and PVB, have been measured in both the transient and steady state regions. The structure of the encapsulants evaluated in this study are shown in Fig. 1 [9]. Approximately 67 wt% of ethylene and 33 wt % of vinyl acetate of EVA, ionomer and PVB were evaluated as the module manufacturer provided them. An Illinois 7001 with 2-cell equipment was used for the experiments, and the test standard of ISO 15106-3 was applied to the measurements. Before starting the measurement, water vapor absorbed in the encapsulant was removed by blowing dry nitrogen separately over both top and bottom chambers. The Illinois test cell with 5 cm diameter, corresponding to a 19.6 cm^2 area was used, and measurements were performed at three different temperatures of 20, 35, and 50 °C. The WVTR as a function of time was measured by blowing humid nitrogen through one of the chambers, and an electrolytic detection sensor was used to detect the amount of permeated water vapor, as shown in Fig. 2. The nitrogen, including water vapor of 60% relative humidity, was injected into one of the two chambers, allowing the transient WVTR to be measured in the other chamber. Measurements were taken every minute, and the results are shown as graphs in the next chapter. According to the encapsulant materials, the saturated time until the steady state
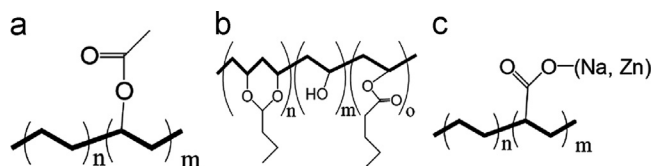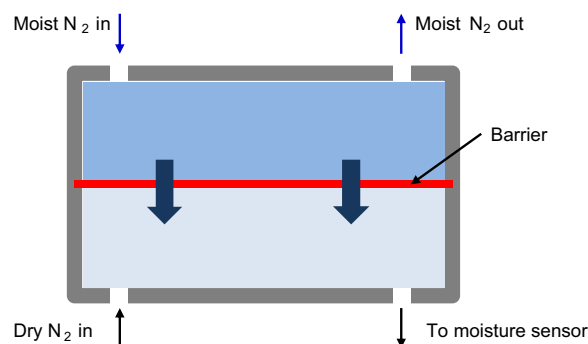

Fig. 2. Experimental set-up for the WVTR measurement.

and the WVTR at the steady state region were measured differently.

2.2. Diffusion and solubility coefficient calculations

The WVTR measured as a function of time is used to calculate the diffusion coefficient because the diffusion coefficient indicates how fast water vapor diffuses through the encapsulant. The diffusion of water vapor through a polymer-based encapsulant is described as a two-step processes combining absorption of water vapor into the encapsulant followed by diffusion of the water vapor [10]. This two-step process can be characterized by the diffusion and solubility coefficients of the encapsulant. The diffusion coefficient indicates how fast water vapor can move into the encapsulant and the solubility coefficient means how much water vapor can be dissolved. The amount of dissolved water vapor in the encapsulant determines the concentration gradient, and the concentration gradient is the driving force for diffusion. Hence, permeation can be determined by the diffusion coefficient multiplied by the solubility as described in Eq. (1) [10]

$$P = DS \tag{1}$$

where P, D and S are permeation, diffusion, and solubility coefficient, respectively. This means the permeation rate of a film is affected by the product of the diffusion and solubility coefficients. Hence, these coefficients should be determined separately to understand the diffusion of water vapor into and within the PV module.

Several methods are currently employed when evaluating the diffusion coefficient. The coefficient can be determined based on recording either the time dependence of the flux or the mass uptake. In the case of the latter, a quartz crystal microbalance is widely used to record the mass change of water vapor and Eq. (2) is one of the solutions for time-dependent diffusion, with the boundary conditions of fixed concentration on one side and zero flux on the other side [11,12]

$$\frac{M_t}{M_\infty} = 2\left(\frac{Dt}{L^2}\right)^{1/2}\left(\frac{1}{\pi^{1/2}} + 2\sum_{n=1}^{\infty}(-1)^n ierfc\frac{nL}{\sqrt{Dt}}\right) \tag{2}$$

At short times ($M_t/M_\infty < 0.6$), this solution can be simplified to Eq. (3) [12].

$$\frac{M_t}{M_\infty} = \frac{2}{L}\left(\frac{Dt}{\pi}\right)^{1/2} \tag{3}$$

hence, by recording the mass change of water vapor, as shown in the graph of Fig. 3, the diffusion coefficient can be determined based on Eq. (3). This method is commonplace in the thin-film industry. It is due to this method that thin films can be fabricated on quartz without any difficulty, and that set-up satisfies the above assumed boundary conditions. In the case of bulk film or sheet, instead of recording the mass change, the isostatic permeation test is widely used. This method records permeation rate as a

Fig. 1. The structure of different encapsulants; (a) EVA, (b) PVB and (c) Ionomer.