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Oxidized low density polyethylene: A potential cost-effective, stable, and recyclable polymeric encapsulant for photovoltaic modules

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ABSTRACT

Oxidized low density polyethylene (oxidized LDPE), with a density of 0.90 g/cm^3 and an oxidized acid number of 15 mg KOH/g, was used as an encapsulant for photovoltaic modules. The electrical stability and peel strength to glass/backsheet of oxidized LDPE encapsulated-modules after accelerated exposure tests were measured. The moisture transport of oxidized LDPE was measured by water vapour transmission rate (WVTR). Light transmittance and yellowness index of modules were determined by spectrocolorimeter and sepectrophotometer, respectively. Thermal properties of oxidized LDPE were determined by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). All measured results of oxidized LDPE-encapsulated modules were compared with EVA-encapsulated modules.

1. Introduction

Long durability of photovoltaic (PV) modules is critical to reduce the life-cycle cost of devices [1]. The promise of a commercial solar cell warranty guarantees 1% power loss after a year usage and the service warranty continues for 20 years. The ability to maintain the stability of PV module efficiency under long-term environment operation mostly relies on a reliable encapsulation. An ideal encapsulant should have characteristics of low-interface conductivity, tight adhesion between encapsulant and substrate, and low moisture permeation through encapsulants.

Polymeric materials have made them the most widely used encapsulants due to their light weight, low material cost, flexible nature, and easier assembly into PV module. Polyethylene (PE) was initially chosen as a polymeric encapsulant because of its simple structure and low cost. [2] However, PE suffers from its opaque and translucent appearance, thus causing poor light transparency of PV modules. Moreover, high modulus of PE lacks the suitability for mechanically protecting a PV module. To overcome these problems, vinyl acetate was added to PE system to form a co-polymer. Because vinyl acetate is a transparent and amorphous polymer, its incorporation could break PE's crystalline nature and increase its transparency. Ethylene vinyl acetate (EVA) copolymer has become one of the mostwidely used polymeric materials for photovoltaic modules due to its low cost and adequate packaging performance [3]. However, vinyl acetate itself produces acetic acid during long-term operation and the created acid might cause corrosion and lead to electrical destruction of cells [4]. The fact that the presence of acetic acid has slight influence in reducing the power efficiency in EVA-encapsulated wafer-based silicon solar cells is because of its relatively large module thickness (~180 μm); however, acetic acid might cause significant electrical destruction in EVA-encapsulated thin film solar cells because it has much thinner cell feature (below 5 μm). Therefore, to find EVA-alternative polymeric materials remains highly requisite.

In this article, we report for the first time using oxidized LDPE as an encapsulant for PV module packaging. The oxidized LDPE studied here has a density of 0.90 g/cm^3 and an oxidized acid number of 15 mg KOH/g. The oxidized LDPE has more amorphous structure than high density polyethylene (HDPE) [5]. A typical cell encapsulated by oxidized LDPE was carried out in a silicon solar cell. Accelerated exposure tests (i.e., damp heat test and humidity free tests), adhesion measurement, and WVTR were conducted to evaluate the performance of oxidized LDPE-encapsulated PV modules. Thermal and optical properties of oxidized LDPE were determined by TGA, DSC and spectrophotometer. In order to compare the encapsulant performance between oxidized LDPE and EVA, all measured results of oxidized-encapsulated modules were compared with EVA-encapsulated modules.

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2. Experimental section

2.1. Materials

Oxidized LDPE (DNP, PV-FS Z68) with a density of 0.90 g/cm^3 was supplied from Dai Nippon Printing (DNP) Co., Ltd. The EVA encapsulant is a commercial product. The formulation of EVA (ethylene vinyl acetate) has 32% vinyl acetate content with a density of 0.96 g/cm^3. The backsheet, obtained from KREMPEL Group Inc. was used for adhesion measurement. The c-Si solar cells of 156 mm × 156 mm were supplied by Delsolar Co., the borosilicate glass plates of 3.2 mm thickness were purchased from Stanley Glass Co., and the ribbons of 2 mm width were obtained from NPC Inc.

2.2. Materials characterization

The Fourier transform infrared (FTIR) spectra of oxidized LDPE were collected at room temperature using a Perkin Elmer Spectrum100 FT-IR Spectrometer. The C–H bond of alkene at 2916.88 cm^{-1} peak can be found, the peak at 1460 cm^{-1} is referred to –C–C– bond of oxidized LDPE. The smooth and broad peak at 3458 cm^{-1} is referred to the OH-group contributions [6]. The carbonyl stretching vibration peak at 1720 cm^{-1} can be found. The peaks at 3458 and 1720 cm^{-1} are referred to the oxidized LDPE ,which consist of carboxylic acid (–COOH) functional group.

The acid number of oxidized LDPE was measured by color-indicator titration following ASTM D974 [7]. 2 g of oxidized LDPE was added into 100 mL of toluene/isopropyl alcohol solution (50:50 v/v), and the resulting solution is titrated at room temperature with a 0.1 M KOH solution. To determine the acid number of oxidized LDPE, the indicator solution, *p*-naphtholbenzein in the solvent of toluene/isopropyl alcohol (50:50 v/v) with the concentration of 10 ± 0.01 g/L, was added. At the end point of acid number determination, the color change could be seen. The acid number of this oxidized LDPE was determined to be 15 mg KOH/g.

2.3. Module preparations

The configuration of c-Si solar cell module is glass/encapsulant/c-Si solar cell/encapsulant/glass. A c-Si solar cell was encapsulated with oxidized LDPE or EVA between two borosilicate glass plates. All of the laminated samples are 180 mm × 180 mm in size. The ribbon was soldered on a solar cell. Fig.1 shows the side view of a typical polymer-encapsulated c-Si cell.

2.4. Lamination process

The lamination process was applied using a Solar Module Laminator (LM-SA-170 × 260-S, NPC Inc.). The lamination process was carried out at a programmed procedure as follows. The sample was loaded at 50 °C at 200 Pa, heated to 85 °C in 6 min, and heated to 110 °C for 2 min holding and a pressure was then applied to a diaphragm on top of the samples. After that, the sample was heated to 150 °C for 8 min, cooled down to 85 °C, and vented to atmospheric pressure.

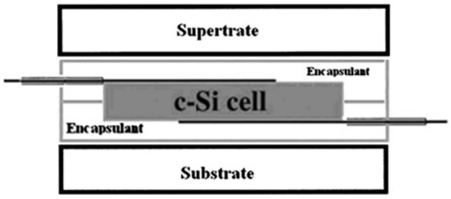

Fig. 1. The side view of an encapsulated - c-Si solar cell with 156 mm × 156 mm size.

2.5. Accelerated exposure tests

Modules were subjected to accelerated weathering in an exposure chamber under a laboratory control. Damp-heat exposure was carried out at a condition of no light, 85 °C and 85% relative humidity (RH) in a GIANT FORCE chamber (GTH-15-20-CP-AR) for 1000 h [8–10]. Humidity-freeze test was carried out at a condition of no light, from 85 °C and 85% RH to −40 °C, for 10 cycles. Relevant properties were measured as a function of exposure time.

2.6. Adhesion measurement

Peel or stripping strength measurement of adhesive bonds was carried out in an American Standard Test Method (ASTM) D903 [11]. Peel-strength measurement was carried out at a separation angle of approximately 180° and a separation rate of 152 mm/min. Samples were then removed from the chamber, and cooled to room temperature. Interfacial adhesion of encapsulated modules was measured using an Instron Test Unit (model 5500R). To prevent evaporation of moisture, the sample was placed in the Instron to ensure centered adhesion and no bending torques on the sample. One thing should be noted that, prior to testing, the adhesive area was measured using a caliper to inspect whether there are any excessive bubbles.

2.7. Water Vapour transmission rate (WVTR)

WVTR was measured following ASTM E96 [12]. Briefly, the test specimen was sealed to the open mouth of a test dish containing a desiccant, and the assembly was placed in a controlled atmosphere at 40 °C at 90% RH. The rate of water vapour movement was determined by periodic weighings through the specimen into the desiccant.

The water vapour transmission rate is calculated as follows:

$$\mathrm{WVTR} = G/tA = (G/t)/A$$

where G is weight change, grains (from the straight line), t is time during weight G occurred, G/t is the slope of the straight line, A is the test area (cup mouth area), and WVTR is the rate of water vapour transmission rate, g/h m^2.

The test area A is 2.23×10^{-3} cm^2 with 24 h for the time during weight change. The G values of oxidized LDPE and EVA are individually 4.24×10^{-3} and 1.07×10^{-1} g . After calculation following ASTM E96, the WVTR of oxidized LDPE and EVA is 1.9–47.9 g/m^2 day, respectively.

2.8. Characterization of electrical performance of modules, and optical and thermal properties of encapsulants

Optical and electrical properties of samples were characterized before, during, and after accelerated exposure tests, . The optical properties of encapsulants were conducted by measuring the integrated transmittance using a HITACHI U3010 spectrocolorimeter. The yellowness index was measured by a Nippon Denshoku SA2000 spectrophotometer. Light current-–voltage (I–V) measurements were conducted for all photovoltaic modules using a Berger PSS30 Simulator. Thermal analysis was measured by DSC (Perkin elmer DSC7e) and TGA (Shimadzu TGA-50H).

3. Results and discussion

3.1. Adhesion

Fig. 2(a) shows the peel strength of oxidized LDPE to glass after 1000 h of a damp-heat test. The decay of peel strength between oxidized LDPE to glass is 2.8% after the test, indicating good water resistance of oxidized LDPE. After damp-heat test, the peel strength to glass of oxidized LDPE is 6.6 kg/10 mm, higher than that of EVA (5.4 kg/10 mm) [13]. Oxidized LDPE has stronger peel strength than EVA because of its 15 mg KOH/g acid number and its hydrophobic nature, which could reduce the ingress of water into the module. Moreover, the lower pH is also known to help stabilize siliconates in aqueous solutions [14] and the presence of acetic acid likely contribute to the loss of EVA's peel strength to glass. Fig. 2(b) shows the peel strength of oxidized LDPE to backsheet after a damp heat test. The loss of peel strength between oxidized LDPE and backsheet after the damp-heat test is 3.5%. The final peel strength between oxidized LDPE and backsheet after damp heat test is 3.6 kg/10 mm, around 3 kg/ 10 mm smaller than that of oxide LDPE to glass. The fact that the oxidized LDPE has stronger peel strength to glass (6.6 kg/10 mm) than to backsheet (3.6 kg/10 mm) might result from the baser characteristic of oxidized LDPE.

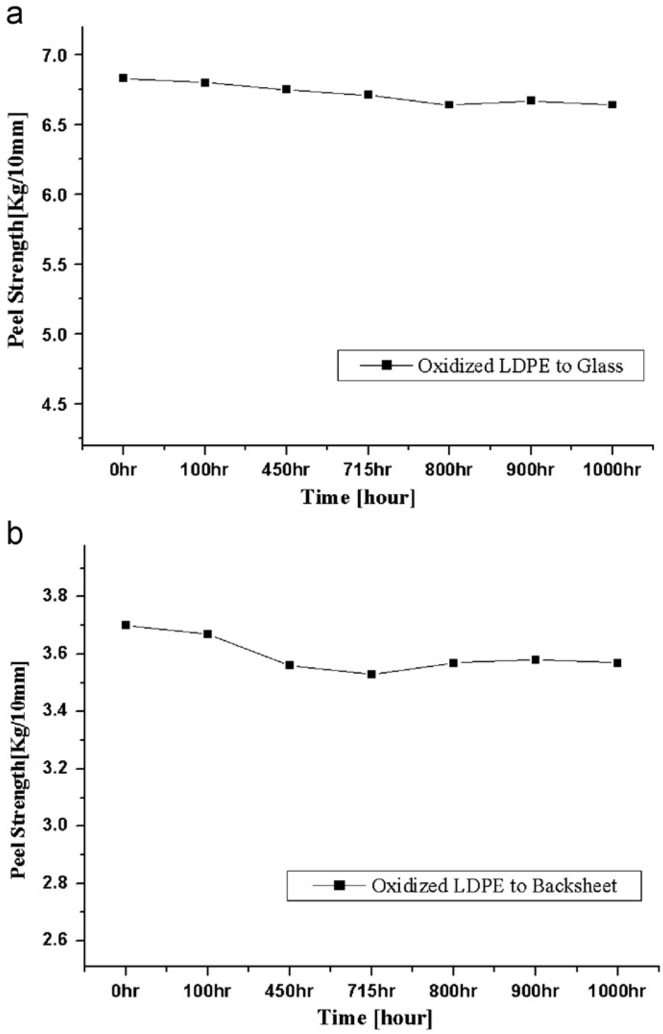

Fig. 2. The peel strength of oxidized LDPE after a damp-heat test: (a) oxidized LDPE/glass and (b) oxidized LDPE/backsheet.

3.2. Physical and optical property

The thermal property of oxidized LDPE during a photovoltaic lamination process was investigated [15,16]. Fig. 3 shows the DSC curve of oxidized LDPE, at a scanning rate of 10 °C/min [17]. The results show that oxidized LDPE has a glass transition temperature around 45.9 °C. Oxidized LDPE starts to melt at first run from 62.8 to 120.7 °C and this period could be denoted as an endothermic process. The melting point of oxidized LDPE is 85.4 °C at first run. An exothermic process was found at 99.1 °C at second run, which could be assigned to the crystalline temperature of oxidized LDPE. At the third run, another endothermic process of oxidized LDPE occurred from 54.9 to 114.9 °C. The repeated endothermic process shows that oxidized LDPE has the characteristic of a thermoplastic polymer.

Fig. 4. shows the light transmittance of oxidized LDPE and EVA. The light transmittance of oxidized LDPE increases rapidly around 380 nm and slowly after 400 nm. At 900 nm, the light transmittance of oxidized LDPE is close to 90%. The light transmittance of EVA is higher than that of oxidized LDPE between 400 and 650 nm, whereas the light transmittance of oxidized LDPE is higher than EVA between 650 and 900 nm. These show that oxidized LDPE has good light transmittance comparable to EVA.

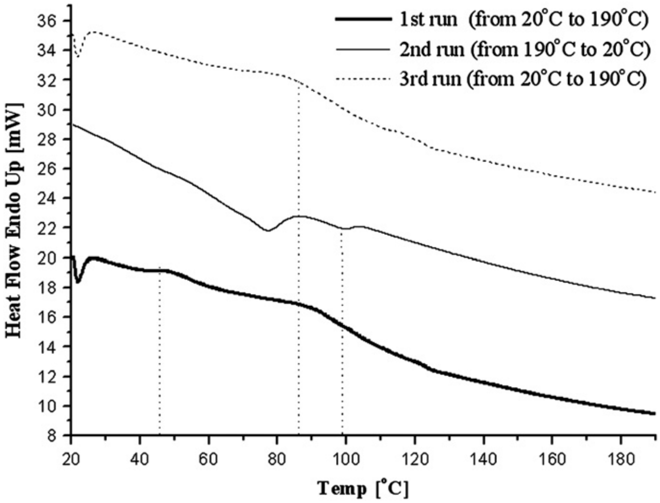

Fig. 3. The differential scanning Calorimetry (DSC) of oxidized LDPE.

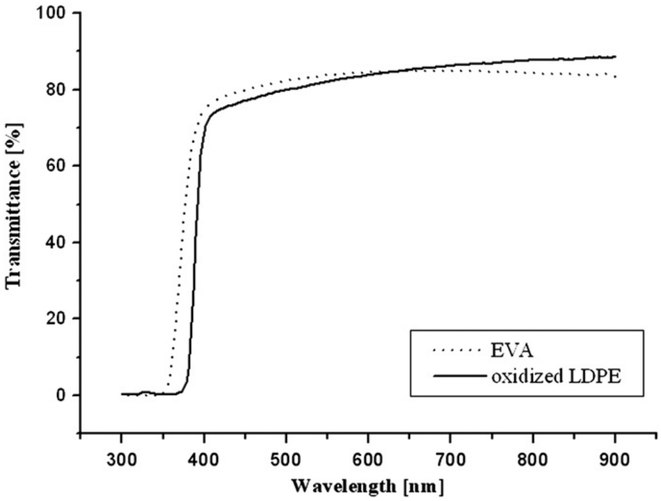

Fig. 4. Light transmittance between oxidized LDPE and EVA.

Fig. 5 shows the TGA graph of oxidized LDPE and EVA at scanning temperatures ranging from 20 to 180 °C. The degradation of oxidized LDPE occurred at 150 °C with the weight loss of 0.042%, whereas the degradation of EVA at 150 °C loses its original weight of 0.415 % (Table 1) [18,19]. These results indicate that oxidized LDPE is more stable than EVA at the fabrication temperature of photovoltaic modules (150 °C).

3.3. *Electrical property, WVTR and the change of yellowness index of modules after accelerated exposure tests*

Fig. 6 shows the electrical performance of a 156 mm × 156 mm c-Si solar cell embedded in the oxidized LDPE and EVA during damp heat tests. After a damp heat test, the decrease of P_{max} of solar cell module encapsulated with oxidized LDPE and EVA is individually 1.4% and 1.7%.

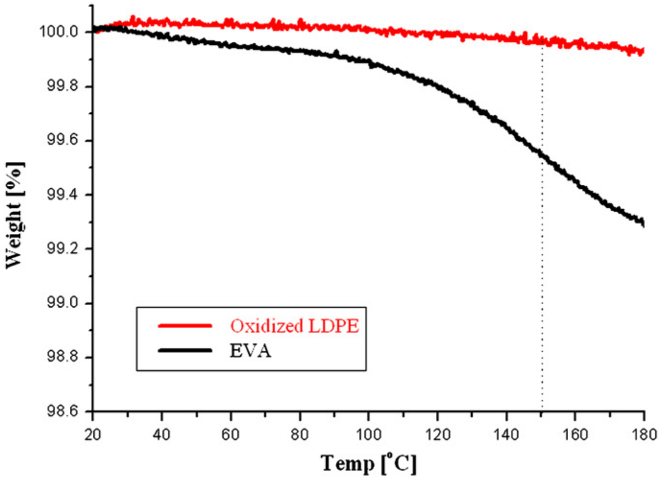

Fig. 5. Variation of TGA curves of oxidized LDPE and EVA.

Table 1
Weight loss of oxidized LDPE and EVA at 150 °C in TGA

Material	Weight loss (%)
Oxidized LDPE	0.042
EVA	0.415

Fig. 7 shows the light current–voltage (*I*–*V*) curves measured for oxidized LDPE- and EVA-encapsulated modules during a humidity freeze test. After humidity freeze test, the P_{max} loss of oxidized LDPE- and EVA-encapsulated module is individually 0.6 %and 0.9%. Since the power loss of oxidized LDPE- and EVA-encapsulated modules was lower than 5%, both oxidized LDPE- and EVA-encapsulated modules could qualify the damp-heat test and humidity freeze test of IEC61215 and IEC61646 regulations [20,21]. One thing that should be noted is that the electrical performance of oxidized LDPE is better than that of EVA, probably due to the better water resistance of oxidized LDPE to EVA. To evidence this assumption, we measured the water vapour transmittance rate (WVTR) as a function of time at 40 °C at 90% RH. As shown in Table 2, the WVTR of oxidized LDPE is 1.9 g/m^2 day, which is much lower than that of EVA (47.9 g/m^2 day), showing more water penetration through EVA into the cell. The reason might be because EVA is more hydrophilic than oxidized LDPE as it originated from its hydrogen bonding.

The change of yellowness index was used to determine the material yellowing of encapsulants directly after an accelerated exposure test. Table 3 shows the change of yellowness index of oxidized LDPE and EVA after humidity freeze tests. The net changes of yellowness index (ΔYI) of oxidized LDPE is only half fold of that of EVA [22]. The result shows that the cross-linking reaction of EVA occurred during the process of EVA curing [23], thus causing discoloration of encapsulants. On the other hand, the thermoplastic nature of oxidized LDPE makes it free of cross-linking, and no corrosive chemical compound forms to discolor oxidized LDPE.

4. Conclusion

The performance of oxidized LDPE-encapsulated photovoltaic modules was investigated. Oxidized LDPE-encapsulated modules show stable peel strength to glass and backsheet over 1000 h after accelerated exposure tests. Oxidized LDPE-encapsulated modules have less than 2% of power loss after tests, demonstrating that the oxidized LDPE could provide good electrical insulation for modules. TGA characterization shows no substantial weight loss of oxidized LDPE at operational temperatures. Light transmittance of oxidized LDPE is similar to EVA. WVTR of oxidized LDPE is only 1.9 g/m^2 day, showing oxidized LDPE could form a solid barrier to prevent water penetration. Oxidized LDPE exhibits thermoplastic characteristic and could be used as a recyclable encapsulant. Oxidized LDPE has much minor material yellowing compared to that of EVA, showing its stability of transparency over long-term usage. Our results show

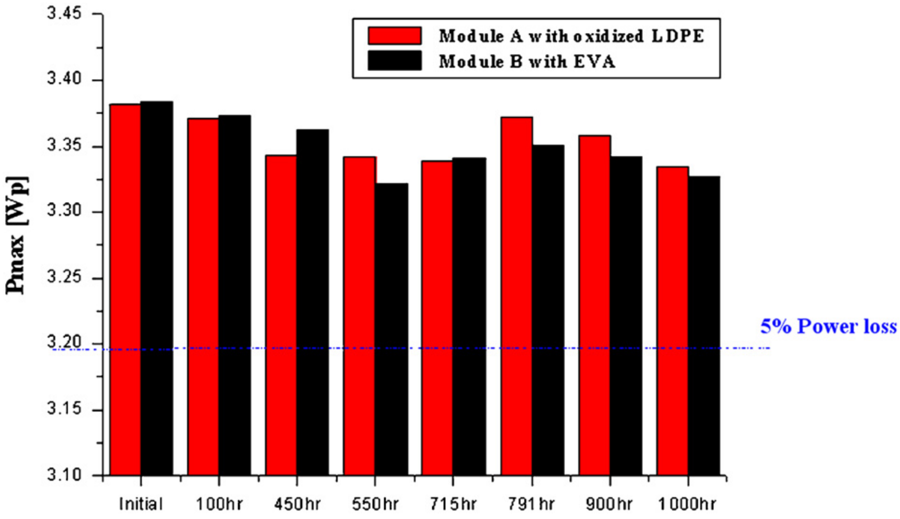

Fig. 6. Light current–voltage (*V*) curves measured for oxidized LDPE and EVA during a damp heat test.

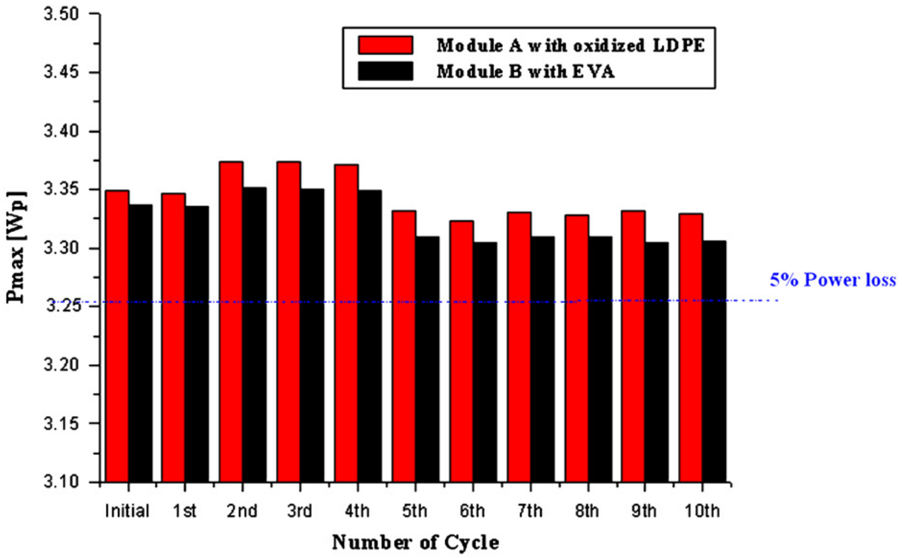

Fig. 7. Light current–voltage (*I*–*V*) curves measured for oxidized LDPE and EVA during a humidity freeze test.

Table 2
Water vapour transmission rate (WVTR) of oxidized LDPE and EVA

Material	WVTR[a] (g/m^2 day)
Oxidized LDPE	1.9
EVA	47.9

[a] WVTR is measured as a function of time at 40 °C/90% RH by ASTM E96.

Table 3
Change of yellowness index of oxidized LDPE and EVA after humidity freeze test

Material	ΔYI
Oxidized LDPE	0.07
EVA	0.14

that oxidized LDPE could provide firm mechanical support, electrical isolation, and thermal stability for photovoltaic modules and could be used as a potential low-cost, reliable, and recyclable polymeric encapsulant.

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