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# High-voltage pulse crushing and physical separation of polycrystalline silicon photovoltaic panels

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ABSTRACT

High-voltage pulse crushing technology combined with sieving and dense medium separation was applied to a photovoltaic panel for selective separation and recovery of materials. The panel was first separated into glass and back sheet layers by high-voltage pulse crushing through microexplosions or shock waves transmitted in the Al electrode and Si substrate (primary crushing step). Then the glass and bus-bar electrode could be separated from the encapsulant by high-voltage pulse crushing of the glass layer. The bus-bar electrode of the back sheet layer could also be separated by further high-voltage pulse crushing. After sieving the products obtained from the secondary crushing step of the glass layer, glass was mainly distributed in the size fraction range of 45–850 μm with a small amount of Si powder. However, purification of the glass (removal of Si powder) could be achieved by dense medium separation at a specific gravity of 2.4. Base metals, such as Cu, Sn, and Pb could be recovered in the large size fraction (1.0–8.0 mm). Ag used in the finger and bus-bar electrodes was highly condensed in the sieved product fraction with sizes of less than 20 μm, 2.0–4.0, and 4.0–8.0 mm, and its content exceeded 3000 mg/kg. However, the amount of Ag in these fractions represented only 33.2% of the total amount of Ag in the panel. Thus, to increase the Ag recovery ratio, other separation methods will be needed. We confirmed that dense medium separation at a specific gravity of 3.0 could achieve Ag condensation from the Si and glass, and that this represents a promising option for enhanced Ag recovery from crushed products.

## 1. Introduction

Photovoltaic power generation does not emit $CO_2$ gas while in use and represents an effective and secure energy source. Owing to the merits, installations of photovoltaic power generation systems have increased continuously to date (IEA-PVPS, 2017). The estimated lifetime of photovoltaic panels is 20–30 years (Goe and Gaustad, 2014); thus, the number of disposed panels is forecast to increase in the future (Weckend et al., 2016). Therefore, consideration of the disposal of photovoltaic panels is necessary. A silicon photovoltaic panel is composed of frames, a junction box, glass, encapsulant, a back sheet, and a photovoltaic cell, which consists of a Si substrate and Cu, Ag, and Al electrodes. Because photovoltaic panels contain valuable resources, recycling of the panels is required.

Recycling technologies for photovoltaic panel have been developing in recent years. There are three main approaches to recycling: mechanical (Berger et al., 2010; Granata et al., 2014), thermal (Klugmann-Radziemska et al., 2010; Radziemska et al., 2010), and chemical (Doi et al., 2001; Klugmann-Radziemska and Ostrowski, 2010; Klugmann-Radziemska et al., 2010; Radziemska et al., 2010; Kim and Lee, 2012; Kang et al., 2012) methods. These methods have the following advantages and disadvantages. Mechanical methods are easy and low cost; however, the liberation of materials is poor compared with other methods. Thermal methods can remove the encapsulant, recover glass and the photovoltaic cell. However, the treatment cost of this method is high owing to the energy required for heating, and gas emitted while heating the encapsulant must be treated. Chemical methods can be used to separate glass and the photovoltaic cell with reduced contamination, such as that from the encapsulant; however, these treatments are high cost and require a relatively long time. Therefore, the development of recycling technology to separate these materials with high efficiency and low cost is required to avoid the problems with the aforementioned methods of recycling photovoltaic panels. Thus, we have focused on a high-voltage pulse crushing technology, which has previously been applied to liquid crystal displays (Dodbiba et al., 2012), printed circuit boards (Duan et al., 2015; Zhao et al., 2015), and mineral ores (Wang et al., 2011, 2012). These studies have reported on the high selective crushing performance of the technology.

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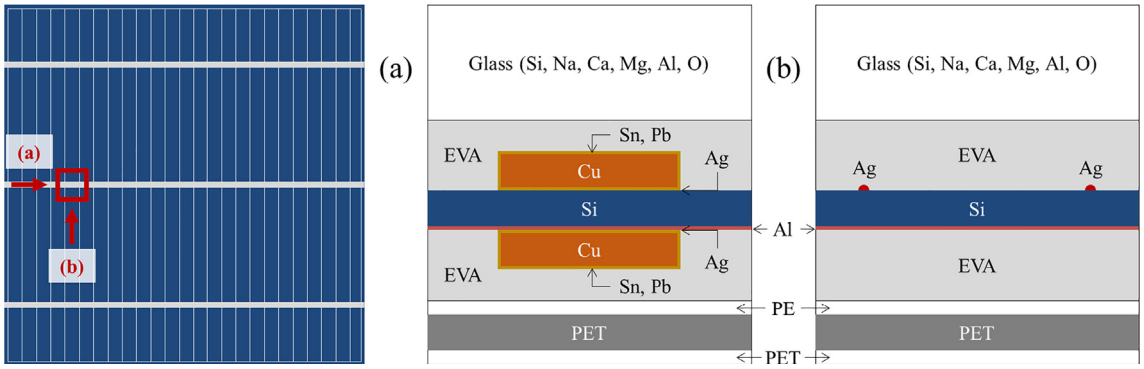


**Fig. 1.** Cross-sectional diagrams of the photovoltaic panel used in this study. (a) Cross section in the direction with a bus-bar electrode; and (b) Cross section in the direction with a Ag finger electrode (cited from Akimoto et al., 2017 and partly revised).

In this study, we apply high-voltage pulse crushing technology to photovoltaic panel crushing, combined with sieving and dense medium separation. The objective of this study was to establish a method for selective separation and recovery of materials in photovoltaic panels.

## 2. Materials

The subject of this study was recycling of a polycrystalline silicon photovoltaic panel. An end-of-life photovoltaic panel (1650 mm × 988 mm × 45 mm, 18.54 kg, 250 W) from a recycler was used for the experiments (Fig. 1). First, the external frames and junction box were removed from the panel. We then manually cut the panel into squares with dimensions of 50 mm × 50 mm × 4.2 mm (approximately 20 g). Cut samples were used in the high-voltage pulse crushing experiments. A larger (wider) panel size is desirable to simplify the shredding treatment before electrical pulse crushing. We decided on this panel size (i.e., 50 mm × 50 mm × 4.2 mm) based on the maximum size that could fit at the bottom of crushing vessel.

Fig. 1(a) and (b) show that an Al electrode was located under the Si substrate, and these layers were encapsulated in ethylene vinyl acetate (EVA). The encapsulant was sandwiched between glass and a back sheet, which had three layers. Fig. 1(a) shows that Cu electrodes (bus-bar electrodes) were present on a Si substrate and an Al electrode. Solders (Sn and Pb) were found around the Cu electrodes. Ag electrodes (finger electrodes) were observed on the Si substrate, as shown in Fig. 1(b). Table 1 summarizes the material contents of each of the cut photovoltaic panel samples. The composition was estimated from elemental analysis of the cut panel samples with the use of inductively coupled plasma atomic emission spectrometry (ICP-AES; Spectro Arcos, Ametek, Inc., Berwyn, PA, US) after acid dissolution. Glass was the main component of the panel and its content was measured to be 78.4 wt%. The Si content was 4.0 wt%, and the Cu, Sn, and Pb contents of both the bus-bar electrodes were similar. More than 60% of the Ag content was contained in the other fraction, and this portion was related to Ag used in finger electrodes. The upper bus-bar electrode (upper surface side) contained three times as much Ag as that contain in the bottom side. It should be noted that this table does not include the contents of the back sheet layers and encapsulant.

## 3. Experimental

### 3.1. High-voltage pulse crushing experiments

High-voltage pulse crushing experiments were performed with a SELFRAG Lab S2.0 instrument (SELFRAG AG, Switzerland). After a piece of the cut panel was put on the bottom electrode in the vessel, the crushing experiments were conducted under the conditions listed in Table 2. The discharge voltage and gap between the electrodes determines the potential gradient across the panel sample and surrounding water for electrical breakdown. In our high-voltage pulse crushing experiments, the gap between the electrodes was set to be 20 mm; however, for a discharge voltage of 90 kV the gap was set to be 10 mm because electrical breakdown did not occur when the distance was set at 20 mm. The discharge frequency was set to be 5 Hz for all conditions.

The panels were separated into two layers in the primary crushing step, as described below. To elucidate the separation mechanism of the panel into two layers, we observed fracture surfaces after the primary crushing step, under the optimal conditions, by scanning electron microscope (SEM; VE-9800, Keyence, Japan) and energy-dispersive X-ray spectroscopy (EDX; EDAX Genesis, Ametek, Inc., Berwyn, PA, US). Each layer was then crushed under the conditions summarized in Table 3. The obtained products were observed visually at appropriate times.

The product obtained by crushing under the optimal conditions was sieved through 11 different sieves (20, 45, 90, 150, 300, 500, and 850 μm, and 1.0, 2.0, 4.0, and 8.0 mm). The concentrations of Ag, Al, Ca, Cu, Mg, Na, Pb, Si, and Sn in each particle size range were determined by ICP-AES after dissolution by acid ($HNO_3$, HF, and $H_3BO_3$) with the use of an Ecopre system® (ACTAC, Japan). Undissolved encapsulant was removed by filtering with a PTFE filter (pore size: 0.2 μm) before the ICP-AES analysis. Partial sampling of the sieved products by the method of quartering was conducted for ICP-AES analysis of the size fractions of 20–45, 45–90, 90–150, 150–300, 300–500 and 500–800 μm. Whole samples were dissolved and analyzed for the size fractions of –20 μm and 2.0–4.0 mm. For the size fractions of 1.0–2.0, and 4.0–8.0 mm, the bus-bar electrode and encapsulant were manually separated, and whole amount of the bus-bar electrode was dissolved and analyzed separately. For the size fraction of 1.0–2.0 mm,

**Table 1**
Content of each material in cut photovoltaic panel samples (wt%).

| | Glass | Si substrate | Cu | Sn | Pb | Ag | Al electrode |
|---|---|---|---|---|---|---|---|
| Glass | 77.7 | – | – | – | – | – | – |
| Bus-bar electrode (Upper surface side) | 0.00009 | 0.001 | 0.55 | 0.057 | 0.042 | 0.010 | 0.000008 |
| Bus-bar electrode (Bottom side) | 0.0002 | 0.004 | 0.55 | 0.056 | 0.040 | 0.003 | 0.00007 |
| Other | 0.62 | 4.0 | 0.0006 | 0.0009 | 0.0008 | 0.025 | 0.19 |
| Total | 78.4 | 4.0 | 1.1 | 0.11 | 0.083 | 0.038 | 0.19 |