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Pulse laser recovery of high-purity colloidal silver spheres from end-of-life crystalline silicon solar panels

Sowon Choi [a,1], Heewon Kang [a,1], Eunji Park [a], Jihye Yang [a], Allan Gomez-Flores [a], Hyeon Jin Jung [b], Soo Won Heo [b], Jung-Hyun Lee [c], Hyunsung Jung [b,*], Hyunjung Kim [a,*]

[a] Department of Earth Resources & Environmental Engineering, Hanyang University, Seongdong-gu, Seoul 04763, Republic of Korea
[b] Nano Convergence Materials Center, Emerging Materials R&D Division, Korea Institute of Ceramic Engineering and Technology (KICET), Jinju-si 52851, Gyeongsangnam-do, Republic of Korea
[c] Department of Chemical and Biological Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea

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ABSTRACT

Crystalline silicon photovoltaic (c-Si PV) modules, regarded as first-generation solar cells, are expected to generate a significant volume of end-of-life materials in the coming years due to their limited lifecycle. We propose a novel recycling process to recover silver from spent c-Si PV modules, producing high-purity silver spheres through photoreduction using a nanosecond pulsed laser. In detail, a leaching efficiency of ~100 % was shown with an optimized lixiviant concentration (1 M HNO_3), temperature (70 °C), time (60 min), and solid–liquid ratio (75 g/L). To recover high-purity silver from the leachate, interfering ions other than silver were removed through pH adjustment, and the loss rate of silver was only 1.9 %. High-purity spherical silver particles were recovered by irradiation with a nanosecond pulsed laser at 100 mJ for 60 min to the Ag_2O suspension, which was produced by adding NaOH to the purified leachate. The final recovery efficiency of silver was ~ 98 % through leaching, impurity removal, and laser reduction from the waste PV cell. A preliminary life cycle assessment indicated that the process has lower energy consumption and environmental impact than conventional techniques, though economic performance still requires improvement.

1. Introduction

Renewable energy generation has steadily increased, and the proportion of renewable energy to electricity production reached 30 % worldwide in 2023 [1]. Solar power production has grown rapidly, accounting for more than 11 % (1294 TWh) of renewable energy in 2022, and is expected to increase significantly in 2030 [1,2]. The production of solar modules is expected to increase further as solar power production growth [3,4]. Crystalline silicon (c-Si) photovoltaic (PV) modules account for 90 % of modules produced to date, and with an average lifespan of about 25 years, the problem of managing waste modules has only recently emerged issue [5,6]. According to the International Renewable Energy Agency (IRENA), the cumulative volume of spent PV modules worldwide is projected to reach at least 60 million tons and up to 78 million tons by 2050 [7]. Disposal of these modules poses environmental risks: incineration can release hazardous gases such as hydrogen fluoride and dioxins, while landfilling can lead to long-term persistence and potential leaching of toxic substances into the environment [8–14].

The c-Si modules typically consist of an aluminum frame (12–14 wt %), glass (68–72 wt%), junction box, polymers including ethyl vinyl acetate (EVA) and back sheet (PVF, polyvinyl fluoride; PVDF, polyvinylidene fluoride) (8–10 wt%) (Fig. 1A) [3]. In Fig. 1B, the PV cell in the module is sandwiched between polymers, and the cell has a copper ribbon busbar and is fingerprinted with silver as the front electrode. Aluminum particles are printed in layers or lines as the rear electrode. Among the valuable metals in the modules, silver accounts for 0.03–0.08 wt%, but comprises 9 % to 23 % of the value [3]. Silver is a precursor metals with distinct properties such as corrosion resistance and catalytic activity and has the highest electrical conductivity among all metals, allowing wide use as a switch, electrode, and bonding wire for electronic devices. In particular, the silver used as the front electrode of PVs accounts for 17 % of the total usage [15]. Demand for silver to use in PV modules and electronic devices will increase further in the future,

* Corresponding authors.
E-mail addresses: hsjung@kicet.re.kr (H. Jung), kshjkim@hanyang.ac.kr (H. Kim).
[1] These authors equally contributed to this work.

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