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**Energy**  
**News**

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**에너지융합기술 혁신인재 양성사업단**

**Innovative Education & Research Center for Energy Convergence Science and Technology**

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## KIT Energy 소식

### 한국전기연구원(KERI)-금오공대, 전고체전지 성능 UP ‘황화실리콘 최적 제조기술’ 개발

- 하윤철 박사 및 박철민 교수팀, 높은 반응온도에서의 황의 증기압 상승 난제 극복
- 고체전해질의 가격경쟁력 및 품질 향상 기여, 국제 학술지 표지논문 게재



한국전기연구원(KERI) 차세대전지연구센터 하윤철 박사팀과 금오공대 신소재공학부 박철민 교수팀이 전고체전지 상용화를 앞당길 수 있는 ‘고체전해질용(아지로드ایت 계열) 황화실리콘(SiS<sub>2</sub>) 저가 제조기술’을 개발했다.

전고체전지는 양극과 음극 사이에서 이온을 전달하는 전해질을 액체가 아닌, 화재나 폭발 위험성이 낮은 고체로 대체한 것이다. 그러나 제조공정 및 양산화의 어려움, 높은 단가 등 상용화까지 해결해야 할 많은 과제를 안고 있어 전 세계적으로 연구개발이 활발하게 진행되고 있고, KERI에서도 여러 성과를 이뤄냈다.

이번에 하윤철 박사팀이 주목한 소재는 황화실리콘이다. 전고체전지용 고체전해질에 황화실리콘(SiS<sub>2</sub>)을 첨가하면 이온 전도도 및 수분 안정성(moisture stability)을 향상시킬 수 있다는 것은 학계에서 널리 알려진 사실이다. 하지만 황과 실리콘의 합성 과정에서 높은 반응온도가 필요하고, 이에 따른 황의 증기압이 너무 커지는 문제가 발생하는 등 황화실리콘의 제조를 위한 공정 난이도가 매우 높다. 이러한 이유로 황화실리콘은 현재 가격이 20그램(g) 당 약 170만원에 달할 정도로 비싸다.

KERI의 성과는 황화실리콘 제조를 위한 최적 공정 기술을 개발하고, 이를 전고체전지용 고체전해질에 적용할 수 있는 발판을 마련한 것이다. 연구팀은 황과 실리콘의 배치를 최적화하여 합성 조건을 확립하고, 800도의 높은 반응온도에서도 황의 기화에 따른 증기압을 버틸 수 있는 완벽한 밀폐 환경을 구현하는 데 성공했다. 결과물도 상용 제품의 품질과 대등했다. 연구팀은 만들어진 황화실리콘을 고체전해질 제조에 활용했고, 2배 이상의 높은 이온 전도도 및 수분 안정성을 가지는 것을 확인했다. 공정의 최적화로 과정은 단순화하고, 제조비 감소도 기대할 수 있는 결과다.

KERI 하윤철 박사는 “그동안 황의 증기압 상승을 해결하기 위해 국내외 많은 연구진이 고가의 원료를 사용하거나, 특수 공정을 도입하는 등 어려움을 겪었는데, 우리의 성과로 고체전해질용 황화실리콘을 저렴하고 쉽게 제조할 수 있는 길이 열리게 될 것”이라고 전했다.

한편 연구팀은 이번 황화실리콘을 고체전해질뿐만 아니라 액체전해질 기반의 리튬이온전지 음극 활물질 분야에도 적용하여 유의미한 결과(충·방전 과정에서의 충상구조 소멸 및 회복 현상 세계최초 규명)를 얻기도 했다. 이러한 황화실리콘 관련 전반적인 연구결과는 우수성을 인정받아 에너지·연료 분야 세계적 논문인 ‘저널 오브 머터리얼즈 케미스트리 에이(Journal of Materials Chemistry A, IF: 14.511)’의 표지논문으로 최근 선정됐다.

KERI는 해당 기술에 대한 특허 출원을 준비하고 있다. 또한 이번 성과가 전고체전지 관련 기업(고체전해질 생산 및 극판/멤브레인 제조 장비 기업, 극판 전해질막 및 셀 제조업체 등의 많은 관심을 받을 것이라 보고, 관련 수요 업체를 발굴하여 황화실리콘 제조 공정의 스케일업(Scale-up) 및 상용화를 추진한다는 계획이다.

한국전기연구원 보도자료(2023.03.20.) [https://www.keri.re.kr/\\_prog/\\_board/?mode=V&no=13893&code=sub0601](https://www.keri.re.kr/_prog/_board/?mode=V&no=13893&code=sub0601)

◆ 관련 기사 ◆

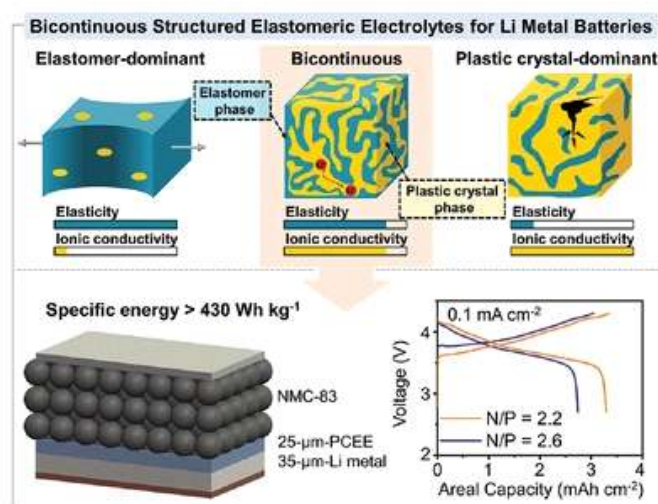
중앙일보	KERI, 금오공대와 황화실리콘 제조기술 개발...전고체전지 상용화 눈앞	<a href="https://www.joongang.co.kr/article/25148519">https://www.joongang.co.kr/article/25148519</a>
신소재경제	전기연-금오공대, 전고체전지 상용화 앞당긴다	<a href="http://amenews.kr/news/view.php?id=52887">http://amenews.kr/news/view.php?id=52887</a>
경남신문	전기연, 전고체전지 상용화 앞당긴다	<a href="http://www.knnews.co.kr/news/articleView.php?idxno=1399670">http://www.knnews.co.kr/news/articleView.php?idxno=1399670</a>
부산일보	KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="https://www.busan.com/view/busan/view.php?code=2023032023354880402">https://www.busan.com/view/busan/view.php?code=2023032023354880402</a>
경남매일신문	전기연·금오공대, 황화실리콘 제작 전고체전지 상용화 앞당긴다	<a href="http://www.gnmaeil.com/news/articleView.html?idxno=515360">http://www.gnmaeil.com/news/articleView.html?idxno=515360</a>
일요신문	KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="https://ilvo.co.kr/?ac=article_view&amp;entry_id=448912">https://ilvo.co.kr/?ac=article_view&amp;entry_id=448912</a>
경남도민일보	전기연, 차세대 배터리 '전고체 전지' 상용화 한발짝 더	<a href="http://www.idomin.com/news/articleView.html?idxno=820303">http://www.idomin.com/news/articleView.html?idxno=820303</a>
파이낸셜 뉴스	전기연, 차세대 배터리 '전고체 전지' 상용화 한발짝 더	<a href="https://www.fnnews.com/news/202303201802485771">https://www.fnnews.com/news/202303201802485771</a>
노컷뉴스	전기연 '황화실리콘 최적 제조기술' 개발...전고체전지 상용화 앞당겨	<a href="https://www.nocutnews.co.kr/news/5912635">https://www.nocutnews.co.kr/news/5912635</a>
한스경제	[에너지공기업 데일리 이슈] KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발 외	<a href="http://www.sporbiz.co.kr/news/articleView.html?idxno=647023">http://www.sporbiz.co.kr/news/articleView.html?idxno=647023</a>
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핀포인트뉴스	KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="https://www.pinpointnews.co.kr/news/articleView.html?idxno=183595">https://www.pinpointnews.co.kr/news/articleView.html?idxno=183595</a>
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에너지데일리	전기연, 황화실리콘 최적 제조기술 개발... 전고체전지 성능 제고	<a href="http://www.energydaily.co.kr/news/articleView.html?idxno=135489">http://www.energydaily.co.kr/news/articleView.html?idxno=135489</a>
서울신문	한국전기연구원-금오공대, 고체전해질용 황화실리콘 저가 기술 개발	<a href="https://www.seoul.co.kr/news/newsView.php?id=20230320500060">https://www.seoul.co.kr/news/newsView.php?id=20230320500060</a>
디지털조선일보	화재위험 없는 '전고체 배터리' 고효율 생산법 찾았다	<a href="https://digitalchosun.dizzo.com/site/data/html_dir/2023/03/20/2023032080110.html">https://digitalchosun.dizzo.com/site/data/html_dir/2023/03/20/2023032080110.html</a>
투데이에너지	KERI, '황화실리콘 최적 제조기술' 개발	<a href="http://www.todayenergy.kr/news/articleView.html?idxno=258694">http://www.todayenergy.kr/news/articleView.html?idxno=258694</a>
매일건설신문	전기연구원, 금오공대와 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="http://mcnews.co.kr/78206">http://mcnews.co.kr/78206</a>
조선비즈	전고체전지 가격 낮추고 효율 높인다... 국내 연구진, 황화실리콘 생산 공정 개발	<a href="https://biz.chosun.com/science-chosun/technology/2023/03/20/64EDWYAVDIENNEVOE4MLWTVV7Q">https://biz.chosun.com/science-chosun/technology/2023/03/20/64EDWYAVDIENNEVOE4MLWTVV7Q</a>
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한국원자력신문	전기연구원-금오공대, '황화실리콘 최적 제조기술' 개발	<a href="http://www.knpnews.com/news/articleView.html?idxno=24487">http://www.knpnews.com/news/articleView.html?idxno=24487</a>
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뉴스1	한국전기연구원-금오공대, 전고체전지 상용화 선두	<a href="https://newsis.com/view/?id=NISX20230320_0002232810">https://newsis.com/view/?id=NISX20230320_0002232810</a>
헤럴드경제	리튬이차전지 비켜라... '폭발위험 없는 전고체전지 성능 UP'	<a href="http://news.heraldcorp.com/view.php?ud=20230320000165">http://news.heraldcorp.com/view.php?ud=20230320000165</a>
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뉴스웍스	KERI-금오공대, 황화실리콘 최적 '제조 공정 기술' 개발...고체전해질 제조 활용	<a href="http://www.newsworks.co.kr/news/articleView.html?idxno=708943">http://www.newsworks.co.kr/news/articleView.html?idxno=708943</a>
파이낸셜뉴스	전고체전지용 핵심소재를 저가로 만든다	<a href="https://www.fnnews.com/news/202303200921251974">https://www.fnnews.com/news/202303200921251974</a>
워크투데이	KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="http://www.worktoday.co.kr/news/articleView.html?idxno=33537">http://www.worktoday.co.kr/news/articleView.html?idxno=33537</a>
전자신문	전기연-금오공대, '황화실리콘 최적 제조기술' 개발	<a href="https://www.etnews.com/20230320000008">https://www.etnews.com/20230320000008</a>
ZDNet Korea	전기연, 전고체전지 전해질 안정성 높일 핵심 소재 기술 개발	<a href="https://zdnet.co.kr/view/?no=20230317162730">https://zdnet.co.kr/view/?no=20230317162730</a>
뉴스1	전기연, 황화실리콘 저가 제조기술 개발...전고체전지 상용화 기대	<a href="https://www.news1.kr/articles/4985220">https://www.news1.kr/articles/4985220</a>
전기신문	KERI-금오공대, 전고체전지 성능 UP '황화실리콘 최적 제조기술' 개발	<a href="https://www.electimes.com/news/articleView.html?idxno=317112">https://www.electimes.com/news/articleView.html?idxno=317112</a>

## Advanced Materials

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## Role of Bicontinuous Structure in Elastomeric Electrolytes for High-Energy Solid-State Lithium-Metal Batteries

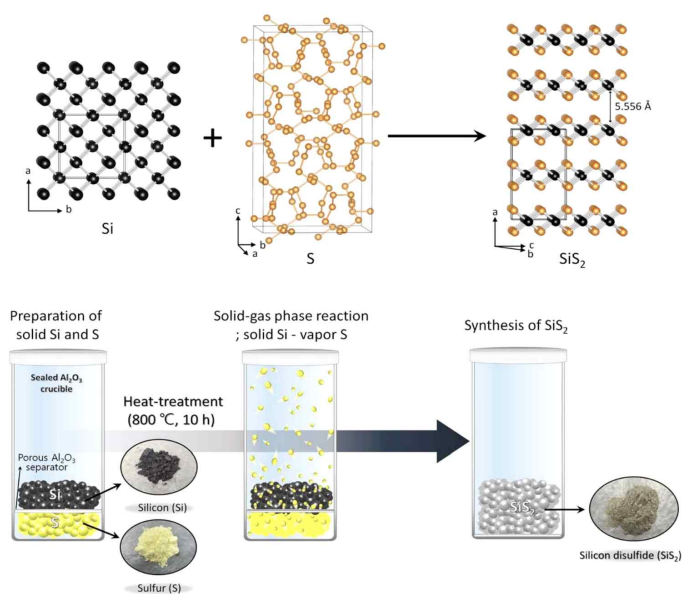
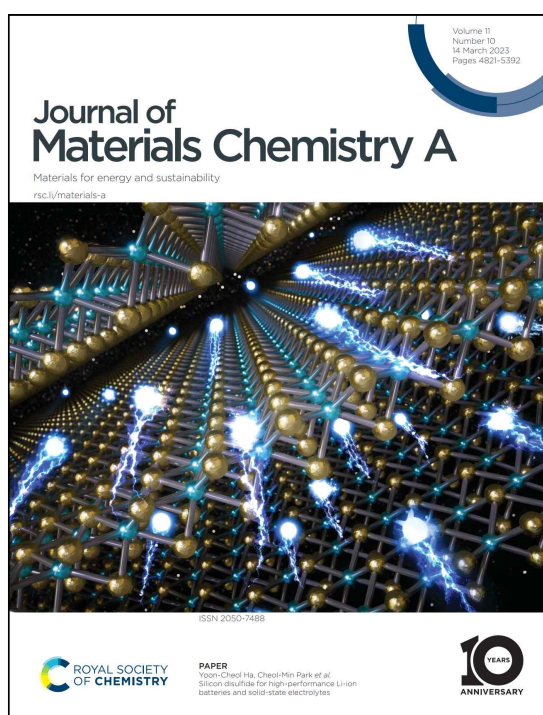
Junghun Han, Michael J. Lee, Kyungbin Lee, Young Jun Lee, Seung Ho Kwon, Ju Hong Min, Eunji Lee, Wonho Lee, Seung Woo Lee\*, and Bumjonn J. Kim\*



Solid-state lithium (Li)-metal batteries (LMBs) are garnering attention as a next-generation battery technology that can surpass conventional Li-ion batteries in terms of energy density and operational safety under the condition that the issue of uncontrolled Li dendrite is resolved. In this study, various plastic crystal-embedded elastomer electrolytes (PCEEs) are investigated with different phase-separated structures, prepared by systematically adjusting the volume ratio of the phases, to elucidate the structure-property-electrochemical performance relationship of the PCEE in the LMBs. At an optimal volume ratio of elastomer phase to plastic-crystal phase (i.e., 1:1), bicontinuous-structured PCEE, consisting of efficient ion-conducting, plastic-crystal pathways with long-range connectivity within a crosslinked elastomer matrix, exhibits exceptionally high ionic conductivity ( $\approx 10^{-3}$  S cm $^{-1}$ ) at 20 °C and excellent mechanical resilience (elongation at break  $\approx 300\%$ ). A full cell featuring this optimized PCEE, a 35  $\mu$ m thick Li anode, and a high loading LiNi $_{0.83}$ Mn $_{0.06}$ Co $_{0.11}$ O $_2$  (NMC-83) cathode delivers a high energy density of 437 Wh kg $_{\text{anode+cathode+electrolyte}}^{-1}$ . The established structure-property-electrochemical performance relationship of the PCEE for solid-state LMBs is expected to inform the development of the elastomeric electrolytes for various electrochemical energy systems.

## Silicon disulfide for high-performance Li-ion batteries and solid-state electrolytes

Ki-Hun Nam, Do-Hyeon Kim, Young-Han Lee, Su Choel Han, Jeong-Hee Choi,  
Yoon-Cheol Ha\*, Cheol-Min Park\*



Layered materials have attracted considerable attention in recent years due to their diverse properties, including tunable bandgaps, valley polarization, and weak van der Waals interlayer forces, which enable a wide variety of promising applications. Among them, silicon disulfide ( $\text{SiS}_2$ ) exhibits interesting chemical and physical properties. However, synthesizing  $\text{SiS}_2$  remains difficult due to the high pressure and temperature requirements and the easy vaporization of the S source. Herein, we establish a simple large-scale synthesis of layered orthorhombic  $\text{SiS}_2$  using a solid-gas phase reaction. Additionally, it is evaluated for its Li-storage properties as an anode material for Li-ion batteries (LIBs). The  $\text{SiS}_2$  nanocomposite, which was fabricated using amorphous carbon in a simple mechanical process, has a high lithiation/delithiation capacity of 1610/1363 mA h  $\text{g}^{-1}$ , high initial coulombic efficiency of 84.7%, extremely high cycling stability after 800 cycles, and high rate capability. Furthermore,  $\text{SiS}_2$  is incorporated into a Li-argyrodite solid-state electrolyte ( $\text{Li}_6\text{PS}_5\text{Cl}$ , SSE) used in all-solid-state batteries (ASSBs), resulting in commendable air/moisture stability and high ionic conductivity with low activation energy. Accordingly, the large-scale synthesis method, exceptionally high Li-storage characteristics, and remarkable SSE application of the layered  $\text{SiS}_2$  make it highly suitable for a variety of applications.

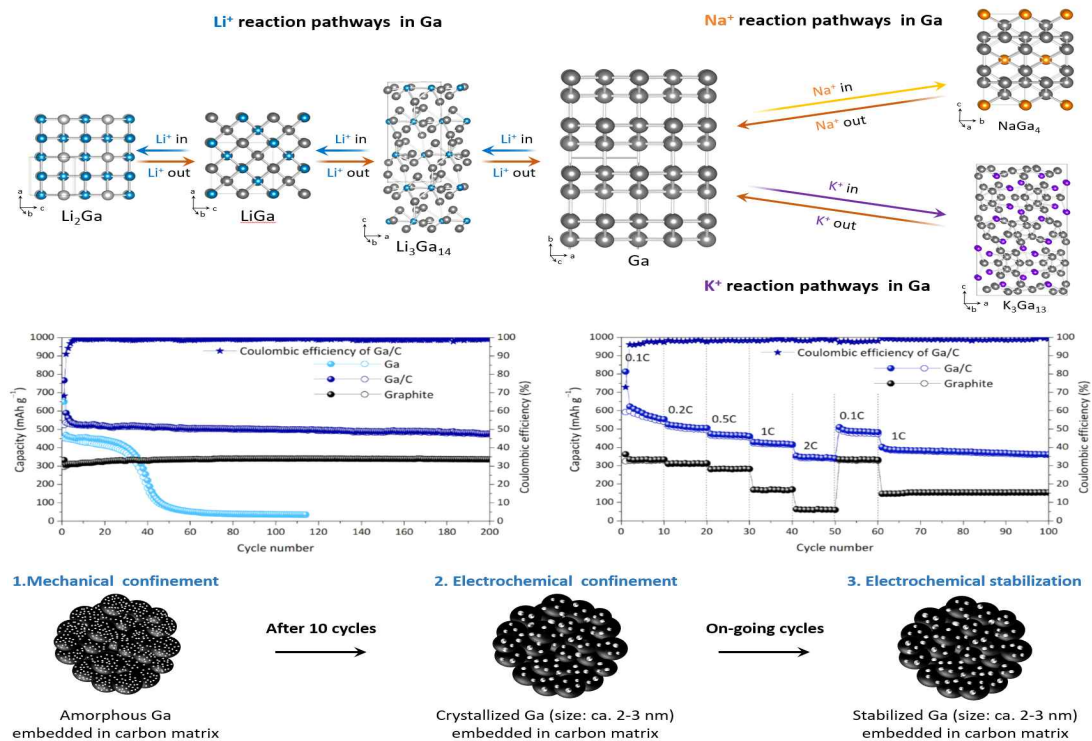
## 에너지저장

Journal of Energy Storage

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## Li/Na/K-ion reaction pathways in Ga and high-performance amorphous Ga composite anodes for Li-ion batteries

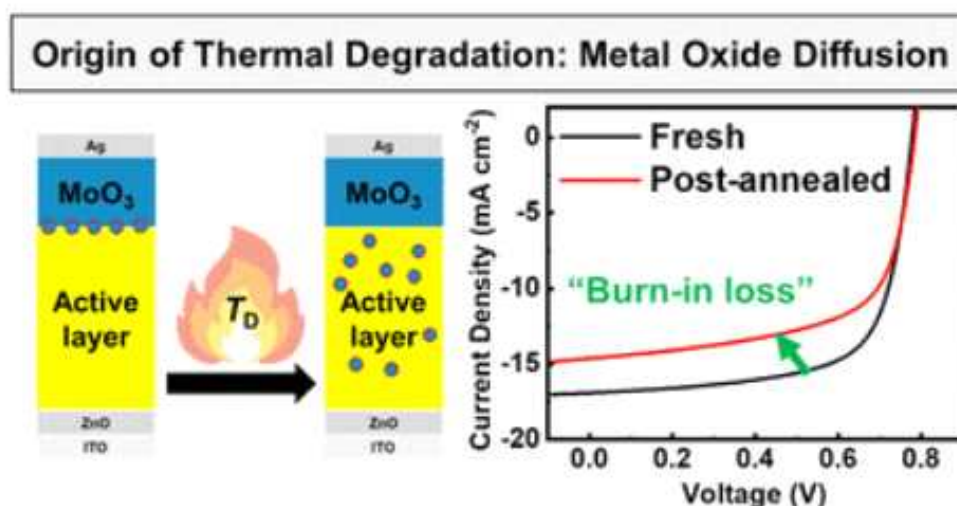
Young-Han Lee, In-Su Hwang, Jeong-Hee Choi\*, Cheol-Min Park\*



To achieve high-performance Ga anodes for alkali-ion batteries, the electrochemical Li/Na/K-ion reaction pathways in Ga are thoroughly elucidated using ex situ analytical tools. Ga exhibits a high Li-ion storage reaction owing to the formation of Li<sub>2</sub>Ga (theoretical capacity: 769 mAh g<sup>-1</sup>). However, it exhibits poor Na- and K-ion storage reactions owing to the formation of NaGa<sub>4</sub> (theoretical capacity: 96 mAh g<sup>-1</sup>) and K<sub>3</sub>Ga<sub>13</sub> (theoretical capacity: 89 mAh g<sup>-1</sup>), respectively. The high Li-ion storage reaction in Ga demonstrates its potential as an anode for Li-ion batteries (LIBs). Therefore, we fabricate an amorphous Ga composite (Ga/C) comprising amorphous Ga homogeneously distributed in an amorphous carbon using a simple one-pot solid-state mechanical process. Ga/C exhibits high reversible capacity, long-term Li-ion storage stability, and high rate capability. In addition, three-step confinement of amorphous Ga in the composite during continuous cycling is demonstrated and suggested as an enhancement mechanism for high-performance Ga/C anodes for LIBs. The interesting Li-ion storage reaction in Ga and high-performance amorphous Ga composites are expected to be highly applicable to LIB anodes.

## Impact of metal oxide diffusion and materials design on thermal stabilities of non-fullerene polymer solar cells

Dongmin Lee, Yongchan Jang, Jeonga Kim, Sang Young Jeong, Han Young Woo, Donggu Lee, Jongbok Kim, Youngmin Lee, Changyeon Lee\*, and Wonho Lee\*



Non-fullerene acceptor-based polymer solar cells (NFA-PSCs) can exhibit high morphological stability under thermal stress, often resulting in the fabrication of thermally stable NFA-PSCs. Here, our stability study with systematic steps shows that high morphological stability of active layers does not necessarily guarantee high thermal stability for NFA-PSCs. Furthermore, a degradation pathway is elucidated by using two NFA-PSCs comprising well-known polymer donors and non-fullerene acceptors such as PTB7-Th, PBDB-T-2Cl, and ITIC-4F. Morphologies of the PTB7-Th:ITIC-4F and PBDB-T-2Cl:ITIC-4F blends are highly stable at a high temperature of 110  $^{\circ}\text{C}$ . However, the corresponding NFA-PSCs degrade severely at the same temperature. For example, all the NFA-PSCs show an efficiency reduction of greater than 30% within an hour, particularly owing to the significant decrease in the short-circuit current density (JSC) and fill factor (FF). A series of experiments, including time-of-flight secondary ion mass spectrometry measurements, demonstrate that the penetration of metal oxide molecules into the photoactive layer occurs upon heating, resulting in degradation. The diffused molecules can act as charge recombination centers, leading to decreases in JSC and FF. Finally, we provide insights, from a material design perspective, into the prevention of undesirable penetration of metal oxide molecules.

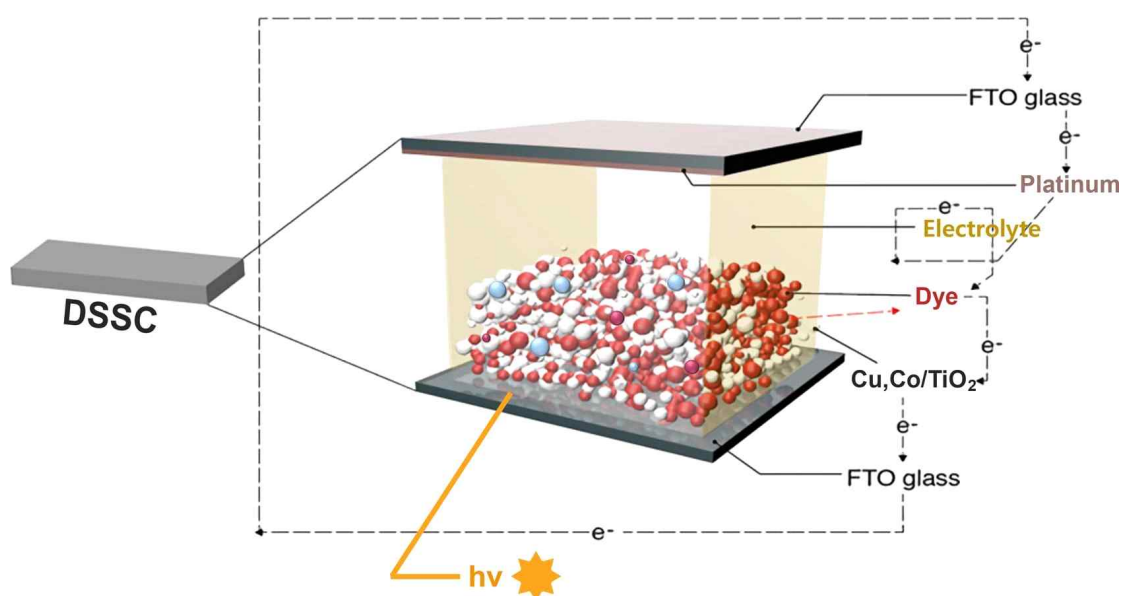


Applied Surface Science

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## Efficiency improvement of dye-sensitized solar cells using Cu,Co/TiO<sub>2</sub> photoelectrodes doped by applying ultrasonic treatment

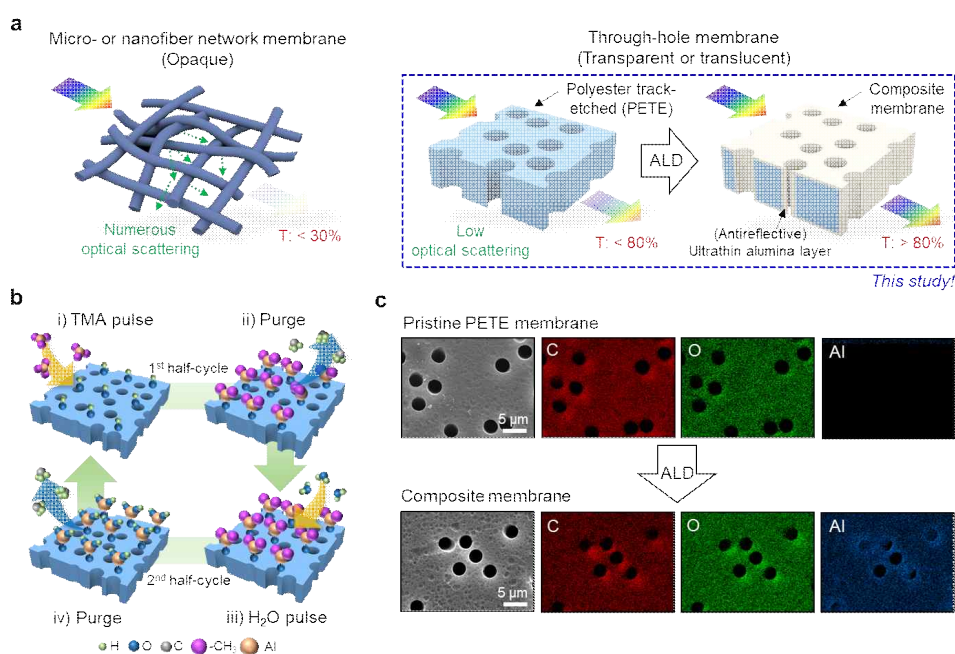
Jae-hun Bae, Hwang-Ju Jeon, Sung-Ho Cho, Yong-beom Cho, Sung-Eun Lee, Tae-Oh Kim



In this study, a dye-sensitized solar cell (DSSC) doped with Cu, Co was fabricated by simultaneously sonicating TiO<sub>2</sub> and a trace amount of a transition metal precursor. The cavitation bubbles occurred during sonication resulted in defects on the surface of the TiO<sub>2</sub> particles. As ultrasonic treatment was applied, doping was successfully performed even though Cu and Co were added in small amounts. The surface activation of TiO<sub>2</sub> was confirmed by performing XPS, and the doping of Cu and Co was verified by employing TEM-EDS analysis. Fabricating doped TiO<sub>2</sub> as a photoelectrode and analyzing it using UV-Vis spectroscopy demonstrated that the amount of dye adsorption was significantly increased. In addition, the reduction in electron transfer resistance was confirmed by applying EIS, and the factors contributing to efficiency improvement were investigated by calculating the chemical capacitance and recombination resistance. The maximum energy-conversion efficiency of the DSSCs fabricated by TiO<sub>2</sub> which doped with Cu and Co by ultrasonic treatment was 4.16%, and that of the DSSCs fabricated with TiO<sub>2</sub> not doped with a transition metal was measured at 2.93%. As above, TiO<sub>2</sub> was doped with a transition metal using ultrasonic treatment, contributing to the improvement of the performance of the TiO<sub>2</sub> photoelectrode.

## Through-hole composite membrane with an ultrathin oxide shell for highly robust and transparent air filters

Taehyun Ryu, Junyong Ahn, Junyong Park\*



Exploring pore structures that are optically transparent and have high filtration efficiency for ultrafine dust is very important for realizing passive window filters for indoor air purification. Herein, a polyester track-etched (PETE) membrane with vertically perforated micropores is investigated as a cost-effective candidate for transparent window filters. The pore size, which governs transparency and filtration efficiency, can be precisely tuned by conformally depositing an ultrathin oxide layer on the PETE membrane via atomic layer deposition. The maximum visible light transmittance ( $\sim 81.2\%$ ) was achieved with an alumina layer of approximately 55 nm, and the resulting composite membrane exhibited competitive filtration efficiency compared to commercial products. The chemically inert alumina layer also increased resistance to various external stimuli and enabled simple cleaning of the contaminated membrane surface with a solvent. The membrane installed on an insect screen effectively maintained its filtration performance ( $\sim 85\%$  for PM<sub>2.5</sub>) even after 10 reuse cycles under extremely harsh conditions (PM<sub>2.5</sub> concentration:  $\sim 5000\ \mu\text{g cm}^{-3}$ ). The proposed through-hole composite membrane can expand the choice of aesthetic window filters to situations that require high outside visibility and daylighting.

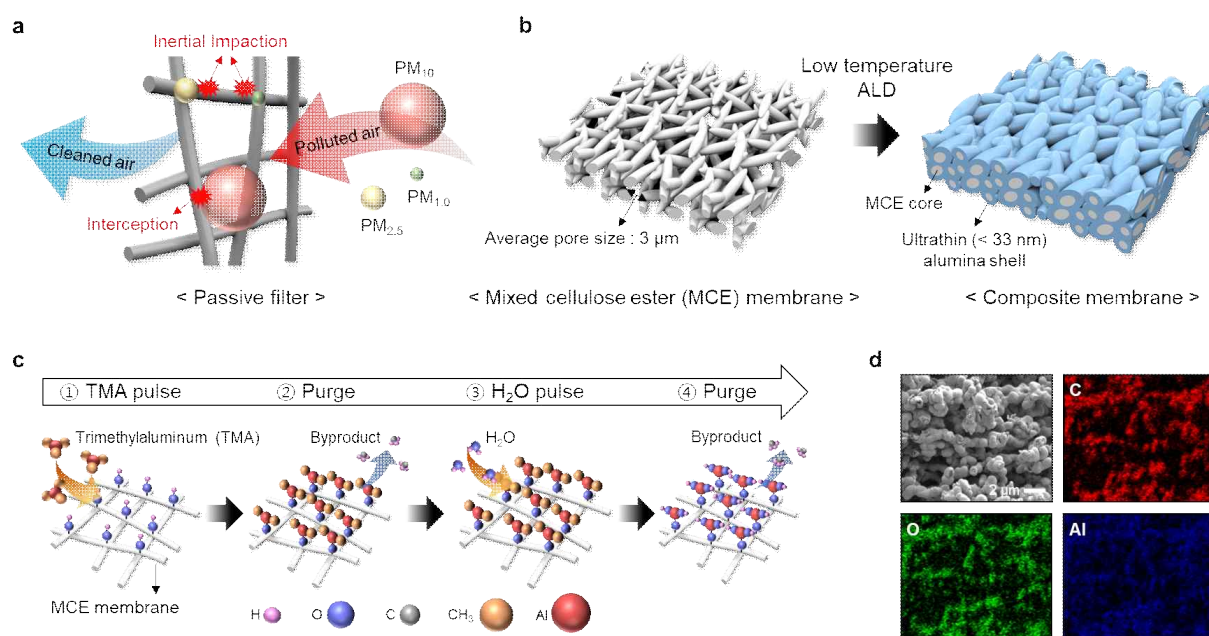
## 환경에너지

### Separation and Purification Technology

volume 309, Merch 2023, p123012 (Impact Factor : 9.136)

## Core-shell structured, mixed cellulose ester-alumina composite membranes for air filters with improved environmental resistance

Junyong Ahn, Hyunsol Park, Taehyun Ryu, Junyong Park\*



In this study, a composite membrane was developed by conformally coating an ultrathin Al<sub>2</sub>O<sub>3</sub> layer through low-temperature (90 °C) atomic layer deposition (ALD) on a hydrophilic mixed cellulose ester (MCE) membrane with a 3D networked microporous structure. The thickness of the deposited Al<sub>2</sub>O<sub>3</sub> layer, without clogging the pores of the membrane, was precisely controlled by varying the number of ALD cycles from 100 to 300. The ultrathin (~33 nm) Al<sub>2</sub>O<sub>3</sub> layer greatly enhanced the resistance to various environmental stimuli and contributed to the improved removal efficiency of airborne particulate matter (PM), owing to the reduced pore size. The resulting composite membrane installed on an insect screen exhibited excellent removal efficiency (>99%) for PM of various sizes (PM<sub>1.0</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>) at a controlled flow rate of 1 L/min. In particular, unlike polypropylene-based commercial PM filters that strongly rely on electrostatic adsorption for PM filtration, the reduction in the PM removal efficiency caused by water or ethanol was negligible in the developed composite membrane, enabling long-term use even in extreme environments.