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Low temperature fabrication of Fe₂O₃ nanorod film coated with ultra-thin g-C₃N₄ for a direct z-scheme exerting photocatalytic activities†

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We engineered high aspect ratio Fe₂O₃ nanorods (with an aspect ratio of 17 : 1) coated with g-C₃N₄ using a sequential solvothermal method at very low temperature followed by a thermal evaporation method. Here, the high aspect ratio Fe₂O₃ nanorods were directly grown onto the FTO substrate under relatively low pressure conditions. The g-C₃N₄ was coated onto a uniform Fe₂O₃ nanorod film as the heterostructure, exhibiting rational band conduction and a valence band that engaged in surface photoredox reactions by a direct z-scheme mechanism. The heterostructures, particularly 0.75g-C₃N₄@Fe₂O₃ nanorods, exhibited outstanding photocatalytic activities compared to those of bare Fe₂O₃ nanorods. In terms of 4-nitrophenol degradation, 0.75g-C₃N₄@Fe₂O₃ nanorods degraded all of the organic pollutant within 6 h under visible irradiation at a kinetic constant of $12.71 \times 10^{-3} \text{ min}^{-1}$, about 15-fold more rapidly than bare Fe₂O₃. Further, the hydrogen evolution rate was $37.06 \mu\text{mol h}^{-1} \text{ g}^{-1}$, 39-fold higher than that of bare Fe₂O₃. We suggest that electron and hole pairs are efficiently separated in g-C₃N₄@Fe₂O₃ nanorods, thus accelerating surface photoreaction *via* a direct z-scheme under visible illumination.

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1. Introduction

Efforts to replace traditional fossil fuels are increasing because of the energy crisis and environmental contamination.^{1,2} One of the many fascinating green technologies is photocatalytic degradation of organic pollutants and sustainable hydrogen production employing solar energy.^{3–5} Many inorganic,⁶ organic,⁷ metal,⁸ metal oxide,^{9–13} and non-metal¹⁴ materials have been used to reduce wastewater pollution and generate sustainable energy. However, the rapid recombination rates of charge carriers on catalytic surfaces reduce the photocatalytic efficiencies of single-component catalysts. Thus, semiconductor-based photocatalysts have received considerable attention; heterostructures of many materials afford reasonable band levels, maximizing rapid photocatalysis.^{15–18} As the conduction and valence band levels differ, electron/hole pairs created using solar energy do not readily combine, improving photocatalytic performance. Nevertheless, heterostructure photo-oxidation/reduction reactions are

compromised by the short energy bands of heterostructures compared to single-phase materials.¹⁹

The direct z-scheme, which recombines weaker oxidative holes and reductive electrons from semiconductors, has emerged as a major research area because the scheme may improve surface charge transfer and separation.^{20–22} Various direct z-scheme photocatalysts have been studied, including g-C₃N₄/Ag₃PO₄,²³ Fe₂O₃/Cu₂O,²⁴ and Bi₂O₃/g-C₃N₄.²⁵ However, these heterostructures lack stability when exposed to sunlight and are difficult to synthesize. Useful heterostructures would be simply synthesized and exhibit excellent stability.

Recently, graphitic carbon nitride (g-C₃N₄), a polymeric non-metallic semiconductor, has been widely studied as a photocatalyst. Fabrication is inexpensive and simple, the material is carbon/nitrogen-rich and is non-toxic.²⁶ Furthermore, g-C₃N₄ exhibits a band gap of 2.6 eV, which is eminently suitable in terms of pollutant degradation and hydrogen evolution.^{27–29} However, pure g-C₃N₄ exhibits rapid recombination of photo-generated electron/hole pairs, severely compromising photocatalytic activity. To reduce the recombination rate, heterostructures using different conduction and valence bands to host (reducing) electrons and (oxidizing) holes are required.^{30–34}

The transition metal oxide Fe₂O₃ can utilize solar light of wavelengths up to 600 nm; the band gap is ~ 2.1 eV. Thus, Fe₂O₃ exhibits great potential because of its low cost, abundance, and good chemical stability.³⁵ Moreover, Fe₂O₃ has a 2.38 eV valence

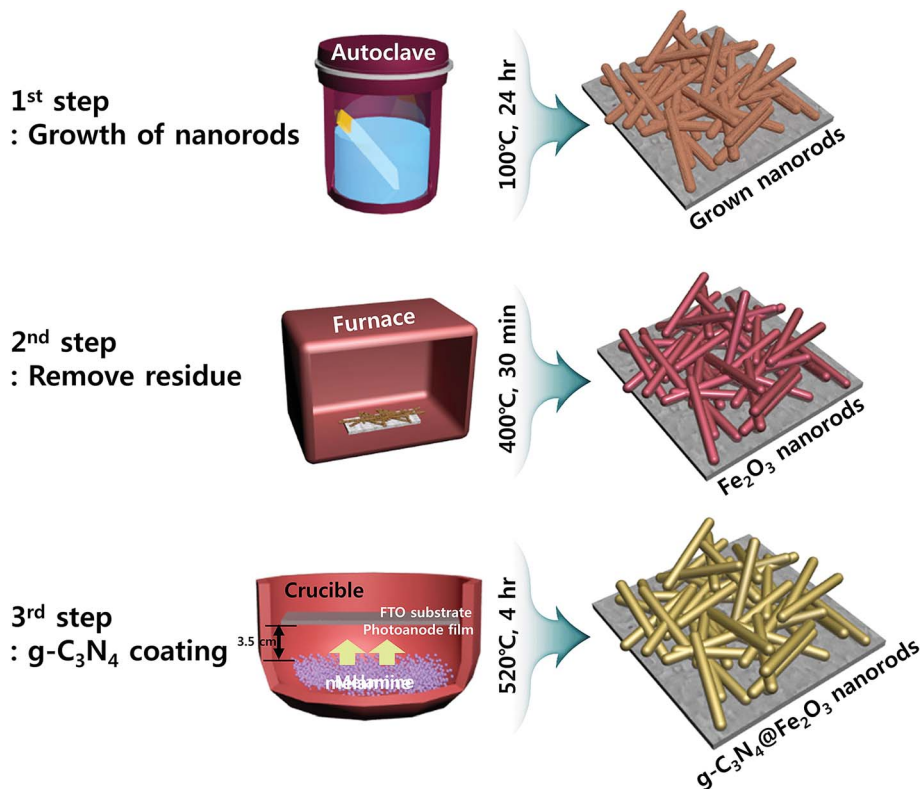
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Scheme 1 Fabrication of facile and simple heterostructures of g-C₃N₄@Fe₂O₃.

band that can be exploited by the direct z-scheme mechanism of photocatalysis; thus, Fe₂O₃ can serve as a photoactive material.³⁶ However, Fe₂O₃ has a short hole diffusion length and exhibits rapid charge recombination, rendering the photocatalytic efficiency low.³⁷ Therefore, Fe₂O₃ must be combined with other semiconductors in heterostructures featuring separation of electron/hole pairs, allowing photo-oxidation and reduction using the direct z-scheme system.

Many Fe₂O₃/g-C₃N₄ heterostructures, including powder-like bulk composites, have been developed to eliminate organic pollutants and evolve H₂ under visible irradiation.^{38–41} However, such heterostructures, when exposed to solar illumination, exhibit gradual reductions in electron movement, compromising photocatalysis compared to that of one-dimensional (1D) structures.⁴² To overcome this problem, we fabricated g-C₃N₄@1D Fe₂O₃ nanorods using the simplest procedure; *In situ* growing of high aspect ratio of Fe₂O₃ nanorods with solvothermal method at 100 °C for 24 hours was followed by ultrathin coating of g-C₃N₄ layer using melamine precursors with thermal evaporation method to degrade 4-nitrophenol (4-NP) and evolve H₂. The prepared 1D Fe₂O₃ nanorods coated with ultra-thin g-C₃N₄ layers can be fabricated in a straightforward, cost-effective manner to show the direct z-scheme system. We explored the physicochemical properties of our materials and optimized the g-C₃N₄@Fe₂O₃ nanorods in terms of photocatalysis; we then compared the materials to that of bare Fe₂O₃ nanorods for its potential application in photocatalytic fields such as H₂ evolution, artificial photosynthesis or even more electrocatalysts and battery applications.

2. Experimental

2.1 Materials

We used the Fe₂O₃ precursor ferric chloride (FeCl₃) and the g-C₃N₄ precursor melamine (Junsei, Japan). Sodium nitride (NaNO₃), hydrochloric acid (HCl), acetonitrile, sodium sulfate (Na₂SO₄) and hydrogen peroxide (H₂O₂) were all purchased from Daejung (Korea). Triethanolamine (TEOA) (Samchun, Korea) and H₂PtCl₂ (Sigma-Aldrich, USA) were used to trigger H₂ evolution. Conductive fluorine-doped tin oxide (FTO, 15 mΩ) served as the photoanode film. *p*-nitrophenol was purchased from Kanto (Japan). All chemicals were used without further purification.

2.2 Preparation of a Fe₂O₃ photoanode and g-C₃N₄ coating

Fe₂O₃ photoanodes were prepared on FTO substrates using a solvothermal method under relatively low pressurized condition.⁴³ Conventionally, pressurized condition is mostly used for fabrication of Fe₂O₃ photoanodes. However, we have developed relatively low pressure process to fabricate high aspect ratio of nanorods (almost 17 : 1) film with extreme uniformity onto FTO substrate through *in situ* process. Prior to Fe₂O₃ growth, the substrates were sequentially cleaned with acetone, ethanol, and distilled water with sonication for 5 min each time and dried in an oven. 0.2 M FeCl₃ was dissolved in 35 mL of distilled water while 1.4 M NaNO₃ and 0.5 mL of HCl were added. After complete dissolution, 15 mL of acetonitrile was added and this mixture was stirred for 30 min. Plasma-enhanced chemical vapor deposition (PECVD) was used to perform O₂ plasma



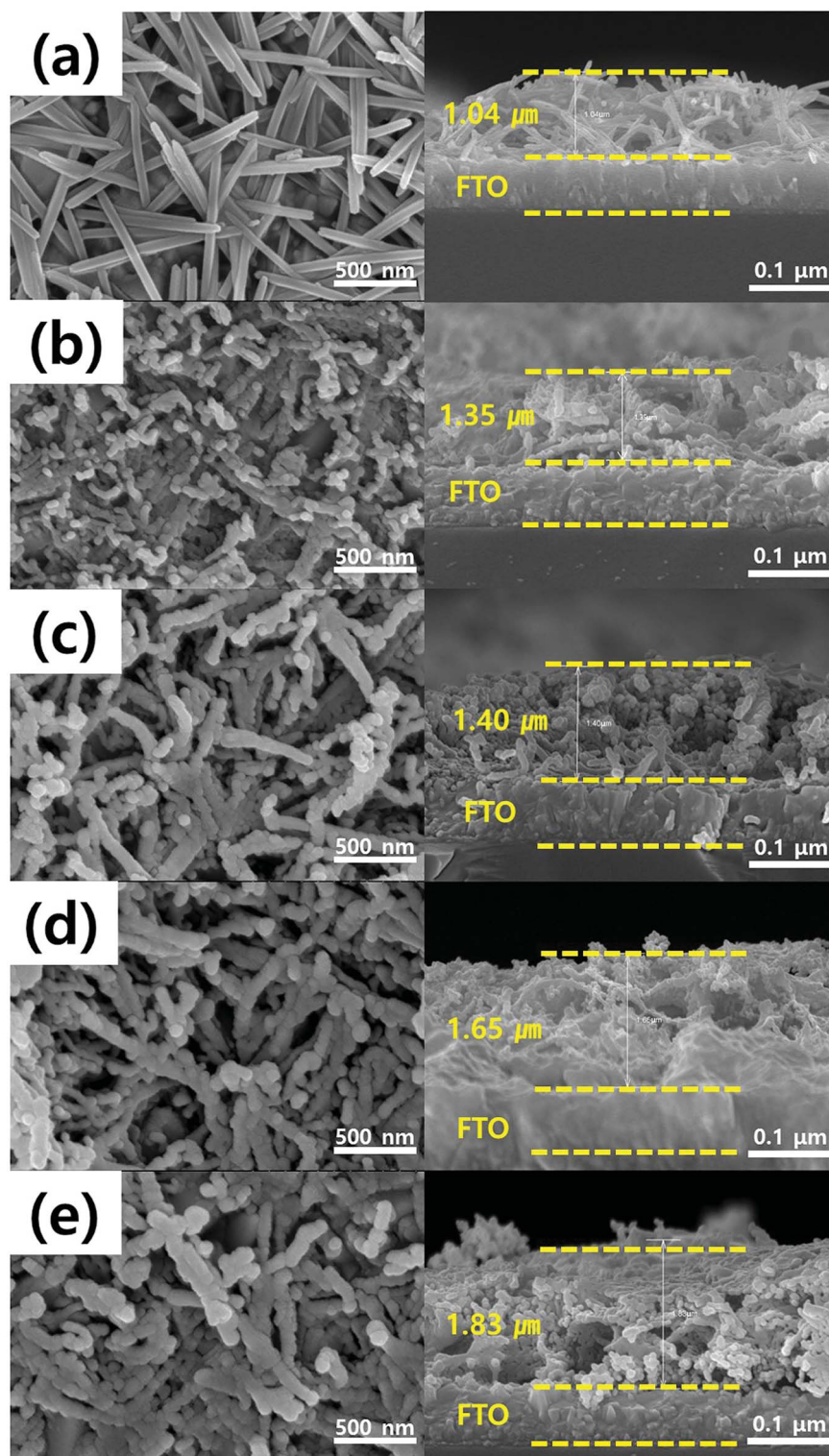


Fig. 1 SEM micrographs of (a) bare Fe_2O_3 , (b) $0.25\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$, (c) $0.5\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$, (d) $0.75\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$, and (e) $1\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$; cross-sections (right-hand) and surface views (left-hand).

treatment, removing any pollutants. The solution described above was transferred to 100 mL of Teflon-lined molds and held at $100\text{ }^\circ\text{C}$ for 24 h in a box furnace. Afterwards, the film was taken out from the mold and dried at ambient atmosphere. Then, the dried film was annealed at $400\text{ }^\circ\text{C}$ for 30 min and

washed several times with distilled water in order to remove any residues left on the top of the film. Fig. S1(b)[†] shows no transformation of this material to hematite phase after annealing at $400\text{ }^\circ\text{C}$ since no peak for hematite is detected. In order to make successful transformation to hematite Fe_2O_3



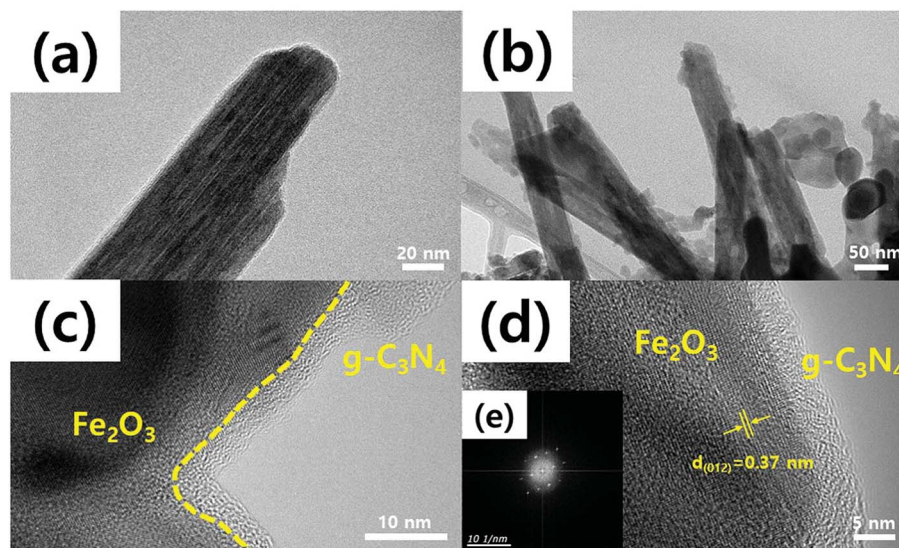


Fig. 2 Transmission electron microscopy (TEM) images of (a) bare Fe₂O₃ nanorods and (b) 0.75g-C₃N₄@Fe₂O₃. (c) High-magnification image of the g-C₃N₄ coating layer on Fe₂O₃ nanorods. (d) The lattice distance of Fe₂O₃ and (e) the fast Fourier transform (FFT) [inset in (d)].

phase, this washed film was annealed again at 520 °C for 4 h where this is denoted as “bare Fe₂O₃” for clarification. To coat the photoanodes with a g-C₃N₄ layer to form heterostructure, various amounts of melamine (0.25, 0.5, 0.75, and 1 g) in powder form were used in alumina crucible for optimization of heterostructure. Photoanode film was placed 3.5 cm apart from the melamine powders, facing each other in the crucible as shown in Scheme 1. Then, the melamine powders were sintered and coated on the surface of the photoanode film through thermal evaporation method at 520 °C for 4 h (10 °C min⁻¹). Finally, g-C₃N₄-coated photoanode films were successfully obtained by this evaporation of melamine powders as the overall procedure is represented in Scheme 1.

2.3 Evaluation of photocatalytic activity

Photocatalytic activity was evaluated using 0.02 mM 4-NP in distilled water. The g-C₃N₄@Fe₂O₃ photoanode films were placed in 250 mL amounts of this solution and 0.5 mL of H₂O₂ was added prior to illumination to accelerate catalytic activity, followed by stirring for 30 min in the dark. The H₂O₂ is used to produce hydroxyl radical (\cdot OH) and OH⁻ species, reducing Fe³⁺ to Fe²⁺ under light condition.⁵¹ Then, 300W Xe arc lamp (>400 nm cut-off filter) was used to illuminate the solution while amount of 3 mL was collected every 1 h until the degradation was complete.

2.4 Photoelectrochemical performance

Photoelectrochemical (PEC) performance was evaluated using a three-electrode in quartz cell. Graphite and Ag/AgCl served as the counter-electrode and reference electrode, respectively. The electrolyte solution was 0.5 M Na₂SO₄ and PEC performance was analyzed using a Xe arc lamp (300 W, model 66984; Oriel, USA) with cut-off filter (>400 nm). A transient photocurrent was applied at 1 V of bias potential *versus* the Ag/AgCl reference

electrode, with light-chopping every minute to allow the response to be observed. Stability testing was performed for 40 h under the same conditions. Linear sweep voltammetry (LSV) was performed at a 20 mV s⁻¹ scan rate from -1 to 1 V. Electrochemical impedance spectroscopy (EIS) was performed from 10⁵ to 0.01 Hz at an amplitude of 20 mV under both dark and light conditions.

2.5 Photocatalytic H₂ production

Photocatalytic H₂ evolution was assessed with the aid of a 250 mL quartz reactor in a closed-gas system under visible illumination. The light source was a 300 W Xe arc lamp fitted with an ultraviolet (UV) cut-off filter (>400 nm), thus delivering only visible light. 10 mg of as-prepared catalytic powder were dispersed in 135 mL of distilled water until they are completely mixed. Then, 9 vol% of TEOA was added into that of aqueous solution to be acted as hole capture. A 1 wt% Pt solution served as the co-catalyst *via in situ* photodeposition. The solutions were uniformly dispersed prior to reaction. The suspension was then transferred to the quartz reactor and purged with N₂ gas to remove O₂. The reactor was sealed with a septum and purged with Ar gas to completely eliminate all air. Evolved gas was detected by a pulsed discharge detector fitted to a gas chromatograph (model 6500GC; YL Instruments, Korea); helium served as the carrier gas.

2.6 Characterization

g-C₃N₄ and Fe₂O₃ morphologies were studied using a scanning electron microscope (SEM; model S4800; Hitachi, Japan) and a transmission electron microscope (TEM) (model JEM 2100F; JEOL, Japan). The crystalline structure and other properties of the Fe₂O₃ phase were analyzed by X-ray diffraction (XRD) (D/Max-2500/PC instrument; Rigaku, USA; Cu-K α source), Fourier-transform infrared spectroscopy (FTIR) (iS10



instrument; Thermo Fisher Scientific, UK), and X-ray photoelectron spectroscopy (XPS) (Sigma Probe instrument, Thermo Fisher Scientific; Al K α source); these modalities were also used to confirm the presence of g-C₃N₄ coatings. The band gap energy was calculated *via* UV-visible spectroscopy (UV-Vis) (model V650; JASCO, Japan). Photoluminescence (PL) (SC-100 instrument; Dongwoo, Korea) and Raman spectroscopy (S-Ram instrument; Dongwoo) were employed to monitor the recombination rate of Fe₂O₃ and g-C₃N₄ under light excitation at 325 nm. All PEC analyses were performed using a potentiostat (Versastat 4 instrument; Princeton Applied Research, USA). The absorbances of photocatalytically degraded solutions were measured *via* UV-Vis spectroscopy.

3. Results and discussion

3.1 Morphology

We fabricated heterostructures using sequential solvothermal and thermal evaporation methods. We obtained top and cross-sectional views to explore how morphologies varied by the extent of coating. Prior to structural observations, chemically grown photoanode films were annealed first at 400 °C for 30 min and then washed several times with distilled water to remove any residue within nanorods that might interfere with electron transfer. As a result, the microstructure showed that the residue was perfectly removed while these nanorods are still strongly attached to the FTO substrate even after washing (Fig. S1(a)†). However, the annealing process at 400 °C for 30 min followed by washing treatments did not convert its structural phase into hematite phase since high intensity of NaNO₃ peaks (JCPDS no. 36-1474) and SnO₂ peaks (JCPDS no. 77-0451) were shown in Fig. S1(b).† To obtain pure hematite Fe₂O₃ nanorods, washed photoanode film was again annealed at 520 °C for 4 h. And finally, the bare Fe₂O₃ film was acquired.

As shown in Fig. 1(a), the FTO substrate contained only Fe₂O₃ nanorods, the surfaces of which were smooth. The observed high aspect ratio would be expected to improve electron transfer and photoactivity (Fig. S2†). After the g-C₃N₄ precursor was evaporated during optimum sintering at 520 °C, nano-sized, agglomerated g-C₃N₄ particles were clearly attached to the Fe₂O₃ nanorods. The thicknesses of these microstructures averaged around 1.5 μ m (from the bottom of the Fe₂O₃ nanorod to the top of the g-C₃N₄ coating). The thickness of the heterostructured films increased as the amount of the melamine precursor increased, from 0.25 to 0.5, 0.75 and 1 g, resulting in increasing thermal evaporation of g-C₃N₄ [Fig. 1(b)–(e)]. A previous study indicated that the precursor level should be varied to optimize the coating layer; thicker layers obstruct incident light and reduce activity.⁴⁵ We performed energy-dispersive spectroscopy (EDS) mapping to reveal the elements of g-C₃N₄@Fe₂O₃ heterostructures; these were (as expected) iron, oxygen, carbon, and nitrogen (Fig. S3†). For comparison, the bulk g-C₃N₄ was observed for its microstructures in terms of agglomeration, reducing the active site from surface area as well as blocking electron pathway under illumination as shown in Fig. S4.† We thus confirmed that well-formed g-C₃N₄@Fe₂O₃

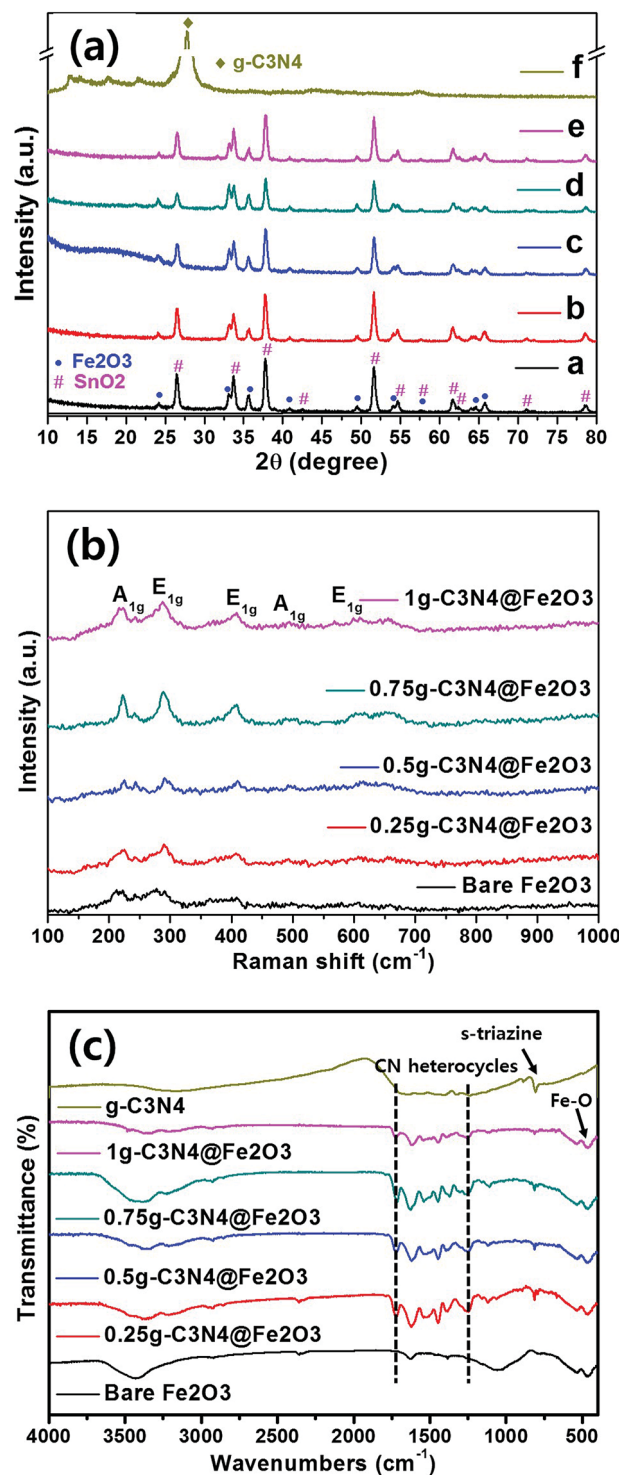


Fig. 3 (a) X-ray diffraction (XRD), (b) Fourier-transform infrared spectroscopy (FT-IR) and (c) Raman spectroscopy data for bare Fe₂O₃, 0.25g-C₃N₄@Fe₂O₃, 0.5g-C₃N₄@Fe₂O₃, 0.75g-C₃N₄@Fe₂O₃, 1g-C₃N₄@Fe₂O₃ and bulk g-C₃N₄.

heterostructures had been created *via* a simple chemical process.

The TEM was used to derive the precise dimensions of the Fe₂O₃ nanorods, the lattice distance, and the g-C₃N₄ thicknesses. Bare Fe₂O₃ nanorods were ~60 nm in diameter



[Fig. 2(a)]. All Fe₂O₃ nanorods had a high aspect ratio (16.7 : 1), enhancing the surface area and thus active sites. The TEM images of g-C₃N₄ coated onto Fe₂O₃ [Fig. 2(b) to (d)] showed that the Fe₂O₃ nanorods were fully covered with g-C₃N₄. Furthermore, the g-C₃N₄ coat was <10 nm in thickness, but this varied slightly because of yield effects during thermal evaporation. If g-C₃N₄ precursors are loaded onto Fe₂O₃ films to different extents under atmospheric conditions, g-C₃N₄ production levels will vary, affecting the final coating layers. Fast Fourier Transform (FFT) [Fig. 2(e)] revealed that the interplanar spacing in Fe₂O₃ was 0.37 nm, corresponding to the lattice distance of the (012) plane for Fe₂O₃. Thus, our heterostructures of 1D Fe₂O₃ nanorods covered with g-C₃N₄ sheets, were successfully synthesized using the relatively low pressurized solvothermal method which have shown good catalytic performance due to efficient separation of charge carriers right at the interface between g-C₃N₄ and Fe₂O₃, resulting in enhanced electron movements along with 1D structures.

3.2 Characterization

Fig. 3(a) shows the Fe₂O₃ crystallinities of bare Fe₂O₃ and all of the prepared heterostructures using XRD analysis. Distinct Fe₂O₃ peaks are evident at 24.10, 33.08, 35.61 and 51.58°, corresponding to the (012), (104), (110), and (116) planes, respectively. The structure was hematite in nature (α -Fe₂O₃), as indicated by the JCPDS 01-084-0306 criteria, and the Fe₂O₃ lattice constants were $a = b = 4.69 \text{ \AA}$ and $c = 13.83 \text{ \AA}$ in the hexagonal structure. In the heterostructures, the sharp diffraction peaks indicated high-level Fe₂O₃ crystallinity and no impurity peak was appeared. The photoanode films were subjected to XRD and the diffraction peaks of the SnO₂ phase were thus observed (JCPDS no. 01-070-6995). The peaks for bulk g-C₃N₄ were observed to be (100) and (002) planes at 13° and 27°, respectively as shown in Fig. S4(b).† The initial peak for (100) plane was presented as the in-plane structural packing of triazine and the other intense peak for (002) plane was presented as the inter-planar spacing from aromatic group of g-C₃N₄.⁴⁴ However, g-C₃N₄ was not detected by XRD; overall, the g-C₃N₄ loadings were relatively low in heterostructure films. Raman spectroscopy was used to identify characteristic Fe₂O₃ peaks [Fig. 3(b)]. Principal peaks were evident at 217, 290, 407, 493, and 603 cm⁻¹, corresponding to the A_{1g}, E_{1g}, E_{1g}, A_{1g}, and E_{1g} modes, respectively.⁴⁶ For the case of bulk g-C₃N₄, the intense peaks were observed at 483.2, 708.6, 754.4, 976.9, 1235.9, 1313.9 and 1566.8 cm⁻¹, relating g-C₃N₄ groups as shown in Fig. S4(c).† Among the Raman peaks, the peaks for g-C₃N₄ structures were presented at 483.2, 754.4, 976.9 and 1313.9 cm⁻¹.⁴⁷ Moreover, the initial peak of 708.6 cm⁻¹ was presented to be the *s*-triazine ring for g-C₃N₄ group. The peaks at 1235.9 and 1566.8 cm⁻¹ are observed to be the disorder in graphite structure and stretching mode in C=N bonding structure, respectively.⁴⁸ However, again, g-C₃N₄ peaks were not detected because the g-C₃N₄ levels were low. Therefore, we used FT-IR to analyze the molecular compositions. In Fig. 3(c), the Fe₂O₃ peaks at 534 and 467 cm⁻¹ correspond to stretching vibrations of the Fe-O bonds of FeO₆ octahedral and FeO₄

tetrahedral sites, respectively.⁴⁹ The bulk g-C₃N₄ was compared for its specific g-C₃N₄ patterns with ones for the heterostructures. The principal g-C₃N₄ peaks range from 1700 to 1200 cm⁻¹, corresponding to stretching vibrations of tri-*s*-triazine in the heterocyclic rings. In detail, the bands at 1448, 1370 and 1250 cm⁻¹ correspond to aromatic C-N stretching vibrations.⁵⁰ Furthermore, the band at 816 cm⁻¹ corresponds to the *s*-triazine unit of the graphite-like sp² bonding state. It is clearly confirmed that all g-C₃N₄ related peaks are shown in the as-fabricated heterostructures as well as bulk g-C₃N₄. Moreover, broad peaks at 3500–3000 cm⁻¹ corresponded to N-H and O-H stretching vibrations caused by surface adsorption of H₂O.⁵¹ Thus, we have confirmed the presence of g-C₃N₄ on Fe₂O₃.

To explore the relationship between the C and N elements and Fe, XPS was performed as shown in Fig. 4. The typical Fe 2p spectrum of bare Fe₂O₃ features two different peaks (Fe 2p_{1/2} and Fe 2p_{3/2}) of binding energies 709.0 eV and 722.8 eV, respectively [Fig. 4(a)]. Between these peaks, a satellite Fe³⁺ peak is apparent. In the O 1s spectrum, bare Fe₂O₃ exhibits principal peaks at 528.0 eV, 528.2 eV, 529.9 eV, and 531.5 eV, which are mainly attributable to Fe-O bonding, lattice oxygen, the hydroxyl group, and surface-absorbed H₂O, respectively [Fig. 4(b)].⁴⁴ Fig. 4(c) shows the 0.75g-C₃N₄@Fe₂O₃ Fe 2p spectrum (peaks at 708.9 eV for Fe 2p_{1/2} and 722.7 eV for Fe 2p_{3/2}) of the g-C₃N₄ coating. Fig. 4(d) shows similarly broad principal peaks at 528.0 eV, 529.0 eV, 529.7 eV, and 531.0 eV.⁵² As g-C₃N₄ coated Fe₂O₃, C 1s and N 1s spectra were detected. The C 1s spectrum exhibits binding energies at 286.5, 285.4, 284.3, and 282.7 eV, corresponding to sp²-hybridized carbon in the tri-*s*-triazine rings C=O, C-O, C-C and C=C bonding, respectively [Fig. 4(e)].^{53,54} In the N 1s spectrum [Fig. 4(f)], the binding energy peaks at 396.1, 397.7, and 399.6 eV correspond to sp²-hybridized nitrogen (C-N=C), tertiary nitrogen [N-(C)₃], and -NH₂ bonding, respectively, and were unique to the g-C₃N₄ moieties.⁴¹ Fig. 4(g) and (h) showed the C 1s and N 1s spectrums of bulk g-C₃N₄ for comparison, respectively. The bulk g-C₃N₄ shows three different peak positions at 288.5, 287.2 and 283.9 eV in C 1s spectrum. The peaks for 288.5 eV, 287.2 eV are for sp²-hybridized bonding of N-C=N in aromatic and C-N bonds in carbon species of bulk g-C₃N₄, respectively. The peak for 283.9 eV is assigned to the carbon contamination during the samples preparation. In N 1s spectrum, the main peak of 397.7 eV is ascribed to C=N-C bonding while the peak of 398.5 eV is ascribed to N-(C)₃ bonded group. The weaker peaks of 400.2 and 403.6 eV are attributed to amino functional groups in aromatic rings of g-C₃N₄ and π -excitation which is positively charged localization in heterocycles, respectively.⁶⁰ When the 0.75 g of melamine is coated onto Fe₂O₃ film to convert into g-C₃N₄ layer, the amounts of coating layer are considerably lower than that of bulk g-C₃N₄. Thus, the carbon and nitrogen spectrums of 0.75g-C₃N₄@Fe₂O₃ showed relatively low intensity compared to that of bulk g-C₃N₄ even though it represented the carbon and nitrogen-related bonding as shown in Fig. 4(e) and (f). Therefore, that obvious peak shift for C=N-C and N-(C)₃ at 397.7 and 398.5 eV suggest the chemically formed hetero-junctions between Fe₂O₃ and g-C₃N₄.



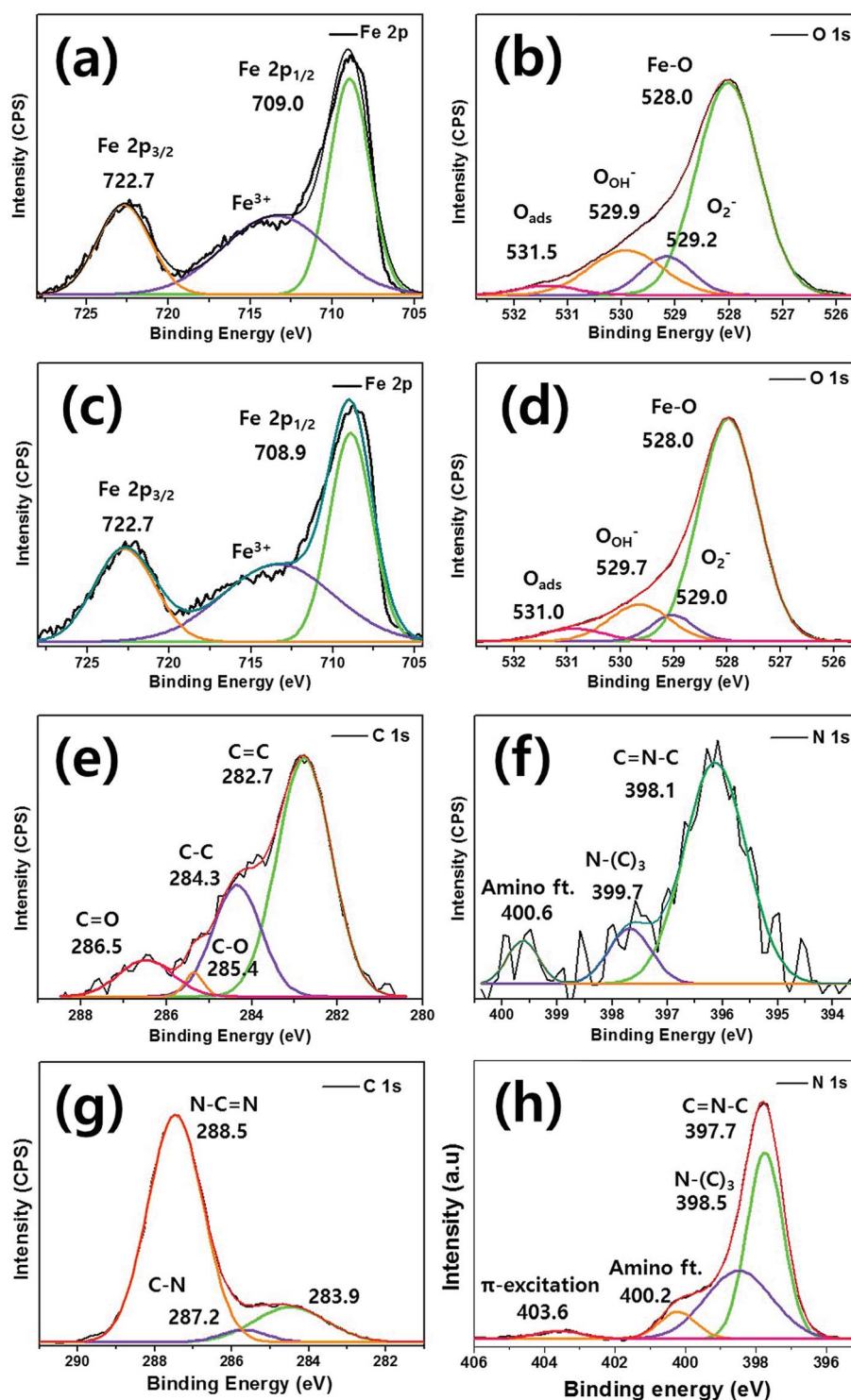


Fig. 4 The chemical binding energies evident on bare Fe_2O_3 spectra of (a) Fe 2p and (b) O 1s. The $0.75\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$ spectra of (c) Fe 2p, (d) O 1s, (e) C 1s, and (f) N 1s and bulk $\text{g-C}_3\text{N}_4$ spectra of (g) C 1s and (h) N 1s based on X-ray photoelectron spectroscopy (XPS) analysis-fitting results.

3.3 Optical properties

To study the absorbance ranges and band gap energies of the prepared films, the optical absorbance was measured from 300 to 800 nm as shown in Fig. 5(a). Bare Fe_2O_3 exhibited a slow absorption edge around 550 nm while the bulk $\text{g-C}_3\text{N}_4$ showed a steep absorption edge around 430 nm. However, when $\text{g-C}_3\text{N}_4$

was coated onto Fe_2O_3 films in different amounts, notable peaks were observed around 550 nm and the absorption edges became steeper because of $\text{g-C}_3\text{N}_4$ coating. Thus, all $\text{g-C}_3\text{N}_4/\text{Fe}_2\text{O}_3$ films exhibited higher absorption intensities than that of bare Fe_2O_3 during the entire UV-visible region, suggesting the enhancement of the absorption ability under



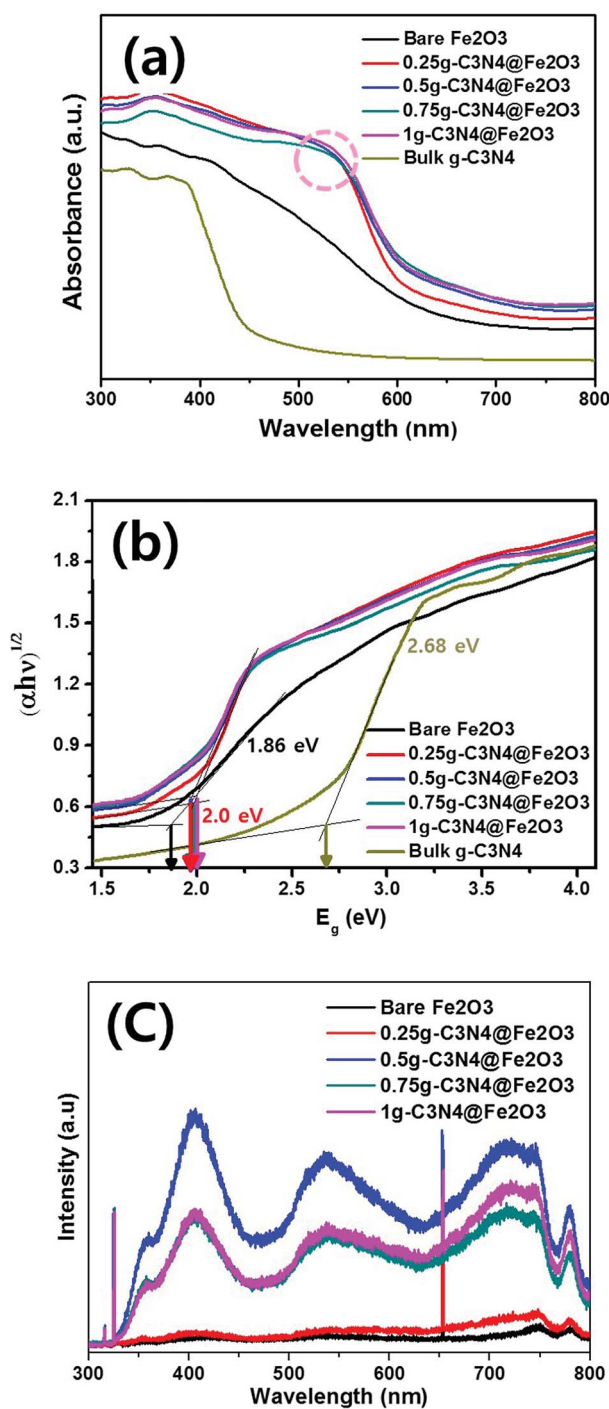


Fig. 5 Band gap energy measurement results based on (a) optical absorbances, (b) calculated absorbances, and (c) photoluminescence for bare Fe_2O_3 , $0.25\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$, $0.5\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$, $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$, $1\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ and bulk $\text{g-C}_3\text{N}_4$.

illumination. The absorbance was calculated into band gap energies using the Kubelka–Munk function in Fig. 5(b). Although there is a difference in the absorption edge, all $\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ films exhibited similar band gap energies of 2.0 eV. When the $\text{g-C}_3\text{N}_4$ is coated onto Fe_2O_3 nanorod film, the band gap difference has occurred for sure, compared to that of

bare Fe_2O_3 film of 1.86 eV. Based on calculated band gap of bulk $\text{g-C}_3\text{N}_4$, it exhibited 2.68 eV of band gap energy. Therefore, as-prepared heterostructure films provided the higher absorption intensity, with extending its utilization of light irradiation, compared to that of bare Fe_2O_3 , confirming successful formation of heterostructure film.

Fig. 5(c) shows PL spectra exploring recombination or transfer of photogenerated electrons and hole pairs between Fe_2O_3 and $\text{g-C}_3\text{N}_4$. Typically, large (>70 nm) nanomaterials do not exhibit PL since optical transition is not possible⁵⁵ and our Fe_2O_3 nanorods also did not show any significant emission peaks. In other words, $0.25\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ film also showed almost no PL emission peak possibly due to small amounts of $\text{g-C}_3\text{N}_4$ loading on bare Fe_2O_3 . The $0.5\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ showed the highest PL intensity among the samples because of the fast charge recombination. On the other hand, the 1g and $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ were observed with similar PL intensity while $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ showed lower intensity than that of $1\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$. This means that $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ makes good heterojunction of interfaces, reflecting effective separation of electron and hole pairs. Furthermore, the bulk $\text{g-C}_3\text{N}_4$ was measured for comparison as shown in Fig. S4(d).† As a result, it showed high PL intensity at 423 nm of wavelength, attributing to fast recombination rate of charge carriers in bulky structures. Of all the photoanodes, $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ associated with rapid electron movement and thus enhancement of PEC-mediated water splitting and photocatalytic performance.

3.4 Photoelectrochemical analysis

We used PEC analysis to evaluate photoresponses in the presence of 0.5 M Na_2SO_4 under visible illumination. Fig. 6(a) shows the transient photocurrents during light-chopping. The overall on–off cycles of all films are presented in Fig. S5(a).† During the on–off cycles, when the light was on, the film photoresponses were rapid. In the curves, the strong spikes in the light-on phases reflect electron–hole recombination on the surfaces during photocatalytic reactions. When recombination is slow, the spike peak is broad and the electron–hole combination exhibits a longer lifetime than that of the bare Fe_2O_3 film because of effective electron/hole separation during irradiation.⁵⁶ Of the various hybrid films, the $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ film exhibited slow and broad recombination, associated with a higher photocurrent (1.0 mA) than the other samples. Bare Fe_2O_3 exhibited almost no current (*ca.* 0.005 mA), whereas stepwise $\text{g-C}_3\text{N}_4$ coating increased the photocurrent proportionately (to 0.25g, 0.5g and 1g C_3N_4 values of 0.02, 0.06 and 0.09 mA, respectively). The photocurrent for bulk $\text{g-C}_3\text{N}_4$ was measured to be 0.04 mA under the same condition, exhibiting similar photocurrent with bare Fe_2O_3 and $0.25\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ film. As expected, the $0.75\text{g-C}_3\text{N}_4@/\text{Fe}_2\text{O}_3$ film exhibited the highest photocurrent because charge separation was effective; recombination was low after the light came on. Surprisingly, the current was about 200-fold that of the bare Fe_2O_3 film because of optimization of the $\text{g-C}_3\text{N}_4$ coating layer, suggesting that photogenerated electrons and hole pairs separated effectively



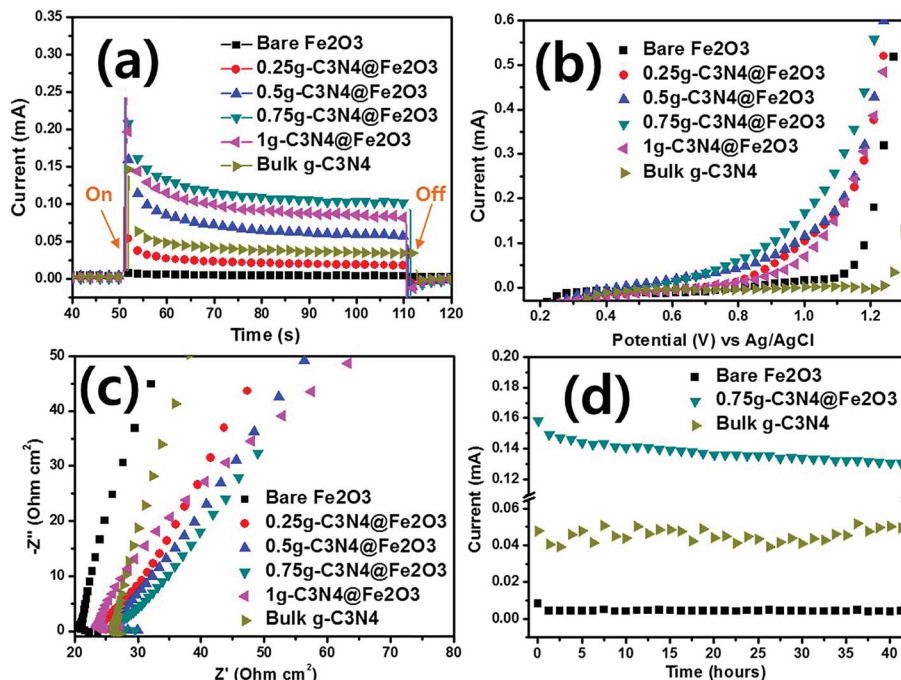


Fig. 6 (a) Photoresponse measurements of transient photocurrents with on/off light. (b) Linear sweep voltammetry (LSV) data. (c) Electrical impedance spectroscopy (EIS) data derived using bare Fe₂O₃, 0.25g-C₃N₄@Fe₂O₃, 0.5g-C₃N₄@Fe₂O₃, 0.75g-C₃N₄@Fe₂O₃, 1g-C₃N₄@Fe₂O₃ and bulk g-C₃N₄. (d) The photoresponse stability of bare Fe₂O₃ vs. 0.75g-C₃N₄@Fe₂O₃ vs. and bulk g-C₃N₄ under visible irradiation.

due to good formation of interface between g-C₃N₄ and Fe₂O₃ in heterojunctions.

The photocurrent *versus* applied potential curves of bare Fe₂O₃, and the various heterostructures, were assessed using

LSV under identical conditions. In the dark, no photoresponse attributable to hybridization was apparent [dashed line in Fig. S5(b)†].⁵⁷ In the light [Fig. 6(b)], the bare Fe₂O₃ and bulk g-C₃N₄ films produced almost no photocurrent according to

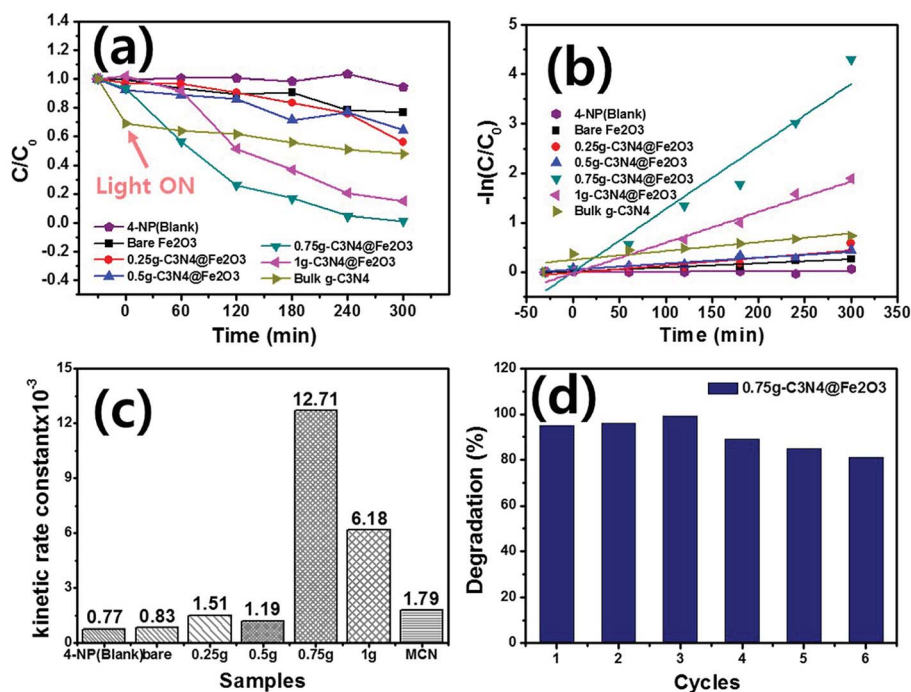


Fig. 7 Photocatalytic degradation of 4-nitrophenol (4-NP). (a) Relative absorbances. (b) Logarithms of absorbances. (c) Kinetic rate constants of 4-NP (blank), bare Fe₂O₃, 0.25g-C₃N₄@Fe₂O₃, 0.5g-C₃N₄@Fe₂O₃, 0.75g-C₃N₄@Fe₂O₃, 1g-C₃N₄@Fe₂O₃ and bulk g-C₃N₄. (d) Reusability testing of 0.75g-C₃N₄@Fe₂O₃ under visible irradiation.



applied potential *versus* Ag/AgCl. In contrast, the various hybrid films exhibited photocurrents. The photoresponses of the 0.25g, 0.5g, and 1g-C₃N₄@Fe₂O₃ films were similar. The 0.75g-C₃N₄@Fe₂O₃ film evidenced the highest performance at 1 V *versus* Ag/AgCl. Therefore, the g-C₃N₄ coat formed a useful heterojunction with Fe₂O₃, reducing the recombination rate of the charge carriers.

EIS was used to measure charge transfers from the g-C₃N₄@Fe₂O₃/electrolyte interface. In the dark, all films tested (bare Fe₂O₃ and the various heterostructures) exhibited higher impedances than in the light [Fig. S5(c)†]. Fig. 6(c) shows the impedances of all samples, where that of bare Fe₂O₃ was highest. In the light, the electrons and holes created favor the separation of charge carriers, reducing interface resistance. All g-C₃N₄-coated films exhibited smaller arc curves than that of bare Fe₂O₃ and bulk g-C₃N₄. The Fe₂O₃ and g-C₃N₄ themselves only, are difficult to overcome the high recombination rate, resulting in high resistance between photocatalysts and electrolyte. Of all films, the 0.75g-C₃N₄@Fe₂O₃ film exhibited the smallest arc radius, suggesting that the heterostructure can effectively support transfer of the abundant electrons, minimizing surface recombination losses and further improving photocatalytic activities.

After PEC evaluation, we performed stability testing under the conditions shown in Fig. 6(d). Only bare Fe₂O₃ and 0.75g-C₃N₄@Fe₂O₃ were subjected to such testing. The latter film remained photoresponsive to 40 h and bare Fe₂O₃ was not photoresponsive. The stability of bulk g-C₃N₄ was also conducted for comparison under visible light and it showed unstable photocurrent of 0.04 mA. Despite a slight decrease in the 0.75g-C₃N₄@Fe₂O₃ photocurrent over time, this remained higher than that of Fe₂O₃. Therefore, the 0.75g-C₃N₄@Fe₂O₃ film was an optimized heterostructure featuring Fe₂O₃ and g-C₃N₄ coating layers.

3.5 Photocatalytic degradation and scavenger test

Photocatalytic degradation of 4-NP by g-C₃N₄@Fe₂O₃ films under visible light was examined. In order to facilitate photocatalytic reactions, 0.5 mL of H₂O₂ was added into 4-NP solution since the 4-NP solution was not degraded at all without presence of H₂O₂ during photodegradation evaluation, as shown in Fig. S6.† Fig. 7(a) illustrates the relative absorbance of all samples by the extent of 4-NP degradation over time. The blank was a pure 4-NP solution (thus, assessing spontaneous degradation). Degradation commenced in the dark for 30 min to

Table 1 The kinetic constants of photocatalytic degradation

| | k min ⁻¹ | R ² |
|---|--------------------------|----------------|
| 4-Nitrophenol | 0.77 × 10 ⁻³ | 0.775685 |
| Bare Fe ₂ O ₃ | 0.83 × 10 ⁻³ | 0.90604 |
| 0.25g-C ₃ N ₄ @Fe ₂ O ₃ | 1.51 × 10 ⁻³ | 0.79317 |
| 0.5g-C ₃ N ₄ @Fe ₂ O ₃ | 1.19 × 10 ⁻³ | 0.87725 |
| 0.75g-C ₃ N ₄ @Fe ₂ O ₃ | 12.71 × 10 ⁻³ | 0.9439 |
| 1g-C ₃ N ₄ @Fe ₂ O ₃ | 6.18 × 10 ⁻³ | 0.95215 |
| Bulk g-C ₃ N ₄ | 1.79 × 10 ⁻³ | 0.78454 |

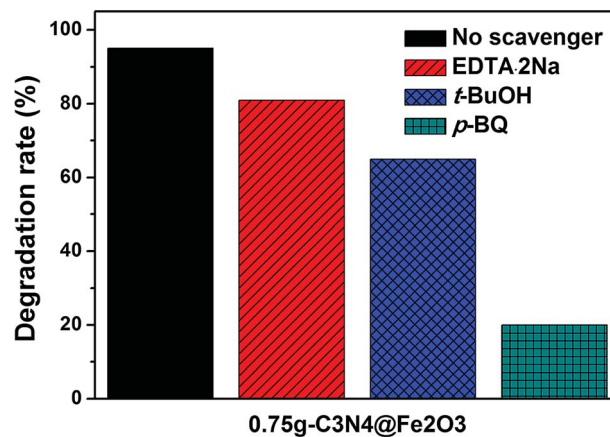


Fig. 8 The scavenger test of 0.75g-C₃N₄@Fe₂O₃ without radical trapping, EDTA·2Na, t-BuOH and p-BQ under visible irradiation.

confirm that adsorption was stable. As a result, few adsorption difference with negligible adsorption properties were observed under a dark state. When the visible light is illuminated, the catalysts started to remove the 4-NP organic pollutant with increasing time. Of the various films, the 0.75g-C₃N₄@Fe₂O₃ film exhibited the highest extent of degradation, removing all 4-NP by 300 min. The 1g-C₃N₄@Fe₂O₃ film also afforded rapid degradation because of the extensive g-C₃N₄ coating. However, the thick coating inhibited rapid transfer of solar energy into the catalyst; thus, the 0.75g-C₃N₄@Fe₂O₃ film was more effective than the 1g-C₃N₄@Fe₂O₃ film. In contrast, the 0.5g and 0.25g-C₃N₄@Fe₂O₃ films exhibited activities similar to that of bare Fe₂O₃ because the g-C₃N₄ coatings were thin.⁵⁸ Each absorbance graph monitored the 4-NP absorption peak at 325 nm (Fig. S7†). For comparison, the bulk g-C₃N₄ was performed for the photocatalytic degradation using 4-NP, exhibiting higher adsorption under the dark condition to be ~31% but showing almost no degradation for 4-NP. To study the kinetic rate, the 4-NP levels were log-transformed and plotted [Fig. 7(b)]. The degradation followed a pseudo first-order equation [the Langmuir-Hinshelwood (L-H) mechanism],⁵ mathematically denoted as follows:

$$-\ln(C/C_0) = kt \quad (1)$$

Based on eqn (1), plots of $-\ln(C/C_0)$ *versus* time were linear; k was the kinetic rate constant (min⁻¹) of catalytic degradation. The correlation coefficient R is shown in Table 1. The kinetic rate constant for 0.75g-C₃N₄@Fe₂O₃ ($12.71 \times 10^{-3} \text{ min}^{-1}$) was ~15-fold higher than that of bare Fe₂O₃ ($0.83 \times 10^{-3} \text{ min}^{-1}$) [Fig. 7(c)]. The k values for 4-NP degradation by 0.25g, 0.5g, 1g-C₃N₄@Fe₂O₃ and bulk g-C₃N₄ were 0.77×10^{-3} , 1.51×10^{-3} , 1.19×10^{-3} , $6.18 \times 10^{-3} \text{ min}^{-1}$ and $1.79 \times 10^{-3} \text{ min}^{-1}$, respectively. The reason for enhancement of photocatalytic degradation going from bare Fe₂O₃ and bulk g-C₃N₄ to g-C₃N₄@Fe₂O₃ heterostructure films, could be explained by the photoresponse result shown in Fig. 6(d). As shown in the figure, the heterojunction formed between g-C₃N₄ and Fe₂O₃ coated with g-C₃N₄, shows higher current than those of bare Fe₂O₃ and



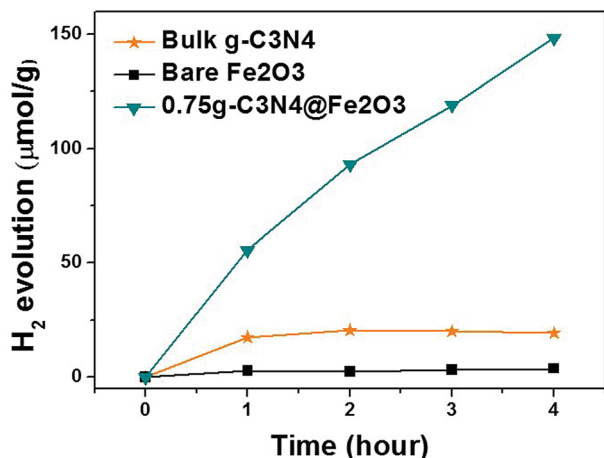


Fig. 9 Hydrogen evolution triggered by bulk g-C₃N₄ from melamine precursors, by bare Fe₂O₃, and by 0.75g-C₃N₄@Fe₂O₃ using Pt as the co-catalyst under visible irradiation.

bulk g-C₃N₄, due to the efficient separation of charge carriers as well as reducing recombination rates at its interface. Consequently, g-C₃N₄@Fe₂O₃ heterostructure film showed better photodegradation ability with higher kinetic rate constant compared to those of bare Fe₂O₃ and bulk g-C₃N₄ film. To explore the reusability of 0.75g-C₃N₄@Fe₂O₃ (which exhibited excellent performance), we recycled the film six times [Fig. 7(d)]. The extent of degradation was >80% after each recycle, indicating good reusability. Furthermore, new 0.75g-C₃N₄@Fe₂O₃ film was prepared to confirm the repeatability in photodegradation ability under the same condition as shown in Fig. S8.† As a result, it shows similar kinetic rate constant with its error range less than 10%. The 0.75g-C₃N₄@Fe₂O₃ film exhibited remarkable photocatalytic degradation of 4-NP, attributable to rapid separation of charge carriers at the g-

C₃N₄@Fe₂O₃ interface and thus promoting photo-oxidation to successfully remove the organic pollutant using a direct z-scheme pathway.

Prior to suggesting possible mechanism of these heterostructures, scavenger tests shown in Fig. 8, are performed to study the photocatalytic reaction in detail. For the photocatalytic activity, there are main free radicals as active species which are hole (h⁺), hydroxyl radical (·OH) and superoxide radical (·O₂⁻). To observe the radical trapping performances, 0.75g-C₃N₄@Fe₂O₃ film was used under light illumination. Here, EDTA·2Na was used to capture a h⁺, *tert*-butanol (*t*-buOH) was used for ·OH and *p*-benzoquinone (*p*-BQ) was used for ·O₂⁻. When the photodegradation rate of 0.75g-C₃N₄@Fe₂O₃ film itself was approximately 95%, EDTA·2Na and *t*-buOH scavengers showed 81% and 65% degradation rates, respectively, suggesting h⁺ and ·OH are not a crucial role in this photocatalytic activity. In contrast, *p*-BQ scavenger exhibited a significant decrease in 4-NP degradation of 20%. Therefore, it was confirmed that O₂⁻ is found to be the main active species that works for 0.75g-C₃N₄@Fe₂O₃ film.

3.6 Hydrogen evolution and its possible mechanism

We evaluated hydrogen evolution to further explore the photocatalytic activities of the films under visible illumination. Fig. 9 illustrates H₂ production by bulk g-C₃N₄, bare Fe₂O₃, and 0.75g-C₃N₄@Fe₂O₃ over 4 h. Only the 0.75g-C₃N₄@Fe₂O₃ film effectively evolved H₂; its performance in this context was excellent. Bulk g-C₃N₄, made using melamine as precursor and bare Fe₂O₃, evolved 4.79 μmol h⁻¹ g⁻¹ and 0.94 μmol h⁻¹ g⁻¹ H₂, respectively. However, the figure for 0.75g-C₃N₄@Fe₂O₃ was 37.06 μmol h⁻¹ g⁻¹, almost 39-fold that of bare Fe₂O₃. Generally, Fe₂O₃ does not produce H₂ because the conduction level of Fe₂O₃ is just below the proton reduction potential.⁵⁹ Even when Pt is added to bare Fe₂O₃ (as a co-catalyst), H₂ evolution remains

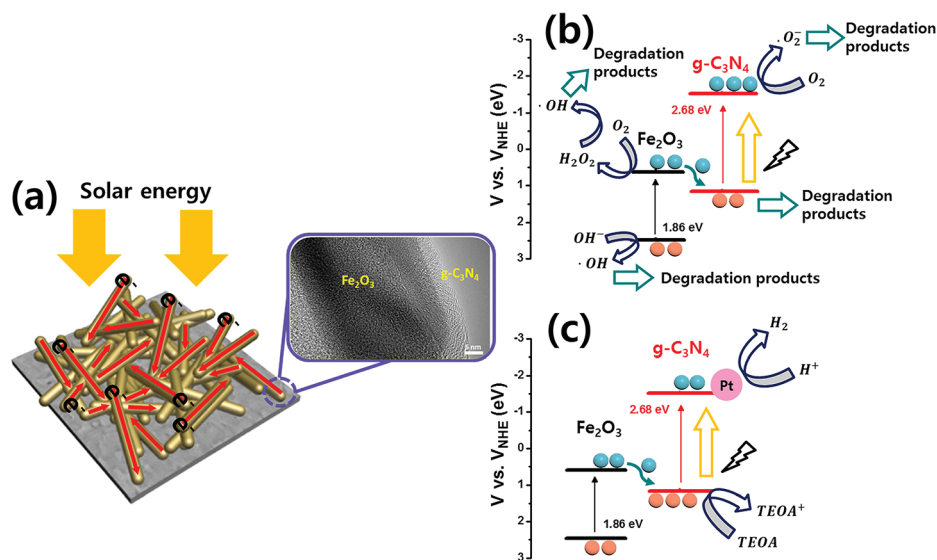


Fig. 10 The direct z-scheme mechanism of 0.75g-C₃N₄@Fe₂O₃ heterostructures showing (a) a graphical schematics, bandgap energy diagrams for (b) photocatalytic degradation and (c) H₂ evolution.



very low because of rapid recombination of charge carriers. The 0.75g-C₃N₄@Fe₂O₃ film forms the optimized interface between Fe₂O₃ and g-C₃N₄ for heterojunction, facilitating electron movements due to reducing its recombination rates of charge carriers. Therefore, these results show that the improvement in several properties, like accelerating electron transfer which can subsequently improve the possibility of photoresponse, can be started through 1D structure.^{60,61}

Based on these results, the mechanisms of g-C₃N₄@Fe₂O₃ heterostructures are shown in Fig. 10. Under solar light irradiation, electrons that are generated are transferred elsewhere by the 1D Fe₂O₃ nanorods, accompanied by recombination losses attributable to the g-C₃N₄ coating. The heterostructures can be used to degrade organic pollutants, or to produce gaseous fuels. In order to prove Z-type mechanism from the photocatalytic mechanism, the schematics of band diagram for the heterostructure in Fig. 10, can be used. As shown in Fig. 10, the electrons from the valence band of Fe₂O₃ is excited to the conduction band of Fe₂O₃ under the light as they are transferred into the valence band of g-C₃N₄, for its band edge being very close for the electron movement. Again, the excited electrons in g-C₃N₄ structure react with oxygen, producing superoxide radical to degrade 4-NP on g-C₃N₄ surface. To prove this point in terms of band edge between Fe₂O₃ and g-C₃N₄, we have measured the valence band of each material using XPS analysis (Fig. S9(a)–(c)†) as well as energy band gap from optical absorbance analysis. As a result, we had measured valence band for g-C₃N₄ to be 1.13 eV while the conduction band for Fe₂O₃ was estimated to be 0.62 eV based on the energy band gap measurement (Fig. 5), proving fairly close band edge between Fe₂O₃ and g-C₃N₄ with Z-type mechanism. Fig. 10(b) shows the 4-NP degradation mechanism. Under visible light, photo-generated electrons from the Fe₂O₃ conduction band are transferred to the valence band of g-C₃N₄, exciting other photo-generated electrons into the g-C₃N₄ conduction band. The resulting holes in Fe₂O₃ react with H₂O and OH[−] to produce ·OH radicals on the surface of Fe₂O₃. Moreover, the photo-generated electrons in Fe₂O₃ react with oxygen molecules at the surface of Fe₂O₃ to produce H₂O₂. ·OH radicals facilitate the removal of 4-NP organic pollutant. Also, electrons from the g-C₃N₄ conduction level react with oxygen on the surface of g-C₃N₄, producing ·O₂[−] and allowing 4-NP to be degraded to water.⁴⁴ From the scavenger test, the main active species in this reaction system is observed to be ·O₂[−] species.⁶² When H₂ is evolved by heterostructures, the direct z-scheme can be used to explain the mechanism detailed previously⁶³ [Fig. 10(c)]. When producing H₂ using Fe₂O₃ and g-C₃N₄, TEOA features hole capture, accelerating electron transfer throughout Pt, and, finally, H₂ production. Therefore, the g-C₃N₄@Fe₂O₃ heterostructures feature separation of charge carriers at the interface, effectively enriching photocatalytic activities and thus allowing 4-NP degradation and H₂ evolution.

4. Conclusion

We successfully synthesized 1D g-C₃N₄@Fe₂O₃ nanorod/film heterostructures using a solvothermal method, to align the

Fe₂O₃ nanorod film and thermal evaporation to ensure uniform g-C₃N₄ coating of the film. The thickness of the g-C₃N₄ coat varied morphologically by the amount of g-C₃N₄ added compared to bare Fe₂O₃. All samples exhibited properties on XRD, FT-IR, Raman spectroscopy, and XPS analysis compatible with reliable formation of g-C₃N₄@Fe₂O₃ heterostructures. Bare Fe₂O₃ exhibited poor electron transfer because of rapid recombination of charge carriers. The g-C₃N₄ coating of Fe₂O₃ films increased the photoresponse performance, as revealed by transient photocurrent, LSV, and EIS measurements. Furthermore, the 4-NP-degrading photocatalytic activity of g-C₃N₄ coated Fe₂O₃ films under visible light was much more rapid than that afforded by bare Fe₂O₃. Of the various heterostructures, the 0.75g-C₃N₄@Fe₂O₃ film exhibited excellent 4-NP degradation for up to 300 min, with a kinetic rate constant of $12.71 \times 10^{-3} \text{ min}^{-1}$, along with stable recyclability. We also evaluated H₂ evolution caused by photocatalytic activity during 4 h of irradiation with visible light. The 0.75g-C₃N₄@Fe₂O₃ film produced 37.06 $\mu\text{mol h}^{-1} \text{ g}^{-1}$ of H₂, 39-fold higher than that produced by bare Fe₂O₃, suggesting that charge separation was efficient and that accumulated electrons accelerated H₂ evolution *via* a direct z-scheme mechanism. Heterostructures composed of g-C₃N₄ coated onto 1D Fe₂O₃ nanorods exhibited remarkable photocatalytic activity under visible illumination; electron transfer through 1D structure and charge separation were highly efficient.

Conflicts of interest

There are no conflicts to declare.

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