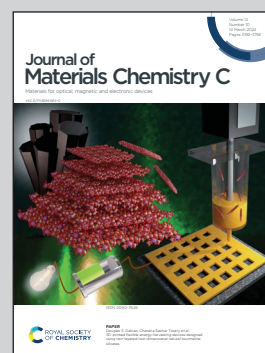


Showcasing research from the group of Professor Jie Ma and Dr Yongming Fu at Shanxi University, China.

Accelerating photocatalytic hydrogen production by anchoring Pt single atoms on few-layer g-C₃N₄ nanosheets with Pt-N coordination

Few-layer g-C₃N₄ nanosheets were successfully modified with Pt single atoms with 1.5 at% through low-temperature incipient wetness impregnation method, increasing the photocatalytic H₂ production rate by two orders of magnitude. Robust Pt-N₆ coordination was achieved by incorporating a Pt atom in the center of the sixfold cavity in g-C₃N₄.

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Accelerating photocatalytic hydrogen production by anchoring Pt single atoms on few-layer g-C₃N₄ nanosheets with Pt–N coordination

Qi Zhang,^{ab} Miao Yue,^{ab} Peng Chen,^{ab} Qingmiao Ren,^{ab} Weihu Kong,^a Chenxia Jia,^a Qianyu Lu,^{ab} Jizhou Wu,^{id}^{abc} Yuqing Li,^{abc} Wenliang Liu,^{abc} Peng Li,^{id}^a Yongming Fu^{id}^{*ab} and Jie Ma^{*abc}

Graphitic carbon nitride (g-C₃N₄) has gained considerable attention as a promising photocatalyst for hydrogen production through water splitting. However, its catalytic efficiency remains severely limited due to the rapid recombination of charge carriers and poor charge-transfer properties. Here, g-C₃N₄ is subjected to modification through the introduction of well-isolated Pt single atoms using a low-temperature incipient wetness impregnation method. The Pt single atoms exhibit a maximum weight ratio of 1.26%, resulting in a giant enhancement of the photocatalytic H₂ evolution rate (336.8 μmol h^{−1}), approximately two orders of magnitude higher than that of pristine g-C₃N₄ (1.8 μmol h^{−1}) during a 22-h-long test with an apparent quantum yield (AQY) of 13.5% at 405 nm. The improved performance and excellent stability in photocatalytic H₂ evolution can be attributed to the formation of Pt–N bonds between Pt single atoms and g-C₃N₄, which creates a new energy level of the N 2p–Pt 5d hybrid orbital for remarkably inhibiting the recombination of photogenerated electron–hole pairs and reducing interfacial charge-transfer resistance.

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1. Introduction

Photocatalytic water splitting is anticipated to be an eco-friendly and enduring method for generating hydrogen (H₂) devoid of detrimental byproducts or emissions.^{1–3} Extensive research has been conducted to identify the most suitable semiconductor-based photocatalysts that possess visible-light responsivity, stability, and reusability. In particular, carbon nitride allotropes have received extensive attention in photocatalysis due to their extended conjugation for fast separation and transfer of the charges.^{4–6} Some studies indicate that graphitic carbon nitride (g-C₃N₄) has emerged as a highly promising candidate for photocatalytic water splitting due to its distinctive electronic structure, exceptional photoelectric characteristics, remarkable stability, and cost-effectiveness.^{7–11} However, the efficiency of g-C₃N₄ in H₂ production is hindered by the limited carrier mobility and the rapid recombination

of electron–hole pairs generated during the photocatalytic process.^{12–14} To enhance the efficiency of photocatalytic H₂ production, a significant approach is the incorporation of cocatalysts, which can facilitate charge transfer and provide reactive sites.

Platinum (Pt) has been widely acknowledged as one of the most efficient cocatalysts for photocatalytic H₂ production due to its low overpotential and favorable Gibbs free energy in H₂ adsorption.^{15–17} Traditional large-scale particulate Pt cocatalysts exhibit limited low atomic utilization and a scarcity of active sites, significantly constraining the utilization efficiency of Pt atoms. Consequently, it becomes imperative to incorporate Pt species in the form of clusters or even isolated single atoms, as this approach offers a viable strategy to optimize atomic efficiency.¹⁸ With the reduction in the volume of the particulate cocatalyst, there is a progressive enhancement in both the specific surface area and atomic utilization. When the volume is decreased to atomic clusters comprising merely a few dozen atoms, a pronounced interaction between the support and the Pt atoms emerges, exerting a substantial effect on the photocatalytic process.^{19–21} Ultimately, upon reducing the cocatalysts to a state of single atom dispersion, the ideal atom utilization attains 100% and the selectivity achieves its utmost level.^{22–25} The presence of homogenous pores in layer-structured g-C₃N₄ offers stable coordination sites for anchor

^a School of Physics and Electronic Engineering & Institute of Laser Spectroscopy, State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University, Taiyuan 030006, China. E-mail: fuyongming@sxu.edu.cn, mj@sxu.edu.cn

^b Xinzhou Institute of Innovation Ecosystem, Shanxi University, Xinzhou 034000, China

^c Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan 030006, China

atoms, while the N atoms within the structure facilitate bonding between pyridine N and active atoms. Thus, $g\text{-C}_3\text{N}_4$ can serve as an appropriate support for the deposition of Pt single atoms, enabling efficient photocatalytic H_2 production.²⁶ In recent years, numerous investigations have documented diverse approaches for synthesizing single-atom Pt catalysts on $g\text{-C}_3\text{N}_4$, including ion exchange,²⁷ reflux reaction,²⁸ photoreduction,^{29–33} and high-temperature pyrolysis.^{34–38} Nevertheless, these methods face constraints when it comes to attaining high loading levels of single-atom Pt catalysts. In this respect, preparing Pt single atom anchored $g\text{-C}_3\text{N}_4$ with high loading and secure trapping is necessary to develop highly efficient photocatalysts.

In this study, the synthesis of Pt single atom anchored $g\text{-C}_3\text{N}_4$ nanosheets with varying Pt contents ($\text{Pt}_x/g\text{-C}_3\text{N}_4$) has been successfully achieved through a low-temperature incipient wetness impregnation method followed by high-temperature pyrolysis. The incipient wetness impregnation method is frequently employed to enhance the loading capacity of single atoms,^{39–41} and lowering the impregnation temperature can additionally suppress the occurrence of agglomeration during the impregnation process. By employing the sequence of low-temperature incipient wetness impregnation, lyophilization, and high-temperature pyrolysis, the dispersion of high-density single atoms can be effectively improved. Characterization analyses have revealed that the isolated Pt single atoms are uniformly dispersed on the surface of $g\text{-C}_3\text{N}_4$, and the formation of Pt–N bonds notably enhances the charge separation and transfer capabilities. The photocatalytic rate of H_2 evolution for $\text{Pt}_x/g\text{-C}_3\text{N}_4$ demonstrates a notable increase compared to both pristine $g\text{-C}_3\text{N}_4$ and $g\text{-C}_3\text{N}_4$ modified with Pt nanoparticles.

2. Experimental

2.1. Synthesis of bulk $g\text{-C}_3\text{N}_4$ powder

Bulk $g\text{-C}_3\text{N}_4$ powder was synthesized through the thermal polymerization of urea. Specifically, 10 g of urea powder was placed in a closed alumina crucible within a muffle furnace (KSL-1100X-S, MTI, China) under a N_2 atmosphere. The furnace was gradually heated to 550 °C at a rate of 1 °C min^{-1} and maintained at this temperature for a duration of 2 h. Subsequently, the resulting yellow $g\text{-C}_3\text{N}_4$ powder was collected and allowed to cool to room temperature before further use.

2.2. Synthesis of few-layer $g\text{-C}_3\text{N}_4$ nanosheets

Few-layer $g\text{-C}_3\text{N}_4$ nanosheets were obtained through the process of ultrasonic-assisted liquid exfoliation. 100 mg of bulk $g\text{-C}_3\text{N}_4$ powder were dispersed in 100 mL of isopropanol and subjected to exfoliation using an ultrasonic crusher with a power of 1 kW for 12 h at room temperature. The resulting dispersion was then centrifuged using a high-speed centrifuge (HC-3018, Zonkia, China) at a speed of 8000 rpm for 10 min. The upper liquid was dried in a vacuum at 50 °C for 6 h to obtain pale yellow few-layer $g\text{-C}_3\text{N}_4$ nanosheets.

2.3. Synthesis of $\text{Pt}_x/g\text{-C}_3\text{N}_4$

The $g\text{-C}_3\text{N}_4$ nanosheets were loaded with Pt single atoms through low-temperature incipient wetness impregnation. A stable suspension was prepared by dispersing 100 mg of the as-prepared few-layer $g\text{-C}_3\text{N}_4$ nanosheets in 100 mL of deionized water and subjecting to ultrasonic treatment at a power of 200 W for 30 min. Subsequently, 0.5, 1, and 1.5 mL of H_2PtCl_6 solutions with a Pt concentration of 1 g L^{-1} were added drop by drop to the suspension. The resulting mixture was then transferred to a refrigerator and allowed to stand for 12 h at 0 °C to facilitate abundant adsorption, followed by rapid cooling to –60 °C. After undergoing freeze-drying in a freeze dryer (SCIENTZ-10N, Ningbo Scientz, China), the as-dried powders were transferred to a muffle furnace under a N_2 atmosphere and subjected to a heating process at 450 °C for 2 h to facilitate the generation of Pt single atoms on the surface of $g\text{-C}_3\text{N}_4$. Finally, the resulting products were dissolved in deionized water, filtered with a 0.22 μm PTFE filter membrane, and dried using a freeze dryer to remove any impurities. The as-prepared samples were designated as $\text{Pt}_{0.5}/g\text{-C}_3\text{N}_4$, $\text{Pt}_1/g\text{-C}_3\text{N}_4$, and $\text{Pt}_{1.5}/g\text{-C}_3\text{N}_4$, respectively. To establish a control, 10 mL of H_2PtCl_6 solution with a Pt concentration of 1 g L^{-1} was introduced into 100 mL of $g\text{-C}_3\text{N}_4$ solution and stirred for 30 min under xenon lamp irradiation to form Pt nanoparticles on few-layer $g\text{-C}_3\text{N}_4$.

2.4. Characterization

The Pt content of the samples was quantified using inductively coupled plasma-optical emission spectroscopy (ICP-OES, Agilent 5510, USA). The surface morphology was characterized with a scanning electron microscope (SEM, Regulus8230, Hitachi) and a transmission electron microscope (TEM, JEM-F200, JEOL) at an acceleration voltage of 200 kV. The identification of crystalline phases, chemical functional groups, and surface chemical states was performed using X-ray diffraction (XRD, Rigaku Miniflex 600, Japan), Fourier transform infrared spectroscopy (FTIR, Thermo Scientific Nicolet iS20, USA), and X-ray photoelectron spectrometry (XPS, Thermo Scientific K-Alpha, USA), respectively. The surface area analyzer (Quantachrome Nova 4000e, USA) was utilized to obtain the Brunauer–Emmett–Teller (BET) specific surface area and pore size distribution. Diffuse reflectance spectroscopy (DRS, Hitachi UH5700, Japan) was employed to acquire the UV-vis absorption spectroscopy data. High angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images were captured using an aberration corrected JEOL JEM-ARM200F operating at 200 keV. X-ray absorption spectroscopy (XAS) measurements of the Pt element were conducted at the XAS beam line of the Shanghai Synchrotron Radiation Facility (SSRF) utilizing an Si(111) double-crystal monochromator, where the experimental data were acquired in the fluorescence mode using an ionization chamber. The steady and time-resolved photoluminescence (PL) spectra were measured using a photoluminescence spectrometer (Edinburgh FLS1000, UK).

2.5. Photoelectrochemical measurements

Electrochemical measurements were performed using an electrochemical workstation (CHI 660E, China) with a standard three-electrode system. The Ag/AgCl electrode and Pt foil were used as the reference electrode and counter electrode in 0.5 M Na₂SO₄ aqueous solution, respectively. Fluorine-tin oxide (FTO) glass coated with the photocatalyst was used as the working electrode. To prepare the working electrode, 5 mg of the photocatalyst was dispersed in 1 mL of ethanol and 20 μ L of Nafion anisole solution (5%) under ultrasonic treatment for 30 min to form a homogeneous slurry. Then, 50 μ L of the obtained slurry was dropped on the conductive surface (10 mm \times 10 mm) of FTO (10 mm \times 30 mm \times 1.1 mm) using a pipette and dried at 60 $^{\circ}$ C for 2 h. The transient photocurrent curves were measured in the *i*-*t* mode by periodically switching a 300 W Xe-lamp (PLS-SXE300, Perfectlight, China) at a 20 s interval under a continuous bias of 0.2 V. The electrochemical impedance spectroscopy (EIS) was conducted at an open circuit voltage with frequency ranging from 0.01 to 100 kHz and an amplitude of 5 mV.

2.6. Photocatalytic H₂ evolution

Photocatalytic water splitting reactions were implemented in a photocatalytic trace-gas generation and analysis system (Labsolar-6A, Perfectlight, China), involving a sealed top-irradiation quartz vessel connected to a closed gas circulation system. In a typical experiment, 50 mg of photocatalysts were added to 90 mL of deionized water and 10 mL of triethanolamine (TEOA) was added as a sacrificial agent. Prior to the photocatalytic test, the air in the reactor is evacuated using a vacuum pump. The evolved H₂ gas was analyzed every 30 min using gas chromatography (GC-2060, FULI, China) with N₂ serving as carrier gas. During the photocatalytic test, a simulated sunlight source was provided by the 300 W Xe-lamp. The reaction temperature was maintained at 2 $^{\circ}$ C using a cooling water circulator. The apparent quantum yield (AQY) of Pt_{1.5}/g-C₃N₄ was determined using the same equipment under irradiation passing through different bandpass filters (365, 405, 420 and 500 nm, respectively) for 4 h. The AQY value was calculated

using eqn (1),

$$\text{AQY} = \frac{2 \times \text{number of evolved hydrogen}}{\text{number of incident photons}} \times 100\% \quad (1)$$

$$= \frac{2RN_Ahc}{IA\lambda} \times 100\%$$

where *R* represents the H₂ evolution rate, *N_A* is the Avogadro constant, *h* is the Planck constant, *c* is the speed of light, *I* is the light intensity, *A* is the irradiation area, and λ is the illumination wavelength.

3. Results and discussion

g-C₃N₄ samples loaded with varying Pt contents have been successfully synthesized using the low-temperature incipient wetness impregnation method, and the ICP-OES analysis reveals that the actual Pt loading percentages of Pt_{0.5}/g-C₃N₄, Pt₁/g-C₃N₄, Pt_{1.5}/g-C₃N₄ and Pt_{NP}/g-C₃N₄ are determined to be 0.38%, 0.90%, 1.26%, and 3.95%, respectively. The observed loss in Pt content can potentially be attributed to incomplete adsorption of Pt species on the surface of g-C₃N₄ during low-temperature treatment. The XRD patterns of all the samples exhibit two characteristic diffraction peaks at 12.9 $^{\circ}$ and 27.7 $^{\circ}$ (Fig. 1a), which correspond to the (100) and (002) planes of hexagonal g-C₃N₄. No discernible peaks or peak-shifts associated with Pt species can be observed for the Pt_{*x*}/g-C₃N₄ samples, suggesting that the presence of Pt does not significantly alter the crystal structure of g-C₃N₄. The FTIR spectrum of few-layer g-C₃N₄ demonstrates distinct peaks at approximately 3100–3500, 1200–1600, and 810 cm^{−1}, which correspond to the vibrational modes of N–H/O–H bonds, aromatic C–N heterocyclic units, and triazine units, respectively (Fig. 1b).³⁴ The FTIR spectra of the Pt_{*x*}/g-C₃N₄ samples exhibit similar peaks to that of pristine g-C₃N₄, suggesting that the introduction of Pt species does not alter the chemical composition of g-C₃N₄.

The BET analyses are depicted in Fig. 2. The N₂ adsorption-desorption isotherms of the samples exhibit a type-IV behavior (Fig. 2a), indicating the presence of mesopores. The BET surface areas of g-C₃N₄ and Pt_{0.5}/g-C₃N₄ are 71.097 and 132.904 m² g^{−1},

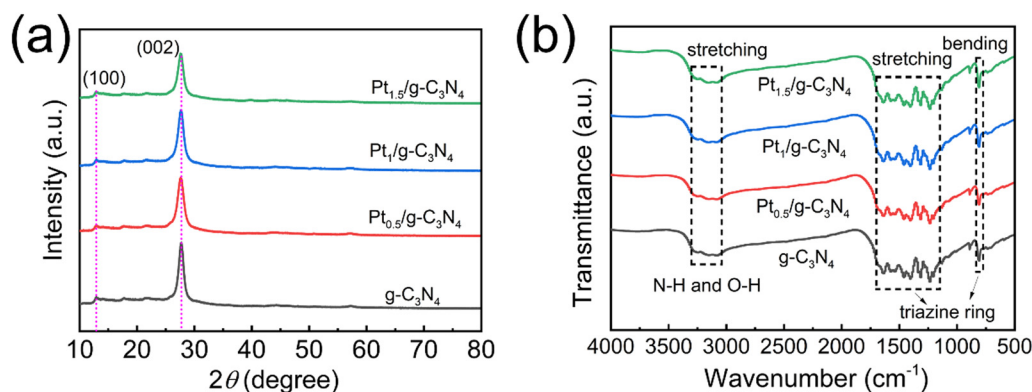


Fig. 1 (a) XRD patterns. (b) FTIR spectra.

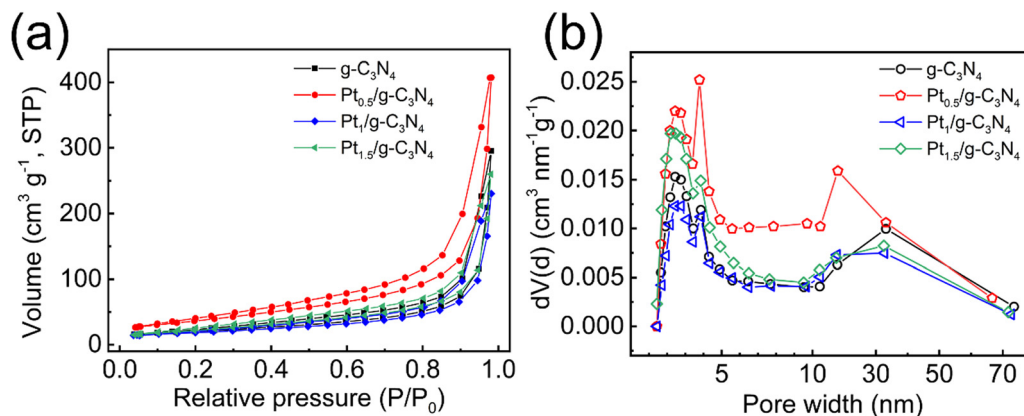


Fig. 2 (a) N_2 adsorption-desorption isotherm. (b) Pore size distributions.

respectively. Fig. 2b displays a quite wide distribution of pore size, confirming the existence of both micropores and mesopores. Interestingly, the pore volumes of pristine $g-C_3N_4$, $Pt_{0.5}/g-C_3N_4$, $Pt_1/g-C_3N_4$, and $Pt_{1.5}/g-C_3N_4$ are 0.322, 0.539, 0.268, and 0.302 $cm^3 g^{-1}$, while the mean pore diameters of these samples are 2.571, 1.897, 2.197, and 1.963 nm, respectively, implying that the adsorption behavior is primarily influenced by micropores and the presence of Pt atoms can enhance the formation of micropores to provide more active sites. The significant increase in the surface area and pore volume of $Pt_{0.5}/g-C_3N_4$ can be attributed to the fact

that the uniform dispersion of isolated Pt atoms can enlarge the interlayer distance of $g-C_3N_4$ structures.^{27,42,43} As the Pt content exceeds 0.5%, the specific surface area and pore volume exhibit a declining trend, but $Pt_x/g-C_3N_4$ still demonstrates the ability to offer an increased number of micropores as active sites for the photocatalytic reaction.

Fig. 3 presents the XPS analysis conducted on the samples to examine their chemical composition and oxidation states. The survey spectra indicate the presence of C and N in the $g-C_3N_4$ sample and Pt in the $Pt_x/g-C_3N_4$ and $Pt_{NP}/g-C_3N_4$ samples

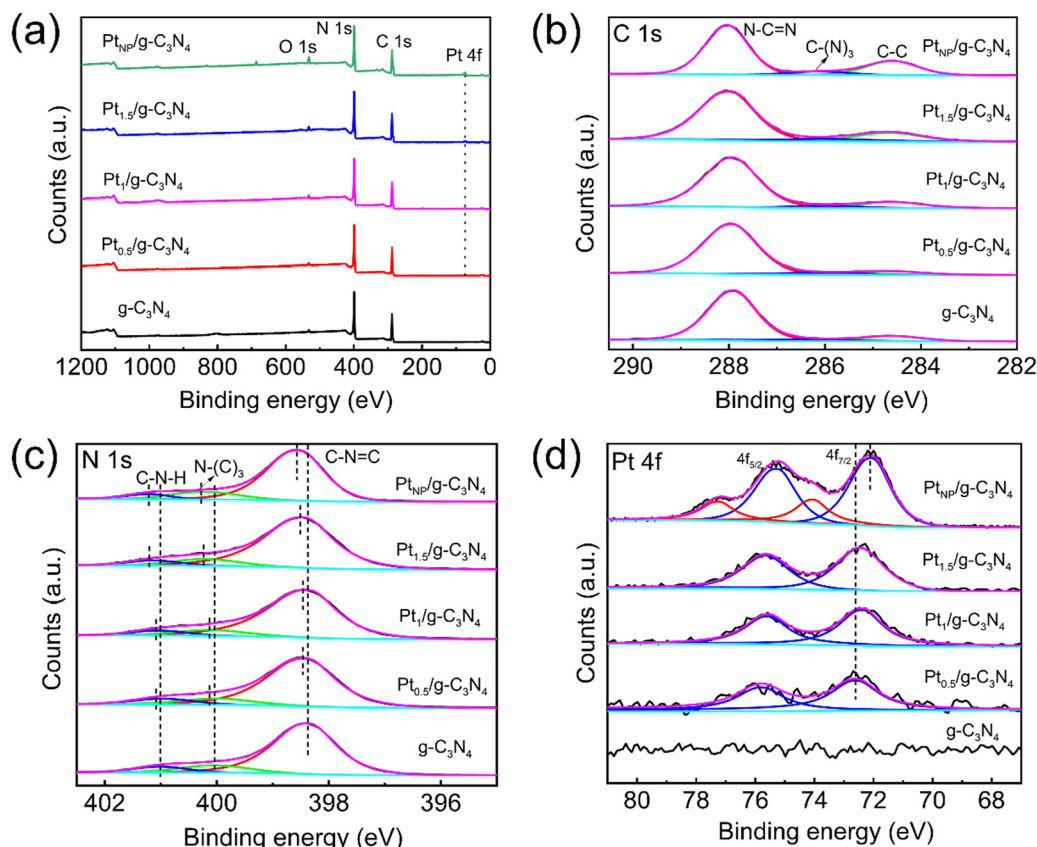


Fig. 3 XPS spectra of the samples. (a) Survey. (b) C 1s. (c) N 1s. (d) Pt 4f.

(Fig. 3a). The high-resolution C 1s spectra are well fitted to three distinct peaks at 287.98, 286.02, and 284.6 eV, corresponding to the N-C=N, C-(N)₃, and C=C bonds, respectively (Fig. 3b).⁴⁴ In the N 1s spectrum of g-C₃N₄, there are three characteristic peaks including 398.36 eV for C-N=C, 400.04 eV for N-(C)₃, and 401.00 eV for C-N-H, respectively (Fig. 3c).⁴⁴ Compared to g-C₃N₄, the three peaks of N 1s shift towards higher energy with increasing Pt loading.⁴⁰ For Pt_{1.5}/g-C₃N₄, the shift values assigned to C-N=C, N-(C)₃, and C-N-H groups are 0.09, 0.14, and 0.13 eV, respectively. The binding energy of N 1s in Pt_{NP}/g-C₃N₄ exhibits a similar shift.⁴⁵ In Fig. 3d, the Pt 4f spectrum of Pt_{NP}/g-C₃N₄ is divided into two sets of double peaks, with the high-energy and low-energy peaks corresponding to the high-oxidation state of Pt clusters and metallic Pt nanoparticles, respectively.^{28,46,47} The Pt 4f_{7/2} and 4f_{5/2} orbitals related to Pt nanoparticles are located at 72.05 and

75.25 eV, while those of Pt_x/g-C₃N₄ are located at 72.45 and 75.65 eV, respectively.^{46,48} The Pt 4f orbitals of Pt_x/g-C₃N₄ roughly corresponding to Pt²⁺ species positively shift by 0.4 eV compared to Pt nanoparticles, which is ascribed to the weakened shielding effect due to the lack of 5d electrons of the outer orbital.^{47,49} Therefore, the alteration in the electron density of the N atom is ascribed to the modification of the Pt atom, thereby confirming the robust electronic interaction between Pt and N atoms (Pt-N bond) at higher density of Pt single atoms.

The distribution and configuration of Pt atoms at high loading density in Pt_{1.5}/g-C₃N₄ are accurately determined through the characterization of an HAADF-STEM image, as illustrated in Fig. 4. Fig. 4a and b are the SEM images of Pt_{1.5}/g-C₃N₄ and Pt_{NP}/g-C₃N₄, indicating that the nanosheets remain ultra-thin after the introduction of Pt species. The corresponding

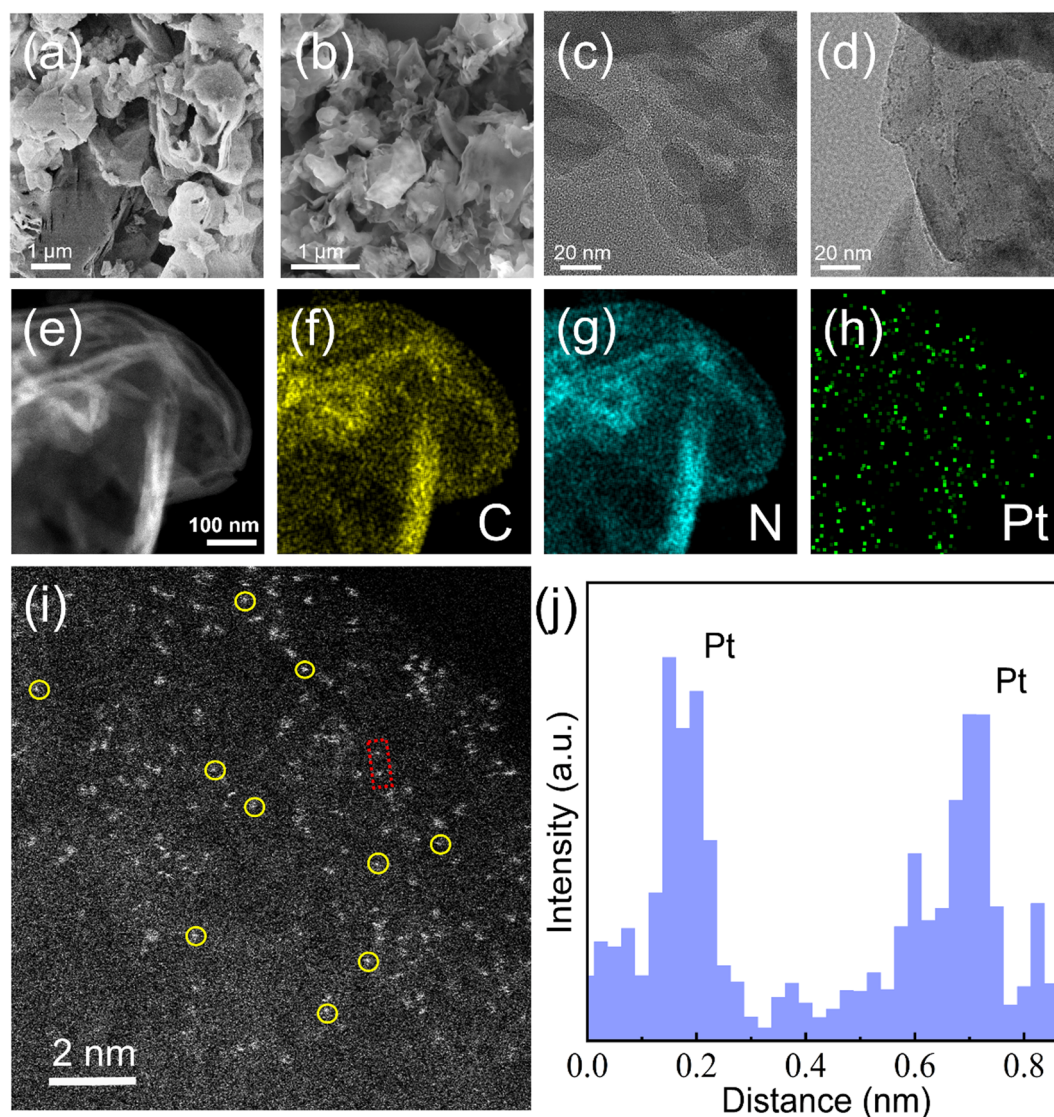


Fig. 4 Morphology of Pt_{1.5}/g-C₃N₄ and PtNP/g-C₃N₄. (a) and (b) SEM images of Pt_{1.5}/g-C₃N₄ and PtNP/g-C₃N₄. (c) and (d) TEM images of Pt_{1.5}/g-C₃N₄ and PtNP/g-C₃N₄. (e) Low-resolution STEM image. (f)–(h) Elemental mapping of C, N, and Pt. (i) HAADF-STEM image. (j) Intensity profile of two Pt single atoms along the middle of the red rectangle in (i).

high-resolution TEM images are shown in Fig. 4c and d, respectively. The Pt nanoparticles can only be observed in $\text{Pt}_{\text{NP}}/\text{g-C}_3\text{N}_4$. Fig. 4e provides a low-resolution STEM depiction of the crumpled few-layer structure of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$. The elemental mapping profiles presented in Fig. 4f–h demonstrate the homogeneous distribution of C, N, and Pt elements, confirming the presence of trace Pt atoms dispersed throughout $\text{g-C}_3\text{N}_4$. Furthermore, the HAADF–STEM image in Fig. 4i reveals densely dispersed bright spots corresponding to Pt atoms, which exist in an isolated single-atom state on the surface of $\text{g-C}_3\text{N}_4$. To quantify the dispersion of Pt single atoms, the distance between adjacent Pt single atoms is determined to be approximately 0.5 nm (Fig. 4j), suggesting a high level of dispersion and individualization of Pt atoms.

The detailed atomic-level structure and coordination information on Pt species is provided by synchrotron-based X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) at the Pt L_3 -edge. $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ exhibit identical XANES spectra with the absorption edge intensity falling between that of Pt foil and PtO_2 (Fig. 5a), confirming that the Pt single atoms in $\text{Pt}_x/\text{g-C}_3\text{N}_4$ are highly reduced to an oxidation state between Pt^0 and Pt^{4+} .⁵⁰ The correlation between the peak intensity of L_3 -edge absorption and the unoccupied density of states of Pt 5d orbitals is evident.⁵¹ Thus, the Pt atoms in $\text{Pt}_x/\text{g-C}_3\text{N}_4$ possess a greater abundance of unoccupied 5d-electron states, which aligns with the observed electron transfer indicated by the Pt 4f XPS spectra. To further analyze the local coordination environment

of the Pt single atoms, Fourier-transform EXAFS analysis is performed (Fig. 5b). The peaks observed in the spectra correspond to distinct coordination shells surrounding the Pt atoms. The prominent peaks of Pt foil and PtO_2 are clearly observed at 2.55 and 1.60 Å, respectively. However, these peaks are absent for $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$, confirming the presence of Pt single atoms, which is consistent with the HAADF–STEM observation. Previous studies have shown that Pt single atoms can be stabilized through covalent bonds with adjacent N and C atoms.^{27,47,50,52} Therefore, the dominant peak at approximately 1.9 Å can be assigned to the Pt–N/C bonds. In this case, the experimental EXAFS spectra of $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ exhibit a satisfactory fit while employing the Pt–N/C pathway. Although the exact coordination of Pt atoms with either N or C presents difficulties, it is more probable to observe Pt–N coordination by examining the significant energy shift of N 1s spectra of $\text{Pt}_x/\text{g-C}_3\text{N}_4$. Based on the EXAFS fitting outcomes (Fig. 5c and d), both the $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ demonstrate comparable coordination numbers ($\text{Pt}_1\text{–N}$: 6.3 ± 0.4 ; $\text{Pt}_{1.5}\text{–N}$: 6.4 ± 0.4) and Pt–N bond lengths (~ 2.41 Å). It should also be noted that when the Pt atom is situated within the central position of a sixfold cavity in $\text{g-C}_3\text{N}_4$, it is expected to exhibit a Pt–N bond length of approximately 2.38 Å.⁴⁰ The EXAFS wavelet transforms provide a method to obtain both the radial distance resolution (R space) and k space resolution simultaneously. Fig. 6a and b show that the maximum intensities of $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ centered at about 6.55 and 6.30 Å^{−1} (k space) are resolved at 1.90 Å (R space), respectively,

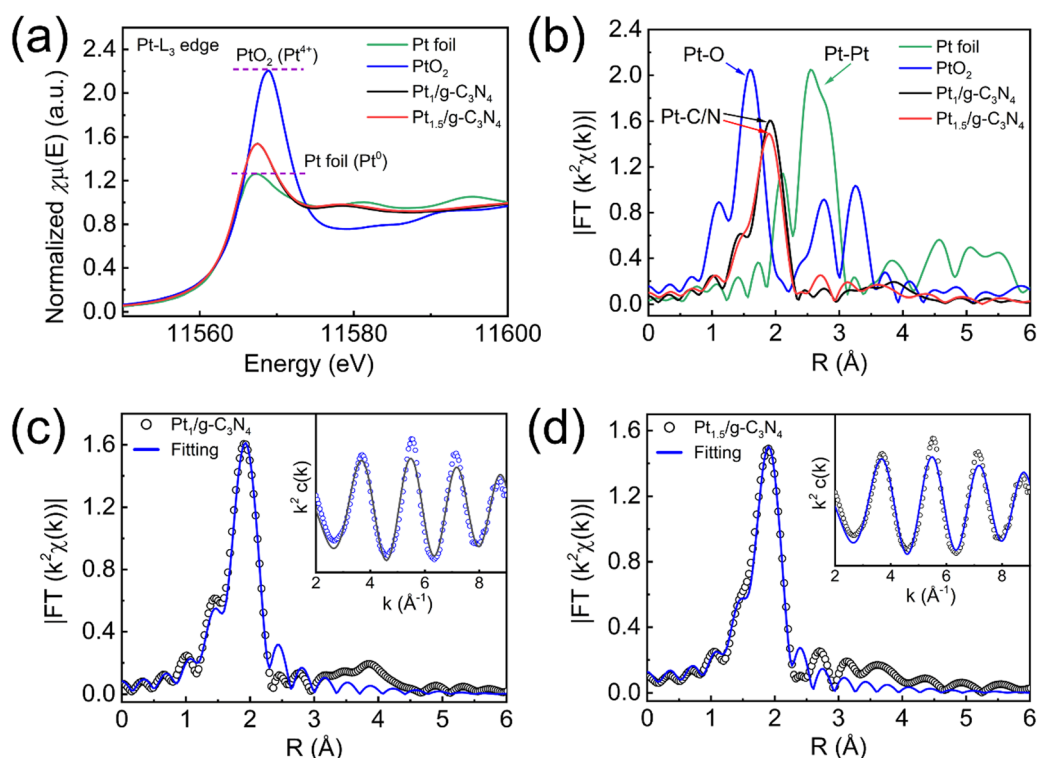


Fig. 5 XAFS of $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$. (a) L_3 -edge XANES spectra. (b) k^2 -weighted FT-EXAFS spectra. (c) Fitted FT-EXAFS spectra of $\text{Pt}_1/\text{g-C}_3\text{N}_4$. (d) Fitted FT-EXAFS spectra of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$.

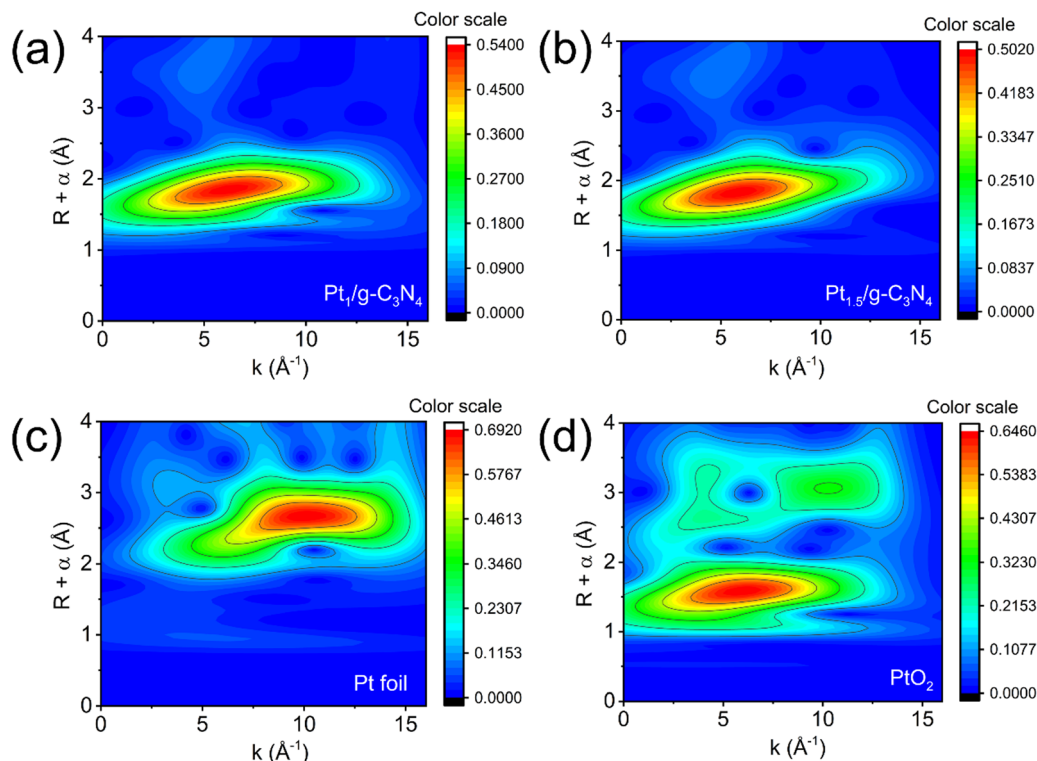


Fig. 6 WT-EXAFS of (a) Pt foil, (b) PtO_2 , (c) $\text{Pt}_1/\text{g-C}_3\text{N}_4$, and (d) $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$.

which are both assigned to the Pt–N coordination structure.^{45,53} Note that the intensities corresponding to Pt–Pt (10.05 \AA^{-1} , Fig. 6c) and Pt–O (6.05 \AA^{-1} , Fig. 6d) coordination for the Pt foil and PtO_2 are not observed for $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$. The coordination analyses provide confirmation of the highly reduced state of the Pt single atoms and their strong interaction with N atoms in an isolated state.

The band structures of the samples are depicted in Fig. 7. The DRS results indicate an increasing absorption intensity in the UV region and a slight red-shift in the absorption edge at approximately 430 nm with increasing Pt content (Fig. 7a), which can be ascribed to the presence of a higher concentration of Pt–N bonds.³⁴ By extrapolating the intercept of the x -axis in the linear region of Tauc plots, the band gaps (E_g) of $\text{g-C}_3\text{N}_4$ and $\text{Pt}_x/\text{g-C}_3\text{N}_4$ are calculated to be 2.67, 2.63, 2.60, and 2.59 eV, respectively (Fig. 7b).⁵⁴ The corresponding valence band potentials (E_{VB}) are calculated using valence band XPS ($V_{\text{B-XPS}}$), yielding values of 1.89, 1.75, 1.20, and 1.17 eV, respectively (Fig. 7c). The E_{VB} and the standard hydrogen electrode ($E_{\text{VB,NHE}}$) exhibit a correlation expressed as $E_{\text{VB,NHE}} = \phi + E_{\text{VB,XPS}} - 4.44$, where ϕ represents the work function of the XPS analyzer (4.2 eV).⁵⁵ Thus, the $E_{\text{VB,NHE}}$ values of the respective samples are determined to be 1.65, 1.51, 1.02, and 0.93 eV. The band structures of $\text{g-C}_3\text{N}_4$ and $\text{Pt}_x/\text{g-C}_3\text{N}_4$ are shown in Fig. 7d, where the conduction band potential (E_{CB}) is calculated using the empirical formula: $E_{\text{CB}} = E_{\text{VB}} - E_g$. It is noteworthy that the E_{CB} of $\text{Pt}_x/\text{g-C}_3\text{N}_4$ tends to be more negative than that of $\text{g-C}_3\text{N}_4$, suggesting that $\text{Pt}_x/\text{g-C}_3\text{N}_4$ has a stronger reduction in protons compared to $\text{g-C}_3\text{N}_4$ in thermodynamics.

The PL spectra reveal that all of the samples show a similar intrinsic fluorescence emission peak within the range of 400–550 nm (Fig. 8a).³⁰ The PL intensity of $\text{Pt}_x/\text{g-C}_3\text{N}_4$ is significantly diminished as a result of the incorporation of Pt single atoms, indicating a pronounced suppression of recombination of photogenerated charge carriers.^{22,46,56} The time-resolved PL-decay spectrum fitted by third-order exponential terms provides direct evidence of the duration of the photo-excited charge carriers (Fig. 8b), showing that the presence of Pt single atoms leads to a shorter lifetime (6.00, 5.80, and 5.90 ns for $\text{Pt}_{0.5}/\text{g-C}_3\text{N}_4$, $\text{Pt}_1/\text{g-C}_3\text{N}_4$, and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$, respectively) compared to $\text{g-C}_3\text{N}_4$ (8.09 ns). The rapid migration of charge carriers between Pt single atoms and $\text{g-C}_3\text{N}_4$ enhances exciton dissociation, thereby effectively inhibiting the recombination of electron–hole pairs.⁴⁹ To assess the charge-separation ability, the photocurrent and EIS properties are examined. In Fig. 8c, the photoelectrode of $\text{Pt}_x/\text{g-C}_3\text{N}_4$ shows a higher photocurrent density in comparison to $\text{g-C}_3\text{N}_4$, indicating superior charge-transfer properties and more efficient photogenerated charge separation in $\text{Pt}_x/\text{g-C}_3\text{N}_4$. Furthermore, the EIS Nyquist plot of $\text{Pt}_x/\text{g-C}_3\text{N}_4$ displays a smaller semicircle compared to $\text{g-C}_3\text{N}_4$ (Fig. 8d), suggesting enhanced charge-transfer ability at the photocatalyst interface and improved electronic utilization. These results indicate that the incorporation of well-dispersed Pt single atoms can effectively augment optical absorption, diminish the band gap and valence band, impede photogenerated carrier recombination, and facilitate interfacial charge transfer. Moreover, the improving effect becomes stronger with the increasing content of Pt single atoms. These outcomes hold

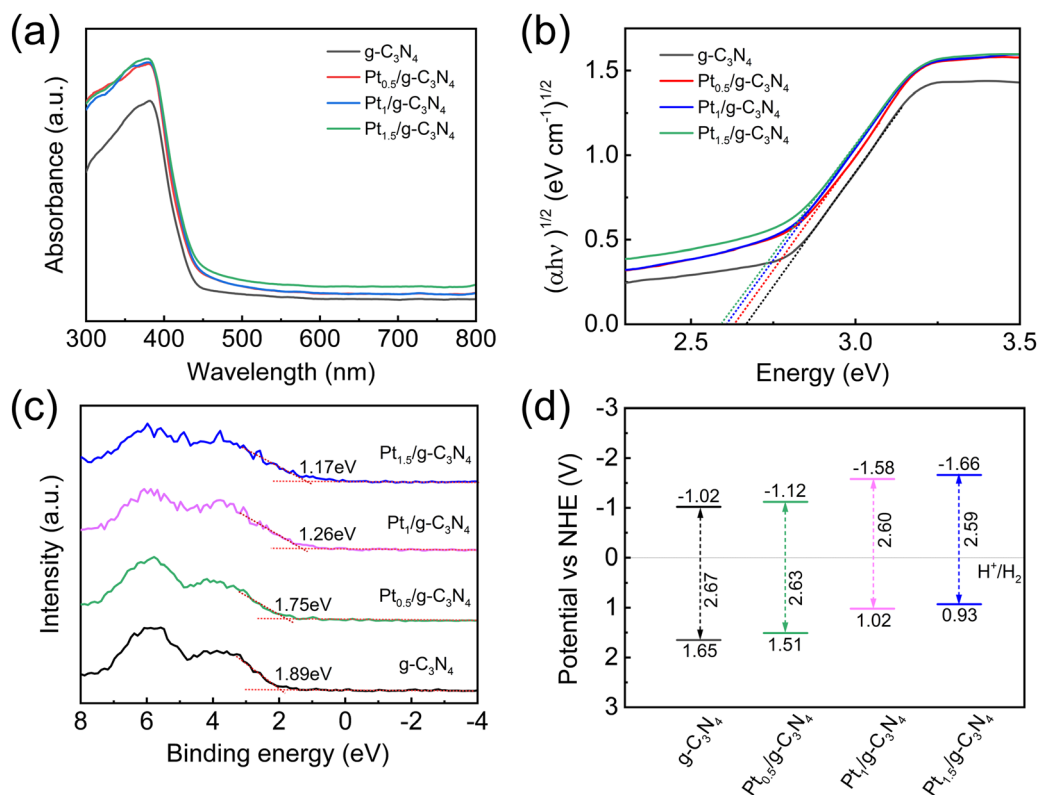


Fig. 7 (a) UV-vis DRS. (b) Tauc plots. (c) VB-XPS. (d) Schematic band structures.

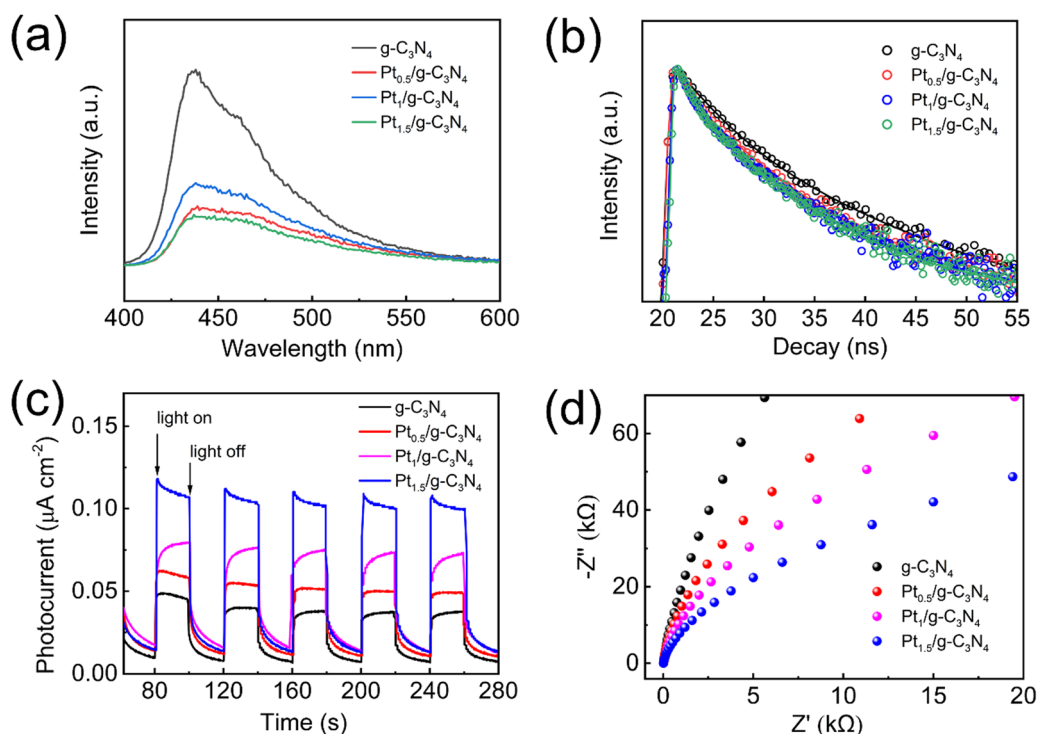


Fig. 8 (a) PL spectra. (b) Time-resolved PL spectra. (c) Transient photocurrent responses. (d) EIS Nyquist plots.

significant implications for enhancing the efficiency of the photocatalytic H_2 evolution reaction.

The advantage of loading Pt single atoms in photocatalytic H_2 evolution is evaluated by varying the Pt content and

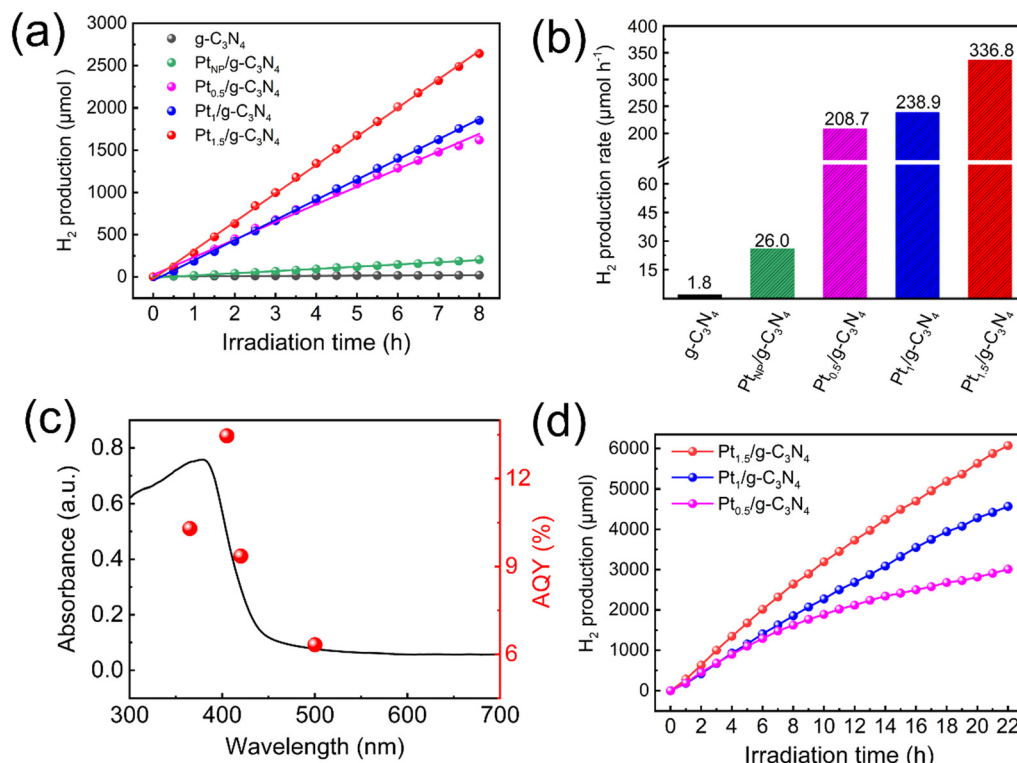


Fig. 9 (a) Time courses for photocatalytic H_2 evolution of $\text{Pt}_x/\text{g-C}_3\text{N}_4$ under Xe-lamp irradiation. (b) Corresponding photocatalytic H_2 evolution rate. (c) AQY of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$. (d) Stability tests for 22 h.

aggregation. As shown in Fig. 9a, the initial H_2 production rate of pristine $\text{g-C}_3\text{N}_4$ is relatively low ($1.8 \mu\text{mol h}^{-1}$), which experiences an increase to $26.0 \mu\text{mol h}^{-1}$ upon loading Pt nanoparticles. Once $\text{g-C}_3\text{N}_4$ is modified with Pt single atoms at a loading content of merely 0.5%, a substantial enhancement of the photocatalytic H_2 production rate is achieved ($208.7 \mu\text{mol h}^{-1}$). The H_2 production rate of $\text{Pt}_{0.5}/\text{g-C}_3\text{N}_4$ is ~ 116 times that of $\text{g-C}_3\text{N}_4$ and ~ 8 times that of $\text{Pt}_{\text{NP}}/\text{g-C}_3\text{N}_4$, despite the amount of Pt source being only 1/20th of $\text{Pt}_{\text{NP}}/\text{g-C}_3\text{N}_4$. With an increase in Pt concentration, $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ exhibit elevated H_2 production rates of 238.9 and $336.8 \mu\text{mol h}^{-1}$, respectively (Fig. 9b). These results indicate a positive correlation between the H_2 production rate and the loading content of Pt single atoms within a reasonable range. The AQY of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ under irradiation at different wavenumbers is shown in Fig. 9c. Against irradiation wavenumbers of 365, 405, 420, and 500 nm, the AQYs are 10.30%, 13.46%, 9.35%, and 6.32%, respectively. The high AQY value and the good match

between AQY and the absorption spectrum indicate that most of the captured photons are involved in the photocatalytic reaction.^{45,57} Compared with other Pt single-atom modified $\text{g-C}_3\text{N}_4$ photocatalysts prepared by different methods, $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ reported in this work exhibits a relatively high loading content of Pt single atoms and excellent photocatalytic H_2 evolution performances, as shown in Table 1.^{28,40,49,58,59}

To study the stability of photocatalytic H_2 production, an extended duration of the H_2 evolution test is conducted. Fig. 9d shows that the H_2 production rate of $\text{Pt}_{0.5}/\text{g-C}_3\text{N}_4$ experiences a noticeable decline after 10 h, which may be attributed to the rupture of the Pt-N bond resulting from inadequate Pt filling between 3-s-triazines. Interestingly, the H_2 production rates of $\text{Pt}_1/\text{g-C}_3\text{N}_4$ and $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ remain relatively constant for 22 h, indicating that the sufficient dispersion of Pt single atoms facilitates an optimal and robust interaction with $\text{g-C}_3\text{N}_4$. To further investigate the reusability, the photocatalytic test of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ is repeated four times, and the used catalyst after

Table 1 A comparison of the photocatalytic H_2 production efficiency of $\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$ reported in this work with those of other Pt single-atom modified $\text{g-C}_3\text{N}_4$ photocatalysts

Samples	Pt loading	Methods	Light sources	H_2 production rates ($\mu\text{mol h}^{-1}$)	AQYs	Ref.
Pt-CN	0.74%	Immersion	30 W LED ($\lambda > 520$)	34.2	0.84% $\lambda = 520$ nm	28
Pt/CN	0.16%	Immersion	300 W Xe lamp ($\lambda > 420$)	318	—	40
Pt/CN	0.11%	Photo-chemical reduction	300 W Xe lamp (AM1.5)	40.1	—	49
Pt-CN	0.38%	Immersion	300 W Xe lamp (AM1.5)	2.9	—	58
$\text{Pt}_{\text{HD}}/\text{CNNT}$	0.32%	Pyrolysis	300 W Xe lamp ($\lambda > 420$)	106.1	13.1% $\lambda = 420$ nm	59
$\text{Pt}_{1.5}/\text{g-C}_3\text{N}_4$	1.26%	IWI	300 W Xe lamp	336.8	13.5% $\lambda = 405$ nm	This work

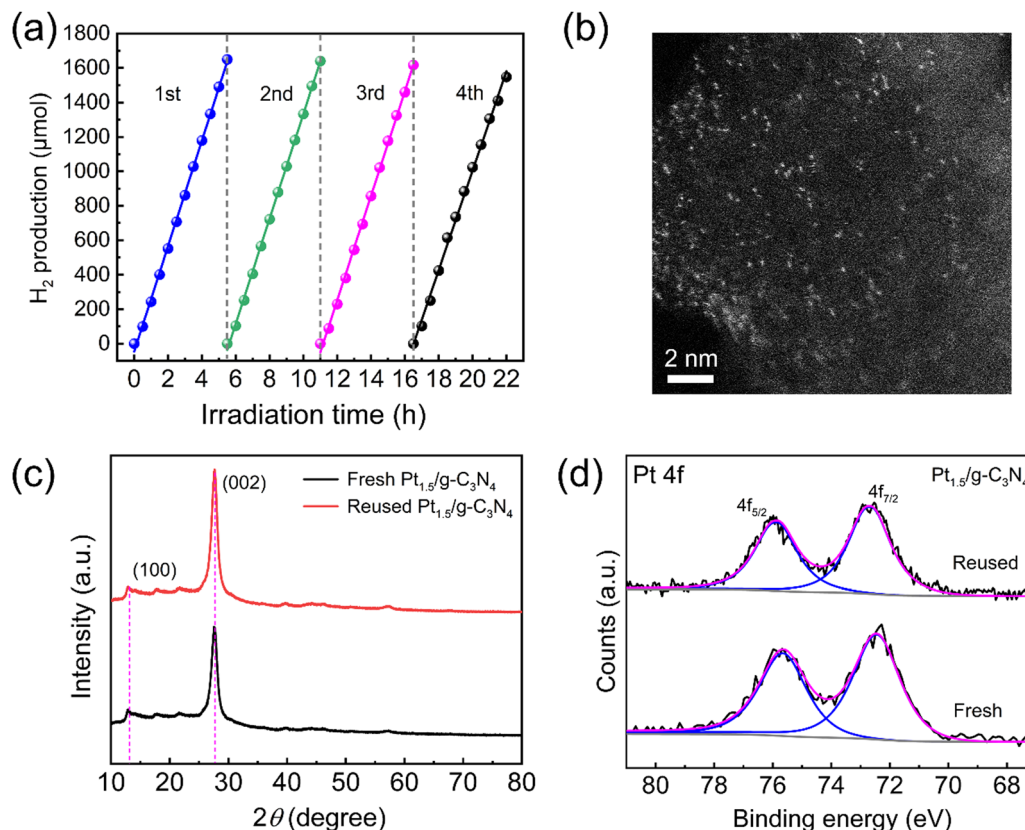


Fig. 10 Reusability of Pt_{1.5}/g-C₃N₄. (a) The photocatalytic H₂ production rate during four cycles. (b) HAADF-STEM image after reaction. (c) and (d) Comparison before and after photocatalytic reaction of (c) XRD and (d) XPS Pt 4f.

the reaction is characterized again, as depicted in Fig. 10. Fig. 10a shows the H₂ production rate of Pt_{1.5}/g-C₃N₄ during four cycles. After four cycles, the H₂ production capability is 5.8% lower than the initial value, exhibiting excellent photocatalytic stability. The HAADF-STEM image of Pt_{1.5}/g-C₃N₄ after photocatalysis is shown in Fig. 10b, indicating that the Pt single atoms maintain a high dispersion in an isolated state without apparent aggregation. Comparing the XRD patterns (Fig. 10c) and Pt 4f XPS spectra (Fig. 10d) before and after 4-cycle-photocatalysis, both the structure of g-C₃N₄ and the valence state of Pt single atoms are not significantly changed. These results demonstrate that Pt_x/g-C₃N₄ exhibits excellent photocatalytic stability after a long photocatalytic reaction even when loaded with a high density of Pt single atoms.

The enhanced mechanism of photocatalytic H₂ production of Pt_x/g-C₃N₄ is illustrated in Fig. 11. Low-temperature treatment reduces the average pore size of the small pores in g-C₃N₄, which may promote the adsorption of H⁺. Furthermore, the strong interaction between Pt 5d and N 2p for the formation of the Pt-N bond plays a key role in the kinetics of the H₂ evolution reaction by effectively accelerating charge transfer and stabilizing active sites for photocatalysis.^{34,40,42,60} Pt single atoms incorporated in the center of the sixfold cavity and forming robust Pt-N₆ coordination introduce new energy levels within the band structure of g-C₃N₄, leading to improved separation of photo-induced electron-hole pairs. Under light

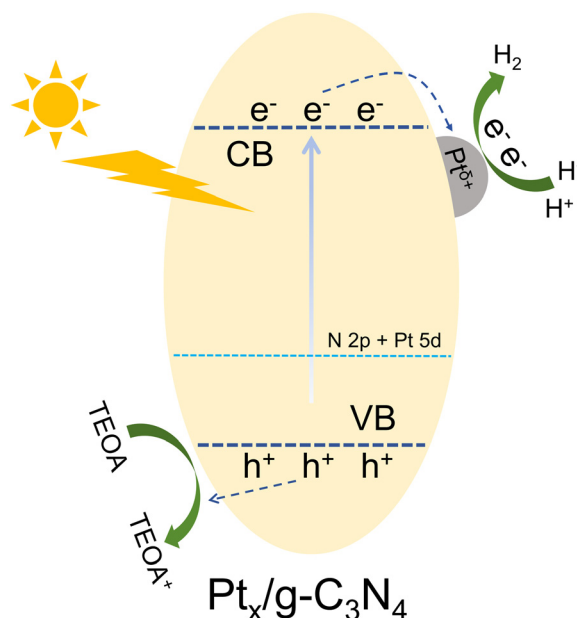


Fig. 11 Mechanism of photocatalytic H₂ production of Pt_x/g-C₃N₄.

irradiation, the photogenerated electrons migrate to Pt single atoms for participating in the H₂ evolution reaction. The stable and efficient production of H₂ is attributed to the optimal

dispersion of Pt atoms and the improved charge carrier dynamics facilitated by the interaction between Pt and g-C₃N₄.

4. Conclusions

In summary, Pt_x/g-C₃N₄ photocatalysts with different Pt contents are synthesized using a low-temperature incipient wetness impregnation method. Pt atoms loaded on g-C₃N₄ in the form of the isolated single atoms even at a high density of 1.5 wt% are demonstrated by HAADF-STEM and EXAFS results. The well-dispersed Pt single atoms provide active sites for H⁺ adsorption. The Pt single atoms incorporated in the sixfold cavity between the three adjacent triazines form strong interaction between Pt and N₆, which generates new doping energy levels and boosts higher transportation and separation efficiency of photo-generated charge carriers for improving photocatalytic H₂ evolution. The photocatalytic H₂ production rates of Pt_x/g-C₃N₄ are roughly two orders of magnitude better than that of the pristine g-C₃N₄, and the stability increases with increasing Pt loading content. This research reflects a significant advancement in photocatalyst design and opens new avenues for the development of efficient hydrogen production systems.

Author contributions

Qi Zhang: resources, investigation; Miao Yue: investigation, writing – original draft; Peng Chen: investigation, formal analysis; Qingmiao Ren: investigation; Weihu Kong: investigation; Chenxia Jia: visualization, formal analysis; Qianyu Lu: resources, writing – reviewing and editing; Jizhou Wu: formal analysis, writing – original draft; Yuqing Li: methodology; Wenliang Liu: writing – reviewing and editing; Peng Li: visualization; Yongming Fu: conceptualization, investigation, writing – original draft; supervision; and Jie Ma: writing – reviewing and editing, supervision, project administration.

Conflicts of interest

There are no conflicts to declare.

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