

Luminescent Transparent Wood from Balsa wood (Ochroma pyramidale) Loaded by Graphite Carbon Nitride for Implication of Photoelectric Device

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Abstract

In this study, metal-free wood-based encapsulating materials for WLED was obtained by using renewable transparent wood as the biological support and the light scattering component, and graphite carbon nitride as the color light emitting component. The graphite phase carbon nitrides with blue and green color were prepared by thermal polymerization through structural regulation of raw materials. The resulting different color phosphors were mixed with epoxy resin, respectively, and then blue epoxy resin, green epoxy resin and red epoxy resin were mixed with a mass ratio of 4:2:1 and adding a proper amount of curing agent. The delignified balsa wood with high porosity was vacuum impregnated with epoxy resin mixture to obtain white luminescent transparent wood (g-C₃N₄ (W)@TW) with better performance such as high transmittance and high haze. It provides a feasible solution for the sustainable development of transparent wood and the application of transparent wood to photoelectric materials.

Introduction

Natural wood is a low-cost, natural, renewable and resource-rich material (Chen et al. 2020). Untreated wood is generally brownish yellow and opaque mainly due to the existence of light absorbing materials, while the opacity is mainly attributed to the existence of the interfaces between pore and cell wall. The refractive index of the material in the cell wall is quite different from that of air in the pore. This is the reason that the light produces refraction, scattering and reflection at the interfaces between pore and cell wall during the propagation of light, and the light cannot pass through the wood. At the same time, part of the light is absorbed by the chromogenic material and the color produces (Zhu et al. 2021). In wood, lignin is the absorption material and accounts for about 30%, especially the chromogenic groups of lignin can make wood have strong light absorption in the visible light region (Wu et al. 2020). Wood also contains other mixed substances that cause light refraction and scattering, such as resin, tannin, pectin, etc. These substances also have different effects on wood color and opacity.

After delignification, the impregnated polymer, which is close to the refractive index of cellulose in cell wall, is selected to fill the pores in the delignified wood. Refractive index mismatch is significantly reduced between cell walls and polymers after impregnation, and light can propagate along the wood growth direction without incident angle (Li et al. 2018). The refraction, reflection and absorption of incident light greatly reduce because the removal of chromogenic substances and the slightly difference of refractive index between pore and cell wall, which makes the wood from opaque to transparent. The transparent wood has high impact resistance and ductility, low thermal conductivity, and can collect sunlight to the maximum extent (Zhang et al. 2019; Fu et al. 2020; wu et al. 2019; Tang et al. 2018; Wang et al. 2019). These characteristics allow the transparent wood to be employed directly as building materials, such as windows. In addition, the transparent wood can be used as a matrix for conductive and magnetic materials (Tang et al. 2018; Wang et al. 2019; Gan et al. 2017). In the preparation of transparent wood, some functional materials can be used to impregnate synchronously and give the transparent wood special functions, which further expand the functionalization direction of wood and its application fields.

High porosity of delignified wood allows fluorescent materials in a certain size range to be doped during polymer impregnation, which can endow the transparent wood with photoluminescence properties (Li et al. 2018; Li and Fu et al. 2018; Liu et al. 2020; Hoglund et al. 2020; Fu et al. 2020). Therefore, the transparent wood can be applied to optoelectronic materials. Chave et al (2006) reported that the wood density varied from 0.11 g/cm³ to 1.39 g/cm³, with an average of 0.64 g/cm³. For the preparation of transparent wood, the high porosity of low-density wood is conducive to polymer impregnation, which can improve the uniformity of polymer distribution in wood and the transparency of transparent wood. Balsa (*Ochroma pyramidale*) is a typical low-density wood because of its fast growth, up to 20 m in height and 75 cm in diameter in 5-8 years (Fletcher 1951). Its density values vary from 0.01 to 0.38 g/cm³ and typically range between 0.10 and 0.25 g/cm³ (Da et al 2007; Borrega et al. 2015), and balsa wood is an excellent raw material for making transparent wood.

White light emitting diode (WLED) has become an indispensable part of our life and has brought great convenience to our daily life. Common LED phosphors in the market mostly adopt rare earth elements, which are a precious national resource and non-renewable (Zhang et al. 2019; Guo 2019; Li et al. 2019; Cheng et al. 2020; Rao et al. 2020). Its preparation process is complex and energy consumption is high (Gaddam et al. 2019; Wang et al. 2017; Zhang et al. 2020). Therefore, developing a renewable fluorescent material with high quantum efficiency as an alternative material has become a problem for scholars. Graphite phase carbon nitride (g-C₃N₄) is an organic and pollution-free fluorescent material, which has the advantages of simple preparation method, low energy consumption and good biocompatibility (Yang et al. 2018; Jigyasa et al. 2021). It is expected to replace rare earth elements as alternative materials for LED lamps.

In this study, balsa wood chips were delignified to remove chromogenic substances and used as the base material of transparent wood. The (g-C₃N₄)-based blue and green phosphors were synthesized and their luminescent properties were tested. The mixture of two synthesized phosphors, red phosphors purchased and epoxy resin was impregnated into delignified wood chips to prepare the white luminescent transparent wood for the application of LED optoelectronic devices. The preparation scheme is illustrated in Fig.1.

Materials And Methods

Materials

The balsa wood chips used in this study were obtained from Fujian Province, China with dimensions of 30 mm × 30 mm × 2 mm (radial Direction). Dicyandiamide and 2,4-diamino-6-phenyl-1,3,5-triazine were purchased from Aladdin Chemical Reagent Co., Ltd. The epoxy resin and curing agent were obtained from Wenzhou Yichen Industrial Co., Ltd, China. Red phosphor was purchased from Shenzhen Diweisheng Technology Co., Ltd, China.

Delignification

Balsa wood chips were immersed directly in NaOH solution with a concentration of 5 wt. % at 90°C for 2 hours. The chips were washed and then moved into NaClO₂ solution for delignification at pH 4.6 and temperature 80°C until being white.

Constituent analysis of wood

Chemical constituents of wood were determined according to the standard method by Technical Association of Pulp and Paper Industry (TAPPI). The wood chips were ground into particles and then screened, and the components passing a 40-mesh screen and remained on a 60-mesh screen were obtained, noted as R60/P40. The R60/P40 components were extracted by the mixture of benzene and alcohol according to TAPPI 204 cm-07. The extracted residues were used for the determination of the chemical composition through TAPPI 211 om-07 for ash, TAPPI 222 om-06 for Klason lignin, TAPPI 203 cm-09 for α-cellulose and TAPPI 249 cm-00 for holocellulose. The hemicellulose content was calculated from the difference between the contents of holocellulose and α-cellulose.

Preparation of transparent wood

The epoxy resin was mixed with a proper amount of curing agent. Then this mixture was used to impregnate the delignified wood chips under vacuum, and the impregnated samples were cured at room temperature for 72 hours to prepare the transparent wood chips.

Synthesis of g-C₃N₄ phosphors

The dicyandiamide in a crucible was heated to 550 °C at a rate of 5 °C/min in a muffle furnace, and then calcined for 2 hours. The resulting product was refluxed at 80°C in 5 mol/L concentrated nitric acid for 6 h, followed the centrifugation and wash until neutral. The products obtained were stripped with ultrasonic treatment in acetone solution, and the blue g-C₃N₄ phosphor was prepared after the centrifugation, noted as (g-C₃N₄ (B)).

The 2,4-diamino-6-phenyl-1,3,5-triazine in a quartz boat was heated to 400°C at a rate of 3°C/min in a tubular furnace, and calcined for 40 minutes. After being cooled to room temperature, the resulting products were dispersed with ultrasonic treatment in acetone solution, and the green g-C₃N₄ phosphor was obtained after the centrifugation, noted as g-C₃N₄ (G).

Preparation of white luminescent transparent wood

The g-C₃N₄ (B), g-C₃N₄ (G) and red phosphors purchased were dispersed in epoxy resin, respectively, and the blue epoxy resin (BER), green epoxy resin (GER) and red epoxy resin (RER) were obtained. The BER, GER and RER were mixed with a mass ratio of 4:2:1, and adding a proper amount of curing agent at the same time. Finally, this mixture was used to prepare the white luminescent transparent wood by the same method as the preparation of transparent wood, noted as g-C₃N₄ (W)@TW, and g-C₃N₄ (W) represents the white g-C₃N₄ phosphor.

Characterizations

Porosity and pore size distribution of wood chips were measured on a Micromeritics Autopore IV 9500 mercury porosimeter. Ultraviolet–visible absorption spectra and fluorescence spectra were recorded with an Agilent Carry 500 spectrophotometer and an Edinburgh F55 fluorescence spectrophotometer. The morphology was observed by Hitachi S-4800 field-emission scanning electron microscopy (SEM). The chemical structure of g-C₃N₄ was characterized by Fourier transform infrared (FTIR) spectra over a Bruker vector-2 spectrophotometer with the potassium bromide (KBr) assay method at the spectral range 400–4000 cm⁻¹. The phase structure of the products was determined by X-ray diffraction measurement (XRD, Rigaku, and D/MAX 2200) operated with Cu target radiation ($\lambda = 1.54 \text{ \AA}$).

Results And Discussion

Characteristics of delignified wood

The xylem in balsa wood is mainly composed of three types of cells: fibers, vessels, and rays (Fig. 2a). Easterling et al. and Da Silva et al. reported that the volume fraction of fibers and rays in balsa are about 80%–90% and 8%–15% respectively, with vessels making up the rest (Da 2007; Easterling 1982). The diameter of fibers is between 14 and 52 μm , while that of the vessels is between 189 and 352 μm , and the rays normally has a rectangular geometry when viewed from the cross section with the size of (14–23) $\mu\text{m} \times (29\text{--}58) \mu\text{m}$ (Borrega et al. 2015). The cell size of balsa wood used in this research is consistent with that described in the literatures (Fig. 2a and 2b). The diameter of pits on the cell wall varies from hundreds of nanometers to several microns (Fig. 2c). The pore size distribution shows that the pore diameter in nature balsa wood ranges from 500 nm to 350 μm (Fig. 2f), which is basically consistent with the observation of SEM.

Wood is mainly composed of three chemical components: cellulose, hemicellulose, lignin and additionally a small amount of inorganic substances, coloring pigments, tannins and other polyphenols. Among them, lignin, coloring pigments, tannins and other polyphenols have chromogenic groups, which can absorb the light with the wavelength of 380–780 nm in the visible light area and make the wood present the corresponding color. This is disadvantageous to the preparation of transparent wood. Therefore, the chromogenic substances must be removed to avoid the light absorption in order to obtain the high light transmittance. Coloring pigments, tannins and other polyphenols can be removed by dissolving in hot alkali solution, while lignin with high content and high relative molecular weight needs to be oxidized and degraded with strong oxidizing chemicals and then dissolved out of the wood chips.

In this study, the color of balsa wood chips changes from light brown to white after hot alkali extraction and delignification (Fig. 2a and 2d), the intercellular layer and fiber cell wall appear more loose compared with that of natural wood (Fig. 2b) and 2d), and lignin content decreases from 24.4% to 0.2% (Fig. 2e), indicating that most of the lignin had been removed. The porosity of wood chips increases from 87.2% to 96.8% due to the swelling of water and the dissolution of lignin and other components (Fig. 2e), and the

pore volume increases significantly in the range of 1-200 μm (Fig. 2g). The increase of small-size pore volume should be attributed to the swelling of fiber pits, the removal of lignin in middle lamella and cell wall, and the dissolution of some cellulose and hemicellulose. The increase of large-size pore volume should be attributed to the water swelling of cell lumen and the dissolution of contents in the lumen.

The increase of wood porosity and pore size after delignification can provide more channels for subsequent resin impregnation and improve the impregnation rate and uniformity.

Characteristics of $\text{g-C}_3\text{N}_4(\text{B})$ and $\text{g-C}_3\text{N}_4(\text{G})$

There are two basic units of triazine ring and 3-s-triazine ring in $\text{g-C}_3\text{N}_4$, and the two basic units extend infinitely to form a two-dimensional lamellar structure similar to graphene, which are combined by van der Waals force (Dong et al. 2014; Sun et al. 2019). The chemical structures of the $\text{g-C}_3\text{N}_4(\text{B})$ and $\text{g-C}_3\text{N}_4(\text{G})$ were confirmed by using FTIR spectra. It can be seen in Fig. 3a that the absorption peak near 808 cm^{-1} corresponds to the bending vibration absorption of triazine derivatives and the peak in the region of $1240\text{--}1650\text{ cm}^{-1}$ corresponds to the C-N aromatic heterocycle, and the peak between 3065 and 3270 cm^{-1} is the N-H stretching mode. The characteristic absorption peak of $\text{g-C}_3\text{N}_4(\text{G})$ is similar to that of $\text{g-C}_3\text{N}_4(\text{B})$, indicating that the main functional groups and structures are similar (Zhang et al. 2020; Jigyasa et al. 2021).

XRD analysis results in the Fig. 3b show that there are two characteristic peaks of $\text{g-C}_3\text{N}_4(\text{B})$ at 12.68° and 27.28° respectively, while the $\text{g-C}_3\text{N}_4(\text{G})$ has only a broad characteristic peak of 27.28° . The 12.68° is attributed to the (100) crystal faces and the 27.7° is ascribed to (002) crystal faces. The (100) peak results from the periodic in-plane structure stacking of aromatic systems. The (002) crystal faces are caused by the interaction of the stacking layers of triazine ring in the aromatic system. The decrease in the absorption peak area of the $\text{g-C}_3\text{N}_4(\text{G})$ is due to the reduction of the number of graphitic layers. Doping of benzene ring makes the absorption wider, which is due to the decrease of the plane size of the layer at the same time during the blocking effect (Zheng 2020; Porcu et al. 2020; Xu et al. 2019; Pattnaik 2019).

C_3N_4 is a typical polymer semiconductor, in which CN atoms are sp^2 hybridized to form a highly delocalized π conjugated system (Che et al. 2019). The Npz orbital and the Cpz orbital constitutes the highest occupied molecular orbital of $\text{g-C}_3\text{N}_4$ and the lowest unoccupied molecular orbital, respectively, with a band gap of $\sim 2.7\text{ eV}$ (Zhu et al. 2017; Tay et al). Therefore, the C_3N_4 phosphors can absorb blue and violet light with a wavelength less than 475 in the solar spectrum to produce fluorescence. The structure of $\text{g-C}_3\text{N}_4$ synthesized by different ways is different, and the performance will also change greatly. The luminescence performance of $\text{g-C}_3\text{N}_4(\text{B})$ and $\text{g-C}_3\text{N}_4(\text{G})$ is detected by fluorescence spectrophotometer as shown in Fig. 3c and 3d. The $\text{g-C}_3\text{N}_4(\text{B})$ emits blue light under the excitation of ultraviolet light, indicating that the phosphor can be effectively excited by ultraviolet light. When the excitation wavelength is 369 nm, the peak emission wavelength of $\text{g-C}_3\text{N}_4(\text{B})$ is 439 nm, and its CIE

coordinates are (0.1735, 0.1388 (Fig. 3c). The g-C₃N₄(G) emits green light under the excitation of ultraviolet light (Fig. 3d). It shows that the phosphor is also excited effectively in the ultraviolet region. When the excitation wavelength is 365 nm, the peak emission wavelength of g-C₃N₄(G) is 529 nm, and its CIE coordinates are (0.3128, 0.4755).

Both of the g-C₃N₄ (B) and the g-C₃N₄ (G) are relatively uniformly particles (Fig.3e and 3f). The particle size of g-C₃N₄ (B) is mainly distributed between 35~130 nm (Fig.3e), with an average of 77.36 nm and a dispersion coefficient of 0.122; While the particle size of g-C₃N₄ (G) is mainly distributed between 200~300nm (Fig.3f), with an average of 244.1 nm and a dispersion coefficient of 0.230. The g-C₃N₄ (B) is smaller than g-C₃N₄ (G), and its particle size is more evenly dispersed. During the preparation of transparent wood, g-C₃N₄ enters the adjacent cell wall or lumen with the resin through the pits or pores formed by dissolved lignin. The minimum pore size is about 500 nm in the [delignified](#) wood (Fig 2f), which is significantly larger than the particle sizes of g-C₃N₄ (B) and g-C₃N₄ (B) synthesized. Therefore, the synthesized fluorescent particles can be successfully entered into the [delignified](#) wood.

Light scattering effect of transparent wood

In the cell wall of delignified wood, there are many natural pores and micropores formed by dissolution of lignin, tannin and other substances, which can provide a channel for polymer impregnation (Zhu et al. 2016). After resin impregnation and curing, those pores/micropores, intercellular layer and cell lumen are filled with epoxy resin (Fig. 4a). Disappearance of the interfaces results in a significant reduction in the refraction, reflection and absorption of light, thus transparent wood is successfully prepared with good transparency (Fig. 4b and 4c).

To study the light scattering behavior of transparent wood, a single green beam with a wavelength of 532 nm is used as the source of incident light. When the incident light passes through the transparent wood, as shown in Fig. 4d, light scattering is perpendicular to the wood growth direction and appears ellipsoid, while the light scattering behavior of glass is very weak only to form a spot in Fig. 4g. When the incident light is in parallel to the wood fiber growth direction, it can propagate along the wood fiber growth direction (Fig. 4e). Whether the angle of incident light makes any transformation, the entire plane of transparent wood can be illuminated (Fig. 4f). This is because the scattering occurs on the interface between the wood cell wall and the impregnated polymer and in the pore of wood cell wall when the photons are transported inside the material (Li et al. 2016; Liu 2017). When a parallel light passes through the glass, the light forms a light column inside, and the propagation angle of light column varies with the angle of incident light as shown in Fig. 4h and 4i. This suggests that stronger light scattering effects in the wood interior can achieve directional scattering compared to glass. Therefore, transparent wood has the excellent development prospect in the areas of photo shaping diffusers, optical building materials and lighting.

Characteristics of g-C₃N₄(W)@TW

After the $g-C_3N_4$ (B), $g-C_3N_4$ (G) and red phosphors were mixed with epoxy resin and the delignified wood was impregnated, the $g-C_3N_4$ (W)@TW was obtained as shown in Fig. 5a. In the natural light, the letters below the $g-C_3N_4$ (W)@TW can be clearly observed, so that the $g-C_3N_4$ (W)@TW shows excellent light transmittance. SEM image of $g-C_3N_4$ (W)@TW shows that phosphor particles are evenly distributed in the cured epoxy resin (Fig. 5b). Under the irradiation of ultraviolet light, the $g-C_3N_4$ (W)@TW emits bright white light (Fig. 5c).

The traditional white principle of the light emitting diode is that when the current stimulates the blue photons through the blue phosphor, the blue photon binds to the surface yellow phosphor to produce white light, but it is discontinuous due to the instability of the electrons. Photoluminescent transparent wood enables ultraviolet light to bind directly with the phosphors inside the wood to produce white light, and the combination of the three phosphors avoids the disconnection of the beams due to the uneven proportion of the phosphors. The $g-C_3N_4$ (W)@TW produced by mixing of $g-C_3N_4$ (B), $g-C_3N_4$ (G) and red phosphors can produce the white light, so that it has a certain development space in the field of lighting and optoelectronic devices.

The UV-vis spectrophotometry was used to detect the light transmittance and haze of $g-C_3N_4$ (W)@TW (Fig. 5d). The light transmittance of natural wood is negligible because of the light scattering between pore interfaces and the interface of different chemical components, and the absorption of light by lignin in the wood cell wall and middle lamella. Lignin removed, the absorption of light reduces and the transmittance of delignified wood slightly increases. When the delignified wood is impregnated with the epoxy resin with a refractive index similar to that of cellulose, their refractive index mismatch decreases and the transparent wood presents a higher transmittance (Zhang et al. 2020). As shown in the Fig. 5d, the light transmittances of TW and $g-C_3N_4$ (G)@TW are relatively high, due to the decrease in refraction after polymer impregnation and the less lignin content (Wu et al. 2020).

The hazes of impregnated transparent wood are shown also in Fig. 5d. Compared with other high transmittance materials such as glass and plastics, transparent wood not only has high transmittance, but also has high haze (Wu et al. 2019). Moreover, the haze of $g-C_3N_4$ (W)@TW is similar to that of the transparent wood, indicating that the fluorescent quantum dots do not significantly affect the haze of transparent wood.

The heat flux can propagate along the transverse and longitudinal direction of wood lumen because both the natural wood and the transparent wood are anisotropic materials (Qiu et al. 2020). It can be seen that the thermal conductivity of natural wood is much weaker than that of glass as shown in Fig. 5e. The thermal conductivity of $g-C_3N_4$ (W)@TW is slightly higher than that of natural wood but still much lower than that of glass. This suggests that glass is a heat conductive material, while natural wood and transparent wood are insulating materials. High thermal conductivity of glass leads to a higher heat flow around the glass, which makes the temperature of surrounding environment higher (Mi et al 2020). As an insulating material, wood can effectively cool down the temperature of surrounding environment and

produce a temperature difference from the external temperature. The thermal conductivity of the transparent wood-based composites is low, which may be phonon scattering effects caused by the phonon resistance between the wood cell wall and multiple interfaces (Zhang 2019).

The g-C₃N₄ (W)@TW with high light transmittance, high haze, and low thermal conductivity provides a feasible solution for the sustainable development of transparent wood and the application of transparent wood to photoelectric materials.

Conclusion

In this study, the chromogenic group of low-density balsa wood was removed by alkali treatment and delignification, and its pore size and porosity were increased at the same time to obtain a transparent wood substrate. The graphite phase carbon nitrides with blue and green color were prepared by thermal polymerization through structural regulation of raw materials. The luminescent transparent wood was prepared by impregnating delignified balsa wood with resin and mixture of blue, green and red phosphors according to the mass ratio of 4:2:1. Luminescent transparent wood with high transmittance and high haze are obtained. Additionally, the impregnation of epoxy resin and luminescent phosphors is slightly effect on the thermal conductivity of balsa wood. The luminescent transparent wood not only retains the excellent properties of transparent wood, but also provides the possibility to apply for optoelectronic field.

Declarations

Disclosure statement

There are no conflicts to declare.

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References

1. Borrega M, Ahvenainen P, Serimaa R, Gibson L (2015) Composition and structure of balsa (*Ochroma pyramidale*) wood. *Wood science and technology* 49(2): 403-420. <https://doi.org/10.1007/s00226-015-0700-5>
2. Chave J, Muller-Landau HC, Baker TR, Easdale TA, Steege H, Webb CO (2006) Regional and phylogenetic variation of wood density across 2456 neotropical tree species. *Ecological applications* 16(6): 2356-2367. [https://doi-org.proxy.library.carleton.ca/10.1890/1051-0761\(2006\)016\[2356:RAPVOW\]2.0.CO;2](https://doi-org.proxy.library.carleton.ca/10.1890/1051-0761(2006)016[2356:RAPVOW]2.0.CO;2)

3. Che H, Liu C, Dong H, Li C, Liu X, Che G (2019) Synthesis of mesoporous g-C₃N₄/S-PAN π -conjugation heterojunction via sulfur-induced cyclization reaction for enhanced photocatalytic H₂ production. *International Journal of Hydrogen Energy* 44(36): 20029-20041. <https://doi.org/10.1016/j.ijhydene.2019.06.038>
4. Chen C, Kuang Y, Zhu S, Burgert I, Keplinger T, Gong A, Li T, Berglund L, Eichhorn SJ, Hu L (2020) Structure–property–function relationships of natural and engineered wood. *Nature Reviews Materials* 5 (9): 642-666. <https://doi.org/10.1038/s41578-020-0195-z>
5. Cheng Z, Guan H, Meng J, Wang X (2020) Dual-Functional Porous Wood Filter for Simultaneous Oil/Water Separation and Organic Pollutant Removal. *ACS Omega* 5 (23): 14096-14103. <https://doi-org.proxy.unimib.it/10.1021/acsomega.0c01606>
6. Da SA, Kyriakides S (2007) Compressive response and failure of balsa wood. *International Journal of Solids and Structures* 44(25-26): 8685-8717. <https://doi.org/10.1016/j.ijsolstr.2007.07.003>
7. Dong G, Zhang Y, Pan Q, et al. (2014) A fantastic graphitic carbon nitride (g-C₃N₄) material: electronic structure, photocatalytic and photoelectronic properties. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews* 20: 33-50. <https://doi.org/10.1016/j.jphotochemrev.2014.04.002>
8. Easterling KE, Harrysson R, Gibson LJ, et al. (1982) On the mechanics of balsa and other woods. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* 383(1784): 31-41. <https://doi-org.proxy.unimib.it/10.1098/rspa.1982.0118>
9. Fletcher MI (1951) Balsa—production and utilization. *Economic Botany* 5(2): 107-125. <https://doi-org.proxy.unimib.it/10.1007/BF02984770>
10. Fu Q, Chen Y, Sorieul M (2019) Wood-Based Flexible Electronics. *ACS Nano* 14 (3): 3528-3538. <https://doi-org.cbu.idm.oclc.org/10.1021/acsnano.9b09817>
11. Fu Q, Tu K, Goldhahn C, Keplinger T, Adobes-Vidal M, Sorieul M, Burgert I (2020) Luminescent and Hydrophobic Wood Films as Optical Lighting Materials. *ACS Nano* 14 (10): 13775-13783. <https://doi-org.cbu.idm.oclc.org/10.1021/acsnano.0c06110>
12. Gaddam S K, Pothu R, Boddula R (2019) Graphitic carbon nitride (g-C₃N₄) reinforced polymer nanocomposite systems - A review. *Polymer Composites* 41 (2): 430-442. <https://doi-org.cbu.idm.oclc.org/10.1002/pc.25410>
13. Gan W, Xiao S, Gao L, Gao R, Li J, Zhan X (2017) Luminescent and Transparent Wood Composites Fabricated by Poly(methyl methacrylate) and γ -Fe₂O₃@YVO₄:Eu³⁺ Nanoparticle Impregnation. *ACS Sustainable Chemistry & Engineering* 5 (5): 3855-3862. <https://doi-org.cbu.idm.oclc.org/10.1021/acssuschemeng.6b02985>
14. Guo Q, Wei M, Zheng Z, Huang X, Song X, Qiu SB, Yang XB, Liu X, Qiu J, Dong G (2019) Full-Color Chemically Modulated g-C₃N₄ for White-Light-Emitting Device. *Advanced Optical Materials* 7 (21): 1900775. <https://doi-org.cbu.idm.oclc.org/10.1002/adom.201900775>

15. Hoglund M, Johansson M, Sychugov I, Berglund L A (2020) Transparent Wood Biocomposites by Fast UV-Curing for Reduced Light-Scattering through Wood/Thiol-ene Interface Design. *ACS Appl Mater Interfaces* 12 (41): 46914-46922. <https://doi-org.cbu.idm.oclc.org/10.1021/acsami.0c12505>
16. Jigyasa, Singh H, Rajput J K (2021) Graphitic carbon nitride nanosheets (g-C₃N₄ NS) as dual responsive template for fluorescent sensing as well as degradation of food colorants. *Food Chem.* 343: 128451. <https://doi.org/10.1016/j.foodchem.2020.128451>
17. Li T, Zhu M, Yang Z, Song J, Dai J, Yao Y, Luo W, Pastel G, Yang B, Hu L (2016) Wood Composite as an Energy Efficient Building Material: Guided Sunlight Transmittance and Effective Thermal Insulation. *Advanced Energy Materials* 6 (22): 1601122. <https://doi-org.cbu.idm.oclc.org/10.1002/aenm.201601122>
18. Li Y, Cheng M, Jungstedt E, Xu B, Sun L, Berglund L (2019) Optically Transparent Wood Substrate for Perovskite Solar Cells. *ACS Sustain Chem Eng* 7 (6): 6061-6067. <https://doi-org.cbu.idm.oclc.org/10.1021/acssuschemeng.8b06248>
19. Li Y, Fu Q, Yang X, Berglund L (2018) Transparent wood for functional and structural applications. *Philos Trans A Math Phys Eng Sci* 376 (2112): 20170182. <https://doi.org/10.1098/rsta.2017.0182>
20. Li Y, Vasileva E, Sychugov I, Popov S, Berglund L (2018) Optically Transparent Wood: Recent Progress, Opportunities, and Challenges. *Advanced Optical Materials* 6 (14): 1800059. <https://doi-org.cbu.idm.oclc.org/10.1002/adom.201800059>
21. Liu KK, Jiang Q, Tadeipalli S, Raliya R, Biswas P, Naik RR, Singamaneni S (2017) Wood-Graphene Oxide Composite for Highly Efficient Solar Steam Generation and Desalination. *ACS Appl Mater Interfaces* 9 (8): 7675-7681. <https://doi-org.cbu.idm.oclc.org/10.1021/acsami.7b01307>
22. Liu Y, Yang H, Ma C, Luo S, Xu M, Wu Z, Li W, Liu S (2020) Luminescent Transparent Wood Based on Lignin-Derived Carbon Dots as a Building Material for Dual-Channel, Real-Time, and Visual Detection of Formaldehyde Gas. *ACS Appl Mater Interfaces* 12 (32): 36628-36638. <https://doi-org.cbu.idm.oclc.org/10.1021/acsami.0c10240>
23. Mi RY, Li T, Dalgo D, Chen CJ, Kuang YD, He SM, Zhao XP, Xie WQ, Gan WT, Zhu JY, Srebric J, Yang RG, Hu L B (2020) A Clear, Strong, and Thermally Insulated Transparent Wood for Energy Efficient Windows. *Advanced Functional Materials* 30 (1): 1907511. <https://doi-org.cbu.idm.oclc.org/10.1002/adfm.201907511>
24. Pattnaik SP, Behera A, Acharya R, Parida K (2019) Green exfoliation of graphitic carbon nitride towards decolourization of Congo-Red under solar irradiation. *Journal of Environmental Chemical Engineering* 7 (6): 103456. <https://doi.org/10.1016/j.jece.2019.103456>
25. Porcu S, Roppolo I, Salaun M, Sarais G, Barbarossa S, Casula MF, Carbonaro CM, Ricci PC (2020) Come to light: Detailed analysis of thermally treated Phenyl modified Carbon Nitride Polymorphs for bright phosphors in lighting applications. *Applied Surface Science* 504: 144330. <https://doi.org/10.1016/j.apsusc.2019.144330>

26. Qiu Z, Wang S, Wang Y, Li J, Xiao Z, Wang H, Liang D, Xie Y (2020) Transparent wood with thermo-reversible optical properties based on phase-change material. *Composites Science and Technology* 200: 108407. <https://doi.org/10.1016/j.compscitech.2020.108407>
27. Rao X, Dou H, Long D, Zhang Y (2020) $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ nanocomposites for photocatalytic degradating gas phase formaldehyde at continuous flow under 420 nm LED irradiation. *Chemosphere* 244: 125462. <https://doi.org/10.1016/j.compscitech.2020.108407>
28. Sun D, Chi D, Yang Z, et al. (2019) Mesoporous $\text{g-C}_3\text{N}_4/\text{Zn-Ti}$ LDH laminated van der Waals heterojunction nanosheets as remarkable visible-light-driven photocatalysts. *International Journal of Hydrogen Energy* 44(31): 16348-16358. <https://doi.org/10.1016/j.ijhydene.2019.04.275>
29. Tang Q, Fang L, Wang Y, Zou M, Guo W (2018) Anisotropic flexible transparent films from remaining wood microstructures for screen protection and AgNW conductive substrate. *Nanoscale* 10 (9): 4344-4353. <https://doi-org.cbu.idm.oclc.org/10.1039/C7NR08367J>
30. Tay Q, Kanhere P, Ng C F, et al. (2015) Defect engineered $\text{g-C}_3\text{N}_4$ for efficient visible light photocatalytic hydrogen production. *Chemistry of Materials* 27(14): 4930-4933. <https://doi-org.cbu.idm.oclc.org/10.1021/acs.chemmater.5b02344>
31. Wang A, Lee C, Bian H, Li Z, Zhan Y, He J, Wang Y, Lu J, Li YY (2017) Synthesis of $\text{g-C}_3\text{N}_4/\text{Silica}$ Gels for White-Light-Emitting Devices. *Particle & Particle Systems Characterization* 34 (1): 1600258. <https://doi-org.cbu.idm.oclc.org/10.1002/ppsc.201600258>
32. Wang M, Li R, Chen G, Zhou S, Feng X, Chen Y, He M, Liu D, Song T, Qi H (2019) Highly Stretchable, Transparent, and Conductive Wood Fabricated by in Situ Photopolymerization with Polymerizable Deep Eutectic Solvents. *ACS Appl Mater Interfaces* 11 (15): 14313-14321. <https://doi-org.cbu.idm.oclc.org/10.1021/acsami.9b00728>
33. Wu J, Wu Y, Yang F, Tang C, Huang Q, Zhang J (2019) Impact of delignification on morphological, optical and mechanical properties of transparent wood. *Composites Part A: Applied Science and Manufacturing* 117: 324-331. <https://doi.org/10.1016/j.compositesa.2018.12.004>
34. Wu Y, Wu J, Yang F, Tang C, Huang Q (2019) Effect of H_2O_2 Bleaching Treatment on the Properties of Finished Transparent Wood. *Polymers (Basel)* 11 (5): 776. <https://doi.org/10.3390/polym11050776>
35. Wu Y, Zhou J, Huang Q, et al. (2020) Study on the colorimetry properties of transparent wood prepared from six wood species. *ACS omega* 5(4): 1782-1788. <https://doi-org.cbu.idm.oclc.org/10.1021/acsomega.9b02498>
36. Wu Y, Zhou JC, Huang QT, Yang F, Wang YJ, Wang J (2020) Study on the Properties of Partially Transparent Wood under Different Delignification Processes. *Polymers* 12 (3): 14. <https://doi.org/10.3390/polym12030661>
37. Xu Q, Xu G, Yu Q, Yang K, Li H (2019) Nitrogen self-doped high specific surface area graphite carbon nitride for photocatalytic degradating of methylene blue. *Journal of Nanoparticle Research* 21 (11): 1-13. <https://doi-org.proxy.library.carleton.ca/10.1007/s11051-019-4679-y>

38. Yang H, Li X, Wang X, Chen W, Bian W, Choi MMF (2018) Silver-doped graphite carbon nitride nanosheets as fluorescent probe for the detection of curcumin. *Luminescence* 33 (6): 1062-1069. <https://doi-org.proxy.library.carleton.ca/10.1002/bio.3509>
39. Zhang H, Zheng D, Cai Z, Song Z, Xu Y, Chen R, Lin C, Guo L (2020) Graphitic Carbon Nitride Nanomaterials for Multicolor Light-Emitting Diodes and Bioimaging. *ACS Applied Nano Materials* 3 (7), 6798-6805. <https://doi-org.proxy.library.carleton.ca/10.1021/acsanm.0c01197>
40. Zhang L, Wang A, Zhu T, Chen Z, Wu Y, Gao Y (2020) Transparent Wood Composites Fabricated by Impregnation of Epoxy Resin and W-Doped VO₂ Nanoparticles for Application in Energy-Saving Windows. *ACS Appl Mater Interfaces* 12 (31): 34777-34783. <https://doi-org.proxy.library.carleton.ca/10.1021/acsami.0c06494>
41. Zhang T, Yang P, Chen M, Yang K, Cao Y, Li X, Tang M, Chen W, Zhou X (2019) Constructing a Novel Electroluminescent Device with High-Temperature and High-Humidity Resistance based on a Flexible Transparent Wood Film. *ACS Appl Mater Interfaces* 11 (39): 36010-36019. <https://doi-org.proxy.library.carleton.ca/10.1021/acsami.9b09331>
42. Zhang T, Yang P, Li Y, Cao Y, Zhou Y, Chen M, Zhu Z, Chen W, Zhou X (2019) Flexible Transparent Sliced Veneer for Alternating Current Electroluminescent Devices. *ACS Sustainable Chemistry & Engineering* 7 (13): 11464-11473. <https://doi-org.proxy.library.carleton.ca/10.1021/acssuschemeng.9b01129>
43. Zheng Z, Zeng Z, Guo Q, Pan Q, Qiu J, Dong G (2020) Controllable synthesis of Eu³⁺-doped Y₂O₃ nanocrystal/g-C₃N₄ composites with tunable fluorescence. *Journal of the American Ceramic Society* 103 (8): 4411-4419. <https://doi-org.proxy.library.carleton.ca/10.1111/jace.17130>
44. Zhu B, Zhang J, Jiang C, et al. (2017) First principle investigation of halogen-doped monolayer g-C₃N₄ photocatalyst. *Applied Catalysis B: Environmental* 207: 27-34. <https://doi-org.proxy.library.carleton.ca/10.1016/j.apcatb.2017.02.020>
45. Zhu M, Song J, Li T, Gong A, Wang Y, Dai J, Yao Y, Luo W, Henderson D, Hu L (2016) Highly Anisotropic, Highly Transparent Wood Composites. *Adv Mater* 28 (26): 5181-5187. <https://doi-org.proxy.library.carleton.ca/10.1002/adma.201600427>
46. Zhu T, Sheng J, Chen J, et al. (2021) Staining of wood veneers with anti-UV property using the natural dye extracted from *Dalbergia cochinchinensis*. *Journal of Cleaner Production* 284: 124770. <https://doi.org/10.1016/j.jclepro.2020.124770>

Figures

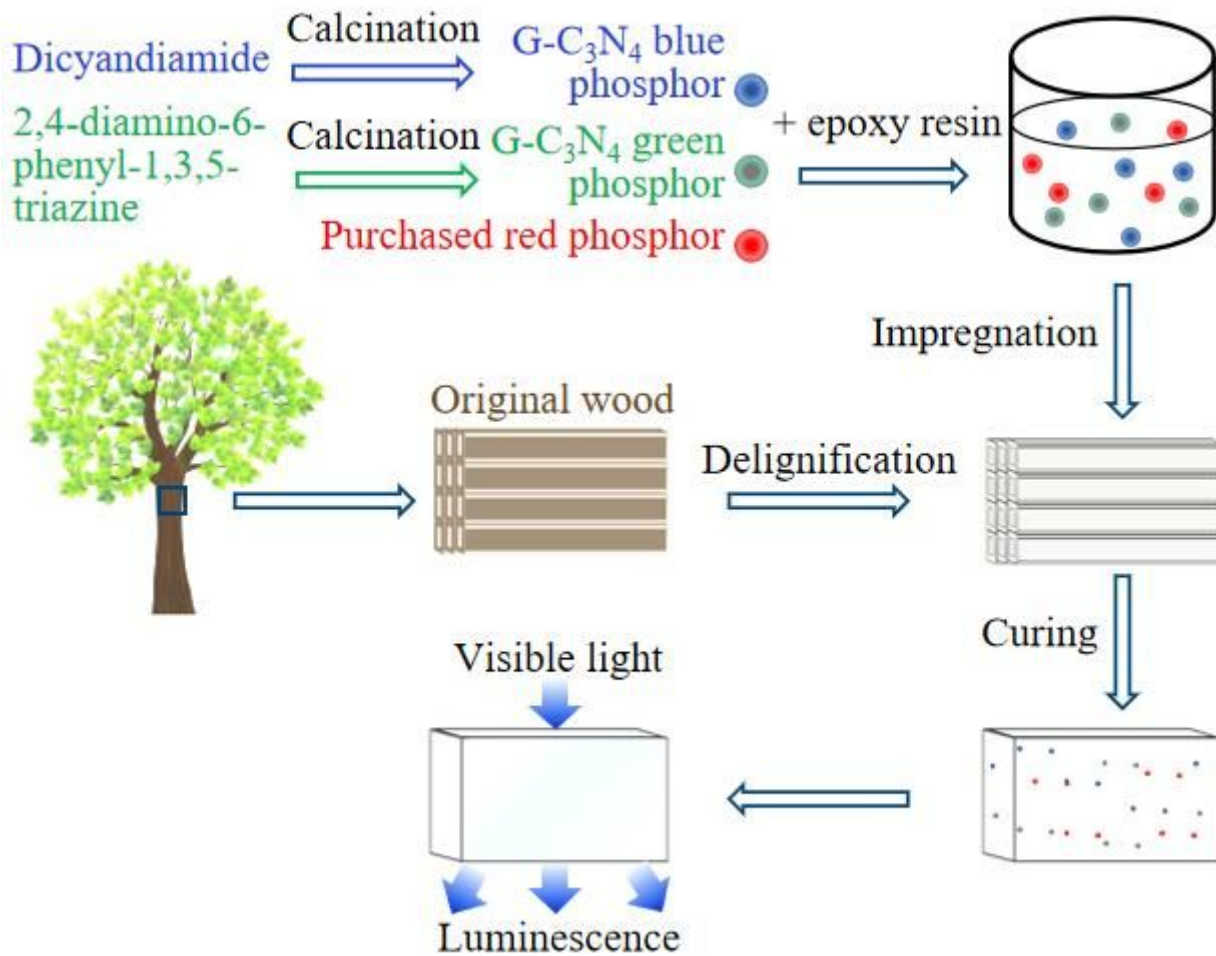


Figure 1

Schematic illustration of the preparation for white luminescent transparent wood

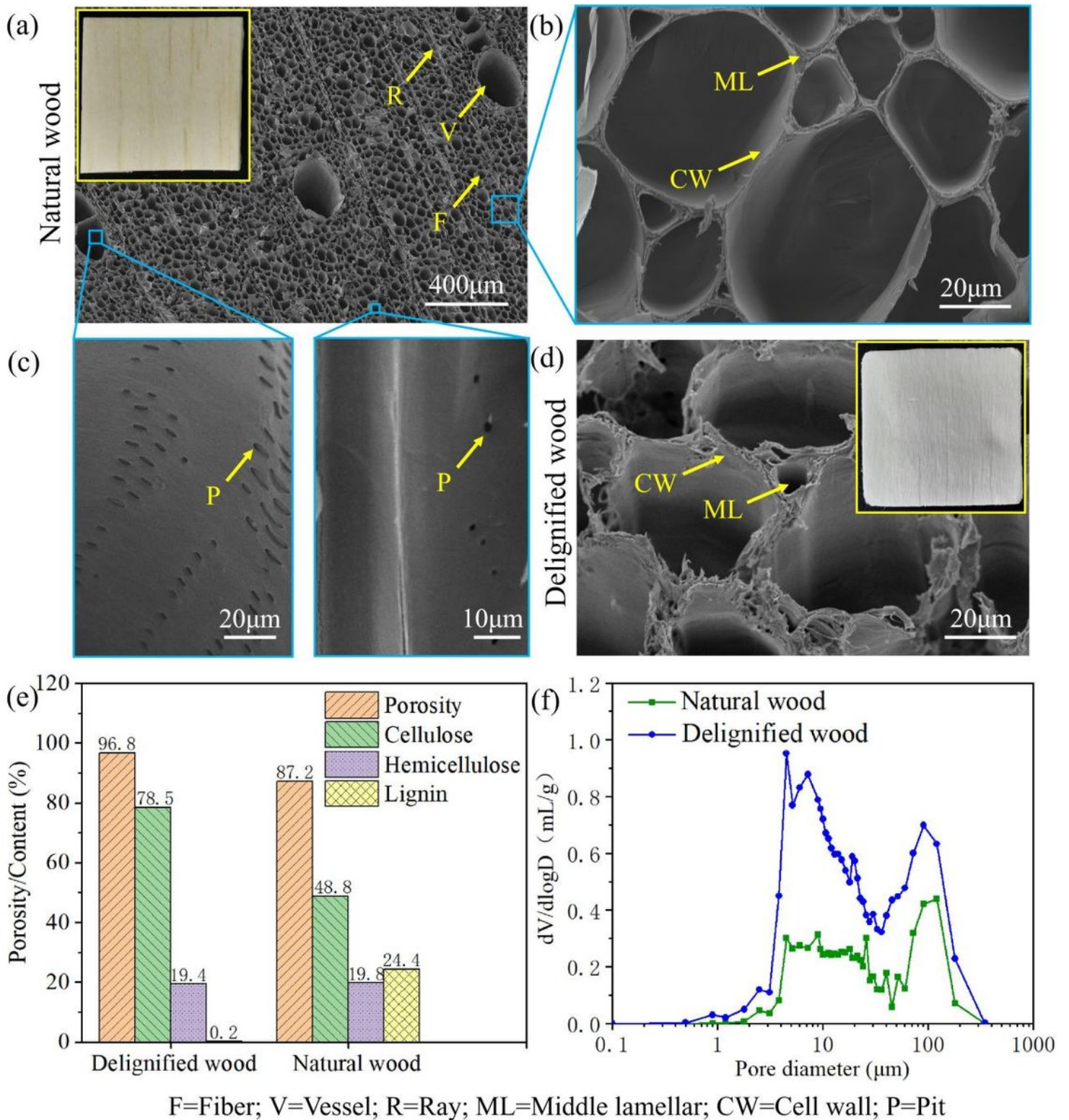


Figure 2

(a) SEM image and photo of natural balsa wood; (b) Local magnification for SEM image of natural balsa wood; (c) SEM image of pits in cell wall of natural balsa wood; (d) SEM image and photo of delignified balsa wood; (e) Chemical constituent analysis and porosity of balsa wood; (d) Pore size distribution of balsa wood

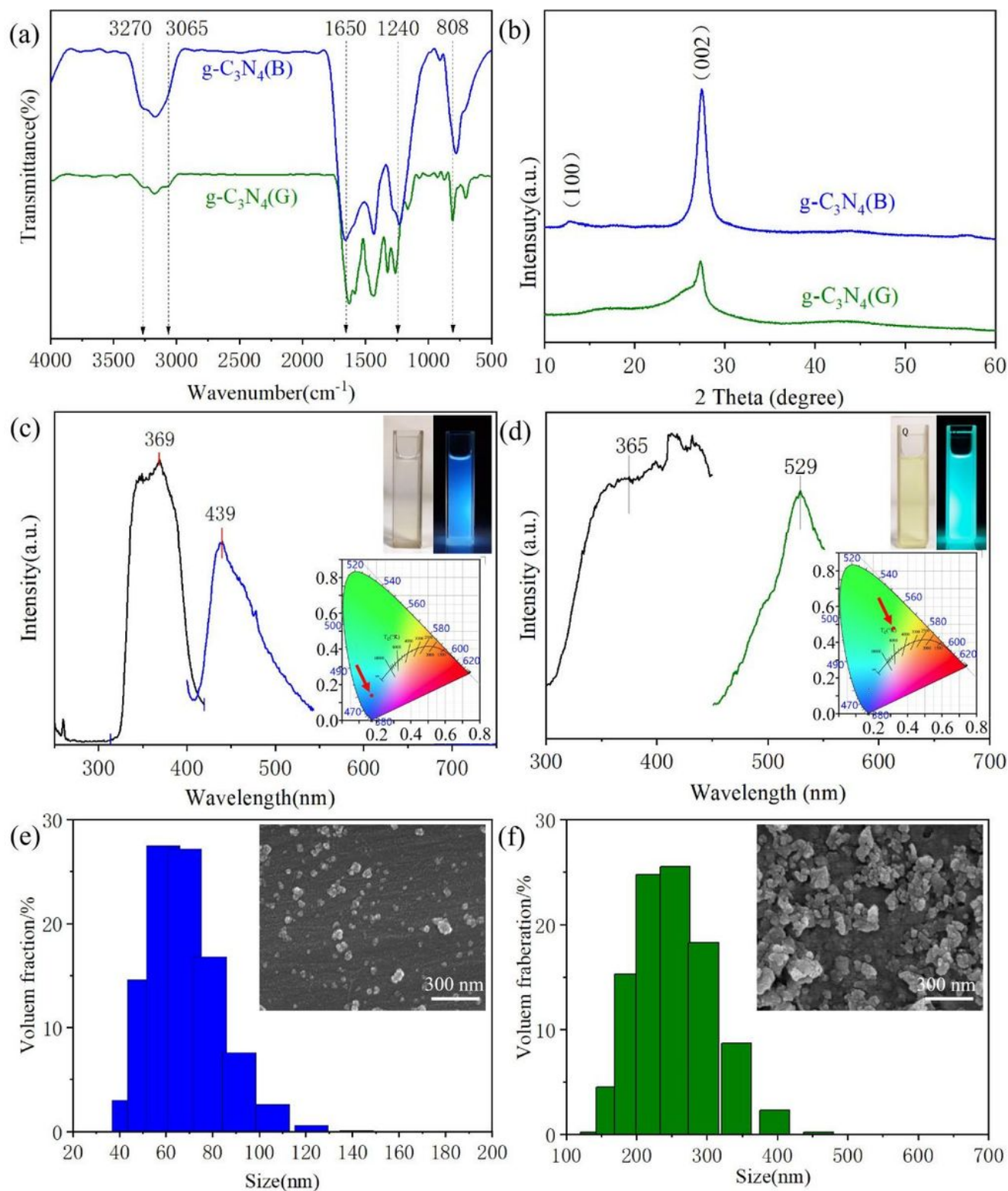


Figure 3

(a) FTIR of the $g\text{-C}_3\text{N}_4(\text{B})$ and $g\text{-C}_3\text{N}_4(\text{G})$; (b) XRD of the $g\text{-C}_3\text{N}_4(\text{B})$ and $g\text{-C}_3\text{N}_4(\text{G})$; (c) The excitation spectrum and emission spectrum of $g\text{-C}_3\text{N}_4(\text{B})$; (d) The excitation spectrum and emission spectrum of $g\text{-C}_3\text{N}_4(\text{G})$; (e) Size distribution and SEM photo of $g\text{-C}_3\text{N}_4(\text{B})$; (f) Size distribution and SEM photo of $g\text{-C}_3\text{N}_4(\text{G})$

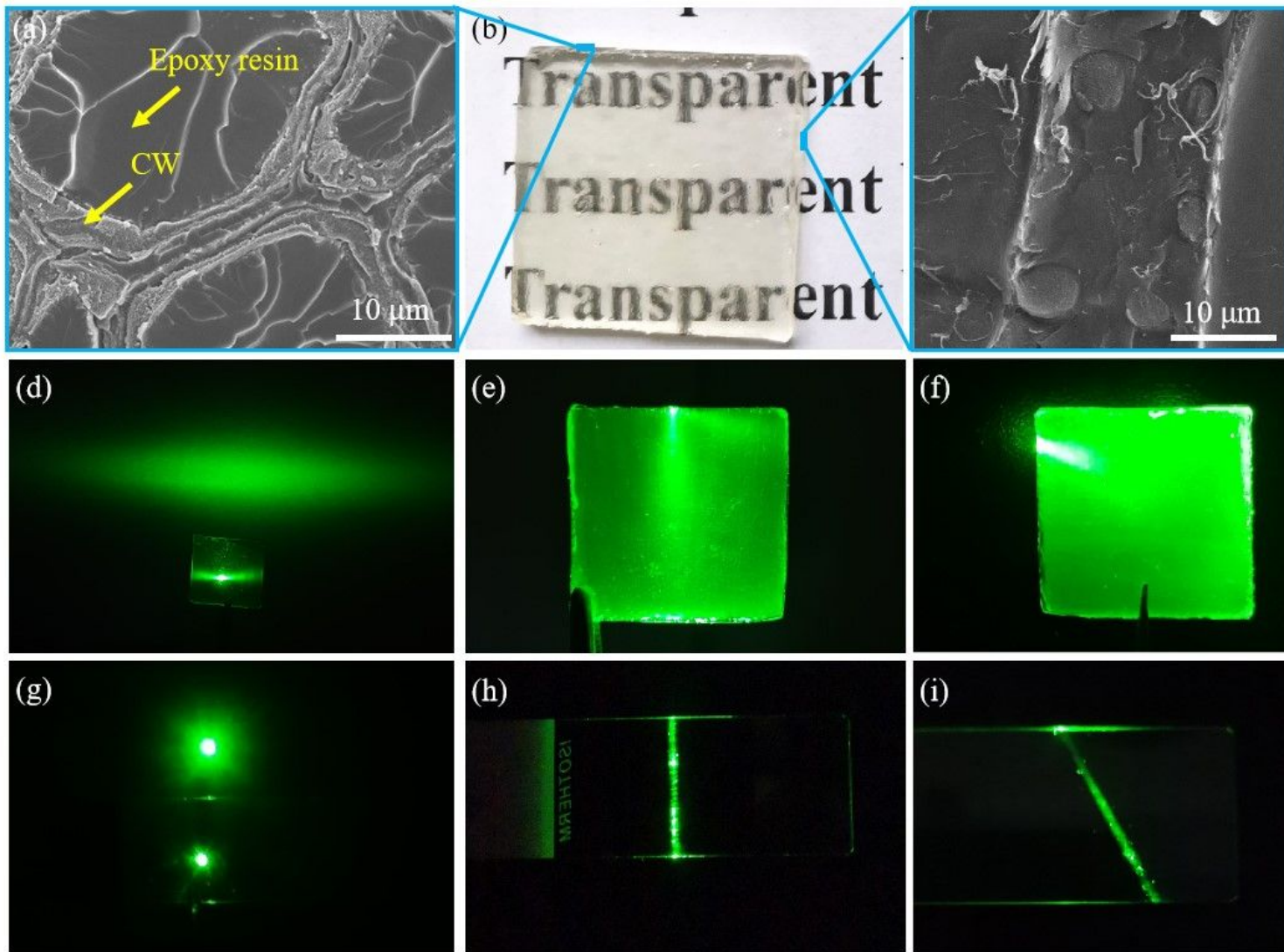


Figure 4

(a) Glass; (b) Transparent wood; (c) SEM image of transparent wood; (d-f) Light illumination diagram of transparent wood at vertical, parallel and 45° angles; (g-i) Light illumination diagram of glass at vertical, parallel and 45° angles

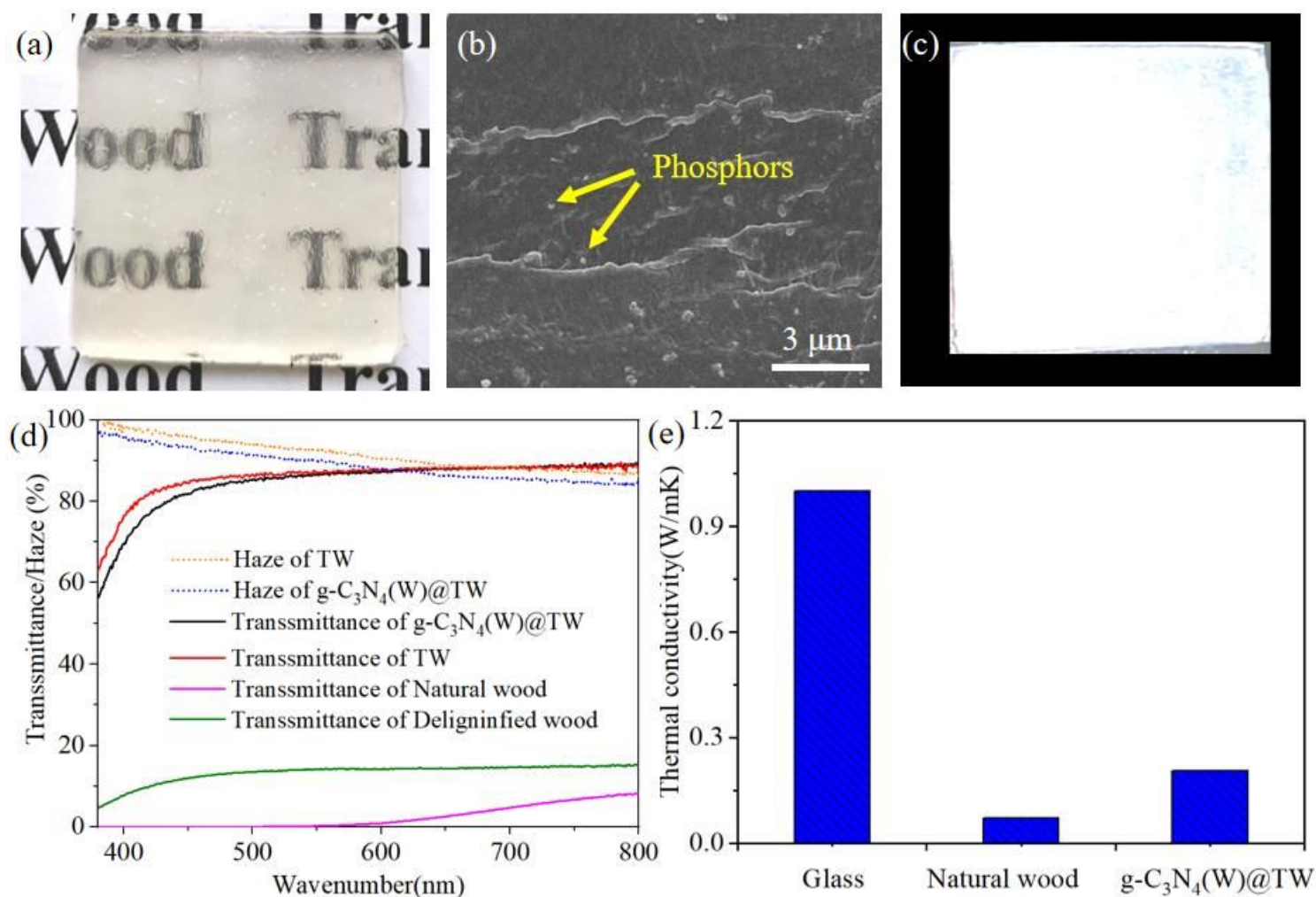


Figure 5

(a) The $g-C_3N_4(W)@TW$; (b) SEM image of $g-C_3N_4(W)@TW$; (c) The $g-C_3N_4(W)@TW$ under the ultraviolet light excitation; (d) Transmittance and haze of the $g-C_3N_4(W)@TW$; (e) Thermal conductivity of the $g-C_3N_4(W)@TW$