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alternatives.

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Organic π -conjugated polymers (CPs) have been intensively explored for a variety of critical photocatalytic applications in the past few years. Nevertheless, CPs for efficient CO₂ photoreduction have been rarely reported, which is mainly due to the lack of suitable polymers with sufficient solar light harvesting ability, appropriate energy level alignment and good activity and selectivity in multi-electron-transfer photoreduction of CO2 reaction. We report here the rational design and synthesis of two novel triphenylamine (TPA) based conjugated microporous polymers (CMPs), which can efficiently catalyze the reduction of CO₂ to CO using water vapor as an electron donor under ambient conditions without adding any co-catalyst. Nearly 100% selectivity and a high CO production rate of 37.15 μ mol h⁻¹ g⁻¹ are obtained for OXD-TPA, which is significantly better than that for BP-TPA (0.9 μ mol h⁻¹ g⁻¹) as a result of co-monomer change from biphenyl to 2,5-diphenyl-1,3,4-oxadiazole. This difference could be mainly ascribed to the synergistic effect of a decreased optical band gap, improved interface charge transfer and increased CO2 uptake for OXD-TPA. This contribution is expected to spur further interest in the rational design of porous conjugated polymers for CO2 photoreduction.

For the past few decades, artificial photocatalysis has been well established as a sustainable technology for CO2 conversion into carbonaceous chemical fuels such as CO, CH₃OH, CH₄, etc.¹⁻⁶ The technology is particularly appealing as it not only holds great promise to handle environmental issue caused by excess CO2 release, but also provides fuels for energy supply. However, high energy input is required for CO2 transformation owing to its remarkable stability with the dissociation energy of C=O bond up to 750 kJ mol⁻¹,6 which

Conjugated microporous polymers (CMPs), a subclass of structurally diverse polymeric materials, have many advantages such as permanent porosity, large surface area, strong visible light activity, facile synthesis, tunable optoelectronic properties, and high chemical and thermal stability, making them attractive candidates for a range of applications, such as gas sequestration and separation,11-15 heterogeneous catalytic sensing, 21,22 and energy storage conversion. 23-27 Recent studies have revealed that porous conjugated polymers (CPs) are promising photocatalysts for CO₂ reduction and their photocatalytic activities could be effectively enhanced by rational molecular design. For instance, Liu et al. reported photocatalytic CO2 reduction using a series of pyrene-based porous CPs in a CO2-saturated ionic liquid, which yielded CO with a rate of 47.37 µmol h⁻¹ g⁻¹ and reaction selectivity reached 98.3% (>420 nm).28 By copolymeriza-

could be improved to give a maximum CO production rate of

18.2 μ mol h⁻¹ g⁻¹ with 81.6% selectivity in the presence of

CoCl₂ and dipyridyl as the co-catalysts.²⁹ Crystalline covalent

organic framework (COF) based CO2-reduction photocatalysts were reported by Huang et al., in which Re(bpy)(CO)3Cl was incorporated into the 2D COF to reduce CO₂ using triethanol-

amine as a sacrificial agent and 98% selectivity was

obtained.³⁰ Despite this exciting progress, these CO₂ reduction

reactions were carried out in CO2-saturated liquid media,

which required the use of organic electron donors, co-catalysts

or ionic liquids, adding cost and complexity. Moreover, the

limited solubility of CO2 in liquid media is unfavorable for

makes it difficult to develop efficient photocatalysts. Since the pioneering report of heterogeneous CO2 photoreduction using

TiO₂ as the catalyst, numerous inorganic semiconductors

have been under active exploration. However, most inorganic

photocatalysts suffer from limited tunability, potential heavy metal toxicity and wide band gap, 7-10 which hinder their prac-

tical applications and thus require the exploration of

reaction. 16-20 tion between 2,4,6-triphenyl-1,3,5-triazine and different comonomers, the charge separation of the resulting polymers

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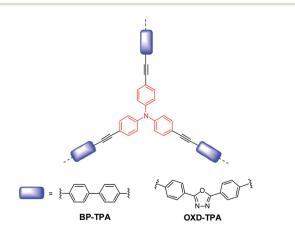
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achieving high reaction efficiency. By contrast, the reduction reaction performed on a gas-solid interface relies on CO2 chemisorption and activation by the photocatalysts, which eliminates the need for liquid media. This simple and environmentally-friendly approach uses only a trace amount of water vapor as the electron donor, which significantly inhibits the competing process of water reduction and favors the selectivity of CO2 reduction.^{1,3} However, to the best of our knowledge, the exploration of efficient polymers for CO2 reduction on a gassolid system remains a great challenge.31 Very recently, Eosin Y-based conjugated porous polymers were developed for CO2 photoreduction, which resulted in a CO production rate of 33 µmol h⁻¹ g⁻¹ with 92% selectivity.³¹ To achieve better photocatalytic performance, new polymers and useful molecular design strategies to reveal the critical parameters that control their photoactivities are highly desirable.

In this study, we present two specially designed CMPs as visible-light-active photocatalysts for the reduction of CO2 to CO only in the presence of water vapor under ambient conditions. The polymer structures are shown in Scheme 1. Triphenylamine (TPA) based CMPs were developed owing to their inherent advantages of high surface area for effective CO₂ absorption, facile preparation, and fine optimization of energy levels. 32,33 The optical band gaps of the as-prepared CMPs could be tuned from 2.38 to 2.22 eV by replacing biphenyl (BP) with 2,5-diphenyl-1,3,4-oxadiazole (OXD). More importantly, the CO production rate could be enhanced to 37.15 μ mol h⁻¹ g⁻¹ with ~100% selectivity under visible light irradiation (>420 nm). In addition, we provide a comprehensive understanding of the photocatalytic activity of polymers by complementary experimental and computational studies, which is critical for future development of conjugated polymers for CO₂ photoreduction.

The synthetic details and characterization of the monomers and conjugated microporous polymers are given in the ESI.† Tris(4-ethynylphenyl)amine was prepared by the Pd(II)-catalyzed coupling of tris(4-bromophenyl)amine and ethynyltrimethylsilane and subsequent deprotection promoted by K₂CO₃.³⁴ Starting from 4-bromobenzoyl chloride, 2,5-bis(4-bro-



Scheme 1 Chemical structures of the conjugated microporous polymers for CO₂ photoreduction in this study.

mophenyl)-1,3,4-oxadiazole was obtained in three high yielding steps as depicted in Scheme S1.† A condensation reaction between 4-bromobenzoyl chloride and hydrazine hydrate afforded 1,2-bis(4-bromobenzoyl)hydrazide, followed by cyclodehydration to give 2,5-bis(4-bromophenyl)-1,3,4-oxadiazole in 71% vield.35 BP-TPA and OXD-TPA were synthesized from tris(4-ethynylphenyl)amine with 4,4'-dibromodiphenyl and 2,5diphenyl-1,3,4-oxadiazole, respectively, by the Sonogashira coupling reaction in an Et₃N/DMF (1:1, v/v) mixture with Pd(PPh₃)₄ and CuI as catalysts. The resulting product was successively washed with water, acetone and methanol followed by Soxhlet extraction (THF and then CH2Cl2). BP-TPA and OXD-TPA are insoluble in all common solvents such as DMF, THF and CH₂Cl₂. The structural characterization of the two polymers was studied by solid-state ¹³C NMR spectroscopy, FT-IR spectroscopy, and elemental analysis. Both polymers show aromatic peaks at 120-150 ppm and peaks at ~91 ppm for quaternary alkynes (Fig. S1 and S2†), consistent with the CMPs synthesized by the Sonogashira polymerization.³⁴ In addition, the peak at 163 ppm in the NMR spectrum of OXD-TPA is ascribed to the carbon atom of oxadiazole. Fourier-transform infrared (FT-IR) spectra analysis confirmed the alkynyl linker of the two polymers by the evidence of stretching vibrations of triple bonds appearing around 2200 cm⁻¹ (Fig. S3†). BP-TPA and OXD-TPA show similarly spherical morphologies revealed by scanning electron microscopy (SEM) measurement (Fig. S4†). Negligible Pd residual was detected in both polymer networks and the content is 0.34% for BP-TPA and 0.54% for OXD-TPA, respectively. The powder X-ray diffraction (PXRD) patterns demonstrated that both polymers exhibited broad diffraction peaks with low intensities in the wide region, indicative of their amorphous nature (Fig. S6†). Thermal gravimetric analysis (TGA) demonstrated their excellent thermostability with 5% weight loss for BP-TPA and OXD-TPA observed at 463 °C and 412 °C, respectively (Fig. S7†).

The porosity of BP-TPA and OXD-TPA was evaluated by N2 sorption isotherm measurements at 77 K. As shown in Fig. 1a, both polymer networks give rise to type I isotherms and exhibit a steep increase in the low relative pressure regions (<0.01) due to their microporosity. The apparent BET surface area of BP-TPA is 512 m² g⁻¹, which is lower than that of OXD-TPA (686 $\text{m}^2 \text{ g}^{-1}$).

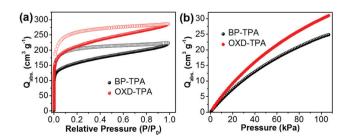


Fig. 1 (a) N₂ sorption isotherm curves of the polymers obtained at 77 K. (b) CO₂ adsorption isotherm curves of the polymers at 298 K.

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Both polymers have similar pore size distributions with pore widths at about 1.1, 1.5 and 2.7 nm, respectively (Fig. S5†). The CO2 uptake capacities of the two polymers at 298 K were evaluated by CO₂ adsorption isotherms. OXD-TPA exhibited a higher volumetric CO2 uptake than BP-TPA (Fig. 1b). In particular, the difference of CO₂ uptake became more distinct with increasing pressure. At P = 100 kPa, the CO₂ uptake capacities of BP-TPA and OXD-TPA were 24.1 and $30.3 \text{ cm}^3 \text{ g}^{-1}$, respectively. The enhanced CO_2 absorbing ability of OXD-TPA compared to BP-TPA is attributed to its higher BET surface area and the dipole-induced electrostatic interactions between the N or O atoms of the oxadiazole unit and the C atoms of CO_2 . 36-38

The UV/vis diffuse reflectance spectra (DRS) and photoluminescence spectra of BP-TPA and OXD-TPA are displayed in Fig. 2a. OXD-TPA with extended π -conjugation shows broader absorption than BP-TPA. Accordingly, the optical band gaps estimated from the absorption onset of the DRS spectra are 2.38 eV for BP-TPA and 2.22 eV for OXD-TPA. Upon excitation at 380 nm, BP-TPA exhibits emission centered at 562 nm, which is slightly blue-shifted to 557 nm for OXD-TPA. Notably, the emission of OXD-TPA is significantly stronger than that of BP-TPA. This is largely due to the twisted conformation between phenyl and oxadiazole in 2,5-diphenyl-1,3,4-oxadiazole, which interrupts the π -conjugation and molecular stacking, thus blue-shifts the emission and enhances the fluorescence intensity. 39,40 In addition, time-resolved photoluminescence decay spectra demonstrated a slightly longer fluorescence lifetime of 0.82 ns for OXD-TPA than that of BP-TPA (0.61 ns) (Fig. S8†). The LUMO levels of polymers were evaluated using cyclic voltammetry (Fig. S9†). Both exhibited well-defined reversible reduction waves with the LUMO levels of -0.41 V (vs. NHE) for BP-TPA and -0.44 V (vs. NHE) for

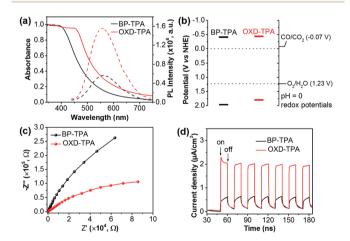


Fig. 2 (a) UV/vis diffuse reflectance spectra (solid line) and photoluminescence (PL) spectra (dashed lines; λ_{ex} = 380 nm) of BP-TPA and OXD-TPA in the solid state. (b) Energy levels of BP-TPA and OXD-TPA relative to the potentials of CO₂ reduction to CO and water oxidation, respectively, vs. the NHE at pH = 0. (c) EIS Nyquist plots and (d) periodic transient photocurrent response of polymer electrodes in 0.5 M Na₂SO₄ aqueous solution.

Table 1 Optical and electrochemical properties, BET surface area and CO₂ uptake data of the polymers

Polymers	Eg a (eV)	$E_{\text{red, onset}}^{b}(V)$	LUMO/ HOMO ^c (V, vs. NHE)	S_{BET} $(\text{m}^2 \text{g}^{-1})$	CO ₂ uptake ^d (cm ³ g ⁻¹)
BP-TPA	2.38	-1.04	-0.41/1.97	2.38	24.1
OXD-TPA	2.22	-1.07	-0.44/1.78	2.22	30.3

^a Estimated from the UV/vis diffuse reflectance spectra onset $(E_{g} =$ 1240/ $\lambda_{\rm onset}$). b Versus Fc/Fc $^+$ in acetonitrile solution, 50 mV s $^{-1}$ scan rate. c $E_{\rm NHE} = E_{\rm Fc/Fc}^+ + 0.63$ V, $E_{\rm HOMO} = E_{\rm LUMO} - E_{\rm g, opt}$. d At P = 100 kPa.

OXD-TPA (Table 1). Accordingly, the HOMO levels of BP-TPA and OXD-TPA were calculated to be 1.97 V and 1.78 V, respectively. The energy band structures of both polymers are well positioned for the reduction of CO₂ to CO, indicating that they are thermodynamically capable of generating CO from CO2 photoreduction under light irradiation (Fig. Photoelectrochemical measurements were conducted to compare the photogenerated charge carrier transport of the two polymers. As shown in Fig. 2c, the Nyquist plot of OXD-TPA exhibits a smaller diameter of the semicircular than that of BP-TPA, revealing a decrease of the charge-transfer resistance by replacing biphenyl with 2,5-diphenyl-1,3,4-oxadiazole. The improved photoinduced charge transport can be further supported by an increased transit photocurrent response of OXD-TPA as shown in Fig. 2d, which reveals a visible-light photocurrent of ~2 µA cm⁻² for OXD-TPA and $\sim 0.5 \, \mu A \, cm^{-2}$ for BP-TPA.

The CO₂ photoreduction reactions over the as-synthesized polymers were carried out in the presence of CO₂ and water vapor under ambient conditions. Interestingly, CO was detected as the only reductive product in the photocatalytic system (Fig. S10b†). As shown in Fig. 3a, after the four-hour irradiation of visible light (>420 nm), OXD-TPA produced 148.6 μ mol g⁻¹ CO, which is much more than that by BP-TPA (3.6 µmol g⁻¹). At 420 nm, the quantum efficiencies are about 0% and 0.19% for BP-TPA and OXD-TPA (Fig. S19†), respectively. To the best of our knowledge, the photocatalytic activity of OXD-TPA (37.15 μ mol h⁻¹ g⁻¹) is much better than that of commonly used g-C₃N₄ and many newly reported CPs under similar conditions (Table S1†).

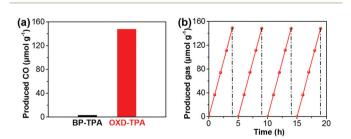


Fig. 3 (a) CO production from the photocatalytic CO₂ reduction over BP-TPA and OXD-TPA after 4 h irradiation (>420 nm) Reaction conditions: 15 mg polymer, CO₂ (1.0 atm), water vapor, room temperature. (b) Time course of photocatalytic CO₂ reduction over OXD-TPA.

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To confirm the photocatalytic process, we have performed a series of control experiments. No reductive products were detected under dark conditions. Upon replacing CO₂ with N₂, only a trace amount of CO could be detected, indicating that CO2 is the reductive agent in the system. When no H2O is added to the reaction system, negligible CO could be measured, which suggests that H2O plays an important role as an electron donor. Notably, H2 and other carbonaceous products, such as CH4, HCHO, HCOOH, and CH3OH were not found in our tests, demonstrating that the separated electrons on the surface of the polymer network are almost exclusively used for CO2 reduction to CO and ~100% selectivity was obtained for OXD-TPA in the photocatalytic reaction.

To study the source of generated CO during the photocatalytic process, an isotopic experiment with ¹³CO₂ (Fig. S11†) was conducted under the same reaction conditions (>420 nm). When ¹²CO₂ was replaced by ¹³CO₂ in the reactor, a gas product with a retention time of 4.026 min was detected, which was different from that of 12CO at 3.958 min (Fig. S10b and c†). In addition, after adding concentrated NaOH aqueous solution into the reactor to remove unreacted ¹³CO₂, the gas sample was subsequently analyzed by MS spectrometry and a peak at m/z = 29 was found (Fig. S12†), which was assigned to 13 CO. This peak was not due to the fragmentation of 13 CO₂ during the MS analysis as the unreacted ¹³CO₂ was completely removed prior to the analysis. Based on all these results, it could be concluded that CO originated from the reduction of CO2 on OXD-TPA.

The photocatalytic CO₂ reduction stability and recyclability of OXD-TPA was evaluated by four cyclic testing (4 h-irradiation in each run). The photocatalytic reactor was treated under vacuum and then refilled with the mixture of CO2 and water vapor after each run. Steady CO production is observed over four runs (Fig. 3b). After the photocatalysis experiments, the recycled polymer did not show any significant structural changes (Fig. S13-S15†), indicating that OXD-TPA is highly stable during the photocatalytic process.

DFT calculations were performed to understand the electronic properties of both polymers. The optimized structures are shown in Fig. S16.† The excited electrons for both BP-TPA and OXD-TPA are distributed all over the backbone, whereas the excited holes are mainly localized in TPA due to its strong electron-donating feature (Fig. S17a and S17b†). Moreover, compared to the BP moiety, the more electronegative OXD moiety impairs the density of excited electrons within the TPA part, which decreases the overlap between the excited electrons and holes in OXD-TPA as compared to that of BP-TPA, indicating less recombination of photogenerated charges in OXD-TPA.

We further studied the adsorption energy of COOH*, which is proposed to be the intermediate for CO₂ reduction to CO, on different positions of BP-TPA and OXD-TPA (Fig. 4a and b), and the corresponding adsorption energies are shown in Fig. 4c. The most stable configurations of COOH* are shown in the insert of Fig. 4c and Fig. S17c.† The most stable adsorbed COOH* has similar configurations but the adsorp-

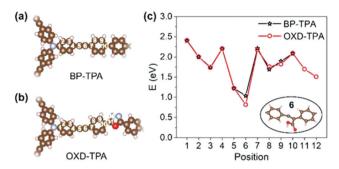


Fig. 4 Different adsorption sites on (a) BP-TPA and (b) OXD-TPA, and (c) the corresponding adsorption energies for COOH*.

tion is ~0.2 eV more stable on OXD-TPA, which facilitates the reduction of CO2.

DFT calculations revealed that the band gaps for BP-TPA and OXD-TPA are 2.47 and 2.38 eV, respectively, which are in agreement with the optical bandgaps obtained in our experiments (2.38 eV for BP-TPA and 2.22 eV for OXD-TPA as shown in Table 1). Notably, the theoretically predicted HOMOs and LUMOs for BP-TPA and OXD-TPA are depicted in Fig. S18a.† The HOMO potential of BP-TPA (0.79 V) is approximate to the one required for water oxidation (0.82 V, neutral conditions), while it is 0.27 V more positive for OXD-TPA. The LUMO potentials of both BP-TPA (-1.68 V) and OXD-TPA (-1.31 V) are much more negative than the reduction potential of CO₂ to CO (-0.53 V). The results reinforced the sufficient redox ability of the two polymers to trigger the photocatalytic reactions in our system. The possible CO₂ photoreduction process for the polymers is described as follows: the CO₂ gas can be absorbed and activated by the porous polymers. Upon the illumination of visible light, the photogenerated electrons (e⁻) could migrate from the LUMO levels to the HOMO levels of the polymer. Subsequently, the absorbed CO2 captures electrons on the polymer surface, forming CO and H_2O ($CO_2 + 2H^+ + 2e^- \rightarrow$ CO + H2O), while the photoinduced holes were utilized for oxidizing water to generate oxygen and hydrogen ions via the half-reaction $(2H_2O + 4h^+ \rightarrow O_2 + 4H^+)$ (Fig. S18b†). The low water concentration in the reaction system could efficiently inhibit the competitive reaction to give H2, CH3OH, CH4, etc. This is beneficial for the high selectivity of polymers. The much better photocatalytic performance of OXD-TPA could be attributed to its smaller band gap, increased dissociation of photogenerated excitons, and more stable COOH*.

Conclusions

In conclusion, we present the rational design of two novel triphenylamine based CMPs for CO₂ photoreduction to CO under visible light irradiation. The CO production rate could be significantly enhanced from 0.9 to 37.15 μ mol h⁻¹ g⁻¹ (>420 nm) with ~100% selectivity, which is much better than the newly reported CPs in similar photocatalytic systems (Table S1†). The enhancement in the photocatalytic activity of

polymers resulting from molecular tuning was fully investigated by experiments and theoretical calculations. Accordingly, we expect that this study will stimulate research interest in designing stable and highly efficient conjugated polymers for CO_2 photoreduction.

Conflicts of interest

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There are no conflicts to declare.

Acknowledgements

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