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Orthogonal stimulation of structural transformations in photo-responsive MOF films through linker functionalization[†]

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Controlling the magnitude of structural dynamics in flexible MOF films by an applied stimulus is largely desired for specific applications such as energy storage. Herein, by introducing chlorine substituents in an azobenzene-infiltrated **CI-DMOF-1** film structure, a significantly slowed structural response is obtained upon photo-switching of the system.

To date, the fabrication of structurally responsive MOF films^{1,2} is encouraged for the development of MOF-based devices, including sensors,3,4 cargo delivery systems5-7 and mechanical storage systems.⁸⁻¹⁰ Implementing a moiety within a film assembly that is responsive to an external stimulus allows for the remote control of MOF film properties.¹¹ Here, light is a particularly attractive stimulus as it is readily available and renewable in the form of sunlight.¹² So far, a large number of structurally flexible photo-active MOFs has been reported, such as DMOF-1 $([Zn_2(bdc)_2(dabco)], bdc = 1,4-benzenedicarboxylate and dabco$ = 1,4-diazabicyclo[2.2.2]octan),¹³ or [Zn(AzDC)(4,4'-BPE)_{0.5}], AzDC = azobenzene-4,4'-dicarboxylic acid and 4,4'-BPE = trans-1,2-bis(4-pyridyl)ethylene.¹⁴ Most of these flexible structures are based on reticular design strategies, where molecular building blocks are replaced within the MOF system.^{15,16} These structures exhibit a tuned flexibility that provides an extra degree of freedom, which offers additional means to exploit dynamics in responsive MOF film systems alongside primary photon stimulation. This concept is introduced as orthogonal stimulation by Peh et al.15 and

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† Electronic supplementary information (ESI) available. See DOI: https://doi.org/ 10.1039/d4ce00221k holds promise for tailoring responsiveness in flexible MOF systems. Following this approach, in this study, we demonstrate a chemical pathway to tune photo-induced structural transformations.15 Replacing terephthalic acid linkers with chloro-functionalized derivatives allows for the fabrication of Cl-DMOF-1 films that are isostructural to the DMOF-1 system (Fig. 1a, right)^{13,17} while exhibiting varied flexibility with changes in growth time (Fig. 1b). Although linker functionalization has been successfully shown for bulk DMOF-1 systems,¹⁸⁻²¹ structural photo-response and its duration for such modified structures has not been examined so far. We tackled this by incorporating azobenzene within Cl-DMOF-1 pores to obtain a photo-responsive film system, which was confirmed by infrared spectroscopic measurements. Time-resolved grazing incidence wide angle scattering measurements (GIWAXS) showed a X-ray



Fig. 1 Schematics of the orthogonal stimulation strategy in MOF films. (a) Structure of the flexible Cl-DMOF-1 framework viewed along the zinc paddlewheel units linked by functionalized Cl₂-bdc and pillared by dabco. (b) Varying the growth time of the Cl-DMOF-1 films leads to rigid or flexible structures. (c) Cl-DMOF-1 films were infiltrated by azobenzene, which upon irradiation with UV light (343 nm) isomerizes from *trans* to *cis* and *vice versa* upon irradiation with blue light (450 nm).

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significantly slowed structural photo-response compared to the DMOF-1 structure (Fig. 1c).²²

To ensure sufficient light penetration accompanied by a controlled propagation of structural photo-response, **Cl-DMOF-1** films were fabricated as heteroepitaxial film structures following a substrate-seeded approach.^{23,24} For this, in the first step, Cu(OH)₂ nanobelts were deposited on glass substrates, which were then converted to Cu₂bdc₂ (see Scheme S1†).²³

Subsequently, the Cu₂bdc₂-on-Cu(OH)₂ films were treated in zinc acetate and placed at 60 °C in the methanolic linker solution containing dabco and a Cl₂-bdc linker (Fig. 1a, see experimental details). However, linker ESI[†] for functionalization in MOFs can potentially vary the thermodynamic stability and, thus, the readiness of the structure to grow.²⁵ To address this issue, in the first step, we altered the growth time of the Cl-DMOF-1 films from 10 to 270 min and studied the alignment of the structure along the Cu_2bdc_2 -on- $Cu(OH)_2$ film surface in a combinatory study by employing SEM (Fig. 2 and S2[†]) and GIWAXS measurements (Fig. S3 and S4[†]), which are discussed below.

In Fig. 2, the top-view SEM images depict the timedependent growth of the Cl-DMOF-1-on-Cu₂bdc₂-on-Cu(OH)₂ film structures. Initially, at a growth time of 10 min, small crystallites appear (Fig. 2a), which were determined using GIWAXS measurements to correspond to the weak growth of the Cl-DMOF-1_{10min} structure (Fig. S3a†). According to the GIWAXS pattern in Fig. S3b,† sharp reflections appear for a growth of 30 min, which are attributed to the formation of the *P4/mmm* phase for the Cl-DMOF-1_{30min} (*a* = 10.93 Å, *b* =



Fig. 2 Representative top-view SEM images of the Cl-DMOF-1 structure grown on the Cu₂bdc₂-on-Cu(OH)₂ substructure for (a) 10 min, (b) 30 min, (c) 60 min, (d) 90 min, (e) 180 min and (f) 270 min. The evolution of crystallite growth is schematically depicted in (g). From left to right: Initially, crystallites preferentially grow in length (10-30 min). After reaching a limiting size, expansion in width begins (60-90 min). Up to 90 min, the crystallites comprise a tetragonal-like shape (width = 0.1 μ m), with the length matching the crystallite height. At 180 min, this characteristic shape is lost, whereupon at 270 min, they transform into a cubic shape displaying cracks or bending of the surface (see red arrow), resulting in shell-like crystallites (see the SEM image in the inset).

10.93 Å, and c = 9.61 Å).^{17,26} Interestingly, (100) reflection shows a shift of $\Delta q = 0.04$ nm⁻¹ between the out-of-plane ($q_{\rm OP} = 5.82$ nm⁻¹) and the in-plane direction ($q_{\rm IP} = 5.78$ nm⁻¹). On the contrary, (001)_{Cl-DMOF-1} and (101)_{Cl-DMOF-1} reflections remain unaltered, indicating that the (100) plane is distorted. This property is attributed to internal strain²⁷ within the **Cl-DMOF-1** structures, which becomes more evident at a growth time of 90 min, causing even splitting of (001)_{Cu₂bdc₂} reflection for the Cu₂bdc₂-on-Cu(OH)₂ substructure (Fig. S4a,† out-of-plane pattern). Kitagawa and co-workers recently delineated that with a decreasing MOF film thickness, surface effects become more pronounced,²⁸ in which heteroepitaxial structures can be a display of strain induced by lattice mismatch.²⁴

Hence, to understand the impact of internal strain, we performed GIWAXS measurements while rotating the Cl-**DMOF-1**_{90min} film sample along the azimuthal angle φ (rotation around the surface normal, see Fig. S5a and b⁺). The behaviour of the $(100)_{Cl-DMOF-1}$ reflection with respect to ϕ in the out-of-plane direction indicates the presence of two crystalline phases. At $\varphi = 0^{\circ}$, the Cl-DMOF-1_{90min} structure was determined to grow in the P4/mmm phase (Fig. S5c and d[†]), as already encountered for structures grown at shorter times. By rotating the sample to larger φ -angles, a second phase appears that is shifted towards higher q, thus resembling the I4/mcm structure (Fig. S5c†). Consequently, the characteristic (001)_{Cu,bdc}, reflection of the epitaxial substructure shifts by $\Delta q = 0.03 \text{ nm}^{-1}$ towards smaller q in the out-of-plane direction (Fig. S5d⁺). It must be noted that the Cu₂bdc₂ substructure of the Cl-DMOF-1_{90min} film was confirmed to comprise a strong azimuthal angle dependence in the in-plane direction (Fig. S5e-g⁺), as was reported for the non-functionalized DMOF-1 film structure.22,23 The $(001)_{\text{Cl-DMOF-1}}$ reflection located at $q_{\text{IP}} = 6.45 \text{ nm}^{-1}$ shows no azimuthal angle dependence in the in-plane direction (Fig. S5b and d[†]). Based on these findings, we consider the growth of this second I4/mcm-like phase a result of relieving the internal strain within the Cl-DMOF-1 structures that arises mainly from the urge to match the Cl-DMOF-1 lattice with the lower Cu₂bdc₂-on-Cu(OH)₂ structure. Thus, at growth times ≤90 min, strained but heteroepitaxially grown Cl-DMOF-1-on-Cu₂bdc₂-on-Cu(OH)₂ film systems are obtained. However, a propagation of the growth time leads to nonepitaxially grown Cl-DMOF-1_{180min} (Fig. S4b†) and Cl-DMOF-1_{270min} structures (Fig. S4c†). Moreover, the absence of preferred alignment in both in-plane and out-of-plane directions is a characteristic of non-epitaxial and bulk structures.24

From SEM micrographs, the evolution of the **Cl-DMOF-1** crystallite growth as a function of time demonstrates the formation of very thin crystallites after 30 min with a size of 1.4 μ m in both length and height (Fig. 2b). The **Cl-DMOF-1**_{60min} crystallites continue to grow in their width (~0.1 μ m; Fig. 2c), which further increases for the **Cl-DMOF-1**_{90min} system (~0.3 μ m; Fig. 2d). However, prolonged growth of the **Cl-DMOF-1**_{180min} system yields crystallites of significantly

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different shapes, where some crystallite surfaces are strongly bent inward (see the red arrow in Fig. 2e). After 270 min, the crystallite size resembles those of reported bulk crystallites¹⁸ with the difference that most larger crystallites comprise cracks (see Fig. 2f), which are referred to as the result of a long-range strain within the structure.²⁹ Some of the Cl-DMOF-1_{270min} crystallites display a hollow core resembling a shell-like structure, which is attributed to the ultimate product of internal stress release (Fig. 2g, see SEM image). The evolution of the Cl-DMOF-1 crystallite growth is schematically depicted in Fig. 2g, where we classify structures grown shorter than 90 min as heteroepitaxial, while subsequent growth yields bulk-like structures. Based on GIWAXS data, we propose for heteroepitaxial structures (growth time <90 min) that the $(h00)_{Cl-DMOF-1}$ plane grows epitaxially onto the $(00l)_{Cu,bdc}$ plane with the *a*-axis of the Cl-DMOF-1 system aligning perpendicular to the substrate. For these structures, the $(00l)_{Cl-DMOF-1}$ plane orients mainly in the out-of-plane direction, which results in the c-axis aligned parallel to the substrate (see Fig. S3a-c†). This alignment was already reported in our earlier study of the oriented DMOF-1 film structure,²² confirming the isoreticular growth approach for the presented functionalized heteroepitaxial film system. However, this is not the case for bulk-like Cl-DMOF-1 film structures (180-270 min), which show a sudden change in the alignment of their structure. This property is envisioned by the appearance of the $(00l)_{Cl-DMOF-1}$ plane in the in-plane direction (≥ 90 min, Fig. S4a[†]). We presume that this inversion in alignment mainly arises from the strained ≥ 180 min structures, resulting in a complete loss of heteroepitaxy accompanied by the sudden change in the shape of the Cl-DMOF-1 crystallites yielding bulk-like structures (see SEM images in Fig. 2). The growth behaviour of the Cl-DMOF-1 films was additionally confirmed by infrared spectroscopic measurements. All pristine structures show strong vibrational bands located around 1388 cm⁻¹ and 1587 cm⁻¹ (Fig. 3 and S6–S8^{\dagger}), corresponding to the symmetric (v_s) and asymmetric



Fig. 3 (a) ATR measurements of the Cl-DMOF-1/AB_{90min} structure during the photo-switch. (b) Comparison of azobenzene vibrational bands between the excited (purple trace, 343 nm - ON) and the relaxed state (blue trace, 450 nm - OFF) revealed the presence of *cis*-azobenzene ($v_{cis-AB} = 698 \text{ cm}^{-1}$) in the former and its conversion to the relaxed *trans*-conformer for the latter, with a shift of $\Delta v_{trans-AB}$ (ON, OFF) = 1.05 cm⁻¹. (c) Photo-cycling of the system successfully isomerized the azobenzene molecule.

stretching (v_{as}) of the carboxylic group bonded to the metal nodes, respectively.22

We further investigated the structural flexibility of the Cl-DMOF-1 films. For this, the photo-active guest molecule azobenzene was incorporated within the Cl-DMOF-1 pores following the vapour-assisted approach (<0.5 molecules per pore, Table S1[†]).²² The success of the infiltration process was confirmed by Fourier transform infrared (FT-IR) attenuated total reflectance (ATR) measurements of the respective Cl-DMOF-1 films. The results show the appearance of the characteristic trans-azobenzene vibrational band located around 691 cm⁻¹ (see Fig. S6-S8†), which experiences a red shift for structures after prolonged growth (30-180 min, Table S2^{\dagger}). Similarly, a red shift in the v_s vibrational band was determined, which is attributed to the carboxylate vibrations arising from the Cl-DMOF-1 structure (Table S2⁺). This behaviour indicates that the internal strain caused by the heteroepitaxial growth of the Cl-DMOF-1/AB structures is directly translated to the infiltrated azobenzene molecule within the pores. In the case of the weakly grown Cl-DMOF-1/ AB_{10min} structure (Fig. S6a[†]), where the main vibrational bands are attributed to the non-coordinated terephthalic acid linkers (see Fig. S6b[†]), azobenzene is expected to accumulate on the surface rather than being incorporated within the pores. Hence, this system can serve as a reference because the vibrational band of azobenzene corresponds to its nonstrained, pristine *trans*-conformer located at $v_{AB} = 690 \text{ cm}^{-1}$ (Fig. S6c[†]).³⁰ In comparison, the Cl-DMOF-1/AB_{270min} system contains azobenzene molecules in a relaxed state ($v_{AB} = 691$ cm⁻¹), which is attributed to the loss of epitaxy. Hence, these findings corroborate SEM and GIWAXS measurements; they show that at growth times exceeding 180 min, the internal stress is overcome, which leads to bulk-like, non-epitaxially grown structures.

In the next step, to test the photo-activity of the incorporated azobenzene molecules with respect to the duration of the structural transformation of the Cl-DMOF-1/ AB systems, we performed ATR measurements combined with two light sources (343 nm and 450 nm; Scheme S2[†]). The results show that short growth times yield rigid Cl-DMOF-1/AB structures where no azobenzene isomerization was possible (Fig. S9a[†]), while the structures obtained after longer growth times exhibit sufficient flexibility to respond to the azobenzene isomerization process (≥ 60 min, Fig. S9b[†]). For the latter films, irradiation by 343 nm prompted the azobenzene within the Cl-DMOF-1/AB pores to enter its *cis*-state ($v_{cis-AB} = 698 \text{ cm}^{-1}$, ON-state), which, after exposure to 450 nm, relaxed fully to its *trans*-conformer ($v_{trans-AB}$ = 693 cm⁻¹, OFF-state; Fig. 3b). The results for the DMOF-1/ AB_{90min} show that in the ON state, about 70% of the infiltrated azobenzene molecules are converted to the cis-conformer, while 30% of the trans-conformer remains 3c). This significantly higher abundance of (Fig. trans-azobenzene molecules within the Cl-DMOF-1/AB_{90min} pores is attributed to the strong stabilization of this conformer owing to the chloro-functionalized MOF



Fig. 4 GIWAXS data for the **Cl-DMOF-1/AB**_{90min} structure. (a) Azimuthal integration of the GIWAXS pattern for the switched (ON, purple pattern) and the relaxed **Cl-DMOF-1/AB** film structure (OFF, blue pattern). The change in the intensity of (001) reflection was used to evaluate the switching times (see inset). (b) Considering the change in the normalized integrated (001) intensity, the forward switch (ON, 343 nm) occurred within $\tau_{\rm ON}$ = 41.7 ± 3 s, (c) while the back switch (OFF, 450 nm) required $\tau_{\rm OFF}$ = 18.4 ± 3 s. Switching constants represent the mean value with corresponding errors derived from experiments conducted by repeating the ON/OFF switch three times.

environment. The relaxed **Cl-DMOF-1/AB_{90min}** structure was found to repeatedly allow the azobenzene to enter its *trans*-isomer, exhibiting a shift of $\Delta v_{cis-AB} = 1.05 \text{ cm}^{-1}$ between the ON and OFF states (Fig. 3b).

We further performed time-resolved GIWAXS measurements to investigate the structural transformations induced within the Cl-DMOF-1/AB90min structure upon photoexcitation. Here, only the Cl-DMOF-1/AB90min structure was tested to confirm the success of the isomerization process of azobenzene upon photo-stimulation (Fig. 4). This is because azobenzene remains non-responsive at shorter growth times (Cl-DMOF-1/AB_{30min}; Fig. S9a[†]), and the bulk-like growth of Cl-DMOF-1/AB structures after 180 and 270 minutes produces inhomogeneous films that hinder light penetration, thus impeding their photo-physical characterization.¹ Detailed analysis of the GIWAXS data for the Cl-DMOF-1/AB90min structure showed that 32% of the crystallites orient preferentially towards the out-of-plane direction (Fig. S10⁺). This result is comparable to the non-functionalized DMOF-1 film structure, which confirms that an oriented and heteroepitaxial Cl-DMOF-1 structure is grown, thus allowing the characterization of its photo-switch.²²

Time-resolved GIWAXS measurements revealed that upon excitation with light of 343 nm, the (001) reflection commenced a shift by $\Delta q = 0.013 \text{ nm}^{-1}$, as determined from

fitting results in the in-plane direction (Fig. 4a). This value is in good agreement with findings reported for the nonfunctionalized DMOF-1 film system.²² Hence, the Cl-DMOF-1/ AB_{90min} structure shrinks when azobenzene enters its cis-conformer, which is reversed by the light of 450 nm upon relaxation to its trans-conformer (Fig. 4b and c). This finding strongly supports the successful isoreticular design strategy as the structural response for the Cl-DMOF-1 is channelled similarly to the DMOF-1 structure.²² From the temporal evolution of the intensity for the (001) reflection under continuous illumination with the respective light sources, the switching constants were deduced for the ON state (343 nm, Fig. 4b) and the OFF state (450 nm, Fig. 4c). GIWAXS measurements showed that the structural response for the ON state was reached after τ_{ON} = 41.7 ± 3 s (343 nm@130 mW cm⁻²), which was reversed within $\tau_{OFF} = 18.4 \pm 3$ s (Fig. 4b and c; 450 nm(a)17.2 mW cm⁻²). In comparison, we reported for the non-functionalized DMOF-1 film structure that the entire switch required 15 s (343 nm@95 mW cm⁻²). 450 nm@17.2 mW cm⁻²),²² therefore rendering the Cl-DMOF-1/AB_{90min} film system to respond significantly slower at similar irradiances (see Table S3[†] for comparison of the two film systems). This finding is reasonable because chlorofunctionalized switchable bulk structures are known to experience a certain loss in flexibility,¹⁶ as indicated by the lack of gate-opening behaviour in bulk Cl-DMOF-1 during N2 sorption experiments, while the DMOF-1 showed a subtle step in the adsorption branch $P/P_0 = 0.003$ (Fig. S13[†]).

In conclusion, we herein prepared Zn-based MOF films using chlorinated terephthalic acid and dabco as ligands, yielding 3D-oriented MOF crystals infiltrated with photoresponsive azobenzene. Upon UV irradiation, we measured orthogonal stimulation. The chloro-functionality imparts rigidity to the oriented MOF film, leading to a strongly decelerated structural photo-response. Depending on the synthesis conditions, different photo-responsive behaviours were observed: films prepared with short reaction times (10– 60 min) showed entirely rigid frameworks, while prolonged growth of the MOF crystals (90–270 min) yielded more flexible structures. Moreover, the azobenzene molecules in the MOF pores can be repeatedly isomerized when triggered by light opening possibilities for their application as mechanical storage systems.^{10,12,15,17}

Conflicts of interest

There are no conflicts to declare.

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