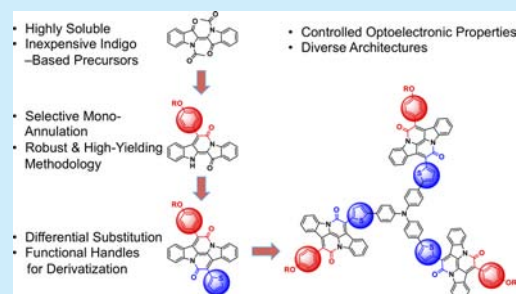


## Stepwise Bay Annulation of Indigo for the Synthesis of Desymmetrized Electron Acceptors and Donor–Acceptor Constructs

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## S Supporting Information

**ABSTRACT:** A selective stepwise annulation of indigo has been demonstrated as a means of providing both monoannulated and differentially double-annulated indigo derivatives. Disparate substitution of the electron accepting bay-annulated indigo system allows for fine control over both the electronic properties as well as donor–acceptor structural architectures. Optical and electronic properties were characterized computationally as well as through UV–vis absorption spectroscopy and cyclic voltammetry. This straightforward method provides a modular approach for the design of indigo-based materials with tailored optoelectronic properties.



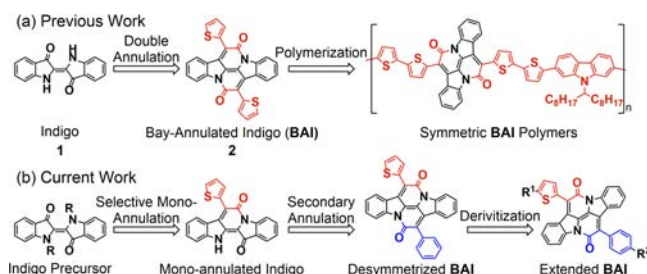
Indigo is known as one of the oldest dyes and has fascinating photophysical properties for a molecule of its size.<sup>1</sup> It has received increasing attention for its potential as a low-cost building unit for electroactive semiconducting materials, given that it is produced industrially at over 50 kilotons per year.<sup>2</sup> With the advancement of the field of organic semiconductors, established dyes and pigments such as perylene imides,<sup>3</sup> diketopyrrolopyrrole (DPP)<sup>4</sup> and isoindigo,<sup>5</sup> have provided a rich source of inspiration for new families of  $\pi$ -conjugated systems and high performance materials.<sup>6</sup> Indigo 1 (Scheme 1a) and related indigoids have shown high ambipolar charge

Through this transformation, the resulting bay-annulated indigo (BAI) 2 features reinforced planarity, enhanced conjugation across the bay, and strong electron accepting ability owing to the conjugated electron-withdrawing amide groups. BAI behaves as an excellent electron acceptor, which has been incorporated in the synthesis of panchromatic small molecules,<sup>12</sup> and low “bandgap” polymers for ambipolar charge transport,<sup>11b,13</sup> organic solar cells<sup>13</sup> and electrochromic devices.<sup>14</sup>

An unexplored approach to synthetically engineer the optoelectronic properties of BAIs is to desymmetrize its structure via sequential annulation of the two bay positions (Scheme 1b). Such desymmetrization not only offers great synthetic flexibility toward more complex donor–acceptor constructs, but also provides fine control over the energy levels through modular synthesis. Desymmetrized functionalization has been explored in electron acceptors such as arene diimide.<sup>15</sup> The commonly adapted stepwise imidation procedure has little influence on the electronic properties of these imide-based acceptors as the substituents are electronically isolated from the core. In desymmetrized BAIs, the different aromatic units attached to the opposite bay positions are expected to have a significant impact on the electronic structures and thus the optoelectronic output.

Stepwise annulation of indigo however has remained unexplored. Promisingly, recent indigo chelation chemistry has hinted at different reactivity of the functional group clusters on each bay position of indigo. The reported diketimine indigo derivative, Ninidigo, forms distinct mono- and bis-BF<sub>2</sub> adducts,<sup>16</sup> as well as metal complexes.<sup>17</sup> A selective covalent annulation protocol is yet lacking and warrants in-depth

**Scheme 1. Previous Synthesis of BAI Compounds and a Proposed Strategy to Access Desymmetrized BAI Acceptors**



carrier mobilities in field effect transistors,<sup>7</sup> however their use as optoelectronic materials is significantly limited due to low solubility. Attempts to improve processability of these materials has stimulated efforts in derivatizing the chromophore, such as placing solubilizing groups on the outer benzene rings,<sup>8</sup> or functionalizing the amine<sup>9</sup> and/or ketone groups<sup>10</sup> in the central bay position of the indigoids.

Among the several chemical pathways to transform indigo into practical electroactive units, a double bay-annulation strategy has emerged as one of the most effective methods.<sup>11</sup>

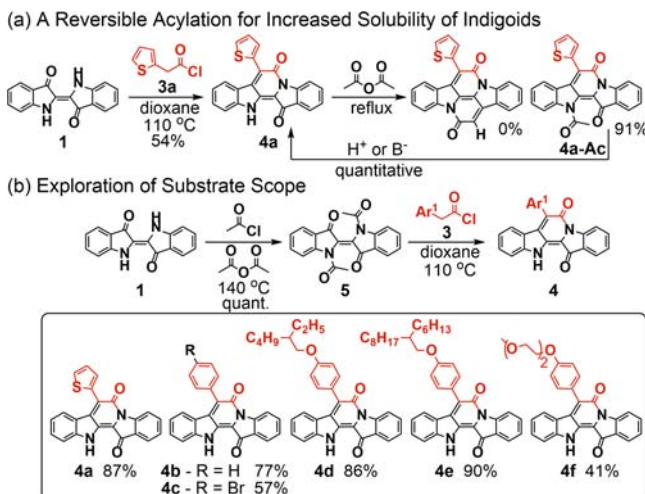
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investigation. Herein we report a detailed synthetic study that provides a high yielding, stepwise strategy toward desymmetrized BAIs.

**Scheme 1b** depicts the desired synthesis of desymmetrized BAI through a monoannulated indigo (MAI) intermediate. If formed selectively and isolated, MAI could be annulated a second time with a different substituted acetyl chloride to form a desymmetrized BAI. Our initial attempt in selective monoannulation employed nearly stoichiometric 2-thiopheneacetic chloride (**3a**) (**Scheme 2a**). When a 1.1:1 mixture of **3a**

### Scheme 2. Improved Synthesis of Monoannulated Indigo via Acetylation



and indigo was heated in 1,4-dioxane at 110 °C, a mixture composed of MAI **4a** (NMR yield: 54%), BAI **2** (NMR yield: 6%) and residual **1** was obtained (entry 1 in Table S1 in [Supporting Information](#), SI). Screening of solvent, temperature, base, Lewis acid, and coupling reagents provided little improvement over 50% yield ([Tables S2 and S3](#)). Utilization of amide coupling reagents with the corresponding substituted acetic acids was also ineffective (**Scheme S1**). The moderate yield of the reaction itself was depressed further by difficult purification of MAI due to the presence of a significant amount of unreacted indigo and side products, all of which have low solubility in common organic solvents.

The monoannulated indigo also experiences low solubility due to the remaining hydrogen bonding and increased tendency to aggregate. In order to promote greater reactivity in the MAI system, attempts were made to increase its solubility by removing the intramolecular H-bonds. An initial reaction of MAI **4a** with acetic anhydride afforded an acetylated product **4a-Ac** with very good solubility in common organic solvents (**Scheme 2a**). When **4a-Ac** was subjected to acidic or basic condensation conditions, no annulation product was formed, instead deacylation occurred to give **4** in quantitative yield. The facile deacylation prompted us to reason that a preacylated indigo compound, such as *N,N'*-diacetylindigo **5**, would be a good alternative starting material which not only ensures high solubility, but also retains good reactivity toward annulation through *in situ* deprotection under acidic reaction conditions.

To test this reaction route, **5** was synthesized in high yield and purity following a modified acetylation protocol<sup>18</sup> that involves treating indigo **1** with acetyl chloride and acetic

anhydride at 140 °C (**Scheme 2b**). As predicted, **5** was significantly more soluble than indigo in the most common organic solvents. When **5** was subjected to reaction with 2-thiopheneacetyl chloride (**3a**) in dioxane, MAI **4a** was obtained in 87% isolated yield. The reaction proceeded much more cleanly compared to that of indigo **1**, with high conversion rate and only trace bis-annulated product (entry 3 in Table S1). The increased solubility of precursors contributed to a significantly higher isolated yield of the desired monoannulated product, with the added benefit of easier tracking and purification due to fewer sideproducts. No acylated **4a-Ac** was isolated from the reaction, suggesting a facile deacylation step following monoannulation. Solvent also plays a role. Changing the solvent to toluene resulted in additional side products with depressed yields (entry 4 in Table S1). Utilizing acetic anhydride as solvent also provided good yield but with product isolated in its acylated form **4a-Ac** (entry 5 in Table S1). Reaction of **1** under these conditions with 2.5 equiv. acetyl chloride (entry 2 in Table S1) showed an improvement in yield (70%) compared to entry 1, presumably through *in situ* formation of **5**.

<sup>1</sup>H NMR experiments provided some insight into the mechanisms of initial deacylation, which are proposed and illustrated in Scheme S2 in SI. As revealed by <sup>1</sup>H NMR studies (**Figure S1**), the formation of acetic anhydride and acetic acid suggested possible transformations that are commensurate with the improvement in yield. Water, which is a byproduct of the cyclodehydration reaction, can form deleterious byproducts through hydrolysis of the acetyl chloride starting material. As water is formed during the condensation, **5** can be deacylated, yielding the less nucleophilic acetic acid, which competes less aggressively for decomposition of the acid chloride. Additionally, once the acid chloride is hydrolyzed it may react further with acetic anhydride or *N,N'*-diacetyl indigo to form a mixed anhydride and re-enter the reaction cycle.

In exploring the scope of this methodology several aromatic acetyl chlorides were employed and shown to be competent reactants for a selective monoannulation (**Scheme 2b**). In addition to phenyl, a 4-bromophenyl MAI **4c** was obtained in decent yield following the same reaction conditions. MAIs **4d–4f** bearing alkyl or glycol chains can also be obtained from the corresponding substituted 2-arylacetyl chlorides in decent to excellent yields.

The synthesis of desymmetrized BAIs was attempted by reacting MAIs with a second equivalent of 2-arylacetyl chloride in xylene at 145 °C, which proceeded smoothly to give a range of desymmetrized BAIs (**Scheme 3**). This stepwise annulation allows the introduction of amphiphilicity onto the opposite bay positions of BAI, such as **6a**, or selective tuning of conjugation via the incorporation of a thiophene unit, such as **6b** and **6c**.

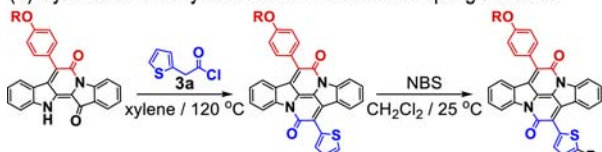
The amphiphilic **6a** was synthesized as a good candidate for the formation of self-assembled monolayers through a Langmuir–Blodgett process.<sup>19</sup> However, **6b** and **6c** are acceptors that could be easily functionalized for incorporation into more complex donor–acceptor systems. As shown in **Scheme 3b**, selective bromination on thiophene units in **6b** and **6c** proceeds in high yield under mild conditions to produce bromides **7b** and **7c**, respectively. Further reaction of these compounds with a number of donor units via Suzuki or Stille coupling conditions gave rise to linear or C<sub>3</sub>-symmetric donor–acceptor systems including BAI adducts of fluorene (**F**) **10**, benzodithiophene (BDT) **11**, and triphenylamine (TPA) **12** (**Scheme 4**). Molecules with similar donor–acceptor architec-

## Scheme 3. Synthesis of Desymmetrized BAI Compounds

## (a) Amphiphilic Bay Annulated Indigo

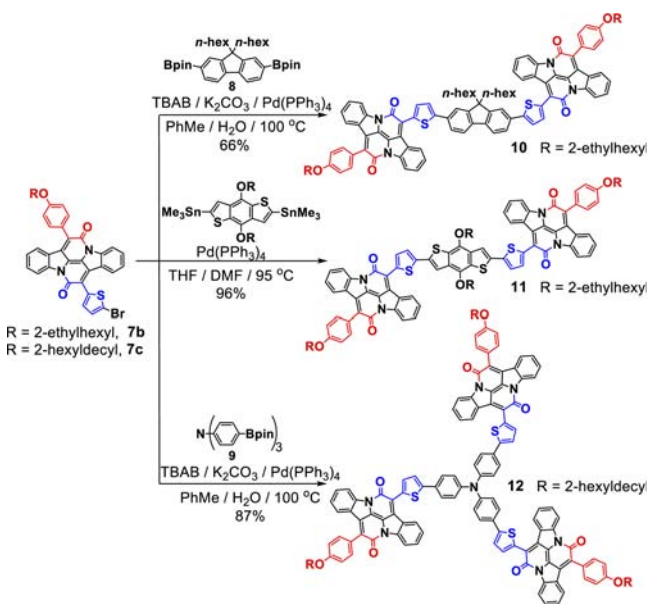


## (b) Synthesis of Desymmetrized BAI Cross-Coupling Partners



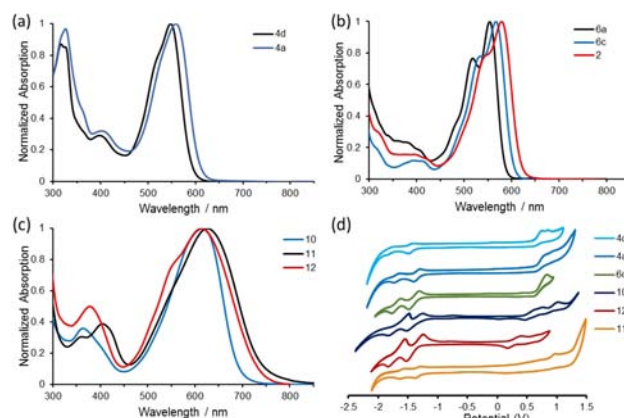
R = 2-ethylhexyl, 4d R = 2-ethylhexyl, 6b, 71% R = 2-ethylhexyl, 7b, 92%  
 R = 2-hexyldecyl, 4e R = 2-hexyldecyl, 6c, 88% R = 2-hexyldecyl, 7c, 91%

## Scheme 4. Synthesis of donor–acceptor systems using BAIs



ture have shown great promise in engineering long-range energy transport, an unusual property dominated by ordered molecular self-assembly in the aggregated state.<sup>20</sup>

The desymmetrized functionalization provides a convenient method to tune the energy levels through the incorporation of different aromatic units on opposite sides of the bay position. Compared to the parent indigo, the MAIs displayed a blue shift of 40–60 nm for its lowest energy absorption peak due to partial loss of the “H-chromophore” characteristics, as revealed by UV–vis spectroscopy (Figure 1a and Figure S2 and Table S4).<sup>9b</sup> A red shift, corresponding to a decrease of 0.04 eV in optical bandgap, is observed when the flanking aromatic substituent is changed from phenyl groups to a more donating thiophene (Figure 1a). The electronic effect of the flanking aromatic units on the optical properties was consistently observed in the doubly annulated BAIs. The stacked absorption spectra of BAIs 6a, 6c, and 2 in Figure 1b and Figure S3 indicated well-resolved and progressive red shifts of the absorption maximum in the order of 0.05 eV, when the aromatic substituents were changed successively from phenyl to thienyl. This is in full agreement with the different electron-donating ability between phenyl and thiophene groups, which confirms good electronic coupling between BAI acceptors and



**Figure 1.** UV–vis spectroscopy of (a) MAIs 4a and 4b, (b) BAIs 6a, 6c and 2, and (c) donor–acceptor conjugates 10–12. (d) Cyclic voltammetry of MAI and BAI compounds, using Fc/Fc<sup>+</sup> as the internal standard (2.5 μM in CHCl<sub>3</sub>, scan rate 100 mV/S).

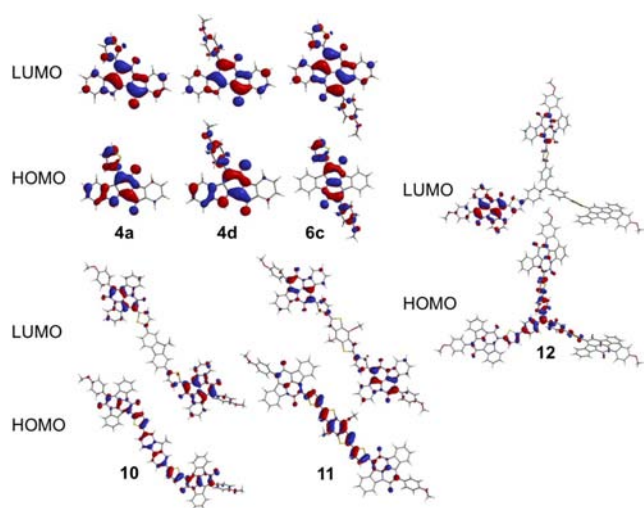
the attached aromatic substituents. The high sensitivity of the optoelectronic properties in response to slight structural modifications further manifests the powerful nature of desymmetrization chemistry. Coupling to stronger donors, such as in the donor–acceptor conjugates 10, 12, and 11, led to more drastic red shifts in the absorption spectra (Figure 1c), corresponding to optical bandgaps of 1.8, 1.7, and 1.6 eV respectively (Table S5 and Figure S3).

The electrochemical properties of MAI and BAI compounds were investigated by cyclic voltammetry. Similar two quasi-reversible one-electron reduction processes were observed for all the compounds, with similar lowest unoccupied molecular orbital (LUMO) energy levels situated within the range of −3.5 to −3.6 eV. The corresponding oxidations were mostly irreversible or pseudoreversible; nevertheless, the highest occupied molecular orbital (HOMO) energy levels and electrochemical bandgaps could be estimated from the onset of redox peaks except for compound 11, which match well with the optical bandgaps (Table S5). The overall trend shows consistent LUMO energies, suggesting the localization of LUMO on the central MAI or BAI core, while the HOMO is strongly dependent on the coupled electron donors.

DFT calculations were carried out to model the molecular orbitals and frontier orbital energies, utilizing a B3LYP functional with the 6-31G\* basis set.<sup>21</sup> The relative order of the calculated HOMO–LUMO energy gap is consistent with the experimental results (Table S5). The theoretical LUMO frontier orbitals of both MAIs and BAI 6c indicated significant delocalization over the AI core with a small contribution from the attached donors (Figure 2 and S4). On the other hand, the HOMO orbitals spread over the central diketopiperidopiperidine unit and extend into the conjugated donor units but with varying degrees of delocalization onto the two benzene rings from the parent indigo. The calculations on the dimeric and trimeric donor–acceptor conjugates further illustrated that the HOMOs have better delocalization along the conjugation backbone, while the LUMOs are mainly localized on BAI units, which is consistent with the experimental observation that they all have very similar LUMO energies.

In summary, we report a highly effective method for stepwise annulation of indigo via a latent diacetylated indigo precursor, which enables the installation of different aromatic units to form desymmetrized BAIs. The employment of the diacetylated





**Figure 2.** Molecular orbital plots of MAIs **4a** and **4d**, BAI **6c**, and the extended donor-acceptor conjugates **10–12**.

indigo significantly increases the synthetic efficiency with enhanced product selectivity, improved conversion rate, and ease of purification compared to a direct annulation protocol. The ability to differentially substitute the core allows the incorporation of BAI-based compounds into a number of low HOMO–LUMO gap donor–acceptor derivatives, including linear and  $C_3$ -symmetric molecules. The self-assembly properties of these materials, as well as characterization of performances in electronic devices, are currently in progress.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b02504.

Experimental details, including synthesis and characterization; computational details (PDF)

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### Notes

The authors declare no competing financial interest.

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