



Synthesis of dihydroindolizines for potential photoinduced work function alteration

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ABSTRACT

Seeking to immobilize photochromophores on metallic surfaces, we have synthesized four molecules which contain both a photoresponsive dihydroindolizine (DHI) core and a sulfur containing moiety, which allow for their assembly onto gold substrates. Sonogashira, Suzuki, or Ullmann couplings are employed to generate pyridines with pendant thioacetates (or disulfides). The pyridines are condensed with spiro[2-cyclopropene-1,9'-[9H]fluorene]-2,3-dimethyl ester affording the targeted DHIs.

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Applying a self-assembled monolayer (SAM) to a metal surface is an effective means for altering the work function of that substrate.^{1–4} When this SAM is placed between a metal and an organic active material, as is present in organic solar cells, organic light emitting diodes, and organic field effect transistors, the bulk organic and metal energy levels can be aligned resulting in highly efficient devices.^{3,5} It is widely accepted that the work function shift is directly proportional to the dipole of the corresponding monolayer.^{3,6} If the dipole could be dynamically altered via stimuli, then

a response in the work function could be induced. Recently, Einaga and co-workers showed this to be possible via a photoresponsive SAM which altered the magnetization and the work function of gold.⁷

We have synthesized a series of dihydroindolizines (DHIs) (Fig. 1) for further study of the same photoresponsive molecular influence on the work function of gold. The immobilized DHI on the surface should be able to switch from its neutral spirocyclic form to its charged zwitterionic conformation when irradiated

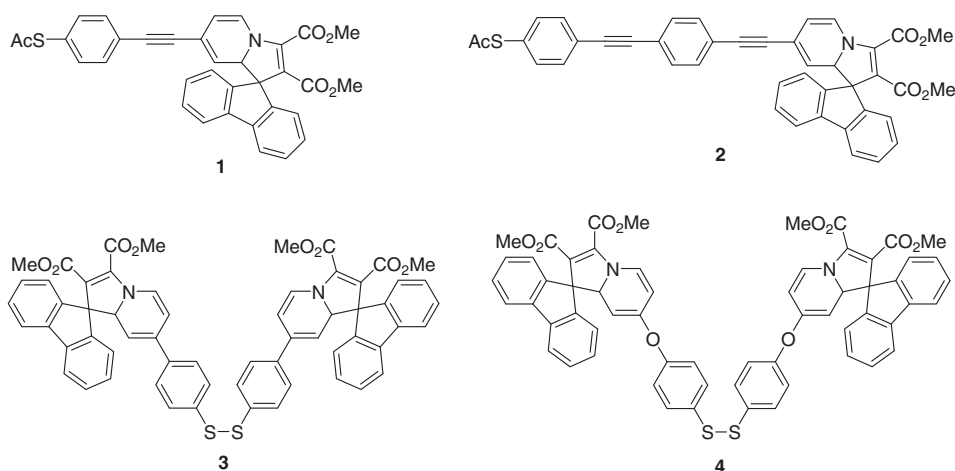


Figure 1. Targeted compounds containing a DHI core and aromatic linker.

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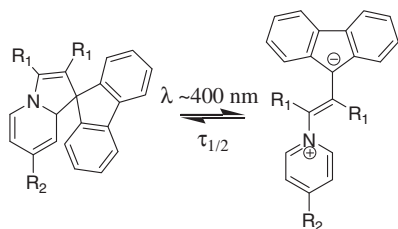
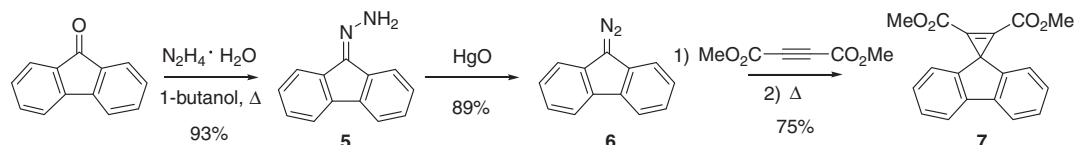


Figure 2. Fluorenyl DHIs **1–4** undergo photoswitching to the betaine form when irradiated ($\lambda_{\text{max}} = 383\text{--}401\text{ nm}$).⁸ The betaine then thermally relaxes back to the spiro form.

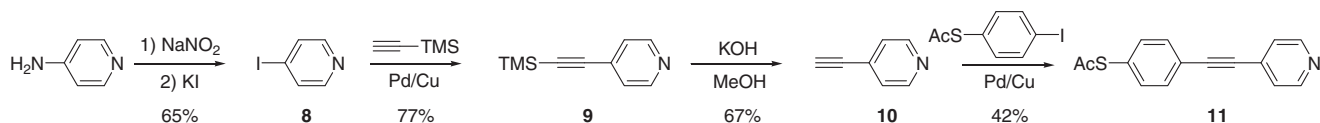
with a specific wavelength of light (Fig. 2).^{8,9} This light induced switch should alter the dipole of the molecule and the work function of the material.

We have incorporated several important parameters into the design of our molecules. First, a rigid backbone allows the molecule, and more importantly the change in dipole, to occur near the surface normal.¹⁰ Second, conjugated-thiol based SAMs allow for improved charge injection and better overall conductance of a material.¹ Third, we can study deprotection-based effects by examining thioacetyl terminated 'linkers' (the portion connecting the DHI to the surface) versus the disulfides. Compounds **1–4** (Fig. 1) meet these criteria and have the ability to bind to a gold surface. The protecting acetyl groups can easily be removed¹¹ from **1** and **2**, and disulfides **3** and **4** will spontaneously assemble.¹²

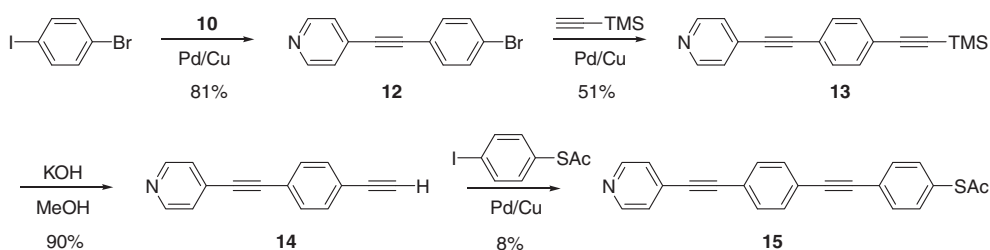
All four target compounds can easily be generated by condensing **7**, spiro[2-cyclopropene-1,9'-[9H]fluorene]-2,3-dimethyl ester, with its respective pyridyl linker. To generate this spirocyclopropene (Scheme 1), fluorenone was converted to the hydrazone **5** via treatment with hydrazine in 1-butanol. Hydrazone **5** was subsequently converted to diazofluorene (**6**) via oxidation with mercuric oxide and sonication.¹³ Treatment of **6** with dimethyl acetylenedicarboxylate generates a pyrazole¹⁴ intermediate which



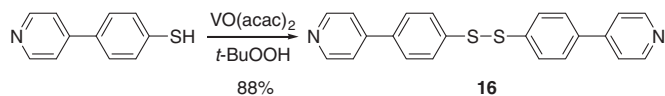
Scheme 1. Synthesis of intermediate **7**, used in condensations for forming **1–4**.



Scheme 2. Synthesis of the first linker, *para*-ethynylpyridine-thioacetyl benzene.



Scheme 3. Synthesis of extended linker **15**.



Scheme 4. Synthesis of short linker **16**.

was converted to cyclopropene **7** by refluxing for 1 h, driving off nitrogen.¹⁵

Scheme 2 outlines the formation of the linker *para*-ethynylpyridine-thioacetyl benzene (**11**), which is used in the generation of the first DHI, **1**. To begin, a low temperature Sandmeyer reaction was employed to generate 4-iodopyridine (**8**) for subsequent cross-coupling reactions.¹⁶ Originally, 4-bromopyridine was utilized, however, its tendency to polymerize led to inconsistent coupling results.¹⁷ Compound **8** was coupled to trimethylsilylacetylene using standard Sonogashira conditions to generate **9** which was readily deprotected with potassium hydroxide in methanol.¹⁸ In our hands, the free alkyne **10** discolors after a few hours. As a result it was coupled to 4-iodophenyl thioacetate immediately, again using Sonogashira protocol.¹⁹

The synthesis of the extended linker **15** was accomplished through a series of Sonogashira couplings and deprotections (Scheme 3). 1-Bromo-4-iodobenzene is coupled with **10** to afford **12**, which was then coupled with trimethylsilylacetylene to generate diyne **13**.²⁰ The free alkyne **14** was generated by deprotecting **13** with potassium hydroxide,¹⁸ and much like Scheme 2, the terminal acetylene was immediately coupled with 4-iodophenyl thioacetate to afford **15**.¹⁹

The short linker, **16**, contains a disulfide bond which should readily attach to gold. Disulfide **16** (Scheme 4) was generated using catalytic amounts of vanadyl acetylacetonate according to a procedure reported by Raghavan et al.²¹ The precursor, 4-(4-thiophenyl)pyridine, was made from a previous procedure by Nichols and co-workers.²²

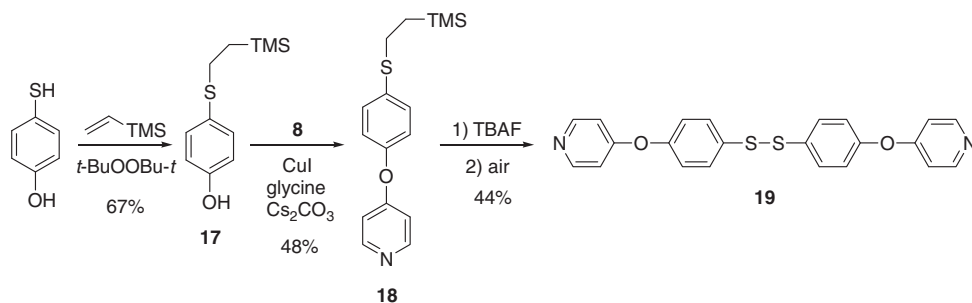
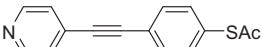
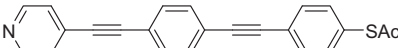
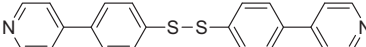
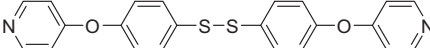
Scheme 5. Generation of ether linker **19**.

Table 1
Four linkers condensed with **7** to generate DHIs and yields

Linker	Ratio (7 :linker)	DHI	Yield
	1:1	1	68%
	1:1	2	96%
	2.1:1	3	71%
	2.1:1	4	46%

The second disulfide, **19**, contains an ether linkage for the purpose of interrupting conjugation. The synthesis of **19** (Scheme 5) begins with 4-hydroxythiophenol which was protected with vinyltrimethylsilane to generate **17**.²³ This allowed for Ullmann coupling with **8** to generate the ether **18**.^{24,25} In our first attempt, the thiol was protected as a methyl thioether. However, in later deprotection steps, the thioether proved to be too robust and our attempts at removal resulted in a cleavage of the diaryl ether. 2-(Trimethylsilyl)ethyl is stable enough to withstand the Ullmann ether synthesis conditions but is easily removed with tetrabutylammonium fluoride²⁶ to generate the thiolate which oxidizes upon exposure to air to yield 4-(4-pyridoxy)phenyl disulfide (**19**).

DHI formation and purification is facile. For **1–4** the appropriate linker was condensed with cyclopropene **7** under nitrogen in the dark for 24 h.²⁷ The pyridine linker attacks the electron deficient cyclopropene ring in **7** by nucleophilic addition,²⁸ and this reaction progress is visually obvious with an immediate color change to dark green. As the reaction continues the mixture changes to a light yellow. The crude mixture is purified by column chromatography. All compounds displayed a sufficient photostability such that column chromatography could be performed without light eliminating measures. Yields of the final DHI molecules ranged from moderate to high (Table 1).

In conclusion, experimental routes have been provided to generate four new DHI species intended to alter the work function of gold in a stimuli-responsive manner. Various palladium and copper catalyzed couplings were used to generate the linkers, and a general condensation of the linker with a spirocyclopropene created the target DHIs. Assembly, characterization, and work function measurements of these photoresponsive molecules are ongoing.

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Supplementary data

Supplementary data (experimental procedures and characterization data) associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2010.10.097.

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