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Synthesis and Characterization of New 2,3-Disubstituted Thieno[3,4-*b*]pyrazines: Tunable Building Blocks for Low Band Gap Conjugated Materials

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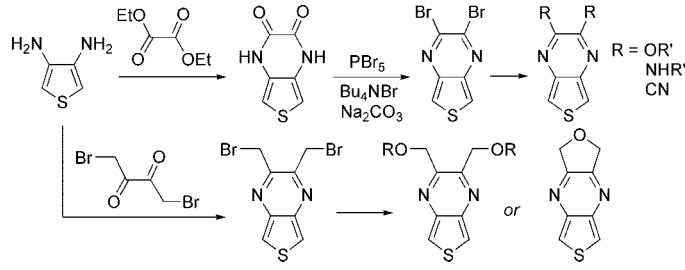

Synthetic methods have been developed for the preparation of new 2,3-dihalothieno[3,4-*b*]pyrazines, from which a variety of new 2,3-difunctionalized thieno[3,4-*b*]pyrazines have been produced as precursors to conjugated materials. Structural, electronic, and optical characterization of these new analogues illustrate the extent to which the electronic nature of the functional groups can be used to tune the electronic properties of the thieno[3,4-*b*]pyrazine unit.

Introduction

The fused-ring thieno[3,4-*b*]pyrazine unit (Scheme 1) has been shown to be an excellent building block for the production of low band gap conjugated organic polymers.[1−10] Homopolymeric poly(2,3-dialkylthieno[3,4-*b*]pyrazine)s have exhibited band gaps as low as ∼0.7 eV,[2−7] and the combination of various thieno[3,4-*b*]pyrazine units with other functionalized thiophenes have produced polymeric materials with reported band gaps ranging from 0.36 to 2.1 eV.[8−10] As many desirable properties of conjugated polymers are dependent on the material's band gap, control of this primary characteristic is an important factor in the production of technologically useful materials, and the application of thieno[3,4-*b*]pyrazines has been one of the more successful approaches to this goal.[1]

The first report of a thieno[3,4-*b*]pyrazine (TP) was the synthesis of 2,3-diphenylthieno[3,4-*b*]pyrazine (**1j**) reported by Imoto and co-workers in 1957.[11] The dialkyl analogues, however, were not reported until the early 1980s, first by Binder

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SCHEME 1. Synthesis of Thieno[3,4-b]pyrazines via Condensation

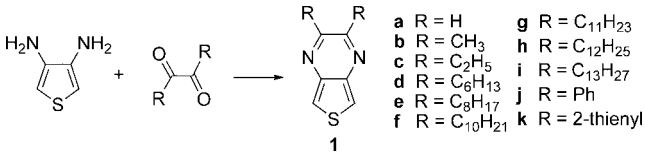
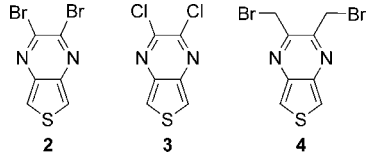


CHART 1. Dihalo-Functionalized Thieno[3,4-*b*]pyrazines



and co-workers[12] and followed closely by Outurquin and Paulmier.[13] Since then, various other research groups have gone on to expand the family of known thieno[3,4-*b*]pyrazines.[2,3,14] Although the synthetic details were improved along the way, all of these groups utilized the straightforward method of condensation as shown in Scheme 1 and thus the choice of functional groups is dependent on the corresponding dione employed. As a consequence, with the exception of a couple of 2-functionalized examples,[13] all known thieno[3,4-*b*]pyrazines have been limited to either the 2,3-dialkyl or 2,3-aryl species. This limitation has resulted in a very narrow range of electronic variance within the family of thieno[3,4-*b*]pyrazines, thus restricting the extent of possible tuning available in the application of these fused-ring units to the production of low band gap materials.

In order to significantly expand the current family of thieno[3,4-*b*]pyrazines, we report herein the synthesis of new dihalo-functionalized thieno[3,4-*b*]pyrazines (Chart 1) as precursors to a wide variety of new analogues. The synthetic versatility of these precursor species has been demonstrated with the production of new thieno[3,4-*b*]pyrazines containing electron-donating and electron-withdrawing groups, and the characterization of these new thieno[3,4-*b*]pyrazines provides insight to the extent that the electronic properties of these species can be tuned through varying the respective functional groups.

Results and Discussion

Synthesis. 2,3-Dihalothieno[3,4-*b*]pyrazines **2** and **3** can be prepared from thieno[3,4-*b*]pyrazine-2,3(1*H*,4*H*)-dione (**5**) in a manner similar to that previously demonstrated for the preparation of 2,3-dihaloquinoxalines (Scheme 2).[15] However, due to the increased reactivity of the thiophene and its tendency to polymerize in the presence of either oxidizing agents or acids, a number of modifications were necessary to produce reasonable yields of the desired dihalothieno[3,4-*b*]pyrazines. Most critically, the methods applied to the quinoxalines are solventless processes and are accomplished as a melt of the two reagents.[15] Application of such conditions to **5**, however, resulted in

SCHEME 2. Synthesis of 2,3-Dihalo-quinoxalines and Thieno[3,4-*b*]pyrazines

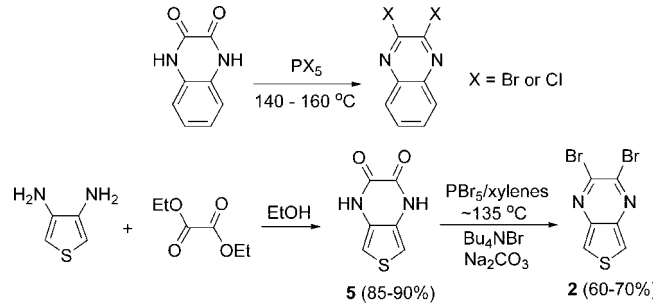
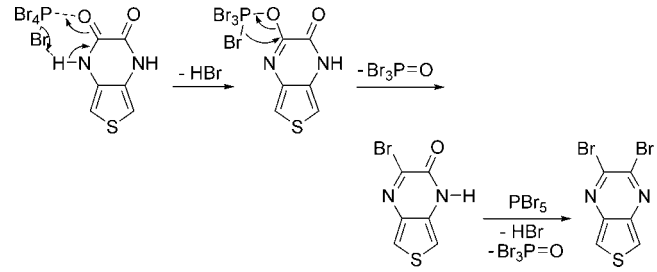


TABLE 1. Reaction Conditions for the Production of 2

entry	addition time of **5**	equiv of PBr_5	base	additive	yield (%)
1	before reflux	2.5			10
2	before reflux	1.5	Na_2CO_3		15
3	before reflux	2.0	Na_2CO_3		32
4	before reflux	2.5	Na_2CO_3		34
5	before reflux	3.0	Na_2CO_3		32
6	before reflux	2.0	Na_2CO_3	Bu_4NBr	40
7	before reflux	2.5	Na_2CO_3	Bu_4NBr	38
8	before reflux	3.0	Na_2CO_3	Bu_4NBr	38
9	after reflux	2.0	Na_2CO_3		28
10	after reflux	2.0	Na_2CO_3	Bu_4NBr	70

SCHEME 3. Proposed Mechanism of the Formation of 2



decomposition with little to no product. It was thus decided that the use of a solvent was required, and xylenes was chosen as an unreactive and high boiling medium. Initial reactions showed that small amounts of **2** could be produced in this fashion and optimization of the reaction conditions was then investigated (Table 1).

While PBr_5 exists in the ionic form $[PBr_4^+][Br^-]$ in the solid state, its form in solution is less well-known.[16] In polar, coordinating solvents such as CH_3CN, it has been determined to exist in the ionic form $[PBr_4^+][PBr_6^-]$, whereas in noncoordinating solvents such as nitrobenzene, CCl_4, or benzene, it exists in its molecular form.[17,18] Assuming then that in xylenes PBr_5 would be molecular rather than ionic, a proposed mechanism (Scheme 3) was constructed on the basis of similar reactions of PBr_5 and amides.[19]

Another factor to consider in the use of PBr_5 solutions is that its molecular form is described by the equilibrium below, with the extent of molecular dissociation depending on the solvent employed.[17,18]

$$PBr_5 \rightleftharpoons PBr_3 + Br_2 \quad (1)$$

As the dissociation in benzene at room temperature has been reported to be essentially complete,[17] one could assume that

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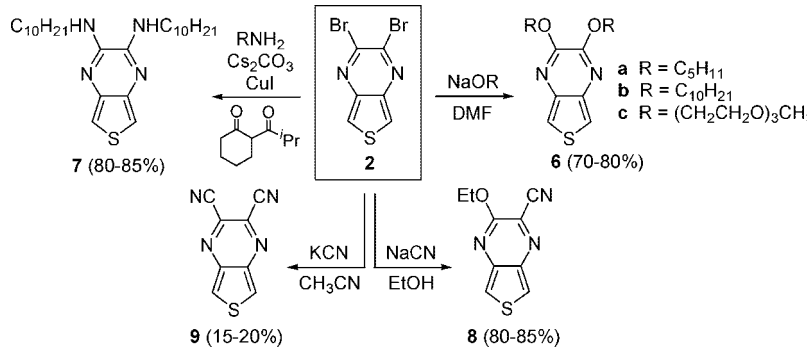
SCHEME 4. Synthesis of New 2,3-Difunctionalized Thieno[3,4-*b*]pyrazines from Precursor 2



the dissociation in xylenes would be similar. To test whether the conversion of **5** to **2** was actually due to PBr_5, the treatment of **5** with PBr_3 or Br_2 were individually investigated. The use of PBr_3 or $POBr_3$ resulted in no production of **2** and only thermal decomposition of **5** was observed. In the case of Br_2, it was found that even at room temperature, selective bromination of the thiophene α-positions occurred, resulting in the isolation of 5,7-dibromothieno[3,4-*b*]pyrazine-2,3(1*H*,4*H*)-dione as previously reported.[20] Thus, both of these results seem to support PBr_5 as the actual brominating agent, regardless of the extent of dissociation.

Because of its similarity to benzene, the dissociation of PBr_5 is thought to be significant in xylenes, at least at room temperature. However, it was found that the treatment of **5** with PBr_5 resulted in no formation of **2** below 100 °C, even though the use of a solvent could theoretically remove the need for the high temperatures formerly needed to form the melt. Overall, it was found that temperatures of greater than 110 °C gave the best results and further raising the temperature had very little effect on the product yield or distribution. As such, it may be possible that the equilibrium given in eq 1 is temperature-dependent. To investigate this, the PBr_5/Bu_4NBr xylenes solution was heated in the absence of **5**, resulting in a color change from red to yellow-orange between 100−110 °C. This color was essentially identical with the solid PBr_5 prior to addition to the solvent, and the loss of the red color of Br_2 is consistent with the shifting of the equilibrium back to PBr_5. With this knowledge, the reaction conditions were then modified in that compound **5** was not added until after the initial heating to remove the dissociated Br_2. As can be seen in entry 10 of Table 1, this resulted in a significant increase in the yield of **2**, presumably due to increased PBr_5 content and reduced side reactions via Br_2.

As can be seen in Scheme 3, the first step liberates HBr and in combination with the oxidizing conditions of the PBr_5 provides ample opportunities for oxidation and polymerization of the thiophene reagent or product. It was therefore found necessary to run the reaction in the presence of Na_2CO_3 in order to neutralize the HBr and reduce decomposition via oxidative coupling. Lastly, it was also found that the addition of soluble bromine salts resulted in increased yields and reduced byproducts (entries 6−8, 10). Without the presence of the added Br^-, the polybrominated species 2,3,5-tribromo- and 2,3,5,7-tetrabromothieno[3,4-*b*]pyrazine were isolated in yields of ∼3−5%, in addition to relatively large amounts of black polymeric material. As these products would result from the presence of Br_2, it may be that the added Br^- reacts with residual Br_2 to generate the less reactive Br_3^-.[21] However, it may be that the Br^- is also important in controlling the high temperature equilibria. Solutions of PBr_5 heated in the absence of the bromine salt did not exhibit the behavior discussed above, but rather Br_2 was evolved at the higher temperature. This result is consistent with the reduced yield found in entry 9 and may suggest that the bromide could be introducing new equlibria involving PBr_6^-.[16]

While the generation of both dibromo- and dichloroquinoxalines occur readily with the appropriate use of PX_5, it was found that this was not the case for the corresponding dihalothieno[3,4-*b*]pyrazines. The dichloro analogue **3** could only be produced in low yields (∼5%), even when applying the optimized conditions developed for the production of **2**. It is believed that this is due to a reduced reaction rate in the case of PCl_5, thus resulting in much greater thermal decomposition of **5**.

In order to explore the application of **2** to the production of new 2,3-difunctionalized thieno[3,4-*b*]pyrazines, a diverse number of new analogues were generated as shown in Scheme 4. New thieno[3,4-*b*]pyrazines include the dialkoxy species **6a**−**c** and cyano species **8** and **9** produced via nucleophilic substitution by the appropriate salts, as well as the alkylamino analogue **7** via catalytic amination.[22] The initial attempts to produce the dicyano **9** via the treatment of **2** with NaCN in ethanol resulted in the surprising asymmetrical species **8**. This compound can be reproducibly made in high yield and is thought to be the result of the high reactivity of the monocyano intermediate, which has been isolated as a byproduct of the reaction. It is thought that this reactive intermediate then undergoes attack by the solvent to substitute the second bromide with the ethoxy functionality. The use of a less reactive solvent did allow the production of the desired dicyano **9**, although in lower yields than desirable. In addition to the desired compound **9**, the monosubstituted 2-bromo-3-cyanothieno[3,4-*b*]pyrazine and unreacted starting material have been recovered from the reaction. Efforts to increase the yield of **9** via extended reaction times resulted in decomposition of **9** and reduced yields.

Lastly, to further expand the variety of functionality possible in thieno[3,4-*b*]pyrazines, the bis(bromomethyl) analogue **4** was produced via the condensation of diaminothiophene with commercially available 1,4-dibromo-2,3-butanedione (Scheme 5).

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SCHEME 5. Synthesis of New 2,3-Difunctionalized Thieno[3,4-*b*]pyrazines from Precursor 4

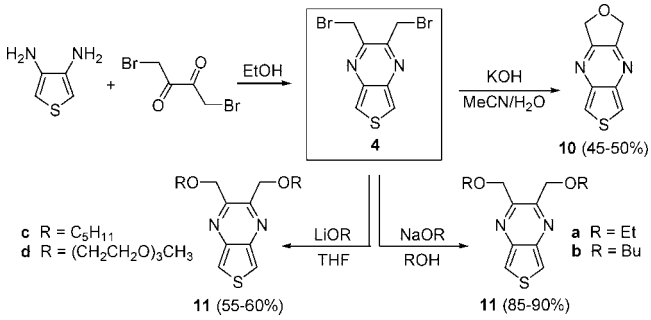

TABLE 2. Experimental Geometrical Parameters of 2,3-Dimethylthieno[3,4-*b*]pyrazine (1b), 2,3-Dihexylthieno[3,4-*b*]pyrazine (1d), 2,3-Bis(bromomethyl)thieno[3,4-*b*]pyrazine (4), Thiophene, and Pyrazine

parameter	1b[a]	1d[b]	4	thiophene[c]	pyrazine[c]
S(1)−C(5)	1.691	1.684	1.700	1.714	
C(5)−C(6)	1.372	1.368	1.373	1.370	
C(3)−C(6)	1.427	1.434	1.434	1.423	1.403
C(6)−N(1)	1.377	1.372	1.373		1.339
N(1)−C(1)	1.308	1.300	1.308		1.339
C(1)−C(2)	1.460	1.463	1.469		1.403
C(1)−C(7)	1.495	1.514	1.489		
C(4)−S(1)−C(5)	94.27	93.68	93.63	92.17	
S(1)−C(5)−C(6)	110.52	111.63	110.77	111.47	
C(5)−C(6)−C(3)	112.44	111.32	112.03	112.45	
N(1)−C(6)−C(3)	121.35	121.27	121.97		122.2
C(1)−N(1)−C(6)	116.05	116.18	115.72		115.6
C(2)−C(1)−N(1)	121.51	122.75	122.68		122.2
N(1)−C(1)−C(7)	117.60	117.84	116.49		

[a] Reference 14. [b] Reference 7. [c] Reference 23.

As in the case of **2** above, ether functionalites (**10**, **11a**−**d**) are then possible via simple substitution reactions.

Crystallography. The X-ray quality crystals of **4** could be grown by the slow evaporation of acetonitrile solutions, and selected bond angles and distances for **4** are given in Table 2, along with the values for **1b**, **1d**, thiophene, and pyrazine for comparison. The structure of **4** agrees quite well with the two previous structures of **1b**[14] and **1d**,[7] with the biggest difference being a shortening of the bond between the pyrazine ring and the bromomethyl group and an elongation of the bond between the 2- and 3-positions.

Comparing the three thieno[3,4-*b*]pyrazines with the gas-phase distances of thiophene and pyrazine[23] shows that the fused thiophene ring is nearly identical to the parent thiophene. As previously seen, however, the fused pyrazine shows some bond fixation.[14] For example, while the delocalized structure of pyrazine results in four equivalent C−N bonds, the fused pyrazine ring exhibits elongation of the thiophene−N bonds and shortening of the exterior C−N bonds. In fact, the exterior C−N bond lengths (i.e., N(1)−C(1) = 1.300−1.308 Å) are very close to the 1.28 Å length of localized C=N bonds.[24]

UV−vis Spectroscopy. The spectral data of the parent thieno[3,4-*b*]pyrazine (**1a**) and its 2,3-difunctionalized analogues are given in Table 3. Representative UV−vis spectra of **1d**, **6a**, **8**, and **11b** are shown in Figure 1. Previous photophysical

TABLE 3. Spectral Data of Thieno[3,4-*b*]pyrazines in CH_3CN

	$S_0 \rightarrow S_1$ (CT)			$S_0 \rightarrow S_2$ ($\pi \rightarrow \pi^*$)		
TP	λ_{max} (nm)	ε (M^{-1} cm^{-1})	f	λ_{max} (nm)	ε (M^{-1} cm^{-1})	f
1a[a]	350	2 400	0.053	299	10 900	0.184
1d[a]	349	1 900	0.019	305	11 200	0.317
1j[a]	340	10 500	0.238	252	26 000	0.658
2	360	1 300	0.017	324	8 700	0.145
3	360	900	0.014	319	6 700	0.122
4	360	2 300	0.025	321	9 700	0.170
6a				303	12 000	0.281
6b				303	12 000	0.258
6c				303	11 400	0.250
7				327	18 400	0.400
8	395	1 300	0.023	326	14 700	0.264
9	400	1 000	0.015	340	6 100	0.122
10	355	2 400	0.030	318	12 200	0.205
11a	355	2 100	0.035	305	9 900	0.197
11b	355	1 600	0.021	305	8 300	0.134
11c	355	1 800	0.028	304	9 200	0.163
11d	355	1 900	0.020	305	6 900	0.162

[a] Reference 25.

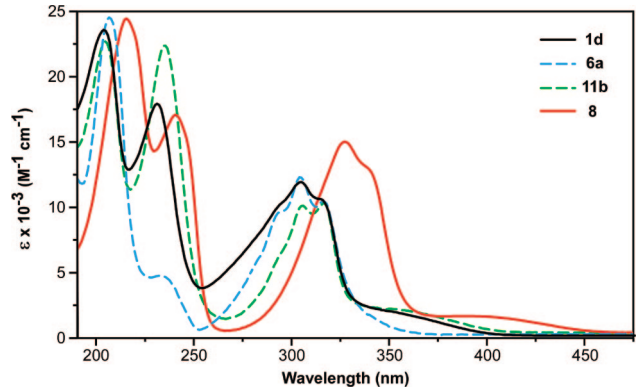

FIGURE 1. UV−vis spectra of various thieno[3,4-*b*]pyrazines in CH_3CN.

studies on thieno[3,4-*b*]pyrazines have shown that both **1a** and its dialkyl analogues exhibit four transitions, of which the lowest energy transition is a broad charge transfer (CT) band centered at ∼350 nm.[25] This CT band results from a transition between a predominately thiophene-localized HOMO and a LUMO of greater pyrazine contribution. A higher energy transition near 300 nm consists of multiple bands of close energetic spacing, which are assigned as various vibrational components of the same $\pi \rightarrow \pi^*$ electronic transition. The extinction coefficients for these bands fall roughly between $8-10 \times 10^3$ M^{-1} cm^{-1}, with corresponding values of approximately 0.20−0.30 for the oscillator strengths, corresponding to moderately allowed transitions. Two significantly stronger $\pi \rightarrow \pi^*$ transitions are also exhibited in the higher-energy region of 200−230 nm.

For the most part, the additional analogues exhibit similar spectra, with a couple of notable exceptions. For example, both the phenyl-substituted **1j** and the alkylamino-functionalized **7** exhibit only two bands rather than four. In both cases, the two observed bands are considerably more intense than the corresponding bands of the other analogues, and it is therefore possible that these bands consist of multiple overlapping transitions. Of greater interest, however, is the fact that the analogues containing electron-donating side chains (**6a**−**c**, **7**)

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TABLE 4. Electrochemical Data for a Series of Thieno[3,4-*b*]pyrazines[a]

	oxidation	reduction	
TP	E_p^a (V)	$E_{1/2}$ (V)	ΔE (mV)
1a[c]	1.55		
1d[c]	1.35	−2.01	150
1j	1.25	−1.80	100
2	1.79	−1.34[d]	
3	1.69	−1.59[d]	
4	1.54	−1.43[d]	
6a	1.26	*b*	
6b	1.24	*b*	
6c	1.18	*b*	
7	0.52,[e] 1.13	*b*	
8	1.51	−1.44	100
9	2.13	−0.93	100
10	1.45	−1.87	100
11a	1.49	−1.85	100
11b	1.47	−1.85	125
11c	1.45	−1.85	100
11d	1.53	−1.85	125

[a] All potentials vs Ag/Ag^+. [b] Not within solvent window. [c] Reference 14. [d] Irreversible, value corresponds to E_p^c. [e] Nitrogen-based oxidation.

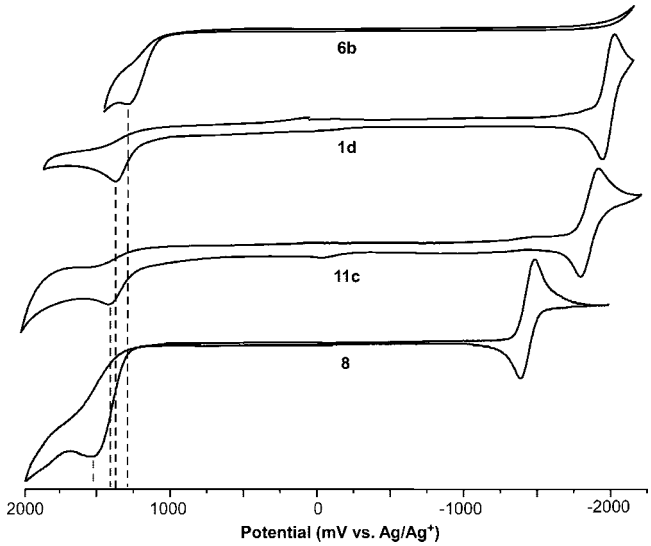

FIGURE 2. Cyclic voltammograms of various thieno[3,4-*b*]pyrazines.

do not seem to exhibit the CT transition typical of thieno[3,4-*b*]pyrazines. As the addition of electron-withdrawing groups causes the CT transition to red-shift as much as 50 nm, it would be reasonable to postulate that the CT transition in compounds **6a**−**c** and **7** has blue-shifted and now overlaps with the next higher energy $\pi \rightarrow \pi^*$ transition near 300 nm. However, in addition to the red-shift of the CT transition, compounds **2**−**4**, **8**, and **9** also exhibit a red-shift of this more intense $\pi \rightarrow \pi^*$ transition, of which a corresponding blue-shift is not observed for compounds **6a**−**c** or **7**.

Electrochemistry. The electrochemical data of the parent thieno[3,4-*b*]pyrazine (**1a**) and its 2,3-difunctionalized analogues is given in Table 4. Representative cyclic voltammograms are shown in Figure 2. As previously reported, thieno[3,4-*b*]pyrazines exhibit a well-defined irreversible thiophene-based oxidation and a quasireversible pyrazine-based reduction.[14] As for most thiophene derivatives, the irreversible oxidation corresponds to the formation and rapid coupling of thiophene-based radical cations ($\tau < 10^{-5}$ s), thus leading to oligomeric and

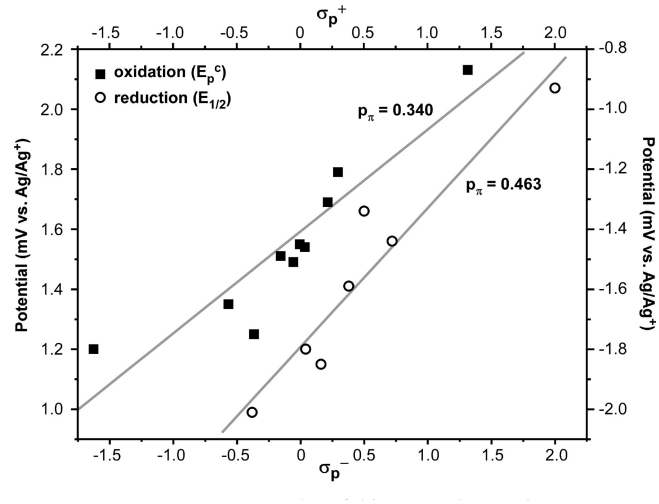

FIGURE 3. Hammett plot of thieno[3,4-*b*]pyrazines.

polymeric species.[26,27] However, unlike typical thiophenes that undergo oxidation ~2 V,[27,28] these oxidations occur at much lower potentials and agree well with the oxidation potentials of other analogous fused-ring thiophene systems (1.1−1.5 V).[28]

The new 2,3-difunctionalized analogues exhibit redox behavior typical of the previous dialkyl and diaryl thieno[3,4-*b*]-pyrazines, although with a greater variance of potentials due to the more significant electronic contributions of the new electron-donating and -withdrawing functionalities. The one exception to this is in the case of compound **7**, in which the alkylamino side chain is also redox active and thus oxidations of both the amine functionality and the thiophene are observed. Here the initial oxidation at 0.52 V is that of the amine, which agrees well with the electrochemistry reported for the related 3-(alkylamino)thiophenes.[29]

As can be seen from Table 4 and Figure 2, the effect of the functional group effects on the potential of oxidation follows normal thiophene trends. That is, electron-donating groups reduce the potential to as low as 1.13 V, while electron-withdrawing groups increase the resulting potential to as high as 2.13 V. As might be expected, the effect on the reduction potentials follows the opposing trend, with electron-withdrawing groups reducing the potential to as low as −0.93 V and electron-donating groups increasing to potential to the extent that the reduction of thieno[3,4-*b*]pyrazines with strongly donating groups such as alkoxy or alkylamino are no longer within the measureable solvent windows of CH_3CN or CH_2Cl_2.

The variations in both the oxidation and reduction potentials correlate well with the respective Hammett substituent constants (σ_p^+ or σ_p^-) of the thieno[3,4-*b*]pyrazines as shown in Figure 3. The shifts in redox potentials are dependent on the polar, steric, and mesomeric effects exerted by the substituents as described by the Hammett−Taft equation:

$$E = \rho_\pi \sigma + S \qquad (2)$$

where $\rho_\pi\sigma$ describes the polar-mesomeric parameters and S accounts for the steric factors.[27,30−32] In cases of low or comparable substituent-based steric interactions (i.e., S is constant),

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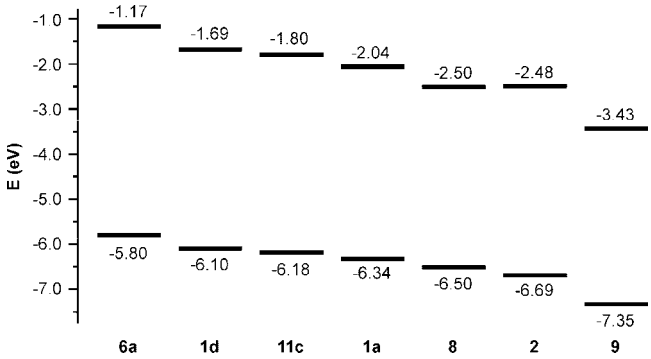

FIGURE 4. Calculated HOMO and LUMO levels for various thieno[3,4-*b*]pyrazines.

linear relationships are found between the potential of oxidation and σ_p^+ (or the reduction potential and σ_p^-).

As seen in Figure 3, both plots (oxidation vs σ_p^+ and the reduction vs σ_p^-) give linear relationships with respective R values of 0.917 and 0.953. The plot of the potential of oxidation gives $\rho_\pi = 0.340$. This value is low in comparison to typical thiophenes ($\rho_\pi = 0.80$),[30] indicating that functional groups have less effect on the potential of oxidation in the case of the fused-ring thieno[3,4-*b*]pyrazines. The lower ρ_π value and reduced functional group effects are similar to those seen in studies of the more conjugated 2,2′-bithiophene systems ($\rho_\pi = 0.37-0.38$).[27,31] The plot of the thieno[3,4-*b*]pyrazine reduction potentials gives the higher value of $\rho_\pi = 0.463$, indicating a higher effect of the functional group on the reduction in comparison to the corresponding oxidation. As the pyrazine ring contributes more significantly to the LUMO than the HOMO,[25] and the functional groups are bound directly to the pyrazine ring, it is not surprising that a greater effect is seen in the corresponding reduction potentials.

Calculations. Density functional theory (DFT) calculations at the B3LYP/6-31G* level were performed for a series of thieno[3,4-*b*]pyrazines to further investigate the tuning effects of the various new side chain functionalizations. As can be seen in Figure 4, the HOMO and LUMO levels determined via the DFT calculations accurately reflect the trends in both the electrochemical and UV−visible measurements. Electron-donating groups destabilize both the HOMO and LUMO levels, while also increasing the corresponding HOMO−LUMO energy gap. In contrast, electron-withdrawing groups stabilize both the HOMO and LUMO levels, while decreasing the HOMO−LUMO energy gap.

Conclusions

New classes of thieno[3,4-*b*]pyrazines containing electron-donating and electron-withdrawing groups have been prepared from 2,3-dibromo- and 2,3-di(bromomethyl)thieno[3,4-*b*]pyrazines. As summarized in Table 5, the use of these new functional groups now allows tuning of the electronic and optical properties of these popular conjugated building blocks. Not only can the potential of oxidation be tuned by approximately 1 V, but the HOMO−LUMO energies can also be modulated by nearly 1 eV. Contrary to common trends in normal thiophene-based systems, the addition of electron-donating groups results in higher HOMO−LUMO energies. The use of electron-withdrawing groups, however, provides reduced HOMO−LUMO energies in the monomers, as well as stabilized HOMO levels that increase the thieno[3,4-*b*]pyrazine stability. As a result, such thieno[3,4-*b*]pyrazines functionalized with electron-withdrawing groups are promising new building blocks for the production of new low band gap materials.

TABLE 5. Summary of Total Tuning Effects in Thieno[3,4-*b*]pyrazines[a]

TP	R_1	R_2	oxidation E_p[a] (V)	reduction $E_{1/2}$ (V)	absorption nm (eV)	HOMO−LUMO calc (eV)
6a	OC_5H_{11}	OC_5H_{11}	1.26	*b*	315 (3.94)	4.63
7	$NHC_{10}H_{21}$	$NHC_{10}H_{21}$	1.13	*b*	335 (3.70)	
1d	C_6H_{13}	C_6H_{13}	1.35[c]	−2.01[c]	349[d] (3.55)	4.41
11c	$CH_2OC_5H_{11}$	$CH_2OC_5H_{11}$	1.45	−1.85	355 (3.49)	4.38
1a	H	H	1.55[c]	*b*	350[d] (3.54)	4.30
2	Br	Br	1.79	−1.34[e]	360 (3.44)	4.21
8	OEt	CN	1.51	−1.44	395 (3.14)	4.00
9	CN	CN	2.13	−0.93	410 (3.02)	3.92

[a] In CH_3CN. All potentials vs Ag/Ag^+. [b] Not within solvent window. [c] Reference 14. [d] Reference 25. [e] Irreversible, value corresponds to E_p^c.

Experimental Section

Materials. 2,5-Dibromo-3,4-dinitrothiophene,[33] thieno[3,4-*b*]-pyrazine,[14] 2,3-dihexylthieno[3,4-*b*]-pyrazine,[14] 2,3-diphenylthieno[3,4-*b*]pyrazine,[14] PBr_5,[34] and 2-isobutyrylcyclohexanone[22] were all prepared as previously reported. Xylenes and THF were distilled from sodium/benzophenone prior to use. All other materials were reagent grade and used without further purification.

3,4-Diaminothiophene. The following is a modification of previously reported methods.[14] Using a mortar and pestle, crystalline 2,5-dibromo-3,4-dinitrothiophene (32.2 g, 100 mmol) was ground to a fine powder and added to concentrated HCl (400 mL) cooled in an ice−water bath. Tin metal powder (71.2 g, 600 mmol) was added slowly to keep the temperature below 15−20 °C. After the addition was complete, the mixture was stirred at 0 °C for an additional 12 h. The solid residue was recovered by vacuum filtration and washed with diethyl ether and CH_3CN until the wash was colorless, giving 22 g of the diammonium salt. The salt was dissolved in water, and aqueous KOH (0.89 M) was added dropwise until the pH reached 7−8. The solution was then extracted with ethyl acetate, dried with anhydrous Na_2SO_4, and concentrated by rotary evaporation at room temperature to give 10 g (90%) of a white crystalline product. Mp 95.5−96.9 °C (lit.[14] 95.5−96.9 °C); ^{1}H NMR δ 3.36 (br s, 4H), 6.16 (s, 2H); ^{13}C NMR δ 101.7, 137.2. All NMR values agree with previously reported values.[14]

Thieno[3,4-*b*]pyrazine-2,3(1*H*,4*H*)-dione (5). The following is a modification of previously reported methods.[13] 3,4-Diaminothiophene (2.85 g, 25 mmol) was dissolved in 20 mL of absolute ethanol. Diethyl oxalate (30 mL, 220 mmol) was added to the solution. The reaction mixture was refluxed for 8 h. After the reaction mixture cooled to room temperature, the solid residue was recovered by vacuum filtration. The product was used without further purification. Yield 85−90%. Mp ∼300 °C (dec) (lit.[13] >300 °C); ^{1}H NMR (*d*-DMSO) δ 11.78 (br s, 2H), 6.74 (s, 2H); ^{13}C NMR (*d*-DMSO) δ 153.6, 127.1, 102.4; IR (KBr) 3270 cm^{-1} (N−H str), 1710 and 1690 cm^{-1} (C=O str). ^{1}H NMR agrees with previously reported values.[13]

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2,3-Dibromothieno[3,4-*b*]pyrazine (2). The reagents PBr_5 (10 mmol), Bu_4NBr (10 mmol), and Na_2CO_3 (1.06 g, 10 mmol) were added to 60 mL of xylenes in a 100 mL round-bottom flask equipped with a condenser with an outlet submerged in 2.5 M KOH aqueous solution. The reaction mixture was heated to reflux, resulting in a color change from deep red to light yellow-orange. Compound **5** (0.84 g, 5 mmol) was then added, and the solution was heated at reflux overnight. Saturated aqueous NH_4Cl solution was added, and the mixture was extracted with CH_2Cl_2. The combined organic layers were then dried with Na_2SO_4, concentrated, and purified by silica chromatography (2% EtOAc/hexanes) to give a yellow solid (60−70% yield). Mp 139 °C (dec); ^{1}H NMR δ 7.97 (s, 2H); ^{13}C NMR δ 140.9, 140.2, 118.6.

2,3-Dichlorothieno[3,4-*b*]pyrazine (3). Compound **3** was prepared as **2** above, substituting PCl_5 and Me_4NCl for the reagents PBr_5 and Bu_4NBr, to give a yellow solid (∼5% yield). Mp 134.2−135.6 °C; ^{1}H NMR δ 7.96 (s, 2H); ^{13}C NMR δ 144.9, 140.2, 118.4.

General Synthesis of 2,3-Dialkoxythieno[3,4-*b*]pyrazines. The appropriate alcohol (6 mmol) was syringed into a mixture of NaH (0.24 g, 6 mmol) in DMF (40 mL) and stirred at room temperature for 5 min. Precursor **2** (0.60 g, 2 mmol) was then added and stirring continued for 2 h. Aqueous NH_4Cl was added and the mixture extracted with CH_2Cl_2. The organic layer was dried with Na_2SO_4, concentrated, and purified by silica chromatography.

2,3-Dipentoxythieno[3,4-*b*]pyrazine (6a). Eluted with 2% EtOAc/hexanes to give a white solid (75−80% yield). Mp 76.1−77.5 °C; ^{1}H NMR δ 7.37 (s, 2H), 4.41 (t, J = 6.8 Hz, 4H), 1.86 (p, J = 6.8 Hz, 4H), 1.43 (m, 8H), 0.94 (t, J = 7.2 Hz, 6H); ^{13}C NMR δ 150.3, 138.4, 112.5, 67.3, 28.4, 28.4, 22.6, 14.2; HRMS *m*/*z* 331.1445 [M + Na]$^+$ (calcd for $C_{16}H_{24}N_2NaO_2S$ 331.1451).

2,3-Didecyloxythieno[3,4-*b*]pyrazine (6b). Eluted with 4% EtOAc/hexanes to give a white solid (70−75% yield). Mp 69.7−71.3 °C; ^{1}H NMR δ 7.37 (s, 2H), 4.41 (t, J = 6.8 Hz, 4H), 1.85 (p, J = 6.8 Hz, 4H), 1.46 (m, 4H), 1.37 (m, 4H), 1.27 (m, 20H), 0.88 (t, J = 6.8 Hz, 6H); ^{13}C NMR δ 150.3, 138.4, 112.5, 67.3, 32.1, 29.9, 29.8, 29.8, 29.6, 28.7, 26.2, 22.9, 14.3; HRMS *m*/*z* 471.2994 [M + Na]$^+$ (calcd for $C_{26}H_{44}N_2NaO_2S$ 471.3016).

2,3-Bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)thieno[3,4-*b*]pyrazine (6c). Eluted with 35% EtOAc/hexanes to give a yellow oil (75−80% yield). ^{1}H NMR δ 7.34 (s, 2H), 4.54 (t, J = 5.2 Hz, 4H), 3.88 (t, J = 5.2 Hz, 4H), 3.71 (m, 4H), 3.64 (m, 4H), 3.61 (m, 4H), 3.50 (m, 4H), 3.33 (s, 6H); ^{13}C NMR δ 149.7, 138.1, 112.7, 72.0, 70.9, 70.8, 70.6, 69.0, 66.2, 59.1; HRMS *m*/*z* 483.1761 [M + Na]$^+$ (calcd for $C_{20}H_{32}N_2NaO_8S$ 483.1772).

2,3-Di(*N*-decylamino)thieno[3,4-*b*]pyrazine (7). DMF (1 mL), decylamine (1.6 mL, 8 mmol), and 2-isobutyrylcyclohexanone (0.067 g, 0.4 mmol) were added via syringe to a flask containing **2** (0.587 g, 2 mmol), Cs_2CO_3 (1.30 g, 4 mmol), and CuI (0.019 g, 0.1 mmol). The suspension was heated at 90 °C for 1 h and then cooled to room temperature. Ethyl acetate (20 mL) was added, and the suspension was filtered to remove inorganic salts and then purified via silica chromatagraphy (7% EtOAc/hexanes) to give a white solid (84% yield). Mp 75.1−76.1 °C; ^{1}H NMR δ 7.18 (s, 2H), 4.81 (br t, J = 5.6 Hz, 2H), 3.43 (dd, J = 5.6, 7.2 Hz, 4 H), 1.60 (p, J = 7.2 Hz, 4H), 1.34 (m, 28 H), 0.88 (t, J = 6.8 Hz, 6H); ^{13}C NMR δ 145.1, 139.0, 109.8, 42.1, 32.1, 29.8, 29.6, 29.5, 29.3, 27.4, 22.9, 14.3; IR (KBr) 3370 cm^{-1} (N−H str); HRMS *m*/*z* 447.3521 [M + H]$^+$ (calcd for $C_{26}H_{47}N_4S$ 447.3516).

2-Cyano-3-ethoxythieno[3,4-*b*]pyrazine (8). Ethanol (100%, 25 mL) was added via syringe to a flask containing **2** (0.357 g, 1.2 mmol) and NaCN (0.15 g, 3.0 mmol). The solution was heated at reflux for 30 min, cooled to room temperature, diluted with 100 mL H_2O, and extracted with CH_2Cl_2. The combined organic layers were dried with Na_2SO_4, concentrated, and purified by silica chromatography (3% EtOAc/hexanes) to give a yellow solid (80−85% yield). Mp 114.8−115.5 °C; ^{1}H NMR δ 8.16 (d, J = 3.6 Hz, 1H), 7.58 (d, J = 3.6 Hz, 1H), 4.55 (q, J = 6.8 Hz, 2H), 1.51 (t, J = 6.8 Hz, 3H); ^{13}C NMR δ 154.7, 139.8, 139.5, 124.6, 122.9, 114.5, 113.4, 64.0, 14.4; IR (KBr) 2230 cm^{-1} (C≡N str); HRMS *m*/*z* 187.0080 [M + H]$^+$ (calcd for $C_8H_3N_4S$ 187.0073).

2,3-Dicyanothieno[3,4-*b*]pyrazine (9). CH_3CN (40 mL) was added via syringe to a flask containing **2** (0.587 g, 2 mmol) and KCN (0.651 g, 10 mmol), and the solution was stirred at room temperature for 24 h. CH_2Cl_2 was then added, and the mixture washed several times with H_2O, dried with Na_2SO_4, concentrated, and purified by silica chromatography (45% EtOAc/hexanes) to give a yellow solid (15−20% yield). Mp 99 °C (dec); ^{1}H NMR δ 8.48 (s 2H); ^{13}C NMR δ 140.2, 129.2, 123.4, 113.8; IR (KBr) 2230 cm^{-1} (C≡N str); HRMS *m*/*z* 206.0384 [M + H]$^+$ (calcd for $C_9H_8N_3OS$ 206.0383).

2,3-Bis(bromomethyl)thieno[3,4-*b*]pyrazine (4). 3,4-Diaminothiophene (2.28 g, 20 mmol) was dissolved in absolute ethanol (40 mL) and added dropwise to a solution of 1,4-dibromo-2,3-butanedione (4.88 g, 20 mmol) in 20 mL of ethanol at 0 °C. The reaction mixture was stirred at 0 °C for 3 h. Water was added, and the mixture was extracted with CH_2Cl_2. The organic layer was dried with Na_2SO_4, concentrated, and purified by silica chromatography (10% EtOAc/hexanes) to give a yellow solid (60−65% yield). Mp 107 °C (dec); ^{1}H NMR δ 8.02 (s, 2H), 4.83 (s, 4H); ^{13}C NMR δ 150.3, 144.6, 118.8, 31.3; HRMS *m*/*z* 467.7994 [M + $AgCH_3CN$]$^+$ (calcd for $C_{10}H_9AgBr_2N_3S$ 467.7929).

1,3-Dihydrofuro[3,4-*e*]thieno[3,4-*b*]pyrazine (10). Compound **4** (0.64 g, 2 mmol) was dissolved in 40 mL of MeCN/H_2O (10:1) mixture, and KOH (0.90 g, 16 mmol) was added to the solution. After stirred for 3 h, the reaction mixture was quenched by water, and the organic layer was extracted by CH_2Cl_2. The combined organic layers were dried with Na_2SO_4 and concentrated by rotary evaporation. The crude product was purified by silica chromatography (12% EtOAc in hexanes) to give a yellow solid (45−50% yield). Mp 117 °C (dec); ^{1}H NMR δ 7.90 (s, 2H), 5.07 (s, 4H); ^{13}C NMR δ 156.4 142.4, 117.2, 70.6; HRMS *m*/*z* 179.0289 [M + H]$^+$ (calcd for $C_8H_7N_2OS$ 179.0274).

General Synthesis of 2,3-Bis(alkoxymethyl)thieno[3,4-*b*]pyrazines. For the short chain systems, an alkoxide reagent was prepared via the addition of NaH (0.24 g, 6 mmol) to 40 mL of the appropriate alcohol and stirred for 5 min. For the preparation of longer alkoxides, BuLi (8.0 mmol) was added to the alcohol (8 mmol) in 50 mL of THF. Precursor **4** (0.64 g, 2 mmol) was then added to the alkoxide solution and stirred for 2 h. Aqueous NH_4Cl was then added, and the mixture was extracted with CH_2Cl_2. The organic layer was dried with Na_2SO_4, concentrated, and purified by silica chromatography (12% EtOAc/hexanes) to give a yellow oil.

2,3-Bis(ethoxymethyl)thieno[3,4-*b*]pyrazine (11a). Yield 85−90%; ^{1}H NMR δ 7.96 (s, 2H), 4.82 (s, 4H), 3.65 (q, J = 7.2 Hz, 4H), 1.27 (t, J = 6.8 Hz, 6H); ^{13}C NMR δ 151.9, 141.7, 117.9, 72.5, 66.9, 15.4; HRMS *m*/*z* 275.0834 [M + Na]$^+$ (calcd for $C_{12}H_{16}N_2NaO_2S$ 275.0825).

2,3-Bis(butoxymethyl)thieno[3,4-*b*]pyrazine (11b). Yield 85−90%; ^{1}H NMR δ 7.96 (s, 2H), 4.81 (s, 4H), 3.57 (t, J = 5.6 Hz, 4H), 1.62 (m, 4H), 1.37 (m, 4H), 0.91 (t, J = 7.2 Hz, 6H); ^{13}C NMR δ 152.1, 141.7, 117.9, 72.9, 71.4, 32.0, 19.5, 14.1; HRMS *m*/*z* 331.1448 [M + Na]$^+$ (calcd for $C_{16}H_{24}N_2NaO_2S$ 331.1451).

2,3-Bis(pentoxymethyl)thieno[3,4-*b*]pyrazine (11c). Yield 55−60%; ^{1}H NMR δ 7.96 (s, 2H), 4.81 (s, 4H), 3.56 (t, J = 6.8 Hz, 4H), 1.64 (m, 4H), 1.33 (m, 8H), 0.88 (t, J = 6.8 Hz, 6H); ^{13}C NMR δ 152.1, 141.7, 117.9, 72.8, 71.7, 29.6, 28.5, 22.7, 14.2; HRMS *m*/*z* 359.1775 [M + Na]$^+$ (calcd for $C_{18}H_{28}N_2NaO_2S$ 359.1764).

2,3-Bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxymethyl)thieno[3,4-*b*]pyrazine (11d). Yield 55−60%; ^{1}H NMR δ 7.97 (s, 2H), 4.87 (s, 4H), 3.73 (m, 4H), 3.67 (m, 4H), 3.62 (m, 12H), 3.52 (m, 4H), 3.34 (s, 6H); ^{13}C NMR δ 151.7, 141.4.1, 117.9, 72.96, 72.0, 70.6(4), 70.6(0), 70.5, 70.4, 59.2; HRMS *m*/*z* 511.2071 [M + Na]$^+$ (calcd for $C_{22}H_{42}N_2NaO_8S$ 511.2085).

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Supporting Information Available: General experimental details and NMR spectra for all compounds; preparation of 5,7-dibromothieno[3,4-*b*]pyrazine-2,3(1*H*,4*H*)-dione; full crystallographic data for **4** in CIF format; details of UV−visible spectroscopy and electrochemistry; full UV−vis data for all compounds; calculation details and tables of the resulting atom coordinates and absolute energies. This material is available free of charge via the Internet at http://pubs.acs.org.

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