Synthesis and linear optical spectroscopy of thioflavylium near-infrared absorbing dyes

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These results further support the ECC theory. However more experimental proof is needed to ensure that the samples are free from any accidental doping.

Experimental

The synthesis and chemical characterization of **III**–**VIII** are described elsewhere.[6, 14] **VI** was obtained from **VII** by borane reduction according to a literature procedure.[17] The polymer **VIII** was synthesized by dissolving 1,3-dihydrobenzo[c]thiophene and 2.5. equivalent *N*-chlorosuccinimide in carbon tetrachloride. This solution was refluxed for 1 h under a N_2 atmosphere. After evaporation of the solvent, the residue was Soxhlet-extracted with ethyl alcohol, tetrahydrofuran, chloroform, and light petroleum ether, and then dried under vacuum. The samples were doped in concentrated aqueous NH_3 for 20 h. The residue was washed twice with methanol and diethyl ether (also twice) and dried under vacuum (Yield: 70%). Infrared spectra were recorded with the FTIR interferometers Nicolet 7000 and 850. Raman spectra were recorded (λ_{exc} = 514 nm) with a Dilor XY with multichannel detector and with FT-Raman interferometer (λ_{exc} = 1064 nm).

For the sake of completeness we add here the vibrational assignment of the observed lines which do not pertain to the issue treated in this paper, but which may be of use for future dynamical calculations. (i) The complex peak near 1460 cm^{-1} in **VI**, **VII** and **VIII** must arise from vibrations of the ITN unit in a conjugated quinoid structure. The frequency of this line changes in the Raman spectra of the other compounds studied, since the chemical structures are different (IV^C = 1442 cm^{-1}, V^C = 1444 cm^{-1}, III^C = 1449 cm^{-1}). (ii) Line E at 1301 cm^{-1} in **VI**, **VII** and **VIII** corresponds to line E at 1312 cm^{-1} in **IV**, 1330 cm^{-1} in **V** and 1336 cm^{-1} in **III**. (iii) Line F at 1166 cm^{-1} in **VI**, **VII** and **VIII** probably corresponds to IV^F = 1161 cm^{-1} and V^F = 1151 cm^{-1} (?). No assignment can be made in the spectrum of **III**. (iv) Line G at 990 cm^{-1} in **VI**, **VII** and **VIII** corresponds to IV^G = 998 cm^{-1}, V^G = 977 cm^{-1}(?) and II-IG = 998 cm^{-1}. (v) The peculiar, sharp line H at 445 cm^{-1} in **VI**, **VII** and **VIII** corresponds nicely to IV^H = 445 cm^{-1}, V^V = 470 cm^{-1}(?) and III^G = 472 cm^{-1}(?). (vi) A line I is observed at very low frequencies in **VI**, **VII** and **VIII** ($\lambda \approx 250$ cm^{-1}) with a corresponding line at 195 cm^{-1} for compound **V**.

Since the frequencies of lines G and H are almost constant in the compounds studied, we suggest assigning them to the vibrations of the benzene ring of the ITN unit. A precise assignment is not possible, since in the frequency range 1600–800 cm^{-1} ring stretching and C–H in-plane wag of aromatic rings are strongly coupled.

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[1] F. Wudl, M. Kobayashi, A. J. Heeger, *J. Org. Chem.*, **1984**, *49*, 3382.
[2] R. Lazzaroni, J. Riga, J. Verbist, J. L. Brédas, F. Wudl, *J. Chem. Phys.*, **1988**, *88*, 4257.
[3] M. Kobayashi, N. Colaneri, M. Boysel, F. Wudl, A. J. Heeger, *J. Chem. Phys.*, **1985**, *82*, 5717.
[4] J. L. Brédas, *J. Chem. Phys.*, **1985**, *82*, 3808.
[5] Y. S. Lee, M. J. Kertesz, *J. Chem. Phys.*, **1988**, *88*, 2609.
[6] I. Hoogmartens, P. Adriaensens, D. Vanderzande, J. Gelan, C. Quattrocchi, R. Lazzaroni, J. L. Brédas, *Macromolecules*, **1992**, *25*, 7347.
[7] E. Faulques, W. Wallnöfer, H. Kuzmany, *J. Chem. Phys.*, **1989**, *90*, 7585.
[8] C. Castiglioni, M. Gussoni, J. T. Lopez Navarrete, G. Zerbi, *Solid State Commun.*, **1988**, *65*, 625.
[9] W. P. Su, J. R. Schrieffer, A. J. Heeger, *Phys. Rev. B*, **1980**, *22*, 2099.
[10] M. Gussoni, C. Castiglioni, G. Zerbi, in *Vibrational Spectroscopy of New Materials* (Eds.: R. J. H. Clark and R. E. Hester), Wiley, New York **1991**, *251–353*.
[11] G. Zerbi, M. Gussoni, C. Castiglioni, in *Conjugated Polymers. The Novel Science and Technology of Highly Conducting and Non-Linear Optically Active Materials*, (Eds.: J. L. Brédas and R. Silbey), Kluwer, Dordrecht **1991**, 435–507.
[12] J. Geisselbrecht, J. Kurti, H. Kuzmany, *Synth. Metals*, **1993**, *55–57*, 4266.
[13] a) B. Horovitz, *Solid State Commun.*, **1982**, *41*, 729.
b) B. Horovitz, *Phys. Rev. Lett.*, **1982**, *47*, 1491.
[14] a) I. Hoogmartens, P. Adriaensens, R. Carleer, D. Vanderzande, H. Martens, J. Gelan, *Synth. Met.*, **1992**, *51*, 219.
b) R. Kiebooms, I. Hoogmartens, P. Adriaensens, D. Vanderzande, J. Gelan, *Synth. Met.*, **1992**, *52*, 395.
[15] I. Hoogmartens, P. Adriaensens, D. Vanderzande, J. Gelan, *Anal. Chim. Acta*, **1993**, *283*, 1025.
[16] M. Gussoni, C. Castiglioni, M. Miragoli, G. Lugli, G. Zerbi, *Spec. Acta*, **1985**, *41A*, 371.
[17] J. Cason, D. M. Lynch, A. Weiss, *J. Org. Chem.*, **1973**, *38*, 1944.

Synthesis and Linear Optical Spectroscopy of Thioflavylium Near-Infrared Absorbing Dyes**

By *Chin-Ti Chen* and *Seth R. Marder**

Near-infrared (NIR) absorbing dyes ($\approx \lambda_{max} > 700$ nm) have recently attracted attention for use in applications including optical recording and printing which employ inexpensive semiconductor lasers that emit light around 800 nm,[1–5] and as photosensitizers in photodynamic therapy (PDT).[6–8]

As part of our studies of nonlinear optical (NLO) materials, we have been exploring the relationships between molecular hyperpolarizabilities and both the degree of ground-state polarization and bond length alternation.[9–12] We have therefore been exploring conjugated systems with strong electron donors and acceptors. In addition, several groups have examined systems in which a π-bridge between the donor and the acceptor contains one or more thiophene rings. For NLO applications, such systems strike a good compromise between the thermal stability associated with having phenyl groups in the π-system and the excellent polarizability of polyene bridges.[13–18]

In some cases the donor-acceptor molecules that we had prepared for NLO applications had strong absorption in the NIR. One particular acceptor that routinely resulted in absorption in the NIR was the thioflavylium group. The use of thioflavylium group to generate NIR dyes had been discussed earlier[19–22] and here we report the syntheses and the visible-NIR spectra for a variety of new thioflavylium chromophores with various donors, conjugation lengths and bridge structures, including those containing thiophene rings.

The synthesis and labeling protocol for compounds in this study are shown in Scheme 1. Briefly, Knoevenagel condensation of 4-methylthioflavylium (or 2-phenyl-4-methyl-1-benzothiopyrylium) perchlorate **1**[19] with various donor substituted aldehydes, **Ald 2-13** produced chromophores **2**–**13** in yields between 44 and 98% (with the exception of **7**, which tended to decompose under the reaction conditions and was isolated in 24% yield). With the exception of **5** and **6** previously reported by Nakazumi et al.,[21, 22] to our

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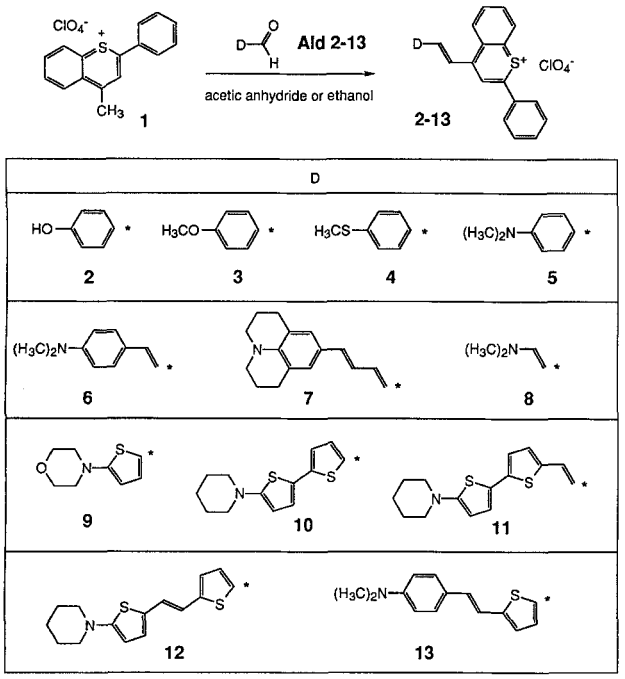

Scheme 1.

knowledge the other thioflavylium chromophores reported here are new compounds.

The visible-NIR spectra of these dyes provides some interesting information about their electronic structure. First, all of the compounds exhibit negative solvatochromism (in dichloromethane and acetonitrile, see Table 1). One interpretation of this result within the conventional view of solvatochromic interactions is that the change in dipole moment for the molecules upon excitation ($\Delta\mu_{eg}$) is negative. We speculate that this may result from either, the sign of the dipole moment changing upon excitation, or the excited state simply having a smaller dipole moment than the ground state.

Table 1. Absorption optical data of thioflavylium chromophores in dichloromethane (1.25×10^{-5} M) and acetonitrile (2.5×10^{-5} M)[a].

	# DB[b]	λ_{max} (nm)		ε (10^4 $M^{-1}cm^{-1}$)		f	
		CH_2Cl_2	CH_3CN	CH_2Cl_2	CH_3CN	CH_2Cl_2	CH_3CN
2	3	556	544	3.6	4.3	0.47	0.67
3	3	570	542	5.1	3.5	0.61	0.50
4	3	598	556	4.7	3.1	0.63	0.49
5	3	730	716	10.7	7.6	0.91	0.80
6	4	832	778	12.7	8.8	1.17	1.03
7	5	882	748	9.3	6.1	1.55	1.47
8	2	562/594[c]	528	5.7/5.7[c]	4.4	0.78	0.85
9	3	704	628	6.4	5.2	0.79	0.93
10	5	848	816	7.6	5.3	1.21	1.21
11	6	936	750	6.9	5.4	1.31	1.30
12	6	948	780	5.3	3.7	0.94	0.89
13	6	932	838	7.3	4.9	0.88	0.83

[a] in acetonitrile compounds **6** and **7** were measured with the concentration of 1.25×10^{-5} M. [b] # DB denotes the number of sequential conjugated double bonds between the donor and thioflavylium moiety. [c] Two values are given because two peaks of equal extinction coefficient are observed for this compound in CH_2Cl_2.

If in the ground state, a lone pair of electrons is somewhat localized on the donor, then upon excitation some of the electron density will be shifted to the acceptor. As a result, the positive charge will be more equally distributed on both ends of the molecule in the excited state relative to the ground state. This then would result in a decrease in dipole moment upon excitation, hence leading to the observed negative solvatochromism (this explanation assumes that the changes in solvent cause only relatively minor changes in the ground-state geometry). It is also worthwhile noting that it is possible that the observed negative solvatochromism *is* also influenced, to some extent, by the different polarizabilities of the solvent as well as by solvent dependent ion pairing effects.

As a function of increasing donor strength, (i.e., $OH < OCH_3 \sim SCH_3 \ll N(CH_3)_2$) the absorption spectra of **2**–**5** display significant bathochromic shifts (Table 1). Compounds with the thioflavylium acceptor exhibit extremely long wavelength absorption relative to analogous compounds containing other acceptors. For example, for **5**, in dichloromethane $\lambda_{max} = 730$ nm; for other compounds of the form $(CH_3)_2N-C_6H_5-HC=CH-A$, where A = 4-nitrophenyl, $\lambda_{max} = 432$ nm; A = 4-(*N*-methylpyridiniumyl), $\lambda_{max} = 500$ nm; A = 2-(*N*-methylbenzothiazoliumyl), $\lambda_{max} = 550$ nm; A = 4-(*N*-methyllepidiniumyl), $\lambda_{max} = 582$ nm.[23] Moreover, with increasing π-conjugation length from **5** to **6** and **7**, the spectra display the expected pronounced bathochromic shifts of the λ_{max} from 730 nm for **5** to 830 nm for **6**, to 880 nm of **7** and with a concomitant increase in the oscillator strength (see Fig. 1 and Table 1).

In compounds **9**–**13** the π-bridge contains thiophene rings between the donor, alkylamino, and acceptor, thioflavylium. In this series, λ_{max} is bathochromically shifted dramatically from the red edge of the visible (704 nm for **9**) well into the NIR (948 nm for **12**) (Fig. 1). It is interesting to note that **11**

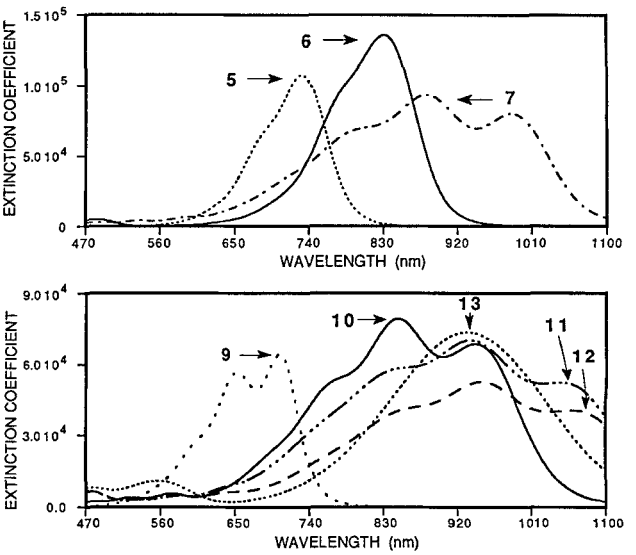

Fig. 1. Visible-NIR absorption spectra of **5**–**7** (top) and **9**—**13** (bottom).

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and **12** are isomers, however, the latter has a slightly longer wavelength absorption and, for reasons that are not immediately obvious, significantly lower oscillator strength (Table 1).

Analyzing ^{1}H-NMR spectra of these dye molecules provides further information about the ground-state structure and, qualitatively, about the extent of charge-transfer from the donor to the thioflavylium acceptor. For chromophore **8**, the pattern of ^{1}H–^{1}H coupling constants (Fig. 2) across the

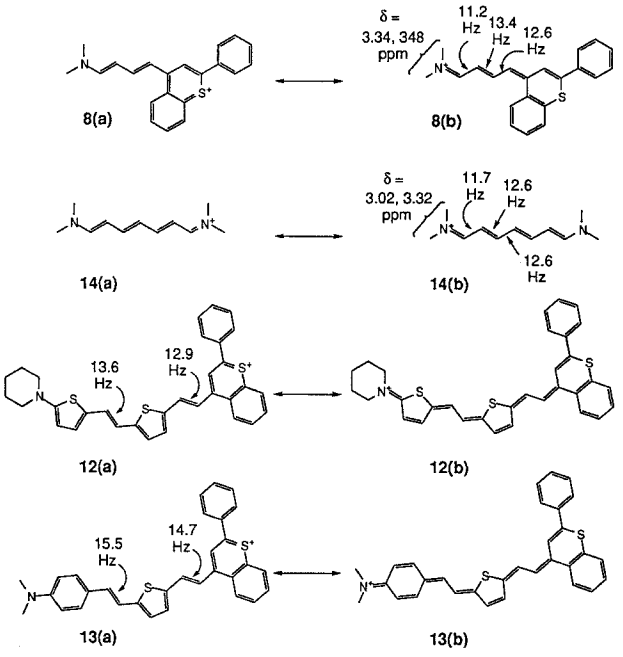

Fig. 2. Canonical charge-transfer resonance structures for **8** and **12**–**14** with *selected* ^{1}*H-NMR* data. The arrangement of the molecules follows the order, from top to bottom, with increasing contribution from the (**a**) form to the ground-state structure. Specifically, there is an equal contribution of (**a**) and (**b**) resonance forms to the ground-state structure of symmetrical cyanine **14**.

trans carbon–carbon double bonds of the conjugated bridge suggests that the ground-state structure of **8** should be better described by the limiting structure **8b** than **8a**, i.e., with positive charge localized on the nitrogen side of the molecules.

Additional evidence for this hypothesis is the observation of two distinct resonances for the hydrogen atoms of dimethylamino group of **8** due to hindered rotation about the bond between nitrogen atoms and the carbon atom on the conjugated bridge to which it is connected. This observation implies that the nitrogen-carbon bond has substantial double bond character indicative of a structure like that shown by resonance structure **8b**.[23, 24]

The ^{1}H–^{1}H coupling constants for the *trans* carbon–carbon double bonds bridging the two aromatic rings increase significantly from 13.6 and 12.9 Hz in **12** to 15.5 and 14.7 Hz in **13** respectively (Fig. 2). This could be viewed as an indication that the contribution of the limiting structure **13b** to the ground-state structure of **13** being relatively less than that of **12b** to the ground-state structure of **12**. Therefore, the extent of charge-transfer character from the nitrogen atom to the thioflavylium group for **13** is less than that for **12**. As a result, **12** has a more cyanine-like structure (i.e., a molecule with equal contributions from each of the two limiting charge-transfer resonance structures as in **14**) and thus this observation is consistent with their relative oscillator strength.

The relatively low extent of charge transfer for **13** can be easily understood by considering the greater loss of aromatic stabilization in the phenyl group in structure **13b** relative to that in donor substituted thiophenyl ring in structure **12b**. Loss or gain of aromatic stabilization upon of charge-transfer has been shown to be an important factor in determining the ground-state geometry and electronic structure.[9, 11, 13–16] These trends are also supported by the characteristic chemical shift of the hydrogen in the 3-position of the thioflavone ring. Thus, in general, as the contribution of resonance form **b** contributes more to the ground-state structure of a compound, the chemical shift of the hydrogen in the 3-position tends to shift upfield. For example, for compounds **2**–**6** the chemical shift for this hydrogen appears between $\delta = 8.4$–9.0 ppm, whereas for compound **8** it appears at $\delta = 7.86$ ppm.

In summary, we have presented a convenient synthetic method for preparing thioflavylium chromophores with reasonable to high yield. The visible-NIR absorption spectroscopy and ^{1}H–^{1}H NMR coupling constant and chemical shift data, provide evidence that thioflavylium moiety is a powerful acceptor for creating near-IR absorbing dyes.

Experimental

Ald 2–**13** were either commercially available (i.e., **Ald 2**–**6** and **Ald 8**) or synthesized by methods previously reported [17,18,25]. The Knoevenagel condensation reactions between **Ald 2**–**13** and **1** were performed either in refluxing acetic anhydride or in ethanol (without any base catalyst, since it resulted in the decomposition of the chromophore products). However, in acetic anhydride, syntheses of **10**–**13**, were hampered by the formation of unknown by-products that were difficult to separate from the desired products. Therefore, ethanol was chosen as the solvent in the synthesis of **10**–**13**, for the ease of purification. Acetic anhydride is also not suitable for preparing **2**, since **2** was acylated under the reaction conditions. Some chromophores (i.e., **2**–**9**) isolated by filtration directly from the reaction solution were already analytically pure. Other chromophores needed further purification such as recrystallization from acetonitrile and ethanol. In general, the donor aldehyde (1.0 eq.) and **1** (0.95 eq.) were mixed together in dry ethanol or acetic anhydride. The mixture was brought to a gentle reflux under nitrogen for 2 to 3 hours. After cooling to room temperature, the product was isolated from the reaction solution by filtration. The product was further purified by recrystallization from acetonitrile and ethanol when necessary.

2 Yield, 94%. ^{1}H-NMR (500 MHz, CD_3CN): $\delta = 9.09$ (d, $J = 7.8$ Hz, 1H), 9.07 (s, 1H), 8.51 (d, $J = 15.6$ Hz, 1H), 8.50 (dd, $J = 8.1$, 1.3 Hz, 1H), 8.29 (d, $J = 15.6$ Hz, 1H), 8.19 (m, 1H), 8.16 (m, 2H), 8.15 (m, 1H), 8.06 (s, 1H), 7.98 (d, $J = 8.9$ Hz, 2H), 7.83 (m, 1H), 7.76 (m, 2H), 7.04 (d, $J = 8.9$ Hz, 2H). Anal. Found (calcd.) for **2**: C, 62.75 (62.22); H, 3.92 (3.89); Cl, 8.10 (8.04); S, 7.35 (7.27).

3 Yield, 78%. ^{1}H-NMR (500 MHz, CD_3CN): $\delta = 9.16$ (d, $J = 8.1$ Hz, 1H), 9.16 (s, 1H), 8.59 (d, $J = 15.6$ Hz, 1H), 8.55 (dd, $J = 8.1$, 1.3 Hz, 1H), 8.39 (d, $J = 15.6$ Hz, 1H), 8.22 (m, 1H), 8.18 (m, 2H), 8.17 (m, 1H), 8.05 (d, $J = 8.9$ Hz, 2H), 7.84 (m, 1H), 7.77 (m, 2H), 7.15 (d, $J = 8.9$ Hz, 2H), 3.93 (s, 3H). Anal. Found (calcd.) for $3 \cdot H_2O$: C, 60.95 (60.95); H, 4.51 (4.48); Cl, 7.42 (7.79); S, 6.82 (6.78).

4 Yield, 44%. ^{1}H-NMR (500 MHz, CD_3CN): d = 9.10 (s, 1H), 9.09 (d, $J = 7.0$ Hz, 1H), 8.53 (dd, $J = 8.1$, 1.3 Hz, 1H), 8.46 (d, $J = 15.6$ Hz, 1H), 8.38 (d, $J = 15.6$ Hz, 1H), 8.21 (m, 1H), 8.16 (m, 2H), 8.16 (m, 1H), 7.92 (d,

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J = 8.5 Hz, 2H), 7.84 (m, 1H), 7.77 (m, 2H), 7.40 (d, J = 8.5 Hz, 2H), 2.55 (s, 3H). Anal. Found (calcd.) for **4**: C, 60.99 (61.20); H, 4.07 (4.07); Cl, 7.61 (7.53); S, 13.54 (13.61).

5 Yield, 85%. ^{1}H-NMR (500 MHz, CD_3NO_2): δ = 8.68 (d, J = 7.9 Hz, 1H), 8.52 (s, 1H), 8.44 (d, J = 14.5 Hz, 1H), 8.04 (dd, J = 7.9, 1.3 Hz, 1H), 7.99 (d, J = 14.5 Hz, 1H), 7.94 (d, J = 9.0 Hz, 2H), 7.92 (m, 2H), 7.87 (m, 1H), 7.84 (m, 1H), 7.69 (m, 1H), 7.66 (m, 2H), 6.94 (d, J = 9.0 Hz, 2H), 3.32 (s, 6H). Anal. Found (calcd.) for **5**: C, 64.21 (64.16); H, 4.77 (4.74); Cl, 7.61 (7.53); N, 2.99 (2.99); S, 6.88 (6.85).

6 Yield, 84%. ^{1}H-NMR (500 MHz, CD_3NO_2): δ = 8.58 (d, J = 8.7 Hz, 1H), 8.46 (s, 1H), 8.45 (dd, J = 12.8, 12.0 Hz, 1H), 8.05 (dd, J = 7.3, 1.8 Hz, 1H), 7.96 (m, 2H), 7.85 (m, 1H), 7.83 (m, 1H), 7.77 (d, J = 9.0 Hz, 2H), 7.73 (dd, J = 13.9, 12.0 Hz, 1H), 7.68 (m, 1H), 7.67 (m, 2H), 7.66 (d, J = 12.8 Hz, 1H), 7.52 (dd, J = 13.9, 12.0 Hz, 1H), 6.96 (d, J = 9.0 Hz, 2H), 3.33 (s, 6H). Anal. Found (calcd.) for **6**: C, 65.62 (65.64); H, 4.93 (4.90); Cl, 7.28 (7.18); N, 2.82 (2.84); S, 6.57 (6.49).

7 Yield, 26%. ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.10 (d, J = 8.7 Hz, 1H),7.85–7.87 (m, 3H), 7.73 (s, 1H), 7.55–7.50 (m, 3H), 7.53 (s, 2H), 7.50 (m, 1H), 7.46 (m, 1H), 7.44–7.40 (m, 3H), 7.33 (d, J = 11.9 Hz, 1H), 7.14 (d, J = 11.2 Hz, 1H), 6.87 (dd, J = 13.5, 11.9 Hz, 1H), 3.63 (t, J = 5.0 Hz, 4H), 2.76 (t, J = 6.0 Hz, 4H), 2.28 (m, 4H). Anal. Found (calcd.) for **7**: C, 69.07 (69.28); H, 5.26 (5.29); Cl, 6.28 (6.20); N, 2.40 (2.45); S, 5.70 (5.60).

8 Yield, 48%. ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.32 (dd, J = 13.4, 12.6 Hz, 1H), 8.19 (dd, J = 7.5, 2.1 Hz, 1H), 8.04 (d, J = 11.1 Hz, 1H), 7.86 (s, 1H), 7.81 (m, 2H), 7.67 (dd, J = 6.9, 2.4 Hz, 1H), 7.59 (m, 1H), 7.58 (m, 4H), 7.18 (d, J = 12.6 Hz, 1H), 6.61 (dd, J = 13.4, 11.1 Hz, 1H), 3.48 (s, 3H), 3.34 (s, 3H). Anal. Found (calcd.) for **8**: C, 60.36 (60.35); H, 4.87 (4.82); Cl, 8.56 (8.48); N, 3.31 (3.35); S, 7.77 (7.67).

9 Yield, 87%. ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.37 (d, J = 13.0 Hz, 1H), 8.28 (d, J = 8.1 Hz, 1H), 7.92 (s, 1H), 7.87 (d, J = 5.4 Hz, 1H), 7.83 (m, 2H), 7.70 (d, J = 7.0 Hz, 1H), 7.63 (m, 1H), 7.60–7.54 (m, 4H), 7.04 (d, J = 13.0 Hz, 1H), 6.97 (d, 5.4 Hz, 1H), 3.89 (t, J = 4.4 Hz, 4H), 3.83 (t, J = 4.4 Hz, 4H). Anal. Found (calcd.) for **9**: C, 58.27 (59.19); H, 4.33 (4.30); Cl, 6.94 (6.87); N, 2.71 (2.72); S, 12.33 (12.43).

10 Yield, 98%. ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.14 (m, 1H), 7.95 (d, J = 13.3 Hz, 1H), 7.76 (m, 2H, 7.75 (s, 1H), 7.72 (d, J = 5.25 Hz, 1H), 7.56 (m, 1H), 7.56–7.52 (m, 5H), 7.50 (m, 2H), 7.25 (d, J = 5.1 Hz, 1H), 7.03 (br d, J = 12.6 Hz, 1H), 6.60 (d, J = 5.2 Hz), 3.58 (t, J = 5.1 Hz, 4H), 1.73 (m, 6H). Anal. Found (calcd.) for **10**: C, 60.49 (60.44); H, 4.45 (4.40); Cl, 6.00 (5.95); N, 2.26 (2.35); S, 16.00 (16.13).

11 Yield, 52%. ^{1}H-NMR (500 MHz, CD_3NO_2): δ = 8.10 (m, 1H), 7.87 (d, J = 5.2 Hz, 1H), 7.78 (m, 2H), 7.76 (s, 1H), 7.74 (dd, J = 12.8, 12.6 Hz, 1H), 7.58–7.49 (m, 7H), 7.40 (d, J = 13.0 Hz, 1H), 7.36 (d, J = 5.1 Hz, 1H), 7.16 (d, J = 12.8 Hz, 1H), 6.90 (dd, J = 13.0, 12.6 Hz, 1H), 6.77 (d, J = 5.2 Hz, 1H), 3.75 (t, J = 5.1 Hz, 4H), 1.85 (m, 6H). Anal. Found (calcd.) for **11**: C, 61.87 (61.77); H, 4.59 (4.54); Cl, 5.77 (5.70); N, 2.28 (2.25); S, 15.38 (15.46).

12 Yield, 70%. ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.09 (dd, J = 8.3, 1.4 Hz, 1H), 7.77 (d, J = 12.9 Hz, 1H), 7.77 (m, 2H), 7.70 (s, 1H), 7.66 (d, J = 5.3 Hz, 1H), 7.63 (d, J = 13.6 Hz, 1H), 7.60–7.45 (m, 9H), 7.18 (d, J = 4.8 Hz, 1H), 7.05 (br d, J = 13.2 Hz, 1H), 3.70 (t, J = 5.1 Hz, 4H), 1.76 (m, 6H). Anal. Found (calcd.) for **12**: C, 62.64 (61.77); H, 4.67 (4.54); Cl, 4.66 (5.70); N, 2.39 (2.25); S, 15.87 (15.46).

13 Yield, 61% ^{1}H-NMR (500 MHz, CD_3CN): δ = 8.80 (d, J = 7.5 Hz, 1H), 8.70 (s, 1H), 8.64 (d, J = 14.7 Hz, 1H), 8.22 (dd, J = 8.3, 1.8 Hz, 1H), 8.02 (m, 2H), 7.99 (m, 2H), 7.82 (m, 2H), 7.76 (t, J = 7.3 Hz, 1H), 7.70 (m, 2H), 7.46 (d, J = 8.8 Hz, 2H), 7.31 (d, J = 4.2 Hz, 1H), 7.31 (d, J = 15.5 Hz, 1H), 7.22 (d, J = 15.5 Hz, 1H), 6.72 (d, J = 8.8 Hz, 2H), 3.03 (s, 6H). Anal. Found (calcd.) for **13**: C, 64.70 (64.63); H, 4.59 (4.55); Cl, 6.21 (6.15); N, 2.44 (2.43); S, 11.17 (11.13).

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[1] M. Emmelius, G. Pawlowski, H. M. Vollmann, *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1445.
[2] *Infrared Absorbing Dyes* (Ed: M. Matsuoka), Plenum Press, New York, **1990**.
[3] T. N. Gerasimova, V. V. Shelkovnikov, *Russ. Chem. Rev.* **1992**, *61*, 55.
[4] J. Fabian, H. Nakazumi, M. Matsuoka, *Chem. Rev.* **1992**, *92*, 1197.
[5] K. -Y. Law, *Chem. Rev.* **1993**, *93*, 449.
[6] *Photodynamic Therapy of Neoplastic Disease* (Ed: D. Kessel), CRC Press, Boca Raton, FL **1990**.
[7] *Photodynamic Therapy* (Eds: B. W. Henderson, T. J. M. Dougherty), Dekker, New York **1992**.
[8] S. B. Brown, T. G. Truscott, *Chem. Br.* **1993**, 955.
[9] S. R. Marder, L. -T. Cheng, B. G. Tiemann, A. C. Friedli, M. Blanchard-Desce, J. W. Perry, J. Skindhøj, *Science* **1994**, *263*, 511.
[10] C. -T. Chen, S. R. Marder, L. -T. Cheng, *J. Chem. Soc., Chem. Commun.* **1994**, 259.
[11] C. -T. Chen, S. R. Marder, L. -T. Cheng, *J. Am. Chem. Soc.* **1994**, *116*, 3117.
[12] R. Ortiz, S. R. Marder, L. -T. Cheng, B. G. Tiemann, S. Cavagenero, J. W. Ziller, *J. Chem. Soc., Chem. Commun.* **1994**, 2263.
[13] C. W. Dirk, H. E. Katz, M. L. Schilling, L. A. King, *Chem. Mater.* **1990**, *2*, 700.
[14] A. K. -Y. Jen, V. P. Rao, K. Y. Wong, K. J. Drost, *J. Chem. Soc., Chem. Commun.* **1993**, 90.
[15] V. P. Rao, A. K. -Y. Jen, K. Y. Wong, K. J. Drost, *J. Chem. Soc., Chem. Commun.* **1993**, 1118.
[16] V. P. Rao, A. K. -Y. Jen, K. Y. Wong, K. J. Drost, *Tetrahedron Lett.* **1993**, *34*, 1747.
[17] S. Gilmour, S. R. Marder, J. W. Perry, L. -T. Cheng, *Adv. Mater.* **1994**, *6*, 494.
[18] S. Gilmour, R. A. Montgomery, S. R. Marder, L. -T. Cheng, A. K. -Y. Jen, Y. Cai, J. W. Perry, L. R. Dalton, *Chem. Mater.* **1994**, *6*, 1603.
[19] A. I. Tolmachev, M. A. Kudinova, *Khim. Geterotsikl. Soedin.* **1969**, 804.
[20] A. I. Tolmachev, N. A. Derevyanko, A. A. Ishchenko, *Khim. Geter. Soed.* **1982**, 1173.
[21] H. Nakazumi, S. Watanabe, S. Kado, T. Kitao, *Chem. Lett.* **1989**, 1039.
[22] S. Watanabe, H. Nakazumi, S. Kado, K. Maeda, T. Kitao, *J. Chem. Res. Synop* **1990**, 50.
[23] C. -T. Chen, B. G. Tiemann, S. R. Marder, unpublished observations.
[24] H. E. Nikolajewski, S. Dähne, B. Hirsch, *Chem. Ber.* **1967**, *100*, 2616.
[25] P. V. Bedworth, S. R. Marder, A. K.- Y. Jen, unpublished observations.

Bioactive Silicon Structure Fabrication Through Nanoetching Techniques**

By *Leigh T. Canham**

The semiconductor silicon has never been judged a promising biomaterial, in contrast with numerous metals, ceramics, and polymers.[1] Whilst in cortical tissue it can be relatively bioinert,[2] its hemocompatibility is poor.[3] This is partly why Si integrated circuit technology is still under development for invasive medical and biosensing applications.[4, 5] Long-term problems of the packaging and biocompatibility of "Si chips" have long been identified as a major issue.[6] Recent advances in Si micromachining and wafer bonding, however, have shown that, aside from its perceived poor biocompatibility, Si itself is an attractive miniaturizable packaging material.[7, 8] We demonstrate here that with simple wet-etching techniques, Si wafer surfaces might be rendered highly bioactive with regard to in-vivo bonding ability. In vitro studies on microporous Si films in simulated body fluids are described. The presence of such films is shown to induce hydroxyapatite growth on top of the microporous silicon and even on neighboring areas of bulk Si, which in isolation show no significant levels of bioactivity. This suggests that Si "biochips" might be developed to bond directly with both living soft tissue and bone,

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