Water as an Ideal Solvent for the Synthesis of Easily Hydrolyzable Compounds: High-Yield Preparation of 2-Pyrrolecarbaldimines and their CVD/ALD-Relevant Cu(II) Derivatives in H_2O[†]

Vladimir V. Grushin,* William J. Marshall

Central Research & Development, E. I. DuPont de Nemours & Co., Inc., Experimental Station, Wilmington, Delaware 19880-0328, USA
Fax: (+1)-302-695-8281, e-mail: vlad.grushin-1@usa.dupont.com

Received: June 16, 2004; Accepted: September 10, 2004

Supporting Information for this article is available on the WWW under http://asc.wiley-vch.de.

Abstract: Water was found to be an ideal solvent for the remarkably high-yield, fast preparation of easily hydrolyzable 2-pyrrolecarbaldimines. In the presence of Cu^{2+}, the reaction afforded, in one step, the corresponding Cu(II) chelates which were demonstrated to meet the initial set of current microelectronics criteria for Cu metal deposition *via* a CVD/ALD process. Electronic effects of the substituent on the imino nitrogen of the Cu complexes were shown to strongly influence the coordination geometry at the Cu center.

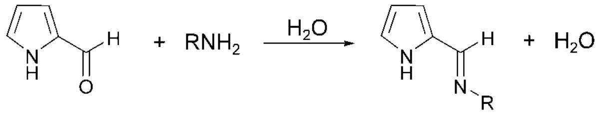
Keywords: chelating agents; chemical vapor deposition; copper; imines; Schiff bases

Since the original 1929 report[1] of the first imino derivatives of pyrrole-2-carboxaldehyde and its Co and Cu chelates, numerous 2-pyrrolecarbaldiminato-metal complexes have been synthesized and have found a number of important applications. Recent examples of exciting applications of 2-pyrrolecarbaldiminato complexes include efficient post-metallocene catalysis of ethylene polymerization with titanium[2] and hafnium[3] complexes, and facile C–H activation with platinum derivatives under mild conditions.[4] Most of the reported ligands of the type 2-pyrrolyl-CH=NR are more stable derivatives of aromatic amines (R = Ar), whereas much more easily hydrolyzable alkyl counterparts are scarce.[2,3,5–8] The Schiff reaction [Eq. (1)][9] is used for the preparation of pyrrolecarbaldimines from the aldehyde and a primary amine.

$$\text{R-CHO} + \text{H}_2\text{N-R'} \rightleftharpoons \text{R-CHNR'} + \text{H}_2\text{O} \qquad (1)$$

The condensation of pyrrole-2-carboxaldehyde is commonly run in anhydrous alcohols such as EtOH[3,5,8] or dry ether[6,7] to minimize the reverse process, hydrolysis. Azeotropic distillation of the H_2O byproduct has also been employed to maximize the yield.[10,11] For aromatic amines, catalysis with acids is often used, which, while speeding up the reaction, can also cause product decomposition and coloring. Regardless of the solvent and conditions employed, the yields for isolated, pure 2-pyrrolecarbaldimines rarely exceed 70% and often are not specified. Close to quantitative isolated yields for pure, colorless pyrrolecarbaldimines are seldom reported.

While the above considerations of the equilibrium in Eq. (1) suggested that H_2O should be avoided as thoroughly as possible, we found that water is a superior solvent for the reaction of pyrrole-2-carboxaldehyde with RNH_2. Running the synthesis in water afforded the desired imines in pure form in ≥90% isolated yield [Eq. (2)]. For alkylamines, the reaction is fast, taking only a few minutes to furnish the products as colorless or slightly yellow crystalline materials or oils. The less nucleophilic aniline reacted with pyrrole-2-carboxaldehyde in water more slowly to give the imine in 94% isolated yield after 3 days. The observed *ca.* 100% selectivity at full conversion eliminated the need for additional purification of the products. Although the alkylimines precipitated out of the aqueous medium, their isolation was performed *via* extraction with hexanes, followed by filtration through a short Na_2SO_4 column,[12] evaporation, and brief vacuum-drying. This extraction procedure is preferred to an alternative isolation technique *via* simple phase separation, washing with water, and drying. To remove the small amounts of water from the product requires a longer exposure to vacuum which can lead to noticeable losses of the volatile products.



(2)

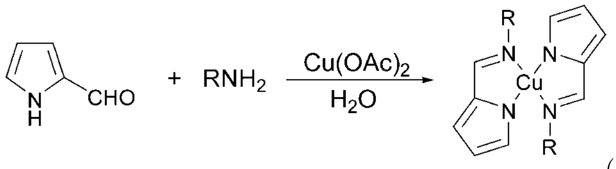
R (isolated yield) = Me (90%); Et (95%); *n*-Pr (97%); *i*-Pr (97%); *n*-Bu (99%); *i*-Bu (99%); *s*-Bu (96%); *t*-Bu (94%); Ph (94%)

DOI: 10.1002/adsc.200404181

Taking into consideration the equilibrium in Eq. (1), the most efficient synthesis of the pyrrolecarbaldimines in water [Eq. (2)] might seem inexplicable. A closer look at the system, however, suggests that both thermodynamic and kinetic factors should favor the high-yield formation of the imines in H_2O. More acidic than MeOH and EtOH, water is a better medium (kinetics) for the synthesis *via* the Schiff reaction which is known to be catalyzed by acids. Once formed [Eq. (2)], the water-insoluble imines precipitate out, thus shifting the equilibrium of Eq. (1) to the right. Indeed, good yields (63–90%) from the reaction of pyrrole-2-carboxaldehyde with RNH_2 have been reported[8] only for the selected few pyrrolecarbaldimines that are poorly soluble in ethanol and hence precipitate upon formation, e.g., R = benzyl, adamantyl. The reaction in EtOH takes hours,[8] whereas in water the condensation is complete within minutes or even seconds.

Our interest in the imino derivatives of pyrrole-2-carboxaldehyde stemmed from their ability to form stable Cu(II) bis-chelates[5,8] which we considered as candidates for copper metal deposition.[13,14] Both the CVD (chemical vapor deposition)[13] and ALD (atomic layer deposition)[14] techniques could be used to deposit thin copper metal films for semiconductor, flat-panel display, and other devices. Due to its high conductivity, resistance to electromigration, and relatively low cost, copper is currently viewed as the most promising metal for integrated circuit interconnects of the future. The modern microelectronics industrial criteria[14] for a Cu metal precursor include sufficient volatility at 0.1–10 torr and 50–200 °C, reducibility with a volatile chemical, and the lack of halogens and oxygen in all reagents involved. This set of initial requirements puts most serious limitations and impediments on the design of molecular precursors for Cu CVD and ALD processes.

The synthesis of pyrrolecarbaldiminato-Cu(II) complexes can be carried out by reacting the ligand, either pre-made or (more conveniently) generated *in situ*, with a Cu(II) salt.[5,8] The Yeh–Barker procedure [pyrrole-2-carboxaldehyde + $Cu(OAc)_2$ + RNH_2 neat or in EtOH][5] afforded some of the Cu complexes in satisfactory yield but did not work for R = *i*-Pr. Once, however, water was used instead of EtOH, the desired Cu bis-chelate was produced in 92% yield. When the reaction with other amines was carried out in water,[15,16] a variety of pyrrolecarbaldiminato-Cu complexes **1a–m** were obtained in considerably better, up to 94% isolated yields [Eq. (3)].



1a – m (3)

1a (R = methyl), 86%; **1b** (R = ethyl), 94%; **1c** (R = propyl), 91%;
1d (R = isopropyl), 92%; **1e** (R = butyl), 88%; **1f** (R = isobutyl), 84%;
1g (R = *tert*-butyl), 46%; **1h** (R = 2-ethylhexyl), 66%; **1i** (R = phenyl), 72%;
1j (R = 3-trifluoromethylphenyl), 55%; **1k** (R = ethoxycarbonylethyl), 54%;
1m (R = isopropoxycarbonylethyl), 69%.

Bis-chelates **1a–m** were prepared [Eq. (3)] on a 0.5–100 g scale and isolated as analytically pure materials. Complexes **1a**, **1c**, **1g**, and **1j** (Figure 1) were characterized by X-ray diffraction data. Selected geometry parameters for these and a few previously reported analogous complexes are presented in Table 1.

The new structural data (Table 1) provide valuable information on the influence of steric[8] and electronic[8,19–21] factors on the distortion from the square-planar geometry in pyrrolecarbaldiminato bis-chelates of Cu(II). As can be seen from Table 1, the dihedral angle between the two chelating NCuN planes varies in a broad range of 0 (R = H) to *ca.* 60° (R = *t*-Bu). While the degree of distortion is believed[8] to be controlled mostly by the steric bulk of R, the new X-ray data (Table 1) indicate that electronic properties of R are also very important. Electron-donating groups cause stronger distortion, with the dihedral angle increasing in the

Table 1. Selected geometry parameters for Cu complexes **1**.

R in **1**	Cu–N(pyr) [Å]	Cu–N(im) [Å]	NCuN/NCuN Interplanar Angle [deg]	Ref.
H	1.950(8)	1.972(9)	0	[17]
Ph (**1j**)	1.952(3), 1.954(3)	2.035(2), 2.054(3)	20	–[a]
p-tolyl	1.940(6), 1.956(8)	2.020(7), 2.020(7)	26	[10]
Ph_2CH	1.959(2)	2.038(2)	29	[8]
$PhCH_2$ (**1i**)	1.951(2)	2.024(2)	33	[8]
Me (**1a**)[b]	1.936(2) – 1.940(2)	2.007(2) – 2.016(2)	32–33	–[a]
n-Pr (**1c**)[c]	1.930(3) – 1.947(3)	1.974(3) – 2.006(3)	42–45	–[a]
t-Bu (**1 g**)	1.937(2)	2.057(2)	57	–[a]
t-Bu (**1 g**)	1.939(8)	2.054(8)	61	[18]

[a] This work.
[b] Three structurally similar molecules in asymmetric unit.
[c] Four structurally similar molecules in asymmetric unit.

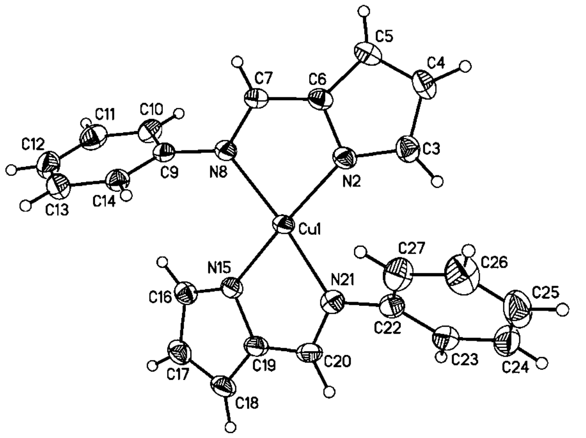


Figure 1. Molecular structure of bis(2-pyrrolecarbaldphenyliminato)copper(II) species **1j**.

order H < Ph < *p*-tolyl < Ph_2CH < $PhCH_2$ ≈ Me < *n*-Pr < *t*-Bu (Table 1). The aryls are less electron-rich than simple alkyls or aralkyls, resulting in smaller dihedral angles. Within the two aryls, the angle is 20° for R = Ph (Figure 1) and 26° for the more electron-donating *p*-tolyl.[10] The derivatives of the smallest methyl and bulkier $PhCH_2$ exhibit very similar angles of 32–33°, whereas the even more cumbersome yet less electron-donating Ph_2CH group leads to a smaller angle of 29°.[8] Small but electron-rich *n*-propyl gives one of the largest angles observed (42–45°). Steric effects, however, should not be neglected. Thus, the dihedral angle increases when going from R = Me (**1a**; 32–33°) to more electron-rich *n*-Pr (**1c**; 42–45°) and further to *t*-Bu (**1g**; 57–61°). At the same time, the Cu–N(im) bond first shortens from 2.01 to 1.99 Å but then elongates to 2.06 Å (Table 1), likely due to steric effects. Also, crystal packing forces may dictate a certain orientation of a substituent, possibly leading to some deviation from the actual dihedral angle in solution.[8]

Importantly, all solid complexes **1** were found to be sublimable under vacuum without decomposition. Conditions for vacuum deposition of the complexes vary depending on the nature of R on the ligand. Thus, in the pressure range of 0.02–1 torr, **1a**–**e** (R = Me, Et, Pr, *i*-Pr, Bu) sublimed cleanly at 85–130 °C, whereas **1j** (R = Ph) sublimed at 150–160 °C. An oil at ambient temperature, **1h** could be distilled under reduced pressure.

Complexes **1** are robust materials that are chemically inert, probably for kinetic reasons. The highly stable 5-membered chelate rings do not open up easily to generate a vacant coordination site that is presumably needed for reactivity. Nonetheless, reducing agents were found to produce Cu metal from **1** at elevated temperatures. When **1a** – **g** (R = alkyl) were exposed to vapors of Et_2SiH_2 no Cu metal formation was observed in the temperature range of 100–210 °C. Under similar conditions, however, **1j** (R = Ph) underwent reduction to produce a thin film of Cu metal at 160–170 °C. Most unexpectedly, slow reduction to Cu metal was observed for **1a**, **b** upon treatment with a 1:1 mixture of NH_3 and H_2 at 180 °C and above. Ammonia or H_2 alone were not as reactive. In one experiment with **1a**, white needle-shaped crystals condensed from the hot gaseous mixture coming from the reduction zone. These crystals were collected and identified by NMR as 2-pyrrolecarbaldmethylimine, the free ligand that would form upon hydrogenolysis of the pyrrole N–Cu bond in **1a**. The role of ammonia and mechanism of reduction remain unknown. Nonetheless, these preliminary results obtained with a simple glass apparatus identify complexes **1** as candidates for a Cu CVD or ALD process.

In conclusion, the most efficient synthesis of easily hydrolyzable alkylimino derivatives of pyrrole-2-carboxaldehyde in water has been demonstrated. The Cu(II) complexes of 2-pyrrolecarbaldimines have been shown to meet the modern microelectronics criteria for Cu metal CVD/ALD precursors.

Experimental Section

General Remarks

All synthetic procedures were performed in air. Amines, pyrrole-2-carboxaldehyde, Cu salts, and other chemicals were obtained from Aldrich and used as received. A Bruker Avance DRX 400 instrument was used for recording NMR data in CD_2Cl_2. Selected representative procedures are given below. A detailed description of the imine and Cu chelate synthesis is presented in the Supporting Information.

2-Pyrrolecarbaldmethylimine

Aqueous methylamine (40%, 10 mL) was added to a stirring suspension of pyrrole-2-carboxaldehyde (5.22 g) in hexanes (150 mL). After 15 min of stirring, the upper organic layer was separated and filtered through a short column filled with anhydrous sodium sulfate. The column was washed with hexanes. The combined hexane filtrates were evaporated to leave the crude product as slightly yellowish crystals; yield: 5.75 g (97%). The latter was sublimed under vacuum to produce pure, white 2-pyrrolecarbaldmethylimine (identical with an authentic sample); yield: 5.35 g (90%). The compound turns yellow and eventually dark brown even if stored under nitrogen.

2-Pyrrolecarbaldisobutylimine

Isobutylamine (4.8 mL, 3.5 g, 4.8 mmol) was added to pyrrole-2-carboxaldehyde (2.3 g, 2.4 mmol) in water (4 mL). After 2 min of stirring, water (15 mL) and hexanes (25 mL) were added, and the stirring continued for 15 min. The organic layer was filtered through a short column filled with anhydrous Na_2SO_4. The aqueous layer was washed with hexanes (3 × 15 mL), and the combined extracts were filtered through the same

Na_2SO_4 column. The combined hexane filtrates were evaporated (N_2) to leave spectroscopically and analytically pure 2-(*N*-isobutylformimidoyl)pyrrole as white crystals; yield: 3.6 g (99%). Anal.: calcd. (%) for $C_9H_{14}N_2$: C 72.0, H 9.4, N 18.6; found: C 72.4, H 9.1, N 18.8; ^1H NMR (CD_2Cl_2, 20 °C): $\delta = 0.95$ (d, 6H, $J = 6.7$ Hz, CH_3), 1.9 (sept, 1H, $J = 6.7$ Hz, Me_2CH), 3.45 (m, 2H, NCH_2), 6.2 (m, 1H, pyrr-H), 6.5 (m, 1H, pyrr-H), 6.9 (m, 1H, pyrr-H), 8.1 (s, 1H, N=C*H*), 10.0 (br s, 1H, NH); ^{13}C NMR (CD_2Cl_2, 20 °C): $\delta = 20.7$; 30.2; 69.3; 109.7; 114.2; 122.0; 130.8; 152.4.

Bis(2-pyrrolecarbaldethyliminato)copper(II) (1b)

To a vigorously stirring mixture of pyrrole-2-carboxaldehyde (45.4 g), $CuCl_2 \cdot 2\,H_2O$ (44.7 g), and water (450 mL) were added 70% aqueous ethylamine (50 mL) and then a solution of NaOH (24.0 g) in water (100 mL). After the mixture was stirred for 3 hours, the black-brown product was separated by filtration, washed with water, and dried. The crude product was dissolved in dichloromethane (500 mL), and the solution was filtered through a short silica gel plug which was then washed with dichloromethane. The combined filtrate and washings were evaporated to a thick paste of the complex in a small amount of dichloromethane, and treated with hexanes (300 mL). After 2 h at +5 °C the black crystals were separated, washed with hexanes (3 × 50 mL), and dried under vacuum. The yield of the analytically pure complex was 68.0 g (94%). Anal.: calcd. (%) for $C_{14}H_{18}CuN_4$: C 55.0, H 5.9, N 18.3; found: C 55.1, H 5.9, N 18.2.

Bis(2-pyrrolecarbaldisopropyliminato)copper(II) (1d)

Isopropylamine (2.0 mL) was added, under stirring, to a mixture of pyrrole-2-carboxaldehyde (1.06 g) and water (10 mL). After 2 min, $Cu(OAc)_2$ (1.20 g) was added. The mixture was stirred at room temperature in air for 1.5 h, then water (50 mL) was added and the stirring continued for 2 more hours. The resulting brown solid was filtered, washed with water, air-dried, and dissolved in dichloromethane. The dark-green solution was filtered and evaporated to leave well-shaped black crystals. The product was recrystallized by dissolving it in boiling heptane and then cooling the solution to +5 °C. The large black crystals were washed quickly with cold hexanes (3 × 3 mL), and dried under vacuum. The yield was 1.71 g (92%), mp 124–125 °C.[5]

X-ray Crystallographic Study

Single crystal X-ray analyses were carried out with a Bruker SMART 1K CCD system. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publications CCDC-241927 (**1a**; R = Me), CCDC-241810 (**1c**; R = Pr), CCDC-241811 (**1 g**; R = *t*-Bu), and CCDC-241809 (**1j**; R = Ph). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: int. code (+44)-1223-336-033, e-mail: deposit@ccdc.cam.ac.uk].

Acknowledgements

We thank Drs. David Thorn and Vsevolod Rostovtsev for a fruitful discussion, and Mr. Gary A. Halliday for technical assistance with some sublimation and reduction experiments.

References

† Contribution No. 8545.

[1] B. Emmert, K. Diehl, F. Gollwitzer, *Ber. Dtsch. Chem. Ges.* **1929**, *62B*, 1733.

[2] Y. Yoshida, S. Matsui, Y. Takagi, M. Mitani, T. Nakano, H. Tanaka, N. Kashiwa, T. Fujita, *Organometallics* **2001**, *20*, 4793.

[3] S. Matsui, T. P. Spaniol, Y. Takagi, Y. Yoshida, J. Okuda, *J. Chem. Soc. Dalton Trans.* **2002**, 4529.

[4] C. N. Iverson, C. A. G. Carter, R. T. Baker, J. D. Scollard, J. A. Labinger, J. E. Bercaw, *J. Am. Chem. Soc.* **2003**, *125*, 12674.

[5] K.-N. Yeh, R. H. Barker, *Inorg. Chem.* **1967**, *6*, 830.

[6] G. C. Van Stein, G. Van Koten, H. Passenier, O. Steinebach, K. Vrieze, *Inorg. Chim. Acta* **1984**, *89*, 79.

[7] J. Barluenga, M. Tomás, E. Rubio, J. A. López-Pelegrín, S. García-Granda, M. Pérez Priede, *J. Am. Chem. Soc.* **1999**, *121*, 3065.

[8] C. M. Wansapura, C. Juyoung, J. L. Simpson, D. Szymanski, G. R. Eaton, S. S. Eaton, S. Fox, *J. Coord. Chem.* **2003**, *56*, 975.

[9] First reported 140 years ago by the then 30-year old Hugo Schiff, see: H. Schiff, *Ann.* **1864/1865**, *Suppl. 3*, 353.

[10] J. A. Castro, J. Romero, J. A. Garcia-Vazquez, A. Castineiras, M. L. Duran, A. Sousa, *Z. Anorg. Allg. Chem.* **1992**, *615*, 155.

[11] M. A. Nesterov, L. G. Menchikov, V. G. Sharf, *Koord. Khim.* **1988**, *14*, 685.

[12] a) It is noteworthy that unlike acidic solids such as the alumina,[12b] neutral Na_2SO_4 did not catalyze the Schiff reaction and was used exclusively for drying; b) F. Texier-Boullet, *Synthesis* **1985**, 679.

[13] J. Rickerby, J. H. G. Steinke, *Chem. Rev.* **2002**, *102*, 1525.

[14] L. Chen, M. Chang, *PCT Int. Appl.* 03/044242, **2003**.

[15] Our work was completed in 2002 (V. Grushin, *PCT Int. Appl.* 2004/015164, **2004**), before the recent similar synthesis of pyrrolecarbaldiminato-Cu complexes in water was reported.[8]

[16] P. Pfeiffer, T. Hesse, H. Pfitzner, W. Scholl, H. Thielert, *J. Prakt. Chem.* **1937**, *149*, 217.

[17] R. Tewari, R. C. Srivastava, *Acta Cryst. B* **1971**, *27*, 1644.

[18] C. H. Wei, *Inorg. Chem.* **1972**, *11*, 2315.

[19] R. H. Holm, A. Chakravorty, L. J. Theriot, *Inorg. Chem.* **1966**, *5*, 625.

[20] H. Yokoi, A. W. Addison, *Inorg. Chem.* **1977**, *16*, 1341.

[21] A. W. Addison, J. H. Stenhouse, *Inorg. Chem.* **1978**, *17*, 2161.