Synthesis and Properties of MoCl₄ Complexes with Thio- and Seleno-ethers and Their Use for Chemical Vapour Deposition of MoSe₂ and MoS₂ Films

Yao-Pang Chang, Andrew L. Hector, William Levason, Gillian Reid* and Joshua Whittam

Chemistry, University of Southampton, Southampton SO17 1BJ, UK.

Abstract

Treatment of trans-[MoCl₄(MeCN)₂] with L (L = Me₂S, Me₂Se, THT, ½ MeSCH₂CH₂SMe) in CH₂Cl₂ solution, or reaction of MoCl₅ with excess L’ (L’ = nBu₂S, nBu₂Se, ½ MeSCH₂CH₂SMe, ½ iPrSCH₂CH₂SPr, ½ MeSCH₂CH₂CH₂SMe, ½ MeSeCH₂CH₂CH₂SeMe) in MeCN, produces the Mo(IV) complexes, [MoCl₄(L)₂] and [MoCl₄(L’)₂], respectively, in good yield. The new complexes have been characterised by IR and UV-vis spectroscopy, elemental analysis and magnetic measurements, whilst crystal structure analyses of trans-[MoCl₄(Me₂S)₂], cis-[MoCl₄{RS(CH₂)₂SR}] (R = Me, iPr) and cis-[MoCl₄{MeS(CH₂)₃SMe}] confirmed their identities and distorted octahedral geometries. The potential of [MoCl₄(nBu₂E)₂] (E = S, Se) as the first examples of molybdenum halide derived single source CVD precursors for the growth of MoE₂ thin films was first probed by TGA, which showed multi-step decomposition processes, with the masses of the final residues consistent with MoSe₂ and MoCl₄ (from E = S; see discussion), respectively. Low pressure CVD experiments conducted at 750 °C (E = S) and 525 °C (E = Se) gave silvery and golden yellow films, respectively. Grazing incidence and in plane XRD data confirmed these to be 2H-MoE₂, whilst the texture of the MoSe₂ was investigated using pole figure measurements. SEM and EDX data, optical and Raman data on the films are also reported.

Introduction

The coordination chemistry of molybdenum extends over nine formal oxidation states (−II to +VI) and has been intensively studied over the last 50 years.¹,² Over this period, in addition to exploring the basic chemistry, much effort has been devoted to studying the binding and reduction of dinitrogen by molybdenum complexes,²,⁴ and in modelling the active sites of molybdoenzymes.⁴,⁵ In the last 10 years the study of early d-block dichalcogenides, including MoS₂ and MoSe₂, has become the focus of much effort. Layered early transition metal dichalcogenides, ME₂ (M = Nb, Ta, V, W, etc.; E= S, Se or Te), are inorganic analogues of graphene, and their properties can be tuned by varying the metal and the chalcogen. Production of the materials as thin films maximises the anisotropy of their magnetic or electronic properties and thus methods to deposit 2D layers are of particular interest currently.⁶,⁸ Applications of these materials in optoelectronics, spintronics, sensors, electrocatalysts and magnetic materials are being actively developed.⁸,⁹ The most common methods of forming MoS₂ or MoSe₂ thin films have been exfoliation from bulk samples, or heating MoO₃ (or sometimes

* Email: G.Reid@soton.ac.uk
molybdenum metal) with S or Se in a hydrogen/inert gas atmosphere, to form the desired MoE₂ (E = S or Se) 2D films on an appropriate substrate.¹⁰⁻¹³ Thermal decomposition of [NH₄]₂[MoS₄] in a hydrogen atmosphere has also recently been reported.¹³

Chalcogenoether complexes of the early d-block metal halides can function as single source CVD precursors for some ME₂ (for example, M = Ti, V or Nb; E = S or Se).¹⁴,¹⁵ Chemical vapour deposition from molybdenum halide complexes has rarely been used to form molybdenum dichalcogenides, although MoSe₂ films were produced by dual source atmospheric pressure chemical vapour deposition (CVD) using MoCl₅ and either Et₂Se or °Bu₂Se.¹⁶ The tetra(thiol)ate complex, [Mo(S'Bu)₄], has also been used to deposit MoS₂ films by CVD.¹⁷

Although there are a few early reports of MoCl₄ complexes with mono-, di- and poly-thioethers and thiamacrocycles,¹₂,¹⁸ the only recent work is the detailed characterisation, including the X-ray crystal structures, of trans-[MoCl₄(Et₂S)₂]¹⁹ and trans-[MoCl₄(THT)₂] (THT = tetrahydrothiophene).²⁰

Here we report the preparation, spectroscopic and structural characterisation of a series of new complexes of molybdenum(IV) chloride with thio- and seleno-ether ligands and the evaluation of a subset of these as single source low pressure CVD reagents for the deposition of the corresponding MoE₂ thin films.

Experimental

Syntheses were performed by using standard Schlenk and glove-box techniques under a dry N₂ atmosphere. MoCl₅ was obtained from Sigma-Aldrich and stored in a glovebox. Tetrahydrothiophene, Me₂S and °Bu₂S were purchased from Sigma-Aldrich and Me₂Se from Strem. Solvents were dried by distillation from CaH₂ (CH₂Cl₂, MeCN), Na (Et₂O) or Na/ benzophenone ketyl (n-hexane). Dichalcogenoethers MeE(CH₂)nEMe (E, n = S, Se; n = 2, 3), °PrS(CH₂)₂S'Pr and °Bu₂Se were prepared via literature methods.²¹,²²

Infrared spectra were recorded using a Perkin-Elmer Spectrum 100 spectrometer in the range 4000–200 cm⁻¹, and samples prepared as Nujol mulls between CsI plates. UV/visible spectra were recorded as powdered solids, using the diffuse reflectance attachment of a Perkin Elmer 750S spectrometer. Microanalyses on new compounds were undertaken by London Metropolitan University. Thermogravimetric analysis (TGA) used a NETZSCH TG209 F1 Libra analyser under a flow of argon at 65 mL/min, contained within a dry, nitrogen purged glovebox. The temperature was increased at a rate of 10 °C/min.

Single crystal X-ray experimental: Data collections used a Rigaku AFC12 goniometer equipped with an enhanced sensitivity (HG) Saturn724+ detector mounted at the window of an FR-E+ SuperBright molybdenum (λ = 0.71073) rotating anode generator with VHF Varimax optics (70 micron focus) with the crystal held at 100 K (N₂ cryostream). Structure solution and refinement were performed using SHELX(S/L)97 and SHELX-2014/7 and were straightforward.²³⁻²⁵ H atoms were added and refined using a riding model. The X-ray data collection details are in Table S1 (ESI). CCDC reference numbers in CIF format are [MoCl₄(NCMe)₂] CCDC 1557208; [MoCl₄(Me₂S)₂] CCDC 557209; [MoCl₄(MeSCH₂CH₂SMe)] CCDC 557210; [MoCl₄(PrSCH₂CH₂S'Pr)] CCDC 1557211; [MoCl₄(MeSCH₂CH₂CH₂SMe)] CCDC 1557212; [MoCl₅(Me₂S)][Me₂SCH₂SMe] CCDC 1557213.
Complex synthesis:

**trans-[MoCl₄(MeCN)₂]**: Was made by a modified literature method.²⁶ MoCl₅ (270 mg, 1.0 mmol) was dissolved in MeCN (20 mL) with stirring for 30 min. to give a dark brown solution. The solution was evaporated *in vacuo*. The resulting dark brown solid was washed by n-hexane (5 mL), the washings decanted off, and the solid dried *in vacuo*. Yield: 249 mg, 78%. Required for C₄H₆Cl₄MoN₂ (319.56): C, 15.02; H, 1.89; N, 8.76. Found: C, 14.84; H, 1.81; N, 8.61%. IR (Nujol/cm⁻¹): 2314, 2283 (MeCN), 335 (Mo-Cl).

**trans-[MoCl₄(THT)₂]**: MoCl₅ (250 mg, 0.915 mmol) was dissolved in CH₂Cl₂ (10 mL). THT (0.26 mL, 2.97 mmol) was then added with stirring for 30 min. during which the solution changed to orange. The solution was taken to dryness *in vacuo*, to produce a dark orange solid. Yield: 296 mg, 78%. Required for C₈H₁₆Cl₄MoS₂ (414.0): C, 23.20; H, 3.89. Found: C, 23.28; H, 3.73%. IR (Nujol/cm⁻¹): 338 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 22 700, 19 400, 16 600 (sh).

**trans-[MoCl₄(Me₂S)₂]**: MoCl₅ (200 mg, 0.75 mmol) was dissolved in CH₂Cl₂ (15 mL). Anhydrous Me₂S (1 mL) was then added with stirring for 30 min. and gave a red-orange solution. The solution was filtered and evaporated *in vacuo*. N-hexane (10 mL) was added to wash the solid and then removed with a syringe. The dark orange solid was dried *in vacuo*. Yield: 206 mg, 76%. Required for C₄H₁₂Cl₄MoS₂ (360.02): C, 13.27; H, 3.34. Found: C, 13.36; H, 3.48%. IR (Nujol/cm⁻¹): 332 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 22 000, 19 400, 16 800 (sh). μₑffective: 2.22 B.M (298 K).

Orange crystals of **trans-[MoCl₄(Me₂S)₂]** grew by allowing a CH₂Cl₂ solution to evaporate slowly in a N₂ atmosphere. A few orange-red crystals were also obtained by recrystallisation of crude [MoCl₄(Me₂S)₂] from CH₂Cl₂; these were found to be [Me₂SCH₂SMe][MoCl₅(Me₂S)] from an X-ray structure determination.

**Alternative method**: MoCl₅ (150 mg, 0.55 mmol) was dissolved in MeCN (10 mL) with stirring to give a dark brown solution. The solution was stirred for another 10 min. and taken to dryness to produce a dark brown solid. The solid was suspended in CH₂Cl₂ (10 mL) before adding Me₂S (3 mL). The suspended solid dissolved immediately after the Me₂S was added to give a red-brown solution. The solution was stirred for another 10 min. and then pumped to dryness, leaving a dark orange solid. The product was spectroscopically identical with the product made from MoCl₅ in CH₂Cl₂.

**trans-[MoCl₄(#Bu₂S)₂]**: MoCl₅ (205 mg, 0.75 mmol) was dissolved in CH₂Cl₂ (10 mL). A solution of #Bu₂S (274 mg, 2.5 mmol) in CH₂Cl₂ (ca. 3 mL) was then added with stirring for 30 min. and gave a red-orange solution. The solution was filtered and evaporated to dryness *in vacuo*. The residue was washed with n-hexane (10 mL), and the dark orange oil dried *in vacuo*. Yield: 250 mg, 62%. Required for C₁₆H₃₆Cl₄MoS₂ (526.31): C, 36.51; H, 6.13. Found: C, 36.15; H, 6.72%. IR (Nujol/cm⁻¹): 334, 305sh (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 41 700, 20 900, 19 100, 18 500 (sh).

**Alternative method**: MoCl₅ (136 mg, 0.5 mmol) was dissolved in MeCN (10 mL) with stirring for 30 min. to give a dark brown solution. The solution taken to dryness *in vacuo* and left a dark brown solid. CH₂Cl₂ (15 mL) was added, followed by a solution of #Bu₂S (0.4 mL, 2.0 mmol) in CH₂Cl₂ (2 mL). The dark solution
changed to red-orange immediately. The solution was then stirred for 15 min. then evaporated in vacuo to afford a dark orange oil. The product was spectroscopically identical to that made from MoCl₅ in CH₂Cl₂.

*trans*-\[MoCl₄(Me₂Se)₂\]: MoCl₅ (200 mg, 0.75 mmol) was suspended in CH₂Cl₂ (15 mL) and Me₂Se (196 mg, 1.96 mmol) was added with stirring for 30 min. and produced an orange-red solution. The solution was filtered and taken to dryness in vacuo. The solid was washed with n-hexane (10 mL), the washings removed with a syringe, and the residual dark orange powder dried in vacuo. Yield: 283 mg, 77%. Required for C₄H₁₂Cl₄MoSe₂ (455.81): C, 10.54; H, 2.65. Found: C, 10.69; H, 2.43%. IR (Nujol/cm⁻¹): 306 (Mo-Cl). μₑff: 2.59 B.M.

*Alternative method*: [MoCl₄(MeCN)₂] (100 mg, 0.31 mmol) was dissolved in 10 mL CH₂Cl₂ with stirring. A solution of Me₂Se (73 mg, 0.65 mmol) and CH₂Cl₂ (5 mL) was then added. The solution was stirred for 1 h. resulting in a red-orange solution. Evaporation in vacuo left a dark orange powder. Yield: 99 mg, 70%. Required for C₁₆H₃₆Cl₄MoSe₂ (455.81): C, 10.54; H, 2.65. Found: C, 10.61; H, 2.54%. The product was spectroscopically identical to that made from MoCl₅.

*trans*-\[MoCl₄(nBu₂Se)₂\]: MoCl₅ (136 mg, 0.5 mmol) was dissolved in MeCN (15 mL) with stirring for 30 min. to give a dark brown solution. The solution was taken to dryness in vacuo and left a dark brown solid. CH₂Cl₂ (25 mL) was added, followed by a solution of nBu₂Se (193 mg, 1.0 mmol) in CH₂Cl₂ (2 mL). The dark solution changed to red-orange immediately. The solution was then stirred for 15 min. then evaporated in vacuo to afford a dark red-orange oil. Yield: 292 mg, 94%. Required for C₁₆H₃₆Cl₄MoSe₂ (455.81): C, 30.79; H, 5.81. Found: C, 30.23; H, 6.00%. IR (Nujol/cm⁻¹): 342s, 305 (sh) (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 40 000, 30 000, 28 000, 22 900, 21 000.

\[MoCl₄(MeSCH₂CH₂SMe)\]: MoCl₅ (205 mg, 0.75 mmol) was dissolved in CH₂Cl₂ (10 mL). A solution of MeSCH₂CH₂SMe (92 mg, 0.75 mmol) in CH₂Cl₂ (ca. 3 mL) was added and the mixture stirred overnight. A deep orange solution and a brown solid formed. More CH₂Cl₂ (10 mL) was added and the solution was filtered. The filtrate was evaporated to dryness in vacuo. Hexane (10 mL) was added to wash the solid and subsequently removed by a syringe. The solid was dried in vacuo to give a dark orange solid. Yield: 157 mg, 58%. IR (Nujol/cm⁻¹): 356, 319, 293 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 41 500, 27 300, 21 000, 19 600. μₑff: 2.66 B.M. Orange crystals grew on allowing a CH₂Cl₂ solution to evaporate in a N₂ atmosphere.

*Alternative method*: MoCl₅ (136 mg, 0.5 mmol) was dissolved in MeCN (10 mL) with stirring for 10 min. to give a dark brown solution. The solution taken to dryness in vacuo, CH₂Cl₂ (10 mL) was added, followed by a solution of MeSCH₂CH₂SMe (180 mg, 1.5 mmol) in CH₂Cl₂ (2 mL). The dark solution changed to light orange-green immediately and deposited a brown solid, which was filtered off. The brown solid was dried in vacuo and washed with Et₂O (ca. 5 mL), then extracted with CH₂Cl₂ (ca. 5 mL). The resulting solution was again taken to dryness in vacuo. Yield: 60 mg, 33%. Required for C₄H₁₀Cl₃MoS₂⋅0.1Et₂O (367.4): C, 14.38; H, 3.02. Found: C, 14.38; H, 3.02% (sample contained ca. 10% Et₂O from wash solvent; this was identified via ¹H NMR spectroscopy).
[MoCl₄(PrSCH₂CH₂SPr)]: MoCl₅ (136 mg, 0.5 mmol) was dissolved in CH₃CN (10 mL) forming dark brown solution. The solution was stirred for 10 min. and then evaporated in vacuo, giving dark brown solid. The solid was dissolved in CH₂Cl₂ (15 mL) and a solution of PrSCH₂CH₂SPr (270 mg, 1.5 mmol) in CH₂Cl₂ (2 mL) was added. The colour changed to orange and solid formed immediately. The solution was stirred for 30 min. and then evaporated in vacuo. The solid was washed with Et₂O (5 mL), the Et₂O removed via a syringe, and the solid was dried in vacuo. Orange powder. Yield: 160 mg, 77%. Required for C₈H₁₈Cl₄MoS₂ (416.11): C, 23.09; H, 4.36. Found: C, 23.90; H, 4.56%. IR (Nujol/cm⁻¹): 371sh, 350, 309 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 41 300, 26 800, 25 000 (sh), 21 000, 18 700 (sh). μ_eff: 2.18 B.M. Orange red crystals grew by allowing a CH₂Cl₂ solution to evaporate slowly under N₂.

[MoCl₄(MeSCH₂CH₂CH₂SMe)]: MoCl₅ (205 mg, 0.75 mmol) was suspended in CH₂Cl₂ (20 mL) and a solution of MeSCH₂CH₂CH₂SMe (109 mg, 0.8 mmol) in CH₂Cl₂ (ca. 3 mL) was added, and stirred overnight to give an orange solution and some orange solid. The solution was removed by a syringe, and the solid washed with hexane (10 mL). The solid was subsequently dried in vacuo. Yield: 83 mg, 30%. Required for C₅H₁₂Cl₄MoS₂ (374.03): C, 16.06; H, 3.23. Found: C, 16.22; H, 3.35%. IR (Nujol/cm⁻¹): 362, 342, 327 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 40 500, 22 070, 19 500. μ_eff: 2.21 B.M. Orange crystals grew by allowing a CH₂Cl₂ solution to evaporate slowly under N₂.

[MoCl₄(MeSeCH₂CH₂CH₂SeMe)]: Was made as described for [MoCl₄(PrSCH₂CH₂SPr)] and obtained as a light orange powder. Yield: 59%. Required for C₅H₁₂Cl₄MoSe₂ (467.82): C, 12.84; H, 2.59. Found: C, 13.01; H, 2.57%. IR (Nujol/cm⁻¹): 332, 308 (Mo-Cl). UV/vis (diffuse reflectance)/cm⁻¹: 41 100, 26 800, 21 000, 18 700.

LPCVD of MoS₂ films using [MoCl₄(nBu₂S)₂]: The precursor (190 mg) dissolved in CH₂Cl₂ (1 mL) was loaded into the closed end of a silica tube in an N₂ purged glove box, and the solvent removed. Silica substrates (ca. 1 × 8 × 20 mm³) were then loaded in the tube and placed end-to-end. The tube was set in a furnace so that the substrates were in the heated zone and the precursor was ca. 2 cm away from the start of the heated zone. The tube was evacuated to 0.1 mm Hg, and the furnace was heated to 750 °C and left for 10 minutes to allow the temperature to stabilise. The tube was gradually moved into the hot zone until evaporation of the precursor began to occur. The position was then maintained until the all the precursor had evaporated. A yellow/orange film was observed at the opposite end of the tube (S). After ca. 30 min. the tube was cooled to room temperature and the tiles were unloaded at ambient temperature in a dinitrogen atmosphere. Silver films were observed on the first two substrates, which corresponds to 735 °C (determined by temperature profiling). The silver films are identical by grazing incidence and in-plane XRD and SEM/EDX analysis.

MoSe₂ films using [MoCl₄(nBu₂Se)₂]: Using the same deposition procedure and with ca. 50 mg of precursor complex. Depositions were undertaken with the furnace temperature set at 400, 450, 500 and 500 °C. A red (Se) film was observed at the far end of the tube and all experiments produced golden/brown films on the
substrates. Temperature profiling for the best MoSe2 films confirmed that the actual deposition temperature was 535 °C. Using larger precursor quantities (ca. 200 mg) led to thicker films being formed.

**Film characterisation:** X-Ray diffraction (XRD) patterns were collected in grazing incidence mode ($\theta_1 = 1^\circ$) or in-plane mode ($\theta_1 = 0.5^\circ$, $2\theta$ scan with the detector scanning in the film plane) using a Rigaku SmartLab diffractometer ($\text{Cu-K}_{\alpha}$, $\lambda = 1.5418$ Å) with parallel X-ray beam and a DTex Ultra 250 1D detector. Phase matching, lattice parameter calculations (MoS2) and Le Bail fitting (MoSe2) used the PDXL2 software package27 and diffraction patterns from ICSD28. Scanning electron microscopy (SEM) was performed on samples at an accelerating voltage of 10 to 15 kV using a JEOL JSM6500 or a Philips XL30 ESEM. Film thicknesses were measured by fracturing the substrate and gold sputtering the edge in order to control charging of the insulating silica surface. Energy dispersive X-ray (EDX) analysis data were obtained with an Oxford INCA x-act X-ray detector (JSM6500) or Thermofisher Ultradry NSS 3 (XL30). Raman spectra were collected using a Renishaw InVia Raman Microscope with a 100 mW He-Ne 785 nm Laser. Optical spectra were obtained in transmission mode using a Perkin-Elmer 750S UV-visible spectrometer.

**Results and Discussion**

Two routes were used to prepare the MoCl4 complexes (Scheme 1), either substitution of the MeCN ligands in trans-[MoCl4(MeCN)2] with the chalcogenoether ligand in CH2Cl2 solution or reaction of MoCl5 with excess ligand in MeCN.

\[
\text{MoCl}_5 \xrightarrow{L} \text{trans-[MoCl}_4L_2] \xrightarrow{\text{trans-[MoCl}_4(\text{MeCN})_2]} \text{trans-[MoCl}_4(\text{E})_2] \rightarrow \text{trans-[MoCl}_4(\text{E})_2] \rightarrow \text{[MoCl}_4(\text{E})_2]}
\]

$L = \text{Me}_2\text{S or tht}$

$E = \text{S, Se}$

$\text{E} = \text{CH}_2\text{CH}_2, \text{CH}_2\text{CH}_2\text{CH}_2$

**Scheme 1** The preparative routes to the MoCl4 chalcogenoether complexes
[MoCl₄(NCR)₂] (R = Me, Et, "Pr) are well known starting materials²⁹-³¹ and an X-ray crystal structure determination of the complex with R = Me showed it to be the trans isomer (see Fig. S1, ESI). The crystals are isomorphous with trans-[WCl₄(MeCN)₂].³¹ In the preparations using MoCl₅, the chalcogen ligand reduces the molybdenum centre, being halogenated in the process, and careful washing is needed to remove the by-products. A few crystals of a minor by-product from the synthesis of [MoCl₄(Me₂S)₂] from MoCl₅ were identified by a crystal structure determination as the sulfonium salt, [Me₂SCH₂SMe][MoCl₅(Me₂S)] (Fig. 1). This cation has also been identified as a product of reaction of MoCl₅ with DMSO;³² in the latter case it was obtained with an [MoOCl₄]⁻ anion.³²

Fig. 1 The structure of one of the two crystallographically independent cations and molybdenum anions in [Me₂SCH₂SMe][MoCl₅(Me₂S)] showing the atom numbering scheme and with ellipsoids drawn at the 50% probability level. The other cation and anion are very similar. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Mo1–Cl4 = 2.3251(17), Mo1–Cl1 = 2.3509(17), Mo1–Cl3 = 2.3633(18), Mo1–Cl5 = 2.3847(18), Mo1–Cl2 = 2.3885(17), Mo1–S1 = 2.5538(19), (cis) Cl–Mo–Cl = 88.10(6)–92.87(7), Cl–Mo1–S1 = 83.14(6)–91.74(6).

The isolated, coordinatively saturated MoCl₄L₂ complexes are mildly hydrolytically sensitive. The crystal structures were determined for trans-[MoCl₄(Me₂S)], cis-[MoCl₄{RS(CH₂)₂SR}⁻] (R = Me, "Pr) and cis-[MoCl₄{MeS(CH₂)₃SMe}⁺] and show the expected six-coordinate geometries (Figs. 2–4), with the chelate bite of the dithioethers responsible for the deviations from regular octahedral geometry. The bond lengths are similar to those in related Mo(IV) complexes.¹⁹,²⁰,³³
Fig. 2. The structure of the centrosymmetric [MoCl₄(Me₂S)₂] showing the atom numbering scheme and with ellipsoids drawn at the 50% probability level. Hydrogen atoms are omitted for clarity. Symmetry operation: i = -x, -y, -z+1. Selected bond lengths (Å) and angles (°): Mo1−Cl1 = 2.3457(5), Mo1−Cl2 = 2.3323(5), Mo1−S1 = 2.5297(6); Cl1−Mo1−Cl2 = 89.39(2), Cl1i−Mo1−Cl2i = 90.61(2), Cl1−Mo1−S1i = 88.65(2), Cl1i−Mo1−S1i = 91.35(2), Cl2−Mo1−S1 = 90.51(2), Cl2i−Mo1−S1 = 89.49(2).

Fig. 3 (a) The structure of [MoCl₄(MeSCH₂CH₂SMe)] showing the atom numbering scheme and with ellipsoids drawn at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Mo1−Cl3 = 2.247(3), Mo1−Cl1 = 2.305(3), Mo1−Cl2 = 2.305(3), Mo1−Cl4 = 2.339(3), Mo1−S1 = 2.519(3), Mo1−S2 = 2.591(3), Cl3−Mo1−Cl1 = 97.61(12), Cl3−Mo1−Cl2 = 98.42(13), Cl3−Mo1−Cl4 = 96.83(11), Cl1−Mo1−Cl4 = 92.47(10), Cl2−Mo1−Cl3 = 92.95(10), Cl1−Mo1−S1 = 87.75(11), Cl1−Mo1−S2 = 82.18(10), Cl2−Mo1−S1 = 91.07(10), Cl1−Mo1−S2 = 85.34(10), Cl2−Mo1−S2 = 77.66(11), Cl4−Mo1−S2 = 92.13(10), S1−Mo1−S2 = 83.62(9).

(b) The structure of [MoCl₄(iPrSCH₂CH₂SiPr)] showing the atom numbering scheme and with ellipsoids drawn at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Mo1−Cl1 = 2.3203(7), Mo1−Cl2 = 2.3295(7), Mo1−Cl3 = 2.3135(7), Mo1−Cl4 = 2.3016(7), Mo1−S1 = 2.5872(7), Mo1−S2 = 2.5730(7), Cl2−Mo1−Cl4 = 93.73(3), Cl4−Mo1−Cl3 = 97.30(3), Cl4−Mo1−Cl1 = 96.60(3), Cl3−Mo1−Cl2 = 96.57(3), Cl1−Mo1−Cl2 = 96.14(3), Cl4−Mo1−S1 = 92.81(3), Cl3−Mo1−S2 = 79.16(2), Cl1−Mo1−S2 = 86.63(2), Cl3−Mo1−S1 = 87.01(2), Cl1−Mo1−S1 = 78.40(2), Cl2−Mo1−S1 = 89.61(2), S2−Mo1−S1 = 84.52(2).
Fig. 4 The structure of [MoCl₄(MeSCH₂CH₂CH₂SMe)] showing the atom numbering scheme and with ellipsoids drawn at the 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (°): Mo1−Cl3 = 2.2686(6), Mo1−Cl1 = 2.3143(6), Mo1−Cl4 = 2.3380(6), Mo1−Cl2 = 2.3486(6), Mo1−S1 = 2.5282(6), Mo1−S2 = 2.5390(6), Cl3−Mo1−Cl1 = 98.40(2), Cl1−Mo1−Cl4 = 97.61(2), Cl3−Mo1−Cl2 = 96.29(2), Cl1−Mo1−Cl2 = 92.82(2), Cl4−Mo1−Cl2 = 97.58(2), Cl3−Mo−1S1 = 87.41(2), Cl1−Mo1−S1 = 83.61(2), Cl4−Mo1−S1 = 79.79(2), Cl3−Mo1−S2 = 86.13(2), Cl4−Mo1−S2 = 78.20(2), Cl2−Mo1−S2 = 85.94(2), S1−Mo1−S2 = 97.370(19).

The complexes are paramagnetic with μₑffective in the range 2.0 – 2.7 B.M. The values are lower than the predicted spin-only value for a d² ion (2.82 B.M.) due to the significant spin-orbit coupling, as expected for 4d elements, and are similar to those observed in related complexes. The solid state UV/visible spectra exhibit two overlapping bands in the range 18 000 – 22 000 cm⁻¹, which can be assigned in approximate Oh symmetry as the d-d transitions, ³T₁g → ³T₁g(P) and ³T₁g → ³T₂g, with ill-defined charge transfer transitions evident at > 30 000 cm⁻¹.

CVD of molybdenum dichalcogenide films

The thermal decomposition of the [MoCl₄(nBu₂E)₂] complexes at atmospheric pressure was first probed using thermogravimetric analysis (TGA). [MoCl₄(nBu₂)₂Se] underwent three mass loss steps at 75–125 °C, 180–200 °C and 200–280 °C, leaving a residual mass of ca. 39.4%, which gradually reduced further as the temperature was raised to 600 °C (Fig. 5). This suggests a complex decomposition pathway with MoSe₂ (40.7 %) or MoCl₄ (38 %) as the final residue. [MoCl₄(nBu₂S)₂] also shows three mass loss steps at 25–160 °C, 170–200 °C and 210–300 °C, leaving a residual mass of ca. 44.9%, which undergoes a further small mass loss (ca. 5%) on heating to 600 °C (Fig. 5). The residual mass is higher than that expected for MoS₂ (30%), but similar to that expected for MoCl₄ (44.7%); some sublimation of MoCl₄ at high temperature would be expected; we note that [NbCl₄(nBu₂S)₂] left NbCl₄ upon heating in vacuo. It is important to note that the TGA experiments are performed at 1 atmosphere pressure under flowing nitrogen, and hence very different from LPCVD conditions. However, TGA does provide a guide to the volatility of the precursors.
CVD test experiments focussed on those complexes bearing \textsuperscript{5}Bu substituents since, unlike Me substituents, these tend to promote elimination of the organic by-products, most likely via $\beta$-hydride elimination reactions. CVD onto silica tiles using \textit{ca.} 30–70 mg of the [MoCl$_4$(nBu$_2$Se)$_2$] precursor resulted in deposition of a reflective golden film on tiles positioned in the hottest part of the furnace at 400–550 °C. Grazing incidence XRD (Fig. 6) showed these films to be the 2H form of MoSe$_2$ ($P6_3/mmc$). Lattice parameters determined from a Le Bail fit to the pattern are $a = 3.2666(10)$ and $c = 13.170(16)$ Å ($R_{wp} = 1.8\%$, $R_p = 1.3\%$; see ESI Fig. S2 for fit). The lattice parameters listed in ICSD for this phase are in the ranges $a = 3.288–3.290$ and $c = 12.90–12.94$ Å.$^{28}$ The films are air and moisture stable (over many months), but easily scratched with a metal spatula. With deposition temperatures higher than 550 °C, MoO$_2$ thin films were recovered, presumably resulting from deposition of molybdenum metal that oxidised post-deposition. Parkin and co-workers previously deposited containing a mixture of the 2H- and 3R-type MoSe$_2$ films using dual source atmospheric pressure CVD,$^{16}$ but we are not aware of any other reports of single phase MoSe$_2$ films from CVD from molybdenum chloride derived precursors.

![Fig. 5 TGA of [MoCl$_4$($^\text{5}$Bu$_2$E)$_2$] (E = S or Se) obtained under flowing Ar (65 mL min$^{-1}$) at ambient pressure with a heating rate of 10 °C min$^{-1}$.](image)
Fig. 6 Grazing incidence XRD (GIXRD, incidence angle = 1°) and in-plane XRD (IPXRD, incidence angle = 0.5°) from MoSe₂ thin films deposited by CVD from [MoCl₄(nBu₂Se)₂] at temperatures as shown. The broad feature at 2θ ∼ 22° is from the SiO₂ substrate. The calculated pattern for bulk polycrystalline 2H-MoSe₂ (P6₃/mmc) with Miller indices is shown for comparison.

The grazing incidence diffraction patterns of the MoSe₂ films are dominated by the 002 reflection, suggesting <00l> alignment of the crystallites. These layered materials typically grow as platelet-shaped crystallites with the ab crystallographic axes in the plane of the crystallites, so this would suggest platelets lying flat on the substrate. An in-plane XRD measurement (Fig. 6) supressed the 002 reflection and enhanced the 100 and 110, supporting this conclusion. SEM images (Fig. 7) showed mainly the edges of platelets suggesting they were standing on edge rather than lying flat, but imaging the edge of a cross-section showed a dense, flat film with thickness of around 130 nm underlying these orthogonally oriented platelets. A pole figure measurement (Fig. 8) taken with 2θ = 13.54° (002 reflection) exhibits a single and sharp peak (FWHM ∼ 10°) with α = 90°, consistent with the vast majority of crystallites adopting the <00l> orientation. The pole figure with 2θ = 56.10° (110 reflection), exhibits a ring with α close to zero (the edge of the peak is cut off as the measurement cannot be made right at the substrate plane), also consistent with the <00l> preferred orientation. Unfortunately, the pole figure at the 103 reflection position was featureless. This may suggest stacking errors reducing its intensity.
Fig. 7 SEM images of MoSe₂ films produced by CVD using ~70 mg [MoCl₄(⁵Bu₂Se)₂] at 550 °C. Top view (left) and cross-section (right).

Energy dispersive X-ray (EDX) analysis data showed significant Si and O from the substrate, in addition to peaks due to Mo and Se, indicating that the films are thin. There was no evidence for any residual Cl in the films. The Mo:Se ratio was quantified as 1:1.9, consistent within error with the formation of MoSe₂.
The crystallite size in the MoSe$_2$ film produced at 550 °C was calculated from the grazing incidence XRD data using the Williamson-Hall method. The 6.6(9) nm size that resulted is much smaller than the largest dimensions of the platelets observed in Fig. 7 (ca. 100 nm), but the observed preferred orientation shows the bulk of the material to be contained within the dense underlying film. The diffraction crystallite size appears to be dominated by this part of the sample. Using a larger amount of precursor (ca. 200 mg) resulted in thicker films, but the optical quality of the films became worse. SEM images (ESI, Fig. S3) showed that some crystallites continued to grow preferentially and thus the film thickness was less consistent over the area of the film.

The Raman spectrum from the MoSe$_2$ film was collected using 785 nm excitation and shows three peaks at 140, 241 and 290 cm$^{-1}$ assigned to the E$_{1g}$, A$_{1g}$ and E$_{2g}$ vibration modes of 2H-MoSe$_2$, respectively (Fig. 9),$^{16,37-40}$ whilst peaks at ca. 317, 455 and 595 cm$^{-1}$ can be attributed to contribution from acoustic phonons to the Raman scattering spectrum.$^{41}$ The optical spectra (ESI, Fig. S4) showed the expected excitonic transition features around 700 nm.$^{42}$

![Fig. 9 Raman spectrum of the MoSe$_2$ film deposited by LPCVD from [MoCl$_4$(nBu$_2$Se)$_2$] at 550 °C](image)

When using similar amounts of [MoCl$_4$(nBu$_2$S)$_2$] (ca. 30–70 mg) to that used in most of the MoSe$_2$ depositions described above, CVD on SiO$_2$ substrates at 750 °C resulted in very thin yellow films. These were too thin to generate any X-ray diffraction in grazing incidence or in plane measurement, or to image effectively in the SEM, but did produce optical spectra consistent with MoS$_2$.$^{42}$ (ESI, Fig. S5). At lower temperatures no deposition occurred. However, by using larger amounts of [MoCl$_4$(nBu$_2$S)$_2$] (200 mg) at 750 °C, silver films were obtained. Grazing incidence XRD (Fig. 10) showed similar features in these films to those seen for MoSe$_2$ in Fig. 7, but with much weaker intensities. The pattern was dominated by the interlayer spacing peak (the 002 reflection), which gives no information on the exact phase of MoS$_2$ produced. However, the in-plane XRD pattern contained stronger 100, 103 and 110 reflections, confirming that, like MoSe$_2$, MoS$_2$ also adopted the
2H structure. The lattice parameters were refined as $a = 3.13(5)$ and $c = 13.7(8)$ Å, although there is significant uncertainty in this result due to the weak, broad peaks. Lattice parameters in ICSD are in the range $a = 3.14−3.16$ Å and $c = 12.29−12.53$ Å.\textsuperscript{28} The suppression of the 002 reflection in the in-plane pattern suggests <001> preferred orientation like that observed in MoSe$_2$, but unfortunately, the scattering from these films was not strong enough for pole figure measurements. The Raman spectrum recorded from the MoS$_2$ film collected using 785 nm excitation showed weak bands at ca. 373 and 406 cm$^{-1}$, assigned as the E$_{2g}$ and A$_{1g}$ vibrational modes in 2H-MoS$_2$.\textsuperscript{37,40,41,43-45}

![Graph showing XRD patterns](image)

**Fig. 10** Grazing incidence (incidence angle = 1°) and in-plane (incidence angle = 0.5°) XRD patterns from the MoS$_2$ thin film deposited from [MoCl$_4$(nBu$_2$S)$_2$] at 750 °C, and the simulated XRD pattern from bulk 2H-MoS$_2$.\textsuperscript{28} The broad feature at 20 ~ 22° is from the SiO$_2$ substrate.

SEM images confirm that the orthogonally oriented crystallites on the MoS$_2$ film are very small, but that the underlying dense layer has a similar thickness to that found for MoSe$_2$ (~150 nm, Fig.11). The weak and broad diffraction data suggest the crystallite sizes may also be smaller in the dense layer. Due to a close overlap between the Mo L$_a$ (2.293 keV) and S K$_a$ (2.307 keV) fluorescence peaks, it was not possible to obtain the Mo:S ratio from the EDX data. However, these did confirm the presence of both elements and there is no evidence for any residual Cl in the films.
Fig. 11 SEM images of MoS₂ films produced by CVD using ~200 mg [MoCl₄(ᵗBu₂S)₂] at 750 °C.

Conclusions
The synthesis and characterisation of a new series of well-defined, distorted octahedral Mo(IV) chloride complexes with mono- and bi-dentate thioether and selenoether ligands has been demonstrated, with single crystal structures determined for several representative examples. TGA analysis of [MoCl₄(ᵗBu₂S)₂] and [MoCl₄(ᵗBu₂Se)₂] suggested they may be sufficiently volatile to be used as sources of MoS₂ and MoSe₂, respectively. This was borne out by LPCVD experiments which produced silver (2H-MoS₂) and golden yellow (2H-MoSe₂) thin films. The identities of the films, crystallite sizes and morphologies were determined via XRD, SEM/EDX, Raman and optical measurements. The successful identification of single source CVD precursors for their deposition is an important development given the very high level of interest in thin films of these materials currently and their range of potential applications.

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References


28. ICSD: Inorganic Crystal Structure Database (ICSD), Fachinformationszentrum Karlsruhe (FIZ), accessed via the EPSRC funded National Chemical Database Service hosted by the Royal Society of Chemistry.


