High Electrical Conductivity in Ni$_3$(2,3,6,7,10,11-hexaiminotriphenylene)$_2$, a Semiconducting Metal–Organic Graphene Analogue

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Supporting Information

ABSTRACT: Reaction of 2,3,6,7,10,11-hexaiminotriphenylene with Ni$_2$ in aqueous NH$_3$ solution under aerobic conditions produces Ni$_3$(HITP)$_2$ (HITP = 2,3,6,7,10,11-hexaiminotriphenylene), a new two-dimensional metal–organic framework (MOF). The new material can be isolated as a highly black powder or dark blue-violet films. Two-probe and van der Pauw electrical measurements reveal bulk (pellet) and surface (film) conductivity values of 2 and 40 S·cm$^{-1}$, respectively, both records for MOFs and among the best for any coordination polymer.

Two-dimensional (2D) electronic materials are of considerable interest due to their potential applications in future electronics.$^1$−$^3$ The most prominent example is graphene, an atomically thin organic 2D material with in-plane π-conjugation.$^4$ Although graphene exhibits exceptional charge mobility and mechanical stability, its use in semiconductor-based devices is limited by its zero bandgap.$^5$−$^7$ Dimensional reduction$^8$ and chemical functionalization$^9$ can increase the bandgap, rendering graphene semiconducting, but these methods drastically reduce its charge mobility and can introduce numerous defects. This has led to a sustained effort toward identifying 2D materials with intrinsic non-zero bandgaps that could replace conventional semiconductors.

Two broad classes of materials have dominated these efforts: layered metal chalcogenides (e.g., MoS$_2$, WSe$_2$) and 2D covalent–organic frameworks (COFs). The former can be deposited as large-area single sheets in a “top-down” approach.$^{10}$−$^{11}$ They have been shown to perform well in device testing$^{12,14}$ but do not easily lend themselves to chemical functionalization and tunability. In contrast, COFs are prepared by “bottom-up” solution-based synthetic methods and are attractive because they are subject to rational modification.$^{15,16}$ Nevertheless, the electronic properties of COFs are largely inferior to those of metal chalcogenides because the functional groups used to connect their building blocks typically do not allow in-plane conjugation.$^{17,18}$

Bridging the divide between 2D inorganic and organic materials is a recent class of “bottom-up” compounds assembled from multitopic dithiolene and π-semiquinone aromatic organic moieties bridged by square-planar metal ions. These 2D metal–organic networks exhibit non-zero bandgaps and good electrical conductivity, enabled by full charge delocalization in the 2D plane.$^{19}$−$^{21}$ They can therefore be described as semiconducting metal–organic graphene analogues (s-MOGs). Certain members of this class have also recently been predicted to behave as topological insulators$^{22,23}$, a realm currently dominated by purely inorganic compounds.$^{24}$

Clearly, the synthesis and characterization of new s-MOGs could give rise to important new electronic materials with exotic electronic states and potential applications in the semiconductor device industry.

Inspired by the success of dithiolene-based s-MOGs, whose metal linkages mimic classic Class III-delocalized homoleptic Ni(dithiolene)$_2$ complexes,$^{25,26}$ we identified Ni(isq)$_2$ (isq = 1,2-diminobenzosemiquinonate) as an attractive target for the construction of a fully charge-delocalized s-MOG. Indeed, although first isolated in 1927$^{27}$ from o-phenylenediamine and NiCl$_2$ in ammoniacal water, Ni(isq)$_2$ evaded structural and electronic characterization for quite a long time$^{28,29}$ but is now known to be fully π-conjugated, with its ground state having a single biradical character.$^{30,31}$ Crystalline Ni(isq)$_2$ itself exhibits high mobility in organic field effect transistors$^{32}$ and increased conductivity upon doping with I$_2$. Here, we show that two-dimensional extension of Ni(isq)$_2$ through the reaction of 2,3,6,7,10,11-hexaiminotriphenylene hexahydrochloride (HATP·6HCl) with ammoniacal NiCl$_2$ produces a new crystalline s-MOG with very high electrical conductivity that is linearly proportional to temperature. Remarkably, the conductivity of the new material vastly exceeds those of previous s-MOGs and other conductive MOFs and is higher than even some of the best organic conductors.

Under conditions mimicking the synthesis of Ni(isq)$_2$, HATP·6HCl was treated with an aqueous solution of NiCl$_2$·6H$_2$O under air, followed by the addition of aqueous NH$_3$ under constant stirring. The reaction mixture was heated to 65 °C and stirred under air for an additional 2 h. This yielded the new material Ni$_3$(HITP)$_2$ (HITP = 2,3,6,7,10,11-hexaiminotriphenylene) as a black powder and a very dark blue-violet film (see Scheme 1). Upon extensive washing with water in an ultrasonic bath, the charge neutrality of Ni$_3$(HITP)$_2$ and implicitly the formation of monoanionic Ni$_3$(HITP)$_2^-$ was confirmed by elemental analysis.

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diiminobenzosemiquinone moieties (Scheme 1, bottom), was confirmed by X-ray photoelectron spectroscopy (XPS). As shown in Figures S1 and S2, XPS spectra of both powder and films (vide infra) of Ni$_3$(HITP)$_2$ show the presence of only Ni, N, C, and O resonance peaks from the material itself and water guest molecules. Cl peaks, expected for any trapped or charge-balancing anionic chlorides that would compensate a possible cationic structure, are absent. Similarly, high-resolution analysis of the Ni(2p) and N(1s) regions of the XPS spectra show a single type of Ni and N atoms, respectively, suggesting that no extraneous Ni$^{2+}$ or NH$_4^+$ ions are present. These ions are the only possible cationic species that could balance an anionic material, and they indicate that Ni$_3$(HITP)$_2$ is indeed neutral, as expected from its similarity with Ni(isq)$_2$.

Powder X-ray diffraction (PXRD) analysis of Ni$_3$(HITP)$_2$ revealed a crystalline structure with prominent peaks at 2θ = 4.7°, 9.5°, 12.6°, and 16.5°, indicative of long-range order within the $ab$ plane (see Figure 1). An additional, weaker and broader peak at 2θ = 27.3°, corresponding to the [001] reflections, is indicative of poorer long-range order along the $c$ direction, as expected for covalently linked layered materials. We simulated several possible stacking arrangements for the 2D sheets of Ni$_3$(HITP)$_2$, including staggered (AA$^+$), eclipsed (AA), and slipped-parallel (AB) orientations. As shown in Figure 1, the experimental pattern rules out the AA$^+$ stacking but agrees very well with both the AA and AB sequences. Although the AA and AB sequences are impossible to differentiate on the basis of PXRD alone, Ni K-edge extended X-ray absorption fine structure (EXAFS) analysis of a sample of Ni$_3$(HITP)$_2$ revealed a spectrum that better agrees with a simulated spectrum of AB than of AA. As shown in Figure S3, a strong Ni···Ni scattering path at R = 3.0 Å (actual Ni···Ni distance = 3.33 Å), expected for AA, is absent in the experimental data.

Additional support for a slipped-parallel AB stacking model came from DFT calculations (see SI for full details). A model structure was developed by optimizing a hydrogen-terminated fragment at the B3LYP-D3BJ/6-31G* level and constraining it to P6/mmm symmetry. A unit cell for the structure was then made by fixing an interlayer separation of 3.3 Å. Periodic single-point energy calculations using the GGA-PBE exchange-correlation functional with D2 dispersion correction were carried out for structures with 82 different $ab$-plane displacements. The potential energy surface (PES) shown in Figure 2 was obtained by interpolating DFT total energies using 2D Lagrange polynomials. This PES suggested that the fully staggered (AA$^+$) stacking is ruled out, and the eclipsed (AA) or slipped-parallel (AB) structures are more stable. Cation-anion interactions are important in determining these structural arrangements.

Figure 1. Experimental and simulated PXRD patterns of Ni$_3$(HITP)$_2$. The inset shows the slipped-parallel structure with neighboring sheets displaced by 1/16 fractional coordinates in the $a$ and $b$ directions.

Figure 2. Contour map of the potential energy surface generated by different translations between A and B layers. Black dots correspond to locations of single-point calculations performed using the PBE-D2 functional. Red lines indicate the borders of the "thermally accessible region" (within $k_B T \approx 0.026$ eV of the minima). The surface was produced by interpolation with 2D Lagrange polynomials on a grid of Chebyshev points. The energy per unit cell has been normalized to zero at the minimum.
The first indication of excellent electrical properties in Ni₃(HITP)$_2$ came from a two-probe measurement of bulk powder compressed as a pellet between two stainless steel rods. Despite the small particle size, the numerous inter-grain boundaries, and the electrode contact resistances, the pellet conductivity of Ni₃(HITP)$_2$ was 2 S cm$^{-1}$. This is on the same order of magnitude as the two-probe pellet conductivity of some of the best organic conductors, including the iconic TTF-TCNQ ($\sigma_{\text{pellet}} = 10$ S cm$^{-1}$). Furthermore, the bulk conductivity of Ni₃(HITP)$_2$ is 1 order of magnitude higher than that of the best s-MOG (Ni-hexathiobenzene, $\sigma = 0.15$ S cm$^{-1}$), and at least 2 orders of magnitude better than those of the most conducting MOFs to date.

Even more remarkable results were obtained for thin films, configurations that are likely more relevant for future devices. Thus, films of Ni₃(HITP)$_2$ deposited on quartz substrates consistently gave conductivity values of 40 S cm$^{-1}$ at room temperature, as measured by the van der Pauw method. The conductivity showed a linear increase with temperature from 77 to 450 K, as shown in Figure 4, a behavior that was reversible upon cooling. Although we have been unable to find a model that unequivocally explains this behavior over the entire temperature range, organic-based semiconductors are notorious for having complicated, mixed charge transport mechanisms; further theoretical and experimental studies will probe the mechanism that is operative here. Most notably, among all coordination polymers, the film conductivity of Ni₃(HITP)$_2$ is exceeded only by that of Cu(4-hydroxythiophenolate) ($\sigma = 120$ S cm$^{-1}$).

Clearly, the nature of charge transport in Ni₃(HITP)$_2$ and its undoubtedly superior single sheet electrical properties warrant further studies, as do its magnetic behavior and its inclusion in electronic devices. The more general picture afforded by these studies, nevertheless, is that metals can mediate very efficient 2D conjugation pathways between electroactive organic molecules, leading to new materials with impressive electrical properties. Although this could perhaps be already gleaned from the vast literature on molecular conductors, the successful application of these concepts to two- and three-dimensionally extended crystalline networks is just emerging and promises to take us on a thrilling intellectual ride.

Figure 4. Variable-temperature van der Pauw conductivity measurement on a ~500 nm thick film on quartz.

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Figure 3. Top: SEMs for films of Ni₃(HITP)$_2$ at various magnifications. Bottom: AFM thickness profile and corresponding 3D AFM image of a representative Ni₃(HITP)$_2$ film.

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213 ■ ASSOCIATED CONTENT
214 Supporting Information
215 Experimental details; EXAFS, XPS, TGA, and UV–vis plots;
216 and additional AFM images. This material is available free of
217 charge via the Internet at http://pubs.acs.org.

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