Crystal structures of transition metal pernitrides predicted from first principles†

Rongmei Yu,†ab Ermiao Sun,ab Liguang Jiao,ab Yongmao Cai,db Hongbo Wangcd and Yansun Yacob

We have extensively explored the stable crystal structures of early-transition metal pernitrides (TMN₂, TM = Ti, V, Cr, Mn, Zr, Nb, Mo, Hf, and Ta) at ambient and high pressures using effective CALYPSO global structure search algorithm in combination with first-principles calculations. We identified for the first time the ground-state structures of MnN₂, TaN₂, NbN₂, VN₂, ZrN₂, and HfN₂ pernitrides, and proposed their synthesis pressures. All predicted crystal structures contain encapsulated N₂ dumbbells in which the two N atoms are singly bonded to a [N₂]²⁺ pernitride unit utilizing the electrons transferred from the transition metals. The strong nature of the single dinitrogen bond and transition metal–nitrogen charge transfer induce extraordinary mechanic properties in the predicted transition metal pernitrides including large bulk modulus and high Vickers hardness. Among the predictions the hardness of MnN₂ is 36.6 GPa, suggesting that it is potentially a hard material. The results obtained in the present study are important to the understanding of structure–property relationships in transition metal pernitrides and will hopefully encourage future synthesis of these technologically important materials.

Introduction

Transition metal (TM) nitrides have attracted considerable attention due to their fundamental importance in crystal chemistry and applications in industry. Most TM nitrides exist on the metal-rich side of the stoichiometric diagram (TM:N > 1), and therefore often exhibit metallic properties. Nitrogen-rich TM nitrides (N:TM > 1) can be synthesized by reacting elemental TM or TM simple nitrides with excess of N₂ gas under high pressure and high temperature conditions. The most common stoichiometry for nitrogen-rich TM nitrides is TMN₂, often referred to as the ‘pernitrides’. Since the initial success on the synthesis of platinum nitride,¹ experimental exploration for novel TM nitrides has expanded substantially, and uncovered new members including PtN₂,² IrN₂,²,³ OsN₂,³ PdN₂,⁴ RuN₂,⁵ RhN₂,⁶ TiN₂,⁷ and FeN₂.⁸ The list is still growing rapidly. Most of these new compounds have very high bulk modulus, a property that potentially leads to applications such as cutting tools and wear-resistant coatings. In particular, the bulk modulus of platinum nitride is comparable to that of cubic BN, a known superhard material, which is about 100 GPa higher than that of pure platinum.³ The extraordinary mechanical properties of TM pernitrides are associated with a particular structural motif. Although their crystal structures may be different, most TM pernitrides contain ultra-incompressible N₂ dumbbells which are held together by strong covalent N–N interaction. Albeit similar to the N₂ molecule in geometry, these N₂ dumbbells are single-bonded in nature, utilizing the electrons transferred from the TM atoms. The strength of the N–N interactions in the N₂ dumbbells are comparable to that in the single-bonded polymeric phase of nitrogen.⁹ As such, the nitrogen atoms in most TM pernitrides are octahedrally coordinated with TM atoms by strong, directional TM–N bonds and form TMN₆ octahedrons which are then interconnected through N–N bonds in three dimensions. Clearly, knowing the crystal structures of TM pernitrides are very important for understanding their extraordinary mechanic properties, however, this is not always an easy task in experiment. A known difficulty is that X-ray diffraction is unable to determine the positions of the nitrogen atoms in TM nitrides due to the large TM/N atomic mass ratio.

Meanwhile, many theoretical studies have been carried out to help resolving the crystal structures of TM pernitrides, and to predict new targets for future synthesis. The structure of OsN₂ was determined to be isostructural to that of marcasite with orthorhombic Pnmm space group.¹⁰ PtN₂ and PdN₂ were found to form in the cubic pyrite structure with the Pa₃ space group.¹¹ RuN₂ and RhN₂ were predicted to have marcasite structure as well¹² which was then experimentally confirmed.¹³ The IrN₂ was
predicted to be isostructural to CoSb2 or arsenopyrite however the subsequently synthesized IrN2 has a baddelyite-type structure. For ReN2, three structures were predicted as possible candidates, namely, rutile structure (P43/mmm), " primitive rhombohedral structure (P4/mmm), and distorted rhenium diboride structure (P4/mmm), but the synthesized ReN2 has the MoS2 structure. On early TM target, MoN2 was synthesized with a rhombohedral MoS2 structure. However, a theoretical study suggests that the thermodynamic ground state of MoN2 should have a hexagonal structure. TiN2 has been predicted to have the tetragonal CuAl2-type structure (I4/mcm) which was successfully synthesized soon after. It is noteworthy that the synthesized TiN2 has a very high bulk modulus of 385 GPa. In addition to the real- ized pernitrides, many others were predicted to exist as well, await for future synthesis. The long list includes ZrN2, CrN2, NbN2, HfN2, WN2, and others. Mechanical properties in particular the elasticity and hardness of TM pernitrides was one of the focal points of these investigations.

In the present study, we systematically explored the stable phases of TM pernitrides adding several new ones (TM = Ti, V, Cr, Mo, Mn, Zr, Nb, Hf, and Ta). Some of these compounds have been studied before but the methods used based on known structure analogy may not guarantee finding the global minima of these phases, as shown in several cases above. To this end we employed a global structure search in combine with first principle calculations aiming to find the true thermodynamic ground states of these compounds. Since the laboratory synthesis of TM pernitrides often requires high pressure, the search is expanded from ambient to high pressures up to 100 GPa. The CrN2 and MoN2 were found to have the same hexagonal structure (P6/mmc), while MnN2 has a P1 structure. TaN2 is predicted to have an orthorhombic CuAl2 structure. For NbN2, the present study uncovers a new monoclinic structure (Cc) which is thermodynamically more stable than the previously proposed CuAl2 structure. TiN2 was found to have the CuAl2-type structure (I4/mcm), which is in agreement with previous experimental and theoretical reports. In addition, VN2, ZrN2, HfN2 and HfN2 were predicted to have the same CuAl2-type (I4/mcm) structure. All predicted TM pernitrides are thermodynamically stable with respect to decomposition to elemental TM and N2 at ambient pressure. CrN2, MoN2, and MnN2 are also found stable against decomposition to simple nitride TMN and N2 at ambient pressure. The established thermal stability suggests that the predicted TM pernitrides are likely synthe-}

sizable at high temperature and can be quenched recovered at ambient conditions.

**Computational approaches**

The investigation of TM pernitrides consists of the determination of ground state crystalline structures and calculation of the properties of interest. The density functional theory (DFT) was used to calculate the enthalpies for these structures (H) in the pressure range 0–100 GPa, and compared to the enthalpies of the decomposition products along two possible decomposition routes:

\[ \Delta H_{f(I)} = H_{TMN_2} - H_{TM} - H_{N_2} \]  
\[ \Delta H_{f(II)} = H_{TMN_2} - H_{TMN} - \frac{1}{2} H_{N_2} \]  

The route (1) describes the decomposition to elemental TM and solid N2, while route (2) is for the decomposition to simple TM nitride (TMN) and solid N2. The relative enthalpy of formation \( \Delta H_f \) has been calculated using the lowest-enthalpy structures of TMN2, TMN, and N2 previously known or obtained from the structure searches as reference structures (see ESIF for details). The results shown in Fig. 1 reveal that all predicted structures of TM pernitrides are thermodynamically stable against the decomposition route (1) at ambient pressure (shown by negative \( \Delta H_f \)). For decomposition route (2), the CrN2, MoN2, and MnN2 are stable at ambient pressure. The rest TM pernitrides are thermodynamically unstable at ambient pressure but quickly become stable at moderate pressures (4.74–
The calculated $\Delta H_f(I)$ and $\Delta H_f(II)$ are listed in Table 1. The proposed pressures of formation for these nitrides (arrows in Fig. 1) are well within the reach of current high-pressure synthesis, which provides a good chance that they can be synthesized under high pressure and then quench recovered to ambient conditions. Among these nitrides the TiN$_2$ has already been realized in laboratory at pressures at a pressure of 73 GPa. Although the starting materials (TiN and N$_2$) and product ($I\bar{4}$/mcm TiN$_2$) are the same, the calculated pressure for its formation is 25.5 GPa, which is lower than the experimental pressure.

Table 1 Calculated equilibrium lattice parameters, $a_0$ (Å), $b_0$ (Å) and $c_0$ (Å), equilibrium volume per f.u. $V_0$ (Å$^3$), bonding length of $d_{TM-N}$ (Å) and $d_{N-N}$ (Å), formation enthalpies of the two reaction routes $H_{f(I)}$ and $H_{f(II)}$, and Vickers hardness for the TMN$_2$ pernitrides predicted in the present study. Comparison is made to previously reported results where possible.

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<th>Crystal</th>
<th>Phases</th>
<th>$a_0$</th>
<th>$b_0$</th>
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by about 50 GPa. The large discrepancy is mainly attributed to the known large energy barrier associated with the formation of TM pernitrides. To overcome the barrier, high temperature is usually required for the synthesis. Thus, we expect moderated higher formation pressures than what calculated here for all predicted TM pernitrides.

The crystal structure and optimized lattice parameters of the predicted TM pernitrides are shown in Fig. 2 and Table 1. For previously synthesized TiN2, our structure search correctly produces its structure at ambient and high pressures, the CuAl2-type structure ($I4/mcm$) (Fig. 2a). The calculated lattice parameters are $a = 4.35 \, \text{Å}$, $c = 5.31 \, \text{Å}$, very close to the experimental values, $a = 4.33 \, \text{Å}$ and $c = 5.29 \, \text{Å}$.

For CrN2, which has yet to be synthesized, we predict its ground state is a hexagonal structure with the $P6_3/mmc$ structure (Fig. 2e). This prediction agrees with previous theoretical studies.

The $P6_3/mmc$ structure is the lowest enthalpy phase of CrN2 from ambient pressure to at least 100 GPa, the highest pressure used in the present study. The $P6_3/mmc$ structure is consisting of MoS2-type CrN2 slabs stacked by covalent N–N bonds with an ABA sequence (Fig. 2e). If the N2 units are considered as a single entity, this structure would reduce to a NiAs-type hexagonal structure. The N–N distance within the N2 units is 1.336 Å, which is much longer than the bondlength in triply bonded N2 molecule (1.10 Å). The bondlength in the N2 units is close to that of a single bond in hydrazine (1.45 Å), and longer than that of a double bond in dinitrogen difluoride (1.21 Å). Thus, we may consider the N2 unit singly bonded, formally a $[N_2]^{4-}$ anion. The CrN2 is nominally a charge transfer $Cr^{4+}N_2^{4-}$, which should form a semiconducting state. The $P6_3/mmc$ structure is also the ground state structure for MoN2 at ambient pressure. A phase transition is predicted for MoN2 at 85 GPa, at which it transforms to a $P4/mmbm$ structure. This prediction agrees with previous theoretical studies as well.

The experimentally discovered MoS2 structure of CrN2 (ref. 17) was calculated to be a metastable phase. The $P4/mmbm$ structure contains MoN8 cuboids that are interconnected by edge-sharing and staked along the perpendicular direction through Mo–N bonds. The N2 dumbells are still retained in the $P4/mmbm$ structure and singly bonded. Unlike CrN2 and MoN2, the other stable pernitride MnN2 has a low symmetry monoclinic $P1/c$ structure. In this structure, the Mn atom is octahedrally coordinated with six N atoms to MN6 octahedra that are interconnected through N–N bonds. The bondlength of the N–N bond is 1.31 Å, similar to those in CrN2 and MoN2.

Fig. 2 Crystal structures for (a) $I4/mcm$-TiN2, (b) $I4/mcm$-VN2, (c) $I4/mcm$-ZrN2, (d) $I4/mcm$-HfN2, (e) $P6_3/mmc$-CrN2, (f) $P6_3/mmc$-MoN2, (g) $P1$-MnN2, (h) $Cc$-NbN2, and (i) $Cmca$-TaN2. All structures are optimized at 0 GPa. Large and small spheres denote TM and N atoms, respectively.
The NbN$_2$ and TaN$_2$ compounds have been previously investigated theoretically, and several candidate structures were proposed based on educated guesses from known structures of chemically similar compounds. The considered structures include $P6_3/mmc$, $P6m2$, $Pa3$, pyrite and fluorite structures. In the present study, however, we found none of this structure corresponding to the ground state of NbN$_2$ and TaN$_2$. The predicted ground state of TaN$_2$ has the $Cmca$ space group instead. In this structure, the $Ta$ and $N$ are sandwiched to form distorted TaN$_4$ quadrangular pyramid which are extended to two dimensional slabs with shared edges. The slabs are intercalated with the $N_2$ dimers along the $c$-axis (Fig. 2i). According to the $N$–$N$ bondlength, i.e., 1.37 Å, the $N_2$ dimers are singly bonded. The $Cmca$ structure is predicted to form at pressures above 13.8 GPa and stays stable to at least 100 GPa. For NbN$_2$, our structure search establishes a monoclinic structure with the $Cc$ space group as its ground state at ambient pressure. The higher enthalpy, e.g., $\sim$29.2 meV f.u.$^{-1}$ at ambient pressure. On the other hand, the $Cmca$ structure is more stable at high pressures which surpasses the $Cc$ structure at 58.6 GPa to become the thermodynamic ground state (Fig. 1h).

To date, VN$_2$, ZrN$_2$, and HfN$_2$ have not been synthesized. In a previous theoretical study, ZrN$_2$ and HfN$_2$ have been predicted to have the same ground state structure as TiN$_2$ since the three TMs are in the same group in the periodic table. Our structure search confirmed this conjecture. Both ZrN$_2$ and HfN$_2$ adopt the CuAl$_2$-type structure ($I4/mcm$) and no phase transitions are found over the entire pressure range investigated (0–100 GPa). A unique feature of the $I4/mcm$ structure is that the TM and $N$ atoms form TM$_N^2$ face-sharing tetragonal antiprisms, rather than TM$_6^4$ octahedrons commonly seen in TM pernitrides (Fig. 2). The neighboring antiprism are connected through $N_2$ dumbbells along $a$- and $b$-axis. The $N$–$N$ bondlengths are 1.42 and 1.46 Å, respectively, for ZrN$_2$ and HfN$_2$. These values are very close to the ideal length of single nitrogen bond (1.45 Å) and those observed in some transition metal pernitrides such as PtN$_2$ (1.41 Å) and OsN$_2$ (1.43 Å). This indicates that the $N_2$ dumbbells are singly bonded with a nominal $[N_2]^{1-}$ state, which is isoelectronic to difluorine $F_2$ (1.43 Å). The previously unknown VN$_2$ is predicted to have the same $I4/mcm$ structure with slightly shorter $N$–$N$ bondlength (1.38 Å).

In view of the pernitride structures described above, TiN$_2$ and VN$_2$ have almost same $N$–$N$ bond lengths (1.37 Å and 1.38 Å), but ZrN$_2$ and HfN$_2$ have longer bond lengths (1.42 Å, 1.46 Å), suggesting the presence of more ‘soften’ $N_2$ in the latter. Clearly, the bondlength here is an indicator of bonding interaction, where the shorter bond equals stronger bond’ conjecture prevails. For $N_2$ quasimolecules, specifically, this also reveals the degree of electron sharing between two $N$ atoms, from triply bonded $[N_2]^{2-}$, to doubly bonded $[N_2]^{1-}$, and to singly bonded $[N_2]^{0}$. The amount of electrons transferred from the transition metal therefore determines the bonding type, and ultimately determine the crystal structure. This is manifested by the fact that the Vickers hardness of the 3d TM pernitrides (32.6 GPa (TiN$_2$), 35.6 GPa (VN$_2$)) are in general higher than those of 4d and 5d TM pernitrides (26.4 GPa (ZrN$_2$), 27.6 GPa (HfN$_2$)). The dynamical stability of the predicted TM pernitrides are verified by the analysis of phonon-dispersion relations in the pressure range of 0–100 GPa (Fig. 3).

Among which, the dynamical stability of TiN$_2$, CrN$_2$, and MoN$_2$ have already been established in previous theoretical studies. The new pernitrides predicted in the present study, namely, VN$_2$, ZrN$_2$, HfN$_2$, MnN$_2$, NbN$_2$, and TaN$_2$, are confirmed dynamically stable from ambient pressure to their thesis pressure, by the absence of imaginary phonon frequency in the entire BZ (Fig. 3). The dynamic stabilities of predicted pernitrides provide a very strong case that they can be recovered at ambient conditions once synthesized under high pressure and high temperature.

Fig. 3 Phonon dispersion relations for (a) $I4/mcm$-VN$_2$, (b) $I4/mcm$-ZrN$_2$, (c) $I4/mcm$-HfN$_2$, (d) $P1$-MnN$_2$, (e) $Cc$-NbN$_2$, and (f) $Cmca$-TaN$_2$ calculated at ambient pressure along high symmetry directions in the Brillouin zone.
To understand the electronic properties and bonding features of these pernitrides, we have calculated their electronic band structure and density of states (DOS) at ambient pressure. The results are presented in Fig. 4 and 5. From the band structures and DOS, all compounds having the $I4/mcm$ structure (TiN$_2$, V N$_2$, ZrN$_2$, and HfN$_2$), the $Cc$ structure (NbN$_2$) and the $Cmca$ structure (TaN$_2$) are metallic owing to the finite DOS at the Fermi level due to multiple bands crossing. Projected DOS reveals that the electronic states at the Fermi level are dominated by the $d$ electrons of TM and $p$ electrons of N (Fig. 5). In particular, there are strong orbital hybridization between the $d$ orbital of TM and $p$ orbital of N in the energy range from $-10$ to 0 eV, indicating the interactions between TM and N are covalent in nature. Moreover, in most of the pernitrides the total DOS has a minimum value at the Fermi level (pseudo gap), which limits the possibility of achieving credible electrical conductivity, but the tendency of opening a band gap at the Fermi level is seen as a stabilization to the structures due to strong interactions between TM and N. The VN$_2$ is an exception in which the Fermi level shifts toward higher energy range and lies outside the pseudogap with relative higher electronic density of states. On the other hand, the compounds with the $P6_3/mmc$ structure (CrN$_2$ and MoN$_2$) and $P1$ structure (MnN$_2$) are semiconductors. In particular the CrN$_2$ is predicted as a direct band gap semiconductor with the band gap of 0.51 eV. The other two pernitrides have indirect band gaps, i.e., 0.38 eV for MoN$_2$ and 1.0 eV for MnN$_2$, respectively.

Further analysis of chemical bonding in these pernitrides has been carried out through crystal orbital Hamilton population (COHP) analysis (Fig. 6). COHP partitions the band-structure energy into different $d$-orbital–$p$-orbital interactions, which can be used to index bonding, nonbonding, and antibonding contributions to the band-structure. Similar to the crystal-orbital overlap population (COOP), the COHP analysis provides a quantitative measure of the bond strengths in crystal structures by the –COHP values, where the positive and negative signs represent bonding and antibonding states, respectively. Here we draw positive –COHP values to the right and negative ones to the left, so the spikes on the left/right hand side correspond to antibonding/bonding states. In general, for TM–N interactions in predicted pernitrides the antibonding states show up in the unoccupied crystal orbitals well above the Fermi level (dotted horizontal zero line), whereas for N–N interactions, the antibonding $1\pi_g^*$ states are primarily between $-4$ eV and the
Fermi level. This is a significant finding, that the $1\pi^*_g$ states are mostly occupied in TMN$_2$ pernitrides. For neutral N$_2$ molecule, the $1\pi^*_g$ states are completely empty, resulting in exceedingly strong triple bonds. Adding two electrons to the $1\pi^*_g$ states would result in double-bonded [N$_2$]$^2$\(^{-}\), which is isoelectronic to O$_2$. Adding two more electrons would fully occupy the $1\pi^*_g$ states and produce single-bonded [N$_2$]$^4$\(^{-}\), which is isoelectronic to F$_2$.

As demonstrated in previous work, for the case of PtN$_2$, electrons transferred from Pt to N results in the full filling of antibonding $1\pi^*_g$ states for which a plausible electronic formulation should be Pt$^{4+}$[N$_2$]$^{4-}$. This single-bond scenario is also applicable to predicted pernitrides TMN$_2$, as seen from the results of the COHP analysis and very similar N-N bond lengths in TMN$_2$ matching to that of F-F distance (1.42 Å), although the exact occupation of the $1\pi^*_g$ states may vary in different TMN$_2$ pernitrides.\(^{29,19}\) This is fundamentally different from alkaline-earth pernitrides such as BaN$_2$\(^{40}\) and SrN$_2$ (ref. 41) which only contain double-bonded [N$_2$]$^{2-}$ units.

Previously, it is suggested that the extraordinary mechanical properties and hardness of TM pernitrides are induced by the single nature of dinitrogen bond and charge transfer from TM to N. In opposite, BaN and SrN have only two electrons in the $1\pi^*_g$ states and therefore exhibit much smaller hardness.\(^{29}\) The charge transfer controls the length of the single bond by providing Coulomb repulsion between two N atoms, and influences the bulk modulus.\(^{26}\) As the predicted TM pernitrides fall into this category, it is interesting to examine their mechanical properties and hardness. The total Vickers hardness ($H_v$) of a compound is expressed as the geometric average of the hardnesses of individual bonds,

$$H_v = \left(\prod_{\mu} (H_{\mu}^{\nu})^{n_{\mu}}\right)^{1/n_{\mu}},$$

where $n_{\mu}$ is the number of bond for the $\mu$th bonding type in the crystal, and $H_{\mu}^{\nu}$ is the Knoop hardness for covalent and polar covalent crystals.\(^{42}\)

$$H_{\mu}^{\nu} (\text{GPa}) = 423.8N_{\mu}X_{ab}e^{-2.79} - 3.4$$

The calculated Vickers hardness of predicted TMN$_2$ pernitrides are shown in Table 1. It is worth noting that MnN$_2$ has the highest hardness (36.6 GPa) among them, while VN$_2$ has a near
second value (35.6 GPa). The NbN2 and TaN2 on the other hand have very low hardness as what one would expect for metals. The high hardness in MnN2 is facilitated by the formation of three-dimensional (3D) covalent networks driven by hybridizations of N-p and TM-d electrons. For VN2, the hardness is associated to the short V–N bonds: the V–N bond is 2.133 Å at ambient pressure, even shorter than the Ti–N bond (2.201 Å) in the isostructural TiN2, a known hard material. In the case of isostructural pernitrides, clearly there is a correlation between the hardness and the strength of the covalent bonds. The calculated bulk \( B \), shear \( G \), Young’s \( E \) moduli and Poisson’s ratio for predicted TMN2 pernitrides are presented in Table 2 and compared with the previous theoretical or experimental results available. The results agree well with the reported theoretical values, demonstrating the reliability of the present calculations. Pugh’s ratio \( G/B \) and Poisson’s ratio \( \nu \) are the factors which describe the ductile/brittle nature of a material. In 1954, Pugh\textsuperscript{43} has proposed that a high value (>0.57) is associated with brittleness and a low value (<0.57) indicates the ductile nature of materials. Frantsevich et al.\textsuperscript{44} has also separated the ductility and brittleness of a material in terms of Poisson’s ratio \( \nu \) and suggested that if the Poisson’s ratio is less than 0.26 then the material will be brittle otherwise the material will be ductile. The calculated Pugh’s ratios and Poisson’s ratio show that all predicted TMN2 pernitrides are intrinsically brittle.

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Fig. 6 Crystal Orbital Hamilton Population (COHP) analysis of various bonds in (a) I4/mcm-TiN2, (b) I4/mcm-VN2, (c) I4/mcm-ZrN2, (d) I4/mcm-HfN2, (e) P6\textsubscript{3}mmc-CrN2, (f) P6\textsubscript{3}mmc-MoN2, (g) P1-MnN2, (h) Cc-NbN2, and (i) Cmca-TaN2 at ambient pressure. The Fermi level (\( E_F \)) is marked by gray dashed line.
except the two metallic ones (NbN$_2$ and TaN$_2$). The obtained bulk modulus for TiN$_2$ is 288 GPa, which is consistent to the theoretical value (284 GPa) predicted by Yu et al.,$^9$ but substantially lower than the measured values (360–385 GPa).$^7$ In view of the discrepancy, the experimental uncertainties in estimating the crystal volumes should be both taken into consideration. In general, the predicted TMN$_2$ pernitrides have high bulk moduli close to that of IrN$_2$ ($B = 327$ GPa), PtN$_2$ ($B = 272$ GPa) and OsN$_2$ ($B = 359$ GPa),$^{23,29}$ indicating that these materials are highly incompressible. From Table 2 one can also see that for isostructural pernitrides, TiN$_2$, VN$_2$, ZrN$_2$ and HfN$_2$, the highest bulk modulus goes to VN$_2$ which has the shortest TM–N distances. The correlation between the bulk modulus and bondlength may be understood from the charge transfer from TM to N. The charge transfer influences the dinitrogen bond strength by increasing Coulomb repulsion between two N atoms and populating the antibonding $^1\pi_2^*$ states, which jointly lead to the elongation of N–N bond and destabilization of the N$_2$ units. Interestingly, MnN$_2$ exhibits the highest Vickers hardness (36.6 GPa) among all pernitrides but only have a moderate bulk modulus (306 GPa), suggesting that the estimate of hardness goes far beyond the bulk modulus.

Conclusions

In summary, we have carried out a thorough investigation of transition metal (TM) pernitrides using the CALYPSO global structure search method and predicted/determined the ground-state crystal structures of TiN$_2$, VN$_2$, CrN$_2$, MnN$_2$, HfN$_2$, NbN$_2$, MoN$_2$, ZrN$_2$, and TaN$_2$ in the pressure range of 0–100 GPa. The structures obtained for TiN$_2$, CrN$_2$ and MoN$_2$ known previously compare well with the available experimental and theoretical results reported in literature. For VN$_2$, ZrN$_2$, HfN$_2$, MnN$_2$, NbN$_2$, MoN$_2$, ZrN$_2$, and TaN$_2$, which have yet to be synthesized, the predicted structures and properties can be used as a guide for future synthesis and theoretical studies. Phonon dispersion relation and formation enthalpy calculations suggest that the predicted TMN$_2$ pernitrides are all thermodynamic and dynamically stable at ambient conditions, which provides a good possibility that they can be quenched recovered once synthesized under high pressure conditions. Similar to PtN$_2$, the predicted TM pernitrides have extraordinary mechanic properties including high bulk modulus and Vickers hardness which are originated from the single nature of N–N bond in [N$_2$]$^{3-}$ pernitride unit and the TM–N charge transfer. New results obtained in the present study push forward the understanding of the crystal structures and electronic properties of transition metal pernitrides at high pressures.

Conflicts of interest

The authors declare no competing financial interest.

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References