

TRANSFORMATION OF EXCITING 3D MAX PHASES TO 2D NEW WONDER MATERIALS

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Topic

MAX Phase (Nanolaminate):

- ▣ Review of fundamentals
- ▣ Exciting new class of materials – **Why ?**
- ▣ MAX phases: Bridging the gap between metals and ceramics -- Characteristics
- ▣ Potential applications

Research in CMP Lab at RU

- ▣ Prediction of yet unobserved phases
- ▣ Substitution – strengthening study: $(\text{Ti, V})_2\text{AlC}_2$ etc.
- ▣ Superconducting MAX phases

MXenes: Stories of wonder materials

- ▣ MAX phases like graphene get two-dimensional

MAX Phases = Nanolaminates

- ▣ **Nanolaminates:** defined as series of **alternating sublayers** with different compositions and/or electron density distributions.

MAX = nanolaminated MX & A layers (see structure)

Binary transition metal carbides i.e. **MX**

are insulators & brittle,

while **MAX phases** are good thermal & electrical conductors as well as exhibit extensive plasticity.

MAX Phase

- **Formula:** $M_{n+1}AX_n$
 - **M** is an early transition metal
 - **A** is an A group element
 - **X** is either C or N

Over 60 phases - most discovered & produced in powder form in the sixties by H. Nowotny & coworkers.

- **First fabricated in bulk and characterized**

(Dr. Barsoum Group at Drexel University, USA)

211

Ti_2AlC^*	Ti_2AlN^*	Hf_2PbC^*	Cr_2GaC	V_2AsC	Ti_2InN
Nb_2AlC^*	$(Nb,Ti)_2AlC^*$	$Ti_2AlN_{0.5}C_{0.5}^*$	Nb_2GaC	Nb_2AsC	Zr_2InN
Ti_2GeC^*	Cr_2AlC	Zr_2SC	Mo_2GaC	Ti_2CdC	Hf_2InN
Zr_2SnC^*	Ta_2AlC	Ti_2SC	Ta_2GaC^*	Sc_2InC	Hf_2SnN
Hf_2SnC^*	V_2AlC	Nb_2SC	Ti_2GaN	Ti_2InC	Ti_2TiC
Ti_2SnC^*	V_2PC	Hf_2SC	Cr_2GaN	Zr_2InC	Zr_2TiC
Nb_2SnC^*	Nb_2PC	Ti_2GaC	V_2GaN	Nb_2InC	Hf_2TiC
Zr_2PbC^*	Ti_2PbC^*	V_2GaC	V_2GeC	Hf_2InC	Zr_2TiN

312

$Ti_3AlC_2^*$	$Ti_3GeC_2^*$
$Ti_3SiC_2^*$	

413

$Ti_4AlN_3^*$

MAX Phases: Bridging the gap between Metals and Ceramics

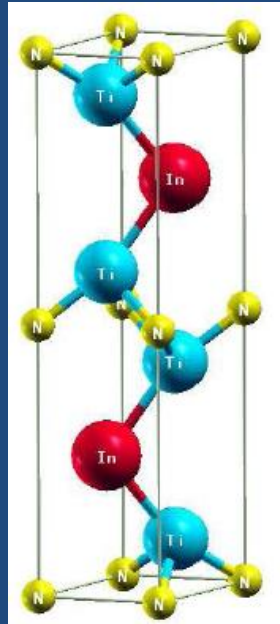
The term “MAX phases” was coined in the late 1990s.

Renewed interest in MAX Phases after Barsoum & El-Raghy's report in 1996 on the synthesis of phase-pure bulk T_3SiC_2 samples & their unusual combination of properties.

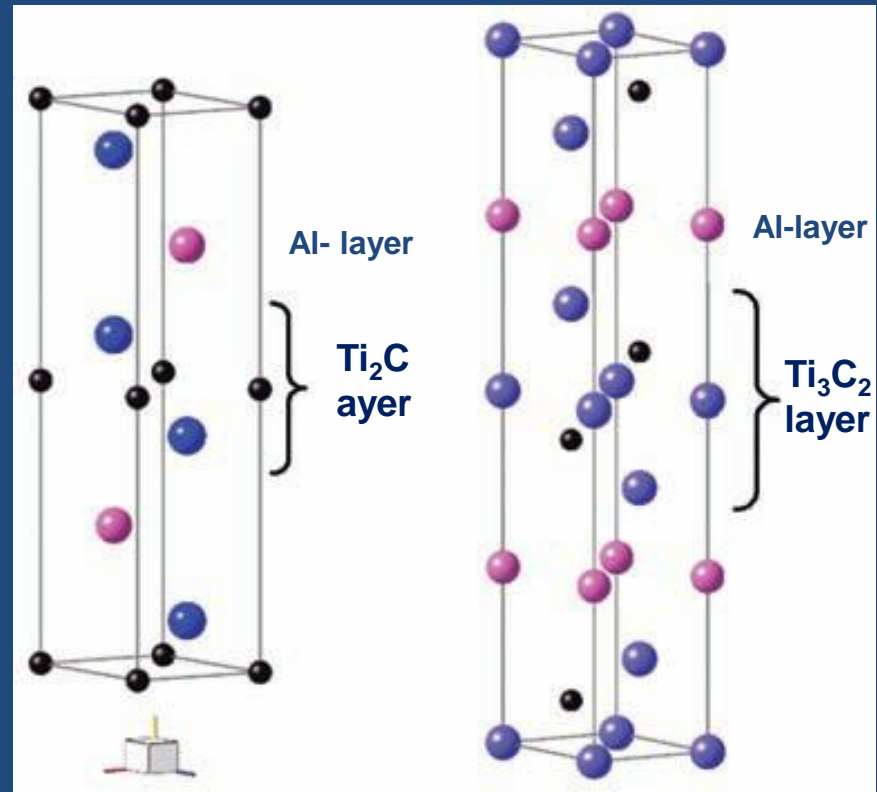
Since then, research on the MAX phases has exploded.

According to ISI, to date ~ 1,200 papers have been published on one MAX phase alone, T_3SiC_2 , with roughly half of those published in the past 6 years.

Structure:



Superconductor



Crystal structures of (a) Ti_2AlC , (b) Ti_3AlC_2
Hexagonal Space Group $P6_3/mmc$

Exciting new class of materials – Why ?

Major Challenges in Engineering

We need versatile materials for developing technologies.: Durable and high performance in extreme environments

1. Simple Facts from Thermodynamics!

- Efficiency of any fuel-burning engine is $\propto T_{\text{operating}}$
- Raise engine *temp.* by 1 °C → Fuel savings of the world's jet alone worth ~ \$1 b/year.

Similar strategy to increase vehicle efficiency by 1 km/litre would save ~ 1 m barrels of oil a day.

- A jet engine made from a material 50% lighter in weight & able to run 200 to 300 degrees hotter would have a staggering economic impact.

Why ? (contd.)

2. Today's jet engines are not running hotter for a simple reason

- ▣ No material exists that can take that kind of heat while spinning furiously.

The same goes for the **internal-combustion engine**; if a car engine could be built with a temp-tolerant material, **its radiator, water pump & cooling water could be thrown away.**

- ▣ **Such an efficient, lighter & higher- T engine would squeeze more *km* from *every litre* of fuel.**

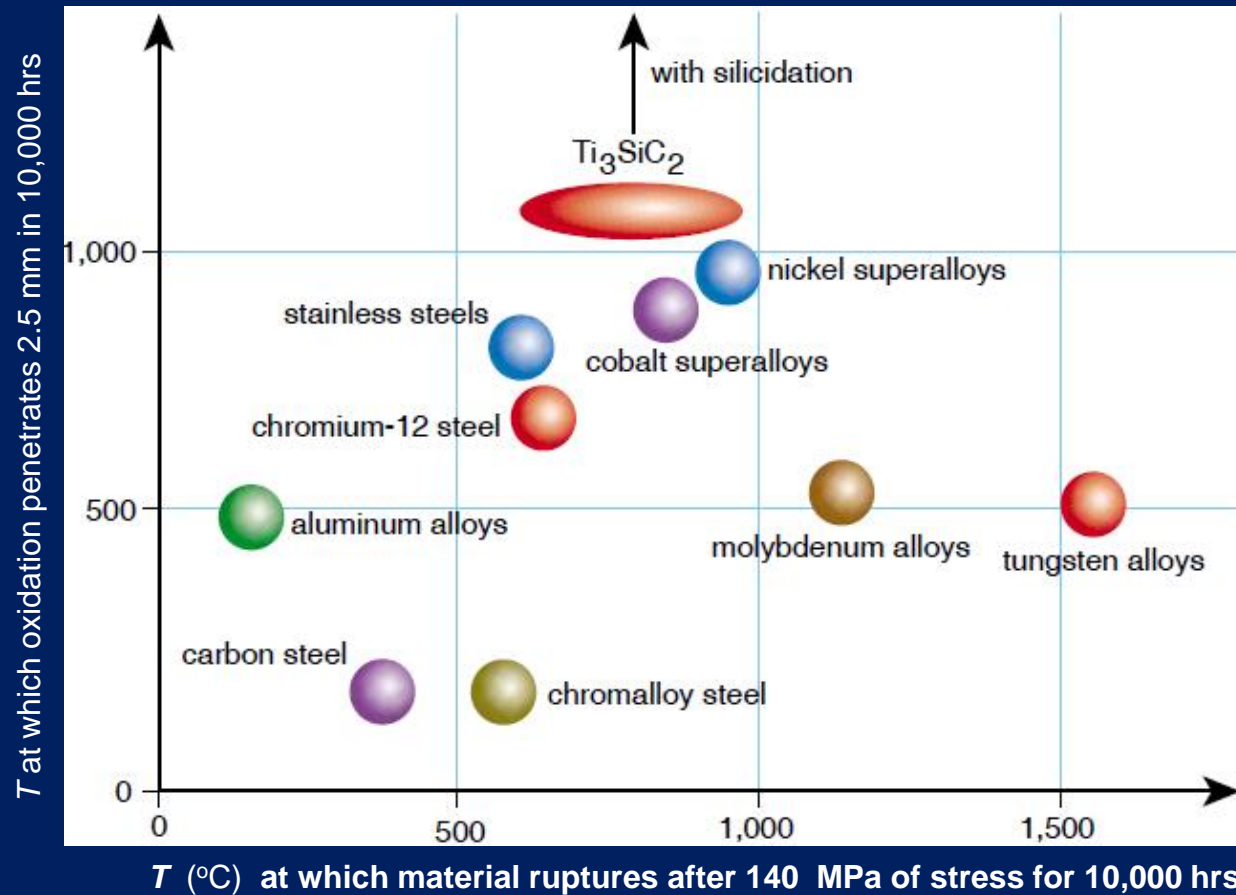
Contd.

- ▣ Growing interest in the MAX phases lies in their unusual, & sometimes unique set of properties that can be traced back to their layered nature .
- ▣ **Stiff, lightweight, machinable, made from relatively inexpensive raw materials, resistant to oxidation & thermal shock, and capable of remaining strong up to $T > 1300$ C in air.**
- ▣ An ideal high-performance structural material for, say, jet engines would have all these qualities - and a new class of materials is thus being explored .
- ▣ **MAX materials form a new class of solids - turn out to be surprisingly soft & machinable, yet also heat-tolerant, strong & lightweight.**

Materials in demanding applications not only must retain their strength, but also need to resist oxidation::



Ti_3SiC_2 possesses both



Characteristics of MAX phases - summary

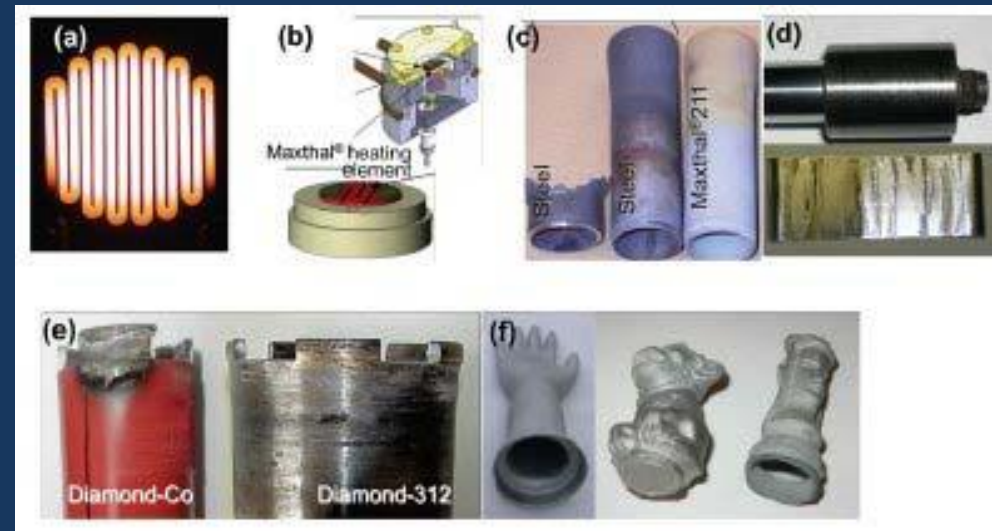
- Good thermal & electrical conductivity
- Low coefficient of thermal expansion
- Resistant to thermal shock
- Resistant to oxidation
- Highly machinable due to lamellar structure
- Exhibit plastic deformation at high T
- High melting point
- Low Density

MAX Phases apply to a emerging class of materials that bridge the gap between properties typical of metals & ceramics.

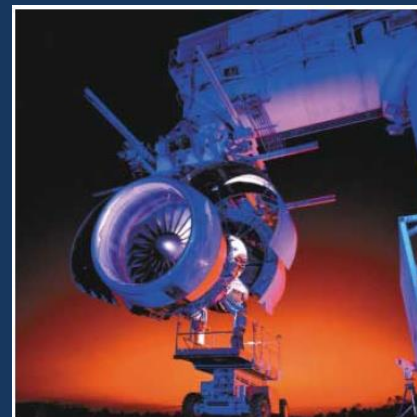
→ MAX phase = Metallic ceramics

Potential applications for the MAX phases

- (a,b) Heating elements,
- (c) Gas burner nozzles in corrosive environment,
- (d) High-T bearings,
- (e) Diamond/Ti₃SiC₂ composites for dry drilling of concrete,
- (f) Very thin walled parts manufactured by slip casting.



Courtesy: Kanthal Corp. and 3-ONE-2, the company Dr. El-Raghy and Barsoum



Future high-performance applications such as jet engines for aircraft. Current engine technology (such as used in Airbus A330 wide-bodied twin-jets) is limited by materials failure at high-T. Lighter engines with materials that could operate at higher T would provide immense benefits in cost savings & fuel efficiency (Courtesy: Pratt & Whitney)

- ❑ Future high-performance applications such as jet engines for aircraft
- ❑ Modified performance cars with ceramic heat shield material can run much hotter

A More Efficient Jet Engine Is Made from Lighter Parts, Some 3-D Printed

By [Kevin Bullis](#) on May 14, 2013

May 2013:: A new generation of Jet engines being developed by the world's largest jet engine maker, [CFM](#) (a partnership between [GE](#) and [Snecma](#) of France), will allow aircraft to use about 15 % less fuel - enough to save about **\$1 million per year per airplane** and significantly reduce carbon emissions.

- ▣ **Prediction of yet unobserved phases**
 - First-principles investigation + Gibbs energy
 - Thermodynamic properties

- ▣ **Substitution – strengthening study:**
 - $\text{Ti}_{2-x}\text{V}_x\text{AlC}$, $\text{Ti}_2\text{Si}_x\text{Al}_{1-x}\text{C}$

- ▣ **Superconducting MAX Phases** (Thermal + optical prop)
 - Nb_2SC , Nb_2SnC , Nb_2AsC , Nb_2InC
 - Ti_2InC , Ti_2InN
 - Mo_2GaC

2014

Zirconium metal-based MAX phases Zr_2AC (A = Al, Si, P and S): A first-principles study

M. T. Nasir, M. A. Hadi, S. H. Naqib and F. Parvin, A. K. M. A. Islam*, M. Roknuzzaman, M. S. Ali Int. J. Modern Physics B28, No. 32 1550022(2014)

[DOI: 10.1142/S0301797913500124](https://doi.org/10.1142/S0301797913500124)

New MAX Phase Superconductor Ti_2GeC : A First-principles Study

M. A. Hadi^{1*}, M. Roknuzzaman¹, F. Parvin¹, S. H. Naqib¹, A. K. M. A. Islam² and M. Aftabuzzaman³ J. Sci. Res. 6 (1), 11-27 (2014)

<http://dx.doi.org/10.3329/jsr.v6i1.16604>

2013

BAND STRUCTURE, HARDNESS, THERMODYNAMIC AND OPTICAL PROPERTIES OF SUPERCONDUCTING Nb_2AsC , Nb_2InC AND Mo_2GaC

M. A. HADI, M. S. ALI and S. H. NAQIB, A. K. M. A. ISLAM* Int. J. Comp. Materials Sci. Eng. 2, No. 21350007 (2013)

[DOI: 10.1142/S2047684113500073](https://doi.org/10.1142/S2047684113500073)

Newly synthesized nanolaminate Nb_2GeC : Hardness, thermodynamic and optical properties by first-principles method

M.S. Ali^a, F. Parvin^a, A.K.M.A. Islam^{b,*} M.A. Hossain^c Computational Materials Science 74, 119–123 (2013) <http://dx.doi.org/10.1016/j.commatsci.2013.03.020>

2012

Ab Initio Investigation of Nitride in Comparison with Carbide Phase of Superconducting Ti_2InX (X = C, N)

M. Roknuzzaman and A. K. M. A. Islam, ISRN Condensed Matter Physics Volume 2013, Article ID 646042 <http://dx.doi.org/10.1155/2013/646042>

MAX phases Nb_2AC (A = S, Sn): An ab initio study

M.T. Nasir, A.K.M.A. Islam* Computational Materials Science 65, 365–371(2012) <http://dx.doi.org/10.1016/j.compsci.2012.08.003>

Phase stability, elastic, electronic, thermal and optical properties of $Ti_3Al_{1-x}Si_xC_2$ ($0 \leq x \leq 1$): First principle study

M.S. Ali, A.K.M.A. Islam*, M.M. Hossain, F. Parvin Physica B407, 4221–4228 (2012) <http://dx.doi.org/10.1016/j.physb.2012.07.007>

Newly Synthesized $Ti_5Al_2C_3$: Electronic and Optical Properties by First-principles Method

M. S. Ali¹, A. K. M. A. Islam^{1*} and M. A. Hossain² J. Sci. Res. 4 (3), 569-575 (2012) <http://dx.doi.org/10.3329/jsr.v4i3.9891>

2011

Structural, elastic, electronic and optical properties of a new layered-ternary Ta_4SiC_3 compound

M.S. Islam, A.K.M.A. Islam Physica B: Condensed Matter 406, 2, 275–279 (2011)

Phase stability and physical properties of hypothetical V_4SiC_3

F. Parvin, M. M. Hossain and A. K. M. A. Islam, arxiv

Structural, elastic, electronic and optical properties of a newly predicted layered-ternary Ti_4SiN_3 : A First-principles study

[M. M. Hossain, M. S. Ali, A. K. M. A. Islam arXiv:1009.0586 \[pdf\]](https://arxiv.org/abs/1009.0586)

Ti_4SiN_3 : A Hypothetical MAX Phase Studied by First-principles Method

M. S. Ali^a, M. M. Hossain^b, R. Parvin^b, and A. K. M. A. Islam^{b,c,*} - submitted (2015)

Prediction of Phases not yet synthesized

- First we check the **occurrences** of MAX phases

Summary

	M_2AX	M_3AX_2	M_4AX_3
Ti-Si-N	×	×	×
Ti-Al-N	✓	×	✓
Ti-Si-C	×	✓	✓ ^a
Ti-Al-C	✓	✓	×
Cr-Al-C	✓	×	×

^aPrepared using thin-film epitaxial growth

We start with Ti-Si-C system:

Relevant aspects of stability:

Intrinsic stability: Gibbs free energy is in a local minimum *w.r.t.* small deformations.

Even if intrinsically stable, a phase does not necessarily exist since there are **competing phases (CP)** which might be thermodynamically favorable.

□ CP is identified through the use of experimentally determined ternary phase diagrams. The position of the MAX alloys in the diagram is determined & the CP identified from the nearby stable points on the diagram.



Stability *contd.*

The stability of a MAX phase can be studied by comparing total energy

The energy difference $\Delta G(T, p)$ between the energy of MAX and that of the competing phases is calculated using:

$$G(T, p) = E_{\text{tot}} + (E_{\text{ZPE}} - T S_{\text{vib}}) + p V$$

Here E_{tot} = Total E (from electronic structure calc.) The 2nd term = zero point energy, & third term = vibrational entropic.

$T = 0, P = 0$: $\Delta E > 0$, unstable; $\Delta E < 0$, stable

Finite T , Finite P : $\Delta G > 0$, unstable; $\Delta G < 0$, stable

$T = 0, P = 0$: $\Delta E > 0$, unstable; $\Delta E < 0$, stable

Finite T , Finite P : $\Delta G > 0$, unstable; $\Delta G < 0$, stable

Phase	Author	Competing phases	$\Delta E = E_{\text{MAX}} - E_{\text{CP}}$ (eV/f.u.)	Reported occurrence
Ti ₂ SiC	a	4/9 Ti ₃ SiC ₂ + 1/9 TiSi ₂ + 1/9 Ti ₅ Si ₃ C	0.014	No
	b	Ti ₃ SiC ₂ , TiSi ₂ , Ti ₅ Si ₃	- 0.032	
Ti ₃ SiC ₂	a	9/5 TiC + 1/5 TiSi ₂ + 1/5 Ti ₅ Si ₃ C	- 0.202	Yes
Ti ₄ SiC ₃	a	Ti ₃ SiC ₂ + TiC	0.012	Yes [#]
	b	Ti ₃ SiC ₂ + TiC	- 0.232	
Ti ₅ SiC ₄	a	Ti ₃ SiC ₂ + 2 TiC	0.043	No
	b	Ti ₃ SiC ₂ + 2 TiC	0.37 ?	
Ti ₅ Si ₂ C ₃	b	Ti ₃ SiC ₂ , TiSi ₂ , Ti ₅ Si ₃	0.36	Intergrown phase (IP) hybrid "523" and "725" MAX phases
		3/2 Ti ₃ SiC ₂ + 1/7 TiSi ₂ + 1/14 Ti ₅ Si ₃		
Ti ₇ Si ₂ C ₅	b	Ti ₃ SiC ₂ , TiC 2 Ti ₃ SiC ₂ + TiC	0.392	IP (2004), Yes (2011)

a. Substitution (solid solution) of MAX

b. Superconducting MAX phases

The following properties are studied

Thermodynamic properties

- T & P dependence of Debye temp.
- T dependence of C_p , C_v
- T and P dependence of thermal expansion

Elastic properties

- C_{ij} , B , shear modulus G , Y , ν
- Vickers hardness, brittleness

Electronic properties

- Electronic band structure, Total and partial DOS

Optical properties

- Dielectric constants, Photoconductivity
- Reflectivity spectrum

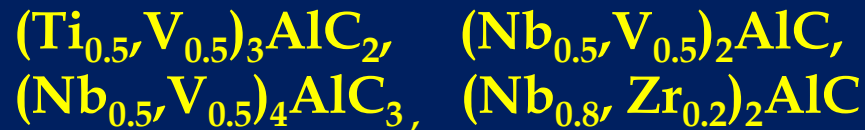
Solid solution & Strengthening

- ❑ **Ti₂AlC can be strengthened by substituting Ti with V to form (Ti,V)₂AlC solid solutions.**
- ❑ **V is smaller, & has 1 more valence electron than Ti**
The weak interaction *transition metal-Al* bonds are reinforced & strengthened.
- ❑ ***B*, Vicker's hardness & other aspects are also studied.**

New Solid Solution of MAX Phases

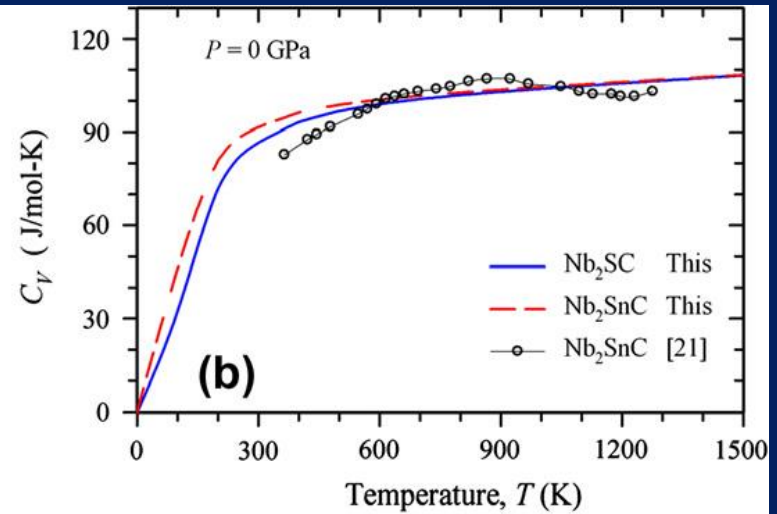
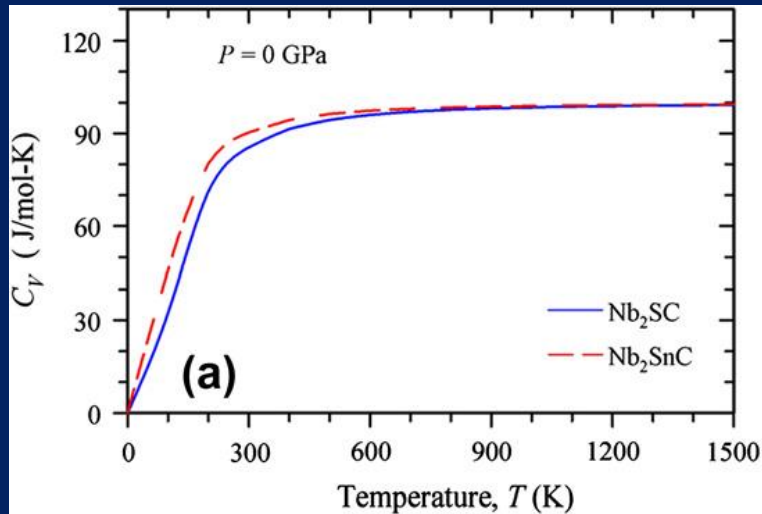
M. Naguiba, et al. Mater.Res.Lett. 2014 Vol. 2, No. 4, 233–240

- **Previously unreported Al containing solid solution $M_{n+1}AX_n$ phases have recently been synthesized.**



- Rietveld analysis of powder X-ray diffraction patterns was used to calculate the lattice parameters & phase fractions.
- Heating **Ti, V, Al & C** elemental powders – in the molar ratio of 1.5:1.5:1.3:2 – to 1, 450 °C for 2 h in flowing argon, resulted in a predominantly **phase pure sample of $(\text{Ti}_{0.5}, \text{V}_{0.5})_3\text{AlC}_2$**
- *The other compositions were not as phase pure & further work on optimizing the processing parameters needs to be carried out if phase purity is desired.*

Thermodynamic properties



$$C_p - C_v = \alpha_v^2(T)BVT$$

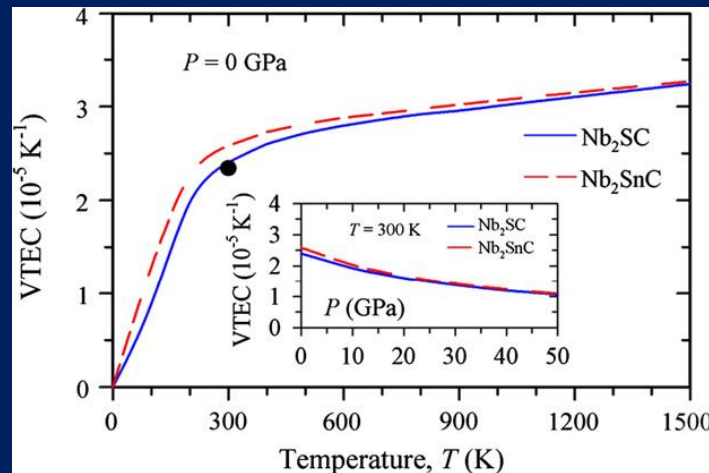
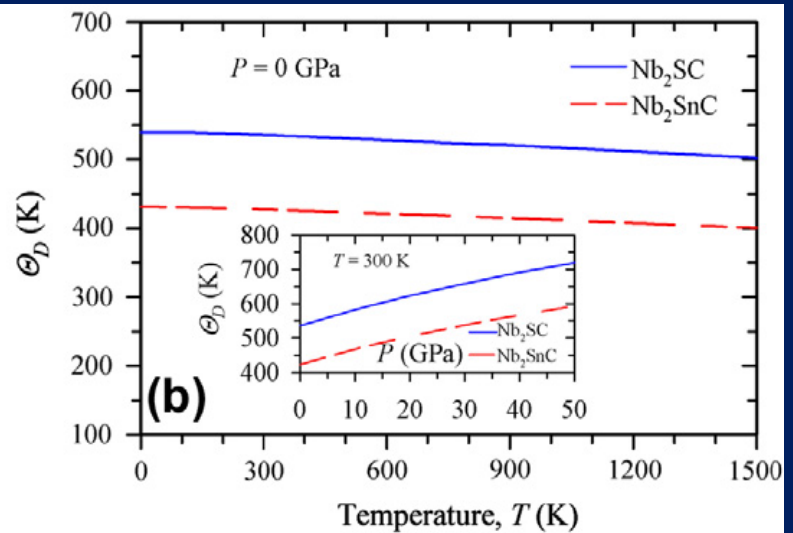
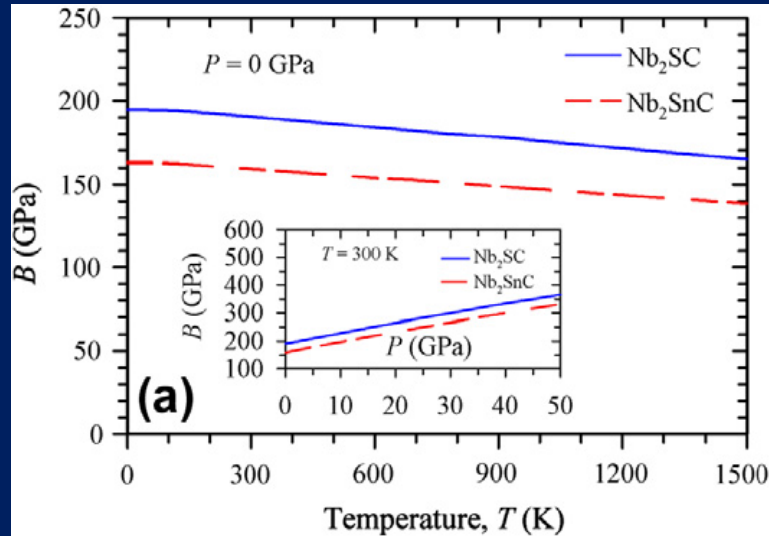
At low T up to ~ 10 °C, $C_p = \gamma T + \beta T^3$

γ and β are the coefficients of electronic & lattice heat capacities.

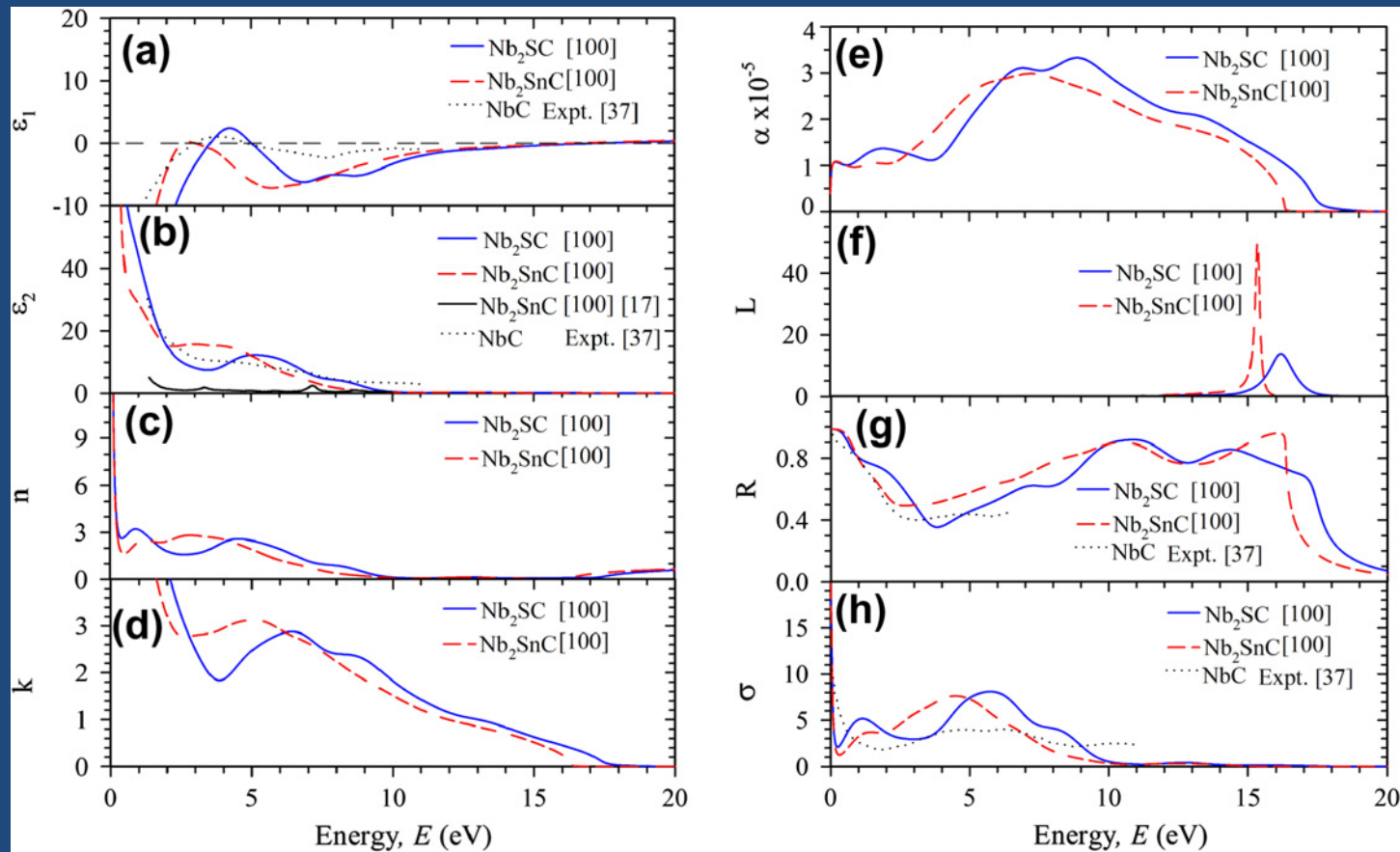
A plot of C_p/T vs T^2 should yield a straight line with slope β & intercept γ .

λ (e-ph coupling constant) is obtained via $\gamma = (1+\lambda) k_B^2 N(E_F)/3$.

Thermodynamic Properties – *contd.*

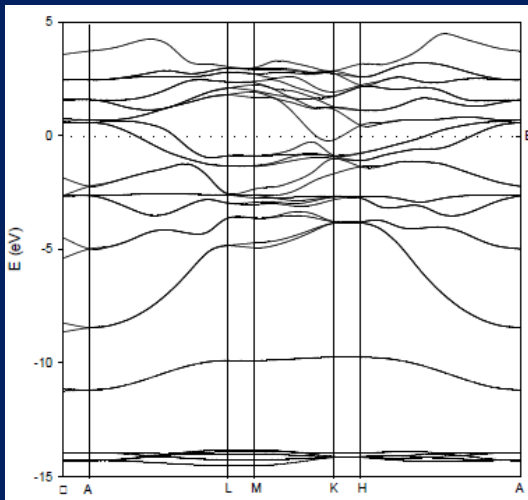


Optical Properties



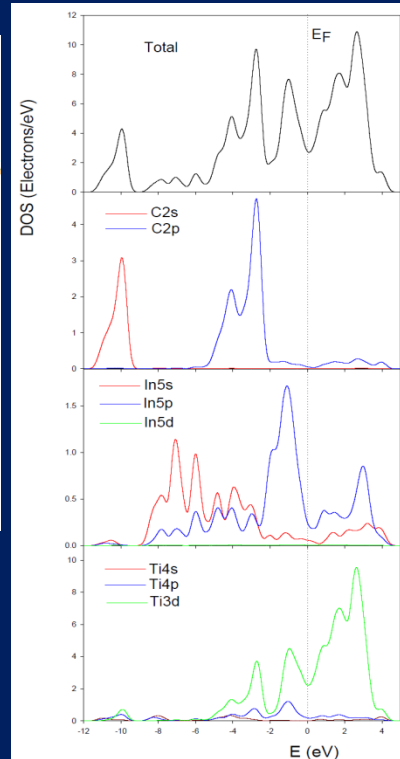
(a) Real and (b) imaginary part of dielectric function, (c) real and (d) imaginary part of refractive index, (e) absorption coefficients, (f) loss function, (g) reflectivity and (h) real part of photoconductivity

Superconductors Ti_2InC and Nb_2SC

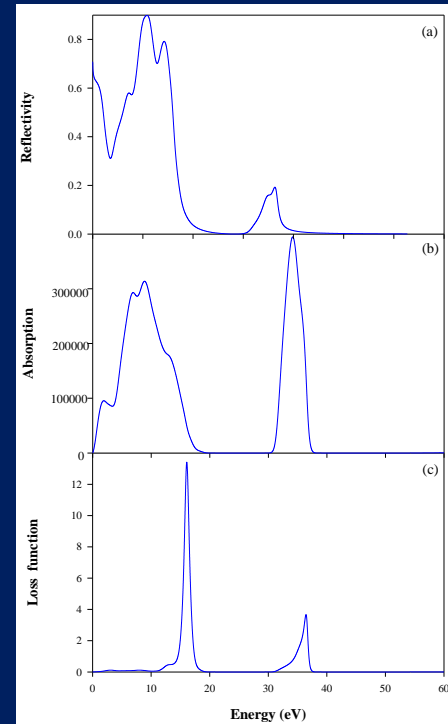


Band structure of Ti_2InC

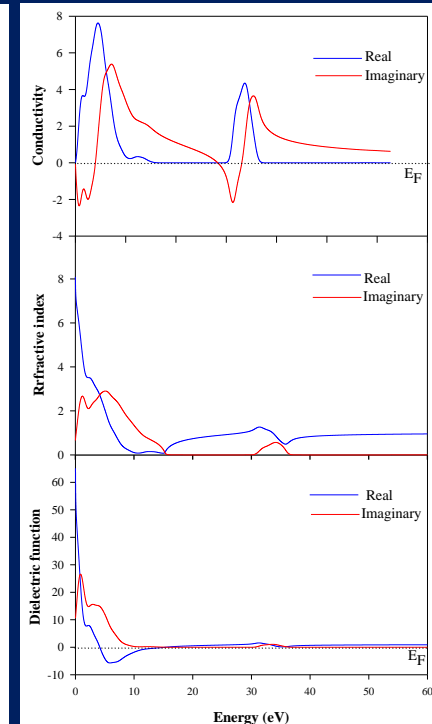
($T_c = 3.1$ K)



Total & partial DOS of Ti_2InC



Optical constants of Nb_2SC ($T_c = 5$ K)



Can calc, *el-phonon* coupling constant

Outlook

Finally, the question: to what extent can the properties of the MAX phases be tuned?

- ▣ **Future research direction** would be systematic exptl. studies of MAX phase solid solutions to elucidate the role of chemistry on phase stability and properties.
- ▣ **To engineer the band structure** by appropriate dopants, so as to achieve desired properties (shifting Fermi level to tune material from metal to semiconductor in a controlled manner).

Outlook (contd.)

- ▣ **A combined theoret./exptl. approach** is needed with **theoret. predictions** of effects of specific dopants & solid solutions on the band structure & corresponding properties; and **exptl. work** aimed at introducing dopants & forming solid solutions in a controlled manner.
- ▣ **Combinatorial thin-film materials synthesis** will be useful to identify MAX phase solid solutions with attractive, and quite possibly novel, properties.

MXenes – Stories of New Wonder Materials

A major breakthrough in Materials Science

Recently a new, large family of two-dimensional (2-D) early transition metal carbides and carbonitrides, called **MXenes**, derived from MAX phases was discovered-- ***These 2-D sheets/structure possess greatly different properties.***

(Collaborative effort of Prof. Barsoum's group at Drexel University)

Graphene (a single-atom thick molecular layer of C) was only the beginning;
Now MAX phases get 2-D as well

- “**MXene**” are produced by etching **A** layer from MAX phases -- “**ene**” is affixed to emphasize their similarity to **graphene**

Formula: $M_{n+1}AX_n$

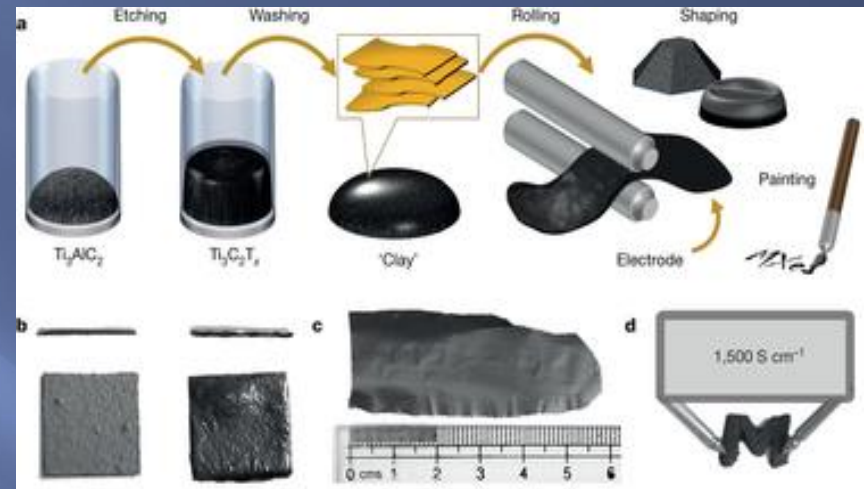
- **M** is an early transition metal
- **A** is an A group element
- **X** is either C or N

Etching process: simply immerse MAX phase in hydrofluoric acid at room temperature.

MXenes are produced with compositions of M_2X , M_3X_2 , and M_4X_3 .

MXenes (contd.)

a, MAX phase is etched in a solution of acid and fluoride salt (**step 1**), then washed with water to remove reaction products and raise the pH towards neutral (**step 2**).



The resulting sediment behaves like a clay; it can be rolled to produce **nanotube-like scrolls**, some with diameters of less than **40 nanometers**, having the potential for a broad range of applications, ranging from energy storage devices to biomedical applications and composites.

MXenes combine the metallic conductivity of transition metal carbide layers with the hydrophilic nature of the hydroxyl or oxygen terminated surfaces. In essence , they behave as “conductive clays”.

MXenes are expected to be good candidates for a host of applications. They have already shown promising performance in electrochemical energy storage systems (e.g. Lithium ion batteries).

to play a crucial role in generation and storage of renewable energy -- new family of 2-D compounds to have unique properties that may lead to ground-breaking advances in energy storage technology.

DFT calculations showed that MXenes’ band gap can be tuned by changing the surface termination, e.g. bare MXene is metallic conductors, while OH or F terminated are semiconductors with small band gap.

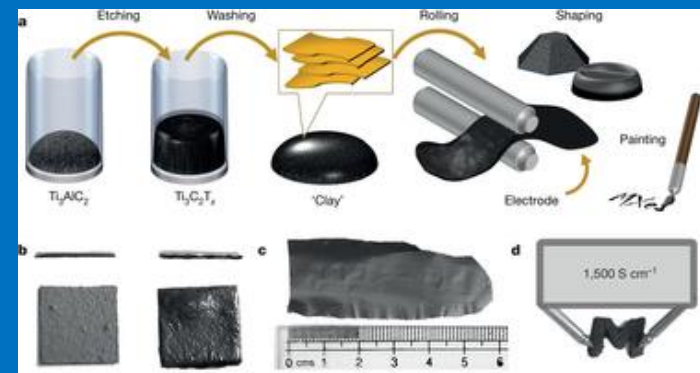
Multilayer MXenes are electronically conductive with conductivity similar to multilayer graphene. Unlike graphene, MXenes show hydrophilic behavior that allow for easy dispersion in aqueous solutions.

Why's it good, then?

MXene was first discovered in 2011. It's a material composed of 2-D titanium carbide derived from MAX Phases.

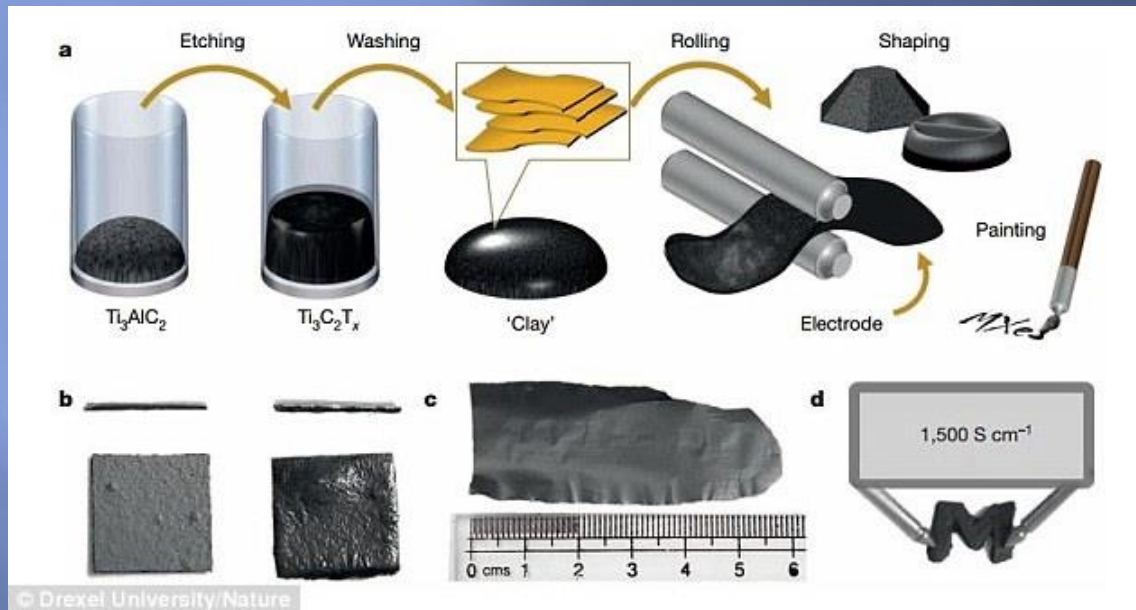
The **three main properties of *MXene*** that should catch our eyes are:

1. **It's hydrophilic.** That means, unlike graphene, it loves water. And that's good news.
2. **It's very malleable.** You can mold it into complicated forms, or roll or press it very flat – both of which are potentially very handy for a material with conductivity.
3. **The material has a very healthy capacitance of 900 F/cm^3** – performance will improve further. *MXene* lost no capacitance after more than 10,000 charge cycles.



Why's it good, then?

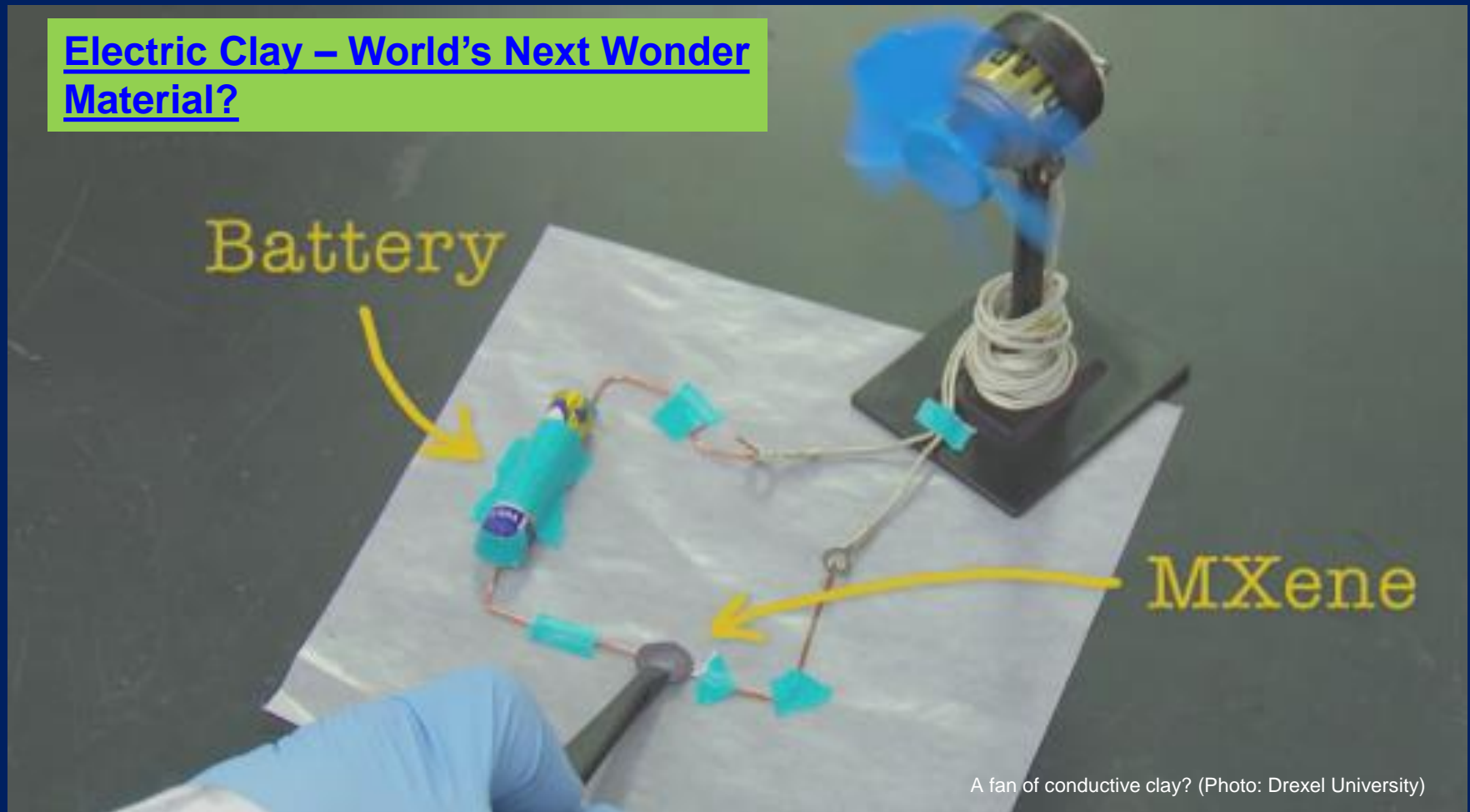
MXene ::: What does it look like under an electron microscope?



This clay-like material, made from etched MXene and water, is not only easier and safer to produce than current electrode material, it's also has twice the capacitance!

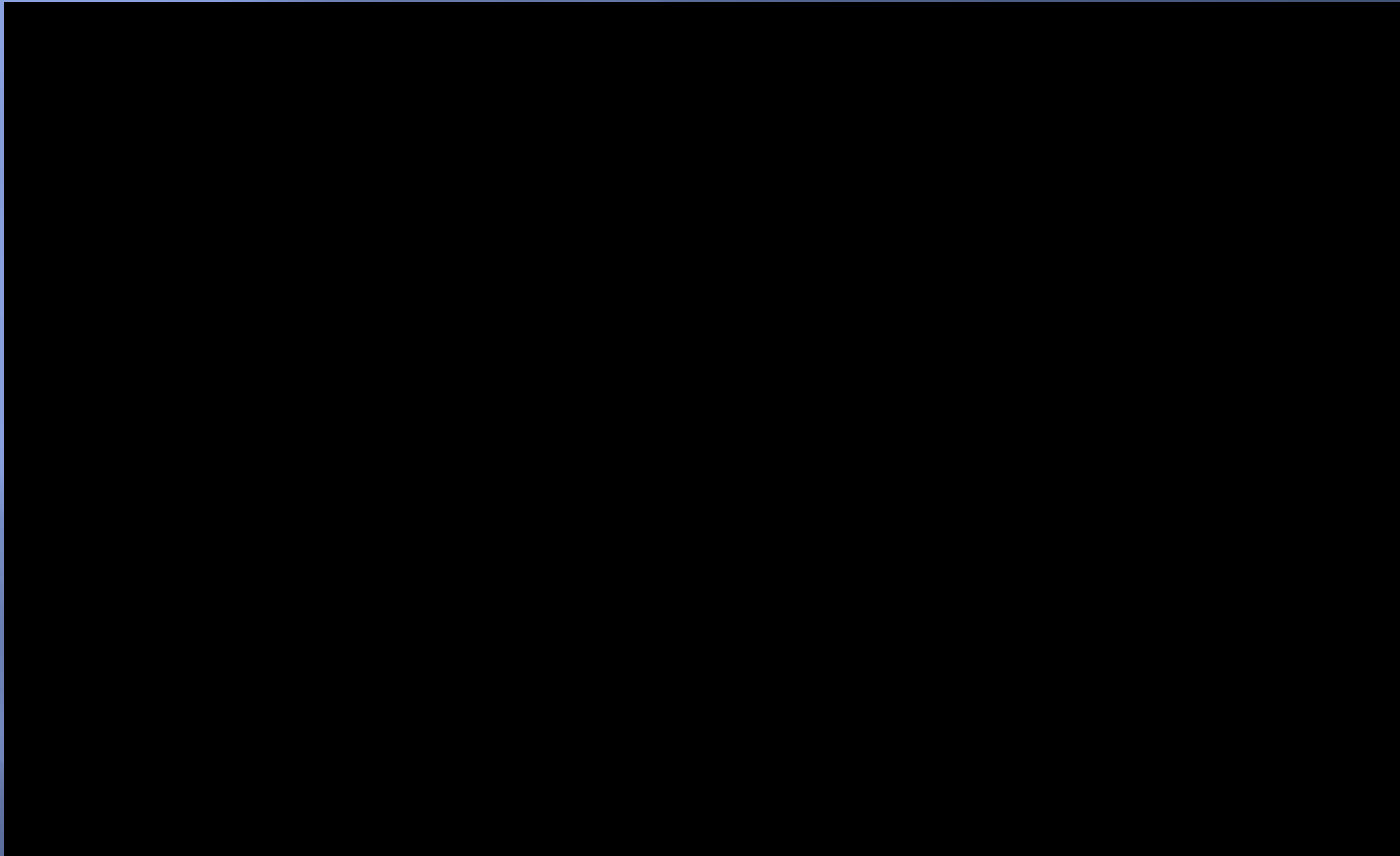
Could this electric clay be the world's next wonder-material?

Electric Clay – World's Next Wonder Material?



A fan of conductive clay? (Photo: Drexel University)

[James Holloway](#), December 1, 2014



MXene nanoribbons

MXene nanoribbons, Shijun Zhao,*ab Wei Kangab and Jianming Xueac, *J. Mater. Chem. C*, 2015, 3, 879-888

Quasi-1-D nanoribbons have great potential for applications in nanoelectronics and nanospintronics due to their unique quantum confinement effects.

First-principles calculations have been carried out to predict the stability as well as magnetic & electronic properties of MXene nanoribbons with either zigzag- or armchair-terminated edges.

Three types of MXene recently realized experimentally, *i.e.* Ti_2C , Ti_3C_2 and V_2C , are considered to construct their corresponding MXene nanoribbons.

MXenes: A major breakthrough in Materials Science

Most notable is that the exfoliated material shows many features of graphene.

For example, it can roll into nanotube-like scrolls, some with diameters of less than 40 nanometers, having the potential for a broad range of applications, ranging from energy storage devices to biomedical applications and composites.

For instance, MXene could be used in energy storage devices such as electrodes of Li-ion batteries, pseudo capacitors, etc.

The researchers also envision its use as reinforcement in composites, similar to clays or graphene, which increase mechanical properties and decrease gas permeability of polymers. A variety of surface chemistries, presence of transition metal oxides and high surface area make MXene potentially attractive for catalytic applications.

Graphene: it's Applications and Uses

The properties of *graphene*, carbon sheets that are only one atom thick, have many potential applications of graphene.

- ❑ Lower cost of display screens in mobile devices.
- ❑ Lithium-ion batteries that recharge faster. These batteries use graphene on the surface of the anode surface.
- ❑ Ultracapacitors with better performance than batteries.
- ❑ Components with higher strength to weight ratios.
- ❑ Storing hydrogen for fuel cell powered cars.
- ❑ Lower cost of fuel cells.
- ❑ Low cost water desalination:
- ❑ Lightweight natural gas tanks
- ❑ Membranes for more efficient separation of gases.
- ❑ Chemical sensors effective at detecting explosives.

Usefulness in details

Lower cost of display screens in mobile devices. Researchers have found that graphene can replace indium-based electrodes in organic light emitting diodes (OLED). These diodes are used in electronic device display screens which require low power consumption. The use of graphene instead of indium not only reduces the cost but eliminates the use of metals in the OLED, which may make devices easier to recycle.

Lithium-ion batteries that recharge faster. These batteries use graphene on the surface of the anode surface. Defects in the graphene sheet (introduced using a heat treatment) provide pathways for the lithium ions to attach to the anode substrate. Studies have shown that the time needed to recharge a battery using the graphene anode is much shorter than with conventional lithium-ion batteries.

Ultracapacitors with better performance than batteries. These ultracapacitors store electrons on graphene sheets, taking advantage of the large surface of graphene to provide increase the electrical power that can be stored in the capacitor. Researchers are projecting that these ultracapacitors will have as much electrical storage capacity as lithium ion batteries but will be able to be recharged in minutes instead of hours.

Components with higher strength to weight ratios. Researchers have found that adding graphene to epoxy composites may result in stronger/stiffer components than epoxy composites using a similar weight of carbon nanotubes. Graphene appears to bond better to the polymers in the epoxy, allowing a more effective coupling of the graphene into the structure of the composite. This property could result in the manufacture of components with high strength to weight ratio for such uses as windmill blades or aircraft components.

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- **Storing hydrogen for fuel cell powered cars.** Researchers have prepared graphene layers to increase the binding energy of hydrogen to the graphene surface in a fuel tank, resulting in a higher amount of hydrogen storage and therefore a lighter weight fuel tank. This could help in the development of practical hydrogen fueled cars.
- **Lower cost fuel cells.** Researchers at Ulsan National Institute of Science and Technology have demonstrated how to produce edge-halogenated graphene nanoplatelets that have good catalytic properties. The researchers prepared the nanoplatelets by ball-milling graphene flakes in the presence of chlorine, bromine or iodine. They believe these halogenated nanoplatelets could be used as a replacement for expensive platinum catalytic material in fuel cells.
- **Low cost water desalination:** Researchers have determined that graphene with holes the size of a nanometer or less can be used to remove ions from water. They believe this can be used to desalinate sea water at a lower cost than the reverse osmosis techniques currently in use.
- **Lightweight natural gas tanks:** Researchers at Rice University have developed a composite material using plastic and graphene nanoribbons that block the passage of gas molecules. This material may be used in applications ranging from soft drink bottles to lightweight natural gas tanks.
- **More efficient dye sensitized solar cells.** Researchers at Michigan Technological University have developed a honeycomb like structure of graphene in which the graphene sheets are held apart by lithium carbonate. They have used this "3D graphene" to replace the platinum in a dye sensitized solar cell and achieved 7.8 percent conversion of sunlight to electricity.

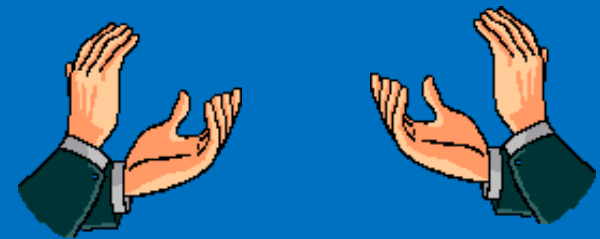
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- **Electrodes with very high surface area and very low electrical resistance.** Researchers at Rice University have developed electrodes made from carbon nanotubes grown on graphene. The researchers first grow graphene on a metal substrate then grow carbon nanotubes on the graphene sheet. Because the base of each nanotube is bonded, atom to atom, to the graphene sheet the nanotube-graphene structure is essentially one molecule with a huge surface area.
- **Lower cost solar cells:** Researchers have built a solar cell that uses graphene as a electrode while using buckyballs and carbon nanotubes to absorb light and generate electrons; making a solar cell composed only of carbon. The intention is to eliminate the need for higher cost materials, and complicated manufacturing techniques needed for conventional solar cells.
- **Transistors that operate at higher frequency.** The ability to build high frequency transistors with graphene is possible because of the higher speed at which electrons in graphene move compared to electrons in silicon. Researchers are also developing lithography techniques that can be used to fabricate integrated circuits based on graphene.
- **Sensors to diagnose diseases.** These sensors are based upon graphene's large surface area and the fact that molecules that are sensitive to particular diseases can attach to the carbon atoms in graphene. For example, researchers have found that graphene, strands of DNA, and fluorescent molecules can be combined to diagnose diseases. A sensor is formed by attaching fluorescent molecules to single strand DNA and then attaching the DNA to graphene. When an identical single strand DNA combines with the strand on the graphene a double strand DNA is formed that floats off from the graphene, increasing the fluorescence level. This method results in a sensor that can detect the same DNA for a particular disease in a sample.
- **Membranes for more efficient separation of gases.** These membranes are made from sheets of graphene in which nanoscale pores have been created. Because graphene is only one atom thick researchers believe that gas separation will require less energy than thicker membranes.
- **Chemical sensors effective at detecting explosives.** These sensors contain sheets of graphene in the form of a foam which changes resistance when low levels of vapors from chemicals, such as ammonia, is present.

Ternary ceramics turn out to be surprisingly soft & machinable, yet also heat-tolerant, strong & lightweight

Could the electric clay *MXene* derived from 3-D MAX phases be the world's next wonder-material?

Thank you



A **charge pump** is a kind of [DC to DC converter](#) that uses [capacitors](#) as energy storage elements to create either a higher or lower [voltage](#) power source. Charge pump circuits are capable of high [efficiencies](#), sometimes as high as 90–95% while being electrically simple circuits.

Charge pumps use some form of switching device(s) to control the connection of voltages to the capacitor.

For instance, a two-stage cycle can be used to generate a higher pulsed voltage from a lower-voltage supply. In the first stage of the cycle, a capacitor is connected across the supply, charging it to that same voltage. In the second stage of the cycle, the circuit is reconfigured so that the capacitor is in series with the supply to the load. Ignoring [leakage](#) effects, this effectively provides double the supply voltage to the load (the sum of the original supply and the capacitor). The pulsing nature of the higher voltage output is typically smoothed by the use of an output capacitor.

Combinatorial materials synthesis

The cornerstone of combinatorial materials synthesis is thin-film technology, which enables rapid manufacture of tiny amounts of complex metals layered onto a substrate and heated to mix the elements and create a stable compound.

Application of combinatorial chemistry to making libraries of solid-state thin films is of particular current interest because so much of modern electronics is thin-film based - In such libraries, each member can be individually addressed by adaptations of standard characterization techniques, such as transport or photoluminescence, potentially making trial-error discovery of new materials very efficient.

Schultz and Xiang developed a method of sputtering through masks to deposit thousands of distinct combinations of metal-oxide molecules onto an area the size of a square on a checkerboard, creating the first combinatorial library of advanced materials.

A primary mask is used to lay down a grid of separate squares. A *secondary mask*, laid atop the primary mask, blocks out specific portions of the rows and columns of the grid. By sending the metals through different secondary masks, each metal can be deposited on particular sections of the grid. The resulting materials are then scanned for interesting electrical properties.

The technique was first tested on a small 16-member library of high- T_c superconductors, and was later expanded to 128-member libraries with combinations of seven metals.

Schultz and Xiang (1995 Nov) had used combinatorial libraries to discover new giant magnetoresistive compounds having complex ratios of four to six atoms. In a magnetic field, the electrical conductivity of these metal crystals changes, and they lose as much as 72% to 99.9% of their resistance. Such materials greatly interest the electronics industry as candidates for the next generation of magnetic recording heads.