New Nanomaterial MXenes: Opening Exciting Technological Horizon

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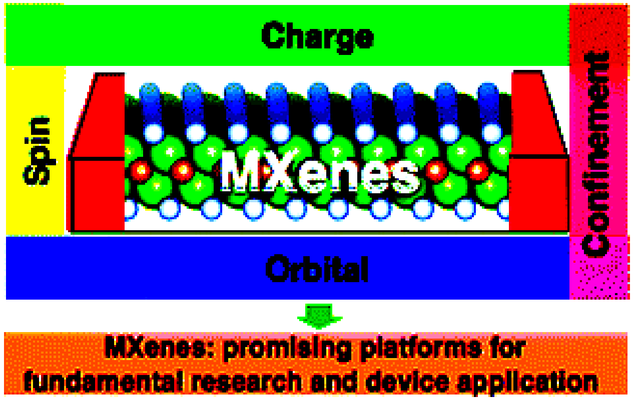
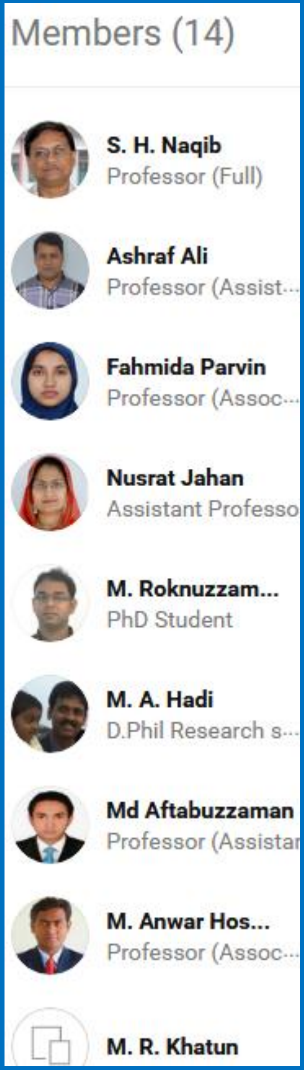


Outlines of Talk

CMP Lab History
Total PG Res. Students = 101 (1984- 2018)
Total Publication = 290 +4 (1969-2018)



- **2D MXenes – New Nanomaterials**

  -- **Stories of the Wonder Materials**
  -- **Synthesis & Applications**

START with

- **3D MAX Phase Materials & Discovery of their Derivative 2D MXenes**

- **Our Research (CCMP: RU & IIUC)**
  MAX & 2D MXenes ➔

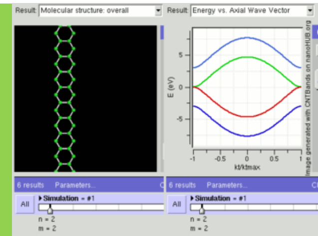
Lab: A K M A Islam

Discovery of WONDER MATERIALS - Major Breakthrough in Materials Science

surface area = 2630 m²/g

- ***Graphene*** **was the first 2D wonder material**

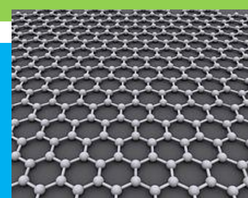
  Discovery: 2004



GNR band structure for zig-zag orientation. Calc. show that zig-zag orientation is always metallic

- ❑ **Isolated at Manchester Univ - Nobel Prize in Physics 2010**

  ➔ A Geim & K Novoselov for ground-breaking expts regarding 2D graphene



- **Now *MXene* – New 2D wonder material**

  Discovery 2011

- ❑ **Derived from parent 3D MAX phases**
- ❑ **"*MXenes*" are produced by etching *A-atom* layer from MAX phases**
- ❑ ***MXenes* adopt 3 structures, as inherited from the parent MAX phases: M_2X, M_3X_2, & M_4X_3**

Surface of a sheet of paper is two-dimensional - can exist as 3, 5, or 7 atomic layers

Any shape that only has a surface area is a 2D shape while shapes with volume are 3D shape

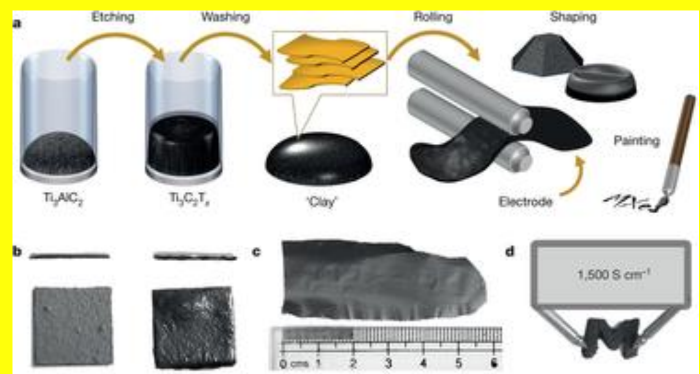
Why's *MXene* good, then?

3 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. 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 >10,000 charge cycles.**

.

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!



Size & Scale of Nanotechnology

➔ showing us just how small nanotechnology actually is.

1 nm = one-billionth of a meter = 10^{-9} m.

'D' of human hair = 100,000 nm = 10^{-4} m

Nanoparticle = 4 nm diameter
Enlarge it 1 million times
➔ 1 small Ant

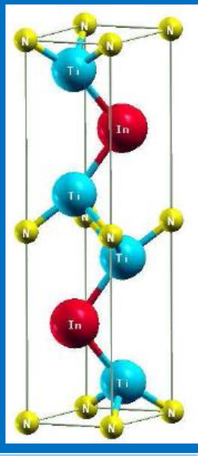
Start with 3D MAX

Now Let's see

- **What is a MAX Phase &**
- **How 2D MXenes are derived from their Parent MAX Phases**

3D MAX Phase

Now > 70 phases-- most discovered & produced in powder form in the 60's by H. Nowotny & coworkers.

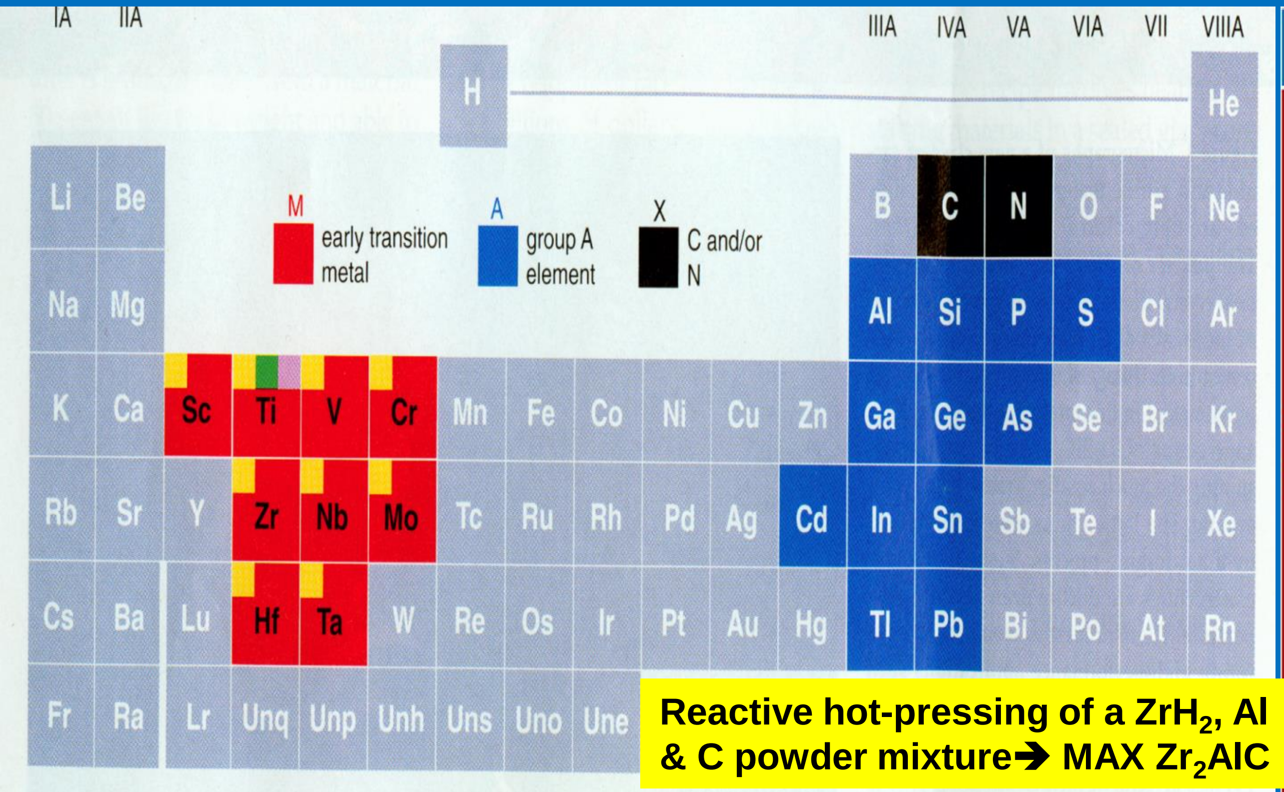


Ti_2InN

Formula: $M_{n+1}AX_n$

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

First fabricated in bulk & characterized
(Dr. Barsoum Group at Drexel University, USA)



Reactive hot-pressing of a ZrH_2, Al & C powder mixture➔ MAX Zr_2AlC

MAX Materials

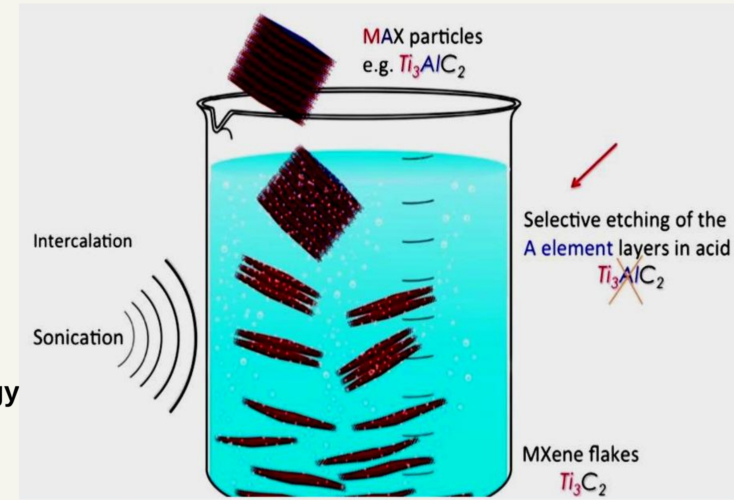
M element		A-group element: s^2 (group 12)	$s^2 p^1$ (group 13)	$s^2 p^2$ (group 14)	$s^2 p^3$ (group 15)	$s^2 p^4$ (group 16)
211 Phases						
	3d	Ti_2CdC	Sc_2InC Ti_2AlC Ti_2GaC Ti_2InC Ti_2TlC V_2AlC V_2GaC Cr_2GaC Ti_2AlN Ti_2GaN Ti_2InN V_2GaN Cr_2GaN	Ti_2GeC Ti_2SnC Ti_2PbC V_2GeC Cr_2AlC Cr_2GeC	V_2PC V_2AsC	Ti_2SC
	4d		Zr_2InC Zr_2TlC Nb_2AlC Nb_2GaC Nb_2InC Mo_2GaC Zr_2InN Zr_2TlN	Zr_2SnC Zr_2PbC Nb_2SnC	Nb_2PC Nb_2AsC	Zr_2SC Nb_2SC
	5d		Hf_2InC Hf_2TlC Ta_2AlC Ta_2GaC	Hf_2SnC Hf_2PbC Hf_2SnN		Hf_2SC
312 Phases						
	3d		Ti_3AlC_2 V_3AlC_2	Ti_3SiC_2 Ti_3GeC_2 Ti_3SnC_2		
	5d		Ta_3AlC_2			
413 Phases						
	3d		Ti_4AlN_3 V_4AlC_3 Ti_4GaC_3	Ti_4SiC_3 Ti_4GeC_3		
	4d		Nb_4AlC_3			
	5d		Ta_4AlC_3			

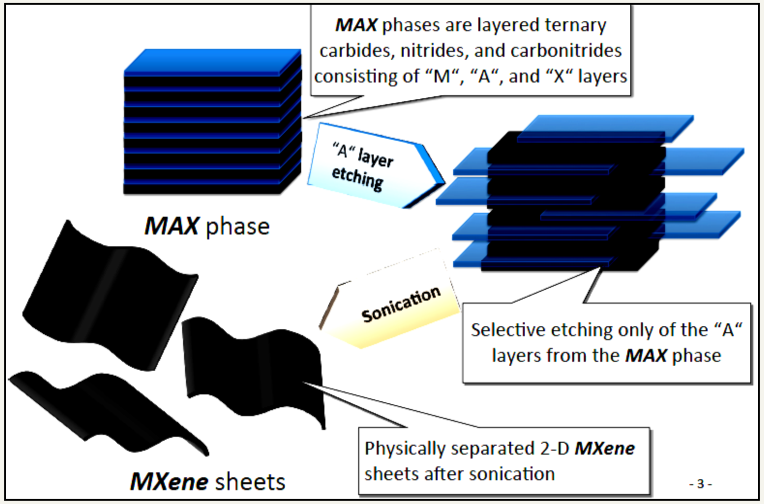
Synthesis of *MXene* from MAX Phase

Sonication

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

Apply sound energy to agitate particles

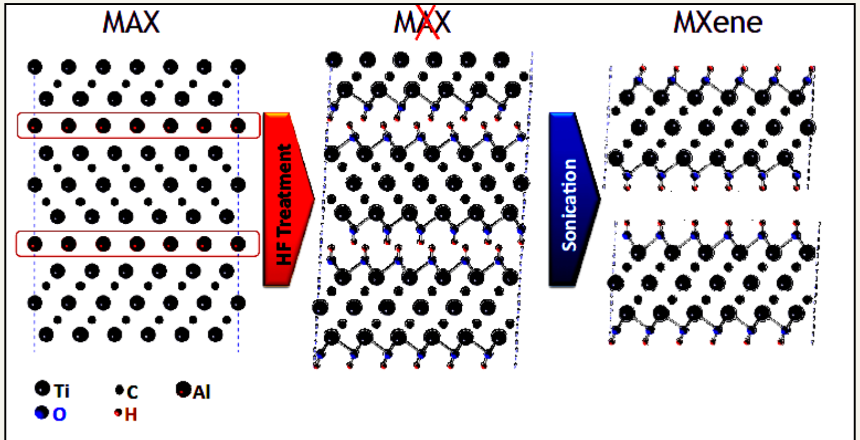




Solution approach to Ti_3AlC_2 Exfoliation & Dispersion

Exfoliate: Wash & Shed flakes from surface

Intercalation : Insertion of a molecule (or ion) into compounds with layered structures



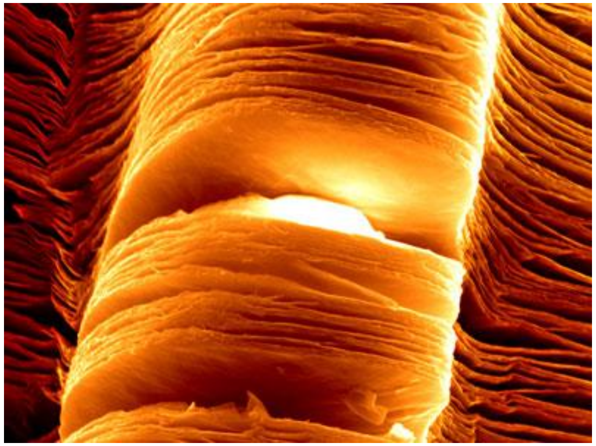
Ti_3AlC_2 in HF 50% for 2 hours at room temperature, then sonication

Structures:
Hexagonal Space Group *$P6_3/mmc$*

MXene singled out

Intercalation **is the insertion of a molecule (or ion) into compounds with layered structures**

HF-etching of Ti_3AlC_2



Exfoliated MXene nanosheets.

(mage: B Anasori, Drexel Univ)

Magnification = 20,000

split into thin flakes
Exfoliate: wash to get rid of flakes

Singled out:

Researchers have also figured out how to break layers of MXenes, which are typically stacked like Pringles potato chips, apart. So far, they've made MXene paper, & are studying what is a single MXene layer can do.

Progress on Grand Challenge

Revolutionary New Forms of Matter with Tailored Properties?

Synthesis, Characterization and Computational modeling reveal how surface and pore morphology, and electronic structure, control the unprecedented performance of MXene Nanoparticles.

Opening of a ‘New Exciting Horizon

- **2D MXenes are at the forefront of materials research : Reasons ➔**

  Exotic electrical, optical & interesting mech. properties due to their atomically thin dimensions

- **Isolation & synthesis of the nanomaterials have opened a New exciting horizon/platform – for exploration & tailoring of superior or hitherto unknown properties**

➔ Promises a range of new technologies

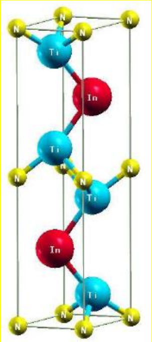
Our Research on MAX and MXene

***A K M A Islam et al* - CMP Lab at Rajshahi University**

Publication = 28 **(only on MAX+MXene)**

MAX Phase (since 2011)

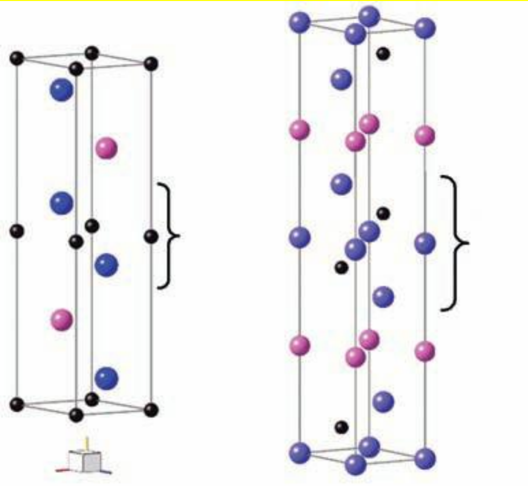
- **Prediction of yet unobserved phases**
- **Substitution – strengthening study: $(Ti, V)_2AlC_2$ etc.**
- **Superconducting MAX phases**
- **Electronic, Optical properties**



Ti_2InN
Superconductor

MXenes: (Last 6 months)

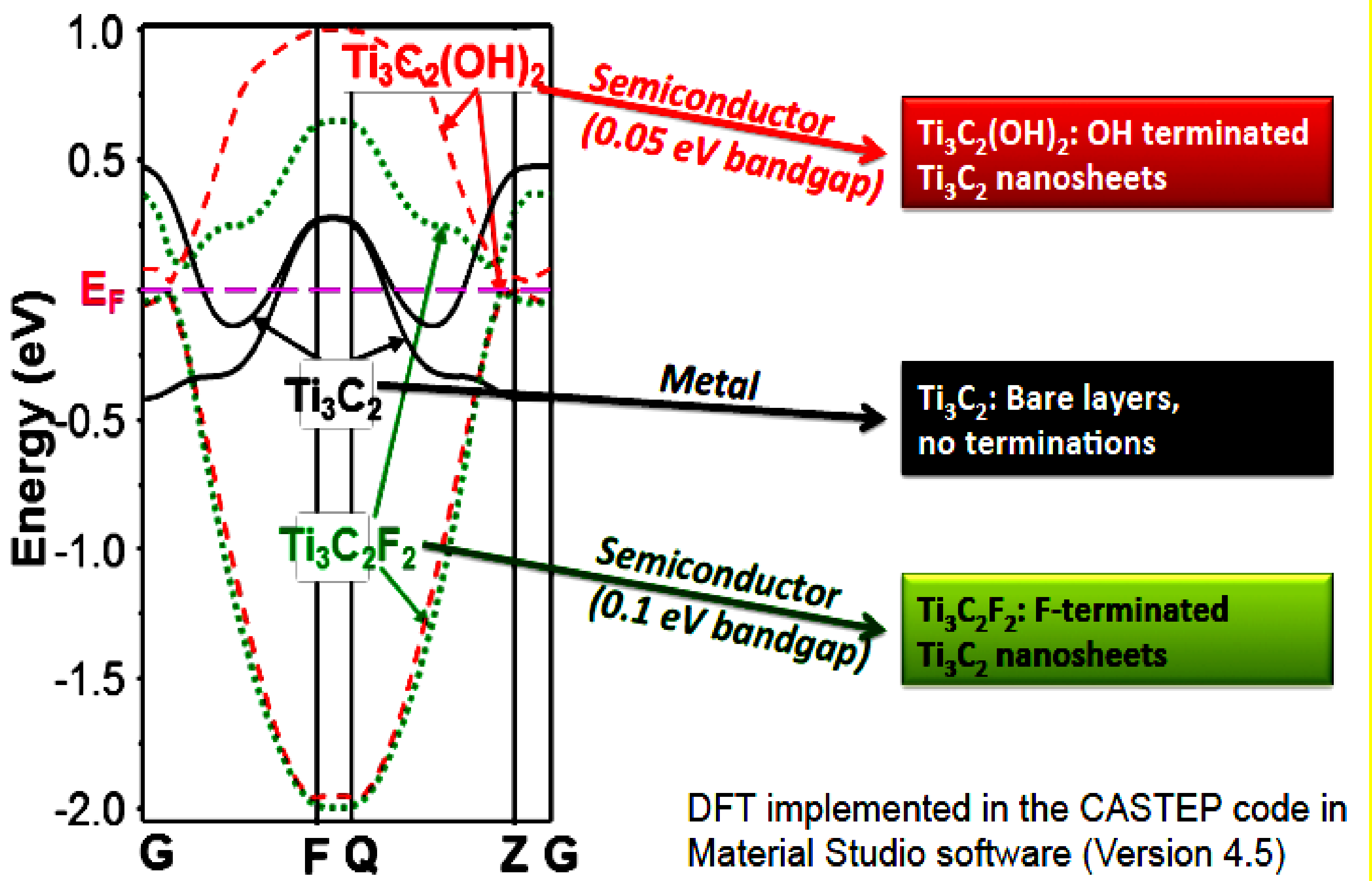
- **Modelling with Pristine and functionalized (terminated) MXenes**
- **Electronic, Optical properties**



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

Electronic Structure of MXenes

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.



DFT implemented in the CASTEP code in Material Studio software (Version 4.5)

M. Naguib, et al. *Advanced Materials* 23 (2011) 4248-4253

MXenes Ability

MXenes have been investigated for

- **Fabrication of e.m. shields,**
- **Promise of faster charging batteries,**
- **Energy storage solutions,**
- **New methods of water purification,**
- **Superior gas sensing ability.**

Applications

- **Electrical Energy Storage**

  Pseudocapacitors, Li-ion batteries, Hybrid devices

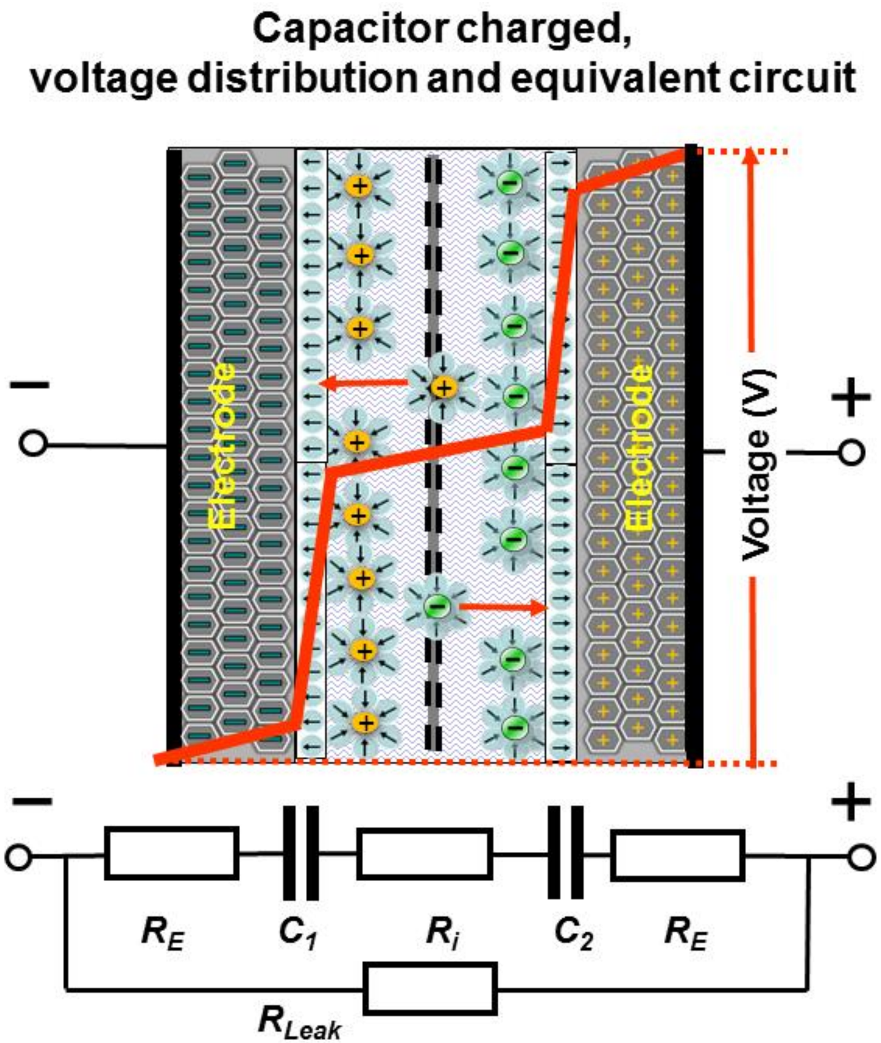
- **Reinforcement for Composites**

  Conductive, high-strength, low-permeability polymers, high strength & high toughness ceramic-metal composites

- **Superior Sensors (chemical, environmental and biological) -** (*e.g. electrochemiluminescent sensor* - 2018)

- **2D and Flexible Electronics**

(Novel 2D $Ti_3C_2T_x$ (MXene)-reinforced polyvinyl alcohol (PVA) nanofibers have been successfully fabricated by electrospinning technique)



A **pseudocapacitor** is part of an electrochemical capacitor, and forms together with an electric double-layer capacitor (EDLC) to create a supercapacitor.

Pseudocapacitance and double-layer capacitance add up to a common inseparable capacitance value of a supercapacitor.

Applications - *contd.*

[2D materials]
2D MXenes make photonic diodes
12 Jan 2018 [Belle Dumé]

- Spintronic Devices - 2D information superhighway
- 2D MXenes make photonic diodes (18 Jan 2018)
- MXenes can contain 'Electromagnetic Pollution'

  Buzzing sound/e.m. noise, caused by radio waves, can originate from anything that creates, carries or uses an electric current, including TV & internet cables, cell phones, tablets & laptops.

- Use in Cell Phones that Charge in Seconds (15 Aug 2017)

Widely reported more Applications

- **Very recently 2D Ti_3C_2 nanomaterial reveals potential as a novel ceramic photothermal agent used for cancer therapy**
- **Resistant to biofouling & offer bactericidal properties ➔ so application in water desalination/ purification membranes**
- **MXene-based <u>Piezoresistive Sensor</u> also can <u>detect human being's subtle bending-release activities</u>**

  ➔ So can be used to harvest wasted frictional energy (e.g. from muscle contractions during typing or walking)

"**bactericidal**" means that it kills bacteria.

The piezoresistive effect is a change in the electrical resistivity of a semiconductor or metal when mechanical strain is applied.
In contrast to the piezoelectric effect, the piezoresistive effect causes a change only in electrical resistance, not in electric potential.

Biofouling or biological fouling is the accumulation of microorganisms, plants, algae, or animals on wetted surfaces

Novel 2D MXene/Sn Composite as Anode In Li-Ion Batteries with Super-High Energy Density Applications

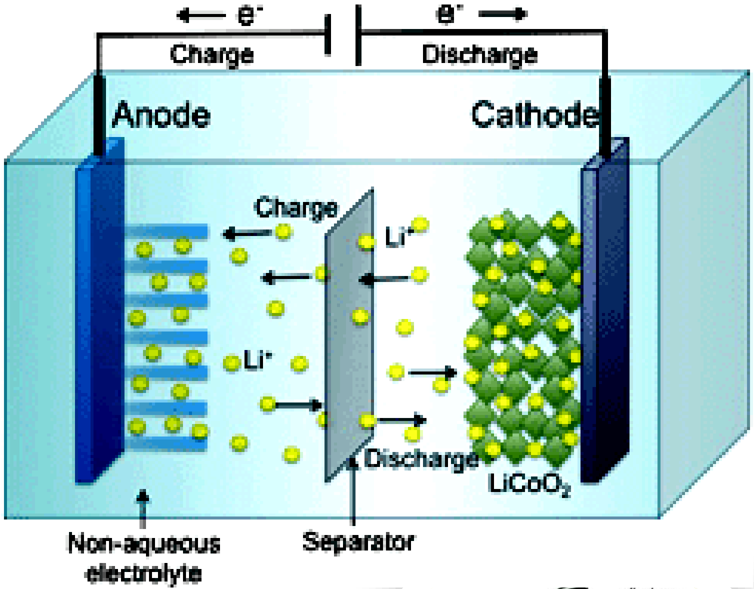
◆ **Li-ion batteries (LIBs), with their high capacity & cycling stability, dominate the portable electronics market.** (Author: J Motimar-2017)

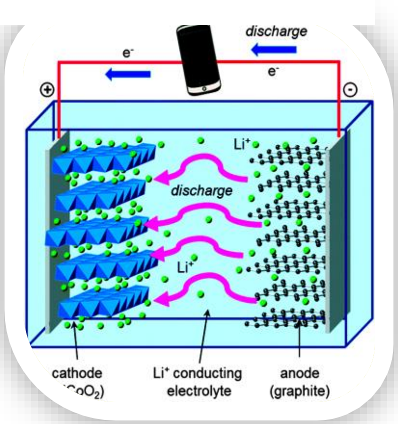
◆ **Novel Li-based battery system:**

<u>Anode electrode:</u> 2D MXene & Sn hybrid nanocomposite.

Significantly enhanced conductivity of 2D MXene along with the uniformly dispersed Sn nanoparticles leads to a drastically increased electrochemical property.

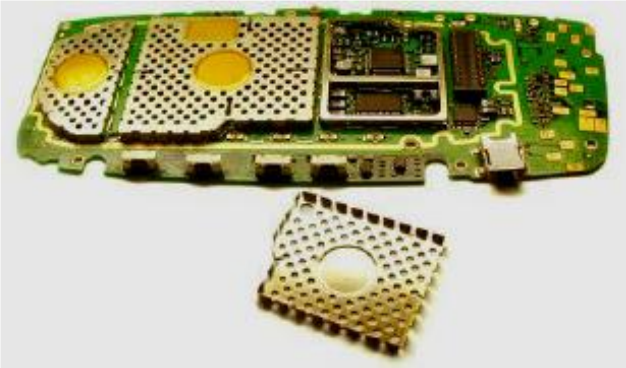
◆ **It shows a greatly improved electrochemical property & energy density.**





Nanomaterial MXene: Best-ever Protection against EM Interference (EMI)

- By: Ann R. Thryft, Materials & Assembly, October 17, 2016



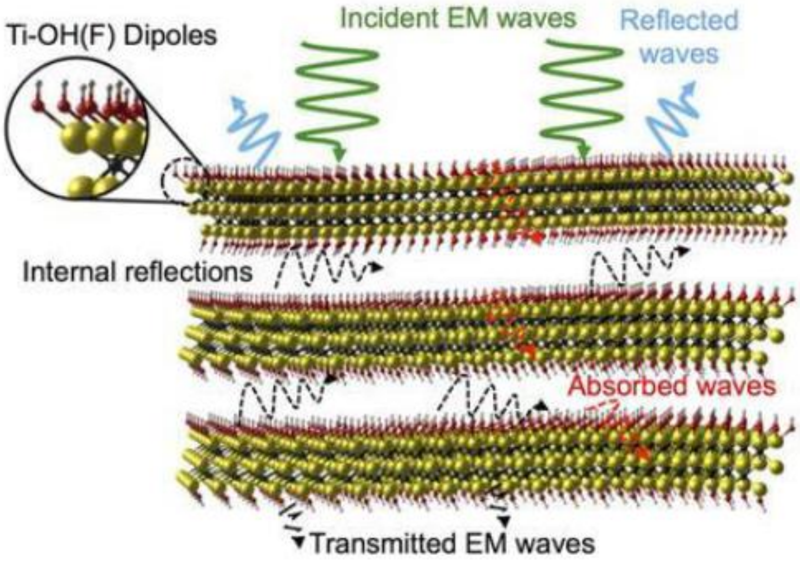
EM radiation from cell phones, tablets, & even TV & internet cables is so prevalent that EM pollution is a growing problem:

- **A nanomaterial coating made of MXene has now been tested in multiple applications.**

Thin coating of MXene (TiC) is shown to be more effective than Cu or Al, metallic ink coatings in EMI shielding - making it an excellent coating for shielding in electronic devices.

EMI and MXene

- Current EM shielding materials add lots of weight & volume to mobile devices, which could be eliminated by using a thin coating of MXene to protect individual components.
- To rival the performance of the 45-micron MXene coating, carbon-polymer composites currently used to meet commercial shielding requirements would have to be over 1 mm thick, which would be far too much weight & thickness for a 7mm-thick iPhone.
- The coatings' good flexibility & high conductivity are also desirable, since they can shield surfaces of any shape. Since much EMI is generated by individual components inside small electronics devices, the material can also shield very small parts. The coating can be applied by spraying it onto any surface.



MXene wards off EMI by absorbing & trapping waves between its layers.

MXene works by both reflecting & absorbing e.m. waves. Some are immediately reflected from the coating's surface. Others pass through but lose energy in the material's atomically thin layers. Lower-energy e.m. waves continue to reflect off of the internal layers until becoming completely absorbed in the structure.

Soft Solution to the Hard-problem of Energy Storage

May 18, 2018, Drexel University

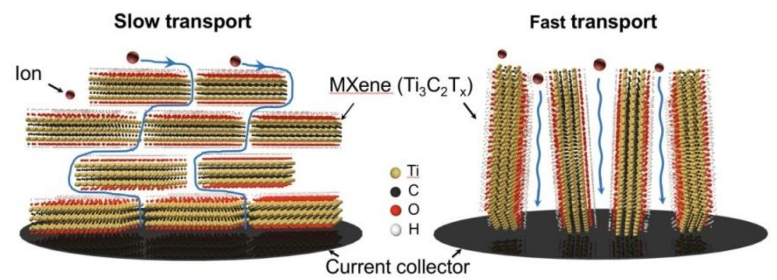
- Atomically thin 2D nanomaterials

➔ Components for faster-charging, longer-lasting batteries & super-capacitors.

Problem with the existing techniques:

- If the thickness of the material layer is increased to ~100 microns (width of a human hair), which is the industry standard for energy storage devices - the materials lose their functionality.

- A study (published in *Nature May 2018)* focuses on using soft materials - similar to those in the liquid crystal displays of phones and televisions - as a guide for self-assembly of MXene sheets.



The resulting electrode films show rapid ion transport, outstanding rate handling, and charge storage equal to or exceeding commercial carbon electrodes.

. . . . . Energy Storage *contd*.

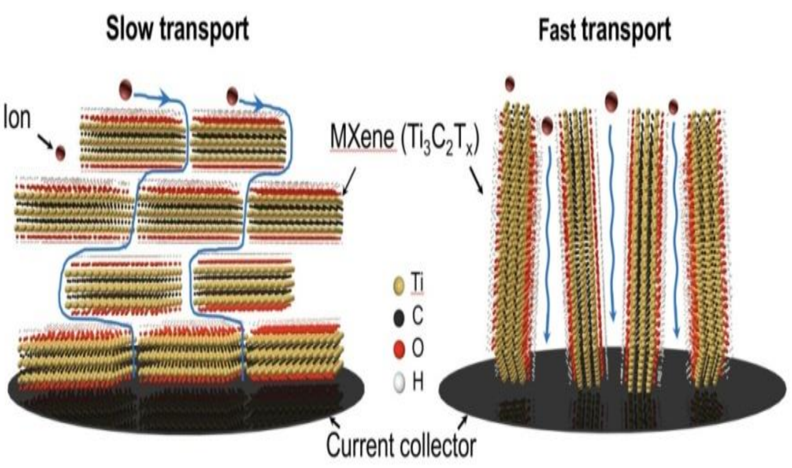
May 18, 2018, Drexel University

The challenge of maintaining the energy density) and power density (how fast the device can charge) of a charge storing material lies in maintaining clear channels for ion movement as the materials are scaled up to larger sizes - of industrial standards.

The Drexel team avoids stacking problem (which inhibits ion diffusion) by propping the MXene flakes in the electrodes vertically.

It might look something like standing up toothpicks in silly putty. In addition to getting them to align vertically, their orientation can also be adjusted by moving the soft material base.

The team's melding of soft matter assembly with hard materials yielded promising results for MXene's future as an energy storage material.



Soft assembly of MXene allows 2-D materials to be stacked vertically, maintaining ion diffusion as thickness of the material is increased.

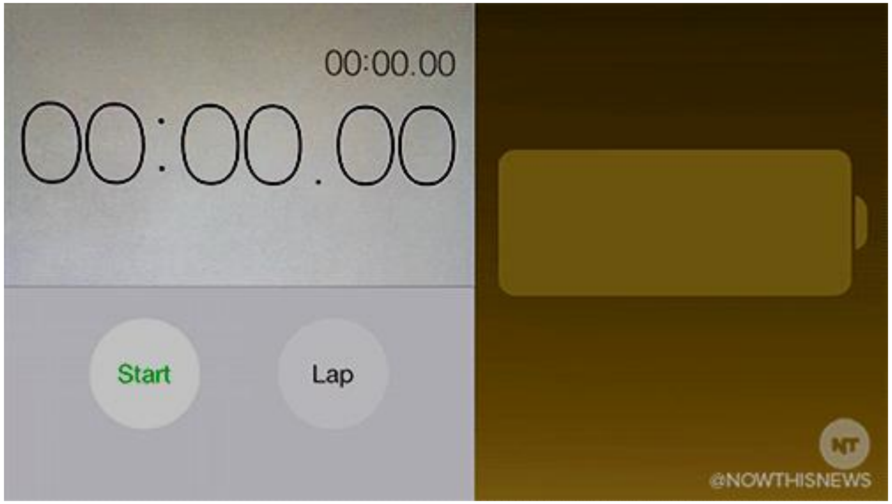
Cdit: Drexel University

MXene: A Breakthrough for Battery Charging

July 30, 2017 by Sarah Chan

No one enjoys waiting for their phone to charge — but using a phone with low battery can be even more stressful.

- **Fortunately, researchers from Drexel Univ. have developed a new battery electrode design that has the potential to eliminate both of those problems. (*Nature Energy*).**
- **The team created the new electrode design from a highly conductive 2-D MXene.**

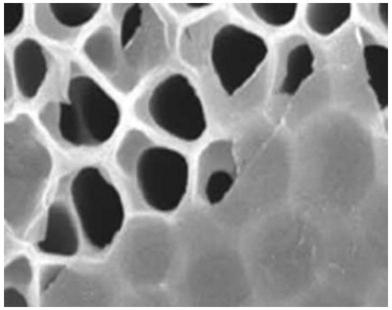


Unlike in Traditional Battery, MXene in this design is able to open up more paths for ions to move quickly throughout the material.

https://i1.wp.com/media.giphy.com/media/xTiTnGs6ugGmS0tKCY/giphy.gif?w=1023&ssl=1

MXene: In Gas Separation

- Hydrogen's (abundant & clean source of fuel) widespread use in the fuel cells of buses, electric cars, & heavy equipment is hindered by the high-cost gas-separation process needed to synthesize pure H_2
- **MXene:** Has extremely effective gas separation characteristics - can be combined with the membranes adopted to purify H_2.
- An electric current to stimulate & disintegrate the atoms in water molecules or filtering a gaseous mixture including H_2, **by using a membrane to isolate H_2 from CO_2.**
- The procedure of gas separation through membrane is the **most efficient & low-cost process.**



studying MXene for use in gas separation

MXene: More Sensitive Gas Sensors for medical diagnostics & more - but dog noses are still superior - I

Published on February 6th, 2018 | By: April Gocha

snout = projecting nose and mouth

- **Dogs have incredible noses - their sniffers are at closer to 100,000 times better than our own.**
- **Dogs have such sensitive snout that they can detect some compounds at a parts per trillion level.**

  That's why dogs are excellent at rescue operations, hunting, detecting drugs, explosives, and even sniffing out human diseases.

  Human bodies are metabolic chemical factories, dogs can sniff out the volatile organic compounds (VOCs) expelled from our bodies - Unique chemical signatures of these VOCs or the presence of particular compounds can provide important clues about the status of our health.

Medical Diagnostics - II

- **Scientists have engineered materials into gas sensors that can sniff out harmful gases, detect toxic fumes, monitor pollution, and even check up on diseases.**
- **Gas sensors to detect and monitor diseases still need a little work - we need better materials that come with not only increased sensitivity, but also reduced noise - to be able to accurately detect, diagnose, and monitor our health.**
- **To detect diabetes, gas sensors must be able to accurately detect acetone compounds on the breath at just 300 - 1,800 parts per billion.**
- **Or to detect peptic ulcers, gas sensors must detect ammonia molecules at 50 -200 parts per billion on the breath.**
- **In the case of gas sensors, the goal is low electrical noise and high sensitivity, which usually come at a trade-off within a. material.**
- **Theoretical work (confirmed by expt) shows that MXenes could offer high sensitivity (with low noise), which would make them excellent gas sensors**

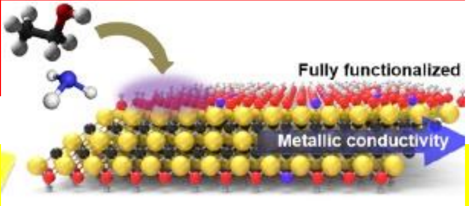
Medical Diagnostics - III

- A group of researchers from Drexel University and KAIST in South Korea has shown that
- Titanium carbide MXene thin films have superior gas sensing ability over existing gas sensor materials, making them particularly suitable for enabling the next generation of medical diagnostic sensor technologies.
- The researchers fabricated $Ti_3C_2T_x$ MXene thin films and tested their ability to sense various gases, including acetone, ethanol, ammonia, propanol, nitrogen dioxide, sulfur dioxide, and carbon dioxide.
- Their results, reported in *ACS Nano*, show that MXene films can accurately and acutely detect the presence of each gas.
- Gas sensors detect presence of a gas by measuring a change in electrical conductivity in the material when the gas is present.
- The MXene sensors had the best response for ethanol, and higher selectivity for gases that hydrogen bond over acidic gases.
- "The high sensitivity of the device may be used for detecting toxic gases or pollutants found in our environment."
- But not only can the materials sense a range of different gases, but they can do so very sensitively, indicating superior potential for medical gas sensors.

Medical Diagnostics - IV

- **MXene can detect gases in the 50–100 ppb ranges, which is below the conc. necessary for current sensors to detect diabetes & a number of other health conditions. (Gogotsi in a release)**
- **Theoretical DFT calculations: scientists found that MXene sensors are so efficient because of excellent conductivity of the metal core channels in the thin films & strong surface adsorption energy, likely due to the presence of hydroxyl groups.**
- **Gagotsi says in the release. "We can also imagine personal sensors that will be in our smart phones or fitness trackers, monitoring body functions and the environment while we work, sleep or exercise, accessible with a tap of a finger. Improving the detection sensitivity with new materials is the first step toward making these devices a reality."**
- **The paper, published in *ACS Nano*, is "Metallic $Ti_3C_2T_x$ MXene gas sensors with ultrahigh signal-to-noise ratio" (DOI: 10.1021/acsnano.7b07460).**

Metallic $Ti_3C_2T_x$ MXene Gas Sensors with Ultrahigh Signal-to-Noise Ratio



$Ti_3C_2T_x$ MXene gas sensor

- **Achieving high sensitivity in solid-state gas sensors can allow the precise detection of chemical agents.**
- **In particular, detection of volatile organic compounds (VOCs) at the parts per billion (ppb) level is critical for the early diagnosis of diseases.**
- **To obtain high sensitivity, two requirements need to be simultaneously satisfied: (i) low electrical noise and (ii) strong signal, which existing sensor materials cannot meet.**
- **2D metal carbide Mxenes (with high metallic conductivity for low noise & a fully functionalized surface for a strong signal) greatly outperform the sensitivity of conventional semiconductor channel materials.**
- **$Ti_3C_2T_x$ MXene gas sensors exhibited a very low limit of detection of 50–100 ppb for VOC gases at room T -- Also, the extremely low noise led to a signal-to-noise ratio 2 orders of magnitude higher than that of other 2D materials, surpassing the best sensors known.**

In summary, Researchers have synthesized $Ti_3C_2T_x$ chemical sensors with superior gas-sensing properties over previously studied materials. $Ti_3C_2T_x$ sensors exhibited high selectivity toward hydrogen-bonding gases over acidic gases

DOI: 10.1021/acsnano.7b07460
ACS Nano 2018, 12, 986−993

MXene Materials could capture Wasted Frictional Energy from Smartphones

- **Imagine when you tap out a message on your smartphone, it would create electric power instead of draining your phone's battery.**
  That scenario could one day be a reality
  (Feb 2018 issue – J. *Nano Energy* ("Metallic MXenes: A New Family of Materials for Flexible Triboelectric Nanogenerators"))

- **Possible to harvest wasted frictional energy, e.g, from muscle contractions during typing or walking.**

- **MXenes, possess high electrical conductivity & the ability to uptake electrons when in contact with polymers & other materials.**

- **This unusual combination of properties makes MXenes useful as components for Triboelectric Nanogenerators (TENG), which turn muscle movements into electric power.**

- **Research suggests the advanced materials could be incorporated into mobile phones, handheld electronics, wearable devices & laptops, ultimately making them self-powering.**

Triboelectric Nanogenerators (TENG)

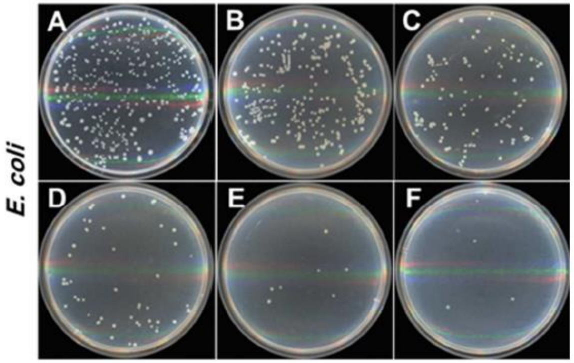
- **MXenes aren't only getting attention recently as gas sensors –**
- **Gogotsi also partnered with researchers from Missouri S&T to publish another paper recently about the potential of MXene materials as triboelectric nanogenerators (TENG) that can harvest wasted mechanical energy. Such MXene TENGs could enable self-powering devices that have the ability to harvest energy from muscle contractions, such as walking or chewing.**

Ref: "Metallic MXenes: A new family of materials for flexible triboelectric nanogenerators" (DOI: 10.1016/j.nanoen.2017.11.044).

Antibacterial Activity of Ti3C2Tx MXene

Health and environmental impacts of the new 2D carbides:

- **Antibacterial properties of single- and few-layer $Ti_3C_2T_x$ MXene flakes in colloidal solution have been investigated.**
- **-- Tested against *Escherichia coli* (*E. coli) and Bacillus subtilis (B. subtilis) by using bacterial growth curves based on optical* densities & colonies growth on agar nutritive plates.**
- **$Ti_3C_2T_x$ shows a higher antibacterial efficiency toward both Gram-negative *E. coli and Gram-positive B. subtilis compared with* graphene oxide (GO), which has been widely reported as an antibacterial agent.**
- **Conc.-dependent antibacterial activity was observed.**



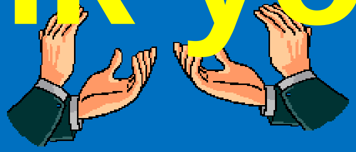
Ti3C2Tx (T is standing for the surface termination, such as -O, -OH or -F)
(ACS Nano 2017 ?

➔ It's hard to guess what the next couple of years will bring to this new area of Nanomaterials Science.

But it's clear that this is **only the beginning**

AND a bright tomorrow awaits us.

Thank you



- 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 if 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.

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.

2D Material based Spintronics

- **Spintronics holds the promise for future information technologies. Devices based on manipulation of spin are most likely to replace the current silicon complementary metal-oxide semiconductor devices that are based on manipulation of charge. The challenge is to identify or design materials that can be used to generate, detect, and manipulate spin. Since the successful isolation of graphene and other two-dimensional (2D) materials, there has been a strong focus on spintronics based on 2D materials due to their attractive properties, and much progress has been made, both theoretically and experimentally. Here, we summarize recent developments in spintronics based on 2D materials. We focus mainly on materials of truly 2D nature, that is, atomic crystal layers such as graphene, phosphorene, monolayer transition metal dichalcogenides, and others, but also highlight current research foci in heterostructures or interfaces. In particular, we emphasize roles played by computation based on first-principles methods which has contributed significantly in the designs of spintronic materials and devices. We also highlight challenges and suggest possible directions for further studies.**

WIREs Comput Mol Sci 2017, 7:e1313. doi: 10.1002/wcms.1313

2D MXenes make photonic diodes

- 12 Jan 2018 Belle Dumé
- **The first ever "optical" diodes made from the 2D material Ti_3C_2 and fullerene (or carbon-60) retain their saturable absorption (or increased light transmission at higher laser powers) even after being exposed to air or low-energy plasma irradiation. This means that their optical properties are stable under these conditions, making them useful as optical isolation for high-power lasers and as saturable absorbers for Q-switching laser components that allow short pulses to be generated.**
- **"In electronic circuits, devices such as electronic diodes allow the flow of electrons in just one direction (forward bias) but not in the other (reverse bias)," explains team leader Ramakrishna Podila of Clemson University in the US. "To achieve a similar diode action for photons is very challenging, however, because we know that light travels in both directions (if I see you then you see me). In our work, we have combined two materials (2D Ti_3C_2 MXene and fullerene, or C60) that have contrasting nonlinear optical properties to make a device that does allow for one-way transmission of light. In other words, we have made an optical diode."**
- **MXenes are a new class of 2D transition-metal carbides, nitrides and carbonitrides that interact with light in a unique way. Researchers recently found that 2D $Ti_3C_2T_x$ (where T_x can be functional groups such as –OH and –F) has nonlinear saturable absorption that could be useful for mode locking in femtosecond lasers.**