A novel universal light-based technique to control valley polarization in bulk materials

An ICFO team, together with international collaborators, report in Nature a new method that achieves for the first time valley polarization in centrosymmetric bulk materials in a non-material-specific way.
This i¿½universal techniquei¿½ may have major applications li ked to the control and analysis of different properties for 2D an 3D materials, which can in turn enable the advancemen of cutting-edge fields such as information processing and qua tum computing.

April 24, 2024

Electrons inside solid materials can only take certain values of energy. The allowed energy ranges are called i¿½bandsi¿½ and the space between them, the forbidden energies, are known as i¿½band-gapsi¿½. Both of them together constitute the i¿½band structure

¿½ of the material, which is a unique characteristic of each specif
c material. When physicists plot the band structure, they usually see that the resulting cur
es resemble mountains and valleys. In fact, the technical term for a local energy maximum o
 minimum in the bands is called a i¿½valleyi¿½, and the field which studies and exploits
ow electrons in the material switch from one valley to the other is called i¿½valleytronicsi¿½
. In standard semiconductor electronics, the electric charge of the electrons is the most us
d property exploited to encode and manipulate information. But these particles have oth
r properties that could also be used for the same purpose, such as the valley they are in. In t
e past decade, the main aim of valleytronics has been to reach the control of valley populati
n (also known as valley polarization) in materials. Such an achievement could be used to crea
e classical and quantum gates and bits, something that could really drive the development
f computing and quantum information processin
. Previous attempts presented several drawbacks. For example, the light used to manipula
e and change valley polarization had to be resonant, that is, the energy of its photons (t
e particles that constitute light) had to correspond exactly to the energy of the band-gap
f that particular material. Any small deviation reduced the efficiency of the method s
, provided that each material has their own band-gaps, generalizing the proposed mechani
m seemed something out of reach. Moreover, this process had only been achieved f
r monolayer structures (2D materials, just one-atom-thick). This requirement hindered i
s practical implementation, as monolayers are usually limited in size, quality and difficult
o enginee
. Now, ICFO researchers **Igor Tyulnev**, **Julita Poborska**, **Dr. Lenard Vamos,** led by **Prof. ICREA Jens Biegert**, in collaboration with researchers from the Max-Born-Institute, the Max-Planck Institute for the Science of Light, and Instituto de Ciencia de Materiales de Madrid have found a new **universal method to induce valley polarization in centrosymmetric bulk materials.** The discovery, published in Nature, unlocks the possibility to control and manipulate valley population without being restricted by the specific chosen material. At the same time, the method can be used to obtain a more detailed characterization of crystals and 2D materials.

Valley polarization in bulk materials is possible

The adventure began with the experimental group led by ICREA Prof. at ICFO Jens Biegert who initially wanted to experimentally produce valley polarization using their particular method in 2D materials, following the lines of what had been theoretically proved in a previous theoretical paper by Alvaro Jimenez, Rui Silva and Misha Ivanov. To set up the experiment, the initial measurement was tried on bulk MoS2 (a bulk material is made of many monolayers stacked together) with the surprising result that they saw the signature of valley polarization. i¿½When we started working on this project, we were told by our theo
y collaborators that showing valley polarization in bulk materials was rather impossiblei?

½, explains Julita Pobor
ka. The theoretical team remarks as well how, at the very beginning, their model was
nly suitable for single 2D layers. i¿½At a first glance, it seemed that adding more layers
would hinder the selection of specific valleys in the sample. But after the first experimental re
ults, we adjusted the simulation to bulk materials and it validated the observations surpri
ingly well. We did not even try to fit anything. It is just the way it came outi¿½, adds Pro
. Misha Ivanov, the theorist leader. In the end, i¿½it turned out that yes, you can actua
ly valley polarize bulk materials that are central symmetric, because of the symmetry cond
tionsi¿½, conclud
s Poborska. As Igor Tyulnev, first author of the article, explains, i¿½our experiment consist
d in creating an intense light pulse with a polarization that fitted this internal structure. The
esult was the trefoil fieldi¿½, whose symmetry matched the triangular sub-lattices th
t constitute hetero-atomic hexagonal materialsi?
½. This symmetry-matched strong field breaks the space and time symmetry within the mater
al, and, more importantly, the resulting configuration depends on the orientation of the tre
oil field with respect to the material. Therefore, i¿½by simply rotating the incident light fie
d, we were able to modulate the valley polarizationi¿½, concludes Tyulnev, a major achiev
ment in the field and a confirmation of a novel universal technique that can control and ma
ipulate the electron valleys in bulk ma

The experimental process

The experiment can be explained in three main steps: First, the synthesis of the **trefoil field**; then its **characterization**; and finally, the actual production of **valley polarization**.

The researchers emphasize the incredibly high precision that the characterization process required, as **the trefoil field is made of not just one, but two coherently combined optical fields**. One of them had to be circularly polarized in one direction, and the other needed to be the second harmonic of the first beam, polarized with the opposite handedness. They superimposed these fields onto each other, so that the total polarization in time traced the desired trefoil shape.

Three years after the initial experimental attempts, Igor Tyulnev is thrilled by the recent Nature publication. The appearance in such a prestigious journal recognizes the new universal method which, as he states, i¿½can be used not only to control the properties of a wide variety of chemical species, but also to characterize crystals and 2D materialsi¿
?. As Prof. ICREA at ICFO Jens Biegert remarks: i¿½Our method may provide an im
ortant ingredient to engineer energy efficient materials for efficient information storage a
d fast switching. This addresses the pressing need for low-energy consumption devi
es and increased computational speed. I cannot promise that what we have provided
is THE solution, but it is probably one solution on this big challe

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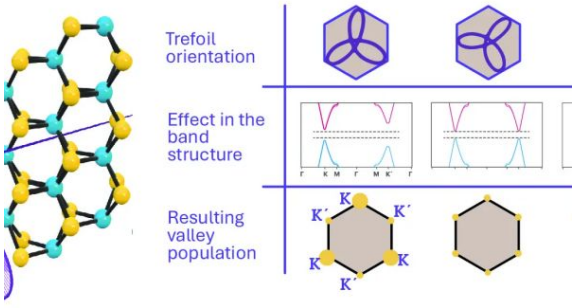
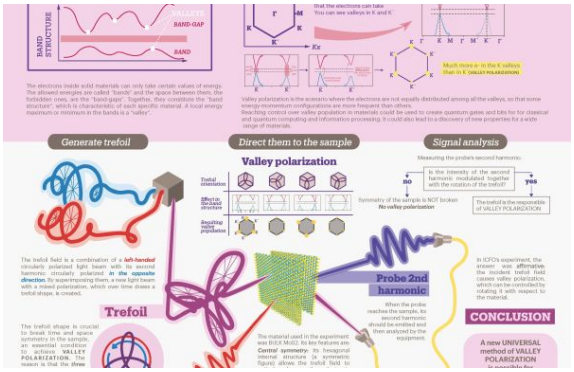
Bibliographic reference

Valleytronics in bulk MoS2 with a topologic optical field, Igor Tyulnev, Alvaro Jimenez-Galan, Julita Poborska, Lenard Vamos, Rui F. Silva, Philip St. J. Russell, Francesco Tani, Olga Smirnova, Misha Ivanov, Jens Biegert, 2024, NATURE, https://www.nature.com/articles/s41586-024-07156-y



Schematic of the valley polarization effect, where the incident trefoil field (in purple) causes valley



Infographic of Valley Polarization

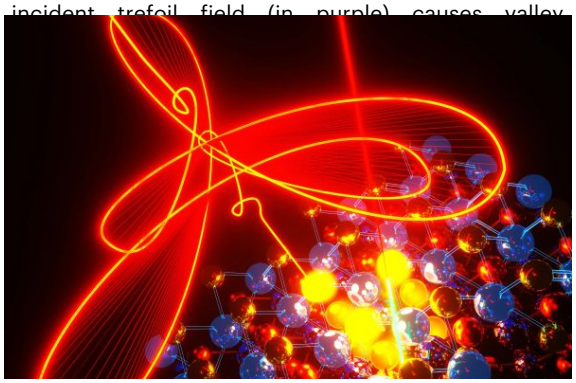


Illustration showing the valleytronics effect. Image credit: ICFO / Ella Maru Studio

Video Abstract