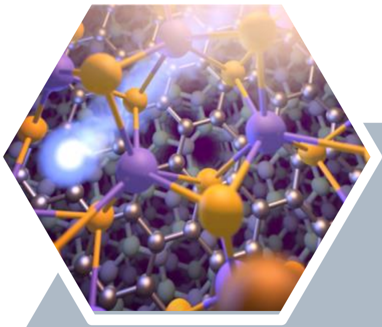
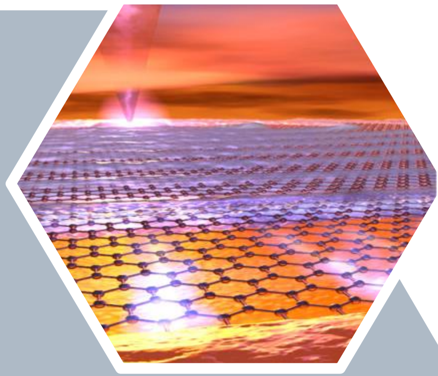
Dr. Frank Koppens

Born 27 June 1976

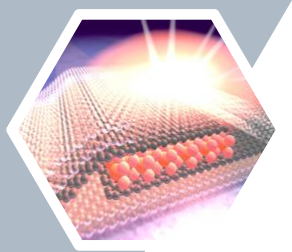
Group Leader: Quantum Nano-optoelectronics

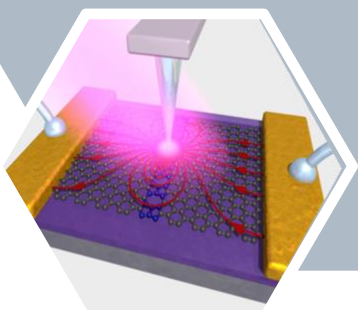




Scientific fields:

- Graphene and 2D materials
- Nano-photonics
- Opto-electronics
- Quantum photonics and technologies
- Solid-state physics





Institution:
ICFO- Institute of Photonic Sciences
ICREA Professor

Nominated by: Prof. Dr. Lluis Torner
Barcelona, April 2019

Summary of Research Achievements

Highly-Cited Researcher:

Included in Clarivate's selection (formerly WoS). In 2018, this list contained:

- Only five scientists in Spain (for any age), in the physics category.
- Only **one** scientist in Spain of age ≦42, in the physics category.

Publications

- **> 18.000 citations, h-index 47 (google scholar).**
    - Highest cited scientist in Spain in physics and engineering for age ≦42
- **38 publications in Science, Nature and Nature family. Total number of publications: 87.**
- 23 publications are ranked by WoS as Highly Cited papers (i.e., they belong to the top 1% of the academic field)
- 6 publications have been cited more than 1000 times (google scholar)
- 29 publications have been cited >100 times (google scholar)
- Most-cited Nano Letters paper of 2011 (>1770 citations)

Ramon-y-Cajal Fellowship: ranked 1st nationwide in 2013 in the Physics area (score : 100/100)

Principal Investigator in Projects

- **ERC Consolidator grant: Toponanop**
  Topological Nanophotonics
- **ERC Starting grant: Granop**
  Graphene Nanophotonics
- **ERC Proof-of-concept grant: GraQuaDot**
  Novel ultrasensitive imaging sensors based on graphene-quantum dot hybrid technology
- **ERC Proof-of-concept grant: Graphealth**
  Hybrid quantum dot and graphene wearable sensor for systemic hemodynamics and hydration monitoring
- **ERC Proof-of-concept grant: GTRACK**
  Hybrid quantum dot and graphene wearable sensor for eye tracking
- **WP Opto-electronics Graphene flagship**
- **Graphene flagship Core3 spearhead project: Autovision**
  Autonomous Vehicle Imaging System in the Infrared that Operates at Night and under adverse weather conditions
- **SGR 2014-2016, 2017-2020**
- **Marie Curie Career Integration grant: Graphene Nanophotonics (Granop)**
- **Explora-Ingenio (FECYT): Luzca**
  Absorción total de la luz en una capa atomica de carbón
- **Explora-Ingenio (FECYT): 2D**
  Diodo emisor de luz infrarroja
- **Plan Nacional (Mineco): 2DPower**
  Photoresponse and conversion in 2D materials: ultra-fast and ultra-small
- **Plan Nacional (Mineco): 2D-NanoTop**
  2D material nano-topological-photonics
- **Retos-Coloboracion (Mineco): Graqdoblea**
  Detectores infrarrojos híbridos basados en grafeno y puntos cuánticos para seguridad alimentaria fabricados a escala de oblea

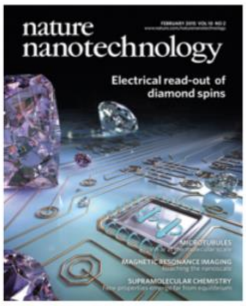
Leaderhip in the European Graphene Flagship

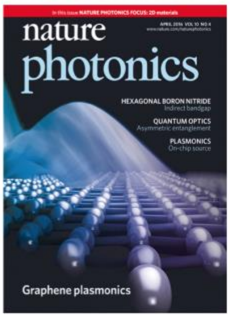
- Co-Chair of the Executive Board of the whole Flagship
- Leader work-package Optoelectronics of the whole Flagship

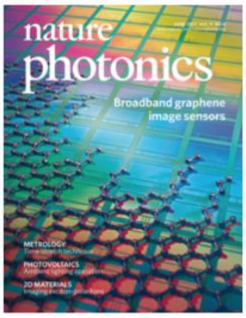
Main Awards:

- **"Christiaan Huygensprijs" in 2011. Highest award for PhD thesis in the Netherlands**
  PhD thesis on quantum information processing with single electron spins. This prestigious is awarded to the young scientist who made the most important contribution to physical sciences during the last 4 years.
- **"IUPAP Young Scientists Award" from the International Commision for Optics in 2015**
  The prize is given every year to only one young scientist worldwide. Koppens' citation states "For his remarkable, outstanding, groundbreaking, pioneering and numerous contributions to Nano-Optoelectronics.".
- **"Research Prize of Catalonia for Young Talent" in 2015**
  The Research Award of Catalonia ("Premi Nacional") in the Young Talent category is given each year to recognise a young researcher who stand out for the quality and excellence of his/her scientific work.

Top 35 publications







Graphene and 2D Materials for Silicon Technology
Nature (2019, accepted)
Flexible graphene photodetectors for wearable fitness monitoring
Science Advances (2019, accepted)
Nano-imaging of intersubband transitions in van der Waals quantum wells
Nature Nanotechnology 13, 1035–1041 (2018)
Probing the ultimate plasmon confinement limits with a van der Waals heterostructure
Science 360, 291 (2018)
Tuning quantum nonlocal effects in graphene plasmonics
Science 375, 187-191 (2017)
Dissociation of two-dimensional excitons in monolayer WSe_2
Nature Communications 9, 1633 (2018)
Ultrafast nonlinear optical response of Dirac fermions in graphene
Nature Nanotechnology 13, 41-46 (2018)
Electrical 2π *phase control of infrared light in a 350nm footprint using graphene plasmons*
Nature Communications *9, 1018 (2018)*
Out-of-plane heat transfer in van der Waals stacks through electron-hyperbolic phonon coupling
Nature Photonics 11, 421-424 (2017)
Broadband image sensor array based on graphene-CMOS integration
Nature Photonics 11, 366-371 (2017)
Extraordinary linear dynamic range in laser-defined functionalized graphene photodetectors
Science Advances 3, e1602617 (2017)
Thermoelectric detection and imaging of propagating graphene plasmons
Nature Materials 17, 204-207 (2017)
Polaritons in layered two-dimensional materials
Nature Materials 16, 182-194 (2017)
Graphene-based mid-infrared room-temperature pyroelectric bolometers with ultrahigh temperature coefficient of resistance
Nature Communications 8, 14311 (2017)
Acoustic terahertz graphene plasmons revealed by photocurrent nanoscopy
Nature Nanotechnology 12, 31-35 (2017)
Tuning ultrafast electron thermalization pathways in a van der Waals heterostructure
Nature Physics 12, 455-459 (2016)
Real-space mapping of tailored sheet and edge plasmons in graphene nanoresonators
Nature Photonics 10, 239-243 (2016)
Picosecond photoresponse in van der Waals heterostructures
Nature Nanotechnology 11, 42-46 (2015)
Direct observation of ultraslow hyperbolic polariton propagation with negative phase velocity
Nature Photonics 9, 674-678 (2015)
Generation of photovoltage in graphene on a femtosecond timescale through efficient carrier heating
Nature Nanotechnology 10, 437-443 (2015)
Electrical control of optical emitter relaxation pathways enabled by graphene
Nature Physics 11, 281-287 (2015)
Highly confined low-loss plasmons in graphene–boron nitride heterostructures
Nature Materials 14, 421-425 (2015)
Ultrafast electronic read-out of diamond NV centers coupled to graphene
Nature Nanotechnology 10, 135-139 (2015)
Photodetectors based on graphene, other two-dimensional materials and hybrid systems
Nature Nanotechnology 9, 780-793 (2014)
Controlling graphene plasmons with resonant metal antennas and spatial conductivity patterns
Science 344, 1369-1373 (2014)
Three-dimensional optical manipulation of a single electron spin
Nature Nanotechnology 8, 175-179 (2013)
Photoexcitation cascade and multiple hot-carrier generation in graphene
Nature Physics 9, 248-252 (2013)
Optical nano-imaging of gate-tunable graphene plasmons
Nature 487, 77-81 (2012)
Hybrid graphene-quantum dot phototransistors with ultrahigh gain
Nature Nanotechnology 7, 363-368 (2012)
A quantum spin transducer based on nanoelectromechanical resonator arrays
Nature Physics 6, 602-608 (2010)
Near-field electrical detection of optical plasmons and single plasmon sources
Nature Physics 5, 475-479 (2009)
Locking electron spins into magnetic resonance by electron-nuclear feedback.
Nature Physics 5, 764 (2009)
Coherent control of a single spin with electric fields
Science 318, 1430-1433 (2007)
Driven coherent oscillations of a single electron spin in a quantum dot
Nature 442, 766-771 (2006)
Control and detection of singlet-triplet mixing in a random nuclear field
Science 309, 1346-1350 (2005)

Research results

Quantum information processing with single electron spins

The PhD work of Koppens involved the first realization of a **quantum bit**, based on the spin of a **single** electron. He demonstrated the fully quantum coherent manipulation of a single electron spin, confined in a quantum dot, and published several works on in-depth studies on decoherence phenomena. These achievements were a milestone for spin-based quantum information processing as they showed for the first time that an electron spin could be used as a quantum bit **[Science 2005; Nature 2006; Science 2007; Nature Physics 2007, PRL 2008]**. The work was the starting point of the very active field on spin-based quantum information processing, and was an important motivation for the launch of QTech in Delft (funded by Microsoft, Intel, Dutch government, etc), aiming at the development of a scalable quantum computer. Scalable quantum computers have the potential to enable certain calculations – e.g. for security or complex simulations of materials and medicine – that would take too long for a regular computer.

Media coverage:

- Covered by 4 radio channels, including the national news.
- Highlighted in >10 dutch newspapers and several international newspapers.

Award: Christiaan Huygens award for best national PhD thesis in two years (in the entire field of sciences)

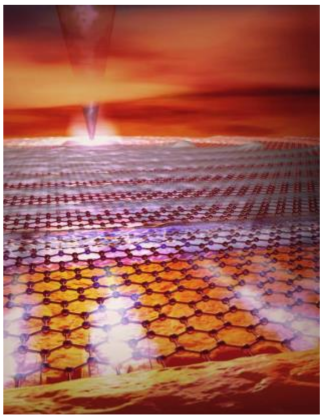
Controlling light at the nanoscale with the thinnest materials in the world

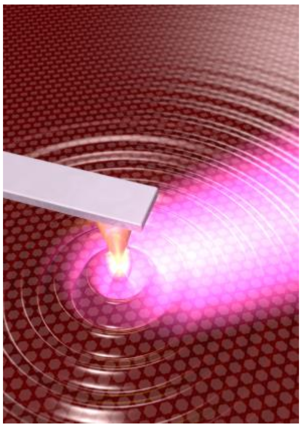
Initiation of the new field of graphene nanophotonics

The discovery of graphene – a one-atom thick carbon-based material – in 2004 sparked tremendous interest due to its electronic, mechanical and optical properties. In 2011, Koppens discovered that graphene is also an excellent material for the manipulation of light at the scale of a few nanometers and even down to the scale of a single atom. This was possible by exploiting so-called plasmons: oscillating electrons coupled to light. Koppens was leading the first theoretical framework of this new field with a highly cited forward-looking publication **[Nano Letters 2011, cited>1700 times].** Koppens was also in charge of the first experimental observation of propagating graphene plasmons **[Nature 2012, cited>1300 times, Science 2014, Nature Materials 2015].** The experiments revealed for the first time that graphene is an excellent host for guiding, confining and electrical manipulation of light at nanoscale dimensions. It was demonstrated that strongly confined light could even be controlled with small electrical voltages, a capability that was never possible before. The achievements have opened the new field of graphene nano-photonics and nano-optoelectronics, bridging the boundaries of solid-state physics, opto-electronics, quantum optics, and plasmonics. The large number of citations of the publications of Koppens in this field show that a strong research community emerged as a result of these achievements.

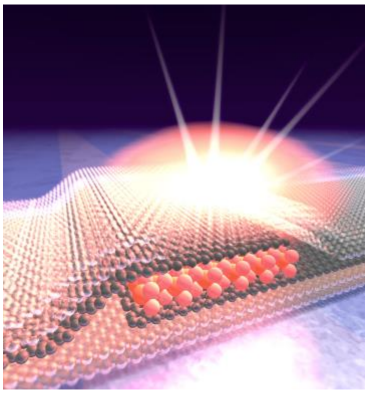
Electrical detection of graphene plasmons

Koppens realized that graphene is at the same time an excellent nano-photonic and electronic material, and found several novel schemes for the electrical conversion of plasmons **[Nature Materials 2017].** The techniques were used to show the first plasmons in graphene for Terahertz frequencies, which exhibit unique physical properties (acoustic plasmons) [**Nature Nanotechnology 2017, Science 2017].**



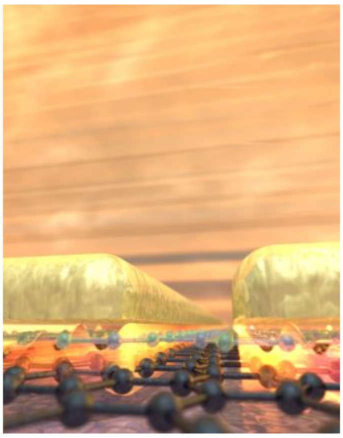


Nano-lego for light



Graphene is only one of the hundreds of atomically-thin materials. Interestingly, these 2D materials can be stacked on top of each other, literally atom-by-atom, as if it was atomically thin lego. In this way, these heterostructures can be built from new material combinations, and novel properties and capabilities can be tailored inside the laboratory. Koppens applied this concept to control light at the atomic scale. We reviewed these concepts of controlling light in fundamentally different ways [**Nature Materials 2017, cited >295 times**].

Confinement of light to one atom: a world record



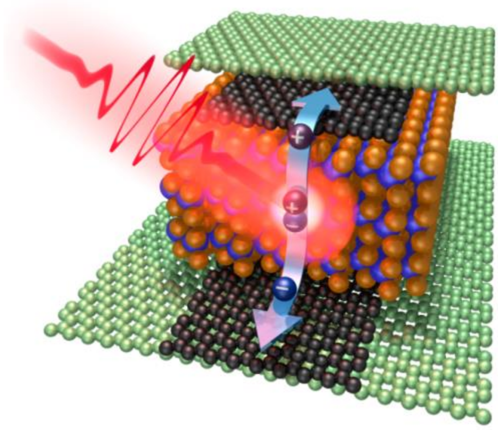
The scientific community has for a long time been searching for ways to confine light into extremely tiny spaces. The reason is that confined light can function as an ultra-fast communication channel, for example between different sections of a computer chip, and it can also be used for ultra-sensitive sensors or novel on-chip nanoscale lasers. So far, the perception was always that stronger confinement of light would lead to more losses. However, Koppens found that this is not the case, as with 2D material heterostructures this paradigm could be shifted.

By building a heterostructure of graphene, metal and a one-atom thick insulator, it was possible to reach the ultimate limit of the confinement of light **[Science 2018]**. The results of this discovery enable a completely new set of opto-electronic devices that are less than one nanometer thick: e.g. ultra-small optical switches, detectors and sensors. Due to the paradigm shift in optical field confinement, extreme light-matter interactions can now be explored that were not accessible before.

The quantum microscope

By exploiting this extreme confinement of light, Koppens demonstrated that light can be used to "see" the quantum nature of an electronic material **[Science 2017]**. This was achieved by capturing light in graphene and slowing it down so much that it moves almost as slow as the electrons in the graphene. Then something special happens: electrons and light start to move in concert, unveiling their quantum nature at such large scale that it can be observed with a microscope. With a near-field nanoscope, it was possible to "see" the light ripples moving on the graphene, about 300 times slower than light, and dramatically different from what is expected from classical physics laws.

Ultra-fast conversion of light into electricity and graphene-based integrated photonics

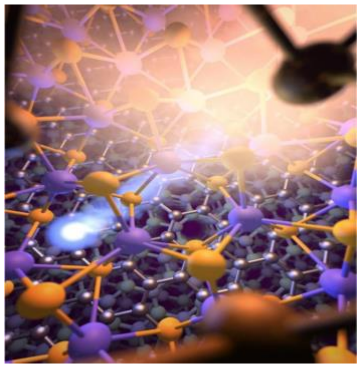


Understanding how light is converted into electricity in materials – a process known as photodetection – is one of the central goals in the field of optoelectronics. This knowledge provides the basis for designing faster optical communications systems and more efficient solar energy conversion modules, two major technological challenges of our time. Unraveling these electronic processes is paramount for identifying the physical limits of these new materials and improving their photodetection performance. We reviewed these dynamics and detection processes in a highly cited publication **[Nature Nanotechnology 2014, cited>1390 times].**

We fabricated and investigated various types of photodetectors based on novel heterostructures of 2D materials:

- We demonstrated record-fast (>100 GHz bandwidth) and highly efficient (IQE>70%) photodetectors by combining graphene and semi-conducting 2D materials [**Nature Nanotechnology 2016].**

- We showed that the spectral range of 2D materials heterostructures extends to the infrared due to a novel interlayer photodetection mechanism called photo-thermionic emission [**Nature Communications 2016].**

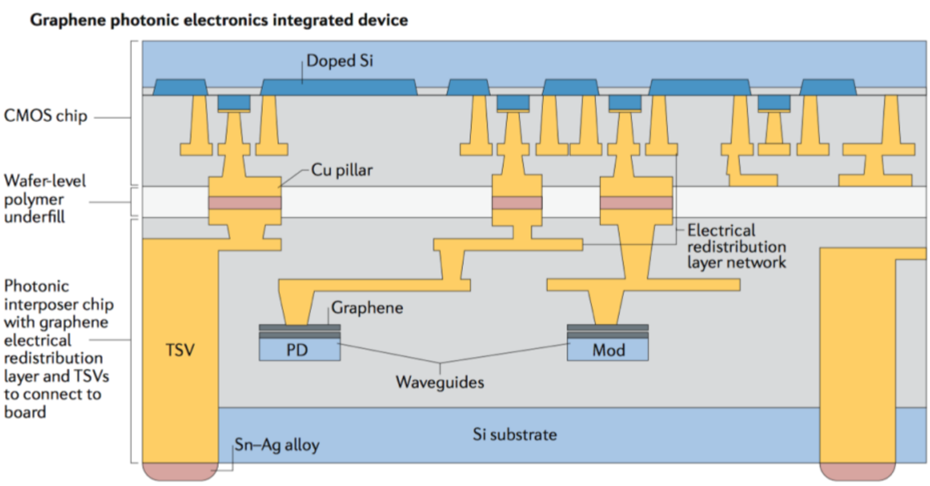


- We investigated the photoresponse mechanism of semiconducting 2D materials and identified, for the first time, exciton tunnel ionization and free carrier drift as the main processes limiting the photocurrent generation [**Nature Communications 2018].**

- We studied lateral and vertical graphene-based photodetectors and showed that they convert light into an electrical signal extremely rapidly, in less than 50 femtoseconds, via the photo-thermoelectric effect [**Nature Nanotechnology 2015].**

- We observed ultra-fast carrier interactions at femtosecond times, including multiple hot-carrier generation and hot-carrier mediated photodetection. The understanding of these fundamentals are essential for ultra-fast photodetection with graphene, and has high impact on the future applications of these detectors for data communications. **[Nature Physics 2013].**

- We presented the vision for graphene-based integrated photonics in a review paper **[Nature Reviews Materials 2018].** It was shown that graphene-based integrated photonics could enable ultrahigh spatial bandwidth density, low power consumption for board connectivity and connectivity between data centres, access networks and metropolitan, core, regional and long-haul optical communications.



Quantum nano-optoelectronic devices

Due to the strong confinement of light enabled by graphene plasmonics, it is an appealing platform for strongly enhanced light-matter interactions, in particular for quantum emitters and for studies on quantum confinement:

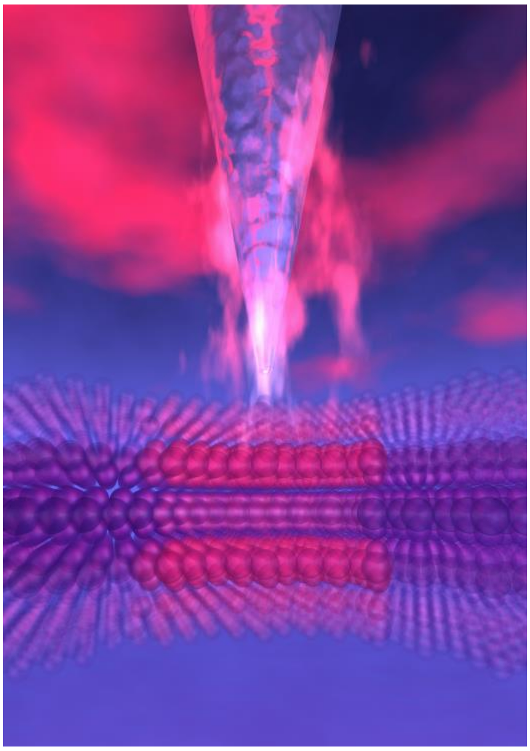
- We demonstrated for the first time the electrical read-out of the spin of a single diamond NV center, trough near-field energy transfer from the quantum emitters to the graphene **[Nature Nanotechnology 2015].** These achievements opened a new direction for sensing, spin read-out, on-chip information processing etc.

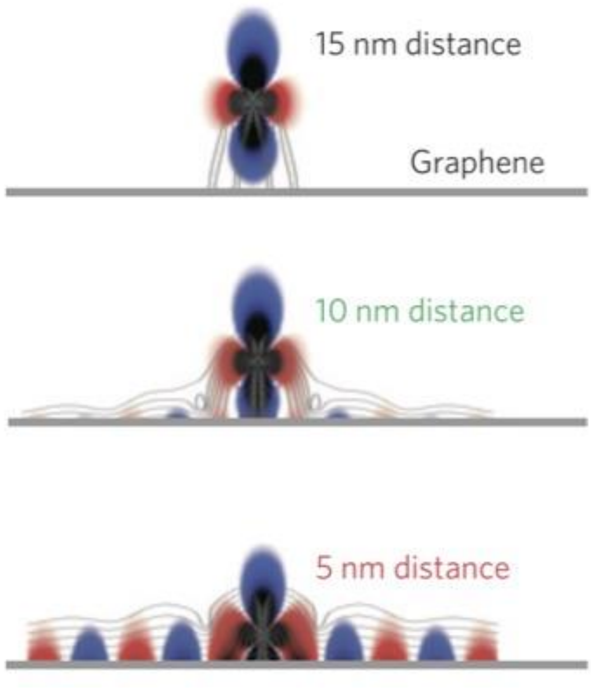
- First demonstration of in-situ tuning of the relaxation pathways of light emitters using graphene **[Nature Physics 2015].** Controlling the energy flow processes and the associated energy relaxation rates of a light emitter is of fundamental interest and has many applications in the fields of quantum optics, photovoltaics, photodetection, biosensing and light emission.

- First observation of quantum confined electrons in few-layer 2D materials and the first application of near-field microscopy to probe optical transitions between these quantum-confined states [**Nature Nanotechnology 2018].** This first experimental identification of intersubband transitions in 2D materials is the first step towards the development of a new class of infrared light emitters and lasers.

- Theoretical work that showed that graphene plasmonics offers a viable route toward achieving nonlinear optical interactions at the single-photon level **[PRL 2013].** This embodies a paradigm shift in terms of controlling and manipulating single photons, and the realization would be an unprecedented scientific breakthrough.

- The first implementation of a graphene mechanical resonator coupled to single photon emitters, and demonstration of emission control trough the mechanical motion of the resonator. **[Nature Communications 2016].**

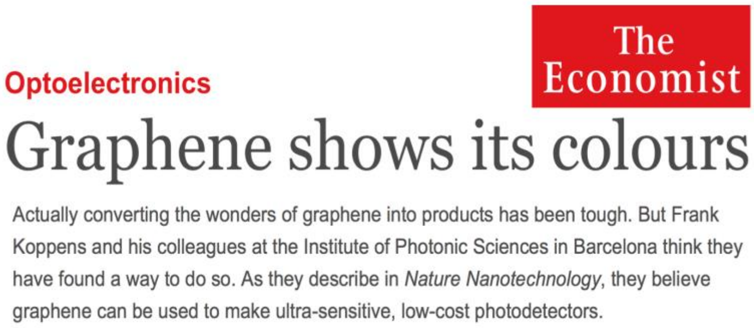




Applications and impact on society

Graphene-based photodetectors: from scientific discovery to mobile world congress

The research group of Koppens discovered a novel type of photodetector based on graphene and quantum nano-particles, with ultra-high sensitivity **[Nature Nanotechnology 2012, Advanced Materials 2015, Nature Communications 2016].** Because the detectors operate for an unprecendent wavelength range, they enable many applications such as medical imaging, night vision, food inspection etc. These detectors were based on a a mechanism that was discovered in the laboratory, but have made it all the way into demonstrations at the Mobile World Congress in Barcelona.


Optoelectronics

The Economist

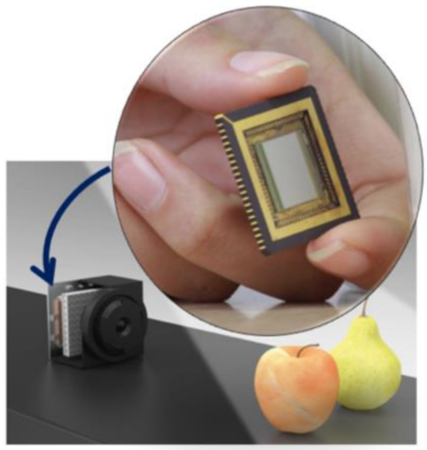
Graphene shows its colours

Actually converting the wonders of graphene into products has been tough. But Frank Koppens and his colleagues at the Institute of Photonic Sciences in Barcelona think they have found a way to do so. As they describe in *Nature Nanotechnology*, they believe graphene can be used to make ultra-sensitive, low-cost photodetectors.

Several exciting prototypes have been developed (and highlighted in "The Economist") to show the direct relevance for applications with high societal impact:

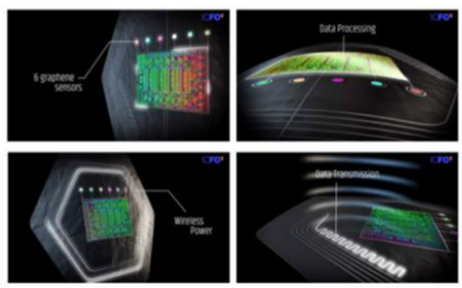
The first graphene camera

Koppens led the project that realized **the first "graphene digital camera"**, for imaging with broadband light and therefore capable of combining day and night vision, imaging objects through fog, and measuring the chemical composition (e.g. of food) **[Nature Photonics 2017].** The prototype was presented at the Mobile World Congress in Barcelona, and several companies expressed strong interest to use the technology in smartphones (e.g. Samsung, Huawei, etc.) and machine vision and food inspection systems. A patent portfolio of more than ten patents has already been built and private investment has been secured, as well >5M€ public funds for the development of more advanced prototopes.



Graphene-based flexible photodetectors for wearable health monitoring

A futuristic wearable "health patch" has been developed, capable of monitoring health and fitness parameters, while maintaining an ultra-compact form-factor and low power consumption [to appear in **Science Advances 2019].** This work was highlighted by EU commissioner Andrus Ansip as "the future of wearables", and selected by the CEO of the GSMA for presentation to high-level visitors and politicians.



Graphene and 2D materials for silicon technology

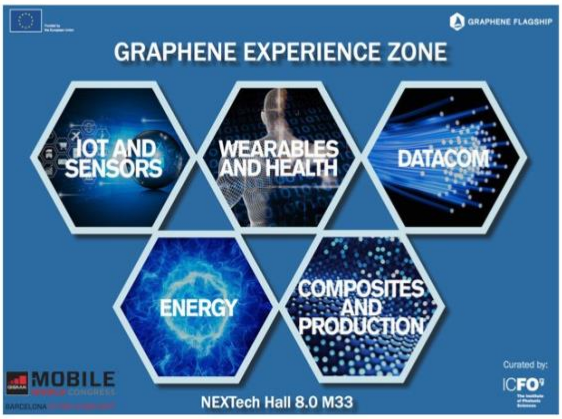
We reviewed the opportunities, progress, and challenges of integrating atomically-thin materials on Si-based nano-systems and the prospects/roadmap for computational and non-computational applications [to appear in **Nature 2019]**.

Leadership

GSMA Chair and Mobile World Congress

Prof. Frank Koppens holds a Chair Program on Graphene sponsored by the GSMA, the world leading association of mobile operators and related companies. This collaboration aims at encouraging and supporting research into the science and technology of graphene and graphene-like materials, as well as promoting their commercial applications.

Koppens initiated the Graphene Experience Zone within the Mobile World Congress. The Mobile World Congress is the world's largest gathering for the mobile industry, organised by the GSMA and held in Barcelona, Spain, in late February every year. The 2017 edition of MWC attracted over 108 000 attendees, 2000 exhibitors and was covered by more than 3 600 members of international press and media. The Graphene Experience Zone - featured at the MWC in 2016, 2017, 2018 and 2019 - is a 135m^2 exhibition showing the latest graphene-based prototypes and products.



Conferences

- Prof. Koppens was **chair of the graphene2017** conference with ~1000 attendees, so far the largest conference on 2D materials in the world.

- He has given **more than 100 invited talks** and colloquia, including keynote and plenary talks at the most prominent international conferences such as CLEO, MRS, SPIE

Graphene flagship

Prof. Koppens has been a **leader within the graphene flagship program** (largest EU program ever, with 1000 Million Euro funding for 10 years) in several aspects:

- Rampup phase (2014-2016):
  - deputy workpackage leader opto-electronics (~20 academic and industrial partners)
  - member of the executive board

- Core1 and Core2 phases (2016-2020):
  - Co-chair of the executive board (and chair-elect)
  - Workpackage leader opto-electronics (largest WP with ~25 academic and industrial partners)

Selected media highlights

The economist: Graphene sees its colors

TV3 - “Quèquicom”, Premi Nacional de Comunicació Científica

TV3 - Valor Afegit **-** La revolució del grafè

Al Jazeera - How one atom thick Graphene will re-engineer our physical world

BBC: graphene; bend and flex for mobile phones

RTVE: La vida despues el móvil **-** El Cazador de Cerebros **-** Pere Estupinyà

Televisio 3 – A la carte: LA REVOLUCIÓ DEL GRAFÈ

Generació Digital – Canal 33 – TV 3: Reportaje sobre el MWC. El grafeno tiene por primera vez un pabellón en el MWC

La Vanguardia: opinion article authored by Koppens

El Pais: Grafeno que absorbe toda la luz

La Vanguardia: (printed/digital) Algunos de los premiados nos cambiarán la vida

El Periódico de Catalunya - Grafè: el material que revolucionarà el món

EFE Futuro - El grafeno, protagonista en el MWC

El Mundo - Grafeno y otros supermateriales para fabricar el futuro

El Mundo - Una trayectoria dedicada a explorar la luz y el grafeno

El Periodico de Catalunya - Europa premia a ocho investigadores que trabajan en Cataluña

NTN24 - El grafeno demuestra su potencial en el Mobile World Congress

TV3 - Arriba el grafè al MWC: pròtesis per al cos i càmeres que ens diuen si la fruita és madura

Android Pit - Grafene: il super materiale per indossabili e internet delle cose

BTV Noticíes – Grafè, monitoratge de constants i abrics que salven vides, avenços en salut al MWC