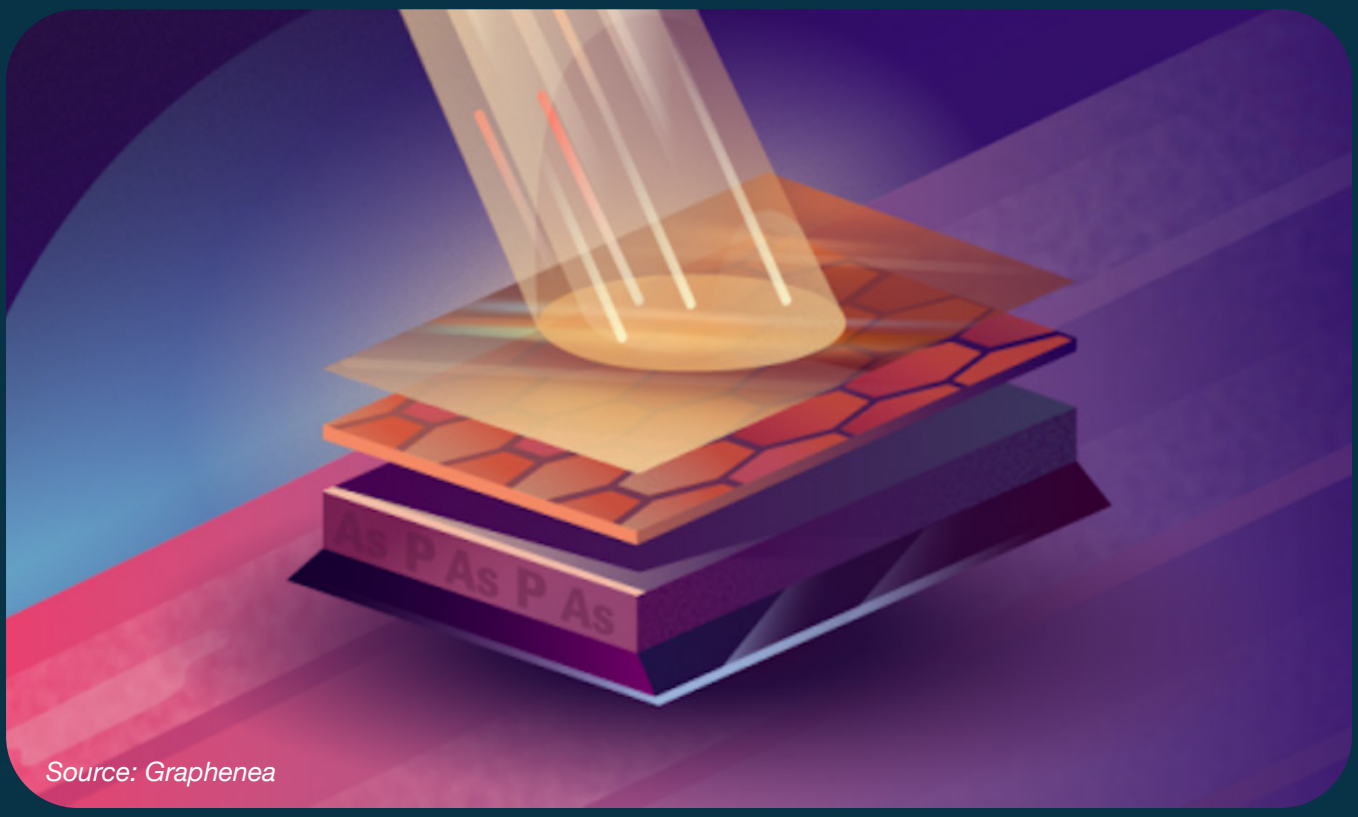
The Graphene Council

Graphene for Optoelectronics

APRIL 2024



Source: Graphenea

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About Graphene

Graphene is a nanomaterial that is made from pure carbon. It is often described as a two-dimensional (2D) material because it is only a few carbon atoms thick and therefore is almost entirely surface area.

Graphene can also be considered a “family” of materials because it comes in many forms and types including graphene oxide, reduced graphene oxide, graphene sheets, graphene flakes and other versions of this amazing material.

The most common way to describe different types of graphene is to count the number of layers of carbon. Graphene can be a single layer of carbon atoms up to and including 10 atomic layers according to ISO Standard definitions.

The number of carbon layers has a significant impact on how the material will perform in a given application. Other important characteristics include the lateral size (how “wide” the particles are) and if the material has been “functionalized” by the addition of other helpful elements or molecules.

Graphene in all its forms derives unique properties from its 2D characteristics and dimensions. These 2D properties make graphene one of the strongest and most electrically and thermally conductive materials ever measured. These attributes make it an extremely interesting material to make other materials better, lighter, stronger, more durable and more recyclable.

Why is Graphene Used in Optoelectronics?

Various types of optoelectronics have been fabricated using graphene. A few examples are photodetectors, polarizers, modulators and mode-locked lasers (lasers that turn on and off very quickly).

An optoelectronic device features a mutual charge-to-photon conversion process. For a light-emitting device, photons are generated due to the recombination of electron–hole pairs, which are injected from a cathode and an anode, respectively. The light emission process is named “electroluminescence” (EL).

While much of the early research focus with graphene was aimed at applying it to electronics, the real opportunity for graphene, according to many experts, has been in the area of photonics and optoelectronics.

It is believed that in these applications the unique combination of optical and electronic properties of graphene could be fully exploited. Unlike electronics, with photonic and optoelectronic applications graphene natural properties could be used even without the material having a band gap.

Graphene’s high carrier mobility enables ultrafast extraction of photo-generated carriers, which leads to high-bandwidth operation. Graphene also has a wide spectral range including the ultraviolet to the infrared.

Properties that make graphene attractive for optoelectronics:

High carrier mobility: Graphene monolayers of high quality can approach a room-temperature electron mobility about an order of magnitude more than commercially available silicon.

Thermal conductivity: Graphene has nearly unmatched thermal conductivity with some measurements putting its ability to dissipate heat at 20 times greater than silicon.

Wide Spectral range: Graphene-based photodetectors can detect the visible and near-infrared range of the electromagnetic spectrum to push into the terahertz range. This is a big deal because terahertz radiation penetrates materials that block visible and mid-infrared light. Detecting it opened up a range of potential applications in medical diagnostics, process control, and even intelligent vehicles.

Converting light into electrical voltage: Photodetectors capable of converting absorbed light into an electrical voltage at speeds of less than 50 femtoseconds. This leads to a bandwidth for these devices in the terahertz range, making them applicable to ultrafast optical communications.

Compatible with wafer-scale production: CVD graphene photodetectors meet the bandwidth levels of 120 GHz achieved by the best silicon waveguide integrated germanium photodetectors. CVD graphene photodetectors were demonstrated to be compatible with wafer-scale production methods that could reach a bandwidth larger than 128GHz, making them suitable for optical data transmission rates beyond 180 Gb/s.

Wide range of applications: All of these capabilities of graphene photodetectors make them suitable for a wide range of applications, including: imaging and sensing systems like night-vision technology; photovoltaic systems; and high-speed optical data transmission.

Applications

Photodetectors

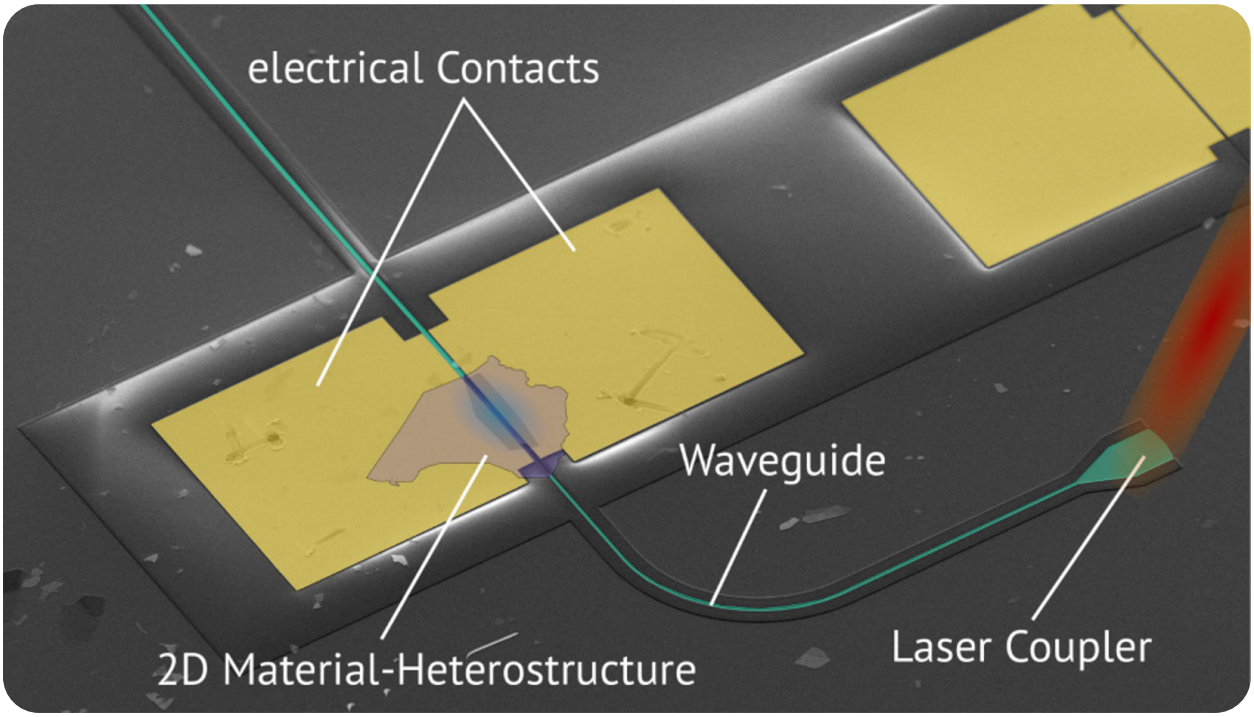
Photodetectors are essentially sensors that detect light or other electromagnetic radiation. A photodetector contains a p–n junction—the points at which p-type and n-type semiconductors are joined together to form the basis of many of the electronic devices we are familiar with—those that convert light photons into current.

The measure of any photodetector is its operating speed, its sensitivity to lower levels of light and how much of the spectrum they can sense.

Graphene-based photodetectors are capable of detecting optical wavelengths from the near-infrared to ultraviolet light, and recently have even proven capable of detecting microwave wavelengths.

For nearly the past decade, graphene-based photodetectors have been made capable of converting absorbed light into an electrical voltage at speeds of less than 50 femtoseconds. This leads to a bandwidth for these devices in the terahertz range, making them applicable to ultrafast optical communications.

Photodetectors have been demonstrated to meet the bandwidth levels of 120 GHz achieved by the best silicon waveguide integrated germanium photodetectors.



Source: ETH Zurich

These CVD produced graphene photodetectors are compatible with wafer-scale production methods and could reach a bandwidth, making them suitable for optical data transmission rates.

While graphene-based photodetectors can detect a wide spectrum of light and electromagnetic radiation and operate at high speeds (terahertz range), it suffers a couple of challenges in optoelectronics. For example, while nearly every single photon the material absorbs generates an electron-hole pair, it doesn't really absorb that much light. According to some estimates, it absorbs less than 3 percent of the photons falling on it.

This weakness has led to combining graphene with quantum dots. For over a decade it's been know that the combination graphene and quantum dots boosted the materials light absorbing capabilities to 25% from 3% on its own. This new absorption capability is due to the quantum dots, and when you combine that with the graphene's ability to make every photon into an electron-hole pair, the potential for generating current is significant.

All of these capabilities of graphene photodetectors make them suitable for a wide range of applications, including: imaging and sensing systems like night-vision technology; photovoltaic systems; and high-speed optical data transmission.

Optical Modulators

There are three basic components of photonic systems: waveguides, photodetectors, and modulators. As one of the key components in photonics systems, an optical modulator is a device used to control the fundamental characteristics of light either propagating in free space or in an optical waveguide.

Graphene has unique advantages for applications in optical modulators. First, it has a high modulation speed enabled by its carrier mobility. In addition, its ultrafast (picoseconds) processes, such as photocarrier generation and relaxation, provide graphene the ability to operate at over hundreds of GHz.

It is also possible to integrate graphene modulators along with a waveguide, resulting in the light-graphene interaction length being further improved.

Most importantly, CVD graphene optical modulators are CMOS-compatible. Graphene also addresses what has been an ongoing problem for optical communication systems. Optical modulators and photodetectors have traditionally been made from different types of material, making it difficult to combine them on an integrated silicon platform. Because of graphene's gapless band structure, it is capable of performing both photodetection and optical modulation.

Since the band structure of graphene does not have any energy specific transitions, the optical response of graphene is flat over a very broad spectrum. In the visible and near infrared wavelengths, graphene yields 2.3% optical absorption thanks to the inter-band transitions between valence and conduction bands.

Graphene also has a wide optical bandwidth because of its unique electronic structure. This bandwidth covers the optical fiber communication bandwidth. Graphene has high optical absorption. Even when it is only one atom thick, it has an optical absorption that is approximately 50 times higher than that of gallium arsenide-based modulators of the same thickness.

Saturable Absorbers

A saturable absorber mirror (SAM) is a mirror within a laser cavity that is used to convert a continuous wave laser into a pulsed laser. The most common type of saturable absorber today is the semiconductor saturable absorber mirror (SESAM).

SESAMs are complex quantum well devices that are expensive, difficult to make, and have a narrow bandwidth. Graphene SAMs, conversely, only require graphene to be transferred onto a mirror, making them easy to make and inexpensive. The band structure of graphene results in a wide bandwidth for graphene SAMs.

Many applications of graphene arise from its attractive characteristics, including its ultra-wideband absorption, controllable inter-band transition, saturable nonlinear absorption and high-mobility carrier transport.

Graphene-based saturable absorber components have been used to enable passive-mode locking in ultrafast laser operation, broad-band tunability, and quality-factor switching. Graphene multilayers have also been employed to generate large energy pulses and to achieve passive-mode locking in lasers with normal dispersion.

Mode-Lock Fiber Lasers

As a result of graphene's excellent properties as saturable absorbers, it is also a key enabler of passive mode-locking of fiber lasers. These mode-locking fiber lasers are used in a wide range of applications such as sources in communication systems, as spectroscopic tools in the laboratory for time-resolved studies of fast nonlinear phenomena in semiconductors and as a source for pulse sensors.

Recently, femtosecond fiber lasers (basically, mode-locked lasers with a pulse width of the order of femto-seconds) have been growing in popularity over conventional solid-state lasers. They have been developed for different biomedical applications, such as optical coherence tomography and multi-photon imaging.

Graphene-based erbium-doped fiber lasers utilize few-layer graphene saturable absorbers. It has been demonstrated that these fiber lasers are able to generate laser pulses at a rate at least 10,000 times higher than the state of the art.

This achievement was accomplished by inserting an additional resonator containing graphene into a fiber-optic pulsed-laser oscillator that operates in the domain of femtoseconds (10-15 seconds). The data transmission and processing speeds are expected to increase significantly by applying this method to data communications.

The opportunities for graphene in mode-locked lasers are good. Because only a small area of graphene is required, more advanced manufacturing techniques may not be required to use graphene for this application. Graphene may find new applications open up for it as a saturable absorber for passively mode-locked semiconductor laser with comparatively easy fabrication techniques.

LEDs

A particular application area in which graphene is being targeted for LEDs is the so-called deep UV LEDs. These UV LEDs are used in air, water and surface purification applications to kill bacteria. They are also used in environmental monitoring, food processing and molecular spectroscopy. Some estimates place the addressable market for graphene in these UV LED applications at between $75 million and $100 million in 2020.

It is in this area of UV LED applications that CVD graphene has a real opportunity. Currently, the transparency of metal oxide conductors is poor in the UV and near-UV region of the spectrum. This negatively impacts the efficiency and brightness of the LEDs. This means there is a real market pull for a transparent conductor in the UV region and CVD graphene is the perfect candidate.

In addition, CVD graphene has high thermal conductivity compared to metal oxide transparent conductors. This translates into better heat dissipation and improved diffusion efficiency of CVD graphene over metal oxide transparent conductors.

Summary

Graphene currently has commercial applications in optoelectronics. These are not lab curiosities, but real-world products integrating graphene.

It is important to note that there are many types of graphene and it is therefore critical to match the correct variety of graphene to a particular application.

Unfortunately, in this relatively new market, not everyone who claims to be selling graphene is in fact selling bona fide graphene material. This is why The Graphene Council recommends sourcing your material from one of our member companies and Verified Graphene Producers. In this way you know from the start you are working with qualified suppliers.

Successful application developers work with qualified graphene producers. Working with a reputable supplier will help to identify the appropriate type of graphene for your and optimize its effectiveness in your products.

About The Graphene Council

The Graphene Council was founded in 2013 with a mission to serve the global community of graphene professionals. Today, The Graphene Council is the largest community in the world for graphene researchers, academics, producers, developers, investors, nanotechnologists, regulatory agencies, research institutes, material science specialists and end-users.

The mission of The Graphene Council is to support the adoption of graphene to solve critical applications and engineering challenges. We do this through the establishment of internationally recognized standards, rigorous material testing, education and disseminating the latest research and development news, and connecting customers with qualified supply chain partners.

We connect the entire ecosystem, from university-based researchers to innovative graphene producers, to established end-user industry companies looking for the next advancement in materials.

The result is a single resource that can support your product development needs from concept to execution.

The Graphene Council

www.thegraphenecouncil.org

Leading the Adoption of Graphene

The Graphene Council

Our Services

The Graphene Council provides a wide range of services and resources to support and promote the interests of all graphene sector stakeholders including users of graphene, producers, researchers, regulators and investors.

Information & Publications:

- **The Graphene Report:** Covers all aspects of graphene production, applications, standards and a review of more than 200 commercial producers of graphene. Based on primary research and industry-specific data, it is the most comprehensive and up-to-date report on the graphene sector available.
- **Weekly Intelligence:** Weekly Graphene Intelligence Briefing brings you the very latest graphene application, corporate, patent and research news from around the world.
- **Research Journal:** Partnered with Springer Nature to produce the peer-reviewed 'Graphene and 2D Materials' journal, covering the nexus of research and commercial application.

Verification Programs

A rigorous in-person inspection and verification of graphene production facilities, evaluating producers, products, and material functionalization to ensure credibility, authenticity, and compliance with industry standards.

Materials Testing

Collaborating with world-class testing facilities, The Graphene Council offers comprehensive testing and characterization services, ensuring adherence to the latest international standards and best practices. This includes the provision of Technical Data Sheets and Safety Data Sheets aligned with the Graphene Classification Framework for your material's compliance needs.

Networking

Through webinars, conferences, and trade shows, we foster connections among graphene industry professionals. We facilitate partnerships between companies and verified graphene producers and partners for supply chain and application development.

Market Assessment and Supply Chain Validation

Thorough market assessments provide valuable insights to businesses entering the graphene industry. Robust supply chain validation services help ensure reliability and adherence to industry standards for graphene-related materials and products.

Standards Development

Developing global standards for graphene through key collaborations with ISO, ASTM, BSI, IEC, IUPAC, and others, creates transparency and trust in the sector. Volunteer driven standards, such as the Graphene Classification Framework (GCF), are widely used in the industry.

Regulatory Compliance

Providing crucial EPA/TSCA registration services for materials in the US helps with regulatory compliance. Global workplace exposure monitoring services help to mitigate Health, Safety, and Environmental (HSE) related risks for companies.

Due Diligence

Comprehensive technical assessments for potential investments or acquisitions in the graphene sector, covering both technical and market-related aspects, supporting informed decision-making.

Consulting Services

Helping companies with more effective market development, application testing, and seamless product integration by leveraging a vast global network of commercial, technical and academic experts.

Contact Us

US address:
The Graphene Council
208 King Street
New Bern NC, 28560 USA
TEL. +1 202 294 5563

UK address:
The Graphene Council Ltd.
First Floor, Swan Buildings,
20 Swan Street, Manchester
M4 5JW, UK
TEL. +44 0 161 854 1736
Company Number 12888260
VAT 360 4024 39

info@thegraphenecouncil.org
www.thegraphenecouncil.org