ULISSES publishable summary

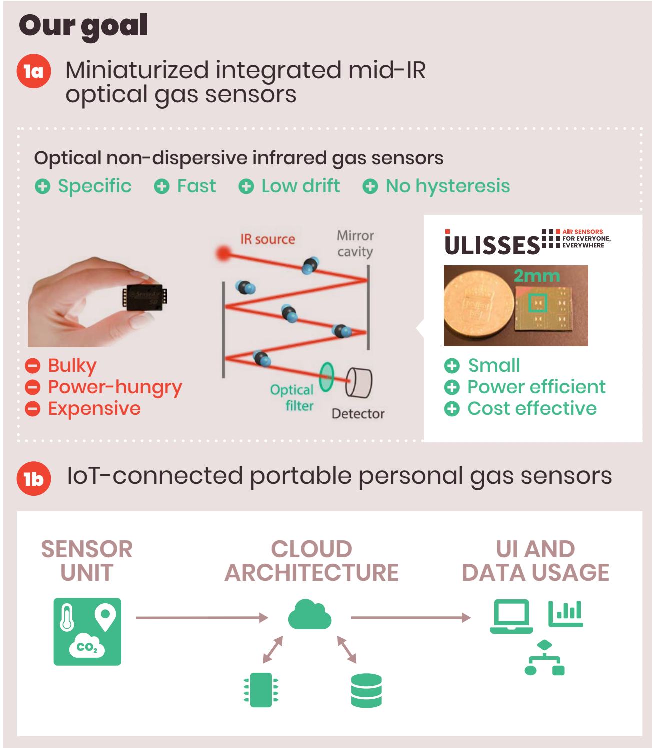
August 2022

OUR OBJECTIVES

We, the partners of the ULISSES project, want to enable everyone to know if the air we breathe in our everyday life is good or not, to make the best choices for our health and life quality, and to improve air quality in the long run. In cities, outdoor air quality varies dramatically from one block to another and from one hour to the next. Thus, to measure air quality, we need a dense mesh of small portable gas sensors that report data in real time. Amongst the different types of gas sensors, optical gas sensors, which use infrared light to detect gas, are sensitive and robust, and offer the highest stability and specificity. However, they are currently too bulky, power hungry, and expensive, to be widely employed.

In the ULISSES project, we are developing new millimetre-sized on-chip optical gas sensors working in the mid-infrared spectral range that can be mass-produced and integrated in portable devices[1a]. Optical gas sensors require a light source, a light path, and a light detector. Our new sensors rely on integrated waveguides, which are very tiny optical fibres guiding light on the surface of a chip, and 2D materials such as graphene and platinum diselenide, which can both generate infrared light and detect it by converting it into an electric signal. Along with the sensors, we are also developing the techniques and tools to efficiently produce them in large quantities at a low cost.

Moreover, we want our sensors to be connected and smart, to be part on the Internet of Things (IoT). Not only do the sensors have to communicate their measurement data from wherever they are, for example by sending it to a cloud database via the internet, but they also must overcome their own imperfections and ageing to provide reliable data for a long time. To ensure that, in ULISSES we are developing machine learning algorithms that allow the sensors help each other stay calibrated by exchanging information about their measurements[1b].

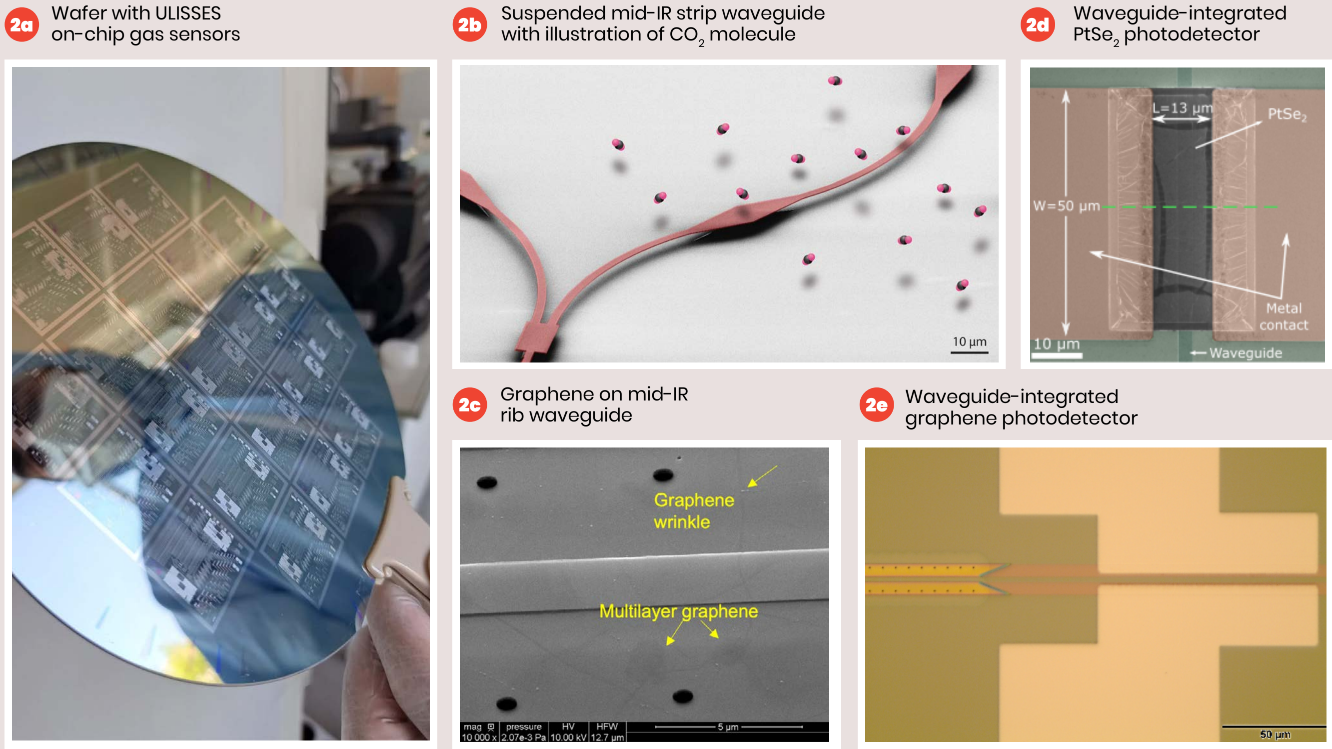


In summary, ULISSES is advancing the technologies for the mass implementation of air quality sensors.

WORK PERFORMED AND ACHIEVEMENTS SO FAR

At this point in the project, we fabricated the first batch of complete on-chip gas sensors that comprise graphene infrared light emitters, silicon waveguides, and graphene photodetectors[2a]. Building up to that, we designed, fabricated, and tested the components individually and in different variants. We studied platinum, graphene, and platinum diselenide infrared emitters, different designs of infrared waveguides[2b,2c] and their performance as paths for the infrared light for gas sensing, and graphene and platinum diselenide detectors[2d,2e]. We also developed integrated

Our technology Silicon photonics and 2D materials



tuneable optical filters that allow the measurement of different infrared wavelengths and thus of different gases, all on the same chip. Moreover, we developed a technique to place small protective but gas-permeable caps on the gas sensors, to keep them safe from dirt and dust.

All along, we also dramatically advanced the fabrication techniques required to produce the sensors in large volumes, particularly the methods to integrate 2D materials on semiconductor wafers. Typically, the placing of graphene on wafers or chips is a manual process that consists in "fishing" the thin graphene layers that are floating like jellyfish in a liquid bath with the target substrate. This is of course not suited for high-quality mass fabrication. In ULISSES, we developed wafer-scale dry transfer processes that result in good graphene transfer, also on surfaces with topography such as waveguides, and are much better suited for mass production[2c]. For platinum diselenide, we developed two different growth methods: thermal assisted conversion (TAC) and metal-organic chemical vapour deposition (MOCVD). TAC is a two-step process in which a thin layer of platinum is first deposited and then converted (selenized) into platinum diselenide. With MOCVD, instead, the platinum diselenide is grown in a single-step process and the resulting material is of better quality.

To make the sensor smarter and more reliable, we developed machine learning algorithms for networked cloud-connected sensors that allow the sensors to stay calibrated with support from their peer or superior sensor friends. Each sensor can learn from its own and other sensors' history and self-estimate its own reliability. Also, the sensors can get information from other high precision sensors and run self-calibration procedures.

To demonstrate the potential of an IoT network of mobile air quality sensors, we prepared wireless cloud-connected air quality sensing units for our on-chip gas sensors. While the ULISSES sensors are still being developed, we equipped the units with traditional carbon dioxide sensors and teamed up with the electric taxi company Bzzt to test the units and our network. We installed the units, which are geotagged, on five Bzzt taxi pods in Stockholm, so that they continuously record the air quality at any position. We found that such a small number of sensors provides surprisingly good mapping of the carbon dioxide levels in the city centre, thanks to the semi-random movement of the taxi pods[3]. The collected data is useful for a variety of applications. For example, we developed a route planning tool that works as a Google Maps plug-in and identifies the route with the lowest exposure to exhaust gas, based on the real air quality data.

To ensure that our new sensors meet the needs and expectations of future users, we established a forum of stakeholders that follow the project, providing insights in the challenges they face, as well as valuable feedback and ideas.

PROGRESS BEYOND THE STATE OF THE ART, EXPECTED RESULTS UNTIL THE END OF THE PROJECT AND POTENTIAL IMPACTS

The use of graphene and other 2D materials currently struggles to advance beyond research and into industrial applications. An important reason is that the production and integration techniques still rely on manual processes, and thus have poor reproducibility and yield and are not scalable to mass production. The new methods developed in ULISSES enable the application of 2D materials in large-scale semiconductor processes, not limited to the production of gas sensors.

Current optical gas sensors are assembled from multiple components into a package of a few cubic centimetres volume, consume power on the order of 100 mW, and each sensor can detect only one gas. The recent ULISSES breakthroughs on waveguide-integrated 2D material photodetectors and emitters, and waveguide-based gas sensing, aim at packing multiple sensors for different gases on a single chip, to achieve multi-gas sensing with a three order of magnitude reduction in sensor size and power consumption, thus enabling maintenance-free battery powered operation for the first time. By the end of the project, we aim at demonstrating multi-gas sensing with our on-chip sensors and a detailed characterization of the devices.

Demonstration
Mobile networked CO_2 sensors on Bzzt taxi pods in Stockholm

3 Air quality mapping in Stockholm

This development, together with IoT intelligence for self-calibration, will enable mobile and personal gas sensors embedded in portable devices, as well as widespread sensors installation in public infrastructure such as street illumination, and on buses and taxis. The ULISSES technology aims at empowering the general public to monitor and put demands on their air quality, as well as at providing authorities with new tools to measure air quality and the outcomes of interventions.

www.ulisses-project.eu

ULISSES
AIR SENSORS FOR EVERYONE, EVERYWHERE

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