Graphene Interferometric Modulator Displays - GIMOD Project

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ABSTRACT

Within the GIMOD Project, SCALE Nanotech and Graphenea Semiconductor have designed and developed graphene interferometric modulator displays (GIMOD) to push for the technology commercialization before 2022. Free-standing chemically-vapour-deposited graphene MEMS were optimized to enhance the optical modulation of light when electrically actuated. Our joint efforts were focused in transforming the GIMOD research into a breakthrough innovation, with the ultimate objective of fabricating, characterising and demonstrating cm^2-size microdisplay prototypes in an industrially scalable manner.

Keywords: AR/VR; HUD; graphene; display; MEMS; light modulation; ultrahigh resolution; high refresh rates; new company.

1. INTRODUCTION

Displays are one of the key components in portable electronic devices. In augmented/virtual reality (AR/VR) headsets and in heads-up displays (HUD), the display technology determines the product capabilities and user experience. However, current display technologies like organic light emitting diode (OLED) and liquid crystal displays (LCD) face challenges to meet the requirements for AR/VR & HUD applications. These applications require high resolution displays with tiny pixels that can change their colour at high refresh rates while consuming little power. Graphene Interferometric Modulator Display (Graphene IMOD or GIMOD) technology is the solution.

GIMOD is a disruptive green tech for next-gen colourful displays: it combines the large dynamic range and power saving of liquid-based displays (LCD, electrowetting, electrophoretic) with the speed and gamut of solid-state displays (OLED, microLED). GIMOD is a reflective-type or e-paper technology whose pixels are micro-electromechanical systems (MEMS): electrically-controlled graphene micro-membranes that modulate the colour from the ambient light by their mechanical movement. Therefore, GIMOD uses no power to inefficiently generate light because it recycles light from the environment which, in addition, enhances the colour contrast in bright environments. Moreover, each GIMOD pixel is full-spectrum and diffraction-limited in size, hence eliminating the need of subpixels, which enables the ultimate resolution (>25000 pixels per inch -ppi-), a 1/3 reduction of data bandwidth and an incredibly low power consumption, all demanded by AR/VR and HUD markets to offer a truly-real virtual experience. Last but not least, GIMOD does not require the use of expensive and toxic rare-earth materials; on the contrary, GIMOD integrates graphene, a biocompatible and environmentally-friendly material produced from small quantities of natural gas (methane).

The main results of the GIMOD Project are:

- Fabrication of 21 ultrahigh-resolution prototypes (proof-of-concept) and 2 QWXGA (2048 × 1152) 0.65” demonstrators with 3630 ppi.
- Optimization of GIMOD design via simulation of GIMOD pixels.
- Display characterisation with custom-made setup.
- Dissemination of results through website and Twitter while planning a scientific manuscript.
- Completion of GIMOD senior team: CEO (serial founder), CTO (GIMOD inventor), CFO (venture capital and investments expert), scientific advisor and display advisor.
- Creation of business plan and pitch to investors.

2. STATE OF THE ART

IMOD technology was initially developed by Iridigm Display Corp in the 90s and later commercialized by Qualcomm MEMS under the Mirasol trademark [1,2]. It used complex MEMS design and fabrication processes, although that did not prevent Mirasol to reach the market with, among others, the Qualcomm Toq smartwatch released in 2013. Despite the large enthusiasm by the public, astronomic investment and the promise of low power consumption, Mirasol displays were unsuccessful, partially due to the unsaturated colours and limited frame rates that prevented video applications, making it a slow e-paper technology [3].

With the advent of ultimately-thin 2D materials like graphene [4], there is a new opportunity to revive and fulfil the hopes for a MEMS-based reflective-type display technology that offers native natural colours, video speeds and low power consumption. GIMOD technology recovers the IMOD's basic principle of light modulation while overcoming its fundamental limitations by using graphene, hence the name Graphene IMOD. GIMOD technology vastly improves the device performance, reduces the complexity and eases the production processes over the original IMOD tech. Recently, circular graphene MEMS were demonstrated as electro-optic pixels in a GIMOD [5]. Despite of this milestone, much work is pending regarding contrast ratio, colour homogeneity and other performance.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The digital world is undergoing a new revolution with the VR/AR and HUD technologies. The immersion/integration levels in their current stage are already disrupting the market of digital games and entertainment; however, as soon as hardware allows, they will transform every other field: aviation and automotive; education and data visualization; engineering, design and Industry 4.0; healthcare and even space. Displays are one of the hardware components that must drastically improve to unlock the full potential of VR/AR technologies. In this context, GIMOD technology appears in the right moment.

The GIMOD Project aimed to develop further the scientific innovation of GIMOD technology and bring it to a breakthrough industrial activity. SCALE Nanotech and Graphenea Semiconductor partnered up once again to explore high-risk avenues, away from incremental innovation, that would enable the disruption of GIMOD in the display market. After multiple iterations, we believe to have generated key know-how and designs that pave the way for the breakthrough. The following table summarizes the comparison between the tech state before and after ATTRACT's GIMOD Project:

	Before ATTRACT	**After ATTRACT**
MEMS shape	Circular	Squared
Filling factor (%)	45	82
Contrast ratio*	0.58:1	1.76:1
Pixel pitch	10-15	7
Resolution (ppi)	2500	3630
Graphene transfer	Not scalable	Scalable

*For a flat spectrum source and normalized to source brightness.

As a consequence of the excellent results, a new startup has been incorporated in 2020 to scale up and commercialize GIMOD technology, expand the portfolio with other technologies, fabricate and sell high-quality high-tech products, and lead the 2D materials industry.

4. PROJECT RESULTS

In the following, we outline the steps taken to fabricate, optimize and characterise graphene-based reflective pixels to show the potential of GIMOD technology and assess its suitability for VR/AR and HUD visors.

Fabrication and simulations

The thermally-grown SiO_2 layer of a silicon dice is micro-patterned to form squared cavities with a given size and pitch. Chemically-vapour-deposited (CVD) graphene layers are transferred onto the patterned substrate and remain free-standing on top of the microstructures, hence forming optical cavities as shown in Fig. 1a with an optical reflectance of (1):

$$R=\left|2r_1e^{i\phi_2}\sin(\phi_1)+r_2e^{-(\phi_1+\phi_2)}-\frac{r_1^2r_2e^{i(\phi_1-\phi_2)}}{e^{i(\phi_1+\phi_2)}+r_1^2e^{-i(\phi_1-\phi_2)}+2r_1r_2e^{-i\phi_2}\sin(\phi_1)}\right|, \quad (1)$$

where $r_{1,2}$ are the air-graphene and air-silicon Fresnel reflection coefficients, and $\varphi_{1,2}$ are the phase changes induced by the optical path through graphene and cavity, respectively [6].

Because CVD graphene and silicon are separated by a dielectric, SiO_2, the resulting pixel is a parallel-plate capacitor. As illustrated in Fig. 1b, the CVD graphene acts as a flexible semitransparent membrane moving towards the underlying silicon surface (fixed mirror) when applying a voltage difference V [5].

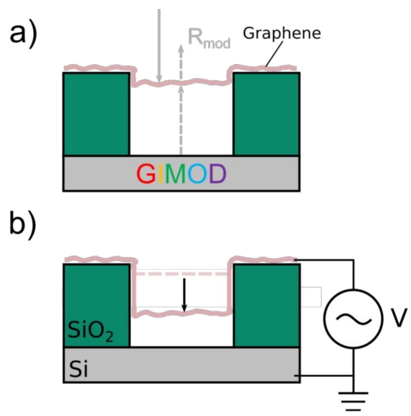

Fig. 1. Sketches of a Graphene Interferometric Modulation Display (GIMOD) pixel at rest (a) and when a voltage difference is applied between the free-standing graphene membrane and the silicon substrate (b).

At this stage, the graphene pixels of 1-10 µm in size can be largely deformed by electrostatic pulling towards the bottom of the cavity (i.e., display maximum electro-mechanical performance) although these behave as low-finesse Fabry–Pérot interferometers (i.e., have low optical performance). In order to improve the modulation effect of the membranes, material films of nanometer thinness are deposited on the free-standing graphene.

To optimize the overall pixel performance, a trade-off between material thickness and mechanical deformation must be found. We used COMSOL Multiphysics to simulate different combinations of materials, film thicknesses and membrane shapes that helped us to design optimal GIMOD pixels.

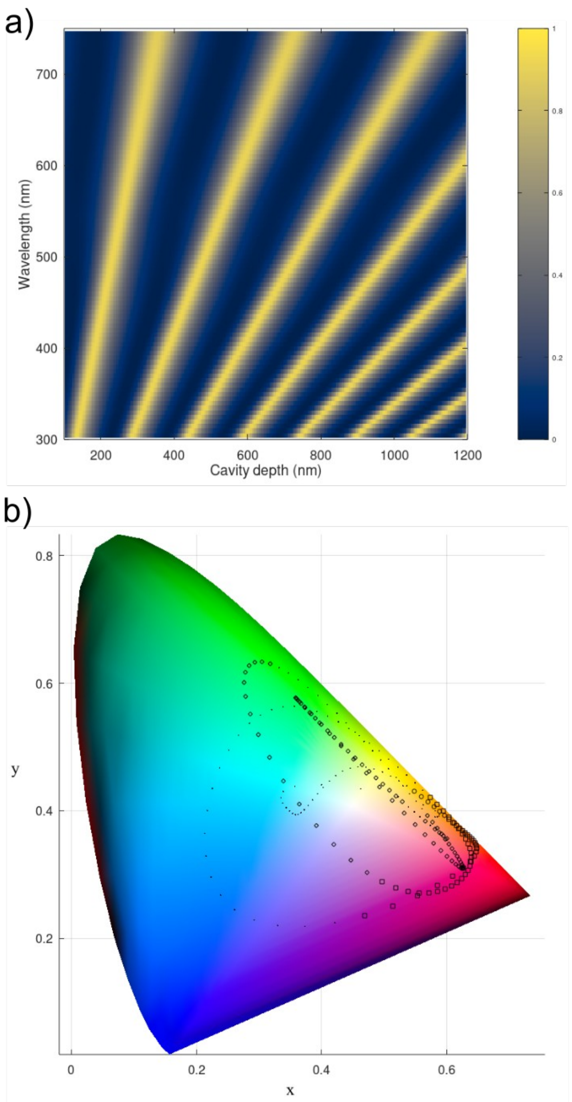

Fig. 2. a) Modulation reflectance colourmap of a GIMOD pixel as function of wavelength and cavity depth. b) Simulated gamut pixel trajectory of that reflectance on the CIE 1931 colour space chromaticity diagram.

After obtaining the modulated reflectance as a function of wavelength and cavity depth for one case (see example in Fig.2a), we apply analysis algorithms to extract figures of merit of that particular combination. One figure of merit is the maximum achievable colour difference that we obtain by converting the spectral reflectance into colour gamut (CIE 1931 xyY colour space), as represented in the *xy* chromaticity diagram in Fig. 2b.

Measurement setup and prototypes

We built a custom colorimetry setup composed of an optical microscope with Köhler illumination, a halogen lamp as a multi-wavelength light source, and an optical spectrometer with colour space conversion [7]. The setup is sketched in Fig. 3. Here, the spectrometer is configured to collect light from the active area of single devices. In addition, a custom ellipsometer is used to study the modulation effect as function of the angle of incidence.

The first prototypes as displayed in Fig. 4 have 3630 pixels per inch (equivalent to 16K+ in a 5" screen) with >400 Hz response time and optical modulation allowing gamuts from red to blue. The contrast ratio and colour difference need to be further improved and are currently being engineered.

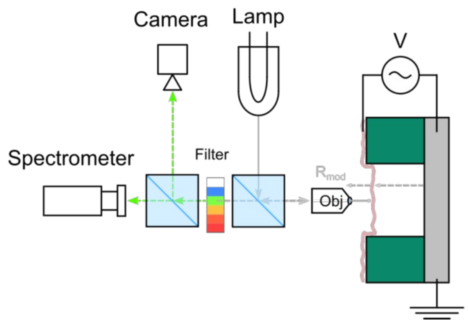

Fig. 3. Colorimetry setup for GIMOD characterisation.

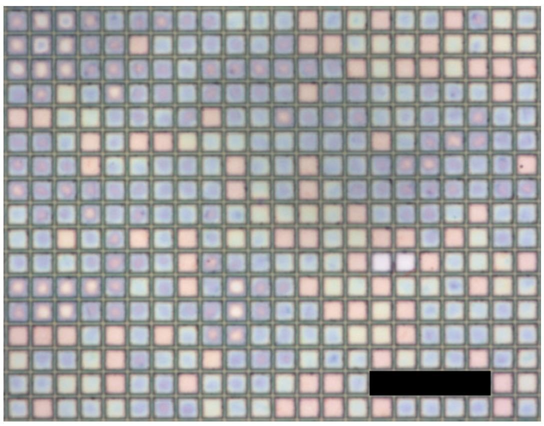

Fig. 4. Full-spectrum squared GIMOD pixels in a 3630 ppi prototype. Scale bar is 35 µm.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

GIMOD technology is at TRL 6: it has been demonstrated in a relevant environment (industry fair and investors) although the display prototypes are colour modules without capability of forming custom images (they do not address pixels individually). In ATTRACT Phase 2, we plan to bring it to TRL 7 in 1-2 years by integrating a backplane technology for single-pixel addressing and producing commercial demonstrators in the form of evaluation kits (complete system including display, electronics and optics).

5.2. Project Synergies and Outreach

To achieve TRL 7 in 1-2 years, we have already secured off-the-shelf backplanes and we want to partner up with backplane developers to make customized ones (in discussions with Fraunhofer, TNO, Philips, imec; planed discussions with TSMC). For R&D and equipment/lab access, we have entered into contractual agreements with Helmholtz Nano Facility at Forschungszentrum Jülich and COPT Zentrum in Germany, and further partnerships in Germany, The Netherlands and Belgium are being discussed. In parallel, we are also talking to potential customers (integrators and manufacturers), brands and end users to complete a value-chain consortium of 5-7 partners covering several EU countries as in Fig. 5.

We have also approached strategic corporations that could help us to enter a niche sector (already validated by potential customers) and could be interested in licensing our technology for markets with high entry barrier.

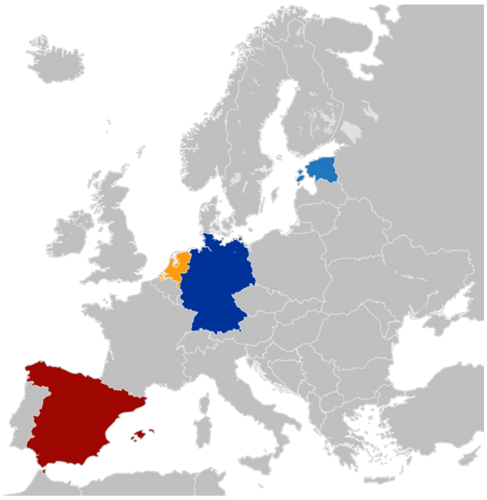

Fig. 5. European Union countries supporting the development and commercialization of GIMOD technology.

In addition, SCALE Nanotech and i-Med Technology (ATTRACT's H3D-VISIOnAiR project) are connected via our "VR/AR for healthcare" network; we believe our GIMOD microdisplays could help them to expand their medical imaging product portfolio, and a joint proposal for ATTRACT Phase 2 will be considered.

Based on our Phase 1 experience, we believe that public dissemination of a future Phase 2 project would be intensified via the same means (dedicated website, project Twitter, open-access online articles). Moreover, the system prototypes (evaluation kits) will not only serve to attract the interest of potential customers, but also to reach end users from the public so we can obtain their feedback and steer the technology in the right direction.

5.3. Technology application and demonstration cases

For ATTRACT Phase 2, we will implement two technology demonstration cases: AR/VR glasses for healthcare (enhanced imaging and diagnosis); and HUD systems for the aviation, automotive and Industry 4.0 sectors (information overlay).

We see our technology as the substitute of LCOS and DLP for projection. Moreover, our graphene MEMS can support biotechnology research as sensors. In the long term we aim to incorporate GIMOD in new and existing tech, and enable new and/or better functionalities such as LiFi and LiDAR.

We intend to spearhead graphene MEMS innovation with the help of Research Infrastructure communities in Europe as stated in 5.2, hence opening up a new multidisciplinary area in the field of micro-opto-electro-mechanical systems (MOEMS) with significant impact on the broader electronics industries in the European Union through the provision of unique knowledge and novel devices. This aligns with the innovation sector 'High-tech Systems and Materials' of the 'Top Sector Policy' as outlined by Dutch government, and has direct impact on three of the European Commission's Key Enabling Technologies: Advanced Materials, Photonics and Nanotechnology.

Besides improving the scientific understanding of graphene MEMS (potential and limitations), we believe that GIMOD could be among the first applications, if not the first, to allow the commercialization of graphene and contribute to drop its price. Therefore, industry would benefit from an early commercialization of other high-tech graphene-based products.

Consequently and with our commitment to social return, we serve to bring benefit to citizens from EU and the World, and the application of GIMOD already looks to solve particular Societal Challenges such as enabling healthcare (better imaging for better diagnosis and treatment), improving transport (safer and smarter information projection), fighting climate change with green materials and, ultimately, leading the transformation towards a society that uses clean, cheap and energy-efficient technologies such as GIMOD.

5.4. Technology commercialization

GIMOD team has a business and technology roadmap to become the leader of graphene MEMS components. A new company to commercialize GIMOD technology has been incorporated in The Netherlands and will have a German branch, with the support of the GIMOD Consortium. The new company will exploit financial instruments from both countries and the European Commission (public funding, loans, blended finance).

The new company follows a ready-to-execute business plan, which includes a detailed market analysis and robust financial plan for the next 5 years. We have already contacted and pitched to 2 different potential investment firms, and we received an initial positive feedback. Negotiations are ongoing and we are confident that we will receive an equity investment of 900k EUR before 2021 Q2.

In addition to private investments, we intend to apply for and count on obtaining:

• Loans – Innovation Loan provided by the Dutch government via RVO (Netherlands Enterprise Agency, Proof of Concept loan via Regional Development Organization in the Netherlands (350K EUR in loans budgeted) and;

• Grants – MIT arrangement provided by the Dutch government via RVO, EIC Fast Track to Innovation and other EC calls (mainly in the photonics domain), Eurostars and other Eureka calls, ESA tenders, etc. (400K EUR in grants budgeted).

5.5. Envisioned risks

Tab.1 summarizes the potential risks and the mitigation actions.

Tab. 1. Risks and corresponding mitigation plans.

Risks	Mitigation action
Customer base limitation to large established players	Following an outbound sales strategy
Possibility to quash part of the functionalities by rising technologies	Following a flexible business strategy, easily switch to other application areas (if needed)
Customer refusal to adapt (political, strategic reasons)	Change market entry strategy – enter the market by ourselves
Unable to raise funding	Change the business strategy and try other applications
Unproven product - unable to meet specifications	Strategic technical collaboration
Unexpected events - act of nature	Insurance, flexibility, and adaptable team

5.6. Liaison with Student Teams and Socio-Economic Study

We are willing to obtain support from master students, that could bring new ideas and new angles, and from experts that can evaluate and advice on our technology applications and business strategy. During Phase 1, resources were limited and we were only able to engage ESADE and attend the Introductory Crash Course in Entrepreneurship; however, we are fully ready and settled for Phase 2: we would share non-confidential information (e.g., white paper) as first step to gain their interest, and we will require a NDA in place to disclose further details (e.g., business plan and pitch). In addition, at least one person from the consortium will be assigned to answer questions in interviews.

6. ACKNOWLEDGEMENT

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

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