Advanced Printed Transistor Biosensors for Food Contaminant Detection

Context and scientific challenge:

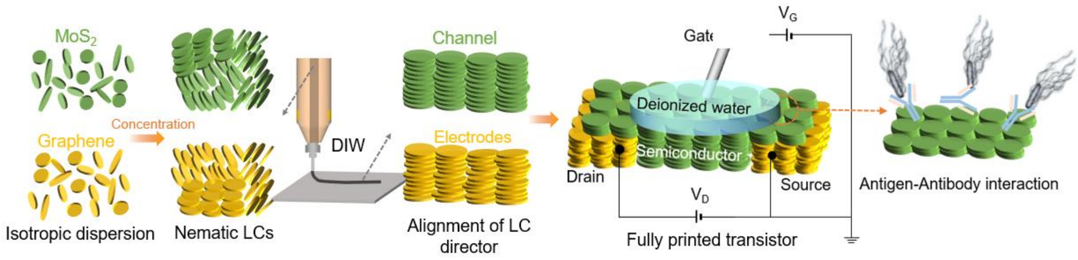
Contaminants such as pesticides, antibiotics, toxins, nitrates, and other chemicals can be entrapped within food at various stages of production, including growth, harvesting, processing, storage, and packing.[1] Exposure to these contaminants through diet or contact impacts the health of the entire population. It poses a significant risk of causing foodborne illnesses, especially for vulnerable groups such as children, the elderly, and the sick.[2] According to a report by the World Health Organization (WHO), approximately 600 million cases of foodborne illness occur each year, resulting in 420,000 deaths annually.[3] European Union has enacted stringent legislation on food control. However, effective control through the entire food production chain remains challenging, particularly when dealing with products imported from jurisdictions with less developed legal systems. Therefore, there is a real need to implement simple, rapid, cost-effective, and accurate food quality control methods, ideally employing portable biosensors that allow on-site detections.

A biosensor is an analytical device composed of a transducer and a biological receptor, which work in tandem to convert a biochemical response into a measurable electronic signal. Recent advances in both biotechnology and material science have led to the emergence of new biosensing technologies. Field-effect transistor (FET) based biosensors are especially desirable for the on-site detection of contaminates in food due to their exceptional sensitivity, rapid response times, label-free operation, low power consumption, and ease of on-chip integration. In a FET, two electrodes (source and drain) connect a semiconductor material (channel), which is covered by a dielectric or electrolyte layer and capacitively coupled with a third electrode (gate). The current flowing through the channel can be electrostatically modulated by a bias applied to the gate. In FET biosensors, channel or gate electrodes are functionalized with specific recognition elements to form an active layer. The selective adsorption of the analyte of interest onto this layer affects the gate potential and capacitive coupling, leading to a change in channel conductance or saturation drain current.[4] This innovative approach enhances the precision and reliability of biosensing technologies, making FET biosensors invaluable in food safety control.

The channel materials play a pivotal role in determining the sensing performance of FET biosensors. Two-dimensional (2D) materials stand out as promising candidates for biosensing, owing to their low cost, high carrier mobility, remarkably low noise levels, ultra-high surface area, and extraordinary physical and chemical properties.[5] Based on 2D materials, FET biosensors have been demonstrated to detect pesticides,[6] heavy metals,[7] or bacterial metabolic volatile indole.[8] Next-generation FET biosensors demand heightened sensitivity at low biasing voltages (<1 V) to prevent biomolecules from being damaged or denatured within aqueous media at elevated electrical potentials.[9] This necessitates a notable improvement in the mobility of printed channel materials. However, the majority of channel materials are printed using isotropic inks, which consist of nanosheets dispersed randomly in liquid carriers. This random distribution results in multiscale disorder within the printed networks of devices,[10] leading to significantly inferior mobility of printed materials to individual nanosheets.

Objectives and scientific approach:

To address the limitation, we propose printing nanosheet materials into 3D ordered structures with high basal-plane alignment. This will generate larger-area junctions where adjacent nanosheets conform to each other, forming atomically clean van der Waals interfaces and significantly enhancing the inter-sheet charge transfer. A new 3D ordered structure will be realized by direct ink writing (DIW) of water-based inks comprised of liquid crystalline nanosheets (Image below). Such aqueous ink contains a number of lyotropic liquid crystal (LC) microdomains formulated by the self-assembly of nanosheets during ink concentration. DIW of LC inks will enable the deposition of ordered materials with patterning at the micro-to-macroscale. The combination of the self-assembly of colloidal nanosheets (from nano to microscale) and digital microfabrication (from micro to macroscale) will enable the generation of new structures with deterministic control across multiple length scales. The nanosheet assemblies (LC monodomains) serve as a bridge between nanoscale and macroscale features, and lead to the unprecedented use of the electronic properties of individual 2D materials. The compact stacking and larger-area van der Waals interfaces within macroscopically 3D ordered nanosheets are expected to boost the electronic conduction in printed patterns, leading to widely applicable FET sensor devices operated at low voltages.



Project concept. Electrochemically exfoliated MoS_2 and graphene nanosheets will be stabilized in water and concentrated into LC inks that will be further printed to make a FET biosensor. An Ag/AgCl reference electrode will be used as a gate electrode to apply bias. Anti-Salmonella antibodies will be immobilized on the channel for detecting Salmonella Infantis thanks to the antigen-antibody interaction.

The key to reaching the objectives of the project is the multiscale control of the nanosheet network structure and the functionalization of recognition elements on channel surfaces. This includes the synthesis of MoS_2 and graphene nanosheets with tightly controlled size and properties, the self-assembly of the nanosheets into LCs in water, printing LCs into ordered functional materials, and combining different nanosheet patterns to make FETs, and immobilizing anti-Salmonella antibodies on MoS_2 channels. The focus here is to study the effect of antigen-antibody interactions with the analyte of interest (Salmonella Infantis) on the electrical signals of FETs. As a proof of concept, we will combine the ordered (semiconductor and conductor) nanosheet patterns layer by layer to make FET devices. The spatially in-plane ordering of MoS_2 and graphene nanosheets is desirable to boost the transistor performances. We target superior carrier mobility of >50 cm^2/Vs, on/off current switching ratio of >10^6, and subthreshold swing of <60 mV/dec. A biosensor prototype will be realized by coupling the favorable electronic characteristics (signal amplification) with high selectivity towards the Salmonella Infantis, which is guaranteed by the immobilization of Anti-Salmonella antibodies on the channel. Salmonella Infantis is prevalent in poultry, red meat, raw egg shells, unpasteurized milk, and dairy products, posing a significant risk to human health as it exhibits multidrug resistance. Here, the development of fast and reliable techniques to detect it at low concentrations in food and water will help protect public health.

Team skills and coherence: This project focuses on leveraging novel functional materials in cutting-edge biosensing technologies, addressing the crucial concern of food contamination exposure among populations throughout their whole life. It is truly interdisciplinary, encompassing soft matter physicochemical processing, functional material engineering, electronics characterizations, and biotechnologies. Its implementation will be ensured by a consortium of researchers from LCMCP and LISE. The PI (J. Yuan at LCMCP) has rich expertise in functional nanomaterials, colloidal inks, and printed electronics. He has developed a series of waterborne electronic inks by using soft matter as starting materials, such as aqueous latex solutions, polyelectrolyte-colloid complexes, LCs of TiO_2 flakes. The Co-PI (L. Fillaud at LISE) has been involved in a wide range of upstream research activities from surface functionalization, molecular electrochemistry to electrolyte-gated FET biosensors. She has acquired recognized expertise in the simulation, design, fabrication, and characterizations of FETs for detecting DNA strands, glucose, and the enzymatic activity of acetylcholinesterase.

Profile of candidate: Prospective candidates should possess, or be on track to acquire, a Master's degree in a pertinent field such as Physical Chemistry, Materials Science, or Soft Matter. While a biology background is not obligatory, preference will be given to candidates with prior experience in biosensors.

Bibliography

1. Bobrinetskiy, II and N.Z. Knezevic, *Analytical Methods*, 2018. **10**(42): p. 5061-5070.
2. Ashley, J., et al., *Biosensors & Bioelectronics*, 2017. **91**: p. 606-615.
3. Kumar, A., M. Castro, and J.F. Feller, *Sensors*, 2023. **23**(8): p. 4017.
4. Elli, G., et al., *Sensors*, 2022. **22**(11): p. 4178.
5. Sedki, M., Y. Chen, and A. Mulchandani, *Sensors*, 2020. **20**(17): p. 4811.
6. Wang, et al., *Chemical Engineering Journal*. 2024. p. 150380.
7. Takagiri, Y., T. Ikuta, and K. Maehashi, *ACS Omega*, 2020. **5**(1): p. 877-881.
8. Lin, Z.H., et al., *Nanomaterials*, 2021. **11**(5):p. 1155.
9. Chennit, K., et al., *Advanced Materials Technologies*, 2023. **8**(2) : p. 2200300.