Next-generation infrared photodetectors utilising advanced semiconductor nanowires on silicon

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ABSTRACT

This project aims to develop next generation infrared photodetectors in the mid-infrared spectral range of 3.0-5.0 um that operate at high operating temperature with high detectivity, much reduced cost and capable integration with silicon CMOS technology. This will be achieved through the use of advanced InAsSb nanowires on silicon substrate. This project demonstrated prototype single element

Keywords: infrared, photodetector, nanowire, silicon.

1. INTRODUCTION

Advances in infrared photodetector-based instrumentation technologies present significant development opportunities across a broad range of industries and applications. From security, health care and biosensing, to food plan analysis, geospatial mapping, petroleum exploration and intelligent transport, infrared photodetectors are the core components of modern light detecting instrumentation and play a key role in all the above applications. Despite this versatility, limitations also exist in relation to these devices. The majority of commercial infrared photodetectors that currently dominate the marketplace are based on either HgCdTe (MCT) or III-V semiconductor materials in planar geometry. Such photodetectors are both costly and difficult to manufacture. In addition, significant challenges also exist around the use of these conventional materials and planar geometry to manufacture large focal plane arrays (FPA).

Photodetectors based on InAsSb semiconductor materials incorporated into a single-crystal nanowire morphology are expected to circumvent the above challenges and in so doing, present opportunities for the development of photodetectors with significantly improved performance characteristics. In particular, the type II InAsSb/AlGaSb core-shell nanowire (CSNW) offers the potential to build uncooled devices with efficiencies exceeding the current state of the art photodetectors, owing to an ability to exploit a newly discovered phenomenon entirely. These devices use a negative photoresponse mechanism, and advances in enhanced light coupling and reduced dark current. The novel architecture presents the potential for high-speed response photodetectors, due to the small capacitance and the extremely high electron mobility. In addition, the monolithic integration with Silicon (Si) technology is extremely attractive to manufacturers in creating large size single photodetectors and large FPA.

Successful completion of this project is anticipated to lead to prototypes for the development of next generation photodetectors with dramatically reduced costs owing to the shortened semiconductor growth time, reduced material consumption, and large size/low-cost Si substrate opportunities.

2. STATE OF THE ART

Current state-of-the-art infrared detectors based on HgCdTe (MCT) are the conventionally accepted technology for photodetection devices. Traditional detectors suffer from high costs and expensive fabrication processes due to their sensitive material stability. As an alternative to MCT, III-V semiconductor materials have attracted increasing efforts in the past few years [1], for developing room temperature infrared detection. This resulted in several new types of photodetector including quantum well intersubband photodetectors (QWIPS), strained layer superlattices (SLSs) and barrier detectors. Each of these technologies requires careful and expensive epitaxial layer growth and demand highly skilled technical capabilities. In addition, the manufacture of large area FPAs requires integration of photodetectors with CMOS signal read-out circuits, which are only possible by complicated hybrid solutions. InAsSb alloy has been proposed as an ideal candidate for room temperature operation due to its long minority carrier lifetime (> 850 ns at 250 K) [2]. However, obtaining high quality InAsSb material requires high technological precision for epilayer growth due to the lattice-mismatch with the substrate material.

In this proposal, we aim to utilise the advances of core-shell nanowires (NW) and unique quantum engineering, to overcome this difficulty. The peculiar geometry of NW offers a number of advantages including efficient strain relaxation, enhanced light absorption [3], long carrier diffusion length [4] and improved carrier collection efficiency [5]. There are challenges to explore the potential of NW for photodetectors, in particular:

- Controllable epitaxial growth of high-quality InAsSb NW materials;
- Severe surface states that degrade the detectivity of the photodetectors;
- Lack understanding of NW device working principle.
- Un-matured device processing for NW containing materials.

This project aims to address these challenges to demonstrate prototype of NW single-element photodetectors.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Through materials optimisation and device processing development, this project produces prototype NW single-element photodetectors exhibiting several advantages over the counterparts. Table 1 shows the detailed comparison in device performance.

Tab. 1. Device performance comparison with counterparts

Performance	MCT	InAs film	InAs NW
Room temperature	√	√	√
CMOS compatible	×	×	√
Cost	high	high	low

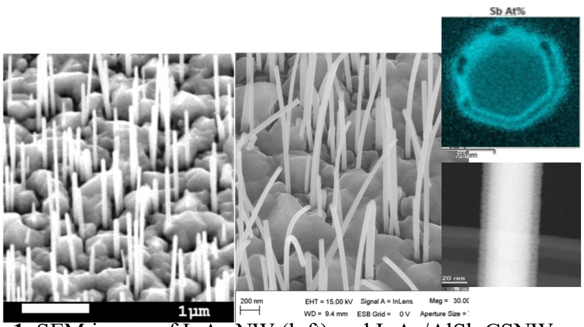

Fig. 1. SEM image of InAs NW (left) and InAs/AlSb CSNW (middle); TEM image of the CSNW: top-view top right and side-view (bottom right).

4. PROJECT RESULTS

We obtained high-quality InAs NW materials and optically efficient InAs/AlSb core-shell NW (CSNW) quantum materials. The NW-containing material device processing flow was also developed in particular the essential steps of PMMA filling, dry etching back for NW top and ultra-thin Au deposition for highly conductive and transparent top contact. Single-element photodetectors with different diameter and NW length were produced and assessed to conclude the optimal geometry of the devices, e.g. small diameter (< 25.0 um), long NW (>3.0 um), and a top contact of Ni/Au (5nm/5nm) provides efficient electrical conductivity and transparency.

Fig. 1 shows the SEM image of the bare InAs NW (left) and InAs/AlSb CSNW materials (middle) and TEM image showing the core-shell structure of top-view (top right) and side-view (bottom right). Table 2 summaries the transparency and reflectivity of Au, Cr/Au and Ni/Au deposition at different thicknesses showing an optimal think film is Cr/Au (5nm/5nm) which gives transmission of 48% (close to bare silicon of 54%).

The I-V profile of single-element InAs-NW/silicon photodetectors with different NW length is show in Fig. 3 (left) with a typical spectral photoresponse measured at room temperature (right). It can be concluded that NW devices with long axial length is functional for photodetection which is attributed to the build-in electric field of the pn-junction.

Tab. 2. Summary of absorption (A), transmission (T) and reflectance (R) for different thin metal film

Thin film (nm)	A	T	R
Silicon	0	0.54	0.46
Au/5	0.01	0.52	0.47
Au/10	0.25	0.12	0.63
Cr/5-Au/5	0.18	0.34	0.48
Ti/5-Au/5	0.08	0.48	0.44

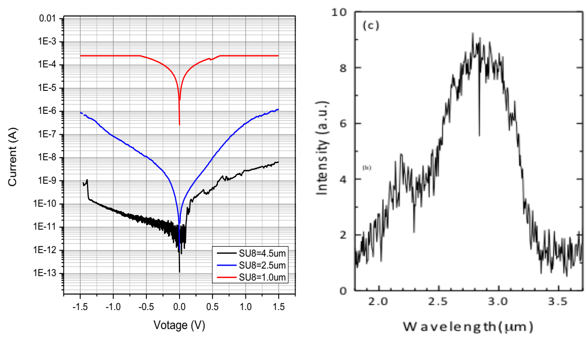

Fig. 3. I-V profile of InAs-NW/silicon single-element photodetector (left); and the spectral photoresponse of the device at room temperature (right).

5. FUTURE PROJECT VISION

We are enthused to potential ATTRACT phase 2 call, to explore our technology further. With participating of new partners, we will forge a consortium that has complimentary expertise in infrared detectors development and product, including Lancaster University, Sheffield University, Liverpool University, Gas Sensing Solution UK and Thales UK. We envisage a three years project of €0.8 m to develop the technology from TRL 2/3 to 4/5 with commercialisation exploration led by industrial partners.

5.1. Technology Scaling

To scale up the technology, we will develop the photodetectors in three aspects: (i) epitaxial growth of large wafer of controllable NW materials in terms of areal density, diameter and length with high uniformity. This will be achieved through patterned SiO2/Si wafers using nano-imprint technology, which has been proven to be the best and low-cost approach for highly uniform and dense NW material; (ii) optimise NW-containing device processing flow for high yield device fabrication with reproducible device performance, this includes materials chemical treatment for leakage current suppression, optimised metal deposition for high electric conductance with high light transparency, anti-reflectance dielectric film deposition; (iii) optimising design of device structure to maximise the light absorption, photo-carriers separation and collection, with more advanced nBn device structure to further improve detectivity and ambient temperature operation.

5.2. Project Synergies and Outreach

We would like to include more organisations with complimentary expertise to reinforce the consortium including Glasgow University for nano-imprint silicon patterning; specialist of infrared photodetector device fabrication at Sheffield University, photodetector evaluation at Thales UK, and infrared photodetector user at Gas Sensing Solution who will deploy our photodetectors onto their gas sensing instrument. With these new participants, the consortium is capable to deliver NW materials, infrared photodetector fabrication, photodetector characterisation, and industrially environmental evaluation, to improve the technology further to TRL4-5.

A website will be created to publish the updates on ATTRACT phase 2 including activities and research outcomes. We will continue to publish the research results in the top journals in the area (Nano Letters, Advanced Functional Materials etc). we will contribute oral and poster presentations to the major conferences and workshops including Internal Conference in MBE, EURO-MBE, Nanowire Workshop, international symposium of sensors and Advanced Semiconductor Manufacturing Conference.

5.3. Technology application and demonstration cases

We aim to implement demonstration case in health, environment and climate change related fields - portable gas sensor instrument using the photodetector de developed, for most common pollutant and hazardous gases in domestic environment, e.g. methane, CO2, CO, nitrogen dioxides and VOC compounds.

The success of the technology has applications in many important fields such as surveillance, food security, smart agriculture, environmental pollution monitoring.

5.4. Technology commercialization

We have been awarded IP Boost grant funded by EC to explore the IP landscape and identify commercial pathways for this technology. This service accelerated the commercialisation of research and Gas Sensing Solution has expressed their interest already.

5.5. Envisioned risks

The core risk will be faced in a potential ATTRACT Phase 2 project for this technology is the nanowire materials growth, which requires a dedicated MBE epitaxial system, system down-time for services will delay the project, this will be mitigated by the use of second MBE system at Lancaster University. Additional risk is related to device fabrication, we will ensure an updated knowledge transfer between the cleanrooms for quick transfer of the device fabrication from one cleanroom to another one if this is needed.

This subsection should include a brief description of the core risks that your project will face in a potential ATTRACT Phase 2 project and a brief explanation of your mitigation strategy.

5.6. Liaison with Student Teams and Socio-Economic Study

Socio-economic study is important for any new technologies, it not only evaluates the importance of the technology but also help to develop or improve the technology further to address the societal challenges and global challenges. Two specialists from the consortium will be engaged with materials preparation and liaison with MSc level students team. This includes Dr Sergey Kafanov, who has internationally leading expertise in nanotechnology will deliver lecturing materials to explain how nanotechnology would help to enable advanced photodetectors; and Mr Julian Hayes, CEO of

Gas Sensing Solutions, who specialises in gas sensing technology will address the advances of spectroscopy-based gas sensing technology and explain how it can be used for pollution monitoring, wellbeing to the people work at home, as well as smart-agriculture.

6. ACKNOWLEDGEMENT

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