TYPE Mini Review
PUBLISHED 07 January 2025
DOI 10.3389/fsens.2024.1521727

OPEN ACCESS

EDITED BY
Sungyong Jung,
University of Texas at Arlington, United States

REVIEWED BY
Arun Uniyal,
Uttarakhand Technical University, India

*CORRESPONDENCE
Melaku Dereje Mamo,
melakudereje26@yahoo.com

RECEIVED 02 November 2024
ACCEPTED 11 December 2024
PUBLISHED 07 January 2025

CITATION
Mamo MD, Zigyalew Y, Gelan SE, Ntsendwana B and Sikhwivhilu L (2025) Advancements in NIR sensing for tuberculosis detection using dilute III-V semiconductors: current status and future prospects.
Front. Sens. 5:1521727.
doi: 10.3389/fsens.2024.1521727

Advancements in NIR sensing for tuberculosis detection using dilute III-V semiconductors: current status and future prospects

Melaku Dereje Mamo[1]*, Yaschelewal Zigyalew[1], Seid Emamu Gelan[2], Bulelwa Ntsendwana[3] and Lucky Sikhwivhilu[3]

[1]Materials Science and Engineering Directorate, Bio and Emerging Technology Institute, Addis Ababa, Ethiopia, [2]Health Biotechnology Directorate, Bio and Emerging Technology Institute, Addis Ababa, Ethiopia, [3]Advanced Materials Division, DSI/Nanotechnology Innovation Centre, Mintek, Johannesburg, Gauteng, South Africa

This mini-review focuses on the use of dilute III-V semiconductors for near-infrared (NIR) sensing and the detection of tuberculosis (TB) in both humans and animals. These composite materials could greatly improve the sensitivity and efficiency of NIR detection. Well, we start off with the effects of TB, old methods of detecting it, and the rise of NIR sensing technologies. The significance of dilute III-V semiconductors for NIR sensing is discussed and the fabrication, properties, and performance of these semiconductors with organic matrices is explored. In this study we test the efficiency of NIR sensors in detecting TB across different species, and discuss the problems and drawbacks that are inherent in the use of these sensors. Lastly, we offer some suggestions for the field of future research and development, stressing the importance of this need for constant innovation. The purpose of this is to hopefully show the possible uses of these hybrid materials, and how they can enhance NIR sensitivity, and open the door to new diagnostic platforms.

KEYWORDS

near-infrared (NIR) sensing, tuberculosis (TB) detection, dilute III-V semiconductors, hybrid materials, device integration, diagnostic platforms

1 Introduction

Tuberculosis (TB) is one of the foremost social determinants of health which has remained a leading international health issue causing illness and death across the globe to human and animals. TB is caused by *Mycobacterium tuberculosis* and results in severe respiratory and systemic infections in animals and humans and cross transmission between animals and human beings. TB is regarded one of the deadliest infectious diseases in the entire world and despite the present-day advancement in medical facilities and technologies, it's amongst the leading ten causes of death globally, approximately 10 million people get affected by the disease in the year, 2020 along with 1.5 million deaths, TB is a serious global concern (WHO, 2020; WHO, 2021). The countries' TB incidence rate for year 2023 as presented in Figure 1 also paint a picture of how severe TB is around the world.

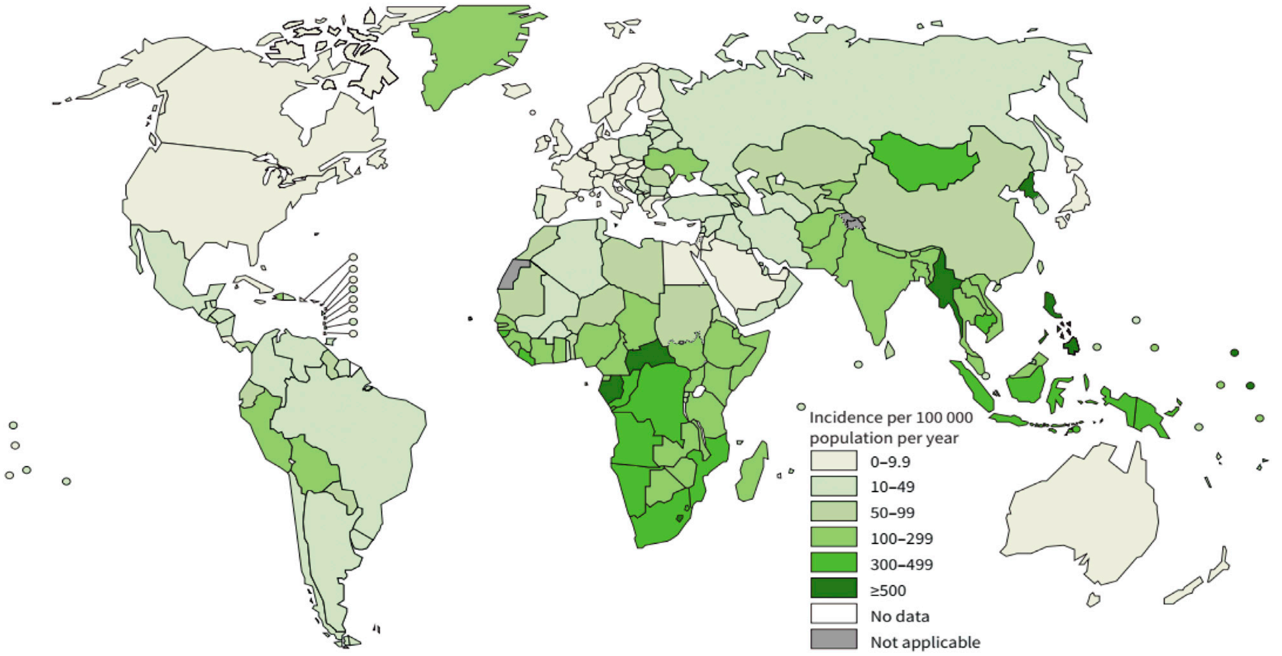

FIGURE 1
Estimated TB incidence rates, 2023. Source: WHO, Global Tuberculosis Report 2023. Retrieved from (WHO, 2024).

1.1 Consequences and potential cross-over of TB from humans and animals

TB has social and economic implications. They most adversely affect the economically challenged populace, compounding poverty and destabilizing the economy. The consequences of losing the workforce productivity and rising healthcare costs are to overload the healthcare systems (Timire et al., 2024). TB that is resistant to the drugs is one of the major challenges. TB is on the rise thanks to multidrug-resistant TB (MDR-TB) and extensively drug-resistant TB (XDR-TB), which complicate the treatment and control of the disease (WHO, 2021).

The effects and the mode of transfer of tuberculosis both to humans and animals is a complicated process with involvement of several microorganisms, *Mycobacterium* bovis and *M. tuberculosis* being the most important. These mentioned pathogens affect health and are considered as the problem in relation to zoonotic transmission. Knowledge of the transmission and spreading of tuberculosis requires integrating human and animals' ecological niches as well as various environmental factors (Conteddu et al., 2024; Duffy et al., 2024).

TB infection is transmitted through aerosols, mouth, remaining in the environment, wildlife and two-way and reservoir host zoonotic transmission. Consequently, it can be transmitted in several ways: Types of transmission includes Human to Human (Centers for Disease Control and Prevention, 2024), Animal-to-Human (Macedo et al., 2020), and Human-to-Animal [(Sawyer et al., 2023; Lombard et al., 2021)] transmission.

Environmental persistence plays a significant role in TB transmission, as *M. tuberculosis* and *Mycobacterium* bovis can survive in the environment, particularly in contaminated water or soil, allowing for indirect transmission (Zhang and Fan, 2022). Interspecies interactions, notably between cattle and wildlife, facilitates the spread of M. bovis, and seasonal fluctuations influence these dynamics (Ferreira et al., 2024). These varied transmission pathways underscore the widespread and persistent nature of TB, as depicted in Figure 2 which illustrates global trends in the estimated number of incident TB cases and the incidence rate from 2010 to 2023.

Tuberculosis alone remains as a human disease and a zoonotic disease require urgent attention and control in systematic manners. To develop a correct approach to measures of preventing the development of tuberculosis in humans and animals it is necessary to understand the ways of the sickness transmission. Considering the harsh impact of tuberculosis on the physic, the national economy and the society in general this disease is still a priority in the activities carried out in the sphere of international health. Transmission from humans to cattle has been documented and hence there is concern on the zoonotic aspect of TB together with the One Health approach in dealing with the TB in both species (Lombard et al., 2021). One Health strategy is a useful approach in TB control and involves the interaction between human, animals and environmental health to manage the transmission risks (Zhang and Fan, 2022).

1.2 Conventional and newly emerging methods of TB detection

Predominantly, TB in humans is diagnosed by clinic examination, laboratory tests and imaging. The conventional approaches to the detection of TB encompasses Sputum Smear

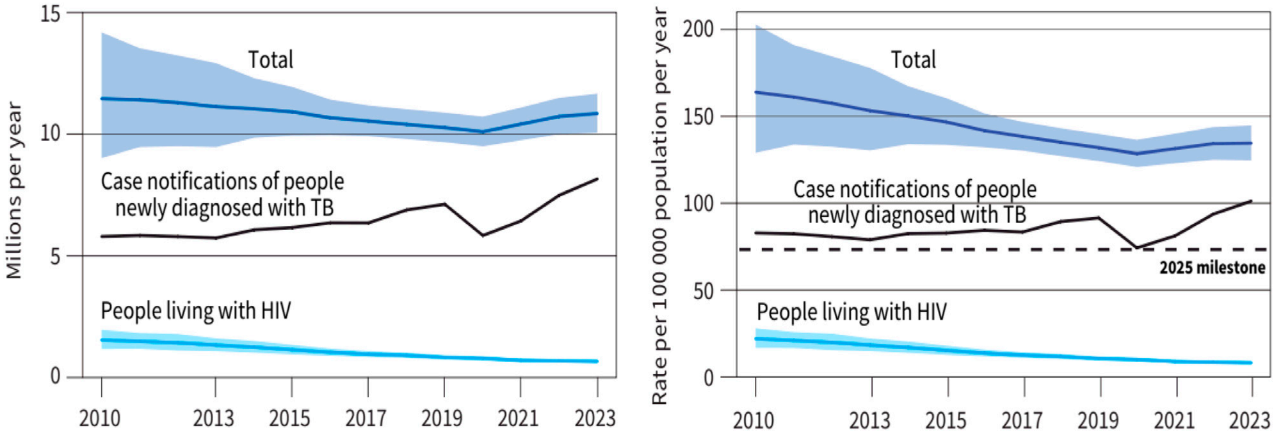

FIGURE 2
Global trends in the estimated number of incident TB cases (left) and the incidence rate (right), 2010–2023[a]. Source: WHO, Global Tuberculosis Report 2024. Retrieved from (WHO, 2024) [a]*The horizontal dashed line shows the 2025 milestone of the End TB strategy, which is a 50% reduction in the TB incidence rate between 2015 and 2025. Shaded areas represent 95% uncertainty intervals.*

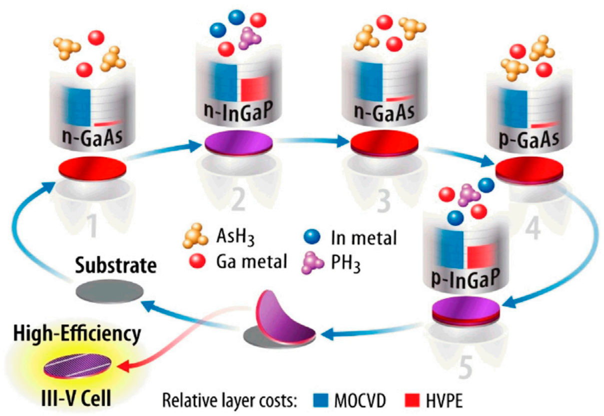

FIGURE 3
Schematic of the in-line HVPE reactor used to grow low-cost single junction GaAs solar cells, together with a substrate reuse technology. Adopted from (Simon et al., 2019).

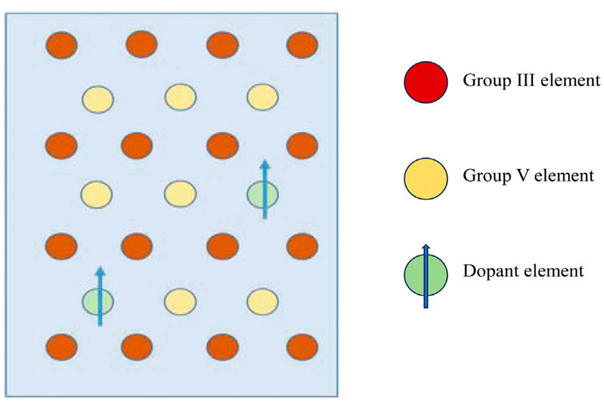

FIGURE 4
Diagram for introduction a small fraction of magnetic dopant element into III-V crystal lattice [Adapted and modified from (Gupta et al., 2020)].

Microscopy, Mycobacterial Culture and Molecular Biology Diagnostics (Xpert MTB/RIF assay, Loop Mediated Isothermal Amplification, and Digital Polymerase Chain Reaction) and Immunological Diagnostics (Tuberculin Skin Test, Cytokine release Interferon-γ assays, Immuno PCR, and Lateral Flow Urine Lipoarabinomannan Assay) (Dong et al., 2022).

Smear microscopy (Ziehl-Neelsen Staining and Fluorescent Microscopy) and culture techniques (Bacterial Culture and Drug Susceptibility Testing (DST)) are the most common methods used to identify TB and have been used for decades (Miller et al., 2017). However, these methods often suffer from limitations including low sensitivity (Shivakumar and Shettigar, 2022) (Wazahat et al., 2023), time efficiency (Dong et al., 2022; Mugenyi et al., 2024), and the need for skilled and laboratory infrastructure (Miller et al., 2017; Januarie et al., 2022). For example, although Bacterial Culture Techniques are regarded as the gold standard, cultures can take 2–4 weeks to provide results, delaying diagnosis and therapy (Mugenyi et al., 2024). Cultures may not identify all resistant strains immediately, but they are regarded as vital for determining drug resistance (ÖZTÜRK et al., 2023).

On the other hand, Chemical Probe Methods, Cell Envelope-Dependent Probes, BlaC-Specific Fluorogenic Probes, Probes Dependent on Sulfatase, Esterase, Protease, and Nitroreductase, Clustered Regularly Interspaced Short Palindromic Repeats, Mass Spectrometry, Immunosensors, and Next-Generation Sequencing Technology are among the new and promising diagnostic techniques for tuberculosis detection (Dong et al., 2022). Although Bacterial Culture Techniques are regarded as the gold standard, cultures can take 2–4 weeks to provide results, delaying diagnosis and therapy (Mugenyi et al., 2024). Cultures may not identify all resistant strains immediately, but they are regarded as vital for determining drug resistance (ÖZTÜRK et al., 2023).

Biochemical detection by Surface Plasmon Resonance (SPR) also has a significant role within the sensing domain to identify many biomarkers due to high sensitivity and real-time measurement execution. Biosensors based on SPR allow measuring the interaction of a great number of biological molecules, so they are widely used in

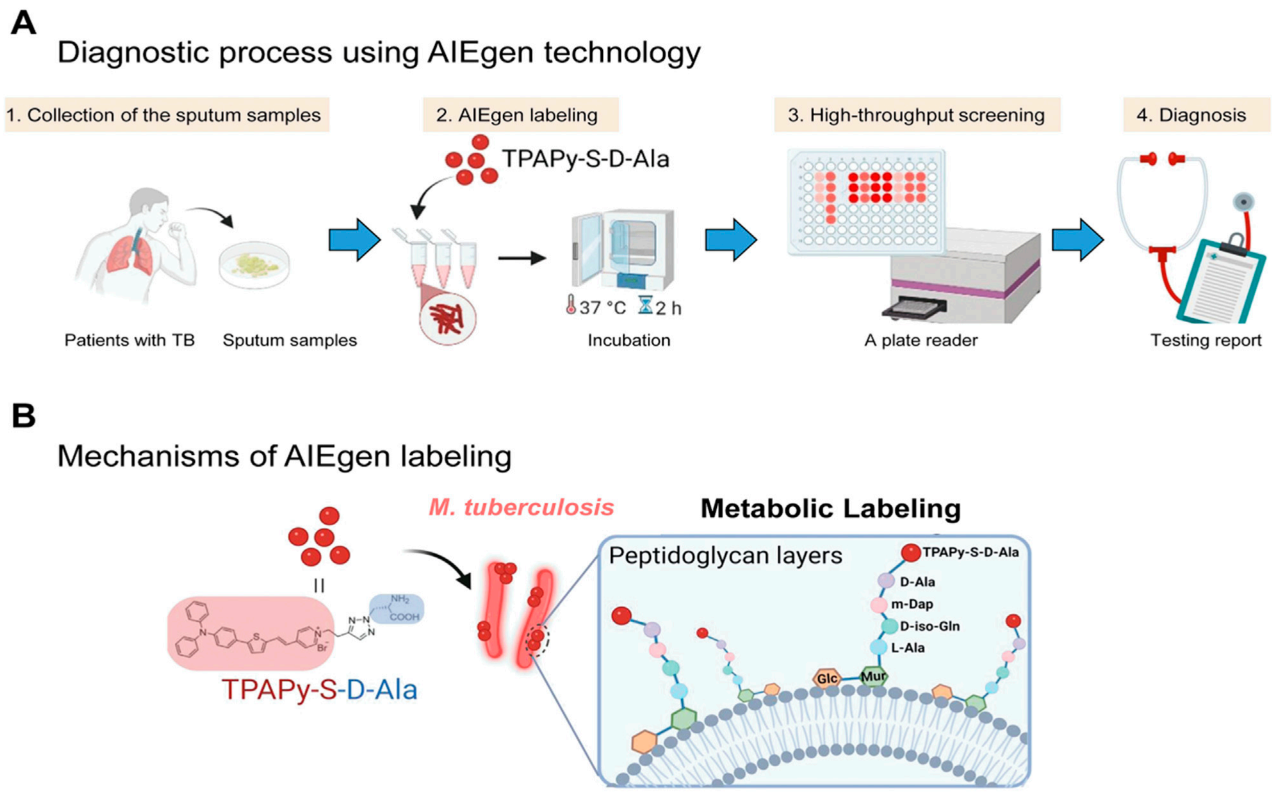

FIGURE 5
Introduction of a newly developed AIEgen for POC diagnosis of a *Mycobacterium tuberculosis* infection. Adopted from (Dai et al., 2023).

the diagnosis of various diseases and monitoring the environmental conditions. Due to their capability of giving simultaneous and label-free detections they are useful in different areas (Homola et al., 1999). Incorporation of SPR with dilute III-V semiconductors helps researchers to design and develop more accurate and efficient TB diagnosis systems so as to enhance further development in the biomedical sensing technologies. And they can attain effective integration of these materials with SRP sensors by developing hybrid structures that enhance their performance and utilizing advanced integration techniques. For example, integration of GaN and other III-V semiconductors in SPR sensors has shown higher detection attributes because of these materials' excellent electronic and opto-electronic features (Senapati et al., 2024). These developments enhance the sensitivity and specificity of SPR sensors. They expand the zones of practical utilization of the diagnostic fields, including TB detection (Kumari et al., 2024).

However, simple and basic methods are still relevant, especially in terms of determining the etiology of infection in developing countries. However, the need for rapid, accurate and inexpensive diagnostic tools remains an impetus for TB research and development.

1.3 Drawbacks associated with conventional TB detection methods

Even if traditional methods are essential for TB diagnosis and treatment, they have shortcomings. Each traditional approach for tuberculosis screening has particular disadvantages that limit its efficiency and accessibility. However, some proponents state that traditional modalities are still necessary in resource-limited settings because of the issues related to cost and standard protocols where technology may not be highly available, therefore a balanced approach between traditional and high-tech diagnostic techniques should be considered (Danasabe Isah and Aliyu Makusidi, 2020).

These-Several-significant disadvantages prevent rapid and accurate diagnosis. Smear microscopy and culture methods have low sensitivity, large false negative rates, and the inability to discriminate live from dead bacteria or antibiotic resistance (Dong et al., 2022). They are also time-consuming and inefficient in that patients may get diagnosed with diseases they do not have or delay seeking appropriate treatment, a situation that is worst in high disease burden settings (Danasabe Isah and Aliyu Makusidi, 2020). These limitations are especially obvious in high-burden settings and among vulnerable patients, such as HIV co-infected individuals with limited sputum output (Lin et al., 2023).

However, it is important to know these limitations and the associated key drawbacks summarized in Table 1 to further refine the tuberculosis diagnostics and better understand the ways to use the integrated approach to early diagnosis and treatment.

1.4 Emergence of NIR sensing for detection and other purposes

NIR spectroscopy uses light absorption to analyze chemical composition in materials (Oñate et al., 2024). And NIR sensors illuminate the examined object with NIR light for non-invasive identification and characterization in different fields. NIR sensing is mostly defined to work in a wavelength of 700–2,500 nm. This range is particularly beneficial as many organic compounds exhibit distinct abs such that there is an ability to identify different materials.

The emergence of this sensing technology presents a promising solution to these challenges. The benefits of NIR sensing involve speed, non-contact nature, high resolution, accurate identification of TB at an early-stage (nan Zhang et al., 2021). This technology can be transformative in TB diagnostics as it can make diagnostics faster and portable for better performance rather than traditional techniques which do not work well in the resource-limited environments.

Its growing applications include food and agriculture (Jha, 2010), medical and pharmaceutical applications (Sakudo, 2016), environmental monitoring (Chandra et al., 2022), and emerging technologies and innovations, as recent advancements in NIR sensing technologies, such as miniaturization, portable devices, and the incorporation of artificial intelligence, have expanded its applications. Up-to-date NIR gadgets are portable which allow real-time evaluation in numerous settings making the technology more available (Gullifa et al., 2023), underlining its possibilities of evolution. Despite these developments, challenges are still ahead as the technologies are little developed in the application of NIR sensing, and the material characteristics have to be optimized and the detection sensitivity has to be improved for various streams.

The key advancements and applications of NIR sensing technologies:

- Organic photodiodes (OPDs) have even higher detectivity (7.4 × 10ˆ11 Jones) and more wide range of sensitivity (500–900 nm), than previous ones and that is why OPDs are more suitable for optical communication and biometrics (Jan et al., 2024).
- These devices have primarily a linear dynamic range of about 74 dB which is suitable for several sensing applications.
- NIR luminescent materials, especially those containing rare earth and transition metal ions, have the potential bioimaging and photodetector properties due to their longer emissions on the operation of more than 1,000 nm (Li et al., 2024).
- Due to the ability to penetrate through the layers of living tissues, those applications embrace medicine diagnostics and environmental monitoring.
- NIR spectroscopy has been applied generally in environmental analysis by virtue of its non-destructiveness and its high sampling throughput that allows *in situ* investigation of soil and water (Wedding et al., 2011).
- This technology identifies contaminants/pollutants and assesses ecological condition, including new threats as micro plastics.
- Machine learning integration with NIR spectroscopy to increase material composition and pollutant detection is applied to foods and medication (Ozturk et al., 2023).
- Carbonized polymer dots (CPDs) are a promising optical material for NIR-II bio imaging, providing real-time, non-invasive disease imaging (Han et al., 2022).
- Their synthesis methods are inexpensive and produce the best imaging applications on the market.

From the materials currently employed in NIR sensing, dilute III-V semiconductors have been found to possess tremendous potential because of their optical characteristics and biocompatibility with tissues (Ayşe, 2018). These semiconductors allow the creation of highly efficient and compact NIR sensors that are essential for diagnostic processes undertaken at the patient's home or office and for screening many people simultaneously (nan Zhang et al., 2021).

However, progress in the specific area of NIR sensing technologies has been remarkable, but there are major knowledge and utility deficiencies that have not been addressed. The lack of comprehensive, up-to-date mini-reviews that compare TB sensing using different dilute III-V semiconductors, failure to point out the current limitations of NIR sensing for TB detection and future research directions makes this mini-review essential.

2 Fabrication of NIR sensors

Some of the critical aspects which define the fabrication of NIR sensors are substrate, absorber layer, electrodes, and encapsulation. Hence, the kind of materials to use in these components is very vital to give the best performance and sensitivity to the NIR sensors.

a) Substrate: Materials commonly utilized in construction of NIR sensor include indium phosphide which is abbreviated to InP and gallium arsenide famously known by its abbreviation GaAs. These materials exhibit good lattice match and high electron mobility for high performance NIR photodetector applications.
b) Absorber Layer: The absorber layer has to be of very thin layer of Indium Gallium Arsenide (InGaAs) with high absorption coefficient in the NIR region. Others which can be used are Lead Sulfide (PbS) and Mercury Cadmium Telluride (MCT) depending on the particular use desired.
c) Electrodes: For a semiconductor material the electrodes are typically created from metals including Gold (Au), Silver (Ag) or Aluminum (Al) because they offer good electrical conductivity and can easily be supplied to the semiconductor.
d) Encapsulation: Coating material such as Silicon Nitride (Si3N4) and Silicon Oxide (SiO2) is employed in encapsulation barrier to shield the sensor and improve its lifespan.

The integration of dilute III-V semiconductors into NIR sensors employ advanced epitaxial deposition methods like MBE and MOCVD (Ayşe, 2018). These methods provide the ability to achieve highly accurate control of the thickness and composition of the semiconductor layers, thus providing the means by which high-quality materials with tailored electronic and optical characteristics could be grown. MBE enables fidelity in the precise deposition of atomic layers to grow high quality dilute III-V semiconductors. For example, GaInNAs layers can be realised using MBE to bandgap properties suitable for specific application in the range of the Near-Infrared. CVD is employed to deposit GaInNAs epitaxial layers of high quality on substrates. This also helps in achieving very high control on the kind and thickness of the semiconductor layers (Raut, 2023).

Some of the more recent techniques such as Hydride Vapor Phase Epitaxy (HVPE) offers a way to grow high quality semiconductor layers with sharp heterojunction interfaces. The HVPE technique is most advantageous in the high throughput rate or in applications that must be manufactured with lower cost production (Simon et al., 2019). For example, the schematic of the in-line HVPE reactor used to grow low-cost single-junction GaAs is depicted in Figure 3. Another method also commonly used simultaneously with epitaxial growth methods to implant nitrogen into III-V semiconductor is implantation of nitride ions and it results in a reduction of the bandgap and improved optoelectronic properties (Liu et al., 2023).

3 Dilute III-V semiconductors

III-V Semiconductors are alloys of compounds from group III and group V elements of the periodic table. Together these parts compose binary compounds such as GaAs or Gallium Arsenide, InP or Indium Phosphide, and AlN or Aluminum Nitride. These semiconductors possess good electron mobility, direct band gaps and a high thermal stability that favors its application in optoelectronics devices; light-emitting diodes (LEDs), lasers diodes, and high-speed electronics.

In Dilute III-V Semiconductors, the term "dilute" is used to describe the inclusion of a small concentration of magnetic atoms into the III-V crystal lattice (Zheng, 2008). These doping elements might be magnetic substrates like elements from the transition metal series or other elements that influence the material's electronic and optical characteristics. For instance, Manganese is added to GaAs lattice to obtain GaMnAs, a material with desired magnetic characteristic, similarly Nitrogen is added to GaInAs to produce desired GaInAsN having a lower bandgap suitable for infrared uses (Ayşe, 2018). The diagram that shows the introduction of a small fraction of magnetic dopant element into the III-V crystal lattice is depicted in Figure 4. For this reason, unlike the conventional semiconductors, they have both magnetic and semiconductor characteristics.

3.1 Preparation and properties of dilute III-V semiconductors

Dilute III-V semiconductors can be grown by various techniques including MBE and MOCVD. These methods enable precise control of the composition of the compound, dopants, and the quality of the crystalline lattice (Zheng, 2008). For instance, it is possible to minimise the band gap in III-V semiconductors through the introduction of nitrogen; the material can therefore be used in devices such as lasers and solar cells (Ayşe, 2018).

a) Structural Properties: Dilute III-V semiconductors often exhibit high crystalline quality and can be can be deposited as a thin film with low density of defects (Ayşe, 2018).
b) Optical Properties: These materials generally possess direct band gaps, which render the appropriate efficiency in optoelectronic processes (Cheng, 2023). For instance, the use of GaInNAs/GaAs quantum wells has been done to investigate on their optical characteristics.
c) Thermal Properties: The thermal stability of dilute III-V semiconductors is of paramount importance since it characterizes the performance of a device. For example, ion beam sputtering and thermal reconstruction techniques are employed to improve their thermal performance qualities (Ghita et al., 2017).
d) Morphological Properties: Essential to fabrication of these devices, the chemical etching and thermal treatments can be utilized to manipulate the surface morphology of these semiconductors (Ghita et al., 2017).

3.2 Performance enhancement of dilute III-V semiconductors

Various performance enhancement modifications have been made in order to improve the electrical, optical, and magnetic properties of dilute III-V semiconductors. These include raising their carrier mobilities, lowering their defects, improving their magnetic characteristics, and making modifications by tuning the band gap, that ensures they are more efficient and effective for use across different applications.

a) Epitaxial Growth Techniques: Through the MBE and MOCVD common preparation processes that are used, doping levels, as well as the overall composition of the material, can be tightly controlled. These are basic methods of obtaining high quality material that can be followed up in one way or the other.
b) Band Gap Engineering: The introduction of specific dopants like Nitrogen to GaInAsN aims at reducing the band gap of the semiconducting material to attain adequate optical characteristics optimum for infrared application especially for the NIR sensing application. For instance, incorporation of Manganese into GaAs lattice and Nitrogen into GaInAs is reported (Ayşe, 2018), Zhao et al., also investigated and discussed the incorporation of Nitrogen into GaInNAs/GaAs quantum well structures along with the reduction of the band gap and improvement of their optical properties for NIR photodetectors (Zhao et al., 2005).
c) Defect reduction: The imperfections in the crystal structures of such semiconductors are normally alleviated through thermal treatments and chemical processes. This also enhances their carrier mobilities and decrease the recombination losses which are key aspects of the material that finds application in electronic as well as opto-electronics.
d) Strain Engineering: For changing and enhancing the electronic and material properties of the semiconducting materials mechanical strains are normally used frequently in conjunction with other methods.
e) Increasing Curie Temperature: Nevertheless, there several attempts that have been made to obtain room-temperature ferromagnetism which is crucial for spintronic related applications such as optimizing doping concentrations and material properties.

TABLE 1 Summary of key drawbacks associated with these traditional methods.

No.	Tests	Drawback 1	Drawback 2	Drawback 3
1	Tuberculin Skin Test (TST)	False Positives: Individuals with prior BCG vaccination or other mycobacterial infections may test positive, complicating diagnosis (Trajman et al., 2013)	False Negatives: Immunocompromised individuals (e.g., those with HIV) may not mount an adequate immune response, leading to false-negative results (Vittor et al., 2014)	Subjectivity: Interpretation of induration size can vary between healthcare providers, affecting consistency (Nevada Division of Public and Behavioral Health, 2018)
2	Interferon Gamma Release Assays (IGRAs)	Cost: IGRAs are generally more expensive than TSTs, which may limit their use in resource-limited settings (Weyer et al., 2011)	Limited Usefulness in Children: IGRAs are less validated for children under 5 years old, leading to uncertainties in diagnosis (Mandalakas et al., 2011)	No Differentiation: Like TSTs, IGRAs cannot distinguish between latent TB infection (LTBI) and active TB disease (Goletti et al., 2022)
3	Sputum Smear Microscopy	Sensitivity Issues: This method may miss up to 50% of cases, especially in patients with low bacillary loads or extrapulmonary TB (WHO, 2016) Sputum smear microscopy has a low sensitivity, often failing to detect TB in patients with low bacterial loads (Dong et al., 2022) (Pai et al., 2023)	Time-Consuming: Preparing and examining slides can take time, delaying diagnosis (Boehme et al., 2010)	Operator Dependency: Accuracy is highly dependent on the skill of the technician, which can lead to variability in results (Boehme et al., 2010)
4	Culture Techniques	Time-Intensive: Culture-based methods require 3–4 weeks for results, delaying treatment initiation (Dong et al., 2022) The slow turnaround of conventional tests contributes to ongoing transmission and increased morbidity (Danasabe Isah and Aliyu Makusidi, 2020)	Laboratory Infrastructure: Requires specialized laboratory conditions and personnel, which may not be available in all settings (WHO, 2016)	Contamination Risks: Cultures can be contaminated, leading to false-negative or false-positive results (Asgharzadeh et al., 2015)
5	Chest X-ray	Non-Specificity: While helpful for suggesting TB, X-rays cannot confirm the diagnosis and may indicate other lung diseases (Centers for Disease Control and Prevention, 2024)	Radiation Exposure: Although low, exposure to radiation is a concern, particularly in populations needing frequent screening (Vo et al., 2021)	Limited Access: Access to radiography may be limited in low-resource settings (Vo et al., 2021)
6	Nucleic Acid Amplification Tests (NAATs)	Cost and Accessibility: NAATs can be expensive and require specialized equipment, making them less accessible in resource-poor environments (Narasimhan et al., 2023)	Limited Sensitivity for Non-Pulmonary TB: These tests may be less sensitive in detecting extrapulmonary TB compared to pulmonary TB (Pai and Ling, 2008)	Potential for False Positives: In certain contexts, NAATs may yield false positives due to the detection of non-viable organisms (Paul E Klapper and van Loon, 2010)

TABLE 2 Techniques for performance enhancement of dilute III-V semiconductors.

Technique	Approach	Objective	Outcomes	Relevant literature
Epitaxial Growth	MBE, MOCVD	High-quality crystal growth with precise doping control	Enhanced material quality	Matsukura et al. (2002)
Band Gap Engineering	Doping with elements like nitrogen	Tuning band gap for specific applications	Optimized optical properties	Zhao et al. (2005)
Defect Reduction	Thermal annealing, chemical treatments	Reducing defects in crystal lattice	Improved carrier mobility	Zhang et al. (2021)
Strain Engineering	Applying mechanical strain	Modifying electronic properties	Enhanced performance	Sun et al. (2010)
Increasing Curie Temperature	Optimizing doping levels, improving material quality	Achieving room-temperature ferromagnetism	Practical applications in spintronics	Matsukura et al. (2002)
Improving Material Quality	Enhanced growth techniques, defect management	Higher crystallinity and fewer defects	Enhanced electronic properties	Park et al. (2020)
Optimizing Doping Levels	Precise control over doping concentration	Balancing magnetic and semiconducting properties	Improved device performance	Schott et al. (2004)

f) Improving Material Quality: Different growth and post-growth methods are employed to minimize defects and increasing the crystal quality and therefore straight away affecting the magnetic and electronic characteristics in the film.
g) Optimizing Doping Levels: The doping concentration determines the magnetic and semiconducting properties for spintronics and optoelectronics and it is very sensitive if the desired balance of the two is to be achieved. For example, GaMnAs is one of the most investigated dilute III-V semiconductors which exhibit ferromagnetic property at low temperature. Scientists pay attention to its elevation of Curie temperature and quality improvement through the reduction of defects and optimum doping (Matsukura et al., 2002).

TABLE 3 Summary of key features of NIR sensor technologies in TB detection.

Technology	Key features	References
AIEgen Labeling	High sensitivity (95.5%) and specificity (100%) for TB detection in sputum samples	Dai et al. (2023)
Photonic Crystal Sensors	High sensitivity (1738.7 nm/RIU), ability to distinguish between TB strains	Mohammed et al. (2023)
Non-Invasive Saliva Test	Uses NIR sensors to detect TB biomarkers from saliva samples	Kasule et al. (2024)
Mobile NIR Sensing	Portable devices for on-site testing and immediate results	Jiang et al. (2024)

TABLE 4 Application of NIR sensors in livestock and their advantages and limitations.

Applications of NIR sensors in livestock	Advantages	Limitations and challenges
1) Bovine Tuberculosis (bTB): Bovine TB, caused by *Mycobacterium* bovis, significantly impacts cattle health and the agricultural economy. NIR sensing has been explored as a tool for early detection and monitoring of bTB (Feng et al., 2021)	a) Cost-Effectiveness: Compared to traditional diagnostic methods, NIR sensing can reduce costs associated with laboratory testing and transport of samples (Bellon-Maurel and McBratney, 2011)	a) Sensitivity: While NIR sensing has shown promise, its sensitivity to low pathogen loads remains a challenge, particularly in early-stage infections (Nißler et al., 2020)
2) Milk Analysis: NIR sensors can analyze milk samples to detect the presence of M. bovis or associated biomarkers, allowing for screening of infected animals within herds (Tsenkova and Munćan, 2021)	b) It offers a non-invasive approach to detecting TB by analyzing spectral fingerprints of *Mycobacterium tuberculosis*, distinguishing it from other bacteria like *E. coli* (Pesala et al., 2012)	b) Field Implementation: The practical deployment of NIR sensors in agricultural settings requires appropriate training and infrastructure, which may not be readily available in all regions (R. M. et al., 2010)
3) NIR-based assays, such as ELISA test, achieved high sensitivity and specificity for bovine tuberculosis, making them suitable for field use (Moens et al., 2023)		c) Capital Investment: The initial cost of NIR equipment can be prohibitive, especially in developing countries (R. M. et al., 2010)
4) Genetically engineered NIR fluorescent reporter strains enable real-time visualization of *Mycobacterium tuberculosis* in live animals, facilitating effective evaluation of drug efficacy (Sommer and Cole, 2019)		

TABLE 5 Opportunities, disadvantages, and challenges of NIR Sensors for other (not human and animal) purposes.

	Opportunities of NIR sensors	Disadvantages and challenges
1	Rapid and non-destructive: Advantageous for continuous monitoring without destroying samples, making it suitable for field applications (Gullifa et al., 2023)	Sensitivity issues: Detecting low concentrations of mycobacterial DNA or proteins in environmental samples can be challenging, limiting the effectiveness of NIR sensors in certain contexts (Nißler et al., 2020)
2	Versatility: The ability to analyze various types of samples, including liquids and solids, broadens the scope of their applications in TB-related research and monitoring (Munawar et al., 2021)	Calibration and Standardization: NIR data interpretation requires careful calibration and standardization to ensure accuracy, which can complicate the deployment of this technology in diverse settings (Liu et al., 2014)

The structured summary for these techniques is listed and summarized in Table 2 below. It is useful to review different goals and accomplishments of each approach and reference pertaining to each method.

4 Evaluation of NIR sensors in TB detection

4.1 For human use

NIR sensors have shown considerable promise in the detection of TB in humans. These sensors u use near infrared spectrum to detect characteristic biomarkers of the TB infection. Research has shown that the use of NIR sensors enhances the possibility of recognizing TB in the shortest time possible, eliminating the traditional methods that take longer time for processing and are compounded with the need for laboratory facilities.

In other clinical research studies, NIR sensors have been tested and found to be highly sensitive and specific thus can be used in diagnosing TB in all settings, including in remote and inadequately-equipped areas. For instance, researchers have shown non-invasive saliva tests which employ NIR sensors for detecting TB biomarkers using NIR sensors; they also use volatile organic compounds in exhaled breath for TB identification, and, by sampling oral swabs, they can obtain rapid and accurate results in TB detection (Kasule et al., 2024). NIR sensors can be accommodated in mobile devices, which makes rapid testing at the site of probable infection possible and get immediate results, which is critical and basis for proper use of the limited resources in a resource-limited environments (Jiang et al., 2024).

Hence, the new generation NIR diagnostics offer more diagnostic value for tuberculosis: Particularly Aggregation-Induced-Emission Luminogen (AIEgen) labeling and photonic crystal sensors, have high sensitivity and specificity for tuberculosis diagnosis. AIEgen Labeling also shows the diagnostic sensitivity of 95.5% and diagnostic specificity of 100% and a diagnostic effectiveness of 95.7% in identification of *M. tuberculosis* in human sputum samples. (Dai et al., 2023). The mechanism illustrating the introduction of a newly developed AIEgen for point-of-care (POC) diagnosis of Mycobacterium tuberculosis infection is depicted in Figure 5.

Photonic Crystal Sensors has the large sensing parameter of up to 1738.7 nm/RIU and also the capability to differentiate the TB strains thereby making the sensors perfect for early diagnosis (Mohammed et al., 2023). NIR sensors demonstrate promise, however, there are concerns when it comes to their widespread application and intensive study in many forms of clinical applications. Table 3 presents an overview of the characteristics of NIR sensor technologies for TB diagnosis.

4.2 For animal use

NIR sensing technology was found to be offering a worthwhile means of identifying the TB for the animals, especially the cattle. Its non-invasive nature and timely outcome can be useful in improving disease management procedures. TB can infect different animals, including livestock and wildlife, hence can pose a risk of zoonotic transmission to humans. Therefore, it is important to detect TB early in animas to avoid incidence and to promote overall animal welfare.

New techniques using NIR spectroscopy are also novel tagging techniques that hold promise for detection of *Mycobacterium* TB in cattle especially where standard procedures may not work well. For example, current studies present saliva diagnostic tests that identify biomarkers of TB with the help of NIR sensors. These sensors can quantify volatiles in the breath to establish the infection with TB and determine TB biomarkers in oral samples rapidly. A recent study in clinical trials showed that NIR sensors provided high sensitivity and specificity, which recommend the method for early TB diagnosis in a range of healthcare models, including remote and developing nations.

Previous studies revealed that NIR sensors can selectively detect TB biomarkers in animal tissues to aid veterinary medicine and wildlife management. For instance, NIR fluorescence imaging has been applied to measure the activity of TB drugs in live mice, thus, dynamic evaluating the bacterial load (Sommer and Cole, 2019). Furthermore, NIR sensors have been utilised in identification of *Mycobacterium* bovis DNA in nasal swabs and saliva of experimentally infected calves (Palmer et al., 2024). Table 4 summarizes the application of NIR sensors in livestock and their advantages and limitations. These advances suggest that NIR technologies have the ability to revolutionize the way that TB is diagnosed in people and animals (Dai et al., 2023). The possible integration of NIR technology could help boost the performance of the identification of TB in animals, which can be useful in containing possible outbreaks.

4.3 For use in others

The principle of NIR sensing technology is quite broad not only in the diagnosis of human beings and animals but also in environmental and pathogen analysis. In TB detection, NIR sensors show attractive enhancement in the diagnostic techniques through the use of certain optical properties to enhance the detection parameters of the target pathogen *M. tuberculosis*, which is paramount in early diagnosis of the disease. These sensors examine how chemicals absorb near-infrared light and how specific chemical bonds and molecules are present; thus, changes related to tuberculotic biochemical changes in the environment, including the soil or water, can be detected (Beć et al., 2021).

NIR sensing is also used in environmental monitoring to identify the presence of *M. tuberculosis* or *Mycobacterium* bovis in contaminated environments needed in the understanding of the location of TB reservoirs within the environment (Dai et al., 2023). In the same regard, NIR sensors quantify the amounts of organic matter and microbial loads in soil that might harbour TB pathogens (Pereira et al., 2024). It is also applied, for example, inindustrial processes that involve fermentation to produce antibiotics or other chemicals that are used in tuberculosis cure (Mobed et al., 2024).

Moreover, NIR sensors have potential in hospital environments, labs, and other facilities that potentially expose people to airborne TB, as estimators of how vulnerable the environment is to spewing TB across large areas. The opportunities, disadvantages, and challenges of NIR sensors for other (not human and animal) purposes are summarized in Table 5. They can also be incorporated in portable diagnostic devices on field surveys and often epidemiological investigations as they give fresh data.

5 Challenges and limitations

5.1 Challenges associated with material compatibility and stability

The degradation of optical and electronic quality of GaInNAs when grown on GaAs substrates is influenced by several factors:

a) Lattice Mismatch: One of the most critical issues associated with the present high-index substrate is lattice mismatch. The lattice mismatch between the high-index substrates and dilute III-V semiconductors, such as GaInNAs on GaAs, generates a high density of dislocations and defects that affect the material's electronic and optical properties (Shan et al., 2006). For example, When GaInNAs is grown on GaAs substrate, since the lattice constants of both materials differ, some strains will be created, resulting in dislocations that act as non-radiative recombination centers. These centers reduce the efficiency of photoluminescence and carrier lifetime, which are critical for optoelectronic appliances (Speck and Rosner, 1999; Ayşe, 2018).
b) Thermal Stress: Another serious concern is the tendency of these materials to degrade at high temperatures. Temperature plays a critical role in the degradation of material properties during device fabrication or during operation. (Ayşe, 2018), (Shan et al., 2006). Temperature-induced stresses in dilute III-

V semiconductors can degrade their long-term reliability and performance by causing defect formation, dislocation glide, and material fatigue. These stresses can be caused by thermal cycling or high-temperature exposure, which result defect formation in the form of dislocations and/or cracks that degrade the mechanical reliability and electronic characteristics of the devices. Cumulatively, it leads to higher device failure rates, and reduced operational lifetimes (Ayşe, 2018).

Thermal expansion coefficient variation between the substrate and epitaxial layers also results to stress and dislocations within the material (Fahrenkopf et al., 2024). The mismatch in thermal expansion coefficients between the substrate and epitaxial layers can cause the epitaxial layer to expand or contract at a different rate compared to the substrate during temperature changes. This induces thermal stress, leading to the formation of cracks and dislocations. These defects degrade the material quality and performance of NIR sensors, causing shifts in wavelength response and reduced sensitivity. For example, during thermal cycling, the difference in expansion rates can create mechanical stress, resulting in micro-cracks and delamination (Du et al., 2022).

c) Threading dislocations: In dilute III-V semiconductors NIR sensing, threading dislocations serve as recombination centers where carriers recombine non-radiatively. This results in a decrease in the internal quantum efficiency and, therefore, of device performance. The decrease in carrier lifetime and increased non-radiative recombination contributes to the decrease in the responsivity and increase of the noise levels of the NIR sensors. This in turn negatively affects the signal-to-noise ratio, making the sensors less sensitive to NIR signals (Nakamura, 1998).

Chemical property reactivity is also one of the issues, GaAsPN and the other semiconductors may degrade when it reacts with some metals used in the contact of devices (Gupta and Gupta, 2016). For instance, in case of GaAsPN, thermal cycles can make a significant change in the stress level of this material which in turn influences its lifetime reliability and performance.

5.2 Solutions and further studies

- Scientists are looking for different ways of solving the problems such as the lattice mismatch and other challenges. For example, there is a realization that strain engineering methods will be used to tackle issues like lattice mismatch (Du et al., 2022). The introduction of a graded buffer layer to intermediate the substrate and the active layer then decreases the formation of defects because the strain can be distributed progressively (Du et al., 2022). A graded buffer layer also progressively alters its composition to cope with lattice mismatch and thereby minimize formation of dislocations.

For instance, the use of a GaAsN buffer layer can minimize the threading dislocation density of GaInNAs.

Gradually changing the composition in the intermediate layers can also make the stress between the different materials more lenient and minimize the defects or faults (Ungersboeck et al., 2006). This technique is being tried to optimize the GaInNAs based devices. Incorporation of superlattices of InGaAs and GaAsP has been proved to have strain controlling impact and give a high-quality material.

Furthermore, the synthesis of new material systems and the new growth technique for the effective confinement of dilute III-V semiconductors are under investigation to enhance the thermal stability as well as overall performance (Ondry et al., 1979). For example, when employing quantum dots, the strains can be localized and the effective lattice mismatch will be lower. Regarding growth techniques, MOCVD and MBE are being improved in the preparation of epitaxial layers with enhanced thermal and chemical stability at epitaxial layers.

Another approach is formation of surface passivation layers to prevent the semiconductor to get into chemical reactions and degradation (Zhou et al., 2018). It is crucial to enhance the stability of III-V semiconductor devices, and to do this Al_2O_3 and SiNx are utilized as passivating coatings (Huang et al., 2005). For instance, the atomic-layer deposition (ALD) of Al_2O_3 has been demonstrated to result in excellent electrical characteristics as well as low midgap interface state density in III-V heterostructures (Huang et al., 2005).

By overcoming these challenges through engineering and material science, the usefulness of dilute III-V semiconductors in NIR sensing in tuberculosis can be significantly improved, thus expanding on the current technology for better diagnosis.

6 Recommendations and the way forward

In this mini-review, recent developments in the use of NIR sensing for diagnosis of TB using dilute III-V semiconductors were discussed. The discussion highlights matter such as MBE and MOCVD techniques for growth, thermal mismatch and chemical activity on performance, strain balancing layers related to material properties and advanced characterization techniques.

It is suggested in future research to improve performance and stability, to discover new growth procedures and to analyze unique compositions. The collaborations across disciplines provides the right platform to foster innovation.

To overcome these challenges, strain engineering and advanced characterization techniques should be used. Some approaches of strain balancing layers could help minimize the lattice mismatch, while HRXRD and TEM can help in the fabrication.

Future plans for NIR sensing for TB diagnosis focus on identifying highly sensitive, portable and cost-effective detecting instruments. Further research and development and more interprofessional cooperation are needed to decrease the TB burden worldwide.

Author contributions

MM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation,

Visualization, Writing–original draft, Writing–review and editing. YZ: Writing–original draft. SG: Writing–original draft, Writing–review and editing. BN: Conceptualization, Data curation, Resources, Supervision, Writing–original draft, Writing–review and editing. LS: Conceptualization, Data curation, Resources, Supervision, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

Authors BN and LS were employed by Mintek.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Asgharzadeh, M., Kafil, H. S., Ghorghanlu, S., and Pourostadi, M. (2015). Laboratory cross-contamination of *Mycobacterium tuberculosis* in northwest of Iran. *Egypt. J. Chest Dis. Tuberc.* 64 (3), 665–669. doi:10.1016/j.ejcdt.2015.03.018

Ayşe, E., (2018). Dilute III-V nitride semiconductors and material systems: physics and technology. doi:10.1007/978-3-540-74529-7

Beć, K. B., Grabska, J., and Huck, C. W. (2021). Near-infrared (NIR) sensors in environmental analysis. *Reference Module Biomed. Sci*. doi:10.3390/molecules25122948

Bellon-Maurel, V., and McBratney, A. (2011). "Near-infrared (NIR) and mid-infrared (MIR) spectroscopic techniques for assessing the amount of carbon stock in soils - critical review and research perspectives," 43, 1398, 1410. doi:10.1016/j.soilbio.2011.02.019

Boehme, C. C., Nabeta, P., Hillemann, D., Nicol, M. P., Shenai, S., Krapp, F., et al. (2010). Rapid molecular detection of tuberculosis and rifampin resistance. *N. Engl. J. Med.* 363 (11), 1005–1015. doi:10.1056/nejmoa0907847

Centers for Disease Control and Prevention (CDC) (2024). Tuberculosis (TB) transmission. Available at: https://www.cdc.gov/tb/causes/ (Accessed November 02, 2024).

Chandra, S., and Naiker, M. (2022). "Applications of infrared spectroscopy in environmental contamination," in *Comprehensive analytical chemistry*. Editor D. Cozzolino (Elsevier), 98, 77–90. doi:10.1016/bs.coac.2020.08.003

Cheng, C. (2023). "The-Significance-of-III-V-Semiconductors-in-Future-Electronics," in *Azo materials, editorial feature*.

Conteddu, K., English, H. M., Byrne, A. W., Amin, B., Griffin, L. L., Kaur, P., et al. (2024). A scoping review on bovine tuberculosis highlights the need for novel data streams and analytical approaches to curb zoonotic diseases. *Vet. Res.* 55, 64. doi:10.1186/s13567-024-01314-w

Dai, G., Zhao, P., Song, L., He, Z., Liu, D., Duan, X., et al. (2023) "Devising novel near-infrared aggregation-induced-emission luminogen labeling for point-of-care diagnosis of *Mycobacterium tuberculosis*," in *Biosci Trends*. 17(3):234–238. doi:10.5582/bst.2023.01087

Danasabe Isah, M., and Aliyu Makusidi, M. (2020). Diagnostic evaluation of tuberculosis: existing challenges and merits of recent advances. Available at: www.intechopen.com (Accessed October 11, 2024).

Dong, B., He, Z., Li, Y., Xu, X., Wang, C., and Zeng, J. (2022). *Improved conventional and new approaches in the diagnosis of tuberculosis*. Lausanne, Switzerland: Frontiers Media S.A. doi:10.3389/fmicb.2022.924410

Du, Y., Xu, B., Wang, G., Miao, Y., Li, B., Kong, Z., et al. (2022). Review of highly mismatched III-V heteroepitaxy growth on (001) Silicon. *Nanomaterials* 12 (5), 741. doi:10.3390/nano12050741

Duffy, S. C., Marais, B., Kapur, V., and Behr, M. A. (2024). Zoonotic tuberculosis in the 21st century. *Lancet Infect. Dis.* 24 (4), 339–341. doi:10.1016/S1473-3099(24)00059-8

Fahrenkopf, N., Hucul, D., Morgan, A., Park, S. B., Preble, S., Shabani, J., et al. (2024). Packaging challenges for emerging semiconductor technologies. Available at: https://eps.ieee.org/publications/enews/117-publications/enews/may-2024/1156-packaging-challenges-for-emerging-semiconductor-technologies.html (Accessed: October 26, 2024).

Feng, S., Li, H., Liu, C., Chen, M., Sheng, H., Huang, M., et al. (2021). Real-time *in vivo* detection and monitoring of bacterial infection based on NIR-II imaging. *Front. Chem.* 9 (Jun), 689017. doi:10.3389/fchem.2021.689017

Ferreira, E. M., Cunha, M. V., Duarte, E. L., Mira, A., Pinto, D., Mendes, I., et al. (2024). Mapping high-risk areas for *Mycobacterium tuberculosis* complex bacteria transmission: linking host space use and environmental contamination. *Sci. Total Environ.* 953, 176053. doi:10.1016/j.scitotenv.2024.176053

Ghita, R. V., Logofatu, C., Negrila, C.-C., Trupina, L., and Cotirlan-Simioniuc, C. (2017). "Surface modification of III-V compounds substrates for processing technology," in *Nanoscaled films and layers* (London, United Kingdom: InTech). doi:10.5772/67916

Goletti, D., Delogu, G., Matteelli, A., and Migliori, G. B. (2022). The role of IGRA in the diagnosis of tuberculosis infection, differentiating from active tuberculosis, and decision making for initiating treatment or preventive therapy of tuberculosis infection. *Int. J. Infect. Dis.* 124, S12–S19. doi:10.1016/j.ijid.2022.02.047

Gullifa, G., Barone, L., Papa, E., Giuffrida, A., Materazzi, S., and Risoluti, R. (2023). *Portable NIR spectroscopy: the route to green analytical chemistry*. Lausanne, Switzerland: Frontiers Media SA. doi:10.3389/fchem.2023.1214825

Gupta, A., Zhang, R., Kumar, P., Kumar, V., and Kumar, A. (2020). *Nano-structured dilute magnetic semiconductors for efficient spintronics at room temperature*. Basel, Switzerland: MDPI AG. doi:10.3390/magnetochemistry6010015

Gupta, K. M., and Gupta, N. (2016). "Semiconductor materials: their properties, applications, and recent advances," in *Engineering materials* (Springer Science and Business Media B.V.), 3–40. doi:10.1007/978-3-319-19758-6_1

Han, T., Wang, Y., Ma, S., Li, M., Zhu, N., Tao, S., et al. (2022). Near-infrared carbonized polymer dots for NIR-II bioimaging. *Adv. Sci.* 9 (30), e2203474. doi:10.1002/advs.202203474

Homola, J., Yee, S. S., and Gauglitz, G. (1999). Surface plasmon resonance sensors: review. *Sens. Actuators B Chem.* 54 (1), 3–15. doi:10.1016/S0925-4005(98)00321-9

Huang, M. L., Chang, Y. C., Chang, C. H., Lee, Y. J., Chang, P., Kwo, J., et al. (2005). Surface passivation of III-V compound semiconductors using atomic-layer-deposition-grown Al2O3. *Appl. Phys. Lett.* 87 (25), 1–3. doi:10.1063/1.2146060

Jan, J., Vogliano, A., Ahmed, M., Babics, M., McCulloch, I., Arias, A. C., et al. (2024). High detectivity, near-infrared organic printed photodiode. *Appl. Phys. Lett.* 124. doi:10.1063/5.0176156

Januarie, K. C., Uhuo, O. V., Iwuoha, E., and Feleni, U. (2022). *Recent advances in the detection of interferon-gamma as a TB biomarker*. Deutschland GmbH: Springer Science and Business Media. doi:10.1007/s00216-021-03702-z

Jha, S. N. (2010). *Nondestructive evaluation of food quality: theory and practice*. Berlin Heidelberg: Springer. doi:10.1007/978-3-642-15796-7

Jiang, W., Goncalves, J., and Kostakos, V. (2024). *Mobile near-infrared sensing-A systematic review 0:1*. New York, NY: ACM Comput Surv.

Kasule, G. W., Hermans, S., Semugenze, D., Wekiya, E., Nsubuga, J., Mwachan, P., et al. (2024). Non-sputum-based samples and biomarkers for detection of *Mycobacterium tuberculosis*: the hope to improve childhood and HIV-associated tuberculosis diagnosis. *Oct.* 18, 502. doi:10.1186/s40001-024-02092-z

Kumari, A., Yadav, A., Singh, O. P., and Sharan, P. (2024). A review of surface plasmon resonance (SPR) technology in biosensing: innovations, applications and future trends. *J. Opt.* doi:10.1007/s12596-024-02265-3

Li, H.-H., Wang, Y.-K., and Liao, L.-S. (2024). Near-infrared luminescent materials incorporating rare earth/transition metal ions: from materials to applications. *Adv. Mater.* 36 (30), 2403076. doi:10.1002/adma.202403076

Lin, Z., Sun, L., Wang, C., Wang, F., Wang, J., Li, Q., et al. (2023). Bottlenecks and recent advancements in detecting *Mycobacterium tuberculosis* in patients with HIV. *iLABMED* 1 (1), 44–57. doi:10.1002/ila2.11

Liu, H., Wang, J., Guo, D., Shen, K., Chen, B., and Wu, J. (2023). Design and fabrication of high performance InGaAs near infrared photodetector. *Nanomaterials* 13 (21), 2895. doi:10.3390/nano13212895

Liu, Y., Cai, W., and Shao, X. (2014). Standardization of near infrared spectra measured on multi-instrument. *Anal. Chim. Acta* 836, 18–23. doi:10.1016/j.aca.2014.05.036

Lombard, J. E., Patton, E. A., Gibbons-Burgener, S. N., Klos, R. F., Tans-Kersten, J. L., Carlson, B. W., et al. (2021). Human-to-Cattle *Mycobacterium tuberculosis* complex transmission in the United States. *Front. Vet. Sci.* 8 (Jul), 691192. doi:10.3389/fvets.2021.691192

Macedo, R., Isidro, J., Gomes, M. C., Botelho, A., Albuquerque, T., Sogorb, A., et al. (2020). Animal-to-human transmission of Mycobacterium pinnipedii. *NLM (Medline)* 56, 2000371. doi:10.1183/13993003.00371-2020

Mandalakas, A. M., Detjen, A. K., Hesseling, A. C., Benedetti, A., and Menzies, D. (2011). Interferon-gamma release assays and childhood tuberculosis: systematic review and meta-analysis [Review article]. *Int. J. Tuberc. lung Dis.* 15, 1018–1032. doi:10.5588/ijtld.10.0631

Matsukura, F., Dietl, T., Omiya, T., Akiba, N., Chiba, D., Abe, E., et al. (2002). "Magnetic properties of III–V ferromagnetic semiconductor (Ga,Mn)as," in *Materials science in static high magnetic fields*. Editors K. Watanabe, and M. Motokawa (Berlin, Heidelberg: Springer Berlin Heidelberg), 169–179. doi:10.1007/978-3-642-56312-6_12

Miller, C., Lonnroth, K., Sotgiu, G., and Migliori, G. B. (2017). *The long and winding road of chest radiography for tuberculosis detection*. Sheffield, United Kingdom: European Respiratory Society. doi:10.1183/13993003.00364-2017

Mobed, A., Darvishi, M., Kohansal, F., Dehfooli, F. M., Alipourfard, I., Tahavvori, A., et al. (2024). *Biosensors; nanomaterial-based methods in diagnosing of* Mycobacterium tuberculosis. Elsevier Ltd. doi:10.1016/j.jctube.2023.100412

Moens, C., Saegerman, C., Fretin, D., and Marché, S. (2023). Performance of two commercial serological assays for bovine tuberculosis using plasma samples. *Vet. Immunol. Immunopathol.* 263 (Sep), 110644. doi:10.1016/j.vetimm.2023.110644

Mohammed, N. A., Khedr, O. E., El-Rabaie, E.-S. M., and Khalaf, A. A. M. (2023). Tuberculosis biomedical sensor based on on-chip nanocavity 2D photonic crystal with high sensitivity and quality factor. *Measurement* 222, 113595. doi:10.1016/j.measurement.2023.113595

Mugenyi, N., Ssewante, N., Baruch Baluku, J., Bongomin, F., Mukenya Irene, M., Andama, A., et al. (2024). Innovative laboratory methods for improved tuberculosis diagnosis and drug-susceptibility testing. *Front. Tuberc.* 1 (Jan). doi:10.3389/ftubr.2023.1295979

Munawar, A. A., Yunus, Y., Devianti, D., and Satriyo, P. (2021). "Agriculture environment monitoring: rapid soil fertility evaluation by means of near infrared spectroscopy," in *IOP conference series: earth and environmental science* (Bristol, United Kingdom: IOP Publishing Ltd). doi:10.1088/1755-1315/644/1/012036

Nakamura, S. (1998), 14. American association for the advancement of science. *roles Struct. imperfections InGaN-based blue light- Emit. diodes laser diodes*. doi:10.1126/science.281.5379.956

nan Zhang, N., Lu, C. y., Chen, M. j., Xu, X. l., Shu, G. f., Du, Y. z., et al. (2021). Recent advances in near-infrared II imaging technology for biological detection. *Biomed. Cent. Ltd.* 19, 132. doi:10.1186/s12951-021-00870-z

Narasimhan, V., Kim, H., Lee, S. H., Kang, H., Siddique, R. H., Park, H., et al. (2023). *Nucleic acid amplification-based technologies (NAAT)—toward accessible, autonomous, and mobile diagnostics*. John Wiley and Sons Inc. doi:10.1002/admt.202300230

Nevada Division of Public and Behavioral Health, "Chapter 3: diagnosis of tuberculosis disease," 2018, ch. 3.

Nißler, R., Bader, O., Dohmen, M., Walter, S. G., Noll, C., Selvaggio, G., et al. (2020). Remote near infrared identification of pathogens with multiplexed nanosensors. *Nat. Commun.* 11 (1), 5995. doi:10.1038/s41467-020-19718-5

Oñate, W., Ramos-Zurita, E., Pallo, J. P., Manzano, S., Ayala, P., and Garcia, M. V. (2024). NIR-based electronic platform for glucose monitoring for the prevention and control of diabetes mellitus. *Sensors* 24 (13), 4190. doi:10.3390/s24134190

Ondry, J. C., Zhou, Z., Lin, K., Gupta, A., Chang, J. H., Wu, H., et al. (1979). Reductive pathways in molten inorganic salts enable colloidal synthesis of III-V semiconductor nanocrystals. *Science* 386 (6720), 401–407. doi:10.1126/science.ado7088

Öztürk, C. E., Dönmez, B., Yildiz, P., Çalişkan, E., and Uzan Çakmak, G. (2023). *Diagnosis of tuberculosis by conventional and molecular methods in our laboratory: a 4-year assessment*. Istanbul, Turkey: Phoenix Medical Journal. doi:10.38175/phnx.1384917

Ozturk, S., Bowler, A., Rady, A., and Watson, N. J. (2023). Near-infrared spectroscopy and machine learning for classification of food powders during a continuous process. *J. Food Eng.* 341 (Mar), 111339. doi:10.1016/j.jfoodeng.2022.111339

Pai, M., Dewan, P. K., and Swaminathan, S. (2023). Transforming tuberculosis diagnosis. *Nat. Res.* 8, 756–759. doi:10.1038/s41564-023-01365-3

Pai, M., and Ling, D. I. (2008). Rapid diagnosis of extrapulmonary tuberculosis using nucleic acid amplification tests: what is the evidence? *Future Microbiol.* 3, 1–4. doi:10.2217/17460913.3.1.1

Palmer, M. V., Kanipe, C., Hwang, S., Thacker, T. C., Lehman, K. A., Ledesma, N. A., et al. (2024). Pathogen detection in early phases of experimental bovine tuberculosis. *Vet. Sci.* 11 (8), 357. doi:10.3390/vetsci11080357

Park, J. S., Tang, M., Chen, S., and Liu, H. (2020). *Heteroepitaxial growth of iii-v semiconductors on silicon*. Basel, Switzerland: MDPI AG. doi:10.3390/cryst10121163

Paul E Klapper, A. M. van L., and van Loon, A. M. (2010). Herpesviruses. *Infect. Dis. (Lond).*, 1550–1564. doi:10.1016/b978-0-323-04579-7.00155-6

Pereira, A. C., Pinto, D., and Cunha, M. V. (2024). First time whole genome sequencing of Mycobacterium bovis from the environment supports transmission at the animal-environment interface. *J. Hazard Mater* 472 (Jul), 134473. doi:10.1016/j.jhazmat.2024.134473

Pesala, B., Gavarna, H., Kumar, A., Kumaravelu, C., Scaria, V., and Sivasubbu, S. (2012). "Non-invasive detection of mycobacterium tuberculosis using IR and NIR spectroscopy," in *2012 37th international conference on infrared, millimeter, and terahertz waves*, 1–2. doi:10.1109/IRMMW-THz.2012.6380079

Raut, B. (2023). Chemical vapor deposition process: Advantages, and disadvantages - easy explanation. *Nano. Not*. Available at: https://chemistnotes.com/nanochemistry/chemical-vapor-deposition-process-advantages-and-disadvantages-easy-explanation/ (Accessed November 02, 2024).

R. M.Dixon, C. D. B. (2010). "Application of near infrared spectroscopy to improve animal production in developing countries," in *FAO/IAEA international symposium on sustainable improvement of animal production and health*. Editors M. G., and G. J. V. N. E. Odongo (Vienna, Austria: FAO), 167–174.

Sakudo, A. (2016). *Near-infrared spectroscopy for medical applications: current status and future perspectives*. Elsevier B.V. doi:10.1016/j.cca.2016.02.009

Sawyer, J., Rhodes, S., Jones, G. J., Hogarth, P. J., and Vordermeier, H. M. (2023). Mycobacterium bovis and its impact on human and animal tuberculosis. *J. Med. Microbiol.* 72 (11). doi:10.1099/jmm.0.001769

Schott, G. M., Rüster, C., Brunner, K., Gould, C., Schmidt, G., Molenkamp, L. W., et al. (2004). Doping of low-temperature GaAs and GaMnAs with carbon. *Appl. Phys. Lett.* 85 (20), 4678–4680. doi:10.1063/1.1819522

Senapati, S., Mishra, M., Sahoo, N., and Tripathy, S. K. (2024). Highly sensitive nitride-based SPR biosensor for efficient adrenal gland/blood/breast/cervical/skin cancer detection. *Sens. Biosensing Res.* 45, 100684. doi:10.1016/j.sbsr.2024.100684

Shan, W., Walukiewicz, W., Yu, K. M., Wu, J., Ager, J. W., and Haller, E. E., "New developments in dilute nitride semiconductor research," in *III-nitride semiconductor materials*, London, United Kingdom: Published by imperial college press and distributed by world scientific publishing co., 2006, pp. 399–428. doi:10.1142/9781860949036_0012

Shivakumar, P., and Shettigar, K. S. (2022). Tuberculosis diagnosis: updates and challenges. Available at: www.intechopen.com (Accessed October 14, 2024).

Simon, J., Schulte, K. L., Horowitz, K. A. W., Remo, T., Young, D. L., and Ptak, A. J. (2019). III-V-based optoelectronics with low-cost dynamic hydride vapor phase epitaxy. *Cryst. (Basel)* 9 (1), 3. doi:10.3390/cryst9010003

Sommer, R., and Cole, S. T. (2019). Monitoring tuberculosis drug activity in live animals by near-infrared fluorescence imaging. *Antimicrob. Agents Chemother.* 63 (12). doi:10.1128/AAC.01280-19

Speck, J. S., and Rosner, S. J. (1999). The role of threading dislocations in the physical properties of GaN and its alloys. *Phys. B Condens Matter* 273–274, 24–32. doi:10.1016/S0921-4526(99)00399-3

Sun, Y., Thompson, S. E., and Nishida, T. (2010). *Strain effect in semiconductors: theory and device applications*. Springer US. doi:10.1007/978-1-4419-0552-9

Timire, C., Houben, R. M. G. J., Pedrazzoli, D., Ferrand, R. A., Calderwood, C. J., Bond, V., et al. (2024). Higher loss of livelihood and impoverishment in households affected by tuberculosis compared to non-tuberculosis affected households in Zimbabwe: a cross-sectional study. *PLOS Glob. Public Health* 4 (6), e0002745. doi:10.1371/journal.pgph.0002745

Trajman, A., Steffen, R. E., and Menzies, D. (2013). Interferon-gamma release assays versus tuberculin skin testing for the diagnosis of latent tuberculosis infection: an overview of the evidence. *Pulm. Med.* 2013, 1–11. doi:10.1155/2013/601737

Tsenkova, R., and Munćan, J. (2021). Mastitis diagnostics based on the near-infrared spectra of cow's milk, blood and urine. *Aquaphotomics Bio-diagnostics Dairy*, 213–222. Available at: https://api.semanticscholar.org/CorpusID:245754268 (Accessed October 14, 2024). doi:10.1007/978-981-16-7114-2_19

Ungersboeck, E., Sverdlov, V., Kosina, H., and Selberherr, S. (2006). "Strain engineering for CMOS devices," in *2006 8th international conference on solid-state* *and integrated circuit technology proceedings*, 124–127. doi:10.1109/ICSICT.2006.306094

Vittor, Y., Garland, J. M., and Gilman, R. H. (2014). "State-of-the-Art review molecular diagnosis of TB in the HIV positive population show more add to mendeley," doi:10.1016/j.aogh.2015.01.001Get

Vo, L. N. Q., Codlin, A., Ngo, T. D., Dao, T. P., Dong, T. T. T., Mo, H. T. L., et al. (2021). Early evaluation of an ultra-portable x-ray system for tuberculosis active case finding. *Trop. Med. Infect. Dis.* 6 (3), 163. doi:10.3390/TROPICALMED6030163

Wazahat, R., Haider, M., Chattopadhya, D., and Dudeja, M. (2023). Assessment of conventional and molecular methods in the routine management of tuberculosis in a high tuberculosis burden setting. *Epidemiol. Health Syst. J.* 10 (3), 118–125. doi:10.34172/ehsj.2023.19

Wedding, B. B., Wrightd, C., Grauf, S., White, R. D., and Gadek, P. A. (2011). Near infrared spectroscopy as a rapid non-invasive tool for agricultural and industrial process management with special reference to avocado and sandalwood industries. *Desalination Water Treat.* 32 (1–3), 365–372. doi:10.5004/dwt.2011.2723

Weyer, K., Gilpin, C., Mirzayev, F., and Gemert, W. van. (2011). *Use of tuberculosis interferon-gamma release assays (IGRAs) in low- and middle-income countries: policy statement*. Geneva, Switzerland: World Health Organization.

WHO (2016). *Global tuberculosis report 2016*. Geneva, Switzerland: World Health Organization.

WHO (2020). *Global tuberculosis report 2020*. Geneva, Switzerland: World Health Organization. Available at: https://www.who.int/publications/i/item/9789240013131?form=MG0AV3 (Accessed October 15, 2024).

WHO (2021). *Global tuberculosis report 2021*. Geneva, Switzerland: World Health Organization.

WHO (2024). *Glob. Tuberc. Rep*.

Zhang, K., Luo, W., Huang, S., Bai, X., Shuai, Y., Wu, C., et al. (2021). Effects of rapid thermal annealing parameters on crystal ion slicing-fabricated LiTaO3 thin film. *Appl. Phys. A Mater Sci. Process* 127 (6), 468. doi:10.1007/s00339-021-04627-1

Zhang, M. L., and Fan, W. (2022). The impact of *Mycobacterium tuberculosis* complex in the environment on one health approach- MINI REVIEW article. *Front. Public Health*. doi:10.3389/fpubh.2022.994745

Zhao, Q. X., Wang, S. M., Sadeghi, M., Larsson, A., Willander, M., and Yang, J. H. (2005). Effects of nitrogen incorporation on the properties of GaInNAsGaAs quantum well structures. *J. Appl. Phys.* 97 (7). doi:10.1063/1.1873041

Zheng, N. (2008). Introduction to dilute magnetic semiconductors. Available at: https://api.semanticscholar.org/CorpusID:28319491 (Accessed October 16, 2024).

Zhou, L., Bo, B., Yan, X., Wang, C., Chi, Y., and Yang, X. (2018). *Brief review of surface passivation on III-V semiconductor*. Basel, Switzerland: MDPI AG. doi:10.3390/cryst8050226