

# Research on a Semiconductor Factory Environmental Safety Monitoring System Based on InAs/GaSb Type-II Superlattice Infrared Detection Technology

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**Abstract:** With the rapid development of the semiconductor manufacturing industry, the large quantities of high-risk chemicals, specialty gases, and precision equipment involved in its production processes have brought severe industrial safety challenges. Traditional safety monitoring methods have limitations in sensitivity, response speed, and adaptability to complex environments. Based on InAs/GaSb type-II superlattice infrared detection technology, this paper discusses a smart safety monitoring system for semiconductor factories. The paper first analyzes the typical safety risks and detection requirements in semiconductor manufacturing scenarios; second, it explains the physical advantages of type-II superlattice materials in the field of infrared detection and their application principles in gas leak detection; on this basis, it designs a smart monitoring system architecture of “infrared detection + AI analysis”; finally, it looks ahead to the application prospects of this technology in the field of industrial safety. This study aims to transform cutting-edge semiconductor optoelectronic technology into industrial safety productivity and provide new ideas for the intrinsic safety of semiconductor factories.

**Keywords:** industrial safety; smart safety technology; InAs/GaSb type-II superlattice; infrared detector; gas leak monitoring; semiconductor manufacturing

## 1 Introduction

The semiconductor industry is a strategic, foundational, and leading industry supporting modern economic and social development. However, semiconductor manufacturing processes are extremely complex, involving hundreds of process steps and large quantities of flammable, explosive, toxic, and harmful specialty gases and chemical reagents (such as silane, ammonia, arsine, phosphine, etc.). Once a leak occurs, it can easily lead to major industrial safety accidents such as fires, explosions, poisoning, and environmental pollution. In addition, semiconductor cleanrooms have extremely strict requirements for environmental particles, temperature and humidity, and air pressure. Any slight environmental disturbance may cause enormous economic losses.

At present, point-type electrochemical sensors, catalytic combustion sensors, and traditional non-dispersive infrared (NDIR) sensors commonly used in industrial sites play an important role in gas detection. However, in the face of complex background gas interference in semiconductor factories, trace leak detection requirements, and rapid response requirements, traditional sensors have gradually exposed deficiencies in selectivity, sensitivity, and long-term stability.

As a university physics laboratory instructor, the author mainly engaged in research on InAs/GaSb type-II superlattice infrared detectors during doctoral studies. This technology belongs to third-generation infrared detection technology and has significant advantages such as high quantum efficiency, low dark current, and tunable wavelength, showing great potential in military, aerospace, and civilian fields. This paper will explore how to introduce this cutting-edge optoelectronic detection technology into the field of industrial safety and build a smart safety monitoring

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system for semiconductor factories, in order to provide new theoretical support and practical paths for the “Smart Safety Technology” and “Safety Engineering and Detection Technology”.

## 2 Analysis of Typical Safety Risks and Detection Requirements in Semiconductor Factories

### 2.1 Specialty Gas Leak Risks

In semiconductor manufacturing, specialty gases are widely used in processes such as etching, deposition, and doping. Most of these gases are highly toxic, flammable, explosive, or corrosive. For example, silane ( $\text{SiH}_4$ ) is extremely prone to spontaneous combustion in air and can cause explosions when encountering open flames or high temperatures; arsine ( $\text{AsH}_3$ ) and phosphine ( $\text{PH}_3$ ) are highly toxic gases, and trace leaks can cause fatal harm to the human body. Leaks of such gases often occur during their storage, transportation, and inside reaction chambers. In the early stage of a leak, the concentration is extremely low, making it difficult for traditional sensors to capture it immediately.

### 2.2 Cleanroom Fire and Explosion Risks

A cleanroom is a special space that is enclosed and well ventilated, but it contains large amounts of organic solvents, plastic air ducts, and high-efficiency filters. Once a fire occurs, it spreads extremely quickly, and the combustion products are highly toxic. In addition, due to the high air exchange rate of cleanrooms, gas leaks diffuse rapidly after occurrence, making it difficult for traditional point-type detectors to accurately locate the leakage source, which can easily cause false alarms or missed alarms.

### 2.3 Environmental Particles and Chemical Contamination

Semiconductor manufacturing has extremely high requirements for environmental cleanliness. Tiny particles in the air (such as dust and metal ions) or chemical contaminants (AMC) can directly lead to a decline in wafer yield. Therefore, real-time, high-precision monitoring of the cleanroom environment is not only necessary to ensure product quality but also an important part of preventing safety accidents caused by equipment failures.

## 3 Principles and Advantages of InAs/GaSb Type-II Superlattice Infrared Detection Technology

### 3.1 Physical Principles

The InAs/GaSb type-II superlattice is an artificial semiconductor material formed by alternately growing InAs layers and GaSb layers. In the type-II band alignment, the conduction band bottom of InAs is lower than the valence band top of GaSb, and electrons and holes are spatially separated. By changing the thicknesses of the InAs and GaSb layers, the bandgap of the superlattice can be flexibly adjusted, thereby achieving detection in the mid-wave infrared (MWIR, 3-5  $\mu\text{m}$ ) and long-wave infrared (LWIR, 8-12  $\mu\text{m}$ ) bands. This characteristic gives the material a natural advantage in detecting the infrared absorption peaks of specific gases.

### 3.2 Technical Advantages in Safety Monitoring

Compared with traditional mercury cadmium telluride (MCT) and quantum well infrared photodetectors (QWIP), InAs/GaSb type-II superlattice detectors have the following significant advantages in industrial safety monitoring:

#### 3.2.1 High sensitivity and high detectivity

Because Auger recombination is effectively suppressed, their dark current is extremely low, enabling high signal-to-noise ratio detection at room temperature or near-room temperature, which is crucial for detecting trace gas leaks.

#### 3.2.2 Wavelength tunability

Through band engineering, they can precisely match the characteristic absorption peaks of different hazardous gases (such as methane, carbon monoxide, ammonia, etc.), achieving highly selective gas identification and effectively overcoming cross-interference from background gases.

#### 3.2.3 Fast response

The carrier lifetime of superlattice materials is short, and the detector response speed is fast, enabling real-time capture of the transient process of gas leaks and buying valuable time for emergency linkage.

#### 3.2.4 Stability and integrability

The material growth process is mature, making it easy to fabricate large-scale focal plane arrays (FPAs) and achieve large-range, non-contact safety monitoring.

## 4 Design of a Smart Safety Monitoring System Based on Superlattice Infrared Detection

Combined with the actual scenarios of semiconductor factories, this paper designs a smart safety monitoring system based on InAs/GaSb type-II superlattice infrared detection technology. The system follows the smart safety architecture of “perception-transmission-analysis-decision.”

### 4.1 Overall System Architecture

The system mainly consists of an infrared detection module, a data acquisition and transmission module, an AI intelligent analysis module, and an emergency linkage module. The infrared detection module is responsible for collecting infrared spectral information from specific areas in the factory; the data acquisition module converts analog signals into digital signals and transmits them to the cloud via industrial Ethernet or a 5G network; the AI analysis module uses deep learning algorithms to perform feature extraction and classification recognition on spectral data; the emergency linkage module triggers operations such as alarms, ventilation, or gas source shutoff based on the analysis results.

### 4.2 Design of the Infrared Detection Module

For typical gases in semiconductor factories, an InAs/GaSb type-II superlattice focal plane array with a response band covering the mid-wave infrared is selected. The detector adopts a back-illuminated structure and integrates a narrowband filter to match the characteristic absorption peak of the target gas. For example, for the absorption peak of silane ( $\text{SiH}_4$ ) near  $4.6\text{ }\mu\text{m}$ , a superlattice detector in the corresponding band can be designed. To adapt to the cleanroom environment, the detector needs to be packaged in a well-sealed metal housing and equipped with a sapphire window to ensure its long-term stable operation in a high-cleanliness environment.

### 4.3 Data Acquisition and Transmission

Because the output signal of the infrared detector is weak, a low-noise preamplifier circuit is needed for signal conditioning. The data acquisition card needs to have high resolution (such as 16 bits or more) and a high sampling rate to ensure the integrity of spectral data. The transmission network should preferentially use industrial-grade Ethernet, supplemented by a wireless sensor network (WSN), to achieve full-coverage, no-blind-spot monitoring network deployment in the factory.

### 4.4 AI Intelligent Analysis Module

This is the core embodiment of “smart safety.” The collected infrared spectral data will be input into a deep learning model based on a convolutional neural network (CNN) or long short-term memory network (LSTM). After training on a large amount of gas spectral data, the model can:

#### 4.4.1 Identify gas types

distinguish different types of hazardous gases through the position and intensity of characteristic absorption peaks.

#### 4.4.2 Invert gas concentration:

use the Beer-Lambert law, combined with spectral absorption intensity, to quantitatively calculate gas concentration.

#### 4.4.3 Predict leakage trends

through time-series analysis, predict the changing trend of gas concentration and issue early warnings in advance, rather than only alarming after exceeding the standard.

#### 4.4.4 Suppress false alarms

through multi-spectral fusion and background noise removal algorithms, effectively reduce the false alarm rate caused by environmental temperature and humidity changes or dust interference.

### 4.5 Emergency Linkage and Intrinsic Safety

Once the AI module determines that a gas leak has occurred and the concentration has reached the warning threshold, the system will immediately activate the emergency linkage mechanism: close the relevant gas pipeline valves, start the local exhaust system, turn on emergency lighting, and evacuate personnel. At the same time, the system will push the leak location, gas type, and concentration information to the mobile terminals of safety management personnel in real time, achieving “early detection and early handling,” thereby eliminating accidents in the bud and advancing semiconductor factories toward “intrinsic safety.”

## 5 Reflections on the Integration of Physics Laboratory Teaching and Safety Technology

As a university physics laboratory instructor, the author deeply recognizes that cutting-edge scientific research

technology should not remain only at the laboratory stage but should also feed back into teaching to cultivate students' safety awareness and innovation ability. In the research and development process of this system, multiple cases suitable for university physics laboratory teaching can be extracted. For example, using an infrared spectrometer to measure the absorption spectra of common gases allows students to intuitively understand the Beer-Lambert law; designing a simple gas detection and alarm device based on Arduino or Raspberry Pi exercises students' circuit design and programming abilities.

By integrating the physical principles in industrial safety monitoring into physics laboratory teaching, it can not only stimulate students' interest in physics but also cultivate their ability to solve practical engineering problems, delivering interdisciplinary talents with a broad vision to the field of industrial safety.

## 6 Challenges and Prospects

Although InAs/GaSb type-II superlattice infrared detection technology has shown great potential in industrial safety monitoring, its large-scale application still faces some challenges:

### 6.1 Cost issues

The molecular beam epitaxy (MBE) growth cost of superlattice materials is relatively high, resulting in expensive detectors. In the future, costs need to be reduced through large-size substrate technology and process optimization.

### 6.2 Environmental adaptability

Although the cleanroom environment of semiconductor factories is clean, there is certain electromagnetic interference and vibration. Detector packaging and system integration need to have good anti-interference capability.

### 6.3 Data security and privacy

Smart safety systems involve the transmission and storage of large amounts of internal factory data. How to ensure data security and prevent hacker attacks is an issue that must be taken seriously.

Looking to the future, with the deep integration of artificial intelligence, the Internet of Things, and third-generation semiconductor technology, smart safety monitoring systems based on superlattice infrared detection will develop toward miniaturization, low power consumption, networking, and intelligence. They can be applied not only to semiconductor factories but also extended to broader industrial safety fields such as petrochemicals, coal mines, and fire protection. As scientific researchers, we should actively respond to the national call for "invigorating safety through science and technology" and transform more cutting-edge technologies such as InAs/GaSb type-II superlattices into powerful tools for safeguarding industrial safety.

## 7 Conclusion

Aiming at the severe safety challenges faced by semiconductor factories, this paper proposes a smart safety monitoring system based on InAs/GaSb type-II superlattice infrared detection technology. By analyzing the physical advantages of this technology in sensitivity, selectivity, and response speed, a system architecture covering perception, transmission, analysis, and linkage is designed. The study shows that introducing cutting-edge infrared optoelectronic technology into the field of industrial safety can effectively improve the accuracy and real-time performance of gas leak detection and provide strong technical support for the intrinsic safety of semiconductor factories. At the same time, this paper also discusses the integration path of this technology in university physics laboratory teaching, aiming to cultivate interdisciplinary talents with safety awareness and cross-disciplinary capabilities. In the future, with the continuous maturity of technology and the reduction of costs, smart safety systems based on superlattice infrared detection will certainly play an even more important role in the field of industrial safety.

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