耐腐蝕、高靈敏、可量產：次世代二維材料氣體感測晶片技術

智慧微塵感測器

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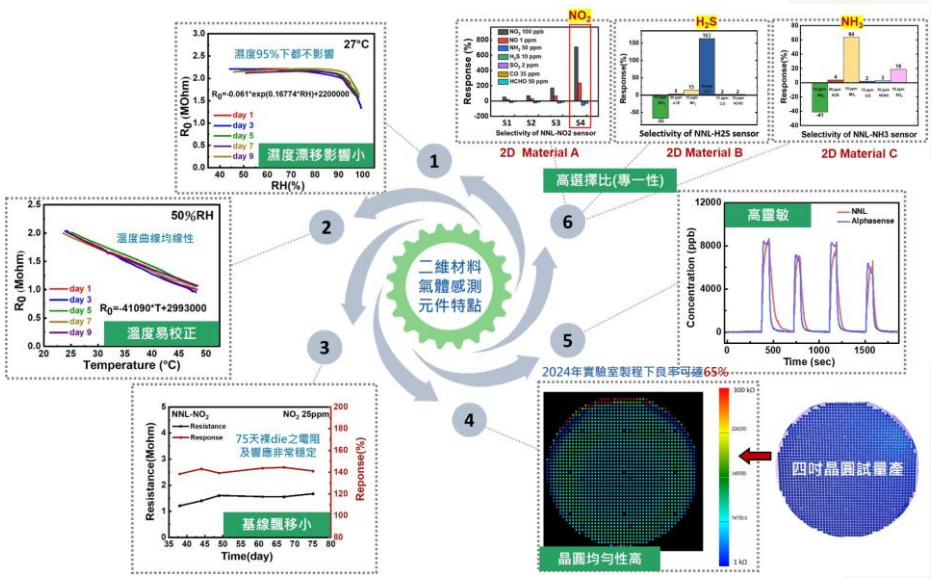
面對電化學感測器衰減快的挑戰，本團隊聚焦於NH_3、H_2S、NO_2等腐蝕性氣體，開發具高耐用性與穩定性的二維材料感測器，降低更換與校正成本。技術優勢包括：濕度與基線飄移小、溫度易校正、高靈敏與選擇比、晶圓均勻性佳。第三方驗證顯示團隊產品對NH_3與H_2S皆優於市售競品，並可即插即用，展現高穩定性與即時性。

計畫亮點

- 市場定位：團隊產品將注重提高耐用性和穩定性，減少感測器衰減的速度，從而延長替換週期並降低總擁有成本。
- 二維材料六大核心技術優勢：(1)濕度飄移影響小(2)溫度易校正(3)基線飄移小(4)晶圓均勻性高(5)高靈敏度(6)高選擇比
- 完成第三方驗證(性能驗證 α-site)：性能驗證顯示團隊元件靈敏穩定，優於市售競品。



產業應用

- 半導體產業-部署在工廠環境中的氣體感測器，用於監測工業過程中的有毒氣體排放和工作場所的空氣品質。
- 推進智慧城市，實時提供精確的環境數據，促進城市公共形象和提升居民的生活品質。

專利資訊：過渡金屬硫族化物二維薄膜的製備方法

專利證書號 US9,460,919 B1	專利權期限 ~2036/03/04

一種製造二維過渡金屬硫族化物薄膜的方法，使用基板、過渡金屬反應膜、硫族元素來源與電漿誘發反應，以形成薄膜。

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AUG.21

Anti-Corrosion, High-Sensitivity, and Scalable: Next Generation 2D Material Gas Sensor Chip Technology

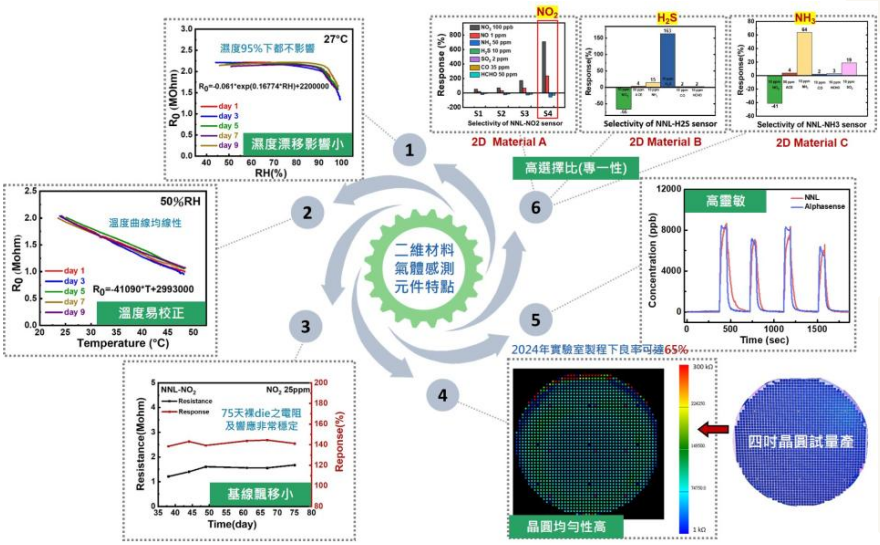
Smart Dust Sensors

Department of Materials Science and Engineering, National Tsing Hua University
Dr. Yu-Lun Chueh, Chair Professor

To address the rapid degradation of electrochemical sensors, our team focuses on detecting corrosive gases, offering durable and stable 2D material-based sensors to reduce replacement and calibration costs. Key advantages include minimal humidity and baseline drift, linear temperature response, high wafer uniformity, atomic-level sensitivity, and tunable selectivity. Third-party tests confirm our sensors outperform commercial ones in NH_3 and H_2S detection with better stability and plug-and-play usability.

Project Highlights

- Market Positioning: Our product focuses on enhancing durability and stability, reducing sensor degradation over time to extend replacement cycles and lower the total cost of ownership.
- Six Core Technical Advantages of 2D Materials: (a) Low humidity-induced drift (b) Easy temperature calibration (c) Minimal baseline drift (d) High wafer-level uniformity (e) High sensitivity (f) High selectivity ratio
- Third-Party Performance Verification (α-site): Independent validation confirms our sensor components are highly sensitive and stable, outperforming commercially available competitors.



Industrial Applications

- Semiconductor Industry – Gas sensors deployed in factory environments to monitor toxic gas emissions during industrial processes and to ensure workplace air quality.
- Advancing Smart Cities – Providing real-time and accurate environmental data to enhance the city's public image and improve residents' quality of life.

Patent：Manufacturing Method of Two-dimensional Transition-metal Chalcogenide Thin Film

Patent Number US9,460,919 B1	Patent Term~ 2036/03/04

A method for manufacturing 2D transition-metal chalcogenide films uses a substrate, a transition-metal reaction film, a chalcogen source, and plasma to induce a reaction, forming a thin film.

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全方位氣體感測晶片陣列之快速智慧讀取電路 設計與演算法實現

智慧微塵感測器

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洪瑞華 講座教授團隊

國立陽明交通大學電機學院
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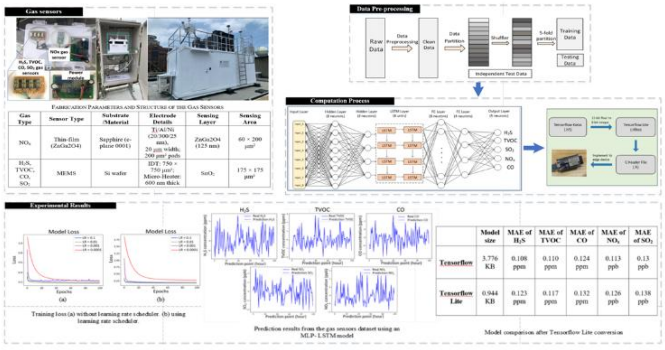
本研究提出一種結合氣體感測器製程與邊緣 AI 的高穩健濃度預測架構。開發了 $ZnGa_2O_4$ 製成的 NOx 感測器與 SnO_2 懸浮式 MEMS 感測器，可偵測多種氣體。為應對交叉靈敏度與環境變化，採用級聯式 MLP-LSTM 模型，分別處理溫濕度特徵與時間序列趨勢。資料經插補、標準化與交叉驗證後，以 Adam 最佳化器訓練並調整學習率。模型對 H_2S、TVOC、CO、SO_2、NOx 的 R^2 分別達 0.889、0.888、0.879、0.875、0.880，顯示優異預測力與適應性。最終部署於 ESP32-DevKitC，透過 TensorFlow Lite for Microcontrollers 實現即時低功耗推論，具高準確率與實務應用潛力。

計畫亮點

- 本研究提出創新的 MLP-LSTM 架構，有效解決氣體感測器的交叉敏感性與環境干擾問題。
- 相較於傳統靜態模型，本方法可同時捕捉空間與時間特徵，提升多氣體預測的準確性。
- 透過線性插補處理缺失資料，並採用 Z-score 標準化特徵值，提升資料一致性。

Multiple Gas Devices Sensing and At-edge Computation



- 模型部署於 ESP32 邊緣裝置，結合 TensorFlow Lite，可即時低功耗推論，實現可攜式與可擴展的環境監測。
- 實驗結果顯示對 H_2S、TVOC、CO、SO_2 與 NOx 的 R^2 分別為 0.889、0.888、0.879、0.875 與 0.880，驗證模型具高度穩定性與實務應用潛力。
- 使用 UCI ML Repository 公開資料集測試，與其他氣體感測系統相比，本研究模型之 MAE 最小（CO: 0.124 ppm、NOx: 113 ppb、H_2S: 0.108 ppm、TVOC: 110 ppm、SO_2: 0.13 ppb），展現優異效能與突破性。

產業應用

- 本技術具高度產業應用潛力，適用於環境監測、智慧城市、工業安全及物聯網空氣品質系統。透過將 MEMS 與 $ZnGa_2O_4$ 感測器整合至 ESP32 等邊緣裝置，搭配輕量化 AI 模型，可即時精準偵測氣體，無需依賴雲端，特別適合資源有限場域。其低功耗、小型化與成本效益設計，便於部署於穿戴裝置、無人機與固定監測站。系統能有效早期偵測 H_2S、SO_2、NOx 等氣體，提升安全性，並藉 AI 強化預測準確度，降低維護成本，推動智慧感測技術之商用化與普及。

專利資訊(1)：氣體感測裝置

專利證書號 I767241B	專利權期限 ~2040/05/27

一種氣體感測裝置,包括一熱絕緣單晶基板、一感測器用以感測氣體的濃度及一加熱器用以提供氣體感測所需的溫度,該感測器及該加熱器都位於該熱絕緣單晶基板的第一表面。該感測器具有微結構以提高感測的準確度。

專利資訊(2)：具懸浮式加熱器之微型氣體感測器

專利證書號 I764184B	專利權期限 ~2040/06/28

本發明提供一種具懸浮式加熱器之微型氣體感測器，其包含一包括一第一表面及一自該第一表面朝一相反於該第一表面之第二表面凹陷的隔熱穴的絕緣性基板、一懸浮式地配置在該隔熱穴上方並貼合於該第一表面之一周緣且是一具有單晶結構的金屬氧化物的圖案化氣體感測層；及一間隔地圍繞該圖案化氣體感測層以懸浮式地配置在該隔熱穴上方並貼合於該第一表面之周緣的圖案化加熱層。

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AUG.21

Smart Dust Sensors

Design and Algorithm Implementation of a High-Speed Intelligent Readout Circuit for an All-in-One Gas Sensor Chip Array

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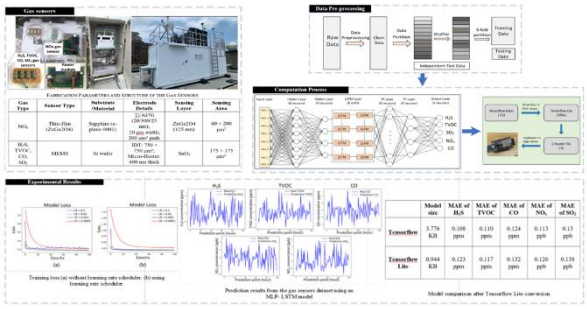
This research proposes a robust gas concentration estimation framework by combining advanced gas sensor fabrication with edge-oriented AI modeling. Two types of sensors were developed: a $ZnGa_2O_4$-based NOx sensor grown on sapphire using MOCVD, and a MEMS-based multi-gas sensor using SnO_2 films and suspended structures for detecting H_2S, TVOC, CO, and SO_2. To improve prediction accuracy under environmental interferences like cross-sensitivity and temperature/humidity variations, a hybrid MLP-LSTM deep learning model was used. Data preprocessing included missing value interpolation, normalization, and cross-validation. The model achieved R^2 values above 0.87 for all gases and was deployed on ESP32 with TensorFlow Lite, enabling real-time, low-power inference on edge devices.

Project Highlights

- This study proposes an innovative MLP-LSTM architecture that effectively addresses the issues of cross-sensitivity and environmental interference in gas sensors.
- Compared to traditional static models, the proposed method captures both spatial and temporal features, significantly improving the accuracy of multi-gas prediction.

Multiple Gas Devices Sensing and At-edge Computation



- Missing data is handled through linear interpolation, and Z-score normalization is applied to enhance feature consistency.
- The model is deployed on an ESP32 edge device, integrated with TensorFlow Lite, enabling real-time, low-power inference for portable and scalable environmental monitoring.
- Experimental results show that the model achieves R^2 values of 0.889, 0.888, 0.879, 0.875, and 0.880 for H_2S, TVOC, CO, SO_2, and NOx respectively, demonstrating high stability and strong practical application potential.
- When tested on the publicly available UCI ML Repository dataset, the proposed model achieves the lowest MAE compared to other gas sensing systems (CO: 0.124 ppm, NOx: 113 ppb, H_2S: 0.108 ppm, TVOC: 110 ppm, SO_2: 0.13 ppb), highlighting its superior performance and breakthrough capability.

Industrial Applications

- The system integrates MEMS and $ZnGa_2O_4$ sensors with MLP-LSTM AI for accurate, low-power gas detection on edge devices, suited for smart cities, wearables, mobile, and remote monitoring.

Patent (1)：Gas Sensing Device	
Patent Number I767241B	Patent Term ~2040/05/27
A gas sensing device includes a thermal insulation single crystal substrate, a sensor for sensing gas concentration and a heater for providing a temperature which is needed for sensing gas. The sensor and heater are in a first surface of the thermal insulation single crystal substrate. The sensor has a micro-structure to improve a sensing accuracy.	

Patent (2)：Micro Gas Sensor With Suspended Heater	
Patent Number I764184B	Patent Term ~2040/06/28
This invention provides a micro gas sensor with suspended heater, which comprises an insulated substrate including a first surface and a heat insulation cavity recessed from said first surface to a second surface opposite to said first surface, a patterned gas sensing layer suspended over said heat insulation cavity and adhered on a periphery of said first surface and been a metal oxide with single crystal structure, and a patterned heating layer surrounded apart from said patterned gas sensing layer and adhered on said periphery of said first surface such that said patterned heating layer suspends over said heat insulation cavity.	

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創新預警的首選- MEMS氣體感測

智慧微塵感測器

國立高雄科技大學車輛工程系
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全球氣體感測元件需求趨勢愈來愈大，本團隊開發全球微機電製備之低功耗&快速響應氣體感測元件，核心技術包含(1).低耗能加熱設計(2).3D感測元件結構製造(3).特殊感測薄膜製程(4).老化穩定測試。氣體感測器之相關產品，絕大多數為國外廠商製造，國內自主設計落地生產刻不容緩。因此本計畫產品將成為客戶採購國產感測器元件之唯一選項，達到進口替代之效果，成為系統模組客戶端提升其產品品質之最大助力。

計畫亮點

- 學術界團隊/國內業者共同開發MEMS氣體感測器，應用於VOC環境偵測。
- 進行模組與雲端物聯網監控系統的實測驗證。
- 研究成果微機電感測器元件開發，衍生新創公司促成新創公司技術移轉計畫。

產業應用

- 感測器關鍵技術(包含：模擬設計、感測薄膜製程、測試、模組及系統等)至產業落地試量產。
- VOC 氣體感測器市場：適用於半導體設備、化工設備產業、智慧化設備產業、家電設備。

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開發智慧城市應用之微型硫化氫氣體感測模組

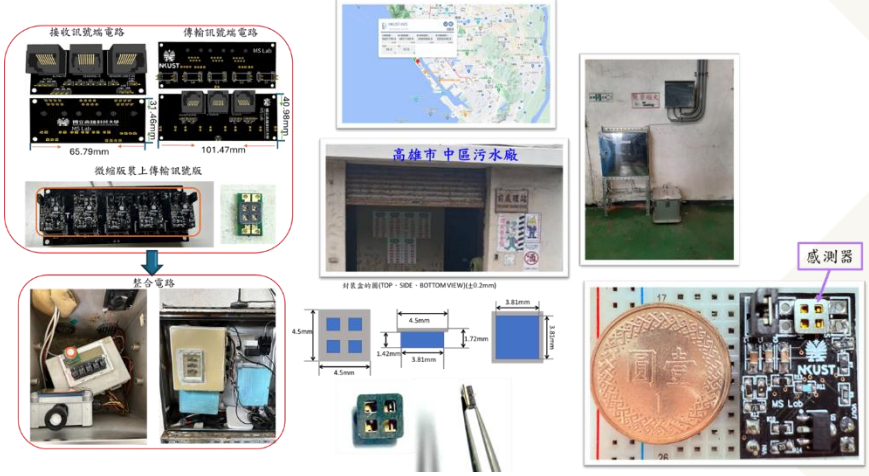
智慧微塵感測器

國立高雄科技大學電子工程系
薛丁仁 教授

本團隊感測器晶片以TSRI南區分中心的6"~8"MEMS技術服務平台製作，晶片完成後在高雄科技大學半導體封測類產中心所建置的氣體感測晶片封裝技術進行小批量試產封裝感測晶片，達到低耗能、低成本，快速響應、高靈敏度、高穩定性及高選擇性之微型硫化氫氣體感測晶片，並將電路模組系統精簡化、標準化及封裝化，協助學界完成感測元件模組國產化，建立自主感測器技術能量。並於高雄旗津中區污水廠進行場域聯網架設與實測，包含實測場域設置測試訊號、聯網及供電等功能，與環境溫度及濕度計與國際標竿之氣體感測器進行量測數據比對，並將數據回傳至科技雲端平台，形成區域監控網絡，提升國內產業界於氣體感測產品與智慧聯網監控產業競爭力。

計畫亮點

- 在TSRI南區分中心開發MEMS氣體感測晶片，高靈敏度H_2S晶片型氣體感測器，晶片微小，尺寸0.7mm * 0.7mm * 0.4mm
- 在旗津中區污水廠進行場域聯網架設與實測
- 國際標竿氣體感測器進行量測數據比對
- 市售感測器進行量測數據比對
- 目前本計畫所開發之感測器已完成產品封裝及整合入訊號電路板



產業應用

- 在TSRI南區分中心開發MEMS氣體感測晶片，高靈敏度H_2S晶片型氣體感測器，晶片微小，尺寸0.7mm * 0.7mm * 0.4mm
- 本產品為新開發，佈點可循跡漸進先從1.恆溫恆濕之環境使用(如半導體製造工廠，儲藏室、材料分析實驗室)，2.環境溫度變化不大使用(如汙水廠、下水道、廠務.....)推廣。

專利資訊：氣體感測器之結構

專利證書號 I706571	專利權期限

本發明為一種微型氣體感測器結構，包含中空結構、絕緣層、低應力介電層、加熱元件和電極，感測薄膜設於加熱元件上，中空結構底端有氧化物層。此設計提升了支撐效能和穩定性，能感測超過500℃的高溫，增加產品競爭力和實用性。

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AUG.21

Development of a Micro Hydrogen Sulfide (H_2S) Gas Sensing Module for Smart City Applications

Smart Dust Sensors

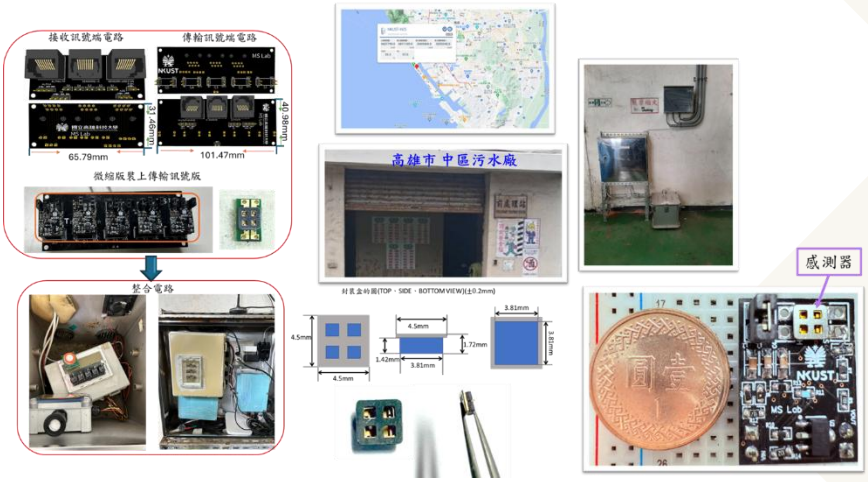
Department of Electronic Engineering,
National Kaohsiung University of Science and Technology
Dr. Ting-Jen Hsueh

The sensor chips developed by our team were fabricated using the 6"–8" MEMS technology service platform at the TSRI Southern Regional Center. After fabrication, the chips underwent small-scale pilot packaging production at the gas sensor chip packaging facility established within the Semiconductor Packaging and Testing Center of National Kaohsiung University of Science and Technology. The resulting micro hydrogen sulfide gas sensor chips feature low power consumption, low cost, fast response, high sensitivity, high stability, and high selectivity. Furthermore, the circuit module system was streamlined, standardized, and packaged, assisting academia in achieving localization of sensor component modules and establishing independent sensor technology capabilities.

Field deployment and testing were carried out at the Qijin Central District Wastewater Treatment Plant in Kaohsiung, including setup and testing of signal transmission, networking, and power supply functions. Measurement data were compared with environmental temperature and humidity meters as well as internationally benchmarked gas sensors. The collected data were transmitted back to a cloud technology platform to form a regional monitoring network, thereby enhancing the competitiveness of domestic industries in gas sensing products and smart networked monitoring systems.

Project Highlights

- Developed MEMS gas sensing chips at the TSRI Southern Regional Center, creating a highly sensitive H_2S chip-type gas sensor with a compact size of 0.7 mm × 0.7 mm × 0.4 mm.
- Conducted field networking setup and on-site testing at the Qijin Central District Wastewater Treatment Plant.
- Performed measurement data comparisons with internationally benchmarked gas sensors.
- Performed measurement data comparisons with commercially available sensors.
- The gas sensor developed under this project has completed product packaging and has been integrated into the signal circuit board.



Industrial Applications

- Developed MEMS gas sensing chips at the TSRI Southern Regional Center, creating a highly sensitive H_2S chip-type gas sensor with a compact size of 0.7 mm × 0.7 mm × 0.4 mm.
- This product is newly developed, and deployment can be progressively expanded:

First in environments with constant temperature and humidity (such as semiconductor manufacturing plants, storage rooms, or materials analysis laboratories),Then in environments with relatively small temperature variations (such as wastewater treatment plants, sewers, or facility management sites) for broader promotion.

Patent：Structure of a Gas Sensor

Patent Number I706571	Patent Term

This invention relates to a micro gas sensor structure comprising a hollow structure, an insulating layer, a low stress dielectric layer, a heating element, and electrodes, with a sensing film disposed on the heating element. An oxide layer is formed at the bottom of the hollow structure. This design enhances support performance and stability, enables sensing at high temperatures exceeding 500 °C, and improves both product competitiveness and practicality.

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智慧微塵感測器技術研發服務平台

智慧微塵感測器

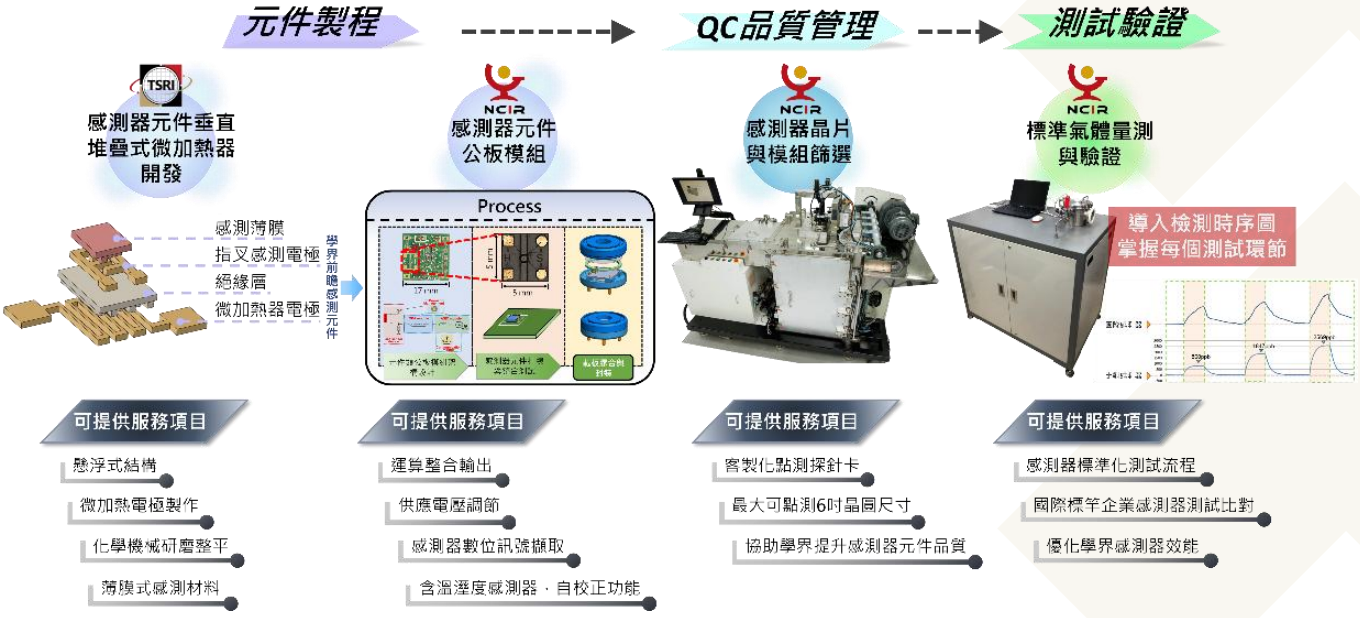
國家實驗研究院國家儀器科技研究中心
陳峰志 資深研究員團隊

國家實驗研究院國家儀器科技研究中心
蕭文澤 研究員

本計畫建構完善的感測器製程服務平台(感測器異質整合製程平台與感測器聯網與模組化整合測試平台)，協助學界完成感測元件模組國產化，建立自主感測器技術能量。以前瞻工程實踐與整合測試技術研發為基礎，透過實際佈點與物聯網技術串接成區域監控網絡，有效提升國內產業界於氣體感測產品與智慧聯網監控產業競爭力。

計畫亮點

- 學術界團隊/國內業者共同開發半導體式、微型光譜儀/光學式氣體感測元件技術。
- 建構氣體感測器元件用公板模組，橋接學界前瞻感測器技術。
- 建構標準氣體測試驗證平台與標準化測試流程，並與國際標竿感測器平行比對，藉以作為提升感測器效能之依據。
- 結合學界前瞻技術研發與法人平台加值，建構感測器國產化自主研發能量，建立產業聚落與落實產業應用。



產業應用

- 介接感測器關鍵技術(如：材料、製程、電路、模組及系統等)至產業落地試量產。
- 衍生在民生、社會、工業應用題材，如：(1)環保署標準測站、(2)半導體製程場域、(3)汙水處理廠與(4)智慧城市應用

專利資訊：多點測試裝置

專利證書號 I687691	專利權期限 2020/3/11~2038/12/16

可應用於特定氣體半導體或電子元件之點測設備中之固定探針卡，進行點測作業前通入特定氣體於裝置內部，以機構設計將氣體導引流向探針針尖所在區域，複數個探針針尖同時接觸晶片的焊墊，進行晶片電性測試，確保品質。

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AUG.21

Smart Dust Sensor Technology R&D Service Platform

Smart Dust Sensors

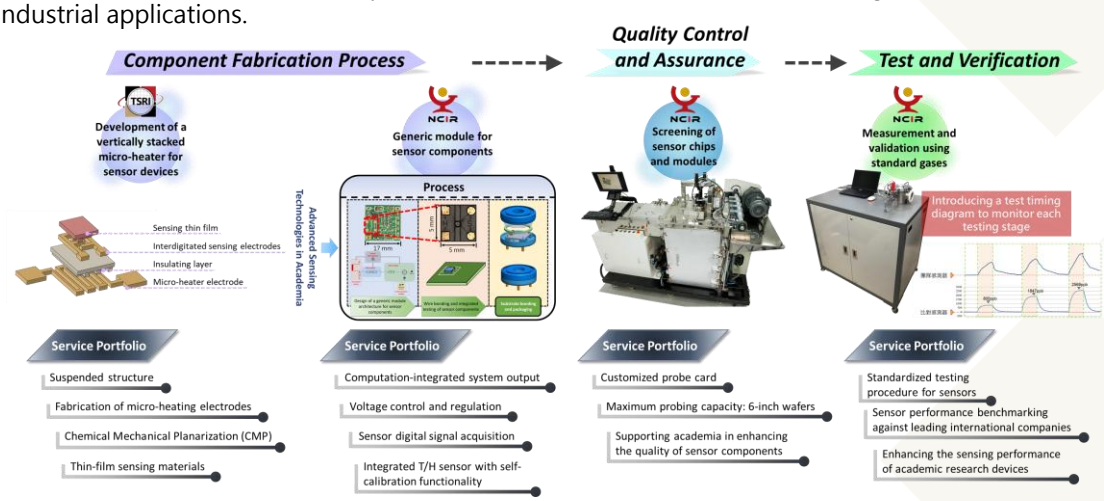
National Center for Instrumentation Research
Dr. Fong-Zhi Chen

National Center for Instrumentation Research
Dr. Wen-Tse Hsiao

This project aims to establish a comprehensive sensor fabrication service platform, comprising a heterogeneous sensor integration process platform and a sensor networking and modular integration testing platform. The objective is to support academia in localizing sensor module development and fostering domestic capabilities in sensor technologies. Grounded in forward-looking engineering practices and integration testing technology development, the project will implement real-world sensor deployment and utilize IoT technologies to form a regional monitoring network. This approach is expected to significantly enhance the competitiveness of the domestic industry in gas sensing products and smart networked monitoring systems.

Project Highlights

- Collaborative development between academic teams and domestic industry on semiconductor-based, miniaturized spectrometer, and optical gas sensor technologies.
- Integration of advanced academic research with the value-added capabilities of institutional platforms to cultivate domestic self-sufficiency in sensor R&D, foster industrial clustering, and promote real-world industrial applications.



Industrial Applications

- Bridging critical sensor technologies to pilot-scale industrial implementation and localized productions - such as materials, fabrication processes, circuits, modules, and systems.
- Expanding applications to civilian, societal, and industrial domains, including:
- (1) Environmental Protection Administration (EPA) standard monitoring stations, (2) semiconductor manufacturing facilities, (3) wastewater treatment plants, and (4) smart city applications.

Patent：Multi-probing Device

Patent Number I687691	Patent Term 2020/3/11~2038/12/16

A probing device is applied to a probing and testing system for semiconductor or electronic components, especially to a probing and testing system that is used to input a specific gas inside. To fix a probe card at one end of the probing device, and then introducing a specific gas into the interior of the probing device before starting the probing operation, and guiding the specific gas to the area of the probe tips on a probe card by the mechanical design. A plurality of probe tips simultaneously contact a plurality of pads of a plurality of dies on the wafer, and an appropriate voltage or current is applied to perform an electrical test of dies on the wafer to ensure product quality.

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基於微型光譜儀的全場域超微型氣體檢測及微型光譜儀應用開發

智慧微塵感測器

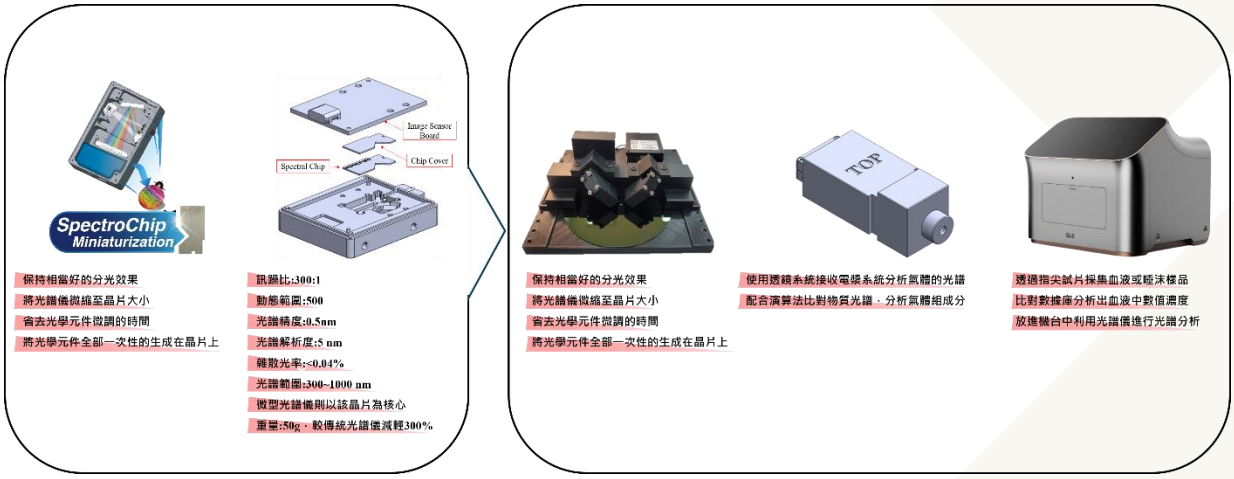
國立臺灣科技大學自動化暨控制研究所
柯正浩 教授

本計畫旨在開發超微型光學氣體感測器，結合光譜分析技術與物聯網介面，實現全場域即時氣體監測。核心技術包括：微型光譜儀、薄膜氣體吸附、電漿光譜感測系統。

光譜感測系統：使用自研微型光譜儀（Spectrochip）搭配特定波長光源，檢測氣體分子對光譜的干涉變化，並透過參數調整（如曝光時間、訊號增益）提升靈敏度。

智能薄膜材料：與工研院及光洋應材合作開發多種氣敏薄膜（如二氧化鈦、氧化鋅、三氧化鎢、量子點薄膜），可依目標氣體（CO、CO_2、H_2S、NO_2等）切換，並通過溫度、濕度檢量線優化檢測精度（R^2>0.9）。

電漿光譜感測系統：使用Spectrochip量測真空管中電漿之光譜波長，進而分析該綜合氣體中不同氣體組成。



計畫亮點

- 微型化與多氣體檢測：僅3微米薄膜厚度即可實現高靈敏度，且可更換薄膜偵測不同氣體。
- 環境適應性：在80°C至200°C、濕度20%-70%範圍內，光譜波長位移與環境參數高度線性相關，確保戶外應用可靠性。可對環境變化進行補償。
- 跨界合作：整合學界（台科大）、研究機構（工研院）與產業（光洋應材），加速技術落地。
- 低成本光學方案：自製光譜儀取代傳統拉曼光譜等高價設備，降低部署門檻。
- 場域安全性：可通過光纖進行遠距離偵測，不需要通電，降低了場域安全風險。

產業應用

- 智慧工廠：即時監控生產線有害氣體（如CO、H_2S），預防風險。
- 智慧城市：部署於大眾運輸系統或公共區域，偵測空氣污染物（PM2.5、NO_2），優化環境品質。
- 智能家居：整合居家物聯網，偵測室內CO_2濃度或瓦斯洩漏，提升居住安全。

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AUG.21

Micro-spectrometer-based Full-field Ultra-miniature Gas Detection and Micro-spectrometer Application Development

Smart Dust Sensors

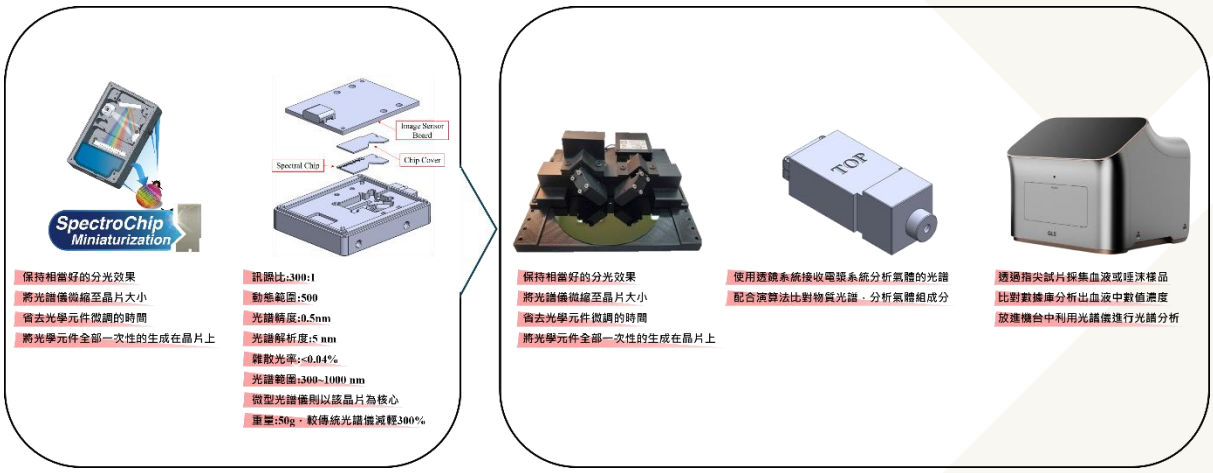
Graduate Institute of Automation and Control,
National Taiwan University of Science and Technology
Dr. Cheng-Hao Ko

This project aims to develop ultra-miniature optical gas sensors, combined with spectroscopic analysis technology, to realize real-time gas monitoring in the whole field. The core technologies include: micro-spectrometer, thin-film gas adsorption, and plasma spectral sensing system.

Spectroscopic Sensing System: This system uses a self-developed micro-spectrometer (Spectrochip) paired with a specific wavelength light source to detect spectral interference changes caused by gas molecules. Sensitivity is enhanced by adjusting parameters such as exposure time and signal gain.

Smart Thin-Film Materials: In collaboration with ITRI and Advanced Optoelectronic Technology Inc., we've developed various gas-sensitive thin films (such as titanium dioxide, zinc oxide, tungsten trioxide, and quantum dot films). These films can be swapped depending on the target gas (e.g., CO, CO_2, H_2S, NO_2) and detection accuracy (R2>0.9) is optimized using temperature and humidity calibration curves.

Plasma Spectroscopic Sensing System: This system uses the Spectrochip to measure the spectral wavelength of plasma within a vacuum tube, thereby analyzing the different gas compositions within a mixed gas environment.



Project Highlights

- Miniaturization and multi-gas detection: High sensitivity can be achieved with a film thickness of only 3 microns, and the film can be changed to detect different gases.
- Environmental adaptability: Highly linear correlation between spectral wavelength shift and environmental parameters in the range of 80°C to 200°C and 20% to 70% humidity, ensuring reliability in outdoor applications. Compensates for environmental changes.
- Cross-border cooperation: Integration of academia (NTUST), research institutes (ITRI) and industry (OPTOTECH) to accelerate technology implementation.
- Low-cost optical solution: Self-built spectrometer replaces traditional Raman spectroscopy and other high-priced equipment, lowering the deployment threshold.
- Field security: Long-distance detection via optical fiber without power supply reduces field security risk.

Industrial Applications

- Intelligent Factory: Real-time monitoring of hazardous gases (e.g. CO, H_2S) in the production line to prevent risks.
- Smart City: Deployed in public transportation systems or public areas to detect air pollutants (PM2.5, NO_2) and optimize environmental quality.
- Smart Home: Integrate the Internet of Things (IoT) in the home to detect indoor CO_2 concentration or gas leakage to enhance residential safety.

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