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## Novel H<sub>2</sub>S sensing mechanism derived from the formation of oligomeric sulfide capping the surface of gold nanourchins†

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A gold nanourchin (AuNU) probe with a novel sensing mechanism for monitoring H<sub>2</sub>S was developed as a feasible colorimetric sensor. In this study, AuNUs that are selectively responsive to H<sub>2</sub>S were fabricated in the presence of trisodium citrate and 1,4-hydroquinone using a seed-mediated approach. Upon exposure of the AuNU solution to H<sub>2</sub>S, the hydrosulfide ions (HS<sup>-</sup>) in the solution are converted into oligomeric sulfides by 1,4-hydroquinone used as a reducing agent during the synthesis of AuNUs. The oligomeric sulfides formed in the AuNU solution upon the addition of H<sub>2</sub>S were found to coat the surface of the AuNUs, introducing a blue shift in absorption accompanied by a color change in the solution from sky blue to light green. This colorimetric alteration by the capping of oligomeric sulfides on the surface of AuNUs is unique compared to well-known color change mechanisms, such as aggregation, etching, or growth of nanoparticles. The novel H<sub>2</sub>S sensing mechanism of the AuNUs was characterized using UV-Vis spectroscopy, high-resolution transmission microscopy, X-ray photoelectron spectroscopy, surface-enhanced Raman spectroscopy, secondary ion mass spectroscopy, liquid chromatography-tandem mass spectrometry, and atom probe tomography. H<sub>2</sub>S was reliably monitored with two calibration curves comprising two sections with different slopes according to the low (0.3–15  $\mu$ M) and high (15.0–300  $\mu$ M) concentration range using the optimized AuNU probe, and a detection limit of 0.29  $\mu$ M was obtained in tap water.

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## 1 Introduction

H<sub>2</sub>S is a potentially fatal substance in the workplace and for workers in many industries, including farms, oil refineries, and sewage treatment. Low-level exposure to H<sub>2</sub>S usually causes irritation of the mucous membrane and skin, whereas high-level exposure causes fatal toxicity. H<sub>2</sub>S is readily water-soluble and exists as a hydrosulfide ion (HS<sup>-</sup>) in aqueous solutions with pH 6–12.<sup>1–5</sup>

Although U.S. Environmental Protection Agency has not established a standard for H<sub>2</sub>S, the U.S. Occupational Safety and Health Administration has set an 8 h average professional standard of 20 ppm. The World Health Organization suggests that H<sub>2</sub>S gas concentrations should not exceed a 7  $\mu$ g m<sup>-3</sup>, average over a half hour period.<sup>6–9</sup>

Various instrumental analysis methods such as flow injection analysis,<sup>10</sup> ion exchange chromatography (IC)<sup>11</sup>, electrochemical methods,<sup>12–14</sup> ultra-performance liquid chromatography-tandem mass spectrometry (LC-MS/MS),<sup>15,16</sup> and fluorometry<sup>17</sup> have been employed to analyze the concentration of H<sub>2</sub>S. However, these analytical techniques generally require the use of state-of-the-art analytical apparatus and laborious sample pre-treatment, and must be performed by well-trained experts. This has motivated the recent development of several original and innovative nanoparticle probes for H<sub>2</sub>S detection.

Gold and silver nanoparticles (AuNPs and AgNPs) are commonly used in chemical sensors for H<sub>2</sub>S; in particular, colorimetric analysis using these nanoparticles is common because of facile, cost-efficient manufacturing, and the user-friendliness of colorimetric analysis.<sup>18–25</sup> Visual sensing using AuNPs/AgNPs for H<sub>2</sub>S in aqueous systems involves mechanisms based on aggregation,<sup>26</sup> etching,<sup>27</sup> or growth<sup>28</sup> of nanoparticles. In addition to the colorimetric sensing mechanisms of AuNPs established to date, a novel mechanism using gold nanourchins (AuNUs) was found for the detection of H<sub>2</sub>S in this study. In seed-mediated synthesis using dual reducing agents, citrate and 1,4-hydroquinone were used together to generate an urchin

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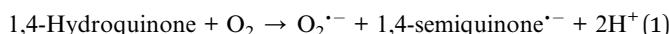
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morphology of AuNP with multiple-tips on the {111}, {200}, {220} and {311} crystalline faces.<sup>29</sup>

In this study, the AuNU solution was exposed to H<sub>2</sub>S existing as HS<sup>−</sup> in aqueous solutions, as described above. Hydrosulfides spontaneously form oligomeric sulfides by reacting with 1,4-hydroquinone, which is used as a reducing agent in the synthesis of AuNUs (see below).<sup>30,31</sup>



Superoxide (O<sub>2</sub><sup>·−</sup>) is formed during the oxidation of 1,4-hydroquinone to a 1,4-semiquinone anion radical (eqn (1)). This radical reduces hydrosulfide to a hydrosulfide radical (eqn (2)), which initiated the formation of oligomeric sulfides (S<sub>n</sub><sup>2−</sup>) with various chain lengths (n = 1–9) (eqn (3)–(5)).

The colorimetric change mechanism in the AuNUs upon the addition of H<sub>2</sub>S is unique compared to those in nanoparticles due to the aggregation, etching, or growth of AuNPs,<sup>26–28</sup> based on UV-Vis absorption. The H<sub>2</sub>S sensing mechanism of the AuNUs was characterized using UV-Vis spectroscopy, high-resolution transmission electron microscopy (HR-TEM), X-ray photoelectron spectroscopy (XPS), surface-enhanced Raman spectroscopy (SERS), LC-MS/MS, time-of-flight secondary ion mass spectroscopy (TOF-SIMS), and atom probe tomography (APT). The color-change mechanism in the AuNU solution upon the addition of H<sub>2</sub>S should be investigated to determine the origin of the localized surface plasmon resonance (LSPR) frequency perturbation in a manner different from that of the conventional sensing mechanism.

The AuNUs responded selectively to H<sub>2</sub>S, as indicated by a clear change in the color of the solution from sky blue to light green. In addition, none of the studied metal cations or anions interfered with the H<sub>2</sub>S monitoring. The prepared AuNU probe for H<sub>2</sub>S was optimized with respect to pH, temperature, and salt concentration. Additionally, the limits of detection (LOD) and linearity were determined. We concluded that this optimized AuNU probe could be employed as a simple and practical system for real-time H<sub>2</sub>S detection owing to its high capacity for H<sub>2</sub>S sensing.

## 2 Materials and methods

### 2.1 Chemicals and reagents

Hydrogen tetrachloroaurate (III) trihydrate (HAuCl<sub>4</sub>·3H<sub>2</sub>O), trisodium citrate (TSC) and H<sub>2</sub>S were purchased from Sigma-Aldrich (St. Louis, MO, USA). The anions F<sup>−</sup>, Cl<sup>−</sup>, Br<sup>−</sup>, I<sup>−</sup>, NO<sub>2</sub><sup>−</sup>, NO<sub>3</sub><sup>−</sup>, SO<sub>4</sub><sup>2−</sup>, ClO<sub>3</sub><sup>−</sup>, ClO<sub>2</sub><sup>−</sup>, ClO<sub>4</sub><sup>−</sup>, BrO<sub>3</sub><sup>−</sup>, CH<sub>3</sub>COO<sup>−</sup>, C<sub>2</sub>H<sub>5</sub>COO<sup>−</sup>, C<sub>4</sub>H<sub>7</sub>O<sub>2</sub><sup>−</sup>, C<sub>8</sub>H<sub>4</sub>O<sub>4</sub><sup>2−</sup>, Cr<sub>2</sub>O<sub>7</sub><sup>2−</sup>, C<sub>6</sub>H<sub>5</sub>O<sub>7</sub><sup>3−</sup>, NaSCN<sup>−</sup>, CO<sub>3</sub><sup>2−</sup>, PO<sub>4</sub><sup>3−</sup>, S<sub>2</sub>O<sub>8</sub><sup>2−</sup>, SCN<sup>−</sup>, C<sub>6</sub>H<sub>8</sub>O<sub>4</sub><sup>2−</sup>, C<sub>6</sub>H<sub>5</sub>COO<sup>−</sup>, C<sub>2</sub>H<sub>4</sub>O<sub>2</sub>(COO)<sup>2−</sup>, C<sub>4</sub>H<sub>3</sub>O<sub>5</sub><sup>3−</sup>, C<sub>3</sub>H<sub>2</sub>O<sub>4</sub><sup>2−</sup>, C<sub>2</sub>H<sub>4</sub>(COO)<sup>2−</sup>,

C<sub>2</sub>H<sub>5</sub>COO<sup>−</sup>, C<sub>3</sub>H<sub>4</sub>O<sub>3</sub><sup>2−</sup>, HCOO<sup>−</sup>, (C<sub>2</sub>O<sub>4</sub>)<sup>2−</sup>, SiO<sub>3</sub><sup>2−</sup>, C<sub>2</sub>H<sub>3</sub>O<sub>3</sub><sup>−</sup> and CN<sup>−</sup> were purchased from AccuStandard (New Haven, CT, USA). HCl, NaOH and 1,4-hydroquinone were purchased from Samchun Chemical (Gyeonggi-do, Republic of Korea). Double distilled water was obtained from a Milli-Q water purifier (Millipore, Billerica, MA, USA). To examine the usability of the probe, tap, pond and waste water samples were obtained from the laboratory, pond and clarifier tanks, respectively at the Korea Institute of Science and Technology (KIST) campus.

### 2.2 Instruments and analyses

The absorption spectra of the AuNU solutions in the wavelength range of 200–900 nm were measured using a UV-Vis spectrophotometer (S-3100, Scinco, Republic of Korea). The pH was measured using an HI 2210 pH meter (Hanna Instruments, Woonsocket, RI, USA). The H<sub>2</sub>S concentrations in the water samples were analyzed using IC (Metrohm, Ionenstrasse, Herisau, Switzerland). Particle size distribution was evaluated using dynamic light scattering (DLS; Zetasizer, Malvern Instruments, Worcestershire, UK). XPS characterization of the Au–Au and Au–S bonds of the oligomeric sulfides was carried out using a PHI 5000 VersaProbe III system (ULVAC-PHI, Chigasaki, Japan).

The physico-chemical properties of the polymeric chain coated on the surface of the AuNUs were evaluated in the wavenumber range of 100–1800 cm<sup>−1</sup> using a Raman spectrometer (LabRam Aramis, Horiba, Kyoto, Japan) with either a 633 nm or 785 nm diode laser power below 1 mW as the source. The LabSpec 4.16 software was used for Raman peak analysis and deconvolution of the spectra.

The morphologies, surfaces and diameters of the AuNUs and AuNUs with H<sub>2</sub>S (AuNUs-H<sub>2</sub>S) were evaluated using HR-TEM (CM30, Philips, NC, USA). TOF-SIMS was used to characterize molecular chain capping on the surface of the AuNUs.

The analytes were identified by LC-MS/MS on a Waters ACQUITY UPLC system coupled to a Waters SYNAPT G2-Si quantitative time-of-flight mass spectrometer equipped with an electrospray ionization source (Waters Corporation, Milford, MA, USA). The samples were measured in positive mode.

APT offers both 3D imaging and chemical composition measurements at the atomic scale and was performed using a LEAP 4000X HR<sup>TM</sup> system (Ametek Inc., Berwyn, PA, USA). HR-TEM and APT samples were prepared using the precipitates of AuNUs and AuNUs-H<sub>2</sub>S, and the solvent was subsequently evaporated. The APT specimens were further processed by annular milling using a dual beam focused ion beam (FIB; Nova Nanolab 600; Thermo Fisher Scientific, Waltham, MA, USA). An LC-MS/MS instrument (Waters, Manchester, UK) was used to characterize the structure of the polymer chain formed in the AuNUs upon the addition of H<sub>2</sub>S.

### 2.3 Synthesis of AuNUs

AuNUs were synthesized using the seed-mediated growth method.<sup>32</sup> Spherical Au nanoseeds were fabricated by citrate reduction of HAuCl<sub>4</sub>. A 100 mM HAuCl<sub>4</sub> aqueous solution was prepared by dissolving HAuCl<sub>4</sub> (2 g) in double distilled water (50 mL). The HAuCl<sub>4</sub> solution (150 μL) was mixed in a flask with



deionized water (60 mL) under vigorous stirring, and boiling. After boiling, a 1% aqueous sodium citrate solution (1 mL) was immediately added, and the solution was boiled until its color changed to wine red. The solution was then cooled by stirring to form seed solution. The growth solution was prepared by adding aqueous  $\text{HAuCl}_4$  (100 mM, 50  $\mu\text{L}$ ) to distilled water (19.2 mL) under vigorous stirring. Then, Au nanoseeds (100  $\mu\text{L}$ ), 1% sodium citrate (44  $\mu\text{L}$ ), and 1,4-hydroquinone (30 mM, 2 mL) were sequentially added to the solution. The solution was stirred at 25 °C for 30 min to obtain Au nanourchins with multiple tips (Fig. S1†).<sup>33</sup>

#### 2.4 Optical sensing of $\text{H}_2\text{S}$ in real samples

To evaluate the practical application of the newly designed probe, the concentrations of  $\text{H}_2\text{S}$  in tap water, pond water, and waste water obtained from KIST were monitored. A standard  $\text{H}_2\text{S}$  solution was added to tap water and pond water samples to obtain the  $\text{H}_2\text{S}$  concentrations of 150  $\mu\text{M}$  and 300  $\mu\text{M}$ , but waste water was used intact without addition of  $\text{H}_2\text{S}$ . The concentration of  $\text{H}_2\text{S}$  in the samples was measured using the AuNU solution (1000  $\mu\text{L}$ ). The  $\text{H}_2\text{S}$  concentrations measured by the AuNUs were validated using IC.

### 3 Results and discussion

#### 3.1 Optical properties, stabilities, and morphologies of AuNUs and AuNUs- $\text{H}_2\text{S}$

AuNUs with a size of approximately 115 nm were synthesized using the seed-mediated growth method, and Au nanoseeds were fabricated by reducing of  $\text{HAuCl}_4$  with trisodium citrate. The wavelength of the maximum LSPR peak of the AuNUs was 672 nm, and an additional LSPR peak appeared at 421 nm for AuNUs- $\text{H}_2\text{S}$  with a size of ~122.1 nm, introducing a unique absorption accompanied by a color change from sky blue to light green (Fig. 1a). This color change of the AuNUs occurred only upon  $\text{H}_2\text{S}$  addition; that is, other anions did not interfere (see below). The UV-Vis spectra for AuNUs and AuNUs- $\text{H}_2\text{S}$  are shown in the range of 350–900 nm (Fig. 1a), because highly intense UV-Vis absorbance is observed for  $\text{H}_2\text{S}$  and 1,4-hydroquinone in the 200–350 nm range (Fig. S2†). Furthermore, the absorbances of the AuNU solution at 672 nm and the AuNU- $\text{H}_2\text{S}$  solution at 421 nm were measured to evaluate its long-term stability for at least 4 weeks, and the results indicated that the AuNUs and the AuNUs- $\text{H}_2\text{S}$  were relatively stable within  $\pm 3\%$  (Fig. S3†).

Colorimetric changes in nanoparticle solutions upon the addition of specific chemicals have been known to be due to the aggregation, etching, or growth of nanoparticles.<sup>26–28</sup> However, examination of the HR-TEM images and particle size distributions (Fig. 1b and c) showed that the morphology and particle size of AuNUs- $\text{H}_2\text{S}$  did not differ from those of AuNUs. Therefore, it could be deduced that an unrecognized mechanism caused colorimetric and UV-Vis spectral change in AuNUs- $\text{H}_2\text{S}$  relative to those of the AuNU solution. Investigation of the structural changes in the AuNUs upon  $\text{H}_2\text{S}$  addition showed that the AuNU surface was capped by a polymeric chain, as

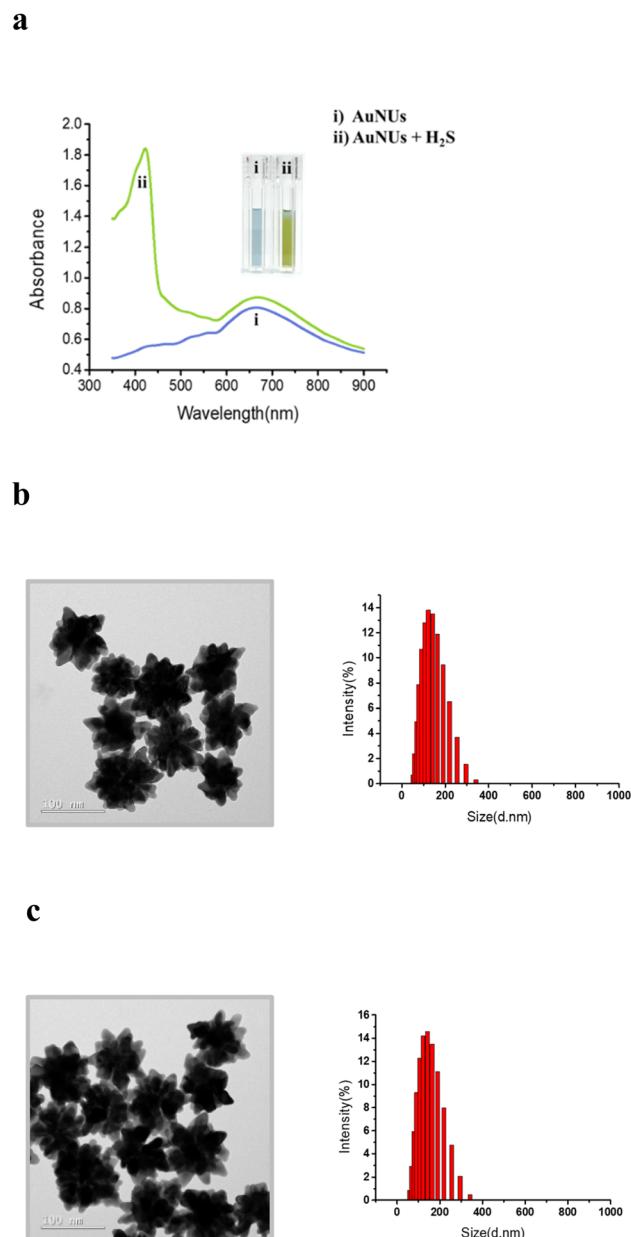


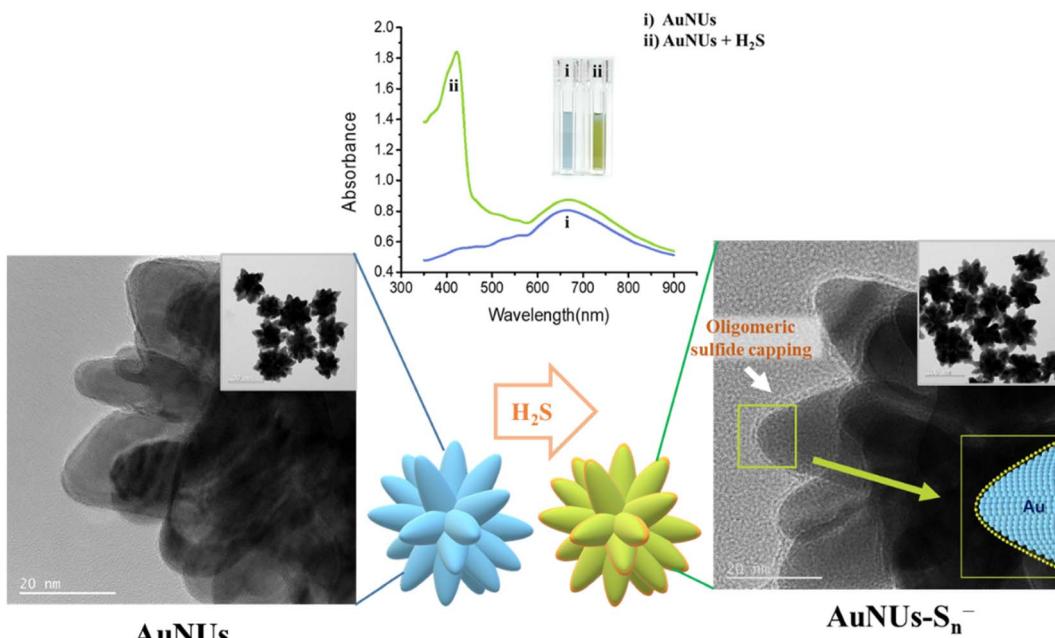
Fig. 1 (a) UV-Vis spectra of AuNUs (sky blue) and AuNUs- $\text{H}_2\text{S}$  (light green). (b) HR-TEM image, and the corresponding particle-size distribution ( $d = 115.4$  nm) of AuNUs. (c) HR-TEM image, and the corresponding particle-size distribution ( $d = 122.1$  nm) of AuNUs- $\text{H}_2\text{S}$  at pH 4.0 and 25 °C in 20 mM NaCl.

indicated by the HR-TEM image in the expanded region on the lower right of Scheme 1. Accordingly, the structure of the molecular chain coating on the surface of AuNUs should be characterized.

#### 3.2 Mechanism of $\text{H}_2\text{S}$ sensing by AuNUs

Colorimetric sensing probes using nanoparticles rely on the variations in the interparticle distance and the morphological change of the nanoparticles that result in both LSPR spectral shifts and color changes. The aggregation of nanoparticles induced by the presence of the target analyte changes the





**Scheme 1** Schematic of  $\text{H}_2\text{S}$  detection by gold nanourchins (AuNUs): UV-Vis spectra, a photograph of UV-Vis samples, synthetic morphologies, and HR-TEM images of AuNUs in the absence and the presence of  $\text{H}_2\text{S}$ . HR-TEM image of the oligomeric sulfide capping on the surface of AuNUs in the presence of  $\text{H}_2\text{S}$  ( $150 \mu\text{M}$ ) was zoomed and drawn schematically.

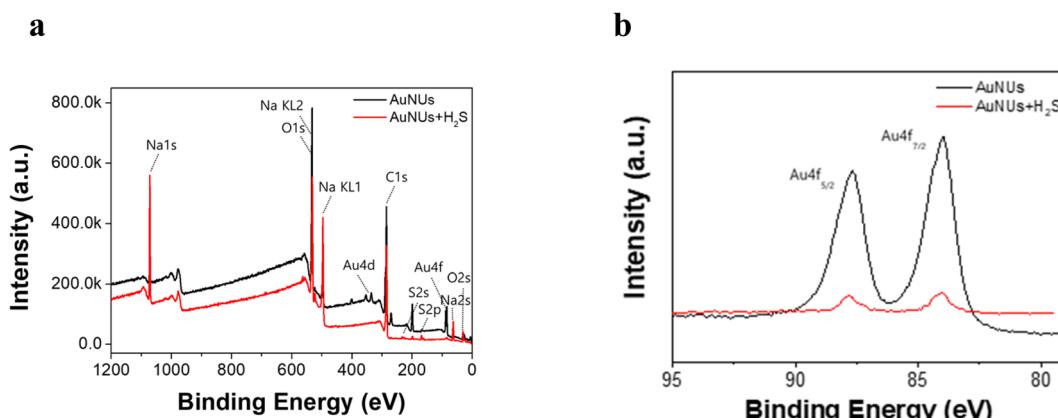
interparticle distance and forms the basis of colorimetric assays.<sup>26</sup> The growth reaction and etching of nanoparticles are known to be additional colorimetric sensing mechanisms arising from morphological changes.<sup>27,28</sup>

It was initially predicted that AuNUs could be applied as a feasible and selective color sensor owing to an LSPR peak shift causing changes in their morphology. Because AuNUs have multiple tips with high crystal energies, it was assumed that their color change originated from morphological changes caused by anion etching.<sup>34,35</sup> However, the intensity of the strong absorption band of the AuNUs at 672 nm did not decrease upon addition of  $\text{H}_2\text{S}$ , and an additional high-intensity peak at 421 nm appeared with no concomitant decrease in the

absorbance intensity at 672 nm. This new band reflected a chemical change at the AuNU surface rather than a morphological transformation of the AuNUs. Thus, the aforementioned polymeric coatings, having formed on the surface of the AuNUs- $\text{H}_2\text{S}$  and observed using HR-TEM, appeared to induce a colorimetric change in the AuNU solution from sky blue to light green (Scheme 1).

### 3.3 Spectroscopic characterization for the surface of the AuNUs- $\text{H}_2\text{S}$

Upon addition to the aqueous AuNU solution,  $\text{H}_2\text{S}$  was immediately ionized to  $\text{HS}^-$  at neutral pH,<sup>36,37</sup> and the hydrosulfide ions were spontaneously converted to hydrosulfide radicals



**Fig. 2** (a) Wide-scan XPS spectra of AuNUs (black) and AuNUs- $\text{H}_2\text{S}$  (red). (b) XPS Au4f spectra of AuNUs (black) and AuNUs- $\text{H}_2\text{S}$  (red) at pH 4.0 and 25 °C in 20 mM NaCl.

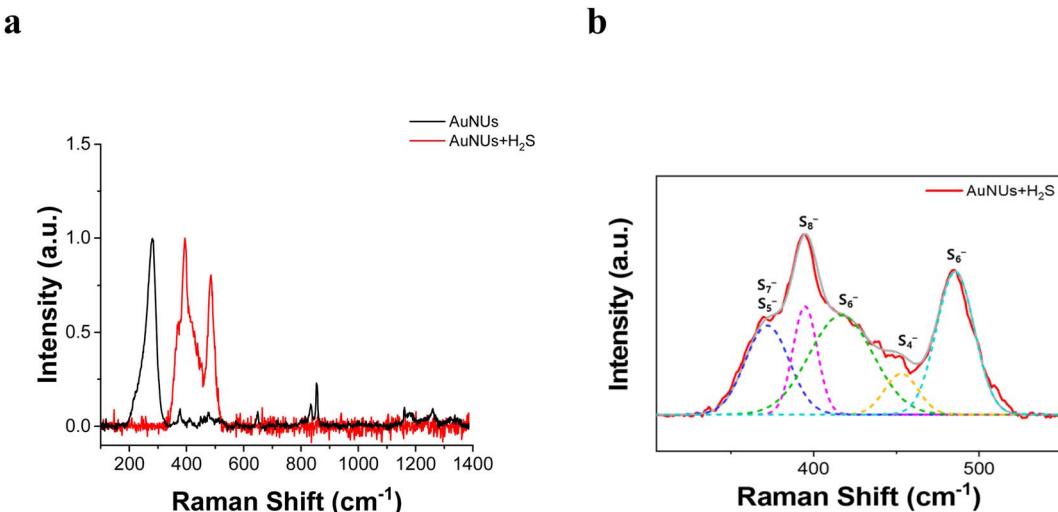


Fig. 3 (a) SERS spectra of AuNUs (black) and AuNUs+H<sub>2</sub>S (red) in the Raman shift range 100–1400 cm<sup>-1</sup> at pH 4.0 and 25 °C in 20 mM NaCl. (b) Deconvoluted Raman peaks with five resolved peaks using the LabSpec 4.16 software. These resolved peaks appear to correspond to oligomeric sulfides S<sub>4</sub><sup>-</sup>, S<sub>5</sub><sup>-</sup>, S<sub>6</sub><sup>-</sup>, S<sub>7</sub><sup>-</sup>, and S<sub>8</sub><sup>-</sup>.

using a 1,4-hydroquinone catalyst, which was used as the reducing agent in the synthesis of AuNUs.<sup>30,38</sup> These hydro-sulfide radicals dissociated into sulfide radicals, which further oligomerized to form oligomeric sulfides. The surface of the AuNUs was likely coated with this oligomeric sulfide and

stabilized through Au–S bonding. The oligomeric sulfide capping on the surface of the AuNUs was displayed on the periphery of the cone with AuNU–S<sub>n</sub><sup>-</sup> (inset on the right-hand side of Scheme 1).

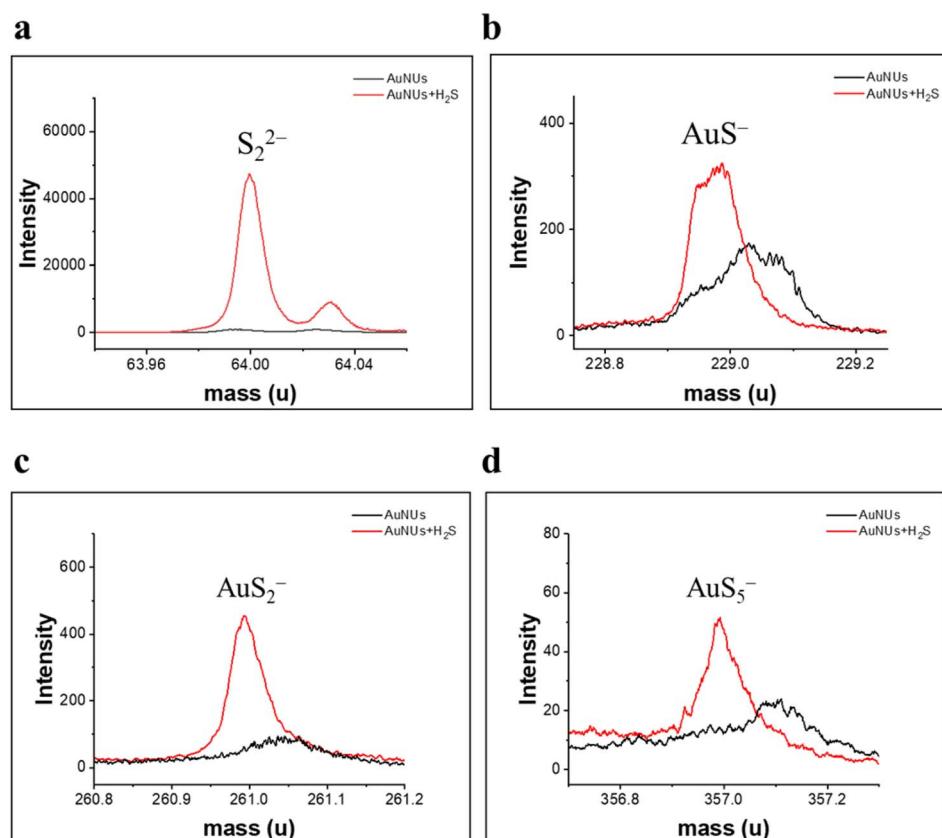


Fig. 4 TOF-SIMS spectra showing characteristic fragments (red) of (a) S<sub>2</sub><sup>2-</sup>, (b) AuS<sup>-</sup>, (c) AuS<sub>2</sub><sup>-</sup>, and (d) AuS<sub>5</sub><sup>-</sup> associated with oligomeric sulfide coated on the surface of AuNUs in the presence of H<sub>2</sub>S and characteristic fragments (black) of AuNUs in the absence of H<sub>2</sub>S.



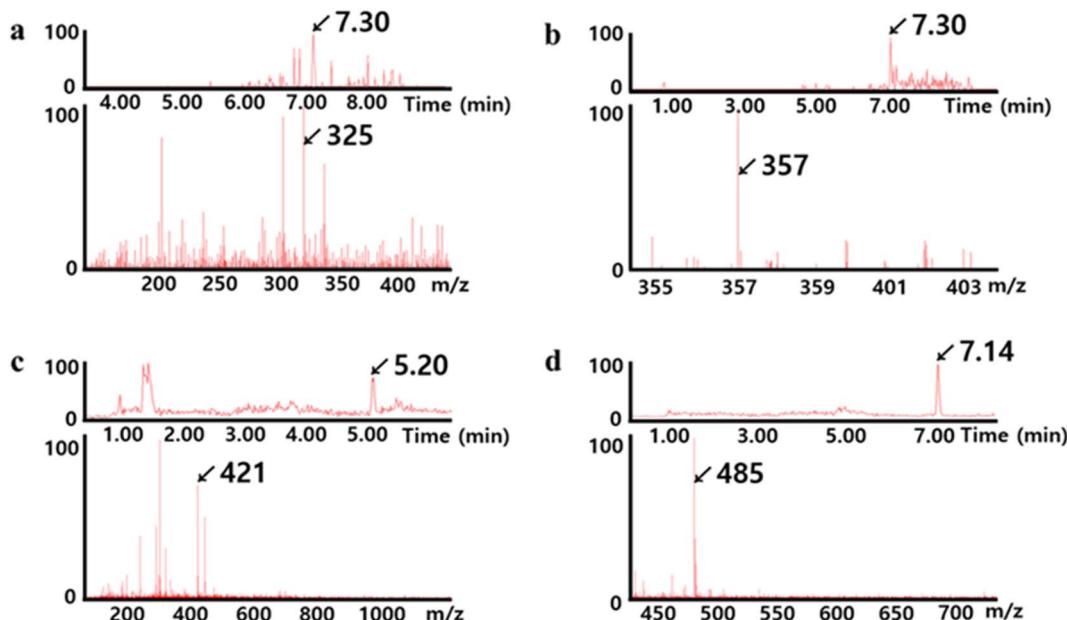


Fig. 5 LC chromatograms (above) and MS spectra (below) for (a)  $\text{AuS}_4^-$ , (b)  $\text{AuS}_5^-$ , (c)  $\text{AuS}_7^-$ , and (d)  $\text{AuS}_9^-$  showing  $\text{Au-S}_n^-$  associated with the oligomeric sulfide coated on the surface of AuNPs.

This oligomeric sulfide chain capping the surface of the AuNPs appeared to be maintained through Au-S bonding, and it was confirmed by XPS. Wide-scan XPS spectra of the AuNPs and AuNPs-H<sub>2</sub>S were recorded to examine the variations in Au 4f (Fig. 2a). The two Au 4f binding energies, representing the Au 4f<sub>7/2</sub> (84.0 eV) and Au 4f<sub>5/2</sub> (87.7 eV) states, exhibited peaks in the XPS spectrum of the AuNPs, which were ascribed to metallic Au. The much smaller XPS peaks of the Au 4f<sub>7/2</sub> (84.1 eV) and Au 4f<sub>5/2</sub> (87.8 eV) states in AuNPs-H<sub>2</sub>S suggested that Au was bound to sulfur (Fig. 2b). These electron-rich sulfur atoms gave rise to a 0.1 eV shift to higher energies of the Au 4f doublets, thus providing XPS validation for the coordination between the Au and S atoms.<sup>39,40</sup>

The sensitivity of the SERS peak with respect to the interactions at the surface of plasmonic nanoparticles makes it particularly suitable for structural investigations of molecular chains in contact with nanoparticles.<sup>41,42</sup> AuNPs with sharp edges and tips exhibit highly sensitive SERS signals upon chemical enhancement due to electron transfer to the AuNPs,

as well as large electromagnetic enhancements around the AuNPs when forming Au-S bonds.<sup>43</sup>

Thus, the chemical structure of the oligomeric chains capping the surface of the AuNPs was characterized using SERS peaks. The SERS peaks for the molecular chains appeared in the 300–550  $\text{cm}^{-1}$  frequency range corresponding to the S-S stretching vibration (Fig. 3a), and these peaks were deconvoluted using LabSpec 4.16 software (Fig. 3b). Raman scattering peaks at 363, 394, 419, and 485  $\text{cm}^{-1}$  appear to originate from the sulfide bonds of  $\text{AuS}_4^-$ ,  $\text{AuS}_5^-$ ,  $\text{AuS}_6^-$ ,  $\text{AuS}_7^-$ , and  $\text{AuS}_8^-$ .<sup>44,45</sup> Therefore, these SERS peaks revealed that the molecular chains in contact with the surface of the AuNPs contained various oligomeric sulfides bound to Au.

Moreover, TOF-SIMS analysis has previously been applied to characterize oligomeric sulfides coated on the surface of AuNPs.<sup>46,47</sup> Specific fragment ions ( $\text{S}_2^{2-}$ ,  $\text{AuS}^-$ ,  $\text{AuS}_2^-$ , and  $\text{AuS}_5^-$ ), found in the TOF-SIMS spectra of the AuNPs-H<sub>2</sub>S solution (Fig. 4), verify that the H<sub>2</sub>S added to the AuNP solution

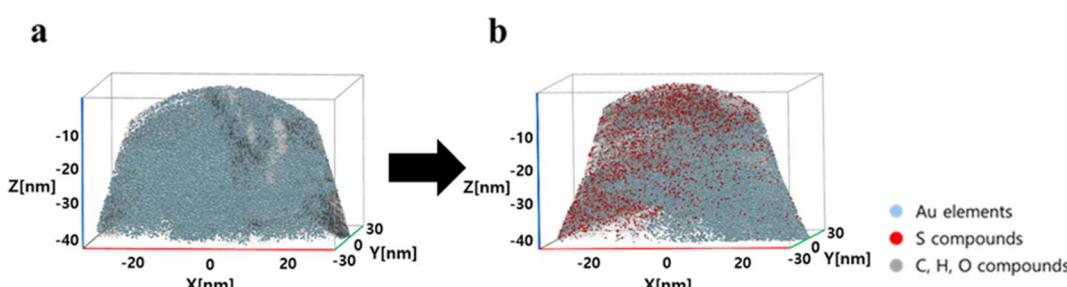


Fig. 6 Associated 3D chemical map of the volume containing a partial section of (a) AuNPs and (b) AuNPs-H<sub>2</sub>S (pH 4.0, 25 °C, and 20 mM NaCl) at near-atomic resolution.

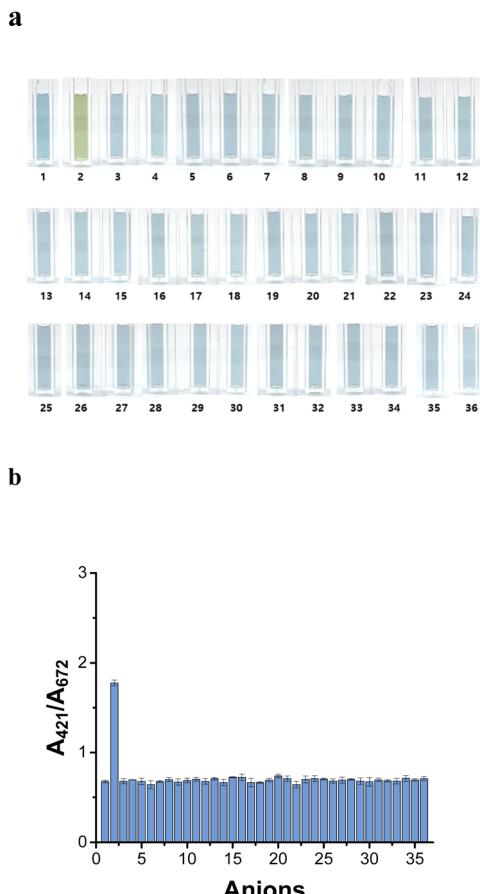


Fig. 7 (a) Photograph of AuNU dispersions upon the addition of 0.15 mM H<sub>2</sub>S or 1.5 mM of anions numbered 3–36: (1) Ctrl, (2) H<sub>2</sub>S, (3) F<sup>−</sup>, (4) Cl<sup>−</sup>, (5) Br<sup>−</sup>, (6) I<sup>−</sup>, (7) NO<sub>2</sub><sup>−</sup>, (8) NO<sub>3</sub><sup>−</sup>, (9) SO<sub>4</sub><sup>2−</sup>, (10) ClO<sub>3</sub><sup>−</sup>, (11) ClO<sub>2</sub><sup>−</sup>, (12) ClO<sub>4</sub><sup>−</sup>, (13) BrO<sub>3</sub><sup>−</sup>, (14) CH<sub>3</sub>COO<sup>−</sup>, (15) C<sub>2</sub>H<sub>5</sub>COO<sup>−</sup>, (16) C<sub>4</sub>H<sub>7</sub>O<sub>2</sub><sup>−</sup>, (17) C<sub>8</sub>H<sub>4</sub>O<sub>4</sub><sup>2−</sup>, (18) Cr<sub>2</sub>O<sub>7</sub><sup>2−</sup>, (19) C<sub>6</sub>H<sub>5</sub>O<sub>7</sub><sup>3−</sup>, (20) CO<sub>3</sub><sup>2−</sup>, (21) PO<sub>4</sub><sup>3−</sup>, (22) S<sub>2</sub>O<sub>8</sub><sup>2−</sup>, (23) SCN<sup>−</sup>, (24) C<sub>6</sub>H<sub>8</sub>O<sub>4</sub><sup>2−</sup>, (25) C<sub>6</sub>H<sub>5</sub>COO<sup>−</sup>, (26) C<sub>2</sub>H<sub>4</sub>O<sub>2</sub>(COO)<sub>2</sub><sup>2−</sup>, (27) C<sub>4</sub>H<sub>3</sub>O<sub>5</sub><sup>3−</sup>, (28) C<sub>3</sub>H<sub>2</sub>O<sub>4</sub><sup>2−</sup>, (29) C<sub>2</sub>H<sub>4</sub>(COO)<sub>2</sub><sup>2−</sup>, (30) C<sub>2</sub>H<sub>5</sub>COO<sup>−</sup>, (31) C<sub>3</sub>H<sub>4</sub>O<sub>3</sub><sup>2−</sup>, (32) HCOO<sup>−</sup>, (33) (C<sub>2</sub>O<sub>4</sub>)<sup>2−</sup>, (34) SiO<sub>3</sub><sup>2−</sup>, (35) C<sub>2</sub>H<sub>3</sub>O<sub>3</sub><sup>−</sup> and (36) CN<sup>−</sup> at pH 4.0 and 25 °C in the presence of 20 mM NaCl. (b) Absorbance ratios ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) of AuNU solution in the presence of H<sub>2</sub>S (0.15 mM) or in the presence of 1.5 mM anions without H<sub>2</sub>S in 20 mM NaCl at pH 4.0 and 25 °C.

was oligomerized to AuS<sub>n</sub><sup>−</sup> by the 1,4-hydroquinone catalyst, as described in the reaction mechanism (eqn. (1)–(5)).

The oligomeric chains capping the surface of the AuNUs were further identified using LC-MS/MS, which enables the detection of oligomeric sulfides of various lengths.<sup>48,49</sup> The LC chromatograms and MS spectra of AuNUs-H<sub>2</sub>S (Fig. 5) indicated that the polymeric chains were oligomeric sulfides, namely AuS<sub>n</sub><sup>−</sup> ( $n = 1–9$ ). Characteristic mass fragments associated with oligomeric sulfide formation were also found in trace amounts of Au<sub>2</sub>S<sub>n</sub><sup>−</sup> ( $n = 1–9$ ) (not shown).

APT is a well-established analytical technique for imaging the 3D structure and chemical constituents of materials at the atomic level in conjunction with FIB sample preparation methods. APT was employed to investigate the changes in certain elements and compounds on the surface of AuNUs upon the addition of H<sub>2</sub>S. APT images of the AuNUs and AuNUs-H<sub>2</sub>S were compared to confirm the presence of sulfide compounds

capping the AuNU surface (Fig. 6).<sup>50,51</sup> An FIB instrument was used to selectively taper the micron-sized samples acquired from the AuNUs and AuNUs-H<sub>2</sub>S. The 3-D chemical map displayed the distribution of Au on the surface of the AuNUs in the absence of H<sub>2</sub>S, whereas sulfide compounds are distinctly observable in the chemical map of AuNU-H<sub>2</sub>S (Fig. 6).

### 3.4 Optimized conditions for obtaining high sensitivity of AuNUs

The sensitivity of the probe to H<sub>2</sub>S was studied by varying the pH, temperature, and salt concentration. The highest

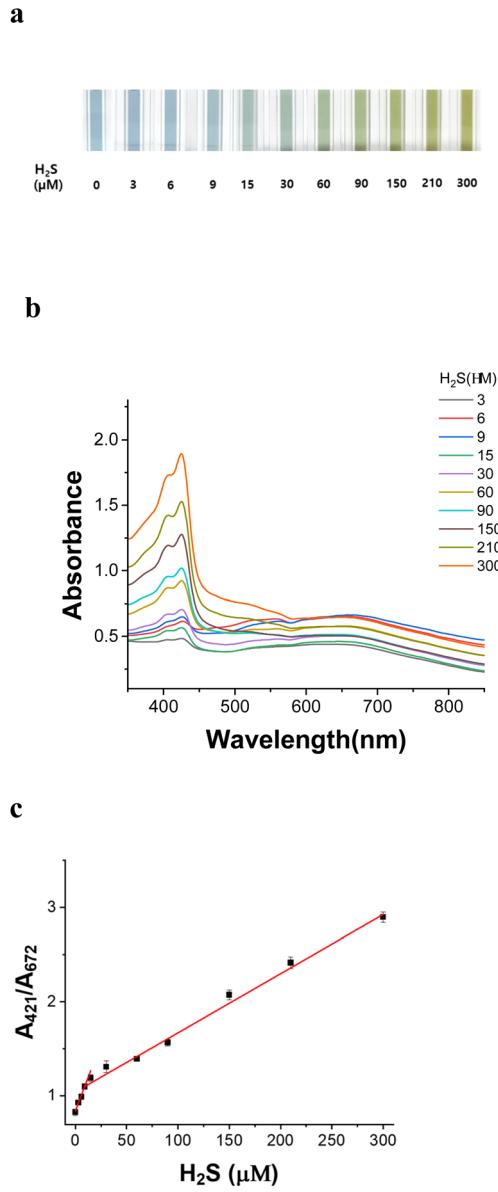


Fig. 8 (a) Photographs and (b) UV-Vis absorption spectra of AuNUs upon addition of various concentrations of H<sub>2</sub>S at pH 4.0 and 25 °C in 20 mM NaCl. (c) Calibration curves for absorption ratios ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) of the AuNU solutions as a function of H<sub>2</sub>S concentration in the ranges of 0.3–15 μM ( $y = 0.85635x + 0.84061$ ,  $r^2 = 0.9984$ ) and 15–300 μM ( $y = 0.18843x + 1.04173$ ,  $r^2 = 0.9954$ ) at pH 4.0 and 25 °C in 20 mM NaCl.



**Table 1**  $\text{H}_2\text{S}$  concentrations in spiked tap water, spiked pond water and real waste water samples determined using the AuNU colorimetric probe and ion chromatography

Amount of $\text{H}_2\text{S}$ added to real samples ( $n = 6$ )									
AuNUs colorimetric probe									
Sample	Concentration ( $\mu\text{M}$ )	Detected concentration ( $\mu\text{M}$ )	RSD (%)	Intraday analysis <sup>a</sup>			Interday analysis <sup>b</sup>		Detected concentration ( $\mu\text{M}$ )
				Recovery (%)	RSD (%)	Accuracy (bias%)	RSD (%)	Accuracy (bias%)	
Tap water <sup>c</sup>	150	148 $\pm$ 4.73	3.20	98.4 $\pm$ 3.15	3.41	8.77	5.11	-1.72	152
300		302 $\pm$ 23.2	7.69	101 $\pm$ 7.75	7.12	-2.27	6.95	2.83	298
Pond water <sup>d</sup>	150	140 $\pm$ 9.86	7.13	93.7 $\pm$ 6.57	6.87	-4.31	5.23	-2.19	146
300		290 $\pm$ 8.55	2.95	96.6 $\pm$ 2.85	3.48	2.58	4.01	2.81	303
Waste water <sup>e</sup>	Unknown	189 $\pm$ 5.14	3.50	97.9 $\pm$ 3.43	4.65	-1.22	3.76	-0.93	192

<sup>a</sup> Intraday analysis: four replicates with 2 h interval. <sup>b</sup> Interday analysis: 1st, 3rd, and 5th day. <sup>c</sup> Tap water: spiked sample. <sup>d</sup> Pond water: spiked sample. <sup>e</sup> Waste water: real sample.

absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) was the index chosen to determine the optimal conditions (pH, temperature, and NaCl concentration) for probe sensitivity. Optimal  $\text{H}_2\text{S}$  probe sensitivity was obtained at a solution pH of 4.0 (Fig. S4a†).

The sensitivity of the AuNU probe was tested as a function of temperature, and it was confirmed that the  $A_{421\text{ nm}}/A_{672\text{ nm}}$  ratio did not change as the temperature increased from 15 to 55 °C in 5 °C intervals (Fig. S4b†). Therefore, 25 °C was arbitrarily chosen as the optimal temperature.

The absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) of the AuNU solution in the presence of  $\text{H}_2\text{S}$  was monitored at various NaCl concentrations and did not change as the NaCl concentration increased from 20 to 120 mM; thus, 20 mM NaCl was arbitrarily chosen as the buffer (Fig. S4c†). Hence, for  $\text{H}_2\text{S}$  added to the AuNU solution probe, the optimal conditions for the AuNU solution probe were selected as pH 4.0, 25 °C and 20 mM NaCl buffer (Fig. S4†).

The reaction kinetics of the AuNUs were studied with various concentrations of  $\text{H}_2\text{S}$  by measuring the UV-Vis absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ). Immediately upon the addition of  $\text{H}_2\text{S}$  to the AuNU solution, oligomeric sulfides on the surface of the

AuNUs were completely formed at approximately 40 s, regardless of the  $\text{H}_2\text{S}$  concentration (Fig. S5†).

### 3.5 $\text{H}_2\text{S}$ selectivity of AuNUs

The  $\text{H}_2\text{S}$  selectivity of the AuNU probe was investigated using various anions, namely  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{ClO}_3^-$ ,  $\text{ClO}_2^-$ ,  $\text{ClO}_4^-$ ,  $\text{BrO}_3^-$ ,  $\text{CH}_3\text{COO}^-$ ,  $\text{C}_2\text{H}_5\text{COO}^-$ ,  $\text{C}_4\text{H}_7\text{O}_2^-$ ,  $\text{C}_8\text{H}_4\text{O}_4^{2-}$ ,  $\text{Cr}_2\text{O}_2^{7-}$ ,  $\text{C}_6\text{H}_5\text{O}_7^{3-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{PO}_4^{3-}$ ,  $\text{S}_2\text{O}_8^{2-}$ ,  $\text{SCN}^-$ ,  $\text{C}_6\text{H}_8\text{O}_4^{2-}$ ,  $\text{C}_6\text{H}_5\text{COO}^-$ ,  $\text{C}_2\text{H}_4\text{O}_2(\text{COO})_2^{2-}$ ,  $\text{C}_4\text{H}_3\text{O}_5^{3-}$ ,  $\text{C}_3\text{H}_2\text{O}_4^{2-}$ ,  $\text{C}_2\text{H}_4(\text{COO})_2^{2-}$ ,  $\text{C}_2\text{H}_5\text{COO}^-$ ,  $\text{C}_3\text{H}_2\text{O}_3^{2-}$ ,  $\text{HCOO}^-$ ,  $(\text{C}_2\text{O}_4)^{2-}$ ,  $\text{SiO}_3^{2-}$ ,  $\text{C}_2\text{H}_3\text{O}_3^-$ , and  $\text{CN}^-$  at concentration of 1.5 mM. Notably, 0.15 mM  $\text{H}_2\text{S}$  induced color variation in the AuNU solution, and no colorimetric changes were observed upon the addition of the other anions (Fig. 7a).

The absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) of the AuNU solution containing each anion was measured to determine the selectivity of the optimized AuNU probe toward various anions (Fig. 7b). The absorbance ( $A_{421\text{ nm}}$ ) of the AuNUs upon  $\text{H}_2\text{S}$  addition increased considerably, whereas the absorbance ( $A_{672\text{ nm}}$ ) of the AuNU- $\text{H}_2\text{S}$  did not decrease. This indicates that the variation in the UV-Vis peaks is not due to conventional

**Table 2** Comparison of  $\text{H}_2\text{S}$  detection performance using previously reported gold or silver nanoparticle-based colorimetric probes and ion chromatography

Nanoparticle probe	Sensing mechanism	Ligand or modified agents	Detection range	LOD	Ref.
AuNPs <sup>a</sup>	Aggregation	AE <sup>a</sup>	3–10 $\mu\text{M}$	0.2 $\mu\text{M}$	18
AgNPs	Aggregation	Dopamine	2–15 $\mu\text{M}$	0.03 $\mu\text{M}$	19
AgNPs	Etching	Chitosan	0.80–6.40 $\mu\text{M}$	0.35 $\mu\text{M}$	20
AgNPs	Nanocluster	CMS <sup>b</sup>	15 to 70 $\mu\text{M}$	0.24 $\mu\text{M}$	21
Cu@Au NPs	Growth	Iodide	0–1.5 $\mu\text{M}$	0.3 $\mu\text{M}$	22
PPF-AgNPs <sup>c</sup>	Growth	PPF <sup>c</sup>	0.7–10 $\mu\text{M}$	0.2 $\mu\text{M}$	23
Au/AgI NPs	Etching	Dimeric nanoparticles	0–80 $\mu\text{M}$	0.5 $\mu\text{M}$	24
Au/Ag NPs <sup>d</sup>	Etching	Core–shell	0.05–100 $\mu\text{M}$	1.0 $\mu\text{M}$	25
AuNUs	Oligomeric sulfide capping	Oligomeric sulfide	2.0–312.5 $\mu\text{M}$	0.29 $\mu\text{M}$	This work

<sup>a</sup> Thiolated azido derivates and active esters. <sup>b</sup> Carboxymethyl cellulose sodium. <sup>c</sup> Poly-polyhedral oligomeric silsesquioxane-formaldehyde. <sup>d</sup> Au/Ag core-shell nanoparticles.



mechanisms such as aggregation, etching, or growth of nanoparticles. Rather, it was attributed to the morphological changes caused by the unique formation of oligomeric sulfides on the surface of the AuNUs, which gave rise to a remarkably high absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ). The absorbance ratio was approximately four times greater than that obtained upon the addition of other anions, demonstrating that a molecular chain on the surface of the AuNUs was not formed upon the addition of other anions.

The  $\text{H}_2\text{S}$  selectivity of the AuNU probe was further tested upon addition of diverse metal ions (Fig. S6<sup>†</sup>) and some sulfur compounds (cysteine, dithiothreitol, 1-thioglycerol, and 2-thiophenecarboxaldehyde) (not shown) at 1.5 mM; the developed AuNU probe exhibited excellent selectivity toward  $\text{H}_2\text{S}$  and no reaction to the metal ions.

### 3.6 Quantitative analysis of $\text{H}_2\text{S}$ using AuNUs

The color variation caused by  $\text{H}_2\text{S}$  in the AuNU solution is related to the quantity of  $\text{H}_2\text{S}$  as indicated by UV-Vis spectroscopy. The color of the AuNU solution gradually changed from sky blue to light green with increasing  $\text{H}_2\text{S}$  concentration (Fig. 8a). To evaluate the measurement error, the absorbance ratio ( $A_{421\text{ nm}}/A_{672\text{ nm}}$ ) was observed upon the gradual addition of  $\text{H}_2\text{S}$  (0–300  $\mu\text{M}$ ) in AuNUs (three times at each  $\text{H}_2\text{S}$  concentration) (Fig. 8b). A linear regression analysis was performed. And two calibration curves with good linearity were obtained in the concentration range of 0.3–15  $\mu\text{M}$  ( $r^2 = 0.9984$ ) and 15.0–300  $\mu\text{M}$  ( $r^2 = 0.9954$ ) (Fig. 8c). It was believed that a lower amount of  $\text{H}_2\text{S}$  on the AuNUs added to the AuNUs facilitated the formation of oligomeric sulfides in the AuNU solution, which increased the slope (response or sensitivity). The LOD was determined according to the  $3\sigma/m$  criterion in the calibration plot, with  $\text{H}_2\text{S}$  concentration in the range of 0.3–15  $\mu\text{M}$ . Corresponding to a standard deviation ( $\sigma$ ) of 0.084 and a calibration plot slope ( $m$ ) of 0.85365, the LOD for this novel probe was estimated to be 0.29  $\mu\text{M}$  in the tap water sample.

### 3.7 Usability of the AuNU probe in real samples

To demonstrate the applicability of the AuNU probe, we measured its absorbance intensities in the tap and pond water samples spiked with 150.0 and 300.0  $\mu\text{M}$   $\text{H}_2\text{S}$  and in a real waste-water sample with unknown  $\text{H}_2\text{S}$  concentration. The  $\text{H}_2\text{S}$  concentration in the water samples determined using the AuNU probe was in good agreement with the amount of  $\text{H}_2\text{S}$  added to the water samples, as well as with concentrations determined using IC (Table 1). Hence, the AuNU probe developed for  $\text{H}_2\text{S}$  detection may be superior to IC instruments in terms of analytical cost, operational simplicity, and expertise required. In addition, the sensing mechanism of the AuNU-based assay for  $\text{H}_2\text{S}$  differed from that of other conventional probes (Table 2).

## 4 Conclusions

In this study, we developed a novel AuNU nanoprobe for the feasible and selective colorimetric sensing of  $\text{H}_2\text{S}$ . This  $\text{H}_2\text{S}$

sensing probe is based on the formation of oligomeric sulfides on the surface of AuNUs, which manifests a new distinctive absorbance peak at 421 nm and changes the color of the AuNU solution from sky blue to light green. The mechanism of colorimetric alteration by oligomeric sulfide formation in AuNUs differs from conventional sensing mechanisms such as aggregation, etching, or growth of nanoparticles. This AuNU probe can determine  $\text{H}_2\text{S}$  concentrations without interference from surrounding anions, providing a simpler  $\text{H}_2\text{S}$  assay compared with previous nanoprobes functionalized with various ligands. The AuNU probe accurately determined  $\text{H}_2\text{S}$  in real waste water samples and demonstrated a better performance than the IC instrument in terms of time, selectivity, convenience, and cost. The development of a smartphone-based colorimetric sensing method for  $\text{H}_2\text{S}$  is currently underway.

## Conflicts of interest

The authors have no conflict of interest in the publication of this manuscript.

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## References

- 1 T. L. Guidotti, *Internet J. Toxicol.*, 2010, **29**, 569–581.
- 2 M. C. Shivanthan, H. Perera, S. Jayasinghe, P. Karunananayake, T. Chang, S. Ruwanpathirana, N. Jayasinghe, Y. D. Silva and D. Jayaweeraabandara, *J. Occup. Med. Toxicol.*, 2013, **8**, 1–5.
- 3 H. Kfir, S. Rimbrot and A. Markel, *Int. J. Med.*, 2015, **108**, 977–978.
- 4 J. Jiang, A. Chan, S. Ali, A. Saha, K. J. Haushalter, W.-L. M. Lam, M. Glasheen, J. Parker, M. Brenner, S. B. Mahon, H. H. Patel, R. Ambasudhan, S. A. Lipton, R. B. Pilz and G. R. Boss, *Sci. Rep.*, 2016, **6**, 20831.
- 5 P. C. Ng, T. B. Hendry-Hofer, A. E. Witeof, M. Brenner, S. B. Mahon, G. R. Boss, P. Haouzi and V. S. Bebarta, *J. Med. Toxicol.*, 2019, **15**, 287–294.
- 6 T. Ausma and L. J. De Kok, *Front. Plant Sci.*, 2019, **10**, 743.
- 7 A. M. El-Melih, L. Iovine, A. A. Shoaibi and A. K. Gupta, *Int. J. Hydrogen Energy*, 2017, **42**, 4764–4773.
- 8 K. Jones, *Toxicol. Lett.*, 2014, **231**, 374–377.
- 9 S. L. M. Rubright, L. L. Pearce and J. Peterso, *Nitric Oxide*, 2017, **71**, 1–13.
- 10 Y. J. Yuan and H. Kuriyama, *Biotechnol. Lett.*, 2000, **22**, 795–799.
- 11 W. Zgagacza, R. Zakrzewska, K. Urbaniak, G. Chwatko and A. Nowickia, *J. Chromatogr. B*, 2020, **1157**, 122309.
- 12 J. R. Hall and M. H. Schoenfisch, *Anal. Chem.*, 2018, **90**, 5194–5200.
- 13 M. D. Brown, J. R. Hall and M. H. Schoenfisch, *Anal. Chim. Acta*, 2019, **1045**, 67–76.

14 T. J. Sherbow, G. M. Kuhl, G. A. Lindquist, J. D. Levine, M. D. Pluth, D. W. Johnson and S. A. Fontenot, *Sens. Bio-Sens.*, 2021, **31**, 100394.

15 B. Tan, S. Jin, J. Sun, Z. Gu, X. Sun, Y. Zhu, K. Huo, Z. Cao, P. Yang, X. Xin, X. Liu, L. Pan, F. Qiu, J. Jiang, Y. Jia, F. Ye, Y. Xie and Y. Z. Zhu, *Sci. Rep.*, 2017, **7**, 46278.

16 L.-A. Lan, S.-Y. Wuc, X.-G. Meng, J.-J. Jiang, M.-Y. Zheng and G.-R. Fan, *J. Chromatogr. A*, 2020, **1625**, 461243.

17 Y. Zhou, F. Mazur, K. Liang and R. Chandrawati, *Chem.-Asian J.*, 2022, **17**, e202101399.

18 Z. Yuan, F. Lu, M. Peng, C.-W. Wang, Y.-T. Tseng, Y. Du, N. Cai, C.-W. Lien, H.-T. Chang, Y. He and E. S. Yeung, *Anal. Chem.*, 2015, **87**, 7267–7273.

19 L. Zhao, L. Zhao, Y. Miao, C. Liu and C. Zhang, *Sensors*, 2017, **17**, 626.

20 K. Shammugaraj and M. Ilanchelian, *Microchim. Acta*, 2016, **183**, 1721–1728.

21 Y. Xue, L. Ma, L. Zhang, W. Zhao, Z. Li and Q. Li, *Polymers*, 2020, **12**, 113.

22 J. Zhang, X. Xu, Y. Yuan, C. Yang and X. Yang, *ACS Appl. Mater. Interfaces*, 2011, **3**, 2928–2931.

23 Y. Zhang, H.-Y. Shen, X. Hai, X.-W. Chen and J.-H. Wang, *Anal. Chem.*, 2017, **89**, 1346–1352.

24 J. Zeng, M. Li, A. Liu, F. Feng, T. Zeng, W. Duan, M. Li, M. Gong, C.-Y. Wen and Y. Yin, *Adv. Funct. Mater.*, 2018, **28**, 1800515.

25 J. Hao, B. Xiong, X. Cheng, Y. He and E. S. Yeung, *Anal. Chem.*, 2014, **86**, 4663–4667.

26 S. Alizadeh and Z. Nazari, *Chem. Rev.*, 2020, **2**, 228–242.

27 K. Kermanshahian, A. Yadegar and H. Ghourchian, *Coord. Chem. Rev.*, 2021, **442**, 213934.

28 N. T. K. Thanh, N. Maclean and S. Mahiddine, *Chem. Rev.*, 2014, **114**, 7610–7630.

29 J. Li, J. Wu, X. Zhang, Y. Liu, D. Zhou, H. Sun, H. Zhang and B. Yang, *J. Phys. Chem. C*, 2011, **115**, 3630–3637.

30 K. R. Olson, Y. Gao and K. D. Straub, *Int. J. Mol. Sci.*, 2021, **22**, 961.

31 M. Hayyan, M. A. Hashim and I. M. AlNashef, *Chem. Rev.*, 2016, **116**, 3029–3085.

32 Y. Xia, K. D. Gilroy, H.-C. Peng and X. Xia, *Angew. Chem., Int. Ed.*, 2017, **56**, 60–95.

33 J. Li, J. Wu, X. Zhang, Y. Liu, D. Zhou, H. Sun, H. Zhang and B. Yang, *J. Phys. Chem. C*, 2011, **115**, 3630–3637.

34 S. Lee, Y.-S. Nam, S.-H. Choi, Y. Lee and K.-B. Lee, *Microchim. Acta*, 2016, **183**, 3035–3041.

35 S.-J. Yoon, Y.-S. Nam, H.-J. Lee, Y. Lee and K.-B. Lee, *Sens. Actuators, B*, 2019, **300**, 127045.

36 E. Cuevasanta, M. Lange, J. Bonanata, E. L. Coitiño, G. Ferrer-Sueta, M. R. Filipovic and B. Alvarez, *J. Biol. Chem.*, 2015, **290**, 26866–26880.

37 J. Myszkowska, I. Derevenkov, S. V. Makarov, U. Spiekerkoetter and L. Hannibal, *Antioxidants*, 2021, **10**, 1065.

38 K. R. Olson, A. Briggs, M. Devireddy, N. A. Iovino, N. C. Skora, J. Whelan, B. P. Villa, X. Yuan, V. Mannam, S. Howard, Y. Gao, M. Minnion and M. Feilisch, *Redox Biol.*, 2020, **37**, 101.

39 M.-C. Bourg, A. Badia and R. B. Lennox, *J. Phys. Chem. B*, 2000, **104**, 6562–6567.

40 G. Greczynski and L. Hultman, *Prog. Mater. Sci.*, 2020, **107**, 100591.

41 R. W. Taylor, R. Esteban, S. Mahajan, J. Aizpurua and J. J. Baumberg, *J. Phys. Chem. C*, 2016, **120**, 10512–10522.

42 M. V. Gorbachevskii, D. S. Kopitsyn, M. S. Kotelev, E. V. Ivanov, V. A. Vinokurov and A. A. Novikov, *RSC Adv.*, 2018, **8**, 19051–19057.

43 J. Reguera, J. Langer, D. Jiménez de Aberasturi and L. M. Liz-Marzán, *Chem. Soc. Rev.*, 2017, **46**, 3866–3885.

44 M. Hagen, P. Schiffels, M. Hammer, S. Dörfler, J. Tübke, M. J. Hoffmann, H. Althues and S. Kaskel, *J. Electrochem. Soc.*, 2013, **160**, A1205–A1214.

45 J. D. McBrayer, T. E. Beechem, B. R. Perdue, C. A. Apblett and F. H. Garzon, *J. Electrochem. Soc.*, 2018, **165**, A876–A881.

46 A. Marcus and N. Winograd, *Anal. Chem.*, 2006, **78**, 141–148.

47 Y.-P. Kim, H. K. Shon, S. K. Shin and T. G. Lee, *Mass Spectrom. Rev.*, 2015, **34**, 237–247.

48 S.-I. Bibli, B. Luck, S. Zukunft, J. Wittig, W. Chen, M. Xian, A. Papapetropoulos, J. Hu and I. Fleming, *Redox Biol.*, 2018, **18**, 295–304.

49 A. Schweighuber, M. Gall, J. Fischer, Y. Liu, H. Braun and W. Buchberger, *Anal. Bioanal. Chem.*, 2021, **413**, 1091–1098.

50 B. E. Janicek, J. G. Hinman, J. J. Hinman, S. H. Bae, M. Wu, J. Turner, H.-H. Chang, E. Park, R. Lawless, K. S. Suslick, C. J. Murphy and P. Y. Huang, *Nano Lett.*, 2019, **19**, 308–6314.

51 K. Jang, S.-H. Kim, H. Jun, C. Jung, J. Yu, S. Lee and P.-P. Choi, *Nat. Commun.*, 2021, **12**, 4301.

