Anisotropic assembly of gold nanorods assisted by selective ion recognition of surface-anchored crown ether derivatives†

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Gold nanorods (NRs) mixed with crown ether derivatives exhibited the efficient and selective recognition of Na^+ and K^+ ions, which were detected by localized surface plasmon absorption in response to dispersed and aggregated gold NRs. Furthermore, in the aggregates preferential end-to-end or side-to-side assembly of NRs was observed which was dependent on the additive concentration.

Currently, there is a great deal of interest in metal nanoparticles due to their shape and size-dependent optical properties, whose origin is localized surface plasmon resonance (LSPR).[1] Nanoparticles have promising applications in a variety of areas, including enhanced spectroscopy,[2] molecular electronics,[3] and chemical sensors.[4] Specifically, since the pioneering research undertaken by Mirkin *et al.* on the detection of single-base mismatches in DNA hybridization using gold nanoparticles,[5] gold nanoparticles have been applied as analytical probes in biotechnological systems such as those used for diagnostic applications and biological imaging.[6]

In terms of (bio)chemical sensor applications, rod-like gold nanoparticles (gold nanorods: NRs) should provide additional benefits compared with similar sized spherical nanoparticles. This is because the LSPR properties of gold NRs can be continuously tuned by adjusting their aspect ratio from the ultraviolet to the infrared region,[7] including the near-infrared region where tissue transmissivity is at its highest due to the low extinction coefficients of the intrinsic chromophores.[8] In addition, the distinctive rod-shaped geometry has an inherently high sensitivity to the local dielectric environment including the substrates, solvents, and adsorbates, as well as the inter-particle spacing of the NRs.

Recently the analyte-induced aggregation of gold NRs has been used for a qualitative and quantitative analysis of amino acids and peptides by employing the significant LSPR wavelength shift.[9] In this system, gold NRs with zwitterionic groups appended to their ends formed a unique end-to-end connection *via* a two-point electrostatic interaction, resulting in considerable inter-plasmon coupling. Therefore, functionalized gold NRs with a variety of molecules will provide a novel nano-detection platform, and function as an anisotropic-shaped colorimetric reporter, which outputs the changes in the local environment surrounding the NR surfaces *via* the highly sensitive LSPR properties. Herein, we report the efficient and selective ion sensing of physiologically important cations such as Na^+ and K^+ using the localized surface plasmon absorption of gold NRs mixed with thiol-modified crown ethers in an aqueous matrix. In addition, we observed the anisotropic aggregates of the gold NRs, which were preferentially oriented in a lateral (side-to-side) or axial (end-to-end) fashion through the ion recognition process, resulting in the characteristic inter-plasmon coupling of their LSPR.

The gold NRs were synthesized by the chemical reduction of $HAuCl_4$ and the subsequent photochemical reaction.[10] The NRs were fairly uniform in shape (average aspect ratio: 3.9) (see ESI†), and well dispersed in water without appreciable aggregation. It is known that cetyltrimethylammonium bromide (CTAB) stabilizes the NRs and disturbs the aggregation. The obtained NR solution was centrifuged twice to remove excess CTAB. Two thiol-modified crown ethers, 2-[(6-mercaptohexyl)oxy]methyl-15-crown-5 (15-crown-5-SH) and 2-[(6-mercaptohexyl)oxy]methyl-12-crown-4 (12-crown-4-SH) were synthesized according to a previously published method.[11] The purified crown ethers (1 mM) were dispersed in NaCl or KCl (1 mM) aqueous solutions, and then several volumes of the solution (0–30 μL) were mixed with 200 μL of the gold NR solution (300 μg mL^{-1}) with moderate stirring for a few minutes at room temperature. The crown ethers should exchange rapidly with CTAB and attach themselves covalently to the gold NR surface due to the higher affinity of the thiol group for gold.

Fig. 1 shows the absorption spectra of the gold NRs on the addition of 15-crown-5-SH dispersed in NaCl or KCl solution. The gold NRs exhibited two plasmon absorption maxima around 680–700 and 520 nm, corresponding to a longitudinal mode along the long axis and a transverse mode perpendicular to the long axis, respectively. When we increased the amount of added KCl solution, the longitudinal absorption intensity of the NRs gradually decreased and the peak was initially red-shifted and then blue-shifted (Fig. 1(B) and inset). The spectral change was caused by the formation of NR aggregates. The recognition of K^+ is proposed *via* a sandwich complex of 2:1 between the 15-crown-5 moiety and K^+. This triggered the coupling of the plasmon absorbance as a result of the NRs proximity to each other. A similar sandwich complexation of 15-crown-5 has been found through the recognition of potassium ions using gold nanoparticles[12] or CdSe/ZnS quantum dots.[13] In the presence of Na^+, the absorption spectra profiles of gold NRs with 15-crown-5-SH remained largely unchanged (Fig. 1(A) and inset). The results originated from the fact that Na^+ was recognized by simple 1:1

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† Electronic supplementary information (ESI) available: synthesis details and characterizations of gold nanorods and thiol-modified crown ethers, and additional absorption spectra and SEM images of the gold nanorod complex. See DOI: 10.1039/b609162h

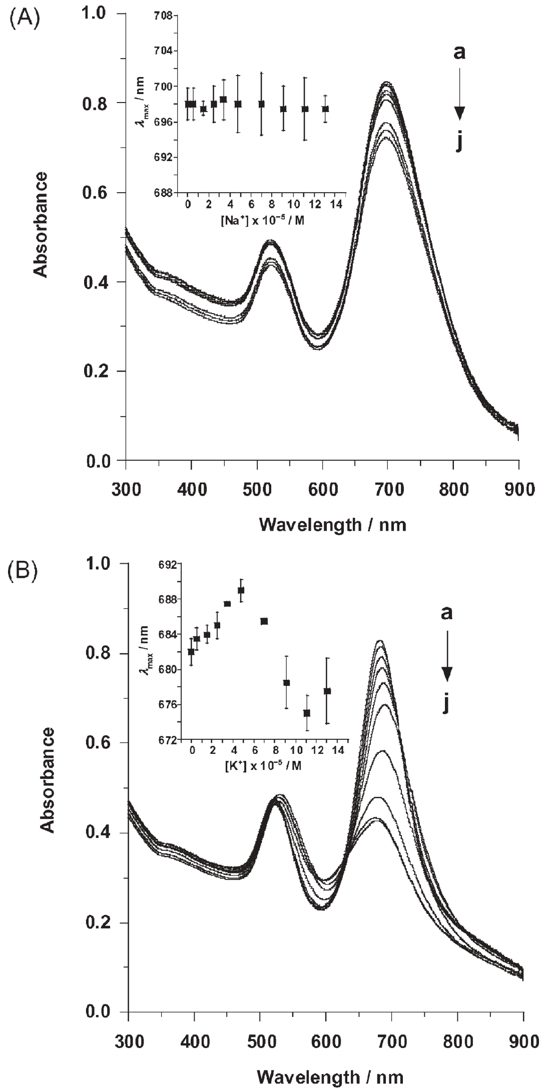
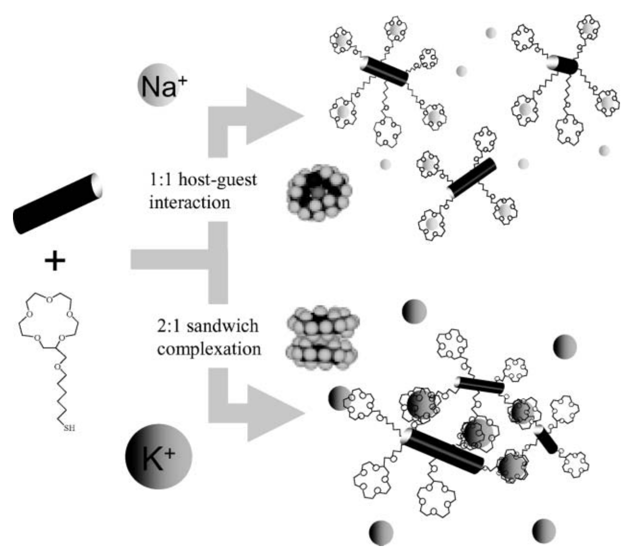


Fig. 1 Absorption spectrum changes of gold nanorods (average aspect ratio 3.9) on addition of 15-crown-5-SH (1 mM) in (A) NaCl aqueous solution (1 mM) or (B) KCl aqueous solution (1 mM) at (a) 0, (b) 1, (c) 3, (d) 5, (e) 7, (f) 10, (g) 15, (h) 20, (i) 25 and (j) 30 μL. Fig. 1 (inset): peak wavelength at λ_{max} of longitudinal mode as a function of Na^+ or K^+ concentration.



Scheme 1 Schematic images of selective ion recognition mechanisms in the gold nanorods with 15-crown-5-SH system *via* 1:1 (Na^+) or 2:1 sandwich (K^+) complexation in aqueous solution.

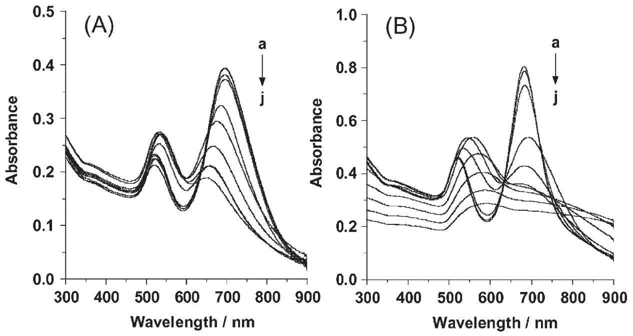


Fig. 2 Absorption spectrum changes of gold nanorods (average aspect ratio 3.9) on addition of 12-crown-4-SH (1 mM) in (A) NaCl aqueous solution (1 mM) or (B) KCl aqueous solution (1 mM) at (a) 0, (b) 1, (c) 3, (d) 5, (e) 7, (f) 10, (g) 15, (h) 20, (i) 25 and (j) 30 μL.

host–guest interactions that correlated with the close fit of the cation to the crown cavity (Scheme 1).

As for the gold NRs mixed with 12-crown-4-SH in Na^+ solution (Fig. 2(A)), the absorption properties showed similar behaviour to that of the gold NR/15-crown-5-SH/K^+ system except for greater peak shifts in the transverse mode. The 12-crown-4 might capture Na^+ with an analogous sandwich complex of 2:1 since the size correlation between the 12-crown-4 cavity and Na^+ ionic diameter is comparable to that between 15-crown-5 and K^+. On the other hand, in the gold NR/12-crown-4-SH/K^+ system, we found greatly broadened peak profiles as we increased the additives. This result is possibly related to the formation of huge gold NR aggregates, which is induced by surrounding large K^+ ions with more than a few 12-crown-4 moieties on the NRs. We confirmed that there was appreciable precipitation when more than 15 μL of additives were supplied. Consequently, the gold NRs mixed with crown ether derivatives exhibited significant differences in their localized surface plasmon absorption, depending on the cation and crown ether species combination, even with the addition of μM scale analytes. The dispersed or aggregated states of the gold NR complex, which is dominated by the ion recognition mechanism, result in further spectral changes due to mutually induced dipoles that depend on inter-particle distance and aggregate size.

We performed a control experiment using no functionalised gold NRs (without crown ethers) titrated with Na^+ solution under identical experimental conditions. In the experiment, the absorption spectra of the gold NRs showed negligible changes when NaCl was added (see ESI†), indicating that the dielectric change in the surrounding medium did not affect the spectra, and moreover that the aggregates induced by salting out were disregarded at such low salt concentrations.

It is interesting to note that the λ_{max} of the longitudinal mode in Fig. 1(B) was at first slightly red-shifted from 682 to 689 nm and then switched to a blue shift at 675 nm, depending on the concentrations of the added 15-crown-5-SH and K^+. As predicted theoretically and confirmed experimentally,[7] as the red shift of the

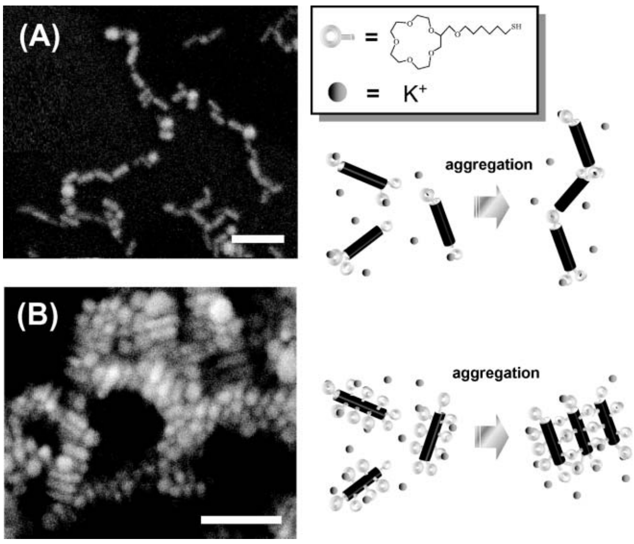


Fig. 3 SEM images of the aggregates of the gold nanorod complex on silicon substrate: (A) end-to-end type by addition of 5 μL of 15-crown-5-SH in KCl solution; and (B) side-to-side type by addition of 50 μL of 15-crown-5-SH in KCl solution. Scale bar: 100 nm.

longitudinal plasmon band becomes greater, the aspect ratio of the gold NR structure becomes larger. Therefore, we consider that the red shift or blue shift of the peak can be attributed to the structural change in the axial (end-to-end) or lateral (side-to-side) orientation of the gold NRs in the aggregates, respectively. In Fig. 3, as expected, we successfully visualized anisotropically assembled gold NR aggregates on a silicon substrate using SEM.[14] It has recently been reported that the edges of gold NRs are dominated by {111} facets and the lateral sides are dominated by {100} and {110} planes,[15–17] and in addition thiol derivatives are preferentially bound to the {111} ends of gold NRs. Therefore, when we supplied a small amount of additive (5 μL, 2.4×10^{-5} M), thiol-modified crown ethers were selectively attached to the edges of the gold NRs, and then the complex was assembled in an end-to-end fashion induced by the formation of a sandwich complexation as shown in Fig. 3(A).‡ In contrast, when we supplied ten times the amount of additive (50 μL, 2.0×10^{-4} M), the crown ethers appeared to be anchored even on the lateral side of the NRs, which led to large aggregates growing in a side-to-side fashion. The end-to-end orientations of gold NRs have recently been observed in several systems such as biotin capped gold NRs–streptavidin,[16] mercapto-carboxylic acids coupled gold NRs,[17] and cysteine or glutathione modified gold NRs.[9] In these systems, the structures of the alignment of the assembled NRs was relatively straight since they were strongly bound by intermolecular interactions such as hydrogen bonding or a two-point electrostatic interaction with two zwitterionic groups. The uniaxial structure thus leads to the uniaxial localized inter-plasmon coupling of NRs, which exhibited a remarkable red shift in the absorption up to the near-infrared region. In our case, however, an electrostatic interaction between crown–ion–crown triggered the NR assembly, and so the joints between NRs bent easily in solution. Therefore, we observed a less clear spectroscopic red shift in solution, and the NRs assembled in a folded end-to-end fashion on the substrates (Fig. 3(A)). Although two possible structures for the sandwich association of 15-crown-5–K^+–15-crown-5, either intra- or intermolecular type, have been discussed,[12,13] we can clearly recognize the intermolecularly assembled structures of NRs *via* the intermolecular association of crown ethers anchored on the NR surface.

In conclusion, we synthesized a complex of gold NRs with thiol-modified crown ether derivatives, and demonstrated the detection of a selective ion recognition process using the localized surface plasmon absorption of the gold NRs. Additionally, we clearly visualized the structural changes in the gold NR aggregates, assembled side-to-side and end-to-end, which depend on the concentrations of added crown ethers and cations. The anisotropic features of gold NRs allow such anisotropic assembly, which is sensitively reflected in their LSPR properties, especially in longitudinal modes. These characteristics offer unique and significant advantages for rod-shaped gold nanoprobes designed to be used with spherical nanoparticles or nanodots.

Notes and references

‡ We show an SEM image of a number of the gold NRs assembled in an end-to-end fashion on a silicon substrate in the ESI†. The anistropic assembly was reproducibly observed.

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