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Mapping SERS in CB: Au Plasmonic Nano-Aggregates

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ABSTRACT

In order to optimize surface-enhanced Raman scattering (SERS) of noble metal nanostructures for enabling chemical identification of analyte molecules, careful design of nanoparticle structures must be considered. We spatially map the local SERS enhancements across individual micro-aggregates comprised of monodisperse nanoparticles separated by rigid monodisperse 0.9 nm gaps and show the influence of depositing these onto different underlying substrates. Experiments and simulations show that the gaps between neighbouring nanoparticles dominate the SERS enhancement far more than the gaps between nanoparticles and substrate.

Metal nanoparticle aggregates support a large number of plasmonic hotspots within the inter-nanoparticle gaps, which can be used to probe molecular vibrations of analytes through surface-enhanced Raman scattering (SERS)^{1,2}. The high sensitivity of SERS and its consequent utilisation as a sensing technique has been demonstrated in a number of studies³⁻¹¹. Various methods have been used to form aggregates from colloidal nanoparticles, including DNA^{7,12}, proteins^{9,13}, dyes¹⁴, alcohols⁶, polymers^{15,16}, and optical fields¹⁷⁻²⁰, however these methods generally form agglomerates with wide variation in configurations and gap sizes. In such systems a large number of molecules across multiple hot-spots are probed in time, producing only a collective overall SERS signal. For typical colloidal aggregation onto a substrate, the very wide range in gap sizes produces broad absorption across the visible and near-infrared spectrum, and sporadically located 'hot-spots' in real space^{21,22}. In all these hot-spot crevices, each molecule sees a different orientation, strength, and resonant frequency of the optical-excited plasmon field. This means that the SERS averages over all field-molecule configurations, which is undesirable for studying selection rules, nonlinear vibrational phenomena, and for robust uniform sensing.

Here, we assemble and probe nanoparticle aggregates with precisely fixed sub-nm gaps, and precisely oriented molecules and optical fields²³. In order to map the Raman signal from *individual* aggregates without having to track these as they diffuse in solution, we bind them onto solid substrates. The optimal SERS emission is found to be on Au substrates rather than SiO₂ or Si, and can be explained from image charge interactions. Placing analyte molecules into these precise sub-nm hotspots of high plasmonic enhancement allows us to spatially map the signals across single aggregates. The tight focusing of light possible in this geometry gives better collection and thus higher SERS signals than with lower NA objectives

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averaging over many aggregates at once, either on substrates or in solution. This enables the robust prospect of sensing sub-nanomolar concentrations, for use in gas sensing and flow microfluidics for pharmaceuticals and biological cell sensing.

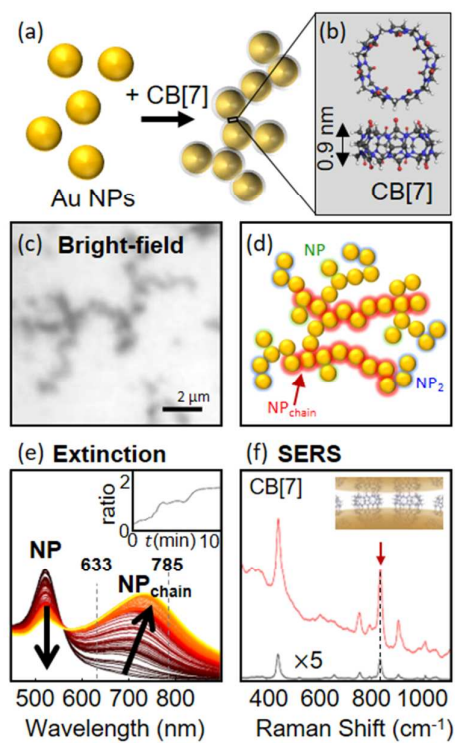


Figure 1. (a,b) Nanoparticle aggregation by addition of cucurbit[7]uril (CB[7]), shown in (b). (c) Bright-field image of aggregate dried onto gold substrate. (d) Schematic distribution of chain (red) and dimer (blue) plasmon modes. (e) Time-resolved extinction spectra over 10 mins, showing decrease in single-particle mode and increase in chain modes (laser wavelengths shown dashed, inset shows ratio of coupled mode to transverse mode over time). (f) SERS spectrum of Au:CB[7] aggregate in solution (red) and CB[7] powder for reference (black, x5 for visibility). Red arrow indicates CB vibration mapped in later images.

The metal nanoparticle aggregates are self-assembled in solution by the addition of the spacer molecule cucurbit[7]uril to 40nm diameter colloidal gold nanoparticles. Cucurbit[*n*]urils (CB[*n*]) are a series of rigid and initially-empty barrel-shaped molecules with hydrophobic cavities and hydrophilic carbonyl portals which bind strongly to gold (Fig.1a,b)²⁴. Previous work shows that CB[*n*] readily aggregates Au nanoparticles forming a precise interparticle separation of 0.9nm, and providing a reliable way to form optically-active long aggregate chains with fractal-like structures²⁵. Such nanoscale gaps between plasmonic metals trap incident light at specific resonant wavelengths, greatly enhancing the optical field and thus the Raman scattering of molecules within the gap. Due to their stiff hollow structures, CB[*n*]s can encapsulate hydrophobic or cationic molecules, making this construct suitable for gas and chemical sensing. Other macromolecules such as cyclodextrin have also been shown to encapsulate analyte molecules for sensing with SERS^{26,27}, however the inter-nanoparticle gaps formed are not as rigidly spaced as those formed with CB[*n*], meaning the plasmon cannot couple to form chain plasmon modes in the same way. Additionally CB[7] is a member of a family of CB[*n*] molecules, which can be selectively chosen to suit the particle analyte of interest. Normally such aggregates are observed in solution, where they fill only a small amount of the optical focal region, thus reducing the available SERS signal. Here, once the aggregates are formed, they are drop cast onto different substrates at sufficiently low concentration to image them individually

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3 (although binding them in-situ within microfluidic channels is also effective). The aggregates are visible in
4 bright-field images (Fig.1c), with corresponding scanning electron micrographs showing their 3D fractal
5 geometry (SI). The strong CB-Au binding (~ 0.3 eV/molecule) means that drop casting aggregates onto a
6 substrate does not markedly change their 3D structure²⁸.
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9 Because the identical plasmonic gaps in such assemblies support degenerate localised plasmon modes,
10 charge oscillations in one nano-gap mix strongly with charge oscillations of surrounding nano-gaps,
11 resulting in spatially-distributed plasmonic modes. These complex modes can be broken down into 3 main
12 types, which are observed in real-time optical scattering as the nanoparticles aggregate together (Fig. 1d,e).
13 Further explanation of this aggregation has been extensively studied in our previous work²⁵. Initially the
14 individual nanoparticles support a monomer plasmon mode at 530 nm. Adding CB[7] first induces
15 dimerization resulting in a new mode at 640 nm while the single particle mode decreases. At later times,
16 higher wavelength chain modes emerge as the aggregate size increases, red-shifting with increasing chain
17 length. Although the single-particle and dimer modes are still supported at the peripheries of large
18 aggregates, the optical response is dominated by chain modes which are delocalised across the entire
19 structure. Nanoparticle aggregates saturate in size once surface coverage of CB[7] limits the probability of
20 further aggregation.
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25 The enhanced optical field within each gap allows the SERS of the surface-bound CB in the gaps to be
26 observed, giving a number of characteristic peaks (Fig. 1f). Here, we use the Raman strength of one
27 particular CB vibration (the 832 cm^{-1} peak corresponding to a ring-breathing mode) as a marker of the SERS
28 activity at each gap site positioned precisely in between nanoparticles. By spatially mapping the intensity of
29 this CB[7] peak, the optical field variations can be tracked over the aggregate structure. As well as the peak
30 intensity of this vibrational mode, the plasmonic background can also be mapped across the aggregate
31 area, and its intensity is found to be directly correlated to that of the SERS peaks.
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35 To understand how to optimise the SERS emission from single aggregates, different substrates are
36 compared (Fig.2). Besides the plasmonic coupling between NPs, there can also be coupling to the
37 underlying substrate^{29,30} and this will be different for the 3 types of plasmonic mode within such
38 aggregates²⁹ (see below). After drop-casting onto the three substrate types (template-stripped gold, bare
39 silicon wafer, and glass coverslip), SERS spectra are mapped using a confocal pinhole with either a 633 nm
40 or 785 nm laser, across $12\mu\text{m}\times 12\mu\text{m}$ areas in 100 nm steps (Fig. 2a-c). The integrated area under the
41 832 cm^{-1} ring-breathing mode is extracted for each spatial position to give a map of SERS emission,
42 normalised to the incident laser power. The aggregate shape is clearly reproduced in these SERS maps on
43 all the substrates, although the signal is much reduced on Si. The strong correlation between bright-field
44 scatter and SERS signals across each point in the image maps is evident for all 3 systems (Fig.2d).
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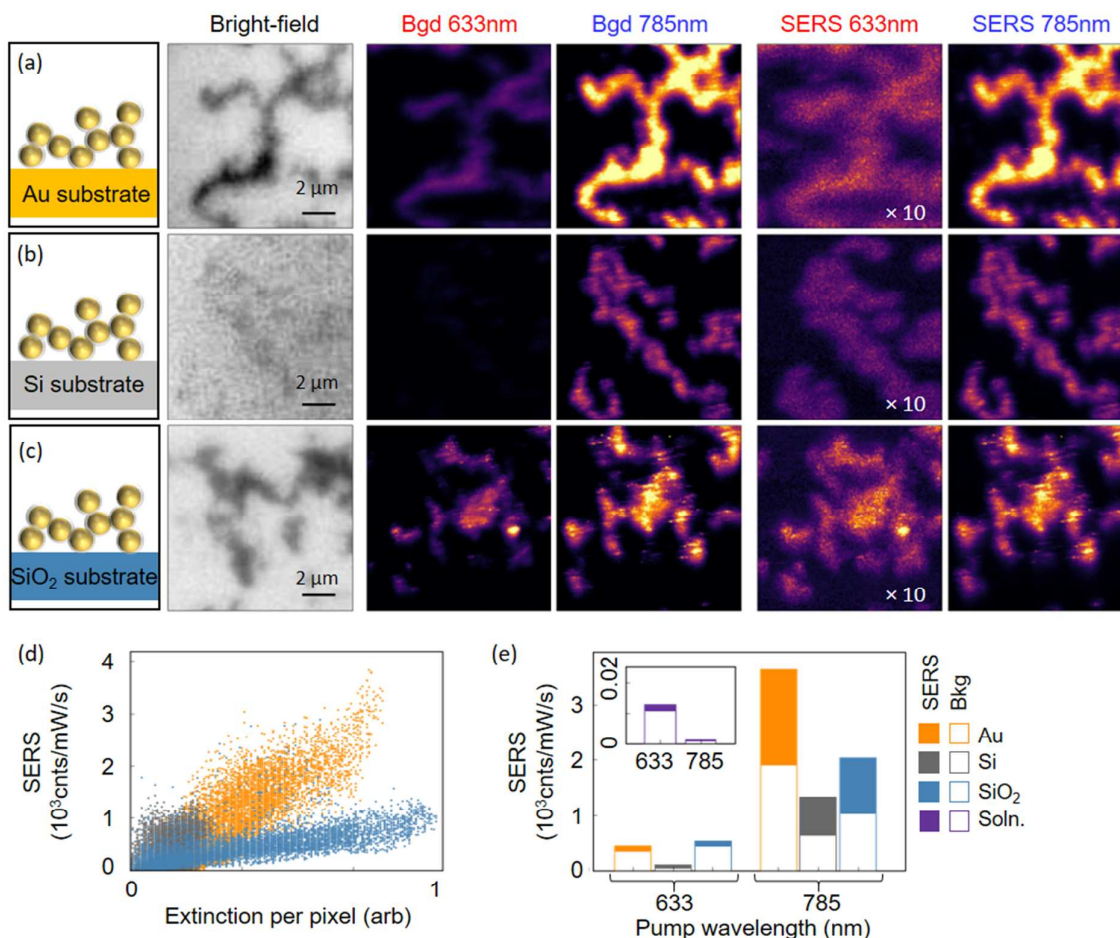
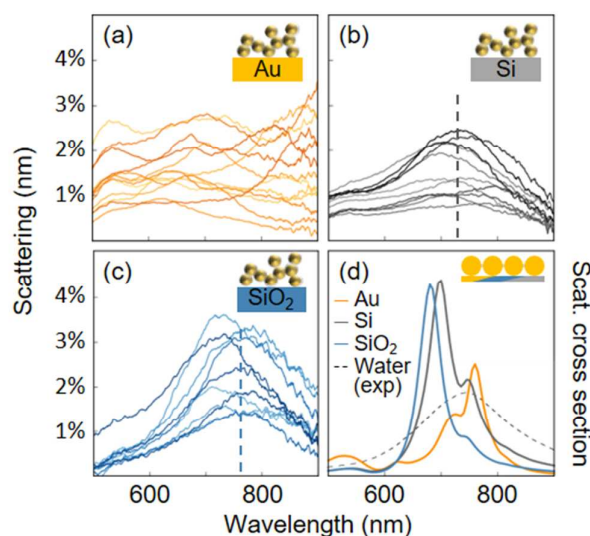


Figure 2. (a-c) Bright-field images and intensity maps showing SERS signals and plasmonic background for AuNP:CB aggregates drop-cast onto (a) gold, (b) silicon, and (c) silicon dioxide substrates. Identical colour scales except where indicated. (d) Scatter plot showing correlation between BF extinction of each pixel and its SERS intensity with 785nm excitation laser, for all three substrates. (e) Stacked bar-chart showing averaged SERS (filled) and background (open) across the mapped aggregate image for different substrates, at excitation wavelengths of 633 and 785 nm. Inset shows equivalent measurement for AuNPs:CB in solution, with pump laser 633 nm (left) and 785 nm (right).

Since on average, scattering is related to the number of CB:Au nanogaps at each pixel, this shows that SERS linearly adds from each nanogap³¹. This is analogous to the typical linear increase of both SERS and extinction with the number of nanoparticles when no coupling between them is present. In order to quantify the efficiency of each aggregate system as a SERS substrate, the average SERS intensity for the aggregate (within its interior region on the map) was calculated. This is shown by the stacked bars in Fig. 2e, with the open bar components indicating the strength of the background signals. The 785 nm laser gives consistently higher signals than using a 633 nm laser, due to its resonance with the chain modes of the Au aggregates, (Fig. 1e, dashed). It also gives SERS peaks of similar strength to the SERS background, while the background dominates at 633 nm. Comparing the SERS intensity between aggregates deposited on the different substrates, shows that deposition onto a gold substrate gives the strongest signals. As we demonstrate below, this is due to the plasmonic coupling of gap plasmons to image charges that occurs when metal nanostructures are placed above gold mirrors. However the SERS signal is only two-fold weaker for aggregates deposited on SiO₂, where there is no such plasmonic coupling to the substrate, suggesting

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3 this coupling is not the dominant factor for SERS enhancement. By calibrating the bright-field reflectance,
4 we are able to estimate that each pixel contributes signal from 1 NP-NP junction containing ~ 100 close-
5 packed CB molecules, and gives a total SERS integrated signal of 1000 cts/mW/s. Thus we estimate that
6 each CB molecule contributes 10 cts/mW/s, in line with the expected non-resonant SERS cross-section and
7 the plasmon local field, matching SERS observations from single nanoparticle gaps containing CBs in the
8 nanoparticle-on-mirror configuration^{30,32}. With unity CCD gain and the optimised system throughput for
9 detection of $\sim 10\%$ this suggests 100 SERS photons emitted/mW/s/molecule for the strongest lines in these
10 non-aromatic molecules.
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14 To compare with the colloiddally-suspended aggregates normally used, equivalent measurements of CB[7]
15 SERS signals are taken with Au:CB aggregates in solution (inset Fig. 2e). The SERS intensity is found to be
16 1000-fold smaller when compared to aggregates deposited on SiO₂, which is the reduction expected due to
17 the dilution of aggregate density within the focal optical volume probed at any time, averaged by diffusion.
18 The amplification in signal due to deposition on a substrate is greater when using a gold substrate, due to
19 the extra degree of plasmonic enhancement. Conversely it is lessened for Si due to absorption into the
20 substrate. Surprisingly we find that the signal from the 785 nm laser in such solution aggregates is now 5-
21 fold weaker than from 633 nm, the opposite ratio to the dried aggregates, even though wet and dry
22 extinction spectra can be similar as we now investigate.
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44 **Figure 3.** (a-c) Dark-field scattering spectra of aggregates on (a) Au, (b) Si, and (c) SiO₂. (d) FDTD simulated scattering cross sections
45 of a 4 nanoparticle chain spaced above Au, Si, and SiO₂ substrates. Dashed line shows experimental results for scattering of the
46 aggregates in water with no substrate.
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48 To understand this more clearly, dark-field scattering measurements are taken to probe the plasmon
49 resonances of a number of aggregates on the different substrates (Fig. 3a-c). These experimental scattering
50 spectra are taken over an assortment of representative aggregates and positions, evidencing expected
51 spatial inhomogeneities (Fig.1d) but generally common features on each substrate. While a weak single-
52 particle mode at 530 nm is always visible, the dominant chain modes are clearly seen to longer
53 wavelengths. These red-shifted peak positions depend on the coupling strength, set by how effectively
54 nanoparticle charge oscillations generate image charges in each substrate. When on SiO₂ the coupled mode
55 is similar as in solution, however it shifts to shorter wavelengths and weakens when placed on Si due to the
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damping by absorption in the semiconductor. This is also the reason that SERS is so much weaker on the Si substrates, since both elastic and inelastic scattering are similarly affected.

By contrast, aggregates on gold instead show especially large variation in this coupled-mode spectral position, shifted far more into the infrared and with multiple resonances. This higher degree of coupling to the gold substrate can be confirmed using full 3D finite-difference time domain (FDTD) simulations. We mimic the experimental configuration with a toy model comprised of a chain of 4 nanoparticles spaced above substrates of gold, Si or SiO₂ (Fig. 3d).^{33,34} The spacer layers at each NP-NP junction as well as the substrate-NP junction have refractive index of 1.4 to match that of CB[7]³⁰. The scattering cross section as a function of wavelength is obtained for normal plane-wave illumination with polarization along the chain. Due to computational intractability it is not feasible to fully model entire aggregates with complex geometries²², hence the modal positions calculated are only indicative (and blue-shifted from experiment as expected for shorter chains³⁵). The stronger coupling of Au substrates to the CB-spaced plasmonic gaps indeed gives higher wavelength modes in the FDTD simulated spectra, as compared to the non-metallic substrates.

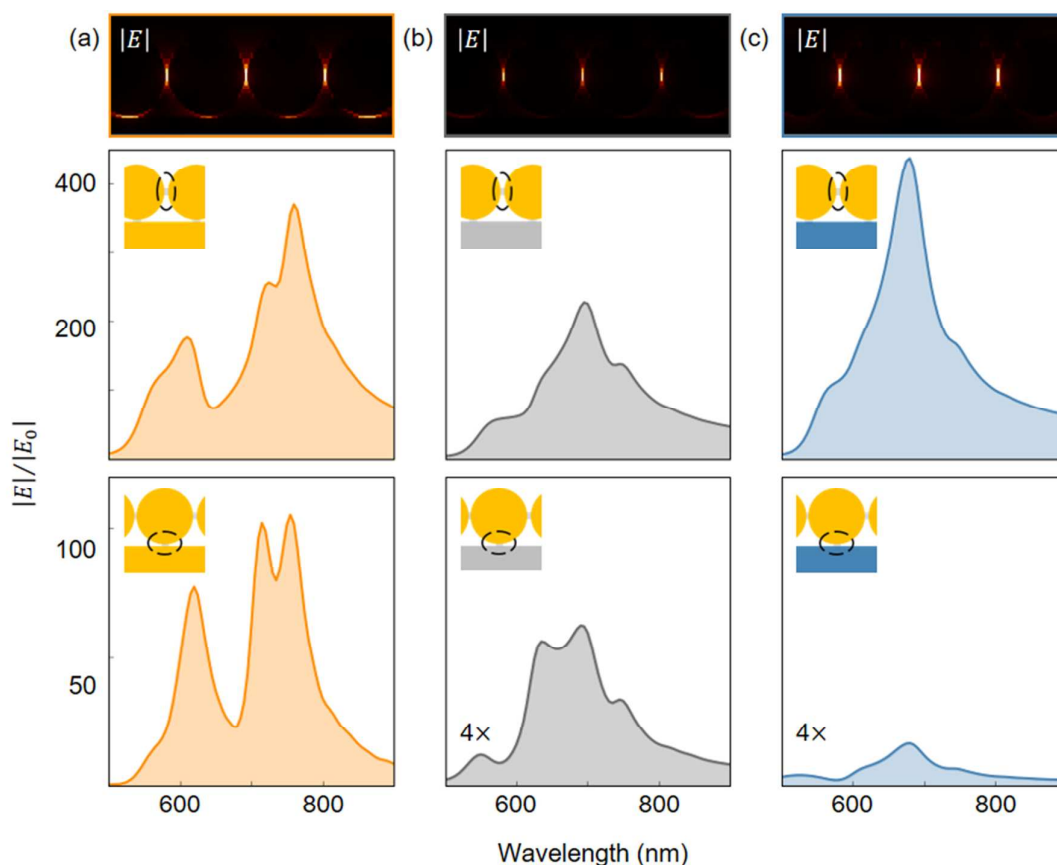


Figure 4. (a-c) FDTD simulations showing $|E|$ surrounding a 4-nanoparticle chain spaced 0.9 nm above an infinite substrate of Au, Si, SiO₂ respectively. Each is shown for the relevant resonant wavelength and colour scales are identical. Graphs below show the near-field spectra at the central NP-NP and substrate-NP junction for each system (dashed region marked).

To identify which regions within the aggregates are involved in the substrate coupling, near-field enhancements, $|E|$ are extracted from the simulations (Fig.4). We distinguish hotspots at the junction

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3 between two nanoparticles (NP-NP junctions) and those at the interface between substrate and
4 nanoparticle (sub-NP junctions). At the substrate-NP junction, the near-field spectra show much higher gap
5 field intensities with the gold substrate. Indeed, this enhancement is often used for single NPs on Au
6 substrates (known as nanoparticle-on-mirror^{29,30}). By contrast in the NP-NP junctions, aggregates on SiO₂ or
7 Au have comparable near-field intensities, with Si again weaker from absorption. Additionally, field
8 intensities in NP-NP junctions are many-fold stronger than in the substrate-NP junction in all cases (Fig. 4
9 lower graphs). This suggests that for dried aggregate geometries the field between nanoparticles is largely
10 responsible for hotspot effects such as SERS, confirming what was indicated by the intensities of SERS maps
11 in Fig.2e. On the other hand, the near-field spectra of the NP-NP junctions are red-shifted for the Au
12 substrate (compared to on the SiO₂ substrate), showing that they are well-coupled to the substrate-NP
13 junctions. For this reason careful choice of substrate is needed in order to maximise SERS signal
14 enhancements.
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19 We thus evidence how signals can be enhanced 1000-fold by casting Au:CB SERS aggregates onto glass,
20 with Au substrates giving an extra factor of two gain due to image charges. Excitation with 785 nm laser
21 light improves the signal-to-noise in SERS emission, due to the decreased background contributions (which
22 come from light emission by electronic Raman scattering coupled by the plasmons^{36,37}). The linearity of
23 SERS emission with number of junctions implies each sums incoherently into the total. Our signals of
24 $>10^3$ counts/mW/s (or >10 counts/mW/s per molecule, input power density $650\mu\text{W}/\mu\text{m}^2$) from
25 *electronically non-resonant, non-aromatic* molecules provides strong encouragement for sensing
26 applications, for instance of neuro-active molecules in urine³⁸. These aggregates remain stable for SERS for
27 indefinite periods, and thus form stable SERS substrates in microfluidics contexts.
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31 In conclusion, we present detailed analysis of the factors controlling the SERS intensity from nanoparticle
32 aggregates with precise identical 0.9 nm gaps, using the CB spacer as a vibrational marker. Our results show
33 that excitation with 785 nm laser light gives the strongest Raman signals from analytes, due to optimal
34 overlap with the resonance wavelength of the chain modes within the aggregates. We additionally
35 demonstrate how deposition of aggregates onto a substrate enhances the SERS signal by a factor of 1000,
36 and even more if plasmonically active substrates are used. We illustrate that the inter-nanoparticle gaps
37 dominate the near-field Raman response rather than the coupling of aggregate to image charges within the
38 substrate. Our findings indicate the need for careful consideration of nano-systems when using surface-
39 enhanced Raman scattering as a sensing technique, and pave the way for robust sensitive measurements
40 suited to personalised healthcare technologies.
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46 **Methods**

47 *Sample preparation:* Silicon wafers are purchased from Si-Mat, and SiO₂ cover slips (50 μm thickness) from
48 Thermo Scientific. Atomically smooth gold substrates are prepared by e-beam evaporation of 100 nm gold
49 layers onto a clean silicon wafer. This is then heated to 60°C, and small pieces of silicon glued to it and then
50 cured, before being peeled off to reveal a ultra-smooth gold surface. The nanoparticle aggregates were
51 self-assembled by adding 25 μl of 1 mM CB[7] solution to 1000 μl 40 nm gold nanoparticles in a citrate
52 buffer (BBI solutions). The aggregates were then drop cast onto the 3 substrates, left to dry and then rinsed
53 with deionized water.
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57 *Simulation:* Finite-difference time-domain simulations were carried out using Lumerical FDTD Solutions
58 v8.12. A simple aggregate geometry was modelled as 4 gold spheres spaced above an infinite sheet of Au,
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Si, or SiO₂ by 4 dielectric cylinders of height 0.9 nm and refractive index 1.4, to correspond to the CB[7] layer. The 4 spheres are also spaced apart from each other by identical cylinders. The construct was illuminated by a normal plane wave.

Raman measurements: Raman microscopy was performed using a Renishaw inVia Raman microscope, using a 100× objective with numerical aperture NA = 0.75. Excitation was performed with either 633nm or 785nm, with a power density of 650μW/μm² for each. All measurements were normalised to laser power and integration time. Measurements were taken with unity CCD gain.

Supporting Information

Scanning electron micrographs show 3D fractal geometry of 80 nm nanoparticle aggregates self-assembled via addition of cucurbit[7]uril.

Acknowledgements

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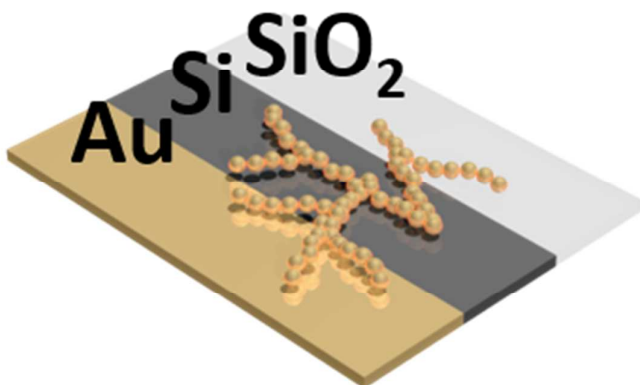
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5 **Mapping SERS in CB: Au Plasmonic Nano-Aggregates**
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27 Graphic visualising a gold nanoparticle aggregate on substrates of gold, silicon and silicon dioxide.
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