Controlling Optically Driven Atomic Migration Using Crystal-Facet Control in Plasmonic Nanocavities

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ABSTRACT: Plasmonic nanoconstructs are widely exploited to confine light for applications ranging from quantum emitters to medical imaging and biosensing. However, accessing extreme near-field confinement using the surfaces of metallic nanoparticles often induces permanent structural changes from light, even at low intensities. Here, we report a robust and simple technique to exploit crystal facets and their atomic boundaries to prevent the hopping of atoms along and between facet planes. Avoiding X-ray or electron microscopy techniques that perturb these atomic restructurings, we use elastic and inelastic light scattering to resolve the influence of crystal habit. A clear increase in stability is found for {100} facets with steep inter-facet angles, compared to multiple atomic steps and shallow facet curvature on spherical nanoparticles. Avoiding atomic hopping allows Raman scattering on molecules with low Raman cross-section while circumventing effects of charging and adatom binding, even over long measurement times. These nanoconstructs allow the optical probing of dynamic reconstruction in nanoscale surface science, photocatalysis, and molecular electronics.

KEYWORDS: nanocavity, nano-optics, SERS, atomic hopping, crystal facet, single-molecule, picocavity

Nanocavities of noble metals are providing a plethora of research directions leading to the realization of single-molecule spectroscopies which conventional top-down fabrication techniques have struggled to reach. Metallic nanocavities offer extreme light confinement with atomic-scale resolution that can boost the detection sensitivity of molecular vibrations while their plasmonic response can be spectrally tuned through the structure morphology. In this way, large-scale, cost-effective, and self-assembled techniques can assist studying plasmonic near-field enhancements and contributing to technological breakthroughs ranging from nanoheat reservoirs and pyroelectric photodetectors to photovoltaics and plasmon-mediated photocatalysis.

The enhanced near-fields arising from free-electron collective oscillations in plasmonic media are strongly dependent on the shape of their nanostructures. Million-fold optical intensity enhancements are achieved in subnanometer gaps formed between two noble metal nanostructures. In such scenarios, contributions from atomic-scale morphology play an important role in controlling the near-field. Atomic structures such as crystallographic planes, facets, and atomic steps within nanogaps directly influence the resulting near-field "hot-spot" distribution. Consequently, considerable effort has been devoted to controlling the growth of nanocrystals, deciphering their influence on plasmonic properties of NPs and estimating the surface energy of primary and high index facets.

RESULTS AND DISCUSSION

Here, we experimentally study the atomic movement of Au atoms on {111} and {100} facets in nanogaps. Nanospheres (NP) and nanocubes (NC) with different crystal facets are assembled on atomically flat mirrors coated with closely
packed self-assembled molecular layers, resulting in a nanostructure-on-mirror geometry (NPoM and NCoM, respectively, Figure 1a,d). The NPoMs have \{111\} gap facets produced when the triangular facets align face-down on the mirror (Figure 1b), while NCoMs have \{100\} facets sitting on the gap formed between nanoparticle and mirror (Figure 1e). By using dark-field scattering and surface-enhanced Raman scattering (SERS) we detect individual Au atom hopping events inside self-assembled nanogaps. We find that single-crystal plasmonic nanoconstructs based on the NCoM geometry give much larger power thresholds for atom migration compared to the more globular NPoM structures. Due to their high stability, such nanoconstructs enable SERS measurements on molecules with low Raman cross sections which demand higher pump powers.

The growth and shape control of nanocrystals is an ongoing challenge in materials science with Au being one of the few materials where a high degree of shape control has been demonstrated. Both the nanocube and nanosphere AuNPs are citrate capped, which compared to PVP-ligand coatings, allows much smaller nanoparticle gaps to form, thus giving much higher optical confinement. The Au mirror substrates are prepared by e-beam deposition on Si wafers using a template-stripping method. For the formation of self-assembled monolayers, the substrates are immersed for 12h in 1 mM biphenyl-4-thiol (BPT) that creates nanogaps of 1.3 ± 0.1 nm.

Figure 1. Atomic hopping and nanoparticle reconstruction. (a) Schematic of NPoM system illustrating atom hopping gradually growing the facet width under intense light illumination. (b) Primary crystallographic facets of globular nanoparticles. (c) TEM of 80 nm diameter NP. (d) Schematic showing NCoM sustains its shape under illumination due to large energy barriers at edges. (e, f) As for (b, c) for 75 nm NCoM. Molecular layer is biphenyl-4-thiol (BPT) that creates nanogaps of 1.3 ± 0.1 nm.

Figure 2. Nanostructure resilience to laser illumination. (a, b) Scattering spectra of (a) NPoM and (b) NCoM, measured before (orange) and after 30 s (blue) of continuous laser illumination. (c) SERS time scans for NPoM, showing unstable backgrounds and appearance of new vibrational lines. (d) Variation in SERS intensity of 1580 cm⁻¹ vibrational mode (orange) and background (purple dashed). (e, f) As for (c, d) for NCoM, showing no new vibrational lines or changes in the background. Pump laser is 633 nm (red arrows in a,b) with intensity 200 µW/µm² in all cases.

633 nm pump wavelength (red arrows). However, while the NPoM (10) mode resonance redshifts by ~40 nm, the spectral peak for the NCoM remains stable at 800 nm. The pump wavelength is chosen in order to amplify the Stokes region of the SERS through the plasmon resonance of the nanoconstructs.

To investigate the NP stability in more detail, SERS spectra are recorded sequentially in time (every 1s) observing the vibrational resonances of the self-assembled monolayer of BPT used as the dielectric spacer (Figure 2c,e). Previous work has shown that large variations of SERS intensity indicate changes in local field enhancement \( E \) since \( I_{\text{SERS}} \propto [E(\lambda_{\text{in}})]^2[E(\lambda_{\text{out}})]^2 \). The similar dark-field scattering amplitudes indicate similar coupling efficiencies for these NCoMs and NPoMs, and indeed, the SERS intensities are thus also similar.

Despite this, the stability of the SERS shows great differences. Extracting the fractional changes in SERS intensity for the strongest vibrational mode at 1580 cm⁻¹ (orange line) and the background (purple dashed line) (Figure 2d,f) shows a
root-mean-square variation in NPoMs which is >3 times larger
than in NCoMs (where this residual mostly arises from small
mechanical movements of the sample under the laser spot). We
note that background variations are also higher in NPoMs,
and may be correlated to local reductions of the plasma
frequency. This allows more field to penetrate into the metal
which increases the electronic Raman scattering (making up
the SERS background). The NPoM constructs all show
changes in SERS intensity >40%, associated with the
progressive detuning of the plasmonic resonance as the facet
diameter increases. In addition, transient vibrational lines are
also observed, arising from the mobilization of adatoms in the
gap which fleetingly result in extreme near-field hot-spots (<1
nm$^3$). No such transients are observed in the case of NCoM
plasmonic constructs.

To better quantify these fluctuations, we perform systematic
studies on 20 particles. Extracting the spectral position of
plasmon resonances before (red) and after (blue) laser
illumination for NPoM and NCoM nanocavities shows the
much larger shifts for NPoMs (Figure 3a,b, bold line in box

![Figure 3. Nanoparticles shape reconstruction seen via dark-field
scattering and SERS. (a, c) Shift in spectral position ($\Delta \lambda$) of
plasmon resonances recorded before (red) and after (blue) laser
illumination for NPoM and NCoM nanocavities, fit to
gaussian distribution. Irradiation intensity is 200 $\mu$W/$\mu$m$^2$.
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which gives mean value, and its outline gives 85% deviation from
mean value (bold horizontal line). (b, d) Variation of SERS intensity for NPoM and NCoM nanocavities, fit to
Gaussian distribution. Irradiation intensity is 200 $\mu$W/$\mu$m$^2$.

from $I = 0.2$ to 2.0 mW/$\mu$m$^2$. At these intensities, the NPoM
systems are wildly unstable with thresholds always below 0.05
mW/$\mu$m$^2$. By contrast, for NCoM nanocostructures at low
power the plasmonic resonances remain stable, and they
redshift slightly only at much higher irradiation intensities
(Figure 4a), with each resonance shifting differently. While the
(20) resonance shows little tuning, the long wavelength (10)
mode can be red-shifted ~15 nm. This is expected for the
larger cube facets where more of the mode tuning is transferred
onto the longer wavelength (10) mode. For different
NCoMs, the power thresholds differ. This is quantified by
fitting the power threshold ($I_{th}$) using a sigmoidal dependence
$\lambda = \lambda_0 + K[1 + \exp\{ -(I - I_{th})/R\}]^{-1}$(Figure 4b,c). Across
many NCoMs these fits show that the longer wavelength (10)
average mode threshold $I_{th} = 0.7$ mW/$\mu$m$^2$ is half that of
the shorter wavelength (20) mode of 1.4 mW/$\mu$m$^2$ (Figure 4d).

To demonstrate the importance of these evident differences
in atomic-scale stability, we show how it allows access to a
much wider range of molecular targets than previously. These
small gap plasmonic cavities have already demonstrated key
advantages in providing large enough SERS enhancements so
that molecules which have no electronic resonances close to
the laser wavelength can be used. Avoiding direct pumping
into higher electronic states removes the inevitable bleaching
that also plagues fluorescence-based sensing. Molecules
without delocalized $\pi$-systems typically have low Raman
cross sections, and it has thus proved difficult to extract
signals from fewer than many millions of them. Here, we show
that a simple carboxylate can be sensed at the <100 molecule
level for long periods of time.

The typical solution to low Raman cross sections is to
increase the laser power; however, as demonstrated above,
this leads to unstable enhancements for NPoMs. To evidence this,
we use 3-mercaptopropionic acid (MPA), a molecular spacer
which forms gaps of 0.8 nm (see S2 section, Supporting
Information) with relatively low Raman cross-section (DFT
calculations indicate 5–10-fold smaller Raman activity than
BPT, Figure S5, Supporting Information). When MPA
monolayers in NPoM constructs are measured, instead of
consistent vibrational lines, sharp distinct peaks are seen which
jump around in distinct steps (Figure 5a).

This arises directly from influence of the atom mobility noted
above, since "picocavities" can form in such nanogaps.
Adatoms are pulled out from the crystal facet by light and
interact with nearby molecules resulting in modified vibrational
states and turning on Raman-forbidden transitions. Extremely
high SERS intensities from individual perturbed molecules are
due to these optical field hot-spots in the 1 nm$^3$ around each
adatom. Since hopping of atoms is rapid on the surface of
globular NPs, picovacavity events last only a few seconds at room
temperature. Consequently, the picocavity occurrence rate
can be directly associated with the presence and movement of
adatoms in self-assembled nanogaps. Over 20 s measurement
at laser intensities of 0.58 mW/$\mu$m$^2$, many different
picocavities are observed in NPoMs, tracking the continuous
diffusion of adatoms on the crystal facet (Figure 5a).

This is compared to recordings of consecutive SERS spectra
for NCoMs (Figure 5b), which despite being at even higher
laser intensities of 1.20 mW/$\mu$m$^2$, show stable nanocavity
vibrational modes without forming picocavities. This
indicates that fewer adatoms or atomic scale defects are
present on the NCoM Au facets. Although both systems give
similar (and weak) SERS intensities from the MPA monolayer,
for the unstable NPoM system these consistent molecular signatures are drowned out by the much larger picocavity SERS emission strengths.

Even more importantly, the NCoM system is also stable to charge movement within the molecular sandwich. The jumps in the NPoM MPA spectra observed in Figure 5a arise from a single molecule as indicated by sudden shifts of the entire vibrational line. These signals correspond to the formation of picocavities. Here, we study different bonding configurations of MPA and nanoconstruct facet where the best fitting with experimental data corresponds to monodendate binding of one O−Au (Figure 5c). Specifically, the 560 cm⁻¹ vibrational mode corresponds to an O−Au stretch with carboxylate group wagging. Adatom-free facets combined with the elevated intensity thresholds of NCoM constructs thus enable long-time single-molecule SERS measurements on molecules with low Raman cross-section.

To understand the different stability of the NPoM and NCoM systems, we consider the surface energy and stability of each Au atom in their lattice which depends on their bonding strength with nearest neighbors. For face-centered cubic (FCC) crystal structures of Au, the surface free energies \( \bar{U} \) of the primary crystallographic facets follow the trend \( \bar{U}_{\{111\}} < \bar{U}_{\{001\}} < \bar{U}_{\{110\}} \).

One factor in the higher stability of NCoMs compared to NPoMs is based on their different crystal habits at the facets of the plasmonic constructs (Figure 1. Nanocubes have atomically flat \{100\} facets at their base bounded by thin truncating \{110\} facets. By contrast, globular NPs are composed of many small facets with multiple edges and atomic steps and typically rest on \{111\} facets, as observed previously from SEMs of the top facet on the NPoM constructs. Au atoms located close to edges, apexes, and steps typically experience lower energy barriers resulting in easier atom mobilization. Recent findings report that hopping is enhanced at facet edges compared to their centers, as atoms sitting close to edges have fewer bonds with neighboring Au atoms that hold them in place. Under intense light illumination, the plasmonic Joule losses in the Au deliver energy to surface atoms (either directly or by nonequilibrium heating) inducing higher mobility of these weaker-bonded facet edge atoms. The activation energy for gold adatom surface diffusion is different depending on the crystallographic facet. For \{100\} the estimated barrier is 3.6 eV (see S1 section, Supporting Information), approximately double that on the \{111\} facet.

Local heating from the incident laser is balanced by cooling through the nanoparticle facet on the mirror, giving temperature rises that can affect the morphology of the nanostructures and consequently their plasmonic resonances. Simulations of nano-optical absorption and heat flow (see S6 section, Supporting Information) show that both NCoMs and NPoMs stay below 352 K even at 1 mW/\( \mu \)m². Compared to nanoparticles embedded in a dielectric, contact to the high thermal conductivity Au substrate here greatly reduces heating.
Indeed one way to consider this movement of adatoms is as a type of surface-melting of the nanoparticle, which occurs at temperatures far below their bulk melting point.

Two observations need to be explained in our data on nanocubes: (A) that despite the >100 bar van-der-Waals attraction to the bottom facet, Au atoms cannot move down to the nanoparticle facet to grow its lateral size (no DF redshifts are seen for NCoMs), and (B) that single adatoms are not moved onto or pulled out from the {100} faces of the NCoMs (no picocavities are seen). Both can be accounted for by the higher adatom energy required on {100} facets, so that even if decaying plasmons give their entire energy to an individual Au atom, it is not enough to drive it on the facet. The sub-ps-thermal decay times imply that only one plasmon energy (1−2 eV) is available at any time for each Au atom.

There remains an additional puzzle in the dynamics and stability of these adatoms. It is not yet clear whether the adatoms forming picocavities are pulled directly out of the center of the facets, or migrate onto the facet from the facet edges. Picocavities in these nanogaps can be formed from adatoms on either facet, the top nanoparticle or the bottom mirror.47 It is thus surprising (but consistent with other observations) that changing the crystal plane on only the nanoparticle from {111} to {100} can prevent also adatoms on the bottom mirror.47 Three interpretations are suggested, all of which imply coupling of metal atoms on the top and bottom facets. The first is that adatoms arise from the edges of facets but can only enter the nanogap cooperatively from top and bottom facet edges (for instance, as adatom pairs). The second is that the immense van der Waals forces between the metal faces, together with the strong intermolecular forces in these SAMs, can imprint the {100} facet of the NC onto the mirror underneath, inducing it to reconstruct into the stable {100} form. Finally, it is possible that an element of self-assembly recognition operates, so that NCS approaching the surface seek to reconstruct the facet of typical globular NPs and creates atomic scale defects, which shift the local metal permittivity and consequently their plasma frequency.22 By contrast, NCoMs have elevated energy activation barriers for atoms to mobilize and thus show significant resilience to constant laser intensity. Atomic-scale reconstruction at high power slightly increases the facet widths, observed as redshifts of the spectral position of the plasmon resonances. For NPoMs, these show >25 nm red-shift while for NCoMs these are spectrally stable below 0.2 mW/μm². We perform consecutive SERS spectra for NPoM and NCoM geometries to study the dynamics of atom hopping on vibrational spectroscopy of molecular monolayers in nanogaps. For NPoMs, unstable peaks are correlated with the presence of adatoms in the gap, which are eliminated in NCoMs. We show that molecules with low Raman cross-section self-assembled in nanocavities can be successfully characterized with SERS.

Further investigations using a systematic study of a wide array of NP morphologies will give much information about various atomic and molecular processes at this deeply subnanometer scale. At the same time, the knowledge should be effective in providing much more robust nanocavities for a wide variety of experiments in surface science, photocatalysis, and molecular electronics.51−54

METHODS

Sample Preparation. To prepare atomically smooth Au substrates, we follow the recipe suggested previously.23 To do so, we used polished 4” Si wafers where their surface was cleaned thoroughly by ethanol and 2-propanol solutions. Then 100 nm Au was deposited directly on a clean Si wafer using a deposition rate of 1 Å/s (LEV Lesker, e-beam evaporator). Further, we glued rectangular pieces of Si (1 × 1 cm) onto the 100 nm Au film using Epo-Tek 377 epoxy, and the wafer was placed on hot plate at a temperature of 150 °C. Here, we kept the temperature at 150 °C for about 2 h and then gradually decreased the temperature in steps of 20 °C (each step 1 h) to avoid thermal stresses. After the wafer cooled down (overnight), the Si pieces were pulled off to expose an atomically smooth 100 nm thick Au mirror. For the realization of single atomic monolayers (SAMs), the Au-coated Si pieces were dipped in 1 mM solution of bipyphenyl-4-thiol (BPT, Sigma-Aldrich, 97%) in anhydrous ethanol (Sigma-Aldrich, < 0.003% H₂O) for 12 h. To form nanometre-scale cavities, 75 nm cubic nanoparticles (NPs) (Nanopartz) and 80 nm globular NPs (BBI Solutions) were deposited directly onto the BPT-treated Au surface. The deposition time (which may vary for NP batches) is 15 s. TEM images were taken at 200 kV, using an FEI Technai G2 F20 X-TWIN TEM. The cubes, and globular NPs, were drop-cast on carbon-film coated TEM grids. Experimental Setup. All dark-field and SERS spectra were measured in a microscope-based setup similar to one reported previously.24 Briefly, the sample was placed on a motorized stage (Prior Scientific H101) which is fully automated using an in-house code written in Python. We used an Olympus BX51 microscope with a long working distance >100 NA 0.8 objective (high NA is essential to excite (10) modes). A spectrally filtered 632.8 nm diode laser (Matchbox, Integrated Optics) with output power of around 70 mW and spectral line width of 0.1 pm is used as the excitation pump. In SERS experiments, we filter laser light with a pair of notch filters centered at 633 ± 2 nm (Thorlabs). Inelastically scattered light from the nanoconstructs was coupled through a tube lens into an Andor Shamrock i303 spectrometer and a Newton EMCCD. For dark-field measurements, we used a halogen lamp to excite our samples. We note that we leave around 30 min to stabilize the lamp power before starting measurements. The reflected light was collected through the objective and splitoff to an imaging camera (Lumenera Infinity-3-1) and a fiber-coupled spectrometer (Ocean Optics QEPRO) for dark-field spectroscopy.

CONCLUSIONS

In conclusion, we demonstrate nanoconstruct geometries that can reduce atom hopping/migration events on gold facets. These are problematic in plasmon-based spectroscopies as they lead to transient vibrational states and drifting of plasmon modes in the extreme optical confinement within nanogaps. Two important features distinguish this work from previous work on nanocubes: their stabilization is by labile citrate ions which are rapidly displaced by the molecular monolayer to give ultrasmall nanogaps, and they are optically accessed from high incident angles to the mirror surface coupling strongly to the (10) mode instead of the weak highly red-shifted (11) mode.22

Intense laser illumination activates hopping of atoms that reconstruct the facet of typical globular NPs and creates atomic scale defects, which shift the local metal permittivity and consequently their plasma frequency.22 By contrast, NCoMs have elevated energy activation barriers for atoms to mobilize and thus show significant resilience to constant laser intensity. Atomic-scale reconstruction at high power slightly increases the facet widths, observed as redshifts of the spectral position of the plasmon resonances. For NPoMs, these show >25 nm red-shift while for NCoMs these are spectrally stable below 0.2 mW/μm². We perform consecutive SERS spectra for NPoM and NCoM geometries to study the dynamics of atom hopping on vibrational spectroscopy of molecular monolayers in nanogaps. For NPoMs, unstable peaks are correlated with the presence of adatoms in the gap, which are eliminated in NCoMs. We show that molecules with low Raman cross-section self-assembled in nanocavities can be successfully characterized with SERS.

Further investigations using a systematic study of a wide array of NP morphologies will give much information about various atomic and molecular processes at this deeply subnanometer scale. At the same time, the knowledge should be effective in providing much more robust nanocavities for a wide variety of experiments in surface science, photocatalysis, and molecular electronics.51−54

ASSOCIATED CONTENT

* Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c04600. Source data can be found at https://doi.org/10.17863/CAM.55243.

Calculations on surface energies of crystal habits, DFT molecular calculations, FDTD near-field simulations,
information regarding large area dark field analysis, and optical heating calculations (PDF)

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Author Contributions
A.X. and R.C. performed dark-field and SERS experiments. E.O. and I.S. developed nanocube samples and assisted with optical measurements. A.X. and J.H. obtained vibrational spectroscopy and DFT calculations of MPA self-assembled nanoconstructs. A.X. and R.C. performed optical heating and FDTD near-field simulations. E.C.G., A.F.K., and J.J.B. supervised the research. A.X. and J.J.B. wrote the manuscript. All authors discussed the results and contributed to the final paper.

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Notes
The authors declare no competing financial interest.

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