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1 **Advanced hybrid plasmonic nano-emitters** 2 **using smart photopolymer**

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10 **Abstract:** The integration of nano-emitters into plasmonic devices with spatial control and
11 nanometer precision has become a great challenge. In this paper, we report on the use of a smart
12 polymer for selectively immobilizing nano-emitters on specific preselected sites of gold
13 nanocubes (GNC). The cunning use of the polymer is twofold. First, it records both the selected
14 site and the future emitters-GNC distance through plasmon-assisted photopolymerization.
15 Second, because the polymer is chemically functionalized, it makes it possible to attach the
16 nano-emitters right at the preselected polymerized sites which subsequently “recognize” the
17 nano-emitters to get attached. Since the resulting active medium is a spatial memory of specific
18 plasmonic modes, it is anisotropic, making the hybrid nanosources sensitive to light
19 polarization. The ability to adjust their statistical average lifetime by controlling the thickness
20 of the nanopolymer is demonstrated on two kinds of nano-emitters coupled to GNC: doped
21 polystyrene nanospheres and semiconductor colloidal quantum dots.

22

23 **1. INTRODUCTION**

24 Organic and inorganic nano-emitters are used for many topical applications ranging from nano-
25 optics and nano-photonics to biomedicine and cell biology. [1–3] When weakly or strongly
26 coupled to metal nanoparticles, their key properties can be controlled: (e. g.) lifetime, [4,5]
27 quantum yield, [6] fluorescence directivity, [7] emission intensity, [8] and spectral
28 properties [9]. The integration of these hybrid nano-emitters as optical nanosources into
29 photonic nanodevices is of interest for research and technological innovation due to their
30 miniaturization and multi-applications.

31 However, the integration of the emitters near metallic nanostructures with spatial control
32 and nanometer precision in the three space dimensions remains a challenge. In the simplest
33 way, the emitters are dispersed randomly on the plasmonic structures, without any position
34 control. [10,11] By adding a spacer layer, the separation distance between the emitters and
35 metallic structures can be controlled along one direction. [12–14] To achieve 3D spatial control
36 of emitters relative to metallic nanostructures, a method based on trapping emitters in an
37 isotropic silica shell covering the entire metallic nanoparticles has been reported. [15,16]
38 Scanning-based methods have been reported to study in a controlled way the coupling between
39 emitters and metallic nanostructures. [17,18] The DNA origami-assisted method, as a powerful
40 approach, has been used for building special plasmonic nanoantennas and linking together
41 plasmonic nanostructures and nano-emitters. [19–22] For the structures presenting a gap,
42 including dimers and particles-film structures, DNA origami has proved to be able to place
43 emitters, even a single one, within the gap. [23–27]. In other words, DNA is generally used for
44 both bridging particles together and attaching nano-emitters. In the case of single metal

45 nanoparticles, the whole surface of particles is functionalized. With this approach, it is thus
46 difficult to control the anisotropy of the emitters distribution around single plasmonic
47 nanostructures. With the use of a DNA clamp, gold nanoparticles have been placed at three
48 special positions around a single nanorod, but the DNA clamp and special capture strands on
49 the clamp limit the shapes and size of the host nanostructures and it is hard to change capture
50 positions for a defined clamp [28]. Besides, DNA-based hybrid nanosystem are pretty fragile
51 in the sense that, for the survival of DNA origami, one needs to be in a salty liquid environment,
52 which limits the types of available metallic nanoparticles, and requires complicated steps. This
53 environment requirement limits the use of this approach for direct integration into nanophotonic
54 circuits. Although site-selective coating based on anisotropic chemical growth on metal
55 nanostructures was reported, [29–32] there are still challenges in achieving anisotropic
56 distribution of the emitters themselves near metal nanoparticles. As a matter of fact, controlling
57 in the three space dimensions, the anisotropic spatial distribution of emitters in the vicinity of
58 single metal nanostructures still constitutes a challenge.

59 Near-field plasmonic photopolymerization has proven to be an effective technique to trap
60 light-emitting quantum dots and molecules inside polymer volumes that are integrated at
61 electromagnetic ‘hot-spots’ [33,34]. The anisotropic distribution of emitters can be controlled
62 by choosing the plasmonic mode used for nanophotopolymerization. However, since the
63 emitters are initially randomly distributed inside the photopolymerizable formulation, the
64 spatial distribution of the emitters is still not precise enough. In particular, the distance between
65 the nano-emitters and the metal nanoparticle in the structures of Ref. 33 is not controlled. In
66 addition, because the emitter is pre-dispersed within the formulation, it is difficult to consider
67 the influence of the curing laser on the emitter during the photopolymerization process, such as
68 the two-photon absorption by the emitters, and the possible light force that may squeeze the
69 emitters outward.

70 In this letter, we report on the use of a smart nano-polymer that allows us to address the
71 above issues. The smart nature of the polymer is twofold. First, it is a photopolymer that
72 reticulates at the plasmonic hot spot of the metal nanoparticle, allowing one to keep the memory
73 of the selected electromagnetic sites. This “memory” is spatially anisotropic and also decides
74 the distance between the plasmonic nanostructure and the future nano-emitter to be attached.
75 Secondly, it is chemically pre-functionalized to electrostatically “recognize” the nano-emitter
76 that can get selectively attached to the pre-designed sites.

77 Our approach is actually based on the association of three controlled elements: plasmonic
78 nanostructures, smart photopolymer and nano-emitters.

79 **2. EXPERIMENTAL SECTION**

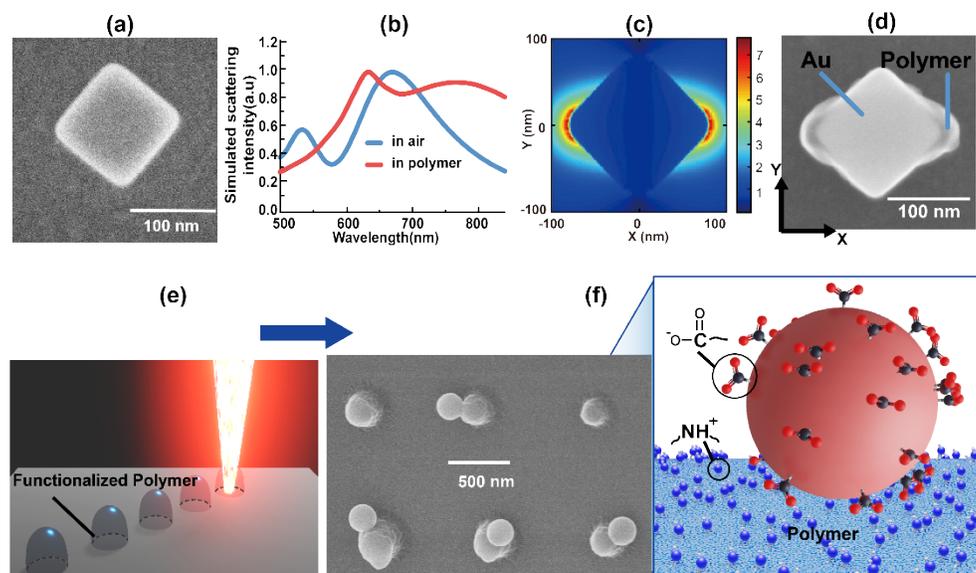
80 **A. Plasmonic nanostructures**

81 The plasmonic nanocavities used are 125-nm gold nanocubes (GNC, Fig. 1(a)) made by
82 chemical synthesis using the method already described in detail in Ref.35. These cubes,
83 deposited on an ITO-coated glass substrate, present a dipolar plasmon resonance at 670 nm in
84 air, see blue curve in Fig. 1(b), suitable for resonant near-field two-photon polymerization. [33]

85 **B. Smart photopolymer**

86 The photopolymer has been designed for plasmon-induced two-photon nanoscale
87 polymerization [33, 34] but has been modified: it is also a functionalized polymer that grabs
88 the emitters to its surface by electrostatic interaction. In that way, we can control both the
89 number of emitters attached to the polymer surface and the average emitter-metal surface
90 distance by adjusting the thickness of the polymer on the plasmonic structure. The

91 photosensitive formulation consists of 4.99 mmol of Pentaerythritol triacrylate (PETA)
 92 monomer functionalized by 2.51 mmol of methyldiethanol amine (MDEA), 0.039 mmol of 2-
 93 Isopropylthioxanthone (ITX) was added to absorb light and make interaction with MDEA to
 94 initiate the two-photon polymerization reaction and 1.13 mmol of monomethyl ether of
 95 hydroquinone (MEHQ) inhibitor was added to control the spatial confinement of the
 96 polymerization process. After photo reticulation and development, the polymer surface presents
 97 a high density of amino groups 10^8 molecules per μm^2 determined by the orange 2 test.



98

99 **Fig. 1** Gold nanocubes, nanoscale photopolymerization and surface functionalization. (a) SEM image of a
 100 representative single gold nanocube. (a) Calculated scattering spectrum of a single gold nanocube of 125-nm, in air or
 101 photopolymer medium (refractive index=1.48), on ITO-coated glass substrate (40 nm thickness of ITO layer with
 102 refractive index of 2). (b) FDTD map (at the middle sectional plane of the cube, $\lambda=780$ nm) of the field modulus in
 103 the vicinity of the gold nanocube illuminated with a X-polarized plane wave. (d) SEM image of the hybrid
 104 nanostructure resulting from 2-photon polymerization (TPP) triggered by the field shown in (c). (e) Illustration of the
 105 photopolymerization of mixture of PETA monomer functionalized by amine. (f). Left: SEM image of polymerized
 106 dots whose surface contains amine group. After immersion in a solution of negatively charged functionalized
 107 fluorescent doped polystyrene spheres (200-nm diameter), the fluorescent spheres attached on four of the six polymer
 108 dots by electrostatic interaction. Right: schematic representation of the electrostatic interaction.

109 More information about the smart photopolymer can be found in Ref. 36. The obtained
 110 polymer nanotemplates are intended to be immersed in acidic medium solution of negatively
 111 charged nano-emitters, resulting in the specific attachment of these nano-emitters on the
 112 polymer surface. In other words, during immersion, the negatively charged nano-emitters
 113 selectively assemble, by electrostatic interaction, on the positively charged functionalized
 114 polymer surface due to the presence of protonated amine groups [Fig. 1(f)].

115 C. Nano-emitters

116 The first considered nano-emitters are fluorescent polystyrene spheres (FPS, from Thermo
 117 Fisher) doped with light-emitting molecules. They are similar to those introduced in Fig. 1 but
 118 they are significantly smaller: their average size is 45 nm (see Appendix B). The absorption
 119 spectrum presents a peak at 580 nm whereas the emission peak is at 620 nm (see Appendix B).
 120 Such FPSs were used by J. de Torres et al. to demonstrate plasmons-mediated fluorescence
 121 energy transfer on silver nanowires. [37] The authors deposited the FPSs by spin-coating and
 122 their spatial distribution was not controlled. The carboxylate-modified FPSs (FluoSpheres,

123 model F8793) used in this letter, are negatively charged and thus able to get selectively
124 positioned to the functionalized polymer surface by electrostatic force.

125 Based on the three above-described elements, advanced hybrid plasmonic nano-emitters
126 can be made.

127 **D. Protocol for fabricating the hybrid plasmonic nano-emitters**

128 The protocol for fabricating the hybrid plasmonic nano-emitter consists of two main steps (Fig.
129 6).

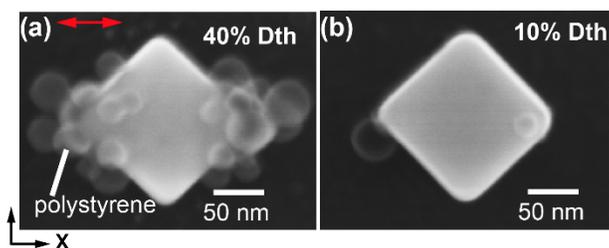
130 Step 1. This step consists of the fabrication of the functionalized nanopolymer on the GNC
131 surface by plasmon-triggered polymerization at 780 nm. [33,34,38] This wavelength efficiently
132 excites the GNC plasmon when this later is surrounded by the liquid photopolymer [see red
133 curve in Fig. 1(b)] and is efficiently absorbed by ITX that is used as a 2-photon absorber. [39]
134 The photopolymerization occurs specifically at the electromagnetic hot spots, when the near-
135 field intensity exceeds a certain intensity threshold. During this step, the selected nanoscale
136 sites are thus recorded by the polymer. After exposure, the deposited polymer volume is
137 revealed through rinsing with acetone and isopropanol for 10 mins separately. Fig. 1(d)
138 illustrates a typical hybrid nanocube, revealed after rinsing, that results from nano-
139 polymerization triggered by the plasmonic dipolar eigenmode excited with a X polarization
140 parallel to the diagonal of the cube [Fig. 1(c)]. The process relies on the control of the incident
141 intensity relative to the threshold dose (D_{th}) of 2-photon polymerization. For getting the result
142 shown in Fig. 1(d), the incident laser dose was 40% of the threshold dose, so that no
143 polymerization occurs, except in the near-field of the GNC [illustrated in Fig. 1(c)] where the
144 local dose gets higher than D_{th} through plasmon enhancement.

145 The used experimental configuration for this step is shown in Appendix A, Fig. 7.

146 Step2. Following step 1, the sample is immersed into the FPS solution for 40 min. The FPSs
147 were stabilized by carboxylic acid and have negative charges on their surface. During
148 immersion and due to the presence of amine groups on the polymer (positive charges) FPSs get
149 attracted by the polymer, leading to the selective attachment of FPSs on its surface by
150 electrostatic interaction. During this step, the pre-recorded smart polymer gets revealed by
151 selectively attaching nano-emitters.

152 **E. Selective attachment of fluorescent spheres at the nanocube corners**

153 By adjusting the dose used for step 1, we were able to control the nanopolymer's thickness and
154 thus the average distance between the GNC surface and the nano-emitters to be attached. At
155 the same time, increased thickness of polymer leads to the increased number of grafted emitters.
156 Fig. 2 illustrates this point: two different volumes of the polymer lead to a large change in the
157 number of attached FPSs. The effect of the dose on the volume of polymer is clearly shown in
158 Appendix C, Fig. 10. The selective immobilization of FPSs at the two corners of GNC is here
159 successfully demonstrated. The excitation laser used for 2-photon polymerization was X-
160 polarized, resulting in two lobes of smart polymer that took the shape of the local plasmonic
161 field [Fig. 1(c) and 1(d)]. In Fig. 2(a) and 2(b), two identical GNC have been polymerized with
162 two incident doses at 780 nm: 40% and 10% of D_{th} , respectively (step 1). Step 2 results in
163 hybrid FPS/GNC with a number of FPS at each cube corner which is strongly dependent on the
164 dose initially used for step 1: from a tenth of FPSs [Fig. 2(a)] to a few FPSs [Fig. 2(b)]. More
165 examples can be found in Appendix C, Fig. 9. The Appendix H deals with the control of the
166 number of emitters that can attach to the polymer lobes. This number depends on the
167 concentration of emitters in the solution, the size of the emitter, the size of the integrated
168 polymer area and the immersion time. In particular, Fig. 2, Fig. 9 and Fig. 16 illustrate the
169 importance of the latter two.



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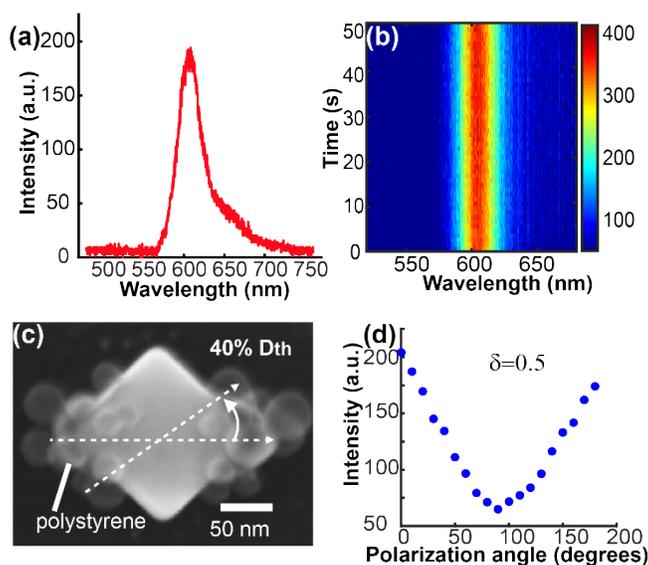
171 **Fig. 2** SEM images of the hybrid FPSs-attached nanostructures fabricated using energy dose of (a) 40% and (b) 10%
 172 of threshold during step 1. The red arrow in (a) indicates the polarization direction of the excitation laser used for
 173 polymerization during step 1.

174 3. RESULTS AND DISCUSSION

175 **A. Photoluminescence properties of the resulting hybrid nano-emitters**

176 Under 532 nm excitation, the fluorescent signal was collected through a 650/150 nm band-pass
 177 filter (Semrock FF01-650/150-25). The fluorescence spectrum from the hybrid FPS-GNC
 178 nano-emitter is shown in Fig. 3(a). In Fig. 3(b), the time trace of fluorescence intensity obtained
 179 during 50 s shows no blinking and a pretty good stability of the fluorescence intensity. This is
 180 due to the large number of dyes inside each FPS giving out an ensemble signal and the
 181 protective environment inside the polystyrene bead isolating the system from the instable
 182 effects from the external environment.

183 These hybrid nanostructures have an anisotropic nanoscale spatial distribution of FPSs that
 184 contributes to the polarization sensitivity of their fluorescence intensity. This feature is
 185 illustrated in Fig. 3(d). The 532-nm excitation light was linearly polarized with a polarization
 186 angle shown in Fig. 3(c). The considered single hybrid nano-emitter has been fabricated during
 187 step 1 using 40% of Dth. In Fig. 3(d), the fluorescence intensity decreases when the polarization
 188 angle of the excitation laser varies from 0° to 90° and increases when the polarization changes
 189 from 90° to 180° . The fluorescence intensity finally goes back to the same intensity level as the
 190 intensity of 0° . The switch from high emission signal to weak emission signal is realized by
 191 rotating the polarization direction, and a signal contrast δ of about 0.5 is obtained. In Fig. 3(b),
 192 the cosine like function, reminding us of the Malus law, is not due to the polarization sensitivity
 193 of the GNC. Rather, it is due to anisotropic spatial distribution of the active medium permitted
 194 by the smart polymer. More data on the polarization sensitivity can be found in Appendix D.



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Fig. 3 (a) Fluorescence spectrum measured from the hybrid FPSs-GNC shown in Fig. 2(a) using polarized green laser of 532 nm wavelength for excitation. A 650/150 nm band-pass filter is used to separate the fluorescent signal from the incident excitation (b) Spectrum time trace, collected for 50s. (c) Definition of the polarization angle for excitation. (d) Fluorescence intensity as a function of the angle of incident polarization defined in (c).

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B. Control of the average gap between GNC and nano-emitters and resulting Purcell factor

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The spatial elongation of the nanopolymer during step 1 can be controlled through incident energy dose. [31, 32] Energy doses ranging from 5% to 70% of D_{th} were used for fabricating hybrid FPSs-attached hybrid plasmonic nanostructures (step 1). The fluorescence lifetime of the FPSs on the hybrid nanostructures, resulting from step 2, was measured to study the influence of the polymer thickness and thus the mean value of the FPS-GNC distance. Fig. 4(a) shows typical lifetime measurements. When the FPSs are directly attached to pure polymer dots without GNC (red curve), the lifetime is longer than it is when the FPSs are attached on the polymer lobes on GNC, which is in agreement with what is expected, i.e., an increase of the radiative and non-radiative deactivation rates in the presence of the metal nanostructure. The lifetime turns out to decrease as the energy dose used for fabrication decreases: green curve (5% D_{th}) demonstrates a much shorter lifetime decay than orange curve (40% D_{th}).

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There are hundreds of molecules in each FPS (3.5×10^2 fluorescein equivalents per polystyrene sphere). In general, the overall decay of all the molecules can be fitted by a sum of exponential functions [42], i.e.,

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$$I_{total}(t) = \sum_{i=1}^N A_i \exp(-t / \tau_i), \quad (1)$$

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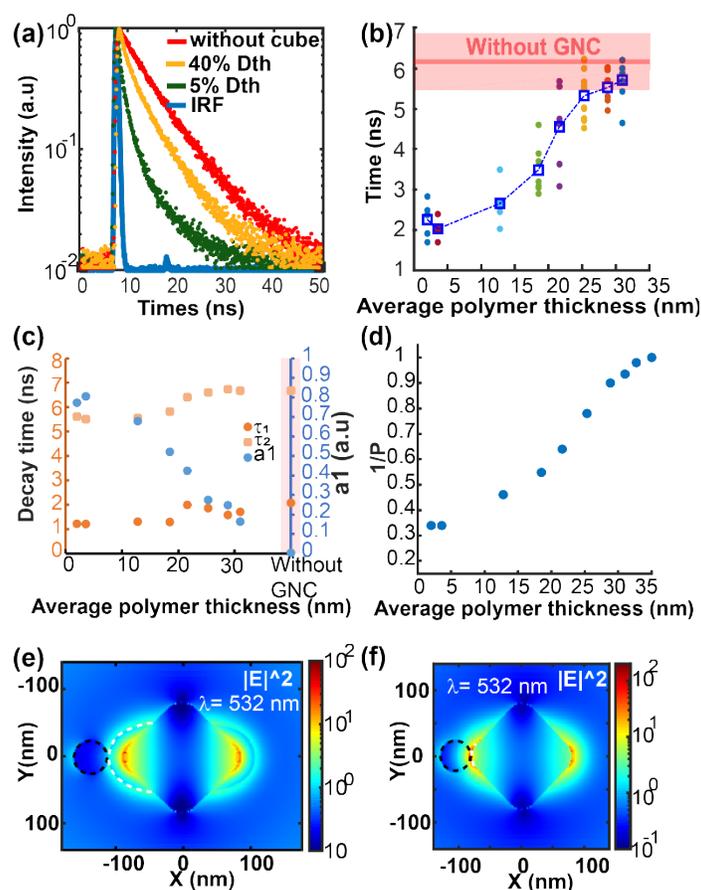
Where N is the number of dyes, $I_{total}(t)$ is the normalized fluorescence intensity at time t from all the FPSs, A_i is the probability density function, and $\sum_i^N A_i = 1$. Parameter i can be viewed as a specific family of molecules that is characterized by lifetime τ_i . The fluorescence lifetime of the FPSs without GNC can be very well fitted using single-exponential function (see Fig.14(a) in Appendix G), suggesting a single family of molecules, with a lifetime in the 6-7 ns range. With the presence of the GNC, the experimental data were fitted by one-exponential, double-exponential and triple-exponential functions. An accurate fit was achieved with double-exponential function, while the third exponential component has near zero probability density (Fig. 14(b)(c), in Appendix G). Hence the whole decay can be expressed as

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$$I(t) = a_1 \exp\left(-\frac{t}{\tau_1}\right) + (1 - a_1) \exp\left(-\frac{t}{\tau_2}\right) \quad (2)$$

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The double-exponential fitting results with different polymer thicknesses are shown in Fig. 4(b). Clearly, we observe a fast decay τ_1 that is contained in the 1-2 ns range and a slow decay τ_2 which is roughly stable within the 6-7 ns range. Considering the size of the FPS and keeping in mind that several FPSs are attached, we assign the fast decay τ_1 to the contribution of the Purcell effect undergone by the dye molecules, while the slow decay τ_2 is assigned to the emission of unaffected/less affected dye molecules (similar treatment as Ref 43). τ_1 can be seen as the mean value of the fluorescence lifetimes (Eq. 1) of the molecules that are sensitive to the GNC. Coefficient a_1 stands for the weight of this fast decay component. It is associated with the proportion of molecules which undergo the Purcell effect. As shown in Fig. 4(b), a_1 increases when the average polymer thickness decreases. This indicates an increase of the proportion of the dye molecules which are affected by the presence of the GNC, in terms of the Purcell effect.



239

240 **Fig 4** (a) Lifetime measurement of FPSs attached on hybrid polymer-cube fabricated by a dose of 40% D_{th} (orange)
 241 and 5% D_{th} (green). (b) Double-exponential fitting results of the lifetime of FPSs: fast decay component τ_1 , slow decay
 242 component τ_2 and the coefficient a_1 of fast decay component changes as the average polymer thickness varies. (c)
 243 Weighted average lifetime of FPSs change along the average distance between the metal surface and FPSs increased
 244 by decreasing the incident dose used for fabricating the hybrid GNC-based nanostructures. Dots of the same color
 245 represent hybrid nanostructures made with the same excitation energy dose. The pink area represents the variation
 246 range of the fluorescence lifetime of FPSs attached on polymer dots in the absence of gold particles. (d) The simulated
 247 average Purcell factor (P) of dipoles varies as the nano-polymer distribution changes by considering different incident
 248 energy dose and resulting average thickness. (e) and (f) are simulated field intensity (at $Z = 25$ nm away from
 249 the bottom of the cube) of a hybrid FPS-GNC nanostructure fabricated using the energy dose of 40% D_{th} and 5% D_{th}
 250 individually. The excitation wavelength is set at 532 nm, and the incident light is polarized along X. The black dotted
 251 line depicts the FPS, and the white dotted line describes the contour of polymer.

252 The weighted average lifetime ($a_1\tau_1 + (1-a_1)\tau_2$) is shown in Fig. 4(c). It is represented as a
 253 function of the “average polymer thickness” defined in the Appendix E. For statistically
 254 assessing the influence of the dose, many (from 4 to 8, corresponding to the different dots in
 255 Fig. 4(c)) hybrid nanostructures have been made for each given dose. Combining the SEM and
 256 AFM analysis before FPSs attachment (see Appendix E, Fig. 12), estimated polymer 3D
 257 distribution and the average polymer thickness can be related to the levels of energy dose.
 258 Consequently, the change in the fluorescence lifetime of FPSs can be presented as a function
 259 of the average polymer thickness, as shown in Fig. 4(c) that clearly statistically reveals a trend:
 260 the lifetime decreases as the average polymer thickness decreases and tends to a stable value \sim
 261 2ns. Fig. 4(d) shows the corresponding simulated results through the inverse of the Purcell
 262 factor, i.e. the ratio of the de-excitation rate with and without the GNC. The fluorescence

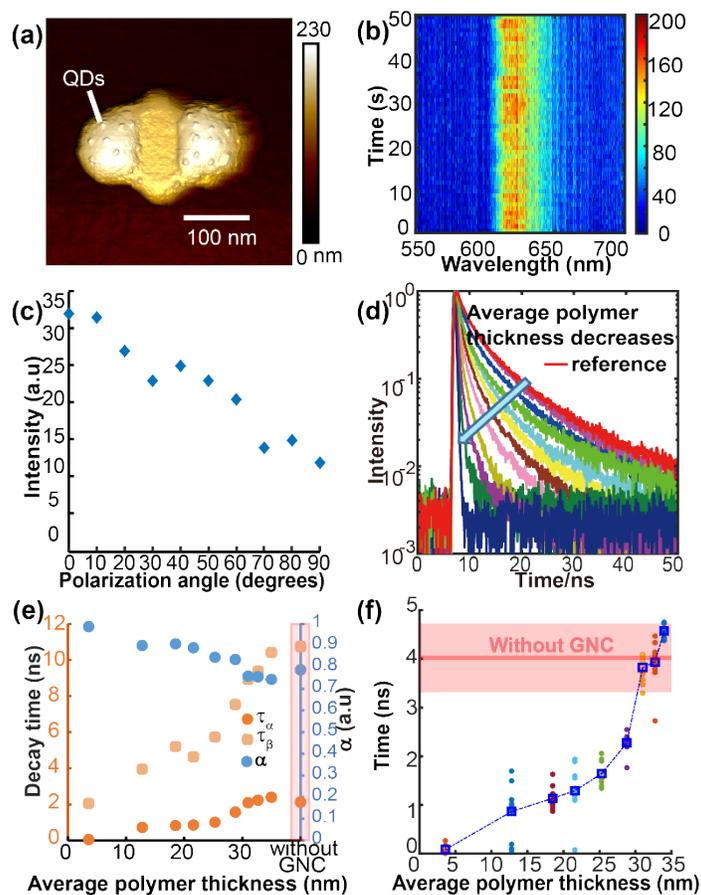
lifetime was calculated by placing dipoles at the center of FPSs at the position corresponding to the polymer distribution, as observed by SEM and AFM (see Appendix E). Fig. 4(c) and 4(d) reveal a consistent lifetime change trend, which confirms that the average polymer thickness is controlled by the incident energy dose used for fabrication of the hybrid nanosource, resulting in the control of the FPS-GNC distance and fluorescence lifetime of FPSs. As a conclusion of this section, through fittings, it turns out that, while τ_1 and τ_2 remain relatively stable, a_1 is very sensitive to the polymer thickness, resulting in significant sensitivity of the resulting averaged weighted lifetime ($a_1\tau_1+(1-a_1)\tau_2$) that can be viewed as a « tunable barycenter » in the continuous sum of lifetimes in Eq. 1.

272 **C. Further Discussion about the contributing molecules within the FPS**

273 From Fig. 4(c) and 4(d), a maximum Purcell factor can be estimated at 3.1 for smallest polymer
274 thickness, which is a rather low factor. Because of FPS' size, even is the polymer thickness is
275 negligible, a large proportion of molecules within the FPS are still too far away from GNC, and
276 the proportion of the unaffected/less affected molecule cannot go to zero. As a result, $(1-a_1)$
277 always >0 . This point is illustrated by Fig. 4(e) and 4(f) in terms of near-field excitation. Two
278 hybrid nanosources were considered: one fabricated with a 40% Dth dose [Fig. 4(e)], polymer
279 thickness = 21.6 nm, (see Appendix E, Table 1) and one fabricated with a 5% Dth [Fig. 4(f)],
280 polymer thickness = 2 nm (see Appendix E Table 1). For simplicity, both hybrid nanosources
281 present a single FPS. The intensity map at $Z=25$ nm ($\lambda=532$ nm) was calculated by FDTD using
282 an incident X-polarized plane wave propagating along Z. The spatial distribution of the
283 intensity reveals the two families of molecules in terms of excitation: in Fig. 4(e), there is a
284 fewer proportion of dyes inside polystyrene sphere that are coupled to the localized field of the
285 GNC ("close"). Even if this near-field map represents the excitation (rather than the
286 deexcitation to the LDOS), it illustrates that the contribution of plasmon-coupled molecules to
287 the average lifetime/Purcell factor of the whole system is weak; most of the molecules whose
288 lifetime play the main role in the whole system are unaffected from GNC ("far"). In Fig. 4(f),
289 a bigger proportion of dyes are coupled to the localized plasmonic near-field and their
290 contribution to lifetime decrease becomes significant. This is consistent with the double
291 exponential fitting results in Fig. 4(b). The above discussions can also explain why when the
292 polymer thickness decreases to the smallest, the weighted lifetime/average Purcell factor does
293 not continue declining but tends to stabilize in Fig. 4(c)/(d).

294 **D. Use of semiconductor colloidal quantum dots as nano-emitters**

295 In order to address the above issue, another approach was investigated: semiconductor colloidal
296 quantum dots were immobilized on a functionalized nanopolymer surface in the close vicinity
297 of a single gold nanocube. Compared to FPS, they can be considered as point-like emitters.
298 After step 1 of fabrication (illustrated in Fig. 1(d)) the hybrid GNC was immersed in a colloidal
299 solution of negatively charged CdSe/ZnS red QDs (with carboxylic acid as reactive group,
300 bought from Mesolight), with emission wavelength at 623 nm and diameter ≈ 12 nm (Fig.
301 8(c)(d), Appendix B). The obtained results, presented in Fig. 5(a), show a precise and selective
302 attachment of QDs on the two corners of the gold nanocube where the functionalized polymer
303 was printed by the plasmon-induced polymerization: Fig. 5(a) is the AFM image of a hybrid
304 polymer/GNC/QDs obtained with a 40 % Dth energy used for fabrication (step 1). It clearly
305 shows QDs attached at the surface of the integrated polymer lobes. More data with different
306 energy doses can be found in Appendix C (Fig. 10).



307

308 **Fig 5.** Use of the smart polymer for coupling spherical CdSe/ZnS quantum dots with gold nanocubes. (a) AFM image of
 309 a hybrid nanosource made with an energy dose of 40 % D_{th} . Attached QDs resulting from step 2 of fabrication are
 310 clearly visible. (b) The spectrum time trace, signal collected during continuous 50s. (c) Polarization sensitivity of the
 311 hybrid nanosource. (d). Measured lifetime for different hybrid nanosources having different polymer thicknesses. The
 312 red curve represents a reference lifetime decay of QDs attached on a polymer dot without GNC nearby. (e) Double-
 313 exponential fitting results: evolution of fast and slow decay components τ_α , τ_β and coefficient α of fast component as
 314 a function of the average polymer thickness. (f) Weighted lifetime as a function of the average polymer thickness that
 315 depends on the fabrication condition (% D_{th} energy used for near-field photo polymerization in step 1).

316 Fig. 5(b) shows a typical PL spectrum centered at $\lambda=620$ nm collected in the far field for 50 s
 317 (excitation at 405 nm). As for the FPS-based hybrid sources, the active medium is anisotropic,
 318 making the sources sensitive to the incident polarization: Fig. 5(c) shows the PL intensity as a
 319 function of the polarization direction of the excitation at 405 nm (the definition of this direction
 320 is the same as for Fig. 3(c)).

321 QDs generally have multi-exponential decay dynamics, which are due to their surface
 322 defects, surface ligands, inhomogeneities of ensemble sample or other characteristics.[44–46]
 323 Unlike in the situation with FPSs, the reference lifetime from QDs attached on the polymer dot
 324 without GNC nearby can be fitted well by double-exponential decay (Fig. 15(a), Appendix G).
 325 The short-time component and long-time component come from two different decay
 326 pathways [47]. Without QDs, these both lifetime represents a reference that is intrinsic to the
 327 semiconducting nanocrystal

328 With the presence of GNC, QDs' decay is influenced by the Purcell effect depending on
329 their relative positions to GNC. The lifetime of QDs can still be fitted by double exponential
330 functions (Fig. 15(b), Appendix G). Then the normalized intensity can be presented as
331

$$332 \quad I(t) = \alpha \exp(-t / \tau_{\alpha}) + (1 - \alpha) \exp(-t / \tau_{\beta}), \quad (3)$$

333 where the τ_{α} is the fast decay and τ_{β} is the slow decay. α describes the contribution of τ_{α} .
334 Fig. 5(d) shows a typical lifetime measurement of different hybrid nanosources fabricated with
335 different energy doses ranging from 10% to 90% of D_{th} . From Fig. 5(d), the curves are fitted
336 by double-exponential decay, using equation (3) and the fitting results are shown in Fig. 5(e).

337 The origin of this double-exponential decay is different from it is in Eq. (2): In Eq. (3), it
338 results from the intrinsic properties of the QDs [44-47] while it corresponds to two families of
339 molecules in Eq. (2) ("far" and "close" molecules). Due to the small size of QDs, all the QDs
340 are affected in the same way by the presence of the GNC (Fig. 13, Appendix E). As the result,
341 both lifetimes are sensitive to the polymer thickness, as shown in Fig. 5(e).

342 Fig. 5(f) shows the weighted average lifetime ($\alpha\tau_{\alpha}+(1-\alpha)\tau_{\beta}$) for different polymer
343 thicknesses. Again, for each dose, many similar structures (from 6 to 9) were fabricated to get
344 a statistical trend. From Fig. 5(d) and 5(f), it turns out that the weighted average lifetime
345 decreases with the dose, as a result of the decrease of the average distance between quantum
346 nano-emitters and GNC. Fig. 5(e) shows the fitted values τ_{α} , τ_{β} and α , as a function of the
347 average polymer thickness. Compared to Fig. 4(b), Fig. 5(e) reveals different features of
348 interest. In Fig. 4(b), we saw that both decay components are almost stable, and a_1 increases
349 obviously as the polymer thickness decreases, mainly revealing the increase of the proportion
350 of molecules that are influenced by the GNC and a displacement of the barycenter in Eq. 1. In
351 Fig. 5(e), the components are both affected: τ_{α} and τ_{β} decrease together as the average polymer
352 thickness gets smaller. (It is actually impossible to keep τ_{α} and τ_{β} stable, see Fig. 15 (c))
353 Meantime, coefficient α presents a weak increase (0.8 to 1), which is still much tiny compared
354 to the situation of FPS-attached hybrid GNC (in Fig. 4(b), a_1 varies from 0.9 to 0.1). There are
355 two possible explanations for this. First, α not only represents the intrinsic ratio between the
356 two decay pathways but also includes the weak increase of the proportion of QDs influenced
357 by GNC as the polymer thicknesses decreases. Second, the short-time component of QDs
358 already plays the major role in free space, the change of it cannot be distinguished as the change
359 of the long-time component because of the resolution limitation of the set-up. For FPSs, instead,
360 the variation of weighted average lifetimes is mainly due to a_1 . In addition, according to Fig.
361 5F, quite different from Fig. 4(c), the maximum Purcell factor in the situation of attached QDs
362 can get larger than 10. This is because, due to their small size, at a small polymer thickness,
363 quantum dots may be strongly affected by the Purcell effect, and no quantum dots can escape
364 from the influence of GNC.
365

366 4. CONCLUSION

367 The use of a smart photopolymer has been leading to a new kind of plasmonic hybrid
368 nanosources where different types of nano-emitters can be integrated on demand at predesigned
369 sites of the metal nanostructures. The cleverness of the polymer makes possible the selection
370 of the site through local preliminary plasmon excitation resulting in a 3D spatial memory. In
371 particular, it is possible to control the average distance between the metal nanostructure and the

372 emitter to be attached. This latter is recognized by the polymer through charge affinity, leading
373 to its selective controlled attachment.

374 Compared to Ref. 33, many advantages can be stressed. First, we can achieve a wider
375 variety of emitters. While the integration of emitters within the initial acrylate-type liquid
376 formulation is delicate in terms of phase separation and photochemical effects [48], the new
377 approach reported here allows any negatively-charged emitters or particles to attach on the
378 surface of polymer lobes with the help of electrostatic forces. In the future, this approach will
379 open up many routes. For example, even negatively charged nanodiamonds permitting single
380 photon emission [49] could be selectively attached. Second, the main novelty lies on the fact
381 we remain the advantages of our previous method, which can place emitters close to plasmonic
382 structures with anisotropic distribution and further improve it with more possibilities. By
383 placing emitters on the surface of the polymer, the thickness of polymer is also the distance
384 between emitters and plasmonic particles, instead of letting the emitters randomly dispersed
385 inside the whole volume of the polymer lobes. The control of this distance has been leading to
386 an actual lifetime engineering. In order to comment further on this point, let us use the spherical
387 coordinates (ϕ , θ , ρ) of the emitter to be localized. We can control ϕ , θ using the method
388 introduced in Ref. 33. We now control ρ with our new approach of functionalized
389 photopolymer.

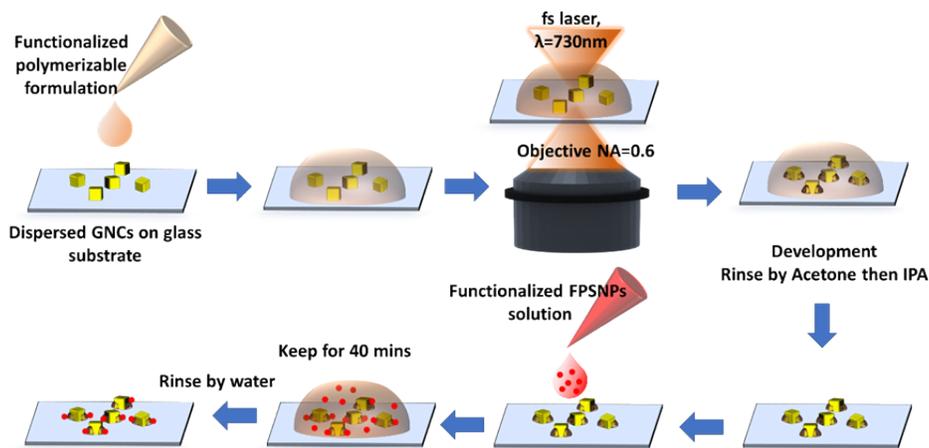
390 Finally, the surface attachment method is likely to avoid bad influence from the laser during
391 polymerization, which may damage the emitters or introduce other effects such as light force,
392 and two-photon absorption, etc. These effects are currently being studied by our team.

393 This approach will be used for fabricating single-photon hybrid nanosources [33] and
394 precisely integrating different kinds of QDs through a multistep process [34], which will be
395 opening new avenues for advanced integrated nanosources based on weak and strong coupling,
396 among which multicolor nano lasers [34,50] that may be controlled by light polarization.
397 Besides, as we demonstrated in Ref. 33, a tunable emitter selection is possible by rotating the
398 incident polarization, through the concept of polarization-dependent spatial overlap integral
399 (overlap between the exciting near-field and the emitters). However, in ref. 33, the excitation
400 was in the blue, which is suitable for emitter excitation but not plasmon excitation. By
401 integrating emitters that efficiently get excited at 780 nm wavelength through either one or two-
402 photon absorption, we would take advantage of the plasmonic hot spot for both integrating and
403 exciting them in the future.

404

405 **APPENDIX A: PROCESS OF FBRICATION**

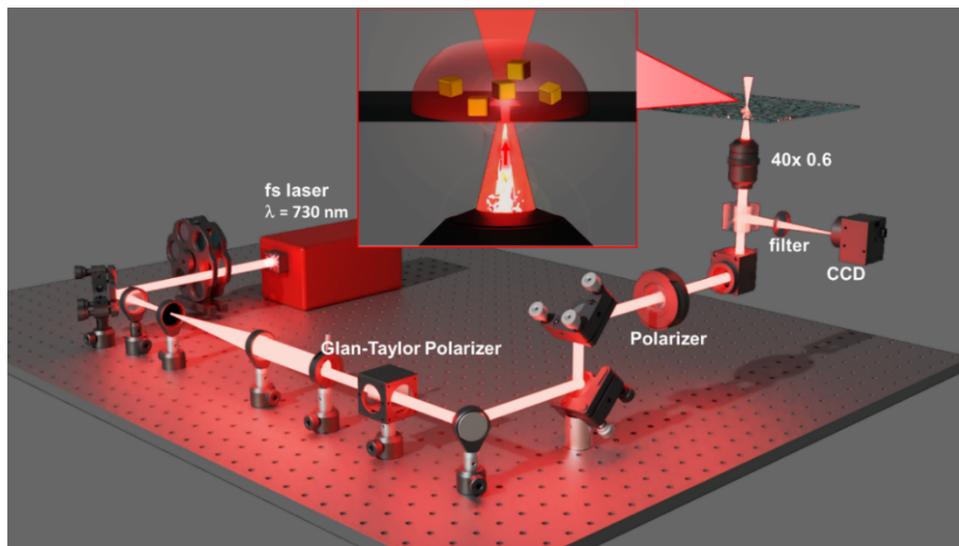
406 The separation distance between each GNC is controlled bigger than 500nm by adjusting the
407 concentration of GNCs in solution, to avoid the influence from each other in the following
408 experiments including 2-photon polymerization and emission measurement.



409
410 **Fig. 6.** The process steps for fabricating hybrid FPSs-attached cubes.

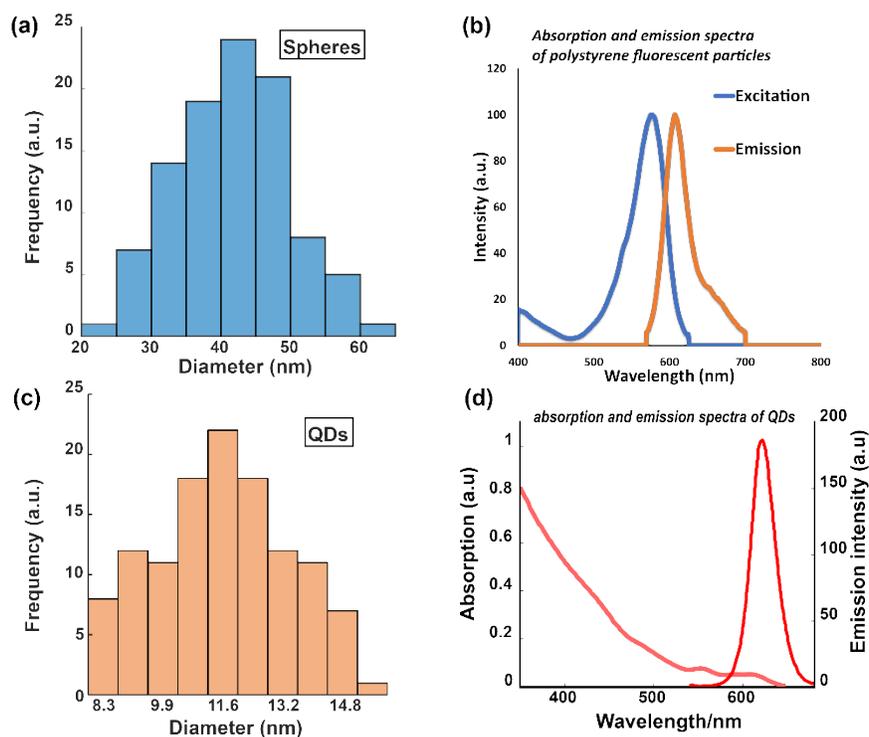
411 **Fig. 6** illustrates the whole steps for preparing hybrid FPSs-attached cubes. And Fig. 7 gives out the optical set-up
412 used for doing 2-photon polymerization on each single GNC. The position of focused laser spot and GNCs are observed
413 by a CCD camera and makes it possible to aim the laser spot at each isolated GNC. Plasmon-triggered 2-photon
414 polymerization process

415 The GNCs are dispersed on a glass substrate with a separation distance between each other
416 bigger than 500nm. A drop of the functionalized photosensitive formulation is then deposited
417 on the pre-identified GNCs sample. Each GNC of consistent size and good shape is exposed
418 one by one using a focused femtosecond laser of 730nm by an objective lens (N. A=0.6) (Fig.
419 7). During polymerization, the exposure time is kept at 1/15 s. The exposure laser energy dose
420 is set below than the polymerization threshold and is defined as the percentage of threshold
421 dose (typical incident dose $D_{in} = 40\% D_{th}$). The polarization direction of curing laser is along
422 the diagonal of the GNCs.



423
424 **Fig. 7** Optical configuration to carry out two-photon polymerization.

425 **APPENDIX B: SIZE OF POLYSTYRENE FLUORESCENT PARTICLES AND**
426 **QUANTUM DOTS**



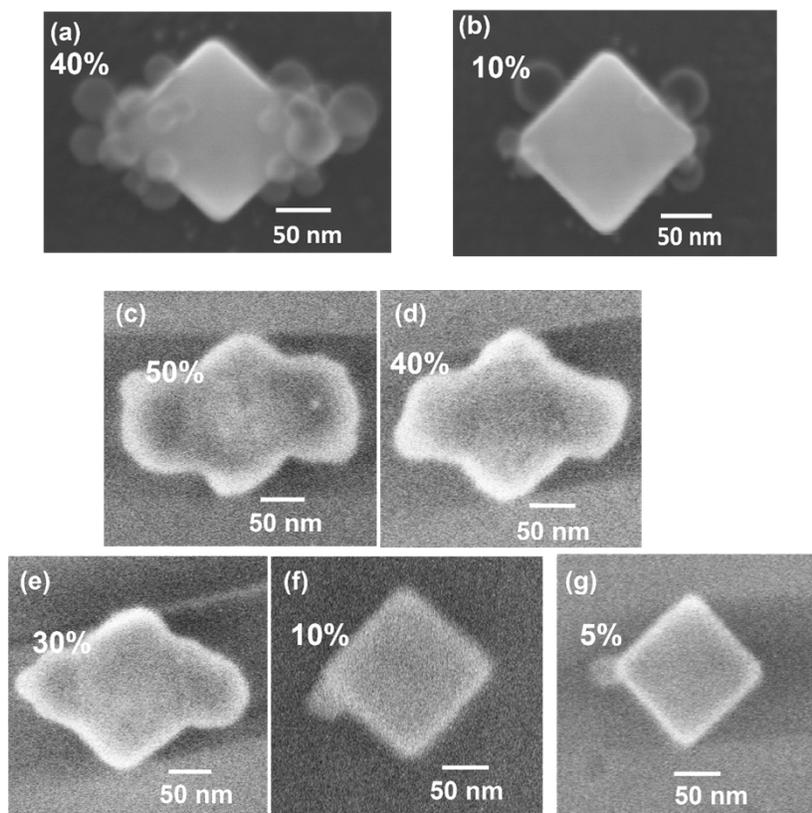
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428 **Fig. 8** (a) Diameter distribution histogram of the polystyrene fluorescent spheres (b) Excitation and emission spectra
 429 of polystyrene spheres measure by UV-visible Cary 100 spectrometer and Fluorescence Spectrophotometer separately.
 430 (c) Diameter distribution histogram of the QDs. The QDs are deposited on glass substrate and then after coating of a
 431 conducting layer, the QDs 'sizes are measured under SEM. Due to the existence of the conducting layer, the size of
 432 the measured QD is several nanometers larger than the real size of QDs. (d) The absorption and emission spectra of
 433 the red QDs in toluene.

434 From Fig. 8(a), the average diameter of this kind of polystyrene fluorescent sphere is around
 435 42.5nm. Different sizes of polystyrene spheres will change the related distance between their
 436 containing fluorescent dye molecules and the GNC, which will lead to errors in the fluorescence
 437 lifetime measurement. When the number of attached polystyrene spheres is relatively large,
 438 since the measured fluorescence lifetime is a statistical average, the influence of the size
 439 difference of polystyrene spheres on the result can be ignored. However, when the hybrid GNC
 440 is fabricated by low dose, the number of attached polystyrene spheres is limited, the size
 441 difference of the fluorescent spheres becomes non-negligible. That can explain why the
 442 measured lifetime in the situation of smallest average thickness is bigger than the second
 443 smallest situation in Fig. 4b of the article.

444 These Fluorescent FluoSpheres beads whose average diameter are around 42nm with the
 445 dyes filling the full volume of the beads and contain 3500 fluorescein equivalents per
 446 microsphere according to the handbook from Thermofisher.

447 **APPENDIX C: MORE EXAMPLES OF HYBRID NANOCUBES**



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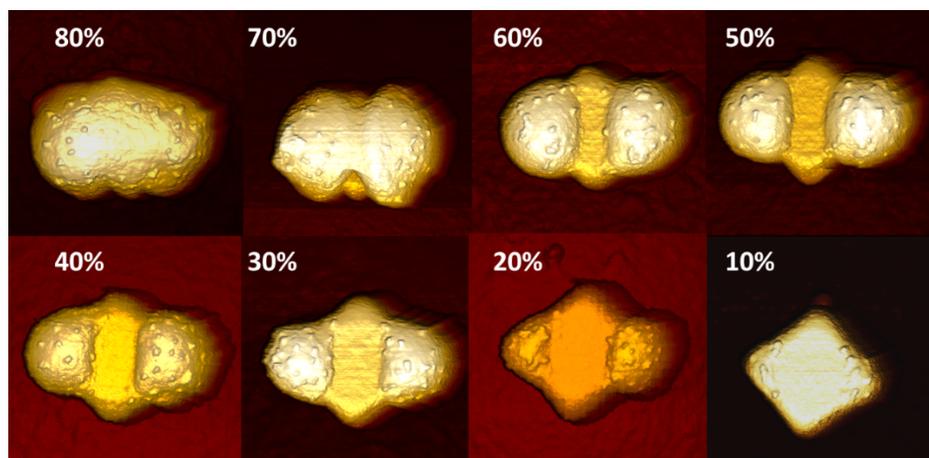
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Fig. 9 More examples of hybrid FPSs-attached gold nanocubes. (a) and (b) SEM images of the hybrid FPSs-attached nanocubes fabricating using 40% D_{th} and 10% D_{th} , and the residence time of FPS solution is 40 mins. 10kV voltage is used for SEM observation. (c) (d) (e) (f) (g) fabricated using 50% D_{th} , 40% D_{th} , 30% D_{th} , 10% D_{th} , 5% D_{th} separately, and the immersion time of the sample in the FPS solution decreased to 10 mins. 1kV voltage is used for SEM observation



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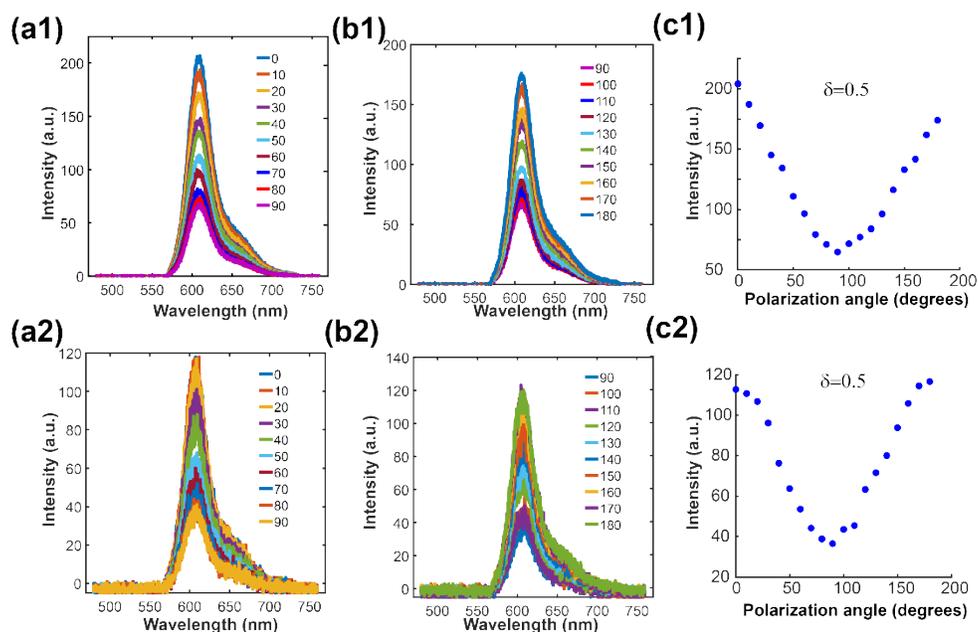
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Fig. 10 AFM images of some hybrid GNC with attached QDs, fabricated using incident doses from 80% decreasing to 10% of D_{th} (step 1).

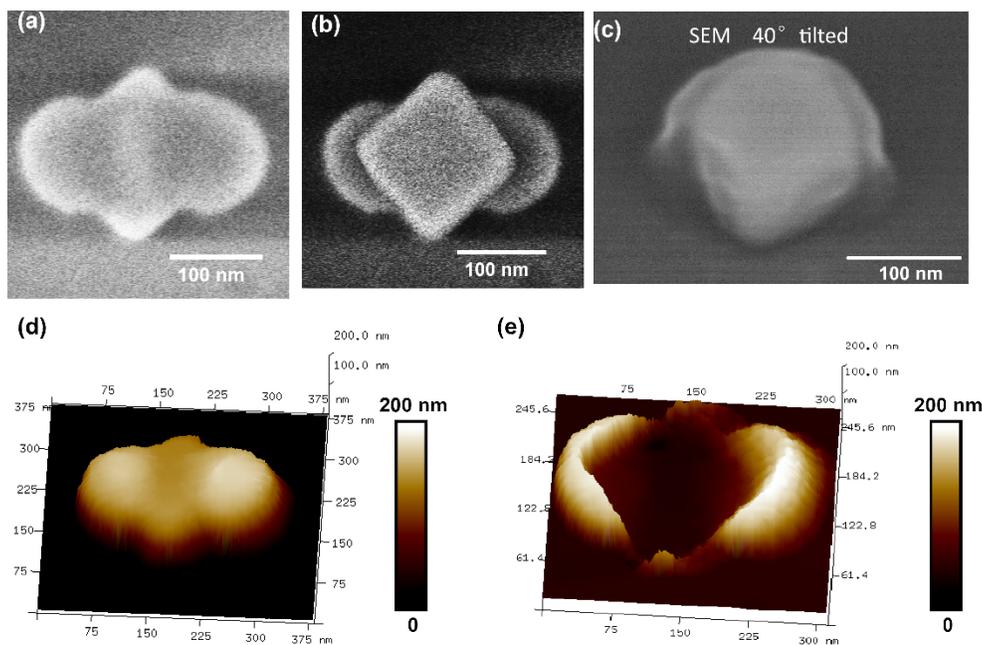
APPENDIX D: POLARIZATION SENSITIVITY OF THE EMISSION INTENSITY



459

460 **Fig. 11** Emission spectra from two hybrid FPSs-attached nanocubes fabricated using same parameters, their exposure
 461 dose is 40% D_{th} . (a1) and (b1) are the emission spectra from the first hybrid FPSs-attached nanocube when the
 462 polarization angle of the laser used for exciting varies from 0 degrees to 90 degrees and 90 degrees to 180 degrees
 463 separately. (c1) is the emission peak intensity changing trend. And (a2) (b2) (c2) are the results from the second hybrid
 464 FPSs-attached nanocube.

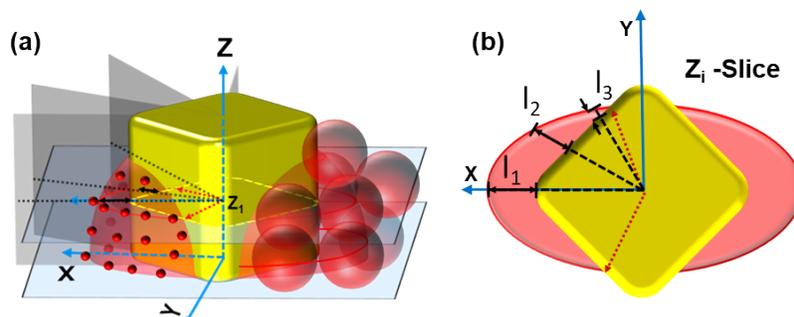
465 **APPENDIX E: 3D POLYMER CHARACTERIZATION AND DEFINITION OF THE**
 466 **AVERAGE POLYMER THICKNESS**



467

468 **Fig. 12** (a) SEM image of a hybrid nanocube without attaching any QDs/polystyrenes (fabricated using 50% D_{th}) (b)
 469 Mixed image, the original SEM image of the cube before exposure is superimposed to (a). (c) 40-degree tilted SEM

470 image. (d) 3D height image measured by AFM of the same hybrid nanocube of (a). (d) 3D height image subtracted by
 471 the original cube's height profile from (c), demonstrating the 3D polymer distribution.



472

473 **Fig. 13.** Average polymer thickness definition and assessment. (a) The whole hybrid cube-polymer structure is cut in
 474 the Z direction to get 20 slices of the cross-section. For each z-slice, a quadrant is sliced into n parts on average
 475 according to angle, and the intersection of the corresponding rays and the polymer profile is averaged to obtain the
 476 average elongation of the polymer under this Z slice. Finally, the polymer thickness of all slices in the z-direction is
 477 averaged to get the average polymer thickness. (b) shows the polymer elongations (l_1 , l_2 , l_3) obtained by the three
 478 tangents when a quadrant is divided into 3 sections in the z_i -slice, then the average value of the three elongation rates
 479 of the polymer thickness of this slice.

480 For Z_i -slice, If the polymer thickness in the third quadrant is sampled at 30-degree intervals
 481 shown in Fig. 13(b), three polymer thickness l_1 , l_2 , l_3 are obtained. Then the average polymer
 482 thickness on Z_i -slice is $(l_1+l_2+l_3)/3$. For each Z_i -slice, keep sampling at 30-degree intervals, and
 483 the number of l obtained will vary with the change of the polymer distribution of each slice.
 484 Finally, the average of all the obtained l is taken as the average polymer thickness.

485

Table 1. Calculated average polymer thickness, when using different dose in percentage of Dth

Percentage of Dth (%)	Average polymer thickness (nm)
5	2
10	3.6
20	12.8
30	18.5
40	21.6
50	25.3
60	28.8
70	31.0
80	32.7
90	34

486

487 APPENDIX F: FLUORESCENCE SIGNAL AND LIFETIME MEASUREMENT

488 A. Optical set-up

489 For fluorescence intensity measurement, every single FPSs-attached hybrid polymer-cube is
 490 excited using 532nm (CW laser, OBIS 532nm) focused by an objective lens of 40 x 0.6, and its
 491 fluorescence signal is collected by the same objective, after fitting by a band-pass filter (FF01-
 492 650/150-25), it is analyzed by a spectrometer. A half-wave plate is used to change the

493 polarization direction of linearly polarized laser and after each polarization rotation, use another
 494 polarizer to check the polarization direction, and fine-tune the laser output light power to ensure
 495 that the power reaching the sample surface remains the same (detected before objective lens,
 496 laser power is set to 10 μ w). For lifetime measurement, a pulsed laser (Picoquant D-TA-530B)
 497 connected with an extra driver box (PDL 800-B), whose repetition frequency is set at 10MHz
 498 is used. The laser beam is focused on the scanning sample hold stage by an objective lens of
 499 100 x 0.95. The laser power detected before objective lens is about 0.5 μ w. For each hybrid
 500 FPSPNs-attached polymer-cube, its fluorescence is collected by reflection, and then after
 501 passing through a band-pass filter (FF01-650/150-25), the collected light is directed by a fiber
 502 towards an APD (Picoquant PMA- 182). The signal is sent to the stand-alone TCSPC Module
 503 (TimeHarp-300), which is linked to the laser driver.

504 **B. Purcell factor simulation**

505 The Purcell factor is calculated by FDTD. For each incident light dose, the corresponding
 506 3D polymer is constructed as a model with a refractive index of 1.5. And set the diameter of
 507 the polystyrene sphere to 50nm. For each case, the hybrid polymer cube is cut into N slices in
 508 the z direction, each Z_i -slice has a specific polymer contour at the z position, as shown in Fig.
 509 13. The FPSs are distributed along the contour of the polymer. To calculate, we only chose
 510 several FPSs along the contour at Z_i . For each nanosphere, calculate the Purcell factor of the
 511 ideal dipole at the center of the nanosphere, and finally average these results to obtain the
 512 average Purcell factor of this z-slice, see Equation (F-1)

$$513 \quad PF_i = \frac{1}{N_i} \sum_{k=1}^{N_i} PF_k \quad (F-1)$$

514 Where N_i is the sampling number of FPSs on Z_i slice.

515 The FPSs are assumed uniformly distributed on the surface of polymer, then for each Z_i -
 516 slice, the number of attached FPSs depends on the length of the polymer contour line.

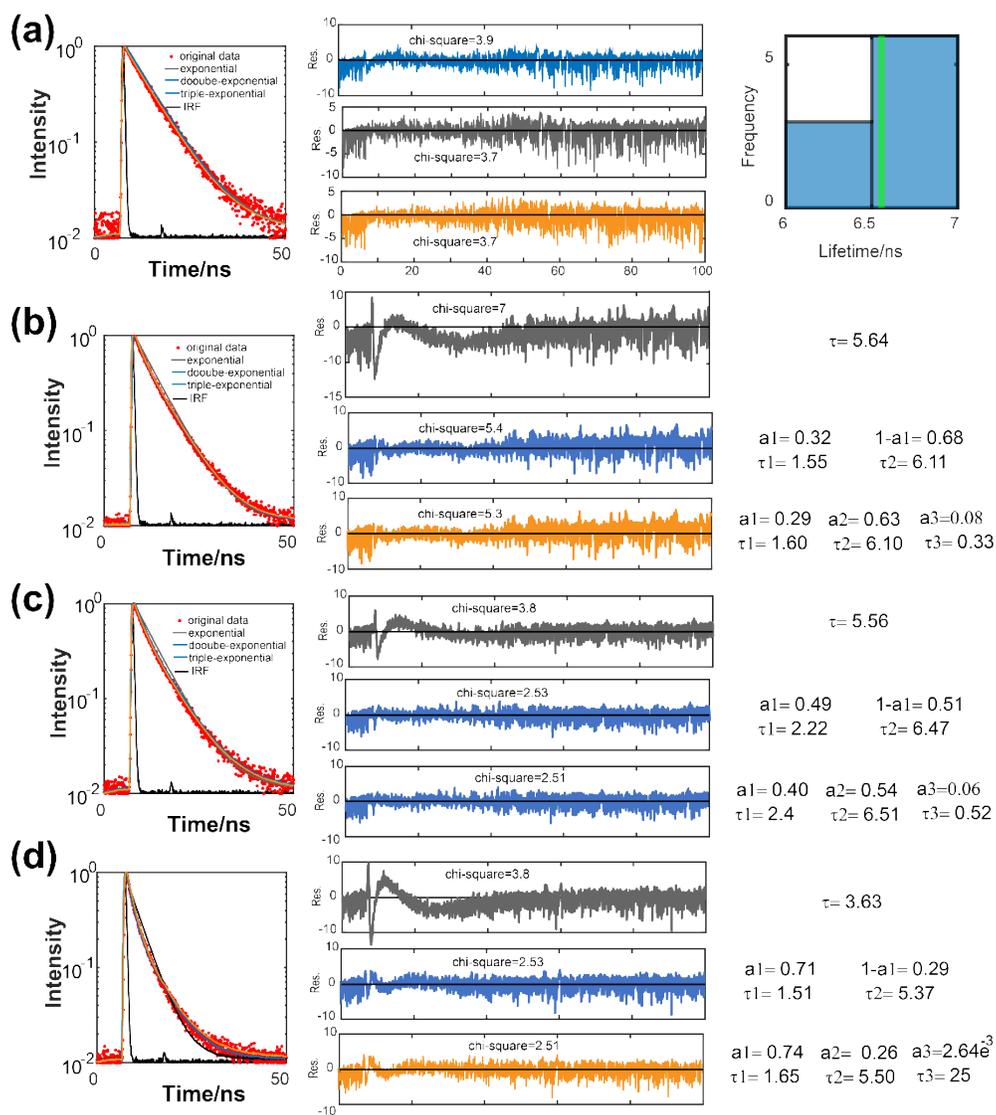
$$517 \quad PF_{total} = (\sum_{i=1}^{i=N} C_i \cdot PF_i) / (\sum_{i=1}^{i=N} C_i) \quad (F-2)$$

518 Where C_i is the length of polymer contour line of Z_i -slice, and N is the number of slices in
 519 z-direction.

520 By this way, the obtained PF_{total} is worked as the average Purcell factor in the case of a
 521 hybrid FPSs-attached polymer-cube fabricated by a certain dose.

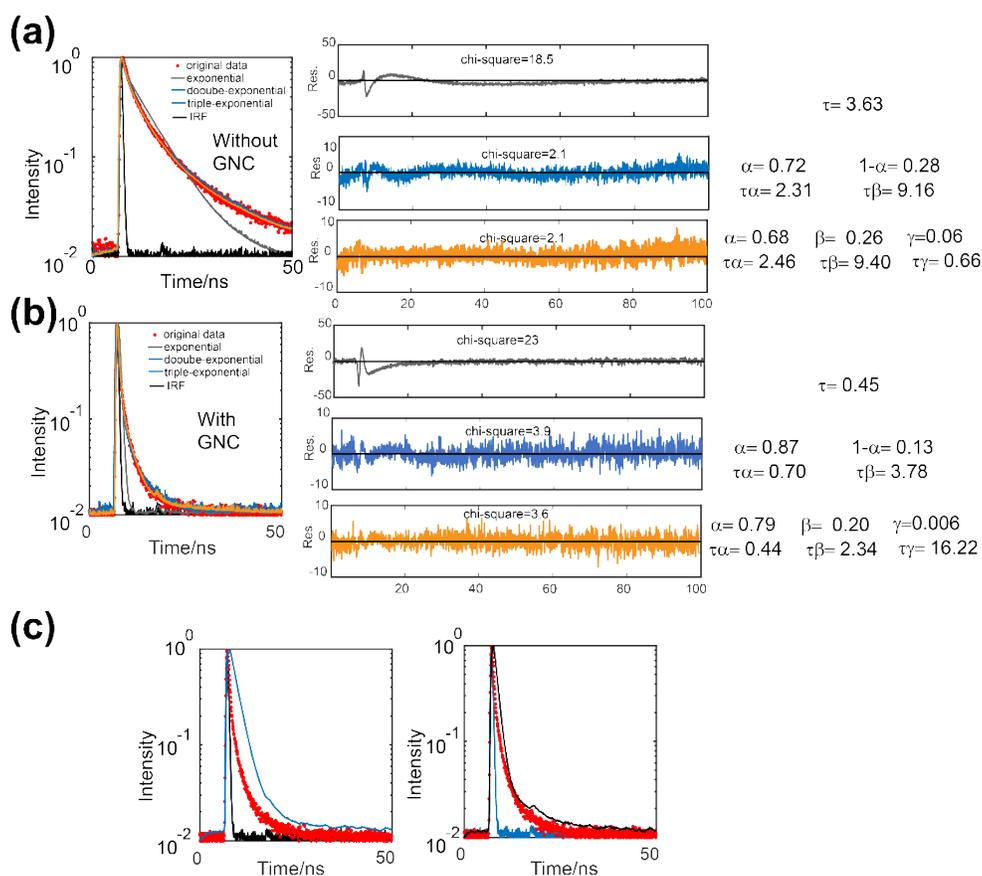
522 For example, of 20% Dth, the polymer volume is cut into 2 slices in the z direction. For
 523 slice1, 3 positions of fluorescent spheres are calculated. For every position, we calculated the
 524 Purcell factor of an orientation-averaged dipole placed in the center of sphere. And the
 525 boundary length of the polymer of this Z_1 -slice is around 48.7nm. For Z_2 -slice, because the
 526 boundary length of polymer is much smaller than diameter of sphere, we only calculate the
 527 Purcell factor at one position. Finally, an average Purcell factor ~ 2.17 was obtained according
 528 to Eq. F-2

529 **APPENDIX G: MULTI-EXPONENTIAL DECAY FITTING OF THE LIFETIME OF** 530 **FPS AND QD IN FREE SPACE**



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Fig. 14 (a) The first row shows an example of the lifetime from FPSs attached on pure polymer dot without Au nanocube nearby. Two kinds of fitting, single-exponential fitting (grey line) and double-exponential fitting (blue line), triple-exponential fitting (orange line) are used here. From the fitting results, the single exponential function can already achieve good fitting result. The far-right image shows the histogram of FPSs' lifetime under single exponential fitting, and the green line represents the average value. For comparison (b) (c) and (d) show three examples of the lifetime from FPSs attached on polymer lobes of GNC.

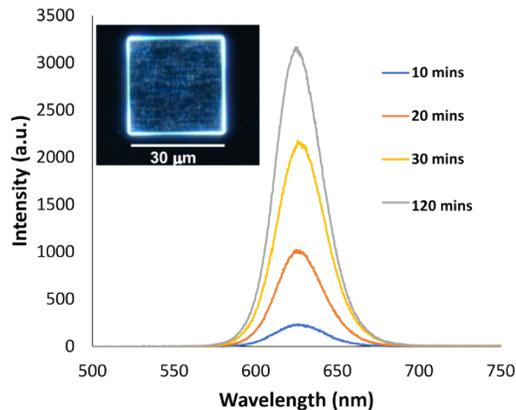


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Fig. 15 Example of the lifetime from QDs attached on pure polymer dot without Au nanocube nearby (a) and with Au nanocube nearby (b). Single-exponential function is not enough to get a good fitting result while double/triple-exponential function can get a better fit. (c) Two failed attempts. By limiting the value range of τ_a (2-3), τ_b (9-10), and τ_α (1-3), τ_β (8-10) to attempt to use similar τ_α , τ_β in (a) to fit the decay curve.

543 **APPENDIX H: NUMBER OF ATTACHED EMITTERS**

544 In Ref. 36, the original principle of this chemically attached method has been described. In this
545 article, gold nanoparticles (diameter~ 50nm) were attached to the smart photopolymer. The
546 control of the surface density (and thus the number) of gold nanoparticles has already been
547 studied. The gold nanoparticles have same size as the fluorescent spheres used in our current
548 manuscript. We expect that their density changes with the immersion time following the same
549 law.



550

551 **Fig. 16** Fluorescence intensity from QDs attached on 2D flat functionalized polymer structure (see inset) with respect
 552 to the immersion time (mins). The excitation laser is 405 nm with a power of 2μm, collection time is kept as 0.1s. The
 553 left top small image (inset) is the dark-field image of the 2D flat polymer square.

554 As far as the QDs are concerned, Fig.16 shows the fluorescence intensity from QDs attached
 555 on a micrometer sized functionalized flat polymer structure. Different times of immersion were
 556 used. Considering the fixed size of the polymer area, this Fig. 16 clearly shows that the intensity
 557 (and thus the related number of attached QDs) strongly depends on the immersion time.

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 564 (École Universitaire de Recherche, contract ANR-18-EURE-0013). The manuscript was written through contributions
 565 of all authors. All authors have given approval to the final version of the manuscript.

566 **Disclosures.** The authors declare no conflicts of interest.

567 **Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may
 568 be obtained from the authors upon reasonable request.

569 Reference

- 570 1. F. Vetrone, R. Naccache, A. Zamarrón, A. Juarraz de la Fuente, F. Sanz-Rodríguez, L. Martínez Maestro,
 571 E. Martín Rodríguez, D. Jaque, J. García Sole, and J. A. Capobianco, "Temperature sensing using fluorescent
 572 nanothermometers," *ACS nano* **4**, 3254–3258 (2010).
- 573 2. J.-H. Kim, S. Aghaeimeibodi, C. J. K. Richardson, R. P. Leavitt, D. Englund, and E. Waks, "Hybrid
 574 Integration of Solid-State Quantum Emitters on a Silicon Photonic Chip," *Nano Lett.* **17**, 7394–7400 (2017).
- 575 3. X. Feng, Y. Li, X. He, H. Liu, Z. Zhao, R. T. K. Kwok, M. R. J. Elsegood, J. W. Y. Lam, and B. Z. Tang, "A
 576 Substitution-Dependent Light-Up Fluorescence Probe for Selectively Detecting Fe³⁺ Ions and Its Cell
 577 Imaging Application," *Adv. Funct. Mater.* **28**, 1802833 (2018).
- 578 4. T. B. Hoang, G. M. Akselrod, C. Argyropoulos, J. Huang, D. R. Smith, and M. H. Mikkelsen, "Ultrafast
 579 spontaneous emission source using plasmonic nanoantennas," *Nat. Commun.* **6**, 7788 (2015).
- 580 5. G. M. Akselrod, C. Argyropoulos, T. B. Hoang, C. Ciraci, C. Fang, J. Huang, D. R. Smith, and M. H.
 581 Mikkelsen, "Probing the mechanisms of large Purcell enhancement in plasmonic nanoantennas," *Nature*
 582 *Photon.* **8**, 835–840 (2014).
- 583 6. Y. Luo, E. D. Ahmadi, K. Shayan, Y. Ma, K. S. Mistry, C. Zhang, J. Hone, J. L. Blackburn, and S. Strauf,
 584 "Purcell-enhanced quantum yield from carbon nanotube excitons coupled to plasmonic nanocavities," *Nat.*
 585 *Commun.* **8**, 1413 (2017).
- 586 7. H. Aouani, O. Mahboub, E. Devaux, H. Rigneault, T. W. Ebbesen, and J. Wenger, "Plasmonic Antennas for
 587 Directional Sorting of Fluorescence Emission," *Nano Lett.* **11**, 2400–2406 (2011).
- 588 8. P. Anger, P. Bharadwaj, and L. Novotny, "Enhancement and Quenching of Single-Molecule Fluorescence,"
 589 *Phys. Rev. Lett.* **96**, 113002 (2006).

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9. H. Leng, B. Szychowski, M.-C. Daniel, and M. Pelton, "Strong coupling and induced transparency at room temperature with single quantum dots and gap plasmons," *Nat Commun* **9**, 4012 (2018).
 10. A. Kinkhabwala, Z. Yu, S. Fan, Y. Avlasevich, K. Müllen, and W. E. Moerner, "Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna," *Nature Photon.* **3**, 654–657 (2009).
 11. S. Khatua, P. M. R. Paulo, H. Yuan, A. Gupta, P. Zijlstra, and M. Orrit, "Resonant Plasmonic Enhancement of Single-Molecule Fluorescence by Individual Gold Nanorods," *ACS Nano* **8**, 4440–4449 (2014).
 12. K. J. Russell, T.-L. Liu, S. Cui, and E. L. Hu, "Large spontaneous emission enhancement in plasmonic nanocavities," *Nature Photon.* **6**, 459–462 (2012).
 13. R. Chikkaraddy, B. de Nijs, F. Benz, S. J. Barrow, O. A. Scherman, E. Rosta, A. Demetriadou, P. Fox, O. Hess, and J. J. Baumberg, "Single-molecule strong coupling at room temperature in plasmonic nanocavities," *Nature* **535**, 127–130 (2016).
 14. T. B. Hoang, G. M. Akselrod, and M. H. Mikkelsen, "Ultrafast Room-Temperature Single Photon Emission from Quantum Dots Coupled to Plasmonic Nanocavities," *Nano Lett.* **16**, 270–275 (2016).
 15. T. Ming, L. Zhao, Z. Yang, H. Chen, L. Sun, J. Wang, and C. Yan, "Strong polarization dependence of plasmon-enhanced fluorescence on single gold nanorods," *Nano Letters* **9**, 3896–3903 (2009).
 16. S.-Y. Liu, L. Huang, J.-F. Li, C. Wang, Q. Li, H.-X. Xu, H.-L. Guo, Z.-M. Meng, Z. Shi, and Z.-Y. Li, "Simultaneous Excitation and Emission Enhancement of Fluorescence Assisted by Double Plasmon Modes of Gold Nanorods," *J. Phys. Chem. C* **117**, 10636–10642 (2013).
 17. A. W. Schell, P. Engel, J. F. M. Werra, C. Wolff, K. Busch, and O. Benson, "Scanning Single Quantum Emitter Fluorescence Lifetime Imaging: Quantitative Analysis of the Local Density of Photonic States," *Nano Lett.* **14**, 2623–2627 (2014).
 18. H. Groß, J. M. Hamm, T. Tufarelli, O. Hess, and B. Hecht, "Near-field strong coupling of single quantum dots," *Sci. Adv.* **4**, eaar4906 (n.d.).
 19. M. P. Bussón, B. Rolly, B. Stout, N. Bonod, and S. Bidault, "Accelerated single photon emission from dye molecule-driven nanoantennas assembled on DNA," *Nat. Commun.* **3**, 1–6 (2012).
 20. X. Lan, X. Zhou, L. A. McCarthy, A. O. Govorov, Y. Liu, and S. Link, "DNA-Enabled Chiral Gold Nanoparticle–Chromophore Hybrid Structure with Resonant Plasmon–Exciton Coupling Gives Unusual and Strong Circular Dichroism," *J. Am. Chem. Soc.* **141**, 19336–19341 (2019).
 21. A. T. M. Yeşilyurt and J.-S. Huang, "Emission Manipulation by DNA Origami-Assisted Plasmonic Nanoantennas," *Adv. Opt. Mater.* **9**, 2100848 (2021).
 22. M. Loretan, I. Domljanovic, M. Lakatos, C. Rüegg, and G. P. Acuna, "DNA Origami as Emerging Technology for the Engineering of Fluorescent and Plasmonic-Based Biosensors," *Materials* **13**, 2185 (2020).
 23. K. Hübner, M. Pilo-Pais, F. Selbach, T. Liedl, P. Tinnefeld, F. D. Stefani, and G. P. Acuna, "Directing Single-Molecule Emission with DNA Origami-Assembled Optical Antennas," *Nano Lett.* **19**, 6629–6634 (2019).
 24. R. Chikkaraddy, V. A. Turek, N. Kongsuwan, F. Benz, C. Carnegie, T. van de Goor, B. de Nijs, A. Demetriadou, O. Hess, U. F. Keyser, and J. J. Baumberg, "Mapping Nanoscale Hotspots with Single-Molecule Emitters Assembled into Plasmonic Nanocavities Using DNA Origami," *Nano Lett.* **18**, 405–411 (2018).
 25. H. Zhang, M. Li, K. Wang, Y. Tian, J.-S. Chen, K. T. Fontaine, D. DiMarzio, M. Liu, M. Cotlet, and O. Gang, "Polarized Single-Particle Quantum Dot Emitters through Programmable Cluster Assembly," *ACS Nano* **14**, 1369–1378 (2020).
 26. G. P. Acuna, F. M. Möller, P. Holzmeister, S. Beater, B. Lalkens, and P. Tinnefeld, "Fluorescence Enhancement at Docking Sites of DNA-Directed Self-Assembled Nanoantennas," *Science* **338**, 506–510 (2012).
 27. J. Heintz, N. Markešević, E. Y. Gayet, N. Bonod, and S. Bidault, "Few-Molecule Strong Coupling with Dimers of Plasmonic Nanoparticles Assembled on DNA," *ACS Nano* **15**, 14732–14743 (2021).
 28. C. Shen, X. Lan, X. Lu, T. A. Meyer, W. Ni, Y. Ke, and Q. Wang, "Site-Specific Surface Functionalization of Gold Nanorods Using DNA Origami Clamps," *J. Am. Chem. Soc.* **138**, 1764–1767 (2016).
 29. F. Wang, S. Cheng, Z. Bao, and J. Wang, "Anisotropic Overgrowth of Metal Heterostructures Induced by a Site-Selective Silica Coating," *Adv. Opt. Mater.* **52**, 10344–10348 (2013).
 30. I. Tijnelyte, I. Kherbouche, S. Gam-Derouich, M. Nguyen, N. Lidgi-Guigui, M. L. de la Chapelle, A. Lamouri, G. Lévi, J. Aubard, A. Chevillot-Biraud, C. Mangeney, and N. Felidj, "Multi-functionalization of lithographically designed gold nanodisks by plasmon-mediated reduction of aryl diazonium salts," *Nanoscale Horiz.* **3**, 53–57 (2017).
 31. V.-Q. Nguyen, Y. Ai, P. Martin, and J.-C. Lacroix, "Plasmon-Induced Nanolocalized Reduction of Diazonium Salts," *ACS Omega* **2**, 1947–1955 (2017).
 32. P. Zijlstra, P. M. R. Paulo, K. Yu, Q.-H. Xu, and M. Orrit, "Chemical Interface Damping in Single Gold Nanorods and Its Near Elimination by Tip-Specific Functionalization," *Angew. Chem. Int. Ed.* **124**, 8477–8480 (2012).
 33. D. Ge, S. Marguet, A. Issa, S. Jradi, T. H. Nguyen, M. Nahra, J. Béal, R. Deturche, H. Chen, S. Blaize, J. Plain, C. Fiorini, L. Douillard, O. Soppera, X. Q. Dinh, C. Dang, X. Yang, T. Xu, B. Wei, X. W. Sun, C. Couteau, and R. Bachelot, "Hybrid plasmonic nano-emitters with controlled single quantum emitter positioning on the local excitation field," *Nat. Commun.* **11**, 3414 (2020).

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34. X. Zhou, J. Wenger, F. N. Viscomi, L. Le Cunff, J. Béal, S. Kochtcheev, X. Yang, G. P. Wiederrecht, G. Colas des Francs, A. S. Bisht, S. Jradi, R. Caputo, H. V. Demir, R. D. Schaller, J. Plain, A. Vial, X. W. Sun, and R. Bachelot, "Two-Color Single Hybrid Plasmonic Nanoemitters with Real Time Switchable Dominant Emission Wavelength," *Nano Lett.* **15**, 7458–7466 (2015).
 35. S. Mítiche, S. Marguet, F. Charra, and L. Douillard, "Near-Field Localization of Single Au Cubes: A Group Theory Description," *J. Phys. Chem. C.* **121**, 4517–4523 (2017).
 36. A. Issa, I. Izquierdo, M. Merheb, D. Ge, A. Broussier, N. Ghabri, S. Marguet, C. Couteau, R. Bachelot, and S. Jradi, "One Strategy for Nanoparticle Assembly onto 1D, 2D, and 3D Polymer Micro and Nanostructures," *ACS Appl. Mater. Interfaces* **13**, 41846–41856 (2021).
 37. J. de Torres, P. Ferrand, G. Colas des Francs, and J. Wenger, "Coupling Emitters and Silver Nanowires to Achieve Long-Range Plasmon-Mediated Fluorescence Energy Transfer," *ACS Nano* **10**, 3968–3976 (2016).
 38. C. Deeb, X. Zhou, R. Miller, S. K. Gray, S. Marguet, J. Plain, G. P. Wiederrecht, and R. Bachelot, "Mapping the Electromagnetic Near-Field Enhancements of Gold Nanocubes," *J. Phys. Chem. C* **116**, 24734–24740 (2012).
 39. K. J. Schafer, J. M. Hales, M. Balu, K. D. Belfield, E. W. Van Stryland, and D. J. Hagan, "Two-photon absorption cross-sections of common photoinitiators," *J. Photochem. Photobiol. A* **162**, 497–502 (2004).
 40. C. Deeb, R. Bachelot, J. Plain, A.-L. Baudrion, S. Jradi, A. Bouhelier, O. Soppera, P. K. Jain, L. Huang, C. Ecoffet, L. Balan, and P. Royer, "Quantitative Analysis of Localized Surface Plasmons Based on Molecular Probing," *ACS Nano* **4**, 4579–4586 (2010).
 41. C. Deeb, X. Zhou, J. Plain, G. P. Wiederrecht, R. Bachelot, M. Russell, and P. K. Jain, "Size dependence of the plasmonic near-field measured via single-nanoparticle photoimaging," *J. Phys. Chem. C.* **117**, 10669–10676 (2013).
 42. E. Fišerová and M. Kubala, "Mean fluorescence lifetime and its error," *Journal of Luminescence* **132**, 2059–2064 (2012).
 43. B. Gökbulut and M. N. Inci, "Enhancement of the spontaneous emission rate of Rhodamine 6G molecules coupled into transverse Anderson localized modes in a wedge-type optical waveguide," *Opt. Express, OE* **27**, 15996–16011 (2019).
 44. K. E. Knowles, E. A. McArthur, and E. A. Weiss, "A Multi-Timescale Map of Radiative and Nonradiative Decay Pathways for Excitons in CdSe Quantum Dots," *ACS Nano* **5**, 2026–2035 (2011).
 45. F. M. Gómez-Campos and M. Califano, "Hole Surface Trapping in CdSe Nanocrystals: Dynamics, Rate Fluctuations, and Implications for Blinking," *Nano Lett.* **12**, 4508–4517 (2012).
 46. O. Labeau, P. Tamarat, and B. Lounis, "Temperature Dependence of the Luminescence Lifetime of Single CdSe/ZnS Quantum Dots," *Phys. Rev. Lett.* **90**, 257404 (2003).
 47. P. Spinicelli, S. Buil, X. Quélin, B. Mahler, B. Dubertret, and J.-P. Hermier, "Bright and Grey States in CdSe-CdS Nanocrystals Exhibiting Strongly Reduced Blinking," *Phys. Rev. Lett.* **102**, 136801 (2009).
 48. Y. Peng, S. Jradi, X. Yang, M. Dupont, F. Hamie, X. Q. Dinh, X. W. Sun, T. Xu, and R. Bachelot, "3D Photoluminescent Nanostructures Containing Quantum Dots Fabricated by Two-Photon Polymerization: Influence of Quantum Dots on the Spatial Resolution of Laser Writing," *Advanced Materials Technologies* **4**, 1800522 (2019).
 49. A. Khalid, K. Chung, R. Rajasekharan, D. W. M. Lau, T. J. Karle, B. C. Gibson, and S. Tomljenovic-Hanic, "Lifetime Reduction and Enhanced Emission of Single Photon Color Centers in Nanodiamond via Surrounding Refractive Index Modification," *Sci Rep* **5**, 11179 (2015).
 50. Q. Zhang, G. Li, X. Liu, F. Qian, Y. Li, T. C. Sum, C. M. Lieber, and Q. Xiong, "A room temperature low-threshold ultraviolet plasmonic nanolaser," *Nature Communications* **5**, 4953 (2014).