REVIEW

doi:10.1038/nature10610

Assembly of hybrid photonic architectures from nanophotonic constituents

Oliver Benson[1]

The assembly of hybrid nanophotonic devices from different fundamental photonic entities—such as single molecules, nanocrystals, semiconductor quantum dots, nanowires and metal nanoparticles—can yield functionalities that exceed those of the individual subunits. Combining these photonic elements requires nanometre–scale fabrication precision and potentially involves a material diversity that is incompatible with standard nanotechnological processes. Although merging these different systems on a single hybrid platform is at present challenging, it promises improved performance and novel devices. Particularly rapid progress is seen in the combination of plasmonic–dielectric constituents with quantum emitters that can be assembled on demand into fundamental model systems for future optical elements.

The advancement of modern technology is still driven considerably by miniaturization. Following the path taken in electronics of reducing devices to their ultimately fundamental forms, for instance single-electron transistors[1–3], now magnetic and optical devices have also been scaled down, creating the increasingly active research fields of spintronics[4] and nanophotonics[5].

A fundamental nanophotonic device, involving single elementary excitations such as photons and spins, offers various advantages over a macroscopic object: its state can be controlled, initialized and read out with a precision at the fundamental quantum mechanical limit; its operational fidelity based on the interconversion of single excitations can approach 100%; and its functionality may be based on coherent rather than incoherent dynamics, allowing for devices that maintain quantum coherence, which is a crucial requirement for applications in quantum information processing[6]. Thus, a fundamental device could outperform traditional devices in terms of operation speed, integrability and energy efficiency.

On the fundamental level, a device consists of various coupled and/or integrated entities, such as single emitters, optical microresonators, optical waveguides and photon-to-electron or photon-to-spin interfaces. If different materials systems are involved (for example a combination of organic and inorganic units), then the resulting device might be appropriately described as 'hybrid'. However, this term can also be used in a broader sense when new functionality is gained from a combination of different physical effects. Examples are the fusion of bioassays and micro- or nanoelectromechanical systems[7] and that of microfluidics and optics[8]. A merging of quantum optics and nanomechanics[9], photonics and atomic physics[10], or quantum optics and plasmonics[11] is likely to provide new fundamental insight as well as novel applications such as quantum coherent devices[12] or quantum-limited sensors[13]. For example, a quantum computer, by contrast with its classical counterpart, needs to maintain coherent superpositions of discrete quantum states, acting as so-called quantum bits. A similar challenge occurs in quantum sensors, where exploitation of entangled quantum states allows for improved precision over classical equivalents. Whereas long storage times of quantum states may be possible, for example in atomic systems, fast read-out and information transfer using integrated optics, that is, an atomic–photonic hybrid system, would be desirable. The quantum mechanical decoherence and energy transfer processes in these hybrid systems are, however, not fully understood. This broader class of hybrid system is the topic of this Review, and I place a particular emphasis on model systems combining metallic and dielectric nanophotonic constituents by scanning probe manipulation.

I will begin by highlighting some key nanophotonic functionalities and then briefly introduce several bottom-up approaches for assembling hybrid nanophotonic systems from their fundamental components. As scanning probe techniques at present offer the greatest versatility, the successful application of such techniques for the assembly of hybrid nanophotonic architectures will be covered in most detail. Advanced top-down approaches based on layered composites[14], organic–inorganic synthesis[15], molecular recognition[16] or soft-matter assembly[17] will not be reviewed.

Functionality on the nanoscale

The intrinsic functionality of a nanophotonic device relies on it providing a significant interaction between light and matter. The most fundamental system consists of a single quantum emitter interacting with a single mode of the electromagnetic field, for example inside a microcavity[18]. Strong and efficient confinement of the electromagnetic field greatly enhances the field strengths and, thus, the strength of the interaction. There are basically two ways to confine the light and enhance its field strength: resonant enhancement in dielectric structures where cavity quantum electrodynamics[19] (CQED) effects can be exploited (Box 1), or plasmonic enhancement using metals[20] (Box 2). In a hybrid device, we might even engineer a combination of the two. Examples of desired or desirable functionalities are as follows.

Light guiding and sorting

A key requirement for a nanophotonic platform is for its different subunits, for example light sources, modulators, filters or detectors, to be connected by optical waveguides. This is a well-developed technique in standard light-wave communication networks and integrated optics. However, a nanophotonic circuit requires tighter confinement and low-intensity operation down to the single-photon level[21]. For dielectric systems, a particularly appropriate structure for nanophotonic devices is a photonic crystal[22], in which a periodic modulation of the index of refraction of a dielectric can guide light tightly and control its dispersion. Figure 1b shows such a device (discussed further below): a photonic

[1]Nano-Optik, Humboldt-Universität zu Berlin, Newtonstrasse 15, 12489 Berlin, Germany.

BOX 1

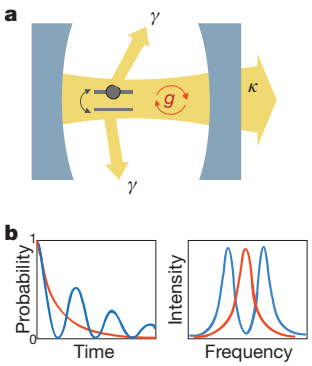
Cavity QED

A typical configuration in which to study CQED[19] is shown in the figure. A single quantum emitter, for example an atom, an ion, a single molecule or a quantum dot, is placed inside a microcavity. Two regimes of the time evolution of the system are distinguished.

In the strong-coupling regime, the dominant process is the coherent interaction between the emitter and a single resonant mode of the microcavity characterized by the coupling constant g. Energy is exchanged between the emitter and the cavity mode in an oscillatory way at the Rabi frequency, $2g$. The energy loss rate through either spontaneous emission from the excited emitter to a continuum of other modes (described by the rate γ) and the photon loss rate through the cavity mirrors (described by the rate κ) is much smaller than the energy exchange rate (γ and κ are both much less than g). The emitter and the field lose their separate identities and have to be described as one coupled system with an own energy-level structure[19]. The coupling constant g is proportional to $1/\sqrt{V}$, where V is the quantization (mode) volume. On the other hand, κ is inversely proportional to the cavity's quality factor Q. The ratio $Q/\sqrt{V}$ should therefore be maximized to reach the strong-coupling regime.

In the weak-coupling regime, the dynamics are incoherent. The coupling constant g is small relative to κ and γ. An excited emitter loses its energy in an exponential decay, but with a decay rate strongly modified relative to an emitter in free space. This is the Purcell effect[94]. The decay is enhanced when the emitter's transition frequency is in resonance with the cavity mode frequency, $\omega = c/\lambda$ (c, speed of light; λ, wavelength), or it may be strongly suppressed. For exact resonance and perfect alignment of the emitter's dipole moment with respect to the cavity field in a medium with refractive index n, the enhancement, or Purcell factor, is $P = (3/4\pi^2)(\lambda/n)^3 Q/V$.

CQED effects were first studied in atomic physics experiments[95], mostly using Fabry–Pérot cavities, but are now widely explored in solid-state systems as well[96].



Box 1 Figure | Basics of CQED. **a**, A typical CQED system consisting of a single quantum emitter (two-level system) coupled coherently, with coupling constant g, to one mode of an optical microcavity. Incoherent processes are spontaneous emission from the emitter to the continuum at rate γ, and photon loss through the cavity mirrors at rate κ. **b**, Time evolution of the excited-state probability and spectrum for the weak-coupling (red) and strong-coupling (blue) regimes.

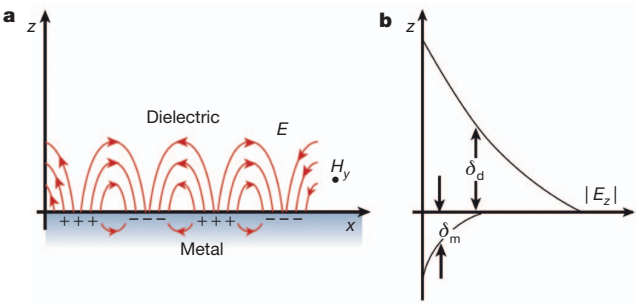
BOX 2

Plasmonic enhancement

Surface plasmon polaritons (SPPs) are electromagnetic excitations propagating at the interface between a dielectric and a conductor[20,24]. They arise from the coupling of electromagnetic fields to oscillations of the conductor's electron plasma. SPPs can be efficiently excited and guided along thin metal strips or wires, called SPP waveguides. Long-range propagation over distances of a few millimetres is possible at telecommunication wavelengths[24]. By comparison with their purely optical counterparts, the narrow spatial confinement to fractions of a free-space optical wavelength makes them ideal building blocks of future chip-based nanophotonic components and devices, although losses in the metal are a challenge. Passive optical elements such as bends, beam splitters and interferometers have been demonstrated[24].

Subwavelength metal particles support localized SPP resonances. With gold or silver, the resonances are in the visible spectral range and have been used for centuries to stain glass. Current applications concern biomarkers or sensors. In addition to a lightning rod effect, that is, the field enhancement near sharp geometrical features, resonances further increase the local electromagnetic field near the metallic surface. Thus, SPPs couple strongly to small particles placed in the near field. One feature is that fluorescence and scattering processes are enhanced by orders of magnitude. A prominent example with a pronounced impact on single-molecule detection is surface enhanced Raman scattering: in experiments on this, enhancement factors of 10^{14} have been observed[97]. Another feature is an increase in the efficiency of nonlinear optical effects for higher-harmonic generation[98] or for low-intensity photonic switches on the single-emitter level[41].

Modern nanofabrication technology makes it possible to fabricate plasmonic structures from the top down. More complex structures such as optical nanoantennae[32] and metallic photonic crystal structures[34], which further improve the performance of plasmonic nanophotonic elements[33], have also been realized.



Box 2 Figure | Basics of surface plasmon polaritons. **a**, An SPP as a collective excitation at a metal–dielectric interface[99]. The electromagnetic field (electric field, E, plotted in the z–x plane; magnetic field, H_y, sketched in the y direction) is drastically enhanced. **b**, The perpendicular field E_z decays exponentially with a characteristic length δ_d (of the order of the optical wavelength) in the dielectric and a characteristic length of δ_m (the skin depth) in the metal.

crystal waveguide guiding light within a thin dielectric film. Frequency-selective elements required, for example, for add–drop elements have also been realized in photonic crystal structures[23].

Whereas the confinement of light in a dielectric structure is ultimately constrained by the diffraction limit, plasmonic waveguides (Box 2) allow concentration of combined electronic and optical excitations (plasmon polaritons) to length scales far below the optical wavelength. Wave guiding is possible along plasmonic wires or along ridges and grooves in thin metal films[24]. A drawback is damping due to losses in the metal, but strategies to combine plasmonic waveguides with gain material in hybrid systems to compensate for losses are being explored[25]. The wavelength-selective transmission of plasmonic nanostructures can also be used for efficient light or photon sorting[26].

Enhanced emission and absorption

In the weak-coupling regime of CQED (Box 1), the Purcell effect can be used to funnel single or a few photons emitted from single emitters such as quantum dots, molecules or colour centres into specific cavity modes with enhanced rate and efficiencies of up to 98% (ref. 27). Efficient coupling to free space or to optical fibres is mandatory for improved

single-photon sources needed in secure quantum cryptography[28] or quantum intensity standards[29]. More-complex nanophotonic elements for these applications also implement funnelling of charge carriers for efficient electrical excitation of single quantum dots (Fig. 1a). The Purcell effect also significantly enhances the transition rate and, thus, the optical response of a device, which is relevant for fast optical modulation or interconnects.

It has been proposed by Chang *et al.*[30] that plasmonic effects will also lead to a strong enhancement of the interaction of single quantum emitters with localized excitations in plasmonic waveguides. A similar effect is exploited when enhancing the optical response of a plasmonic particle to the binding event of a large biomolecule, a technique that is used in plasmonic biosensors[31]. Also, the impedance mismatch between freely propagating light and confined light can be addressed using plasmonic structures. Plasmonic nanoantennas[32] can drastically enhance the emission or absorption rate, whereas periodic metallic nanostructures establish highly directional emission[33] or provide unusual linear properties, such as a negative index of refraction, unavailable in natural materials[34]. These features are of paramount importance for optical outputs or optical interconnects in future nanophotonic systems.

Nonlinear elements and switches

In the strong-coupling regime of CQED, spontaneous emission is negligible relative to the coherent and reversible energy exchange. This exchange is a perfect way to transfer electronic quantum states to photons. In terms of quantum information processing, this establishes an interface between stationary (electronic states) and moving (photons) quantum bits. Also, non-resonant interaction can be used to realize conditional phase shifts of photon states[19]. This is the main functionality required to build an optical quantum computer[35], which in principle could solve problems that no classical computer could[6].

The energy-level structure of a strongly coupled emitter–cavity system (the 'dressed states') is an array of manifolds of increasing energy, each of which corresponds to a discrete excitation of the system. A narrow-band, weak probe beam used to address a strongly coupled system can be on- or off-resonant with respect to the energy difference between two manifolds. In the first case it will be transmitted, but in the second case it will be reflected. As the energy of the manifold depends on the number of photons present in the cavity, the presence or absence of even a single photon can induce transmission (photon-induced tunnelling) or reflection (photon blockade) of the beam[36]. This peculiar effect allows the generation of transmitted light with a non-classical photon statistics[37], and, eventually, the realization of single-photon sources or transistors[36].

Waks and Vučković[38] have shown that a strong nonlinearity can be produced in a cavity–emitter system even if the system is not in the strong-coupling regime. In fact, a single emitter placed inside a cavity add–drop filter can switch on or off the transmission of a coupled waveguide mode as a result of interference effects. This 'dipole-induced transparency' may be used to build a quantum repeater[39], a device that helps to transfer quantum entanglement between two partners. Such a capability would establish fundamentally secure information exchange over arbitrarily large distances. Figure 1b shows a possible experimental configuration for dipole-induced transparency realized using a quantum dot and a photonic crystal structure[40].

In a similar way, a single emitter on a plasmonic waveguide can act as a mirror that can be saturated by only a single excitation. Such an element could be the key ingredient for a single-photon transistor[41] as sketched in Fig. 1d. It could provide the missing nonlinear element for photonic quantum gates, which have so far relied on interference and single-photon detection, for example in integrated photonic circuits[21] and telecommunication fibre systems[42].

A scaling up of fundamental devices will involve two or more elementary entities, for example single emitters, optical resonators or non-resonant optical nanostructures. Configurations may be arranged to act as optical switches, where the state of a single emitter changes the emission frequency of a nearby emitter by means of dipole–dipole interaction[43] (Fig. 1c).

Approaches to nanoassembling hybrid devices

To exploit fundamental interactions in nanophotonic–plasmonic hybrid structures, advanced nanoassembly techniques are required. Various strategies to fabricate fundamental hybrid devices out of different materials and subunits have been demonstrated. Figure 2 summarizes different approaches schematically.

Random assembly

The simplest idea is a random approach by which, for example, different nanoparticles are spin-coated or drop-cast on a substrate (Fig. 2a). By chance, the desired configuration may be found within the ensemble. This approach was used by, for example, Kinkhabwala *et al.*[44], who spin-coated a solution with molecules on a sample with 'bow-tie' plasmonic antennas. Sometimes they found a single molecule well within the

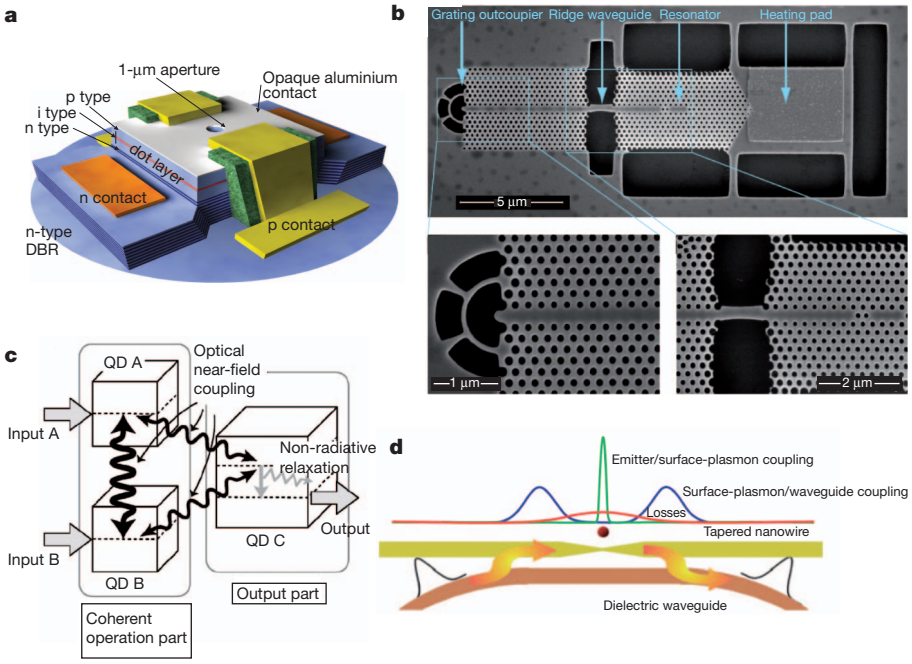


Figure 1 | Nanophotonic functional elements. **a**, Advanced, electrically driven single-photon source: a single semiconductor quantum dot embedded in a light-emitting-diode structure including a distributed Bragg reflector[88] (DBR). **b**, Scanning electron microscopy (SEM) image of an integrated photonic structure to test dipole-induced transparency. The structure includes a grating coupler (left; also shown magnified) and a quantum dot inside a photonic crystal resonator coupled to a photonic crystal waveguide[40] (also shown magnified). **c**, Proposed logic gate based on three near-field-coupled semiconductor quantum dots (QDs) with appropriately aligned energy levels[89]. Depending on the state of two near-field-coupled quantum dots (QD A and QD B, representing two bits) that can be controlled by optical input pulses, resonant energy transfer to a third quantum dot (QD C, serving as output) is possible. **d**, Proposal for a single-photon transistor[41]. A light pulse from a dielectric waveguide is transferred into a plasmon propagating along a tapered metal nanowire. In the tapered region, interaction with even a single emitter is so large that its quantum state state can control the transmission of the pulse.

antenna gap. Such an approach is very inefficient and cannot be scaled up to complex configurations involving three or more constituents[43].

Self-assembly

If there are interactions between the entities (submicrometre particles, large molecules and the like) that are strong enough to overcome thermal diffusion, then self-ordering may lead to deposition of the particles in ordered patterns (Fig. 2b). Van der Waals[45], electrostatic[14] or magnetic[46] interaction may be used to establish self-ordering. For example Min *et al.*[45] describe the formation of cobalt nanoparticle rings and cadmium nanorod superlattices under the influence of magnetic and electrostatic fields, respectively. The advantage of this technique is the control of patterns through modifications of the interactions and the possible fabrication of many configurations in parallel.

Directed self-assembly

Control of spatially ordered structures can be improved by growth or assembly on preprocessed or locally functionalized substrates (Fig. 2c). Etched defects or metal nanoparticles can act as seeds for self-assembled growth of single semiconductor quantum dots[47] or nanowires[48]. Mohan *et al.*[49] used electron beam lithography and etching to fabricate a regular pattern on a GaAs substrate. In this way, pyramidal quantum dots could be grown in a regular array. Also, patterning with chemical[50] markers allows deposition of specific molecules or nanoparticles on predefined sites. Such self-assembly approaches provide spatially well-separated structures that can be addressed individually. Apart from physical defects, local electric, magnetic or optical fields can also create favourable spots for the deposition of particles down to the single-atom level (Fig. 2d).

Select and post-process

This approach relies on the high precision of modern nanofabrication used, for example, for today's metal–oxide semiconductor technology. The approach that I here call 'select and post-process' starts with the fabrication of samples with a random distribution of nano-objects, for example optically active quantum emitters such as quantum dots or nanowires[51]. Subsequently, one object of interest is selected and its relative position on the sample is measured with high precision. Frequently, the substrate is patterned with an array of markers to facilitate this procedure. In a subsequent post-process step, electric contacts, microresonators or other elements are fabricated around or next to the selected object by optical or electron beam lithography (Fig. 2e). Using this technique, a fundamental nanophotonic system consisting of a single semiconductor quantum dot strongly coupled to an optical microresonator (a resonant defect mode in a photonic crystal structure) was realized[52]. As the select and post-process approach starts with a randomly distributed ensemble, it cannot be scaled up to assemble structures with more than one emitter. A possible solution, however, is post-processing of structures with site-controlled emitters[47].

Scanning probes for manual assembly

By comparison with the previously described approach, scanning probes offer the ultimate limit of nanomanipulation, allowing individual constituents to be assembled. First demonstrations with scanning tunnelling microscopes[53] (STMs) and atomic force microscopes[54] (AFMs) showed impressive results in regards to the positioning of single atoms[55] on surfaces.

STM and AFM scanning probes have developed into versatile tools for nanomanipulation and nanoassembly and are particularly useful in assembling hybrid structures. Not only large molecules[56], but also metallic nanoparticles[57] or nanorods[58], semiconductor nanoparticles[59], carbon nanotubes[60] and plastic particles[61], can be manipulated on a large variety of substrates. Modifications of 'dip-pen' nanolithography[62] make it possible to pick up and release nanoparticles in a controlled way[63] (Fig. 2f). Also, optical or scanning electron microscopes can be equipped with triple-axis micromanipulators for simultaneous imaging and manipulation.

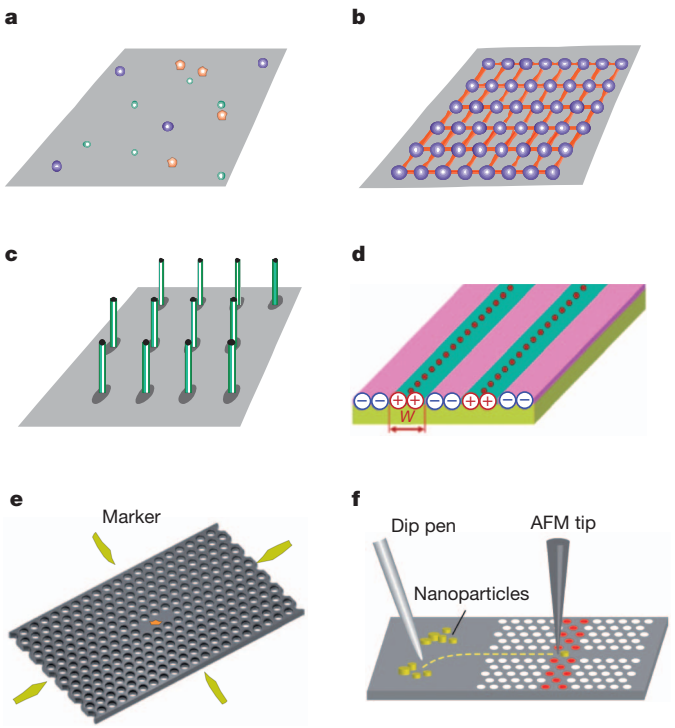


Figure 2 | Different approaches to assembling nanophotonic elements. **a**, Random approach: various particles are deposited randomly. By chance, two particles (here a yellow one and a green one) are close enough to form a coupled pair. **b**, Self-assembly: interparticle interactions, for example electrostatic fields (red lines), mediate a periodic configuration. **c**, Directed self-assembly (seeded growth): nanowires (green) are grown predominately on the prepatterned defects on a substrate. **d**, Directed self-assembly (field-guided assembly): negatively charged particles (red spheres) agglomerate along a positively charged wire pattern (green stripes of width *W*). **e**, Select and post-process: the position of a quantum dot is measured with respect to markers and subsequently a photonic crystal structure (periodic holes) are fabricated. **f**, Scanning probe assembly: particles deposited using a dip pen are precisely positioned with the help of an AFM tip.

Nanophotonic–plasmonic hybrid devices

Among the various approaches to assembling hybrid systems summarized above, scanning probe techniques provide the widest versatility, and so will be the focus of this section. Using such techniques, different configurations can be assembled with the same constituents, allowing a detailed investigation of the constituents' interactions. Furthermore, once assembled, the configurations can be encapsulated to be used as stable nanophotonic units in various applications, such as fibre-coupled single-photon sources[64] for quantum information processing or quantum light standards.

Whereas nanoassembly with scanning probes has been widely used in developing electronic[60], molecular[56] and biomolecular[56] devices, the assembly of nanophotonic elements has reached this point only recently and is still in its early stages. Progress has been hindered by the lack of photostable nanoscopic emitters that allow easy manipulation. At the level of very few or even single emitters under ambient conditions, protection against photobleaching by overgrowth or embedding in films is often required, preventing any additional positioning of the emitters on the substrate. Optically stable emitters appropriate for scanning probe assembly are metallic (plasmonic) nanoparticles[24], semiconductor nanowires[65] or colour centres in diamond nanocrystals[66,67]. Colour centres have particular potential as they represent single quantum emitters even at room temperature[68] (the most widely studied centre is the nitrogen–vacancy centre[66]).

To illustrate the power of scanning probes to assemble nanophotonic hybrid structures in a controlled way, I highlight two examples in more detail.

Plasmonically enhanced single-photon sources

Figure 3 shows a manually assembled, hybrid, single-photon source operating at room temperature[69]. To construct it, appropriate constituents (here metal nanoparticles and diamond nanocrystals) were first isolated and precharacterized. This was done with an AFM (in tapping mode, where only modest interaction with the particles occurs), to map the topology of a larger area, and with subsequent optical investigation, that is, measurements of fluorescence or photon correlations. This investigation provides information about the number of emitters in the particle[70]. This first step is similar to the select and post-process approach described above. However, in a second step active manipulation with an AFM tip (now in contact mode to exert significant force on the particles) was performed and complex configurations were fabricated in a step-by-step procedure (Fig. 3). This is sufficient for a well-defined coupling to plasmons, which requires an accuracy of some tens of an optical wavelength.

In this example, a single nanodiamond containing a single nitrogen–vacancy defect centre was coupled to a single gold particle or sandwiched between two gold particles forming a plasmonic nanoantenna. Plasmonic enhancement (see Box 2 and previous paragraph) leading to an increase in photon yield (number of photons emitted per unit of excitation power) of two orders of magnitude was achieved at room temperature. Even higher values should be possible[44] in a more advanced antenna structure[33], which should also allow directional emission. This excellent coupling of single emitters to plasmonic wires may be used in improved single-photon sources[30] to produce large nonlinearities for the realization of single-photon transistors[41] or to launch single plasmonic excitations into quantum plasmonic circuits.

Nanowire photonic elements

In another example (Fig. 4), various dielectric and plasmonic nanowires were manually assembled to form coupled lasers and waveguides[65]. The end facets of a small semiconductor nanowire can act as optical mirrors forming a Fabry–Pérot-type optical resonator. Optical excitation of the wire's photoluminescence can bring the system above the lasing threshold. In Fig. 4a, two such lasers, respectively made from GaN and ZnO wires, were coupled to a SnO_2 nanoribbon[71]. A triple-axis manipulator with a tungsten probe tip was used to arrange the configuration manually. The SnO_2 nanoribbon acts as an efficient single-mode waveguide to collect and guide the laser light both from the GaN wire and the ZnO wire. Remarkably, the coupling efficiency of laser light into the waveguide approaches 50%, and light can be guided with a loss of $\sim$10 dB cm^{-1}. Optimum coupling is achieved when wire and ribbon are in the 'staggered-bonded configuration', that is, in physical contact over distances of a few micrometres. Simultaneous guiding of light from two (or more) nanolasers establishes the possibility of performing all-nanowire nonlinear wave mixing within single nanocavities. Moreover, the ability to transfer coherent optical pulses over hundreds of micrometres could be applied to shuttle packets of electro-optical information in future computing and communications devices.

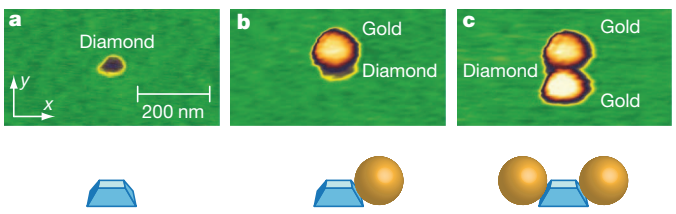


Figure 3 | Stepwise AFM nanoassembly of a plasmonic nanoantenna. a–c, A single nitrogen–vacancy defect centre in a diamond nanocrystal (**a**) is sandwiched between two gold nanoparticles (60 nm in diameter) (**b**, **c**). The sketches (bottom) illustrate the configuration mapped by false-colour AFM imaging (top).

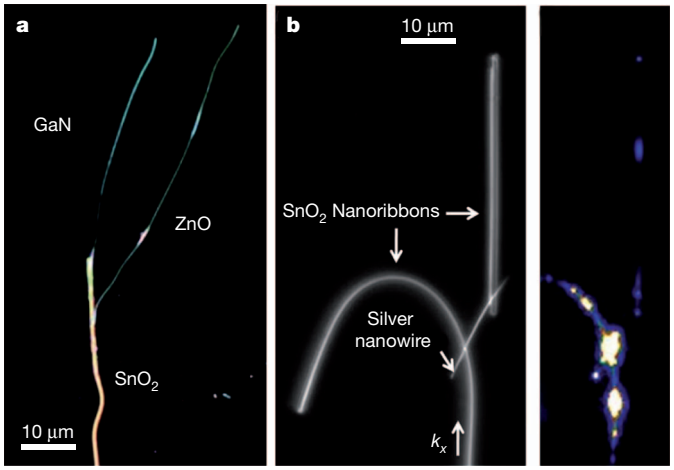


Figure 4 | Nanoassembled photonic–plasmonic wire structures. a, Dark-field image of two nanowire lasers (GaN and ZnO, each $\sim$130 nm in diameter) coupled to a SnO_2 nanoribbon waveguide[71] (with a rectangular cross-section of 240 nm $\times$ 260 nm). **b**, Dark-field (left) and optical (right) images of a hybrid optical–plasmonic routing device consisting of a silver nanowire bridging two SnO_2 nanoribbon waveguides[72]. Excitation light is incident from the bottom of the image (indicated by the arrow labelled k_x).

In Fig. 4b, it is shown how a silver plasmonic nanowire can be used to link two SnO_2 nanoribbon waveguides[72]. A transfer of light can be seen in the optical image. The system represents a hybrid optical–plasmonic routing device that combines the subwavelength confinement of light in a plasmonic structure with low-loss guiding in dielectric waveguides. Efficient integration and connection between plasmonic structures on a nanophotonic circuit can be realized in this way, which is a requirement for the single-photon transistor concept depicted in Fig. 1d. Connection of these structures to the 'outside world' with tapered optical fibres has also been demonstrated[72].

It must be noted that in the example in each of the two previous subsections, a hybrid approach is mandatory. In the first example there is no well-established fabrication technology for the material (advanced photonic structures in diamond), whereas in the second example the required properties of the material (low damping of the silver nanowire) can be established only by chemical synthesis, which is incompatible with lithographic fabrication. Nanomanipulation by means of micromanipulators[73,74] or advanced scanning probe techniques[75] complements the hybrid approach in an ideal way.

Future prospects

So far, several simple nanophotonic hybrid devices have been assembled with scanning probes or micromanipulators. Figure 5 shows some examples additional to those discussed in the previous section. Scaling up to produce more-complex nanophotonic elements in which a small but arbitrary number of emitters are controllably coupled to dielectric or plasmonic nanostructures is in principle straightforward.

A critical outstanding problem is to connect nanophotonic hybrid systems to macroscopic components. Tapered optical fibres[72] or plasmonic antenna structures[32] have proved to be excellent couplers to propagating light in optical waveguides and free beams, respectively, with efficiencies exceeding 90%. A strategy to relax the need for free-beam coupling is to incorporate sources and detectors on the nanophotonic chip itself. Examples of integrated emitters were provided in Figs 3–5 and on-chip detection of single surface plasmons was demonstrated recently[76].

It has to be mentioned that manual assembly with scanning probes has its own flaws. Emitters in solid-state matrices show an inhomogeneous broadening, with the result that in nanophotonic elements exploiting resonances, individual tuning of the emission frequency of each emitter is required. However, techniques for such individual tuning have been developed[77]. Also, emitters embedded in very small carrier particles, for example defect centres in diamond nanocrystals, often show spectral

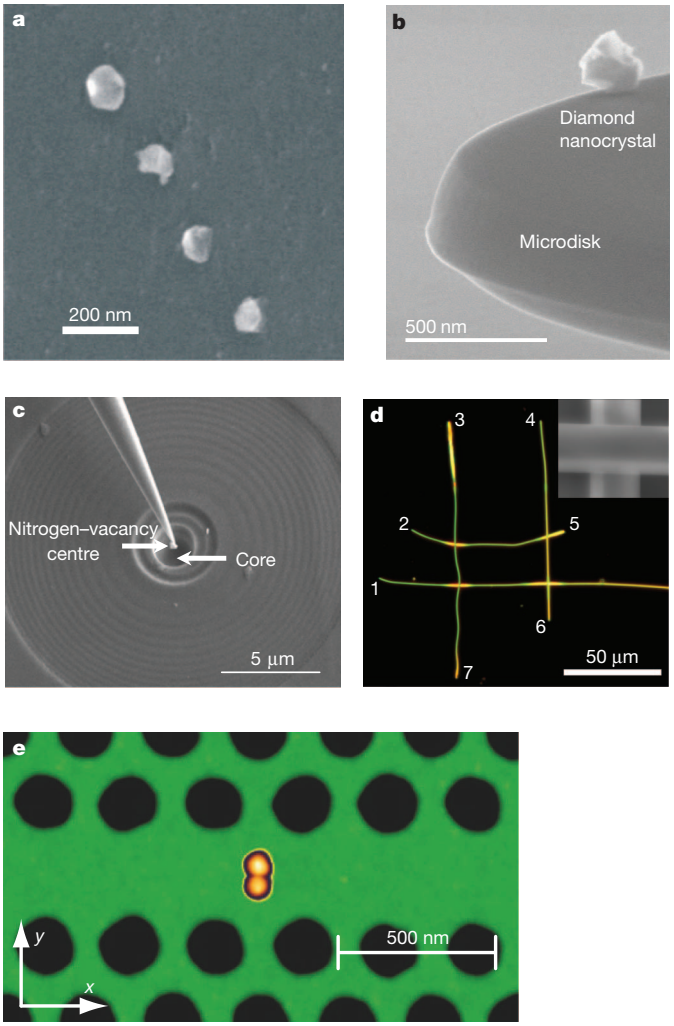


Figure 5 | Different systems assembled using scanning probes. **a**, SEM image of four nanodiamonds arranged in a linear chain[90]. **b**, SEM image of single nanodiamond, containing nitrogen–vacancy centres, placed on the rim of a SiO_2 microdisk resonator[91]. **c**, SEM image of a nanodiamond at the end of a nanomanipulator positioned on the end facet near the core region of an optical fibre[92]. With this set-up, fluorescence from the nitrogen–vacancy centre is coupled directly into the optical fibre[64]. **d**, Dark-field image SnO_2 nanoribbon grid[71]. Inset, scanning electron image of the junction at the lower right vertex. **e**, False-colour AFM image of two gold nanoparticles assembled to form a plasmonic nanoantenna on a photonic crystal heterostructure cavity etched into a thin Si_3N_4 membrane[93]

diffusion, blinking and linewidth broadening[78]. Furthermore, assembling a nanophotonic structure one constituent at a time with a precision of only a few nanometres is instructive for fundamental research and in proof-of-principle experiments, but it is not acceptable as a method of production of devices on a larger scale. However, the successful operation of the first nanophotonic hybrid model systems has motivated efforts to modify or improve established fabrication methods. For example, electron beam and optical lithography have been used to fabricate photonic crystal structures in materials in which this has not previously been possible (for example diamond[79] and GaP[80]), to develop plasmonic structures with reduced damping[81] and to realize integrated optical circuits for optical quantum technology[82]. Another approach is to combine different techniques with the goal of surpassing their individual limitations. One example of this is ion implantation through a perforated atomic force cantilever, which simultaneously provides nanometre spatial resolution and single-dopant operation[83].

The first key functionalities have been successfully demonstrated in hybrid photonic architectures assembled from fundamental nanophotonic constituents. Single photons can be generated, routed, detected and interconverted into other fundamental excitations such as single surface plasmons. Also, nonlinear interactions facilitating logical operations are feasible using CQED or plasmonic effects. There is great potential to establish additional functionality in a hybrid approach by combining optical, magnetic and electrical interactions. First steps towards nanomagnetometry[84], surface plasmon lasers[85], organic plasmon-emitting diodes[86] and single-molecule or single-photon transistors[87] have been taken.

Most of the systems realized so far represent model systems, but a remarkable level of complexity has already been reached. These manually assembled photonic architectures are an exciting test area in which to develop ideas for new functionalities in future nanophotonic hybrid elements.

1. Pothier, H. *et al.* Single electron pump fabricated with ultrasmall normal tunnel-junctions. *Physica B* **169,** 573–574 (1991).
2. Likharev, K. K. Single-electron devices and their applications. *Proc. IEEE* **87,** 606–632 (1999).
3. Klein, D. L., Roth, R., Lim, A. K. L., Alivisatos, A. P., & McEuen, P. L. A single-electron transistor made from a cadmium selenide nanocrystal. *Nature* **389,** 699–701 (1997).
4. Dietl, T., Awschalom, D. D., Kaminska, M. & Ohno, H. (eds) *Spintronics* (Semiconductors and Semimetals 82, Elsevier, 2008).
5. Prasad, P. N. *Nanophotonics* (Wiley, 2004).
6. Nielsen, M. A. & Chuang, I. L. *Quantum Computation and Quantum Information* (Cambridge Univ. Press, 2000).
7. Huang, T. J. Recent developments in artificial molecular-machine-based active nanomaterials and nanosystems. *MRS Bull.* **33,** 226–231 (2008).
8. Psaltis, D., Quake, S. R. & Yang, C. Developing optofluidic technology through the fusion of microfluidics and optics. *Nature* **442,** 381–386 (2006).
9. Kippenberg, T. J. & Vahala, K. J. Cavity opto-mechanics. *Opt. Express* **15,** 17172–17205 (2007).
10. Folman, R., Krueger, P., Schmiedmayer, J., Denschlag, J. & Henkel, C. Microscopic atom optics: from wires to an atom chip. *Adv. At. Mol. Opt. Phys.* **48,** 263–356 (2002).
11. Akimov, A. V. *et al.* Generation of single optical plasmons in metallic nanowires coupled to quantum dots. *Nature* **450,** 402–406 (2007).
12. Cirac, J. I. & Zoller, P. A. A scalable quantum computer with ions in an array of microtraps. *Nature* **404,** 579–581 (2000).
13. Arcizet, O. *et al.* High-sensitivity optical monitoring of a micromechanical resonator with a quantum-limited optomechanical sensor. *Phys. Rev. Lett.* **97,** 133601 (2006).
14. Decher, G. & Schlenoff, J. B. (eds) *Multilayer Thin Films: Sequential Assembly of Nanocomposite Materials* (Wiley, 2003).
15. Yin, Y. & Alivisatos, P. Colloidal nanocrystal synthesis and the organic–inorganic interface. *Nature* **437,** 664–670 (2005).
16. Park, S. Y. *et al.* DNA-programmable nanoparticle crystallization. *Nature* **451,** 553–556 (2008).
17. You, C.-C., Verma, A. & Rotello, V. M. Engineering the nanoparticle-biomacromolecule interface. *Soft Matter* **2,** 190–204 (2006).
18. Vahala, K. J. Optical microcavities. *Nature* **424,** 839–846 (2003).
19. Berman, P. R. (ed.) *Cavity Quantum Electrodynamics* (Academic, 1993).
20. Maier, S. A. *Plasmonics: Fundamentals and Applications* (Springer, 2007).
21. Politi, A., Cryan, M. J., Rarity, J. G., Yu, S. & O'Brien, J. L. Silica-on-silicon waveguide quantum circuits. *Science* **320,** 646–649 (2008).
22. Joannopoulos, J. D. in *Photonic Crystals: Molding the Flow of Light* (Meade, R. D. & Winn, J. N.) (Princeton Univ. Press, 1995).
23. Song, B.-S., Noda, S. & Asano, T. Photonic devices based on in-plane hetero photonic crystals. *Science* **300,** 1537 (2003).
24. Bozhevolnyi, S. & García-Vidal, F. Focus on plasmonics. *N. J. Phys.* **10,** 105001 (2008).
25. Vasa, P. *et al.* Coherent exciton-surface-plasmon-polariton interaction in hybrid metal-semiconductor nanostructures. *Phys. Rev. Lett.* **101,** 116801 (2008).
26. Laux, E., Genet, C., Skauli, T. & Ebbesen, T. W. Plasmonic photon sorters for spectral and polarimetric imaging. *Nature Photon.* **2,** 161–164 (2008).
27. Englund, D., Faraon, A., Zhang, B., Yamamoto, Y. & Vuckovic, J. Generation and transfer of single photons on a photonic crystal chip. *Opt. Express* **15,** 5550–5558 (2007).
28. Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum cryptography. *Rev. Mod. Phys.* **74,** 145–195 (2002).
29. Grangier, P., Sanders, B. & Vuckovic, J. (eds) Focus on single photons on demand. *N. J. Phys.* **6** (2004).
30. Chang, D. E., Sørensen, A. S., Hemmer, P. A. & Lukin, M. D. Quantum optics with surface plasmons. *Phys. Rev. Lett.* **97,** 053002 (2006).
31. Anker, J. N. *et al.* Biosensing with plasmonic nanosensors. *Nature Mater.* **7,** 442–453 (2008).
32. Moerland, R. J., Taminiau, T. H., Novotny, L., van Hulst, N. F. & Kuipers, L. Reversible polarization control of single photon emission. *Nano Lett.* **8,** 606–610 (2008).
33. Curto, A. G. *et al.* Unidirectional emission of a quantum dot coupled to a nanoantenna. *Science* **329,** 930–933 (2010).
34. Smith, D. R., Pendry, J. B. & Wiltshire, M. C. K. Metamaterials and negative refractive index. *Science* **305,** 788–792 (2004).

35. Hofmann, H. F. & Takeuchi, S. Quantum phase gate for photonic qubits using only beam splitters and postselection. *Phys. Rev. A* **66,** 024308 (2002).
36. Imamoğlu, A., Schmidt, H., Woods, G. & Deutsch, M. Strongly interacting photons in a nonlinear cavity. *Phys. Rev. Lett.* **79,** 1467–1470 (1997).
37. Faraon, A. *et al.* Coherent generation of non-classical light on a chip via photon-induced tunnelling and blockade. *Nature Phys.* **4,** 859–863 (2008).
38. Waks, E. & Vučković, J. Dipole induced transparency in drop-filter cavity-waveguide systems. *Phys. Rev. Lett.* **96,** 153601 (2006).
39. Briegel, H. J., Dür, W., Cirac, I. & Zoller, P. Quantum repeaters: the role of imperfect local operations in quantum communication. *Phys. Rev. Lett.* **81,** 5932–5935 (1998).
40. Faraon, A. *et al.* Dipole induced transparency in waveguide coupled photonic crystal cavities. *Opt. Express* **16,** 12154–12162 (2008).
41. Chang, D. E., Sørensen, A. S., Demler, E. A. & Lukin, M. D. A single-photon transistor using nanoscale surface plasmons. *Nature Phys.* **3,** 807–812 (2007).
This paper put forward a proposal for a single-photon transistor using plasmons.
42. Chen, J. *et al.* Demonstration of a quantum controlled-NOT gate in the telecommunications band. *Phys. Rev. Lett.* **100,** 133603 (2008).
43. Sangu, S., Kobayashi, K., Shojiguchi, A. & Ohtsu, M. Logic and functional operations using a near-field optically coupled quantum-dot system. *Phys. Rev. B* **69,** 115334 (2004).
44. Kinkhabwala, A. *et al.* Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna. *Nature Photon.* **3,** 654–657 (2009).
This paper reported the enhancement of emission from single molecules coupled to a plasmonic antenna.
45. Min, Y., Akbulut, M., Kristiansen, K., Golan, Y. & Israelachvili, J. The role of interparticle and external forces in nanoparticle assembly. *Nature Mater.* **7,** 527–538 (2008).
46. Erb, R. M., Son, H. S., Samanta, B., Rotello, V. M. & Yellen, B. B. Magnetic assembly of colloidal superstructures with multipole symmetry. *Nature* **457,** 999–1002 (2009).
47. Sünner, T. *et al.* Scalable fabrication of optical resonators with embedded site-controlled quantum dots. *Opt. Lett.* **33,** 1759–1761 (2008).
48. Fan, H. J., Werner, P. & Zacharias, M. Semiconductor nanowires: from self-organization to patterned growth. *Small* **2,** 700–717 (2006).
49. Mohan, A. *et al.* Polarization-entangled photons produced with high-symmetry site-controlled quantum dots. *Nature Photon.* **4,** 302–306 (2010).
50. Jonas, U., del Campo, A., Krüger, C., Glasser, G. & Boos, D. Colloidal assemblies on patterned silane layers. *Proc. Natl Acad. Sci. USA* **99,** 5034–5039 (2002).
51. Park, H. G. *et al.* Wavelength-selective photonic-crystal waveguide coupled to a nanowire light source. *Nature Photon.* **2,** 622–626 (2008).
This paper reported a photonic structure using active semiconductor nanowires to light up photonic crystal waveguides.
52. Hennessy, K. *et al.* Quantum nature of a strongly coupled single quantum dot-cavity system. *Nature* **445,** 896–899 (2007).
53. Binnig, G., Rohrer, H., Gerber, Ch. & Weibel, E. Surface studies by scanning tunneling microscopy. *Phys. Rev. Lett.* **49,** 57–61 (1982).
54. Binnig, G., Quate, C. F. & Gerber, Ch. Atomic force microscope. *Phys. Rev. Lett.* **56,** 930–933 (1986).
55. Eigler, D. M. & Schweizer, E. K. Positioning single atoms with a scanning tunnelling microscope. *Nature* **344,** 524–526 (1990).
56. Kufer, S. K., Puchner, E. M., Gumpp, H., Liedl, T. & Gaub, H. E. Single-molecule cut-and-paste surface assembly. *Science* **319,** 594–596 (2008).
57. Tong, L., Zhu, T. & Liu, Z. Atomic force microscope manipulation of gold nanoparticles for controlled Raman enhancement. *Appl. Phys. Lett.* **92,** 023109 (2008).
58. Hsieh, S. *et al.* Imaging and manipulation of gold nanorods with an atomic force microscope. *J. Phys. Chem. B* **106,** 231–234 (2002).
59. Junno, T., Deppert, K., Montelius, L. & Samuelson, L. Controlled manipulation of nanoparticles with an atomic-force microscope. *Appl. Phys. Lett.* **66,** 3627–3629 (1995).
60. Thelander, C. & Samuelson, L. AFM manipulation of carbon nanotubes: realization of ultra-fine nanoelectrodes. *Nanotechnology* **13,** 108–113 (2002).
61. Harel, E., Meltzer, S. E., Requicha, A. A. G., Thompson, M. E. & Koel, B. E. Fabrication of polystyrene latex nanostructures by nanomanipulation and thermal processing. *Nano Lett.* **5,** 2624–2629 (2005).
62. Salaita, K., Wang, Y. & Mirkin, C. A. Applications of dip-pen nanolithography. *Nature Nanotechnol.* **2,** 145–155 (2007).
63. Wang, Y., Zhang, Y., Li, B., Lü, J. & Hu, J. Capturing and depositing one nanoobject at a time: single particle dip-pen nanolithography. *Appl. Phys. Lett.* **90,** 133102 (2007).
64. Schröder, T. *et al.* Fiber-integrated diamond-based single photon source. *Nano Lett.* **11,** 198–202 (2011).
65. Yan, R., Gargas, D. & Yang, P. Nanowire photonics. *Nature Photon.* **3,** 569–576 (2009).
66. Jelezko, F. & Wrachtrup, J. Single defect centres in diamond: a review. *Phys. Status Solidi A* **203,** 3207–3225 (2006).
67. Prawer, S. & Greentree, A. D. Applied physics - diamond for quantum computing. *Science* **320,** 1601–1602 (2008).
68. Kurtsiefer, C., Mayer, S., Zarda, P. & Weinfurter, H. Stable solid-state source of single photons. *Phys. Rev. Lett.* **85,** 290–293 (2000).
69. Schietinger, S., Barth, M., Aichele, T. & Benson, O. Plasmon-enhanced single photon emission from a nano-assembled metal-diamond hybrid structure at room-temperature. *Nano Lett.* **9,** 1694–1698 (2009).
This paper reported plasmon-enhanced emission of single photons from a single defect centre.
70. Sonnefraud, Y. *et al.* Diamond nanocrystals hosting single nitrogen-vacancy color centers sorted by photon-correlation near-field microscopy. *Opt. Lett.* **33,** 611–613 (2008).
71. Sirbuly, D. J. *et al.* Optical routing and sensing with nanowire assemblies. *Proc. Natl Acad. Sci. USA* **102,** 7800–7805 (2005).
72. Yan, R., Pausauskie, P., Huang, J. & Yang, P. Direct photonic-plasmonic coupling and routing in single nanowires. *Proc. Natl Acad. Sci. USA* **106,** 21045–21050 (2009).
This paper reported the excitation of plasmons by connecting silver nanowires to an active SnO_2 nanoribbon.
73. van der Sar, T. *et al.* Deterministic nanoassembly of a coupled quantum emitter–photonic crystal cavity system. *Appl. Phys. Lett.* **98,** 193103 (2011).
74. Englund, D. Deterministic coupling of a single nitrogen vacancy center to a photonic crystal cavity. *Nano Lett.* **10,** 3922–3926 (2010).
75. Wolters, J. *et al.* Enhancement of the zero phonon line emission from a single nitrogen vacancy center in a nanodiamond via coupling to a photonic crystal cavity. *Appl. Phys. Lett.* **97,** 141108 (2010).
76. Falk, A. L. *et al.* Near-field electrical detection of optical plasmons and single-plasmon sources. *Nature Phys.* **5,** 475–479 (2009).
This paper reported all-electrical plasmon detection using a field-effect transistor.
77. Hennessy, K. *et al.* Tuning photonic crystal nanocavity modes by wet chemical digital etching. *Appl. Phys. Lett.* **87,** 021108 (2005).
78. Shen, Y., Sweeney, T. M. & Wang, H. Zero-phonon linewidth of single nitrogen vacancy centers in diamond nanocrystals. *Phys. Rev. B* **77,** 033201 (2008).
79. Wang, C. F. *et al.* Fabrication and characterization of two-dimensional photonic crystal microcavities in nanocrystalline diamond. *Appl. Phys. Lett.* **91,** 201112 (2007).
80. Rivoire, K. *et al.* Lithographic positioning of fluorescent molecules on high-*Q* photonic crystal cavities. *Appl. Phys. Lett.* **95,** 123113 (2009).
81. Nagpal, P., Lindquist, N. C., Oh, S.-H. & Norris, D. J. Ultrasmooth patterned metals for plasmonics and metamaterials. *Science* **325,** 594–597 (2009).
82. O'Brien, J., Furusawa, A. & Vučković, J. Photonic quantum technologies. *Nature Photon.* **3,** 687–695 (2009).
This paper reviewed integrated quantum technologies based on optical chips and single photons.
83. Meijer, J. *et al.* Towards the implanting of ions and positioning of nanoparticles with nm spatial resolution. *Appl. Phys. A* **91,** 567–571 (2008).
84. Balasubramanian, G. *et al.* Nanoscale imaging magnetometry with diamond spins under ambient conditions. *Nature* **455,** 648–651 (2008).
85. Noginov, M. A. *et al.* Demonstration of a spaser-based nanolaser. *Nature* **460,** 1110–1112 (2009).
This paper reported the observation of spaser activity from a gold nanoparticle surrounded by a dye-doped silica shell.
86. Koller, D. M. *et al.* Organic plasmon-emitting diode. *Nature Photon.* **2,** 684–687 (2008).
This paper reported electrical excitation of plasmons through coupling to an organic light-emitting-diode structure.
87. Hwang, J. *et al.* A single-molecule optical transistor. *Nature* **460,** 76–80 (2009).
88. Bennett, A. J. *et al.* Microcavity single-photon-emitting diode. *Appl. Phys. Lett.* **86,** 181102 (2005).
89. Sangu, S., Kobayashi, K., Shojiguchi, A. & Ohtsu, M. Logic and functional operations using a near-field optically coupled quantum-dot system. *Phys. Rev. B* **69,** 115334 (2004).
90. van der Sar, T. *et al.* Nanopositioning of a diamond nanocrystal containing a single nitrogen-vacancy defect center. *Appl. Phys. Lett.* **94,** 173104 (2009).
91. Barclay, P. E., Santori, C., Fu, K.-M., Beausoleil, R. G. & Painter, O. Coherent interference effects in a nano-assembled optical cavity-QED system. *Opt. Express* **17,** 8081–8097 (2009).
92. Ampem-Lassen, E. *et al.* Nano-manipulation of diamond-based single photon sources. *Opt. Express* **17,** 11287–11294 (2009).
93. Barth, M. *et al.* Nanoassembled plasmonic-photonic hybrid cavity for tailored light-matter coupling. *Nano Lett.* **10,** 891–895 (2010).
This paper reported Fano-type resonances in a coupled system consisting of a photonic crystal cavity and gold nanoparticles.
94. Purcell, E. M. Spontaneous emission probabilities at radio frequencies. *Phys. Rev.* **69,** 681 (1946).
95. Raimond, J. M., Brune, M. & Haroche, S. Manipulating quantum entanglement with atoms and photons in a cavity. *Rev. Mod. Phys.* **73,** 565–582 (2001).
96. Yoshie, T. *et al.* Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity. *Nature* **432,** 200–203 (2004).
97. Kneipp, K. *et al.* Single molecule detection using surface-enhanced Raman scattering (SERS). *Phys. Rev. Lett.* **78,** 1667–1670 (1997).
98. Lippitz, M., van Dijk, M. A. & Orrit, M. Third-harmonic generation from single gold nanoparticles. *Nano Lett.* **5,** 799–802 (2005).
99. Barnes, W. L., Dereux, A. & Ebbesen, T. W. Surface plasmon subwavelength optics. *Nature* **424,** 824–830 (2003).

Acknowledgements I acknowledge financial supported by the Deutsche Forschungsgemeinschaft (BE2224/9, Sfb 951) and the Bundesministerium für Bildung und Forschung (KEPHOSI).

Author Information Reprints and permissions information is available at www.nature.com/reprints. The author declares no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence should be addressed to the author (oliver.benson@physik.hu-berlin.de).