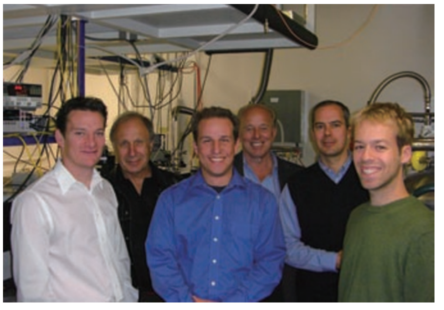
One by one

Whatever format future quantum information systems take, they are likely to involve single photons in some way. *Nature Photonics* spoke to Stefan Strauf at the Stevens Institute of Technology about getting the most out of quantum dots.

What makes for a good source of single photons?
The traditional approach to generating single photons is to use weak laser pulses. To reach the single-photon level, you have to attenuate the light very strongly, limiting the efficiency of the device. Also, the photons emitted are governed by statistics. What we need is a high-efficiency source where we can generate photons one by one. Luckily, nature provides a solution in the form of the two-level system, just like the one we use: self-assembled quantum dots.

In your work, the quantum dots are in an optical microcavity. Why does this help?
The very high refractive index of most semiconductors means that light doesn't want to get out; it is trapped by total internal reflection. The cavity funnels the light in a very narrow output mode, an entirely geometrical collection-enhancement effect. A second phenomenon is the Purcell effect. When the quantum-dot emission is spatially and spectrally resonant with the cavity mode, the single-photon emission is increased, in our case by a factor of two to five.

You have taken an unusual approach to cavity design. Why is that?
One common cavity design is the micropillar, created by etching through alternating layers of semiconductor to form a cylindrical structure with a diameter of one micrometre or less. Unfortunately the etching results in rough sidewalls that scatter light, which limits the time that the cavity contains a photon — as quantified by the *Q*-factor. So we thought, why not have a large device and confine the mode a different way? At the University of California, Santa Barbara, where this research was performed, we built on extensive expertise in confining oxide-tapers, which are used at present inside vertical-cavity lasers. In our single-photon sources such an oxide taper narrows down the optical-mode volume but does not introduce the scattering losses, giving a *Q*-factor as high as 50,000. The larger devices also have the advantage that they are not as brittle as the pillars, making them more practical, and allowing us to attach electrical contacts.



The team in their lab at the Stevens Institute of Technology.

And electrical contacts enable you to control the single-photon states?
The modes in these cavities can be degenerate or, by cavity design, they can be split into modes of different polarization with energies separated by about 100 μeV. The electrical contacts allow us to tune the quantum-dot emission to one mode or the other, enabling control of the polarization of the single photons.

How does your design achieve single-photon generation at such rapid rates?
You would expect that the rate at which single photons can be created is ultimately limited by the lifetime of the dot's excited state. This is about 1 ns or 100 ps, which corresponds to a generation rate in the gigahertz range. But these rates have never been seen in any real-world experiments. One of the limitations is that electrons and holes, when captured, form excitons with a total spin of either one or two. If it is one, then the exciton can couple to the optical field and recombine. But if the total spin is two, then you have a problem: your single-photon source cannot fire. So you want to avoid these so-called dark states from forming. And you can do this by preloading the quantum dots with a single electron. This way, after the capture of an electron–hole pair, there are two electrons, which must have opposite spin owing to the Pauli principle. This means that the electron always finds a bright recombination path. This electron loading could be achieved by doping the semiconductor material to the right level. However, we have chosen to use electrical gates. Basically, we have a tunnelling barrier separating the dots from an electron reservoir. We can then play with the gate voltage to bring the electrons into the quantum dots. This enables us to measure five million single-photons per second, corresponding to a net single-photon generation rate of 100 MHz.

How do you make such sources useful for real applications?
We have been amazed by how many single photons we can get out of these structures. But the start-up companies trying to make practical quantum-cryptography systems are not getting excited yet because these structures have some practical limitations. The current structures operate at a wavelength of 900 nm and at cryogenic temperatures, but in the real world you want to work at room temperature, at telecommunication wavelengths, and with electrical injection. It has already been shown that larger quantum dots, based on the same InGaAs material that we use, can achieve these goals, which is encouraging. When I started in this field five years ago, we were working on individual atoms inside a semiconductor structure. Back then it took us eight hours to record a single-photon signature. With our new sources, the same signature can be measured on a millisecond timescale. I think this is amazing and shows how quickly these sources are developing.

Interview by David Gevaux.

Stefan Strauf and his co-workers have a letter on single-photon sources on p704 of this issue.