

Quantum wells sandwiched tightly between two mirrors can be used to make a new type of laser that can amplify light more than any other known material

Semiconductor microcavities: half light, half matter

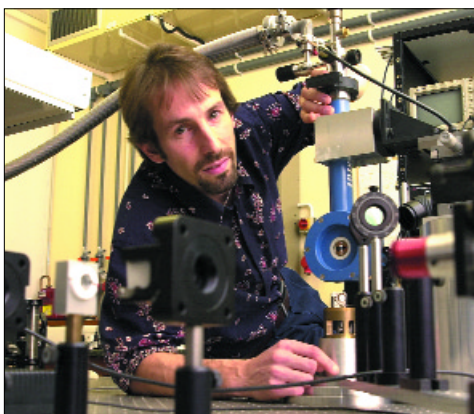
Jeremy J Baumberg

WHAT do you get if you cross light with matter? It is a question that fascinates today's researchers in quantum optoelectronics, who want to see how far the physical states of the world can be intertwined. Although we have a good understanding of the quantum ingredients of optics and solids – photons and atoms – it turns out that assembling these building blocks in deliberately unfamiliar ways can lead to what is new and often quite unexpected behaviour.

Consider “quantum wells”, which form the basis of modern semiconductor lasers. First developed in the 1980s, they lie at the heart of optical-communication and optical-storage technologies such as DVD players and they now have a global market of over £10bn. Quantum wells consist of a thin sheet of crystalline semiconductor sandwiched between two sheets of another semiconductor. The outer layers squash the wavefunctions of electrons within the central sheet, increasing the electrons' energy and their interaction with light. Engineers can control the colour of the light emitted by the laser simply by adjusting the energy levels within the central sheet, which acts as a potential well.

But this bug-sized playground for electrons has not just had technological ramifications. It has also spawned an enormous variety of new physics, including the quantum Hall effect, which can be used as a fundamental standard for measuring the ratio between the charge on the electron and the Planck constant. Over the last ten years researchers have also become increasingly keen to incorporate quantum wells into what are known as “semiconductor microcavities”.

Physicists have found that these painstakingly layered materials can be used to create new quantum states that resemble superfluids and can be used in interferometric quantum devices. Semiconductor microcavities could one day even be used as a new type of ultra-efficient light emitter for optoelectronic interconnects or quantum processors. Firms such as Hitachi and Toshiba are interested in semiconductor microcavities as part of their philosophy that adopting new physical



Bright things – Jeremy Baumberg and his group at the University of Southampton have found that “polariton emitters” can offer huge amplifications.

principles will help them to build future generations of devices and so secure long-term competitive advantages.

Polaritons: part light, part matter

Semiconductor microcavities are basically quantum wells sandwiched between two multi-layer semiconductor mirrors that reflect light with an efficiency of over 99% (figure 1). Any light entering the cavity containing the quantum wells is therefore trapped inside, provided that its wavelength is twice the thickness of the cavity. The light bounces back and forth between the mirrors, with only a tiny fraction (less than 0.1%) leaking through the

mirrors at each bounce.

This ability to trap photons (because of the multi-layer mirrors) and electrons (because of the potential well) forms the basis of vertical-cavity surface-emitting lasers, or VCSELs, which are examples of semiconductor microcavities. Unlike ordinary semiconductor lasers, VCSELs emit radiation perpendicular to the layers. They are also very efficient and need only a tiny amount of power to switch on. These advantages explain why global sales of VCSELs are expected to exceed £1bn by the end of the decade. Now recent research into semiconductor microcavities has revealed that radically new physics can be harnessed to enhance optical emission from semiconductors still further.

So how do semiconductor microcavities work? In general, when a semiconductor quantum well is exposed to light, it only absorbs photons of a certain energy. Some photons with just the right energy can excite an electron from the well's lower-energy valence band to its higher-energy conduction band, leaving behind a “hole” that is positively charged. The excited electron and hole attract each other electrostatically, adopting an orbit similar to that of the electron and proton in a hydrogen atom. This stable composite particle, known as an “exciton”, can only move in the plane of the quantum well.

Excitons are like artificial atoms, except that they are about 100 times larger and interact with light about 100 times more strongly. But because excitons are also about 100 times more

weakly bound than atoms, they are also very fragile. Their presence in a quantum well can be easily spotted using a spectrophotometer. The absorption spectrum reveals a line very close to the energy of the band gap: the line sharpens as the temperature drops below 100 K.

When a quantum well is part of a semiconductor microcavity, however, the excitons decay into photons that repeatedly circulate around until they are reabsorbed by the quantum well. Indeed, the interconversion between light and matter can be so strong that energy cycles between excitons and photons faster than light can leak out of the mirrors or scatter off other particles in the semiconductor. In this regime, which is known as “strong coupling”, it is no longer possible to say if the energy is stored as part of the matter (i.e. the excitons) or in the light (i.e. the cavity photons).

These mixed semiconductor quasi-particles are called “polaritons”. Part light, part matter, they possess new properties that are not seen in either excitons or photons. In fact, combining an exciton – which has about 10% of the mass of an electron – with a massless photon produces either a high-energy “upper polariton” (UP) or a low-energy “lower polariton” (LP). The two polaritons, which are both composed of half an exciton and half a photon, are equally spaced either side of their mean energy. It is rather like crossing an elephant (the exciton) with a river (the photon). The composite “aqua-elephant” has a lower energy if the elephant is going with the flow and a higher energy if it is swimming against the flow.

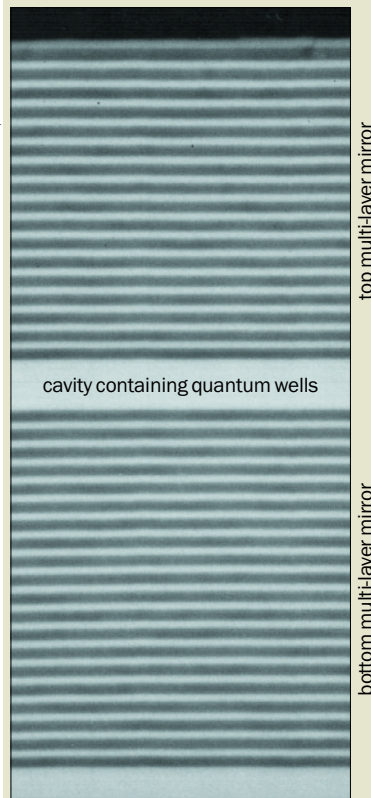
This strong-coupling regime, which indicates that polaritons have been produced, was first observed in 1991 by Claude Weisbuch, Yasu Arakawa and colleagues at the Research Center for Advanced Science and Technology at the University of Tokyo in Japan. They repeatedly saw a sample absorbing two separate components of light at different wavelengths, rather than one.

Origin of polaritons

It is relatively easy to study quantum-well polaritons. After they are excited by a laser, they decay into photons or excitons. The photons will occasionally leak out through the imperfect mirrors of the semiconductor cavity, and can be detected using a spectrometer (figure 2a). Usefully, there is a direct link between the angle, θ , at which the photons leave the sample and the momentum of the polaritons, p , in the plane of the cavity. Measuring the photons’ wavelength (and hence energy) as a function of angle (and hence momentum) therefore provides information about the mass of the polaritons.

Romuald Houdre, Claude Weisbuch and co-workers at the Ecole Polytechnique Fédérale de Lausanne (EPFL) – as well as Maurice Skolnick and co-workers at Sheffield University in

1 Inside a microcavity



A cross section through a semiconductor microcavity. It consists of two multi-layer mirrors surrounding a central cavity 250 nm thick containing six quantum wells. The mirrors are made of alternating sheets of gallium arsenide and aluminium gallium arsenide, while the quantum wells consist of a thin layer of indium gallium arsenide sandwiched between gallium arsenide – all laid down in near-perfect atomic layers.

the UK – have all carried out such experiments. They have found that the energy of the photons emitted by lower polaritons in a microcavity increases with angle, before levelling off above 30° (figure 2b). This energy profile shows that although the polariton is half an exciton, its effective mass – which is proportional to the inverse of the curvature of this angle dependence – is actually less than 1/1000th that of the exciton.

So what controls the wavelength of the photons that the cavity emits? Bouncing back and forth between the mirrors, most of the photons interfere destructively with themselves. Only photons of a certain colour can build up resonantly inside the microcavity. For photons travelling normal to the cavity, it must be possible to fit an integer number of half-wavelengths inside the cavity. In other words, they must have a wavelength, λ , that is either $2L$, $2L/2$ or $2L/3$ etc, where L is the thickness of the cavity.

This would suggest that only certain colours of photons are emitted. However, when the photons enter the microcavity from any direction other than the normal – i.e. $\theta > 0^\circ$ – some of their momentum is now in the plane of the microcavity. This in-plane momentum, p , is given by the expression $p = hk/2\pi = h(\sin\theta/\lambda)$, where h is the Planck constant and k is the wave-vector of the photon. The loss of momentum perpendicular to the layers means that photons entering the microcavity at an angle must have a higher initial momentum if they are to build up resonantly. Constructive interference therefore occurs for

photons of ever-shorter wavelength as the angle at which they enter the sample increases. The bottom line is that cavities can emit light over a range of wavelengths.

A plot of the resonant photons’ energy as a function of angle – or of energy as a function of momentum – therefore follows a steeply rising quadratic curve (figure 3a). Excitons, in contrast, have such a high mass – typically about 10% of the mass of an electron – that their kinetic energy, $\frac{1}{2}mv^2 = p^2/2m$, increases only slightly as a function of momentum, $p = mv$ (see figure 3b).

These graphs of energy versus momentum, which are termed “dispersion relations”, are important because they encode the properties of the polaritons. Indeed, the dispersion relations of the upper and lower polaritons are very different from those of the exciton and photon from which they are made. It turns out that the closer together the original energies of an exciton and photon are, the further apart they repel each other when coupled to make polaritons. The dispersion relation for the upper polariton is flatter than that of the photon, while the lower polariton is severely distorted (figure 3c). What is particularly interesting is that the lower polariton’s dispersion curve actually has a minimum – a trap – that captures low-momentum polaritons. Polaritons spontaneously collect in the trap and emit light straight out of the sample.

Observing microcavities

Since strongly coupled microcavities were discovered in 1991, several groups around the world have been trying to find out how these structures behave. What excited researchers most was a prediction in 1996 by Atac Imamoglu – now at the University of California at Santa Barbara in the US – that polaritons should emit light with incredible efficiency. He realized that polaritons are bosons – particles with integer spin – whereas the electrons that make up excitons are fermions, i.e. they have half-integer spin. For this reason, polaritons can all collect together in a single quantum state, where they collectively emit their energy as light rather than individually as heat. Excitons, in contrast, behave just like the electrons from which they are made: each state can only have at most two electrons – one containing a spin-up electron and the other a spin-down electron. In shunning each other's company, excitons tend to avoid the states that emit light proficiently.

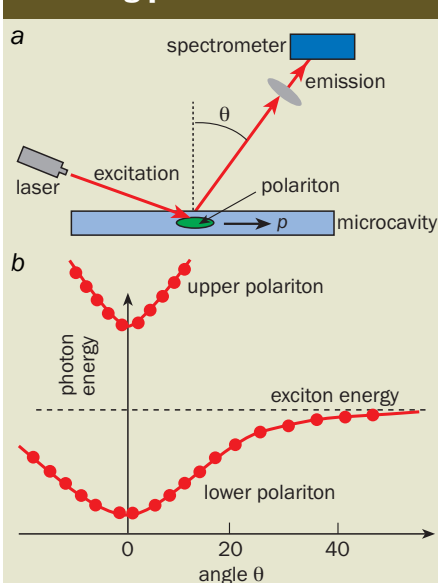
Unfortunately, early experiments by several groups – including that of Imamoglu – found that when a laser was used to excite dense clouds of excitons inside a microcavity, it actually obliterated the strong-coupling regime. In other words, the semiconductor microcavity no longer emitted two lines of light due to the presence of upper and lower polaritons. The problem was that the laser made the excitons scatter more and more off each other, weakening the Coulomb attraction between electron and hole, and so reducing their interaction with light. Therefore all that could be seen was just the normal exciton spectrum.

However, in 1998 two groups – led by Le Si Dang at the CNRS Laboratoire de Spectrométrie Physique in Grenoble and by Jacqueline Bloch at the CNRS Laboratoire de Microstructures et de Microélectronique in Bagnex – found that relatively weakly excited microcavities emitted light in a strange way. Both groups found that turning up the power of the laser shining on the microcavity caused the lower polaritons to emit many more photons at $\theta = 0^\circ$ (figure 4a). This superlinear power dependence proved that polaritons can collect in the lower-polariton trap rather than emit from the upper polariton.

Polariton lasers

In late 1998 I moved to Southampton University from the Hitachi Cambridge Laboratory, and my new group started working closely with Maurice Skolnick's group at Sheffield and with David Whittaker at Toshiba's Cambridge Research Laboratory. In our first experiments at Southampton, led by Pavlos Savvidis, we shone a laser onto a microcavity made from indium-gallium-arsenide quantum wells that had been sandwiched between mirrors made of gallium arsenide and aluminium gallium arsenide. We then calculated how many polaritons had been created as a function of angle by measuring the reflected intensity of a probe laser

2 Probing polaritons



(a) Polaritons that have been excited by a laser beam decay into their components – photons and excitons. There is a direct relationship between the polariton's momentum in the plane of the cavity's layers, p , and the angle, θ , at which the photons emerge. (b) Measuring the photons' energy as a function of angle reveals the presence of upper polaritons (with high energy) and lower polaritons (with low energy).

normal to the sample.

As the pump laser was incident at ever shallower angles, we found that the intensity of the probe pulse emerging from the sample suddenly increased by almost a factor of 100 when θ reached a critical angle of 17° (figure 4b). This response is easy to see even with the naked eye. When θ fell below 17° the intensity of the probe laser dropped off once more. This enormous amplification of the probe light indicated that some new physics must be going on. The amplification also increased exponentially with the power of the pump laser.

It turns out that the amplification is caused by a new type of scattering process, in which pairs of polaritons collide with one another and exchange energy in the process. One polariton steals energy and momentum from the other, with the higher-energy polariton moving up the dispersion relation, and the other dropping down to the bottom of the momentum trap (figure 4c). Polaritons injected by the probe pulse into the bottom of the trap are joined by the scattering polaritons from the pump.

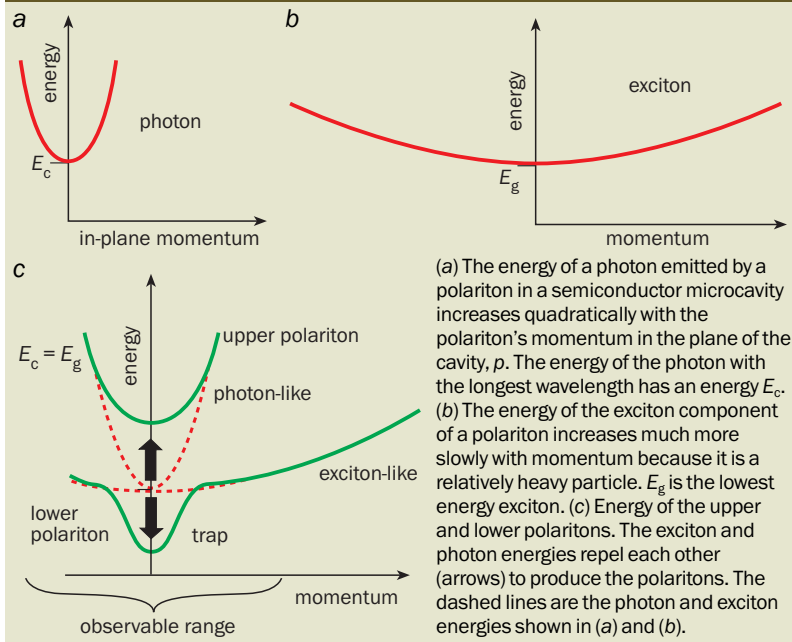
The net result is that an amplified probe beam emerges normal to the sample at $\theta = 0^\circ$, while a much weaker beam – containing photons from the higher-energy polaritons – emerges at 35° . The reason why this scattering only occurs at 17° is that the pump must hit the point of inflection on the dispersion relation to allow simultaneous energy and momentum conservation in the collision. Of course, these angles vary from one material to another. They are set by the inflection point of the dispersion relation, which depends on the refractive index and optical coupling of the quantum wells.

To understand this effect, remember that when two identical fermions collide, they cannot end up travelling simultaneously in the same direction because the Pauli exclusion principle forbids them to be in the same state. On the other hand, when two identical bosons – such as two polaritons – collide, they actually prefer to emerge in the same direction. Indeed, the rate at which they scatter is proportional to $(1 + \mathcal{N}_{\text{final}})\mathcal{N}_{\text{initial}}$, where $\mathcal{N}_{\text{initial}}$ and $\mathcal{N}_{\text{final}}$ are the number of polaritons in the initial and final states, respectively. In other words, the scattering rate increases as more polaritons enter the final state, which is the one at the bottom of the trap.

This process, which is known as “stimulated scattering”, means that the number of polaritons in the final state increases exponentially as the population of the initial state increases. The gain therefore also increases exponentially with pump power and can be higher than 10^7 cm^{-1} . This gain is bigger than that of any other known material – a stunning finding that implies that semiconductor microcavities could be used as light-driven switching devices in ultra-high-capacity all-optical information networks.

These experiments, which use very short laser pulses of just 0.1 picoseconds (10^{-13} s) in length, reveal that the gain is not only high but is also ultra-fast. In fact, the semiconductor

3 Dispersion relations



microcavities are so non-linear that we have recently found that polaritons can change their own dispersion relation, just as an elephant would compress a mattress over which it walked. Polaritons can even stop each other in their tracks and reverse direction. Moreover, Michele Saba, Cristiano Ciuti and Benoit Deveaud at the EPFL in Lausanne have now shown gains of over 5000 in microcavities at temperatures of over 200 K, which suggests that we might soon be able to exploit these enormous optical non-linearities in optoelectronic devices operating at room temperature. The large gains can even be observed with diode lasers, which operate continuously.

Provided that the density of excitons is well below the limit above which they are destroyed, experiments show a clear threshold at which the microcavity emits light efficiently as the intensity of the diode laser increases. The micron-long device is acting as what is known as an optical parametric oscillator (OPO). Unlike a normal laser, this polariton oscillator takes pump photons and converts them directly into two output beams of different wavelength.

Researchers in the Optoelectronic Research Centre at Southampton, and at Stanford University and elsewhere, have for years been trying to improve the efficiency of OPOs using “conventional” materials such as lithium niobate. But thanks to the huge gain shown by semiconductor microcavities, it will be possible to produce micro-OPOs that are 10 000 times smaller. It also promises a new route to high-efficiency polariton laser – or “plaser” – devices.

Key features of plasers

We can summarize some of the key features of plasers that have emerged in recent years.

- They have gains of over 10^7 cm^{-1} – higher than any other known material.
- The electron distribution does not need to be “inverted” as required in a normal laser – i.e. with more electrons in the upper conduction band than in the lower valence band. Instead, stimulated scattering draws polaritons into the trap from the “reservoir” of excitons. Light is emitted when the

photon components of the polaritons at the bottom of the trap leak out.

- In contrast to normal lasers, it turns out that these light emitters can actually work better when heated.
- Their efficiency depends on how easily excitons can drop into the momentum trap without being re-ionized back out of it. As Alexey Kavokin from the Université Blaise Pascal in Clermont–Ferrand and colleagues working within the EU CLERMONT collaboration noted, weak concentrations of electrons in the quantum well should actually help by removing exciton momentum.
- Polariton lasers do not absorb light at the wavelength at which they emit, thus removing a major obstacle to making lasers that turn on with minimal amounts of energy input.

Another major effect of the dispersion trap is to reduce the number of different low-energy electronic states in which the polaritons can end up. What is interesting about the fact that so many polaritons build up in the lowest $k=0$ state is that they all have the same phase. Moreover, their mass, m_p , is so small that their de Broglie wavelength $\sqrt{(\hbar^2/2\pi m_p k_B T)}$ – where k_B is the Boltzmann constant – is about 100 times larger than the diameter of an exciton at the same temperature, T , and comparable with the distance between separate polaritons. The wavefunctions of the polaritons therefore overlap and the system undergoes a phase transition to form a single, macroscopic state that is quantum-mechanically coherent.

In other words, the polaritons form a condensate. It is, however, a dynamic state because each polariton decays within 10 picoseconds by emitting a photon. The reservoir of excitons therefore has to continually replenish the number of polaritons in the lowest state for the condensate to persist. These non-equilibrium polariton condensates are thus somewhat different from Bose–Einstein condensates made from ultra-cold atoms, although they do share many features such as stimulated scattering.

My group has recently measured interference between polariton condensates, revealing “coherence lifetimes” of more than 1000 picoseconds. This is about a thousand times slower than the coherence relaxation times of excitons in a typical semiconductor quantum well, showing how effectively polariton scattering is suppressed. The condensates, which have diameters of around 100 microns, are the first macroscopic quantum states in semiconductors that can be directly optically probed in different locations at the same time.

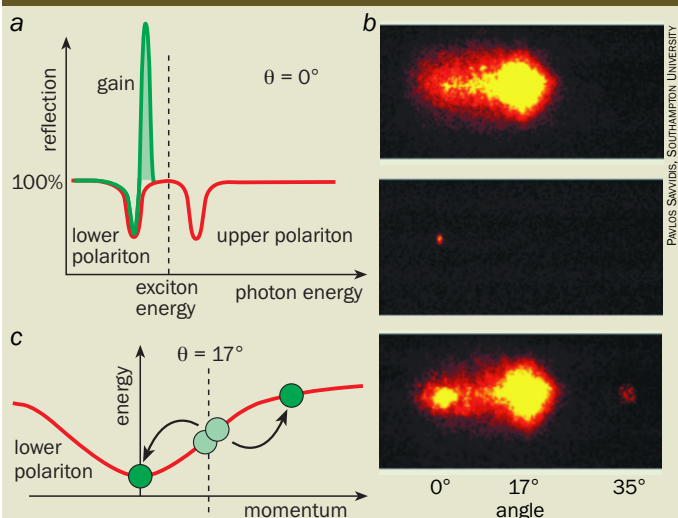
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Microcavities – the future

Research into semiconductor microcavities has progressed at an extremely rapid rate in recent years. Much of this progress is due to the fact that there is a close-knit community of researchers – most of whom are based in Europe – sharing their results and encouraging each other, often through heated discussion. These links may seem to be at odds with the traditional image of individual researchers or groups obtaining

4 Studying polariton lasers



(a) Shining a pump laser onto a microcavity creates polaritons that emit light. The "reflectance" of a second, probe laser as a function of emitted photon energy (red) reveals the presence of the lower and upper polaritons. When the power of the pump laser is sufficiently high, the microcavity acts as an optical amplifier (green). (b) Gain only occurs when the pump laser (top) enters the sample at an angle of 17° . The intensity of the probe laser (middle), which is normally weak, suddenly increases about 100-fold (bottom). A weaker beam also exits the sample at 35° . (c) The amplification is due to "pair scattering", in which pairs of polaritons collide and exchange energy. The higher-energy polariton moves up the dispersion relation, while the other drops to the bottom of the momentum trap.

results entirely on their own, but they reveal the benefits of thriving competition and co-operation that exist in the field.

Microcavity research is now branching out into a number of intriguing new areas. One aim is to create strong-coupling samples at room temperature in which the electron and hole in an exciton are bound together more tightly. This increases the separation between upper and lower polaritons well above typical thermal energies. Materials such as gallium nitride or zinc oxide satisfy this condition, although they are unfortunately not as technologically sophisticated as existing semiconductor heterostructures. Another option could be to use organic materials, for which the energy splitting between polaritons can be enormous.

As these new avenues open up, what is clear is that there is much more to come from mixing light and matter.

Further reading

- G Khitrova *et al.* 1999 Nonlinear optics of normal-mode-coupling semiconductor microcavities *Rev. Mod. Phys.* **71** 1591
- P G Savvidis *et al.* 2000 Angle-resonant stimulated polariton amplifier *Phys. Rev. Lett.* **84** 1547
- M S Skolnick, T A Fisher and D M Whittaker 1998 Strong coupling phenomena in quantum microcavity structures *Semicond. Sci. Technol.* **13** 645
- R M Stevenson *et al.* 2000 Continuous wave observation of massive polariton redistribution by stimulated scattering in semiconductor microcavities *Phys. Rev. Lett.* **85** 3680
- C Weisbuch and J G Rarity (ed) 1996 *Microcavities and Photonic Bandgaps: Physics and Applications* (Kluwer, Dordrecht)
- Y Yamamoto 2000 Half-matter, half-light amplifier *Nature* **405** 629

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