Quasi Particles

Advanced

How to Imagine a Quasi Particle

- Protons, neutrons and electrons are particles. Nobody has a problem with that because most everybody just imagines them as some little ball that can exist by itself even in the absolute vacuum of space. While the "little ball" part of that imagination is faulty, the "can exist by itself" is correct.
    - Now let's look at **photons**. Definitely a particle, but the "little ball" picture is now completely off. A photon can exist be itself but must keep moving.
- If we move one step away from the "little ball" image we can perceive all those particles in a more abstract way as more or less localized carriers of fixed and immutable *properties* like rest mass, charge, spin, and some others that we don't need to worry about.
    - Then we have another set of properties tied to what those particle "*do*", expressed foremost in energy and momentum - quantities that are usually coupled by some dispersion relation and containing other parameters like wavelengths.
    - The important point is that all of the above is covered by quantum theory and that means that all properties are usually quantized and that interactions between those particles must take into account the Pauli principle. This leads to the Fermi-Dirac or Bose-Einstein distributions if more than one particle needs to be "filled" into a system with defined energy levels.
- Now we make another leap of imagination and consider any entity that can be perceived as a carrier of defined properties in the sense alluded to above. This entity then could be either a "real" particle or a *quasi-particle*. Discounting the many elementary particles of high energy physics that are not stable, whatever we are discussing now must have protons, neutrons, electrons and photons as building blocks. So let's see what kind of "quasi" particles that we have already encountered we can compose with these basic ingredients:
    - *Atoms* obviously. We can easily perceive atoms as real particles in their own right; nothing "quasi" about them. So we don't have to dwell on this.
    - *Molecules* and *crystals*. Now we have a problem. We can certainly "see" a $\mathbf{Cl_2}$ molecule as a "real" particle, but not a **DNA** molecule consisting of some **100.000** atoms or a **300 mm Si** wafer. But this is not a real problem, it is just the old tiring story that as things get larger, it is more convenient to switch from particle-oriented quantum mechanics to good old classical mechanics. We don't think of big things as particles anymore (but still as "mass points" for certain questions!).
    - *Holes*, behaving for all purposes like a positively charged electron. Now we have a "real" quasi particle in the sense that you can't take it out of the crystal in which it dwells and look at it. You cannot, to belabor this point somewhat more, make a fine point to a crystal and by applying a high field strength extract a *hole* beam which you focus and scan a cross on a specimen, running a scanning *hole* microscope. With electrons this is everyday technology. Holes in "reality" are still collectives of electrons that follow certain rules.
    - *Phonons* or quantized vibrations of a crystal. The term "elastic waves" is actually better than the term "vibrations", because that's what phonons are: Waves running through the crystal with amplitudes resulting from a local *elastic* deformation - the atoms are somewhat off their equilibrium position. Being a wave, it has a wavelength and thus momentum and some energy; always quantized, of course. So what is the difference to a *photon*? Only that the term "$\boldsymbol{A}$" in the basic wave equation $\boldsymbol{A}(\underline{\boldsymbol{r}},\boldsymbol{t}) = \boldsymbol{A}_0 \cdot \exp(\underline{\boldsymbol{kr}} - \omega \boldsymbol{t})$ has a different unit (distance instead of electrical field strength). If a photon is a particle in vacuum, so is a phonon inside a crystal!
- Holes and phonons are thus *quasi particles* that can only exist inside crystals (or matter). They describe some collective behavior of electrons and atoms, respectively, in a simple and consistent way.
    - It should come as no surprise that we will find more "collectives" that behave in a fashion with defined properties that we can ascribe to a suitable quasi-particle. Let's first look at list of what we have and then discuss those quasi particles very briefly

The Quasi Particle Zoo

Here is a list of crystal-dwelling quasi particles:

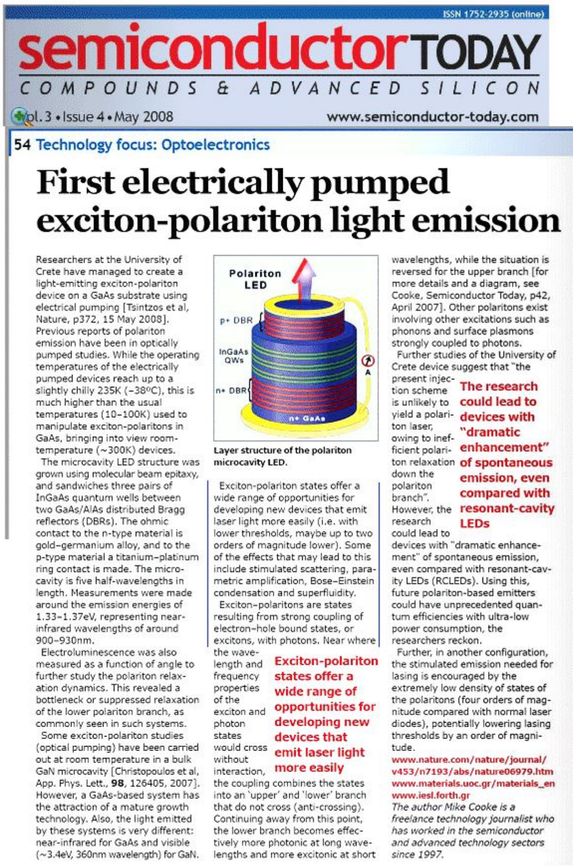
Quasi particle	**Constituents**	**Remarks**
Phonons	Crystal atoms	large momentum little energy Smallest wave length = lattice constants
Holes	Electrons in Valence band	"Define" semiconductors
Polarons	e^- + phonon	Essential to organic semiconductors
Plasmons	Electron collective	Determines optical properties of nanocrystals
Excitons	Bound electron hole pair	Produce the light in **GaP LED's**
Polaritons	Photon + phonon	Pretty strange - but those things do exist.
	Photon + electron	
	Photon + exciton	
Magnons	Crystal magnetic moments (= spins)	The "phonons" of spin waves
..	.....	....
Cooper pairs	2 electrons coupled by phonons	The quasi-particle responsible for **superconductivity**

Now we would need a closer look (= large part of a advanced solid state physics lecture). I'm not doing that here but only give a minimal glimpse at:

Plasmons: Imagine a nanoparticle of **Au**, for example. There is only a small number of atoms and accordingly a small number of free electrons. Now imagine an (oscillating) electrical field acting on that particle - e.g. a photon "coming in".

- If a photon homes in on a large piece of **Au** the electrons in surface near regions feel a force, move a bit and by doing this screen the electrical field - it will not penetrate in the interior of the metal.
- However, if the particle is small enough, all electrons feel the same force, and all electrons behave as one, as an ensemble called "plasma" for reasons easy to guess. What this ensemble of electrons can do is, of course, subject to quantum mechanics, i.e. we must expect that there is some quantization of the energy. The *plasmon* then is nothing but the quantized excitation states of an electron collective - the "plasma". Excitations are more or less restricted to longitudinal oscillations of the plasma. In other words, our electrons in the nanocrystal swing from "left" to "right" in unison at some quantized "Eigenfrequencies" and then can be described just as well as a (standing wave like) plasmon.
- Quantization of energy means quantization of frequencies and that means that only "light" with the right frequency can excite a plasmon in our **Au** nanoparticles. Only this light then will be absorbed, transferring its energy to the plasmon.
- This is easy to show: Put some of your **Au** nanoparticles in otherwise fully transparent glass - it will now look colored because your nanoparticles, depending on their size, take out some wavelengths since light with wavelengths just right to excite plasmons will be absorbed. But you don't have to do this experiment, just look at stained glass windows in medieval churches. The beautiful dark red you see there is obtained in exactly this way! Our forbearers actually knew how to get **Au** nanoparticles in Glass. They just had no idea why and how it worked
- What you can imagine for **Au**, you can imagine for everything else, of course.

- Finally, just to show that I'm not making this up, the beginning of a collection of articles etc. where quasi particles come up as being useful.
- First we have **polaritons**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54 Technology focus: Optoelectronics

First electrically pumped exciton-polariton light emission

Researchers at the University of Crete have managed to create a light-emitting exciton-polariton device on a GaAs substrate using electrical pumping [Tsintzos et al, Nature, p372, 15 May 2008]. Previous reports of polariton emission have been in optically pumped studies. While the operating temperatures of the electrically pumped devices reach up to a slightly chilly 235K (−38°C), this is much higher than the usual temperatures (10–100K) used to manipulate exciton-polaritons in GaAs, bringing into view room-temperature (~300K) devices.

The microcavity LED structure was grown using molecular beam epitaxy, and sandwiches three pairs of InGaAs quantum wells between two GaAs/AlAs distributed Bragg reflectors (DBRs). The ohmic contact to the n-type material is gold–germanium alloy, and to the p-type material a titanium–platinum ring contact is made. The micro-cavity is five half-wavelengths in length. Measurements were made around the emission energies of 1.33–1.37eV, representing near-infrared wavelengths of around 900–930nm.

Electroluminescence was also measured as a function of angle to further study the polariton relaxation dynamics. This revealed a bottleneck or suppressed relaxation of the lower polariton branch, as commonly seen in such systems.

Some exciton-polariton studies (optical pumping) have been carried out at room temperature in a bulk GaN microcavity [Christopoulos et al, App. Phys. Lett., **98**, 126405, 2007]. However, a GaAs-based system has the attraction of a mature growth technology. Also, the light emitted by these systems is very different: near-infrared for GaAs and visible (~3.4eV, 360nm wavelength) for GaN.

Layer structure of the polariton microcavity LED.

Exciton-polariton states offer a wide range of opportunities for developing new devices that emit laser light more easily (i.e. with lower thresholds, maybe up to two orders of magnitude lower). Some of the effects that may lead to this include stimulated scattering, parametric amplification, Bose–Einstein condensation and superfluidity.

Exciton–polaritons are states resulting from strong coupling of electron–hole bound states, or excitons, with photons. Near where the wavelength and frequency properties of the exciton and photon states would cross without interaction, the coupling combines the states into an 'upper' and 'lower' branch that do not cross (anti-crossing). Continuing away from this point, the lower branch becomes effectively more photonic at long wavelengths and more excitonic at short wavelengths, while the situation is reversed for the upper branch [for more details and a diagram, see Cooke, Semiconductor Today, p42, April 2007]. Other polaritons exist involving other excitations such as phonons and surface plasmons strongly coupled to photons.

Exciton-polariton states offer a wide range of opportunities for developing new devices that emit laser light more easily

Further studies of the University of Crete device suggest that "the present injection scheme is unlikely to yield a polariton laser, owing to inefficient polariton relaxation down the polariton branch". However, the research could lead to devices with "dramatic enhancement" of spontaneous emission, even compared with resonant-cavity LEDs (RCLEDs). Using this, future polariton-based emitters could have unprecedented quantum efficiencies with ultra-low power consumption, the researchers reckon.

The research could lead to devices with "dramatic enhancement" of spontaneous emission, even compared with resonant-cavity LEDs

Further, in another configuration, the stimulated emission needed for lasing is encouraged by the extremely low density of states of the polaritons (four orders of magnitude compared with normal laser diodes), potentially lowering lasing thresholds by an order of magnitude.

www.nature.com/nature/journal/v453/n7193/abs/nature06979.htm
www.materials.uoc.gr/materials_en
www.iesl.forth.gr

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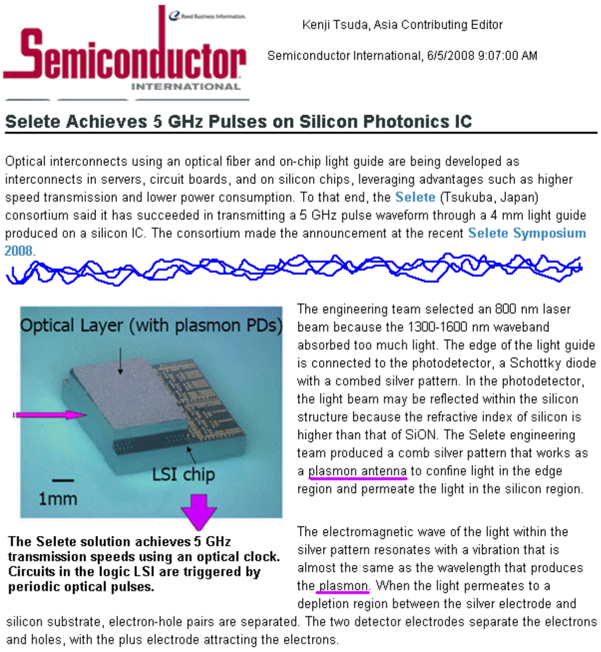
- It can't get much more exotic than that: putting exciton-polaritons to use! The blue lines indicate a part of the article where you will find a lot of the vocabulary used here in this context.

- Now let's look at **plasmons**: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Selete Achieves 5 GHz Pulses on Silicon Photonics IC

Optical interconnects using an optical fiber and on-chip light guide are being developed as interconnects in servers, circuit boards, and on silicon chips, leveraging advantages such as higher speed transmission and lower power consumption. To that end, the Selete (Tsukuba, Japan) consortium said it has succeeded in transmitting a 5 GHz pulse waveform through a 4 mm light guide produced on a silicon IC. The consortium made the announcement at the recent Selete Symposium 2008.

The Selete solution achieves 5 GHz transmission speeds using an optical clock. Circuits in the logic LSI are triggered by periodic optical pulses.

The engineering team selected an 800 nm laser beam because the 1300-1600 nm waveband absorbed too much light. The edge of the light guide is connected to the photodetector, a Schottky diode with a combed silver pattern. In the photodetector, the light beam may be reflected within the silicon structure because the refractive index of silicon is higher than that of SiON. The Selete engineering team produced a comb silver pattern that works as a plasmon antenna to confine light in the edge region and permeate the light in the silicon region.

The electromagnetic wave of the light within the silver pattern resonates with a vibration that is almost the same as the wavelength that produces the plasmon. When the light permeates to a depletion region between the silver electrode and silicon substrate, electron-hole pairs are separated. The two detector electrodes separate the electrons and holes, with the plus electrode attracting the electrons.