# Theory of polaritons in a highly degenerate 2D electron gas

M. Baeten[1], M. Wouters

Theory of Quantum and Complex Systems, Universiteit Antwerpen, Universiteitsplein 1, B2610 Antwerpen, Belgium
[1]e-mail: maarten.baeten@ua.ac.be

## Introduction

Polaritons are the quasiparticles resulting from the strong coupling between a confined photon mode in a microcavity and the excitonic (bound electron-hole pair) resonances in an embedded quantum well, see Fig. 1.

Recently, so-called Fermi edge polaritons in presence of a highly degenerate electron gas inside the quantum well have been experimentally observed [1]. A theoretical understanding however is still lacking. We want to present it here.

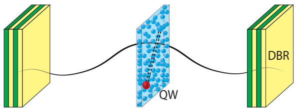


Fig.1: Coherent oscillation between a cavity photon and a quantum well exciton: a polariton

The key to the problem will be to elucidate the behaviour of the bound exciton state as electrons are added in the quantum well. The formalism we use for that is many-body perturbation theory by means of Feynman diagrams. Above a critical density, the bound exciton is found to become metastable and we investigate the fate of the microcavity polariton as a function of doping.

Note that the disappearance of the bound exciton state bears a strong analogy with the quantum phase transition in the Fermi-polaron problem. Also other interesting many-body effects originally investigated within the realm of semiconductor physics, such as the Mahan-singularity and Anderson orthogonality catastrophe, are currently of interest in the community working on ultracold atomic gases.

## Photon self energy: exciton physics

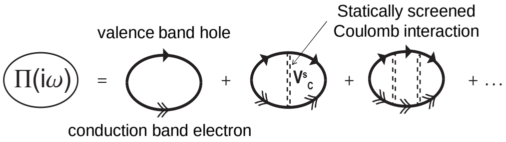
### Polariton = 'dressed' photon

Photon propagator:

$$D\left(i\omega\right) = \frac{1}{i\omega - \omega_c - \Pi(i\omega)} \longleftrightarrow$$

$\omega_c$ : energy of standing wave inside the cavity.

$\Pi(i\omega)$ : photon self energy as the result of excitations in the quantum well. Approximated by the following Feynman diagrams:

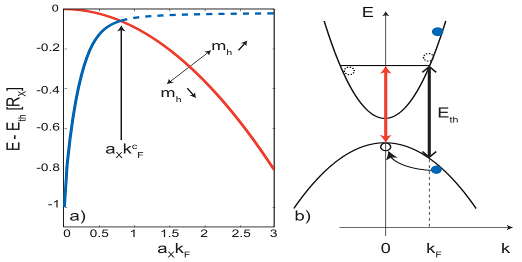


Corresponding integral equation [2] (Bethe-Salpeter eq.) for the vertex factor $P(\mathbf{k}, i\omega)$

$$[\omega - H_X(\mathbf{k},\mathbf{k}',\omega)]P(\mathbf{k}, i\omega) = g \Longrightarrow \Pi(i\omega) = \frac{g}{S}\sum_{\mathbf{k}} P(\mathbf{k}, i\omega)$$

$H_X$ : exciton Hamiltonian taking into account
- Pauli blocking: blue shift of absorption onset.
- Screening of the Coulomb interaction: reduction of exciton binding energy.

The light-matter coupling is denoted g and S is the quantum well surface.



$E_{\rm th}$ : zero of energy – both electron and hole at Fermi wave vector ('Fermi edge')

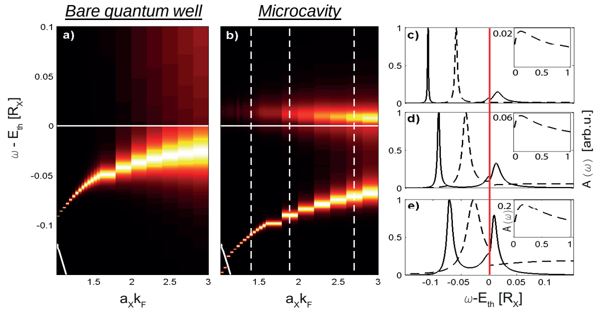
a) Solid blue: stable atomic exciton
Dashed blue: metastable bound (wrt Fermi edge) electron-hole pair: ***Mahan exciton***
Red: lowest energy of free electron-hole pair (double red arrow in b)

b) Bandstructure depicting the decay of the Mahan exciton (blue full circles)
Valence band hole decays to **k=0** by emission of a low energy intraband electron-hole pair (arrow + dashed circles).

## Light-matter coupling

Photon spectral function: $\mathcal{A}\left(\omega\right) = -\frac{1}{\pi}\,\mathrm{Im}\;D\left(i\omega \rightarrow \omega + i\eta^{+}\right)$

Peaks: excitation energy of the quasiparticle
Width: proportional to the lifetime of the excitation



Detuning: $\Delta = \omega_c - E_{\rm th}$

a) $\Delta >> 0$

- Weak coupling, recovering of the Mahan exciton.
- Blue shift + broadening.
- Above Fermi edge: small increase in absorption due to Coulomb interaction (see insets c-e).

b) $\Delta = 0$

- Two new eigenmodes: polaritons
- Smaller linewidth than the exciton due to Rabi splitting (less phase space for the hole)
- Upper polariton exists, even in the regime where no bound electron-hole states are present!

*Different approximations* :

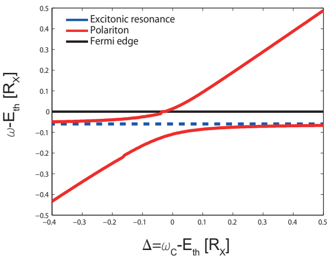
- Beneath Fermi edge: linewidth due to relaxation of valence band hole
- Above Fermi edge: linewidth due to creation of free electron-hole pairs causes absorption, even without inclusion of the hole self energy.
- Also, no 'crossed-ladder' diagrams are taken into account (no Fermi edge singularity)

⇨ Still rather smooth crossover between the two regimes

## Avoided crossing

Changing the photon energy results in the typical anti-crossing of energy levels of two strongly coupled systems (Mahan exciton + photon).

- Very large blue detuning: exciton is being recovered (blue dashed)
- Largest Rabi splitting at resonance with the exciton energy
- Polariton formation in an electron gas due to strong coupling of the cavity mode with the Mahan exciton



## Conclusions and outlook

The microcavity polariton in highly doped semiconductor microcavities is shown to be the result of the strong light-matter coupling between a cavity mode and the Mahan exciton: a metastable electron-hole pair, bound with respect to the Fermi edge. Because the polariton linewidths are found to be much smaller than the exciton binding energy the polaritons are the good quasi particles in a large range of densities. Therefore it should be possible to investigate polariton-polariton interactions in doped quantum wells.

References:
[1] A. Gabbay et al., Fermi Edge Polaritons in a Microcavity containing a high density two-dimensional electron gas, PRL 99, 157402 (2007)
[2] G. D. Mahan, Many-particle physics, Plenum Press.
[3] M. Baeten and M. Wouters, Arxiv:1301.4119