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13. ABSTRACT *(Maximum 200 words)*

During the second year, the AFOSR grant was primarily used to support my student Wenbing Zhang. Wenbing successfully completed a theoretical study of exciton condensation kinetics that resultsed in Ref.2. He then started an experimental investigation of exciton-polaritons under high magnetic fields. During the third year, we continued to study the possibilty of realizing a microcavity excitron polariton laser (MEPL) 1. Our primary achievement is the identification of the fundamental relation between exciton-phonon and exciton-photon interactions that must be satisfied before a MEPL can be implemented 2.

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Electrically pumped microcavity exciton polariton laser

Final Progress Report on F49620-96-1-0343

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I. INTRODUCTION

In this project, we have investigated the possibility of utilizing the *final state stimulation* effect [1] to realize a fundamentally new form of coherent light source, namely, a microcavity exciton-polariton laser (MEPL). When realized, such a device could revolutionize the optoelectronics technology by eliminating the population inversion requirement [2].

Our theoretical efforts enabled us to identify the fundamental relation between exciton-phonon and exciton-photon interactions that must be satisfied before a MEPL can be realized. Even though experimental efforts at UCSB did not provide concrete evidence for MEPL, the Stanford sub-contract with Prof. Y. Yamamoto's group resulted in the first experimental demonstration of final-state stimulation of exciton-polariton scattering. This experiment constitutes a major step in the search for MEPL. Shortly after our AFOSR contract (F49620-96-1-0343) ended, the group of Prof. J. Baumberg reported the first observation of MEPL.

II. KINETICS OF CONDENSATION IN TRAPPED EXCITONS

We carried out an extensive numerical study of the kinetics of condensation in a two-dimensional trapped exciton gas [3]. The crucial quantity that determines the *gain* in exciton and exction-polariton lasers is the cooling rate due to exciton-phonon interaction. The primary motivation for this work comes from the need to describe the cooling of an exciton gas in a quantum-well structure where the interface roughness inevitably localizes the excitons into *random islands*. At least for the low lying states, a parabolic confinement potential provides the best approximation for an arbitrary potential. In addition, we envision that excitons may be confined intentionally using strain fields in lattice-mismatched structures. The majority of the work on exciton condensation on the other hand, have focused on translationally invariant systems. This work aimed at answering two principal questions: (1) the respective role of exciton-phonon and exciton-exciton interactions in determining the condensation time; and (2) the effects of dissipation on the critical temperature for condensation [3].

Our work is also motivated by the theoretical work on trapped BEC gases in atomic physics, where the effects of trapping potential on BEC in low-dimensional systems have been discussed in both the thermodynamic limit and for finite systems. The distinguishing feature of the experiments on cold exciton gases is the importance of cooling due to exciton-phonon interaction and heating due to radiative decay.

Our numerical simulations demonstrated that the presence of radiative decay or *output* from the low-energy states resulted in a heating effect, which in turn increased the critical exciton density for condensation at a fixed lattice temperature. This result is not unexpected as the dissipation process in exciton gases is the opposite of evaporative cooling of atoms in that it preferentially removes low-energy excitons. We also observed that condensation time in the presence of dissipation is longer, despite the fact that excitons in the low-energy excited states are removed from the trap at a rate that exceeds the ground-state decay rate.

We note that in the presence of dissipation and collisions the exciton gas in steady-state can be described by a temperature that remains higher than the lattice temperature. The fact that the radiative heating results in an exciton condensate that is out-of-equilibrium with the lattice is consistent with the matter laser model of exciton condensation, which predicts that the exciton gas temperature in steady-state needs to be higher than the lattice temperature in order to ensure that gain due to *stimulated gain* or cooling of the exciton gas by phonon emission compensates for the loss or heating due to radiative recombination. Finally from a laser perspective, the dissipative trapped exciton gas corresponds to a multimode system where a large number of (excitonic) modes see very similar gain and loss coefficients; our simulations demonstrated that among these modes, the ground-state is *preferred* in that the slightly higher net gain it experiences allows it to win the *mode competition* and results in a single-mode operation when the system is driven well above threshold - or equivalently the mean exciton density is well above the critical density.

III. STIMULATED EXCITON POLARITON SCATTERING

The Stanford group has studied polariton dynamics in a semiconductor quantum well (QW) microcavity, including the exciton-exciton and exciton-phonon scatterings [4]. A bottleneck in the relaxation of excitons into lower polaritons is found, which stems from the reduced density of states of lower polaritons and the relatively long lifetime of the bottleneck exciton with a large in-plane momentum. With this non-equilibrium exciton population as a reservoir, an exciton-polariton laser (boser) based on the exciton-exciton scattering as a gain mechanism was proposed [4].

Experimental evidence for the final state stimulation of the exciton-exciton scattering rate into the upper and lower polariton states with zero in-plane momentum in a GaAs QW microcavity has been obtained [5]. The dependence of the exciton-exciton scattering rate on the exciton density, polariton density, and pump-probe time delay dependence are in good agreement with the theoretical prediction.

A CdTe QW exciton has a smaller Bohr radius by a factor of three than a GaAs QW exciton, so its saturation density is an order of magnitude larger than the GaAs QW exciton. Therefore, it is theoretically predicted that a CdTe QW microcavity should reach a boser threshold well below the exciton saturation density. This prediction was confirmed experimentally [5,6]. The stimulated emission gain up to 30 at just below the oscillation threshold and the coherent emission associated with the self-oscillation in a CdTe QW microcavity was also observed. Finally, the amplitude and phase noise characteristics of such an exciton-polariton laser was studied. The large amount of amplitude-phase correlation and squeezing is expected due to the efficient exciton-exciton scattering.

The final state stimulation into an exciton or polariton state should be also possible in a direct electron tunneling into the exciton or polariton state [7,8]. This process has been studied within the pairing and the interacting boson approximations. This scheme will open up the possibility of coherent matter-wave oscillation or amplification in an electrically pumped device.

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1. W. Zhang, P. Stenius, and A. Imamoḡlu, "Kinetics of Condensation in trapped exciton gases," Phys. Rev. B **56**, 5306-5315 (1997).

2. F. Tassone and Y. Yamamoto, "Exciton-exciton scattering dynamics in a semiconductor microcavity and stimulated scattering into polaritons," Phys. Rev. B **59**, 10830-10842 (1999).

3. R. Huang, F. Tassone and Y. Yamamoto, "Experimental evidence of stimulated scattering of excitons into microcavity polaritons," Phys. Rev. B **61**,R7854-7857 (2000).

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Electrically pumped microcavity exciton polariton laser

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During the third year of the Award, we continued to study the possibility of realizing a microcavity exciton polariton laser (MEPL) [1]. Our primary achievement is the identification of the fundamental relation between exciton-phonon and exciton-photon interactions that must be satisfied before a MEPL can be implemented [2].

The Stanford group has studied polariton dynamics in a semiconductor quantum well (QW) microcavity, including the exciton-exciton and exciton-phonon scatterings [3]. A bottleneck in the relaxation of excitons into lower polaritons is found, which stems from the reduced density of states of lower polaritons and the relatively long lifetime of the bottleneck exciton with a large in-plane momentum. With this non-equilibrium exciton population as a reservoir, an exciton-polariton laser (boser) based on the exciton-exciton scattering as a gain mechanism was proposed [3]. Experimental evidence for the final state stimulation of the exciton-exciton scattering rate into the upper and lower polariton states with zero in-plane momentum in a GaAs QW microcavity has been obtained [4]. The dependence of the exciton-exciton scattering rate on the exciton density, polariton density, and pump-probe time delay dependence are in good agreement with the theoretical prediction.

The experimental efforts at UCSB focused on cooling of optically generated microcavity magneto-polaritons. These experiments did not exhibit the predicted nonlinearity in photoluminescence.

During the second year, the AFOSR grant was primarily used to support my student Wenbing Zhang. Wenbing successfully completed a theoretical study of exciton condensation kinetics that resulted in Ref.[2]. He then started an experimental investigation of exciton-polaritons under high magnetic fields. Unfortunately, in summer 1998, he decided to change his research direction and left the group.

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[1] A. Imamoğlu, R. J. Ram, S. Pau, and Y. Yamamoto, Phys. Rev. A **53**, 4250 (1996).

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[4] R. Huang, F. Tassone and Y. Yamamoto, Phys. Rev. B **61**, R7854 (2000).