First polariton laser with electrical pumping

Researchers claim an important step towards practical implementation of polaritonic light sources and electrically injected condensates.

A transnational team of researchers has reported the first electrically pumped exciton-polariton laser device using an arsenide semiconductor microcavity [Christian Schneider et al, Nature, vol. 497, p348, 2013]. The team was variously based at Universität Würzburg (Germany), University of Stanford (USA), University of Tokyo (Japan), University of Iceland, Nanyang Technological University (Singapore), Russian Academy of Science Institute of Solid State Physics, Technische Universität Berlin (Germany), and National Institute of Informatics (Japan).

Researchers hope that polariton lasing principles will lead to more energy-efficient semiconductor lasers with lower thresholds.

Normal 'weak-coupling' laser diodes use transitions of electrons from the conduction band across the gap to holes in the valence band (electron–hole recombination).

Exciton-polaritons represent mixed quasi-particle states that arise due to strong coupling between photons and

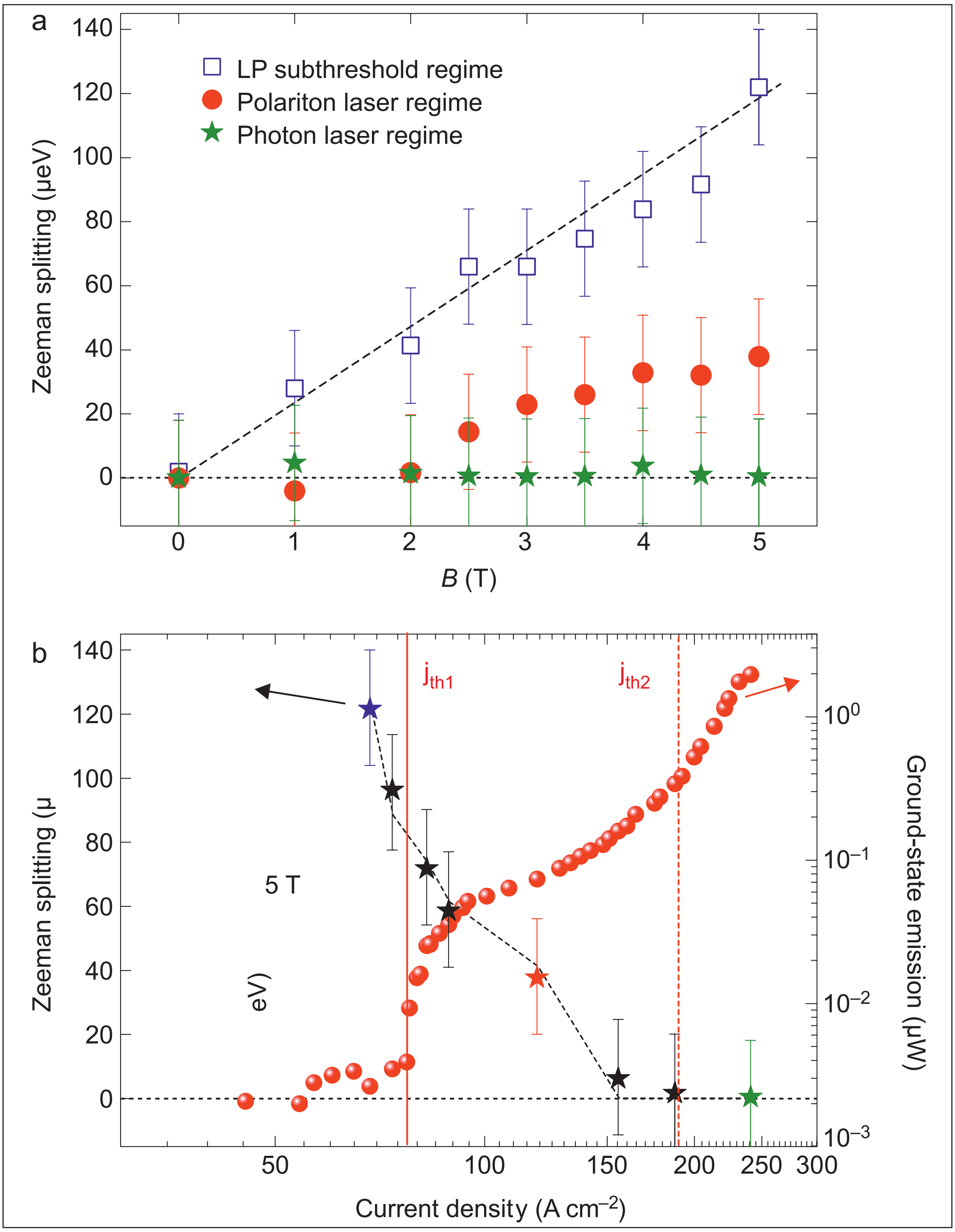

Figure 1. Zeeman splitting of polaritonic emission: (a) mode splitting as function of magnetic field for different current densities in three characteristic regimes; (b) current-density-dependent mode splitting at 5T; light output power is also plotted.

bound pairs of electrons and holes ('excitons'). The dispersion relation for these particles has upper- and lower-energy branches. The pumping of energy into the system accumulates polaritons in a single-particle ground state of the lower-energy branch by a nonlinear stimulated scattering mechanism. A polariton laser generates coherent light by leakage of photons from the system.

For arsenide semiconductors, very low temperatures of around 10K are needed for stable polaritons. However, optically pumped polariton lasing in nitride semiconductors at room temperature was demonstrated in 2007. Also, a one-dimensional polariton condensate in zinc oxide nanowires at room temperature was reported in 2010. Nitride semiconductors and zinc oxide are wide-bandgap semiconductor materials.

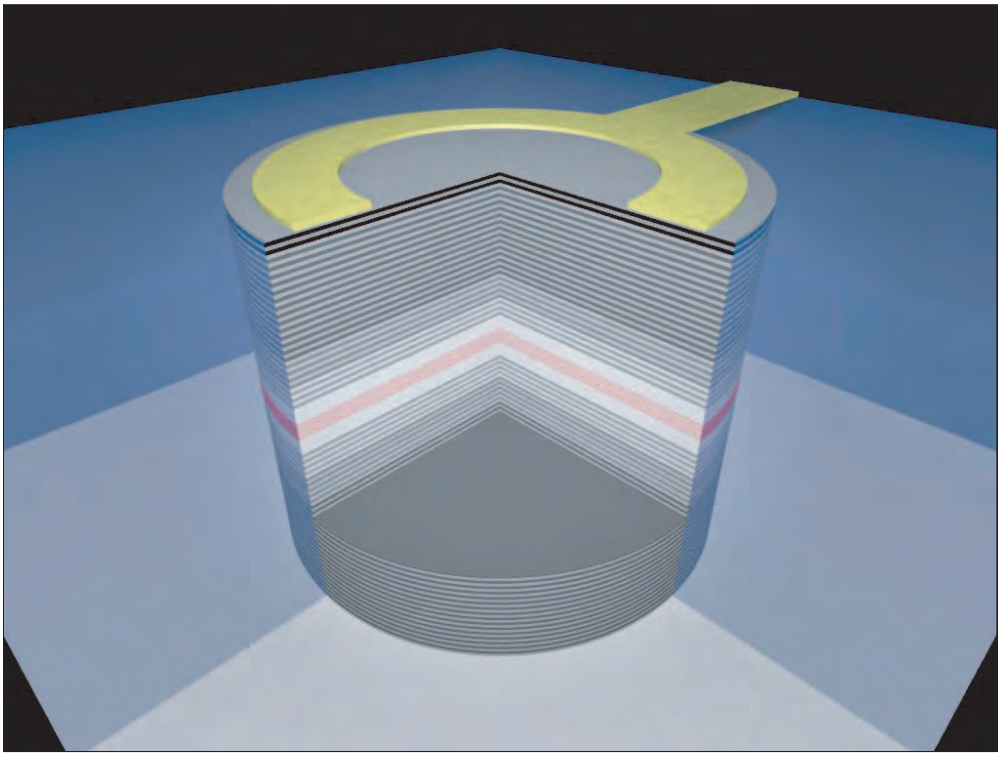

Figure 2. Schematic of quantum well microcavity polariton diode.

The researchers comment: "Our results represent an important step towards the practical implementation of polaritonic light sources and electrically injected condensates, and can be extended to room-temperature operation using wide-bandgap materials."

The researchers carried out an extensive series of experiments on their device to confirm that the laser light produced was from exciton-polaritons and not through the normal weak-coupling interaction that traps photons in a cavity.

Magnetic fields were useful in the discrimination of polariton effects as opposed to cavity-mediated lasing. In particular, the Zeeman splitting effect of the magnetic field allows determination of exciton densities.

The researchers found two current thresholds in operation, which they associated with a transition from incoherent to coherent (i.e. laser) polariton emission and with a transition from polariton to cavity-mediated laser operation. It was found that the Zeeman splitting of the mode decreased as the injected current increased towards the second threshold (Figure 1).

The polariton laser threshold current density was around 82A/cm^2 in zero magnetic field and 77A/cm^2 in a 5 Tesla (5T) field. The second threshold occurs around 190A/cm^2 for both zero and 5T magnetic fields. The researchers believe that the second threshold represents a transition to weak-coupling due to screening effects from the high density of excitons.

The researchers write: "The fact that the [Zeeman] mode splitting at 5T remains detectable up to the current at which the photon lasing threshold is crossed is unambiguous evidence of an excitonic component of our system, due to which the strong coupling is preserved across the first threshold attributed to polariton lasing."

The electrically pumped laser structure was similar to a vertical-cavity surface-emitting laser (VCSEL) with distributed Bragg reflectors (DBRs) above and below the multiple quantum well (MQW) active light-emitting region (Figure 2). The arsenide semiconductor layers were built up using molecular beam epitaxy (MBE) on n-type (silicon-doped) (100)-oriented gallium arsenide (GaAs) substrate.

The bottom n-DBR consisted of 27 pairs of gallium arsenide/aluminium arsenide (GaAs/AlAs) and the top p-DBR consisted of 23 pairs with the same material combination. The doping concentration was graded, reducing towards the MQW region. Delta-doping was applied at every second interface to improve the conductivity of the structure.

The MQW consisted of four indium gallium arsenide (InGaAs) wells with GaAs barriers. The MQW cavity was designed to be one wavelength thick (281nm).

The laser 20μm-diameter pillar structure was fabricated by electron cyclotron resonance reactive ion etching (ECR-RIE), followed by evaporation of a titanium/gold ring p-contact, a thin titanium/gold semi-transparent film on the p-type side, and then a back-side gold-germanium/nickel/gold alloy n-contact. ■

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