Abstract

Coherent optical manipulations of semiconductor quantum dots (QDs) are currently receiving a lot of attention, not only for their fundamental interest but also in view of possible applications in quantum information technology. For a large number of experiments, a QD can be described as a two level system, defined by the presence (upper state) or absence (lower state) of a single exciton. Transitions between these two levels are induced via resonant optical excitation.

In the present work, the QDs are incorporated in a diode structure so that the internal electrical field of the device can be controlled via a bias voltage. This allows for very sensitive and, under certain conditions, quantitative electrical detection of the QD occupancy via the photocurrent. In addition, the QD energy levels can be varied very precisely via Stark-shift tuning. The single exciton transition is observed in the photocurrent as an extremely narrow resonance with a linewidth of only a few μeV.

In the case of cw-excitation, the QD occupancy exhibits a characteristic saturation behavior at high excitation power. This saturation is accompanied by a broadening of the homogeneous linewidth in exact quantitative accordance to theoretical predictions. We thereby verify the theoretical description of the QD as a two-level system. Furthermore, important system parameters like tunneling times and an energy splitting of different polarization states are determined with high precision.

For coherent investigations of the quantum dot we apply picosecond laser pulses. The optical excitation then is considerably faster than the dephasing time of the system. The fundamental experiment in this context is the observation of Rabi oscillations, demonstrating the ability to prepare arbitrary coherent superpositions of the two QD states. In the present work we present weakly damped Rabi oscillations up to pulse areas of almost $9\,\pi$, previously not attainable in semiconductor systems.

Double pulse experiments are used to gain information on the phase of coherent excitations. In these experiments the time evolution of a superposition state, generated by a first pulse, is detected via the interaction with

a second pulse at a well defined delay time. The amplitude of interference fringes exhibits an exponential decay which is used to infer the dephasing time of the QD system. In our device we are able to vary the tunneling rate and therefore the dephasing time via the bias voltage. Coherence times of several hundred picoseconds are reached at low bias voltage. In addition to the exponential decay, the interference amplitude is usually modulated by quantum beats originating from the asymmetry splitting of the QD. The quantum beats can be fully suppressed, though, by applying an appropriate polarization of the excitation light. All fundamental system parameters determined in cw experiments are quantitatively reproduced in the coherent (pulsed) measurements, even though the excitation power typically differs by at least five orders of magnitude.

Based on quantum interference effects we are able to obtain an extremely high sensitivity on the relative detuning of the QD transition with respect to the laser energy. At excitation with double pulses, a variation of the QD resonance via the Stark effect results in Ramsey fringes. The spectral width of the fringes decreases directly proportional to the temporal pulse separation and can get even smaller than the homogeneous linewidth of the transition. In addition, under certain measurement conditions with overlapping pulses, we are able to detect deviations from exact resonance of only a few percent of the laser linewidth.

Coherent control experiments on the biexciton are performed via resonant two-photon excitation. In contrast to single exciton Rabi oscillations the measured population oscillation of the biexciton is not purely sinusoidal in excitation pulse area. The experimental results are well reproduced by a theoretical calculation which relies only on the pulse shape and the biexciton binding energy. Dephasing times of the biexciton state are similar to those of the single exciton, under the applied measurement conditions reaching up to 220 ps.

In conclusion, by placing an InGaAs QD in a diode structure we obtain a single quantum system with electrical contacts. Voltage-based control and electrical detection not only open up a whole range of new possibilities for quantum optical experiments but also might provide a link between classical semiconductor technology and novel, coherent devices in the field of quantum information technology.