Applied Physics Letters

Tunnel-assisted manipulation of intersubband polaritons in asymmetric coupled quantum wells

Cite as: Appl. Phys. Lett. **89**, 171109 (2006); https://doi.org/10.1063/1.2367664
Submitted: 01 August 2006 . Accepted: 10 September 2006 . Published Online: 24 October 2006

Aji A. Anappara, Alessandro Tredicucci, Fabio Beltram, Giorgio Biasiol, and Lucia Sorba

Tunnel-assisted manipulation of intersubband polaritons in asymmetric coupled quantum wells

Aji A. Anappara, Alessandro Tredicucci,[a)] and Fabio Beltram
NEST CNR-INFM and Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy

Giorgio Biasiol
NEST CNR-INFM and Laboratorio Nazionale TASC CNR-INFM, Area Science Park, SS 14 Km 163.5, Basovizza, I-34012 Trieste, Italy

Lucia Sorba
NEST CNR-INFM and Laboratorio Nazionale TASC CNR-INFM, Area Science Park, SS 14 Km 163.5, Basovizza, I-34012 Trieste, Italy and Università di Modena e Reggio Emilia, Via Campi 213/A, I-41100 Modena, Italy

(Received 1 August 2006; accepted 10 September 2006; published online 24 October 2006)

The authors report the external control of the polariton ground state by manipulating the coupling between the intersubband transition and the photonic mode of a GaAs/AlGaAs microcavity. The vacuum-field Rabi splitting is varied by means of charge transfer between the energetically-aligned ground subbands of asymmetric tunnel-coupled quantum wells. The authors propose the use of this structure concept for implementing ultrafast modulation of intersubband polaritons. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2367664]

Intersubband optical transitions in doped quantum wells are the physical mechanisms behind novel optoelectronic devices such as quantum well infrared photodetectors,[1] quantum cascade lasers,[2,3] and ultrafast optical modulators.[4] Apart from their successful application as potential device concepts, they provide an ideal platform for probing fundamental physical properties, such as many-body effects,[5] optical nonlinearities,[6] and quantum coherent phenomena.[7] Recently, the interaction of intersubband excitations with a confined or quasiconfined electromagnetic field has been under intense theoretical study in view of investigating cavity electrodynamics and manipulating the resulting optical response.[8] Cavity field and electronic transition can be viewed as two oscillators which interact strongly when they are brought into resonance, and the coupling is larger than any dephasing time or lifetime. Analogous to the case of atoms and excitons, strong coupling results in a coherent periodic energy exchange between the excitation and the quantized electromagnetic field, with the formation of new elementary quasiparticles. The latter are the eigenstates of the full photon-matter Hamiltonian, and are usually named *cavity polaritons*. The coupled modes exhibit an anticrossing in energy with a level separation termed *vacuum-field Rabi splitting*, in analogy to the atomic physics phenomenon. Intersubband polaritons were first observed through angle-dependent reflectance measurements in GaAs/AlGaAs quantum wells embedded in a resonator based on total internal reflection. A clear mode splitting of several meV was detected up to room temperature.[9] The phenomenon was later studied in the photoconductive response of quantum well infrared photodetectors.[10]

In the strong-coupling case the strength of the optoelectronic coupling is determined by the ratio of the normal-mode splitting to the optical transition energy. Notably, for intersubband polaritonic systems this ratio can be significantly larger than achievable for the atomic or interband excitonic case.[11] Furthermore, in contrast to any other generic electronic excitation, intersubband microcavities represent a particularly appealing system since they allow the tailorability of the resonance parameters (subband spacing, oscillator strength, lifetime, and carrier density) through structural design. In a recent theoretical work, Ciuti *et al.* suggested the possibility to realize an intersubband microcavity system in which an unprecedented *ultrastrong coupling regime* of light-matter interaction can be reached. This was predicted to occur when the vacuum-field Rabi splitting becomes a large fraction of the intersubband transition energy.[12] Using the second-quantization formalism for the Hopfield-like Hamiltonian of the intersubband polariton system in the ultrastrong coupling regime, these authors pointed out the intrinsic nonclassical properties of the polariton ground state. They also suggested the possibility of releasing correlated virtual photon pairs from the polariton ground state through the nonadiabatic modulation of polariton coupling at frequencies of the order of the lower polariton resonance (approximately in the terahertz), in a process reminiscent of the dynamic Casimir effect.[12]

The vacuum Rabi splitting of a collection of oscillators in a single-mode cavity is proportional to the square root of their number N. In essence, the ensemble interacts collectively with the cavity field and behaves as a single oscillator with strength N times larger, thereby increasing the rate at which energy is exchanged with the electromagnetic radiation. For the case of intersubband transitions the role of the oscillators is played by the quantum well electrons. Recently, we have demonstrated the control of polariton coupling through the variation of carrier density. This was achieved by using a biased gate to deplete the quantum wells down to the limit where the Rabi splitting is suppressed and the polariton picture destroyed.[13]

Electrical control by gating, however, would not be suitable for the above purpose since the device capacitance unavoidably limits high-speed modulation. As an alternative, here we propose the use of charge transfer via electron tun-

[a)]Electronic mail: a.tredicucci@sns.it

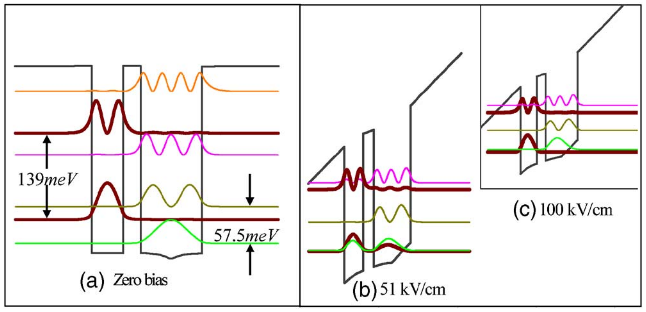

FIG. 1. (Color online) Conduction-band profile of the coupled quantum well structure and moduli squared of the relevant wave functions at (a) zero bias and (b) resonance field of ~51 kV/cm. The inset shows the band profile at an even higher electric field (~100 kV/cm).

neling between the energetically aligned conduction-band ground states of an asymmetric coupled quantum well structure. The time scale for resonant-tunneling processes can easily be of the order of a picosecond or even faster, and a fully optical experiment can also be envisaged to avoid the intrinsic frequency limitation of transport devices. For instance, an electron wave packet could be selectively photoexcited from the valence band in one of the wells, using an ultrafast optical pulse. The wave packet would be a coherent superposition of the two tunnel-split eigenstates, and, therefore, it would oscillate between the two wells with a frequency $\Delta E/h$, where ΔE is the splitting between the symmetric and antisymmetric eigenstates. Coherent electron oscillations at terahertz frequencies were already demonstrated in a similar structure by measuring the emitted terahertz radiation through time-domain spectroscopy.[14]

In this direction, we demonstrate here the control of the polariton ground state in asymmetric quantum wells subject to a static electric field. The principle of operation is to inject electrons by resonant tunneling into the ground state of the cavity-coupled quantum well. The sample is an asymmetric double quantum well structure, in which only the wide well is intentionally doped. The intersubband transition of the narrow well is resonant with the mode of the microcavity. The thickness and doping level of the wide quantum well are chosen to have only the first level populated in the absence of electric field. Since the narrow well is not populated, no polaritons exist and the reflectance measurements at zero bias yield only the cavity mode. When the ground states of the wells are brought into resonance, electrons start tunneling into the narrow well, and polaritons form from their electromagnetic coupling. At an even higher electric field, the majority of charge carriers localize in the ground state of the narrow quantum well, as it is now the lowest-energy subband, and the vacuum-field Rabi splitting is maximum.

The heterostructure was grown by solid-source molecular beam epitaxy on an undoped GaAs (001) substrate. It consists first of a low-refractive-index region composed of a 1.2 μm GaAs layer n doped to 5×10^{18} cm^{-3}, followed by a 1.5 μm thick AlAs layer. The active region features nine periods of asymmetric GaAs coupled quantum wells of thicknesses of 7.2 and 14 nm coupled through a 4 nm thick $Al_{0.33}Ga_{0.67}As$ barrier. The wide quantum well is delta doped in its center to yield a carrier density of 5×10^{11} cm^{-2}. Each period of the coupled wells is separated by a 35 nm $Al_{0.33}Ga_{0.67}As$ layer. The active region is sandwiched between top and bottom GaAs contact layers doped to 5×10^{17} cm^{-3} of thicknesses of 100 and 300 nm, respectively. The $Al_{0.33}Ga_{0.67}As$ spacer layers between the top and bottom contact layers and the active region are, respectively, 50 and 20 nm thick. The heterostructure is completed by a 7.5 nm GaAs cap layer to avoid Al oxidation. The metallic top contact was formed by evaporating Cr/Au with a thickness of 10/200 nm. Annealed Ohmic contacts were provided with Ni/AuGe/Ni/Au of thickness 5/150/5/100 nm, to the bottom contact layer, after wet etching to the appropriate depth. The cavity reflectance was obtained by employing mechanically lapped wedge-shaped prisms, with the facets at an angle of 70° with respect to the cavity plane. The experimental procedure is detailed in a previous article.[13]

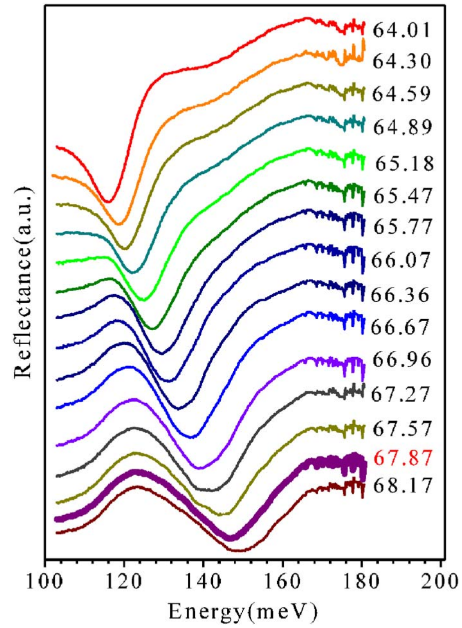

FIG. 2. (Color online) Reflectance measurements of the microcavity at zero bias for different angles of incidence. The measurements were performed in TM polarization at 4 K, with a resolution of 2 cm^{-1}.

The conduction-band profile and the energy eigenstates of the asymmetric coupled quantum well structure were cal-

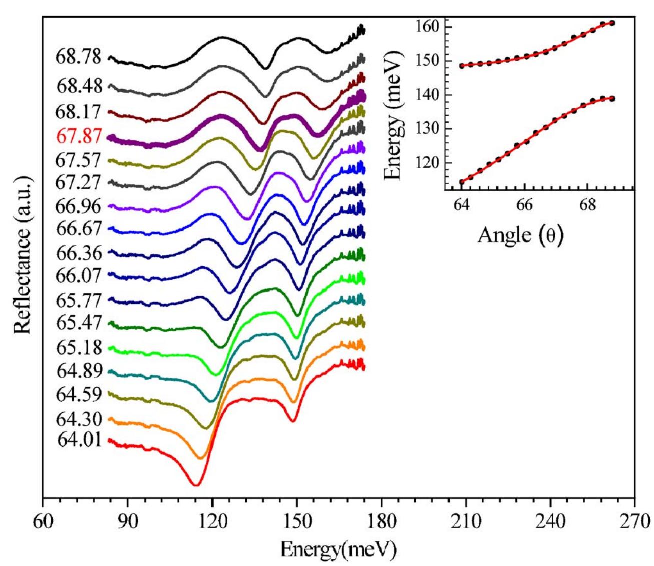

FIG. 3. (Color online) Angle-resolved reflectance data of the microcavity under an electric field of ~100 kV/cm. The inset contains the experimental points corresponding to the energy position of the dips.

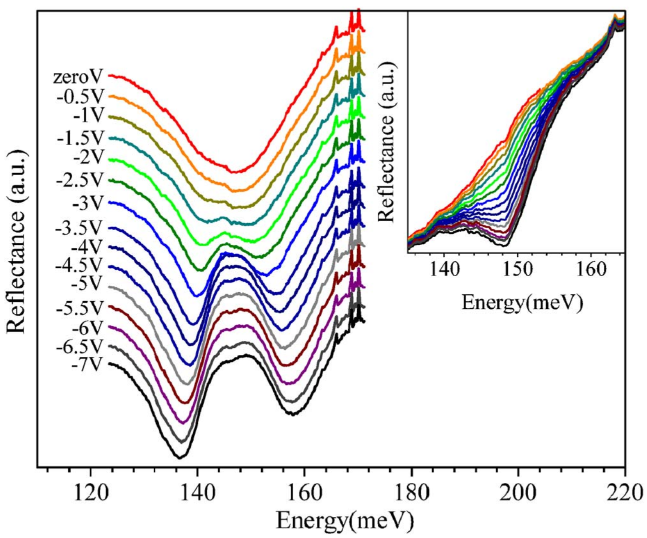

FIG. 4. (Color online) Reflectance spectra at the resonance angle of 67.87° as a function of electric field. The inset shows the intersubband absorption, measured using a 45° waveguide, at different electric fields.

culated by solving self-consistently the Schrödinger-Poisson equations. The band profile and moduli squared of the wave functions at different bias voltages are reported in Fig. 1. At zero bias the intersubband transitions of the narrow and wide quantum wells are at about 9 and 21 μm wavelengths, respectively. The Fermi energy at 4 K was calculated to be 18 meV. At an electric field of about 51 kV/cm, the ground subbands of the quantum wells are brought into resonance. The barrier thickness between the wells was chosen to have an energy splitting of the tunnel-coupled states of about 3 meV, small compared to the polariton linewidths.

The angle-resolved reflectance curves in transverse-magnetic (TM) polarization at zero bias voltage are reported in Fig. 2. By changing the angle of incidence, the cavity mode is tuned over a wide range of energies. The curves are offset for clarity. By depopulating the quantum well that is electromagnetically coupled to the cavity mode, the reflectance spectra exhibit a single peak, as expected.

The angle-resolved TM reflectance measurements at 4 K, with a bias voltage of 7 V ($\sim$100 kV/cm), are plotted in Fig. 3. The cavity mode is tuned across the intersubband transition energy by varying the angle of incidence. The two dips corresponding to the coupled-cavity-intersubband modes can be clearly identified. By increasing the angle, the position of the dips is shifted with a typical anticrossing behavior, manifesting the polariton dispersion. The vacuum Rabi splitting is found to be 21 meV at the internal resonance angle of 67.87°. The energy positions of the dips are plotted in the inset as a function of internal angle to better evidence the polariton anticrossing behavior.

Figure 4 depicts the low-temperature reflectance spectra of the same sample at the resonance angle of 67.87° as a function of bias voltage. At zero bias all the electrons are localized in the reservoir well and the spectrum is single peaked. As the bias voltage is raised, electrons are increasingly transferred into the ground state of the narrow quantum well, resulting in the formation of intersubband cavity polaritons. Since the vacuum Rabi splitting is proportional to the square root of the electron density, the increase in bias voltage increases the splitting, corresponding to the transfer of more and more electrons. The plot in the inset contains the intersubband absorption measured using a 45° waveguide at different bias voltages; in fact no cavity exists at this low angle, which is lower than the critical angle for total internal reflection. The intersubband absorption in the narrow well is nearly zero at zero bias and increases by increasing the (negative) bias, as expected.

Our results demonstrate the control of polariton coupling via the tunneling between the ground states of asymmetric coupled quantum wells. This study represents the realization of a first building block towards the ultrafast modulation of intersubband polariton coupling, which should allow the release of virtual correlated photon pairs from the polariton vacuum.

The authors thank C. Ciuti for valuable discussions and V. Piazza, J. Xu, and R. Green for their precious help.

[1] H. C. Liu, in *Intersubband Transitions in Quantum Wells: Physics and Device Applications II*, Semiconductors and Semimetals Vol. 62, edited by H. C. Liu and F. Capasso (Academic, San Diego, 2000), Chap. 2, p. 129.
[2] J. Faist, F. Capasso, D. L. Sivco, A. L. Hutchinson, and A. Y. Cho, Science **264**, 553 (1994).
[3] C. Gmachl, F. Capasso, D. L. Sivco, and A. Y. Cho, Rep. Prog. Phys. **64**, 1533 (2001).
[4] S. Noda, T. Uemura, T. Yamashita, and A. Sasaki, J. Appl. Phys. **68**, 6529 (1990).
[5] S. Luin, V. Pellegrini, F. Beltram, X. Marcadet, and C. Sirtori, Phys. Rev. B **64**, 041306 (2001); J. Li and C. Z. Ning, Phys. Rev. Lett. **91**, 097401 (2003).
[6] N. Owschimikow, C. Gmachl, A. Belyanin, V. Kocharovsky, D. L. Sivco, R. Colombelli, F. Capasso, and A. Y. Cho, Phys. Rev. Lett. **90**, 043902 (2003).
[7] J. Faist, F. Capasso, C. Sirtori, K. W. West, and L. N. Pfeiffer, Nature (London) **390**, 589 (1997).
[8] A. Liu, J. Appl. Phys. **80**, 1928 (1996); Phys. Rev. B **55**, 7101 (1997); M. Załużny and C. Nalewajko, *ibid.* **59**, 13043 (1999); R. Colombelli, C. Ciuti, Y. Chassagneux, and C. Sirtori, Semicond. Sci. Technol. **20**, 985 (2005).
[9] D. Dini, R. Köhler, A. Tredicucci, G. Biasiol, and L. Sorba, Phys. Rev. Lett. **90**, 116401 (2003).
[10] E. Dupont, H. C. Liu, A. J. SpringThorpe, W. Lai, and M. Extavour, Phys. Rev. B **68**, 245320 (2003).
[11] G. Rempe, H. Walther, and N. Klein, Phys. Rev. Lett. **58**, 353 (1987); J. M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73**, 565 (2001); C. Wiesbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).
[12] C. Ciuti, G. Bastard, and I. Carusotto, Phys. Rev. B **72**, 115303 (2005).
[13] A. A. Anappara, A. Tredicucci, G. Biasiol, and L. Sorba, Appl. Phys. Lett. **87**, 051105 (2005).
[14] H. G. Roskos, M. C. Nuss, J. Shah, K. Leo, D. A. B. Miller, A. M. Fox, S. Schmitt-Rink, and K. Köhler, Phys. Rev. Lett. **68**, 2216 (1992).