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Stark-tunable electroluminescence from cavity polariton states

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Electric-field tunable electroluminescence from intersubband transitions in a quantum well has been demonstrated via the strong coupling of the electronic transitions with an optical cavity mode. The device consists of a quantum cascade structure embedded in a planar metal-dielectric microcavity where electrons can be resonantly injected at different energies, thanks to the polariton dispersion curve. The electroluminescence tuning shows a strong far field angular dependence in accordance with the conservation of the in-plane momentum. Our experiment illustrates that it is possible to connect quantum optics and electronic transport in semiconductor heterostructures.
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Electronic transport and quantum optics have been traditionally two well distinct fields of quantum physics. The first experimental demonstration of the strong coupling regime between light and matter in semiconductor structures was reported already 16 years ago,[1] yet until recently all the experiments have relied on photon injection to excite cavity polaritons. A number of breakthroughs have been demonstrated using optical pumping, from polariton stimulated scattering[2] to polariton lasers,[3] and recently condensation.[4] However, one of the principal advantages of the semiconductor structures is precisely the possibility of exciting the radiative transitions by electrical injection. This crucial characteristic, fundamental of the very vast field of optoelectronics, simplifies enormously the device operation. In the last few months four papers have appeared describing electrical excitation of interband[5–7] and intersubband[8] cavity polaritons. In the latter report it has been proven that electrons accelerated through a cascade structure can populate polariton branches resonantly at the energies at which they are injected.

In this article we demonstrate that by changing the bias applied to the device, the energy of the emitted photons can be tuned, thanks to the formation of hybrid states arising from strong light-matter coupling. In fact, as in a single quantum well the intersubband transition energy is almost insensitive to the Stark effect, field-assisted frequency tunability in quantum cascade (QC) devices is typically achieved with the aid of spatially diagonal radiative transitions. We propose a less conventional approach: by dressing the material excitations with photons, we alter fundamentally the dispersion of the electronic states accessible for light emission, thus the properties of our device. This experiment demonstrates not only a path to achieve frequency tuning in QC structures, but also opens the way to a class of optoelectronic devices where electronic polarizations coherently interact with photons trapped in a microcavity.[9,10]

In Fig. 1 we illustrate the weight of the electronic polarization component as a function of the photon in-plane wave vectors, $k_\parallel$, for weak and strong couplings. This is the most meaningful representation to describe cavity polaritons. In fact, $k_\parallel$ is the quantity that is conserved across the optical interfaces, and it is thus the well-defined quantum number to describe our system. If θ is the angle between the normal to the layers and the direction of propagation of the photons *inside* the substrate, the relation that ties $k_\parallel$ with the angle θ can be written as

$$k_\parallel = E_p \frac{n_s}{\hbar c} \sin\,\theta, \tag{1}$$

where E_p is the photon energy, n_s is the substrate refractive index, $\hbar$ is the Planck constant, and c is the velocity of light.

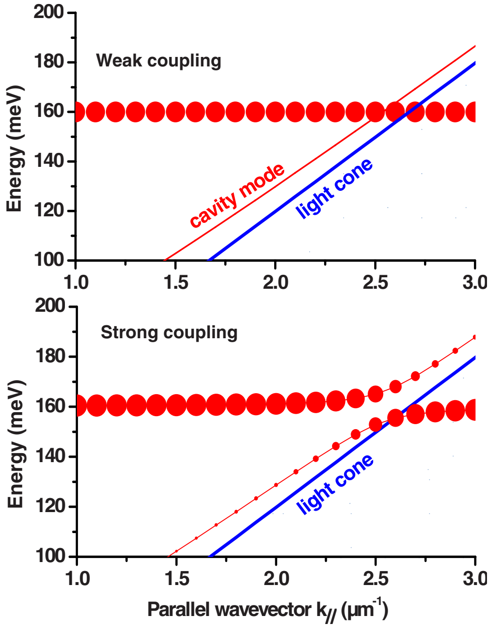

FIG. 1. (Color online) Weight of the electronic polarization component in the reciprocal space for weak (upper panel) and strong (lower panel) couplings. The radius of the dots is proportional to the Hopfield coefficient of the electronic part. The red line represents the dispersion of the cavity mode and the blue line represents the light cone. The region beyond the light cone is inaccessible in this experiment.

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The refractive index of the substrate defines the so-called light cone $k_{LC}=E_p n_s/\hbar c$, which gives the maximum accessible photon momentum (see Fig. 1).

The area of the dots is proportional to the probability of having a quantum of electronic polarization at a given point in the k-space. It is remarkable that in the strong coupling regime, the interaction with the photonic mode gives a finite probability for the polarization to oscillate at energies far from the bare electronic transition.

The device that we have used to probe this effect consists of a QC electroluminescent active material embedded into a planar microcavity, as described in Ref. 8. The active material is a heterostructure based on GaAs/AlGaAs and is composed of 30 identical units of an *injector/quantum-well region*. The structure is provided with metallic contacts and can be both electrically characterized and passively tested by absorption measurements. In the absence of the cavity, electrons are accelerated into the injector at a given energy and then into the first excited state of a single quantum well,[11] from where they can radiatively recombine by photon emission. Due to the presence of the cavity, the new stationary solutions of the system are electronic excitations dressed by photon modes, the cavity polaritons, whose dispersion is illustrated in Fig. 1 (lower panel). Because the energy position of the injector state is tunable through the applied bias, electrons can tunnel into polariton states at different energies, thus exploring the dispersion curve for different in-plane wave vectors $k_{\parallel}$.

Contrary to the case of exciton-polaritons, the anticrossing position is always far from $k_{\parallel}=0$. In fact, light at normal incidence does not interact with the electronic subbands. This is imposed by the intersubband selection rule that allows transitions only for the component of the electric field, E_z, perpendicular to the layers. When designing our structures, therefore, we set the crossing of the optical mode with the electronic transition at a large $k_{\parallel}$ in order to maximize light-matter interaction. Large values of $k_{\parallel}$ are obtained by shining light into the substrate through a facet polished with an angle of 70°.[12]

In our experiment, electroluminescence (EL) spectra are collected at a fixed angle θ and therefore, according to Eq. (1), the system is probed across a straight line in the k-space (see also solid lines in the main panel of Fig. 2). Due to the polishing angle of the facet, θ can be varied from 55° to 85°. For these large angles, we cannot neglect the fact that different photon energies correspond to very different $k_{\parallel}$.[13] As a consequence, the polariton peaks measured in a spectrum at a given angle do not correspond to the same $k_{\parallel}$, owing to their different energies. Essentially the energy position as a function of the angle does not reproduce at all the curve $E_p(k_{\parallel})$.[14] The latter is shown in the main panel of Fig. 2, where we plot the measured absorption peaks (triangles) as a function of $k_{\parallel}$ (the same data as a function of the angle are shown in Ref. 8). The peak positions are in very good agreement with those that can be simulated in the transfer matrix formalism (black line). The measured Rabi splitting is $2\hbar\Omega_R = 11$ meV.[8]

In the inset of Fig. 2, we present a set of EL spectra at different applied bias for $\theta=74.0°$. By changing the bias from 3.25 to 7.75 V, the EL peak shifts more than 35 meV, thus showing a strong Stark shift. The energy positions of the peak are reported in the main panel of Fig. 2 by (blue) circles. When the same experiment is repeated at 63.4° within the same voltage range, the EL peak practically does not move and is locked at ~162 meV (red squares). These phenomena can be understood by recalling that at a fix angle we are exploring the k-space following straight lines. The line $\theta=74.0°$ is almost parallel to the photon part of the polariton mode (blue solid line). In this case, we probe a vast range of $(E_p, k_{\parallel})$ pairs following the polariton dispersion relation. As already explained in Ref. 8, since the injection is resonant, we populate well-defined energies of the polariton branches within the broadening of the injector. By increasing the bias, the energy of the injector is also increased and therefore higher energies in the dispersion relation can be populated. For the straight line corresponding to 63.4°, there is only a very limited range of $(E_p, k_{\parallel})$ pairs that matches the polariton dispersion in the energy region accessible by the tuning of the injector. Hence, only one photon energy can be collected independently on the bias.

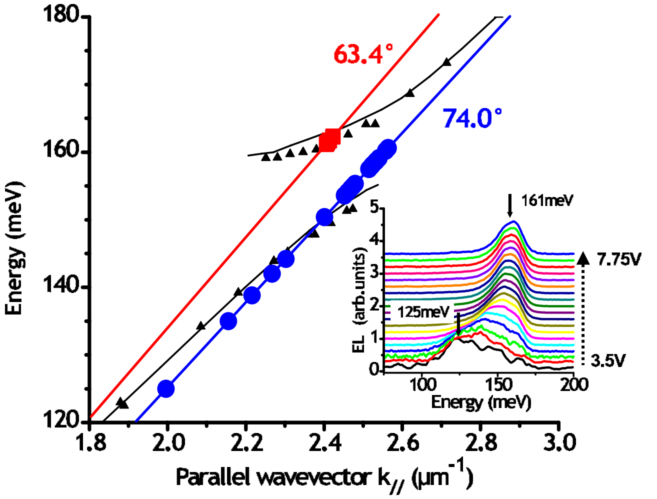

FIG. 2. (Color online) Main panel: energy positions of the polariton peaks obtained by absorption measurements (triangles) compared with the simulated ones (black line) as functions of the photon in-plane momentum, $k_{\parallel}$. The red squares (blue circles) are the energy positions of the EL peaks measured at 78 K at different voltages (ranging from 3.5 to 7.75 V with steps of 0.25 V) and at 63.4° (74.0°) angle. Notice the difference between the Stark tuning of the EL at 74° and 63.4°. The red and blue lines, extracted from Eq. (1), represent the subspace explored during a measurement performed at a fixed angle. Inset: EL spectra measured at 74° internal angle at different voltages (from 3.5 to 7.75 V with steps of 0.25 V). The spectra have been acquired with a Fourier transform infrared spectrometer operated in step-scan mode with a resolution of 8 cm^{-1} and a liquid-nitrogen cooled mercury cadmium telluride detector. The typical pulse width (repetition rate) used is 3 μs (100 kHz).

The Stark tuning is also clearly visible by comparing the three panels of Fig. 3. Here we present two-dimensional (2D) color plots of the EL measured at a fixed voltage in which the color scale corresponds to the light intensity as a function of E_p and $k_{\parallel}$. In the three panels from bottom to top, the voltages are 3.7, 5, and 6 V, corresponding to an injected current of respectively 3.3 mA (10.5 A/cm^2), 60 mA (191.0 A/cm^2), and 268 mA (0.853 kA/cm^2). These 2D color plots, obtained by measuring ~40 spectra at different angles between 55° and 85°, are in our opinion the most compact and comprehensive way to represent the EL from intersubband devices operating in the strong coupling regime. Several features can be observed in these plots. First, in all of them, the presence of the two polariton branches can

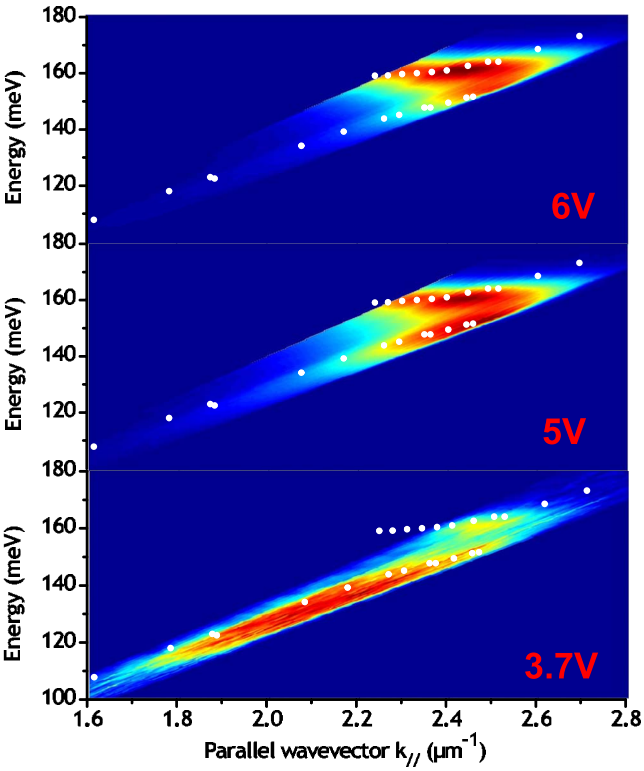

FIG. 3. (Color online) 2D color plots of the EL intensity (color scale) as a function of the energy and the in-plane momentum. The spectra have been recorded under the same experimental conditions as in Fig. 2. The white circles are the two polariton branches as measured in the absorption experiment.

be clearly identified. Second, the maximum of the EL intensity has different ($E_p^{\max}, k_{\|}^{\max}$) coordinates when changing the bias. The variation in $E_p^{\max}$ reflects the Stark tuning: it moves from 130 meV at 3.7 V to 150 meV at 5 V and 162 meV at 6 V. At 3.7 V, the minimum splitting between the two branches is equal to the one extracted from the absorption measurements. At 5 V two maxima are observed. In fact, due to the broadening of the injector, both polariton branches are populated. At higher applied voltages, the injector aligns with the upper state of the quantum well and remains locked to this value.[11] For a further increase in the voltage, most of the electrons in the ground state leave the quantum well. In this case, the difference of the electronic population between the lower and the upper states diminishes, hence the Rabi splitting tends to zero.[15] By comparing the EL dispersion with the one measured in absorption (white circles in Fig. 3), we can notice that at 6 V the Rabi splitting is reduced. The value of the Rabi splitting at this voltage is estimated to be $2\hbar\Omega_R = 4$ meV, corresponding to an electronic density of 1×10^{11} cm^{-2}. The combination of the injection locking and the depletion of the quantum wells are the main effects that prevent us to tune the EL across the polariton upper branch.

In conclusion we have reported evidence of electric field tunable EL from a QC structure operating in the strong coupling regime. The relative tuning $\Delta\nu/\nu$ is in excess of 20% and is visible only for the angles that are tangent to the polaritonic dispersion curve of our system. Our results demonstrate a class of devices with new functionalities originating from the light matter strong interaction.

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