Quantum confinement of exciton-polaritons in a structured (Al,Ga)As microcavity

Alexander S. Kuznetsov,* Paul L. J. Helgers, Klaus Biermann, and Paulo V. Santos
Paul-Drude-Institut für Festkörperelektronik, Leibniz-Institut im Forschungsverbund Berlin e. V., Hausvogteiplatz 5-7, 10117 Berlin, Germany

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The realization of quantum functionalities with polaritons in an all-semiconductor platform requires the control of the energy and spatial overlap of the wave functions of single polaritons trapped in potentials with precisely controlled shape and size. In this study we reach the confinement of microcavity polaritons in traps with an effective potential width down to 1 µm, produced by patterning the active region of the (Al,Ga)As microcavity between two molecular beam epitaxy growth runs. We correlate spectroscopic and structural data to show that the smooth surface relief of the patterned traps translates into a graded confinement potential characterized by lateral interfaces with a finite lateral width. We show that the structuring method is suitable for the fabrication of arrays of proximal traps, supporting hybridization between adjacent lattice sites.

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I. INTRODUCTION

The strong coupling of the resonant light field (cavity mode) and quantum-well excitons in a planar semiconductor microcavity (MC) results in a Rabi splitting leading to the creation of exciton-polariton quasiparticles (simply, microcavity polaritons, MPs) [1–4]. MPs display a wide range of attractive properties arising from their dual light-matter nature, such as bright directional emission, lasing [5,6], macroscopic spatial coherence at Kelvin temperatures [7], Bose-Einstein-like condensation (BEC) [8], and strong nonlinearities [8–10]. MPs offer a pathway to bridge conventional microelectronics and quantum technologies in an all-semiconductor platform [11]. Many fundamental effects have been demonstrated with polaritons, such as topological edge states [12], Josephson oscillations [13], superfluidity [14], lattice effects [15–17], etc.

In order to achieve quantum functionalities (e.g., qubits [18], topological circuits [19], and quantum simulators [20]) one needs polariton confinement potentials as well as engineered lattices supporting polariton interactions and coherent control down to a single polariton level. Specifically, the low effective mass of MPs (typically on the order of 10−4 of the free electron mass \( m_e \)) and, consequently, their µm-sized thermal de Broglie wavelength (on the order of a few µm at 4 K), favors the observation of confinement effects under µm-size modulation potentials. Different approaches have been reported to create polariton modulation potentials based on the energy control of MP excitonic or photonic components [21–27]. A particularly attractive approach for the formation of MP traps and lattices is the patterning by shallow etching of the MC spacer followed by overgrowth by molecular beam epitaxy (MBE) [28–31]. Here the MBE growth is interrupted after the deposition of the MC spacer (cf. Fig. 1)—the sample is then structured by shallow etching and reinserted into the MBE chamber for the growth of the upper distributed Bragg reflector (DBR). This structuring approach is particularly useful since it affects only the MPs photonic modes while keeping intact the quantum wells (QWs) embedded into the MC spacer, which are very sensitive to etching-induced defects. In addition, it allows the fabrication of traps and lattices of arbitrary shape and large confinement potentials. Finally, the structuring procedure is compatible with the formation of tunable lattices and traps via the dynamic modulation by acoustic fields [25].

While previous studies have demonstrated the confinement of MPs in traps as well as intertrap interactions in lattices produced by MBE overgrowth [28,29,31], little attention was given to the correlation of the physical shape of the traps and the spatial profile of the resulting MP trapping potential. One of the reasons is that most of these studies have addressed traps with dimensions of a few µm, for which the shape of the confinement potential are close to the ones defined by the lithographically patterned areas on the MC spacer. The situation changes significantly for smaller traps. In particular, the MBE overgrowth process on the patterned surface is not conformal and also directionally anisotropic [32–34]. As a result, the overgrowth smoothens the lateral interfaces and distorts the shape of the structures defined by etching of the MC spacer. The precise knowledge of the resulting MP potential profiles is critical for design of tunnel-coupled traps with µm sizes. Likewise, the spatial extent of the potential imposes a limit on the on-site interaction strength of single polaritons, which for unconfined polaritons lies in the range of 0.01 [35,36] to 1 meV \( \mu m^2 \) [37].

In the present work we show the ability to confine polaritons in arrays of µm-sized intracavity traps created by patterning an (Al,Ga)As MC in-between growth steps by molecular MBE. We present a detailed study of the impact of the structuring and subsequent MBE overgrowth on the energy of the confined states, aiming to determine the minimum confinement dimensions that can be achieved by the process. The investigations were carried out by combining structural data obtained by atomic force microscopy (AFM) with spectroscopic studies using spatially resolved reflection, and spatially and momentum resolved photoluminescence (PL) to probe the MP energy levels and wave functions. We show that the MBE overgrowth process gives rise to a graded potential profile for the lateral interfaces of the traps with different interface widths along the [−110] and [−1−10] surface directions of the (001) GaAs.
energies.

molecular beam epitaxy, resulting in regions with different polariton reflectors (DBRs) was varied by combining etching and overgrowth by structured spacer enclosing GaAs QWs grown on a GaAs(001) substrate. The thickness of the spacer between the distributed Bragg reflectors (DBRs) was varied by combining etching and overgrowth by molecular beam epitaxy, resulting in regions with different polariton energies.

FIG. 1. A sketch of the (Al,Ga)As microcavity (MC) with the structured spacer enclosing GaAs QWs grown on a GaAs(001) substrate. The thickness of the spacer between the distributed Bragg reflectors (DBRs) was varied by combining etching and overgrowth by molecular beam epitaxy, resulting in regions with different polariton energies.

In the following section (Sec. II) we describe the design and processes for the fabrication of the structured MC as well as the structural and spectroscopic techniques used in the studies. The experimental results are presented in Sec. III: here we start by analyzing the impact of the MBE overgrowth on the shape of the mesas (Sec. III A) and by addressing the polariton energy levels in extended etched and nonetched areas (Sec. III B). Experimental results demonstrating MP confinement in 2D and 3D and their relationship to the confinement dimensions are then presented in Secs. III C 1 and III C 2, respectively. Section III D presents a direct spectroscopic evidence of coupling between proximal traps in arrays. In Sec. III E we discuss the condensation of MP in a single trap as well as the mechanisms limiting the linewidth of the emission lines. Section IV summarizes the main results of the studies.

II. EXPERIMENTAL DETAILS

The structured (Al,Ga)As MC was grown on a 2 inch (001) GaAs substrate by MBE (cf. Fig. 1). We first grew a 4.43-μm-thick composition-graded lower DBR consisting of 36 λ/4 (λ is the optical wavelength) pairs of Al0.15Ga0.85As/AlxGa1−xAs with Al composition x continuously reducing from 0.80 in the first stack to 0.45 in the last stack. The first 120 nm of the Al0.3Ga0.7As MC spacer were then deposited including six 15-nm-thick GaAs QWs placed at the antinode positions of the MC optical mode. The structure was subsequently capped by a 170-nm-wide Al0.15Ga0.85As layer spacer. The sample was taken out of the MBE chamber and then patterned by means of photolithography and wet chemical etching. The latter creates mesas with a nominal height of 12 nm of different shapes in the exposed spacer layer, thus inducing a lateral modulation of the cavity thickness and, therefore, of the cavity energy in the final structure. The etching depth was selected to blueshift the optical cavity mode in the etched areas by 9 meV (4.5 nm) with respect to the nonetched regions. The upper surface of the etched layer corresponds to a node of the optical cavity mode of the whole structure. In this way, we minimize potential impact of roughness or impurities introduced by the ex situ patterning on optical properties of the structure. Furthermore, the shallow patterned layer is located more than 140 nm above the QWs, so that we can safely assume that they remain unaffected by the processing.

The sample was then reinsered into the MBE system, cleaned by exposure to atomic hydrogen (30 min at 450 °C at a pressure of 2 × 10−5 mbar), and overgrown with a λ/4 Al0.15Ga0.85As layer, followed by the upper DBR. The latter consists of 20 λ/4 pairs of Al0.15Ga0.85As/Al0.75Ga0.25As.

The morphology of the overgrown sample surface was observed by atomic force microscopy (AFM) using a Bruker dimension edge system.

The sample was designed to be in the strong coupling regime both in the etched and nonetched regions, leading to MPs in these two regions with different energies and photon/exciton contents. The lateral modulation was used to create 2D (wires) and 3D (dots) confinement in nonetched areas surrounded by etched barriers, which were probed by low-temperature reflection and photoluminescence (PL).

Reflection and photoluminescence (PL) spectra of different regions of the sample were recorded at 10 K using a liquid nitrogen-cooled CCD camera (Princeton Instruments) coupled to a spectrometer (SPEX 750M). The spatially or momentum resolved PL studies were performed under excitation by a focused laser beam from either a tunable Sirah Matisse Ti:sapphire CW laser or a quasi-CW laser diode (repetition frequency = 40 MHz) emitting at 635 nm. The 2D images, recorded on the CCD, map the spectral distribution of the reflectivity and PL along the image cross section defined by the spectrometer slit.

III. RESULTS AND DISCUSSION

A. Structural properties

The overgrowth of the structured spacer results in a measurable relief of the sample surface. The latter was probed by scanning an AFM tip over the surface of the patterned areas, as shown for rectangular (i.e., wirelike) surface mesas in Fig. 2(a). The nominally 12-nm-thick mesas defined in the MC spacer give rise to a surface relief with a height of 15 nm after the MBE overgrowth. For large mesas [e.g., Fig. 2(b)], the dimensions correspond to the ones defined in the spacer region by photolithography and the etching process. For smaller mesas, however, the surface structures reproduce the intended shape along the y||[−1−10] surface direction but their edge profiles become broader along the perpendicular x||[−110] direction [Figs. 2(c) and 2(d)].
In order to quantify the changes in the shape, we first compared the size of the surface mesa with the dimensions of the etched structures. Figure 2(e) shows an exemplary AFM profile along the [−1−10] direction of the nominally $w_{y,\text{nom}} = 8\mu m$-wide wire of Fig. 2(b). From the measurement we extract the actual wire width ($w_{y}$) along [−1−10], defined as the full-width at half-maximum (FWHM) of the AFM profiles. The dots in Fig. 2(f) display the FWHM of the AFM profiles $w_{x}$ and $w_{y}$ along [−1−10] and [−1−10] direction of the surface profiles, respectively, as a function of the nominal widths of the mesa defined in the MC spacer. The measured points for $w_{y}$ follow closely a linear relation $w_{y} = w_{y,\text{nom}} + \Delta w_{y}$, as confirmed by the small value for the deviation $\Delta w_{y} < 0.3\mu m$ with respect to the line $w_{y} = w_{y,\text{nom}}$ (diagonal dashed line). The latter indicates that the surface mesa dimensions along $y||[−1−10]$, as defined in the MC spacer. In the case of the $x||[−1−10]$ direction the linear slope of $w_{x}$ is also preserved. Note, however, that $w_{x}$ is on average 1$\mu m$ larger than the nominal width, thus indicating a substantial size increase along this direction.

In addition to the change in average dimensions, a second consequence of the shape anisotropy is a change in the abruptness of the mesa edges. The latter will be quantified in terms of the interface widths $L_{x}$ and $L_{y}$ along $x$ and $y$, as defined in Fig. 2(e). The widths of the left ($L_{\text{Left}}$) and right ($L_{\text{Right}}$) lateral interfaces were found to be approximately the same for both crystallographic directions. The value of $L_{i}$ ($i = x,y$) was determined as the average value $(L_{\text{Left},i} + L_{\text{Right},i})/2$. The dependence of $L_{i}$ on the nominal width of the wires is summarized in Fig. 2(f). The lateral interfaces are much more abrupt along $y$ (with $L_{y} \leq 1\mu m$) than along $x$ (with $L_{x} \approx 2\mu m$). This difference in lateral interface widths is attributed to a combination of three factors. The first is the atomic incorporation rate at the shallowly inclined etched sidewalls (about 10 deg with respect to the sample plane) during MBE growth, which is distinct from the one for the normal (001) surface. The other two factors are associated with the (2 × 4) reconstruction of the growing surface, which leads to (i) an enhanced diffusion of adatoms along $x||[−1−10]$ and, simultaneously, to (ii) a more efficient incorporation at step edges along the perpendicular direction [32–34]. The resulting effect is a smoothening of the lateral interface profile, which is much more pronounced for the $x$ than for the $y$ direction.

According to Fig. 2(e), interface smoothening is essentially independent of the width of the mesas. The growth-induced shape anisotropy of the interface has, therefore, a stronger impact on small structures defined within the spacer. In particular, small square mesas, see Fig. 3(a), turn into rectangular structures with rounded shape at the sample surface, as illustrated in Fig. 3(b) for an etched mesa with a nominal width of 4$\mu m$. The cross sections of the mesa height displayed in Figs. 3(c) and 3(d) show that the edge profiles along the $x||[−1−10]$ direction are much smoother than the ones along $y||[−1−10]$. We will show in Sec. III C 2 that the shape anisotropy has a pronounced effect on the symmetry and emission energy of the confined MP levels.

B. Polariton energy levels

Optical reflectivity at 10 K was employed as the basic characterization tool to access the optical properties of the etched and nonetched areas of the sample. The spatial reflectivity map displayed in Fig. 4(a) was recorded by imaging a 110-μm-long and 3-μm-wide area of the sample surface on the slit of the

FIG. 2. Surface relief of different regions of the microcavity. (a) A schematic representation of a wirelike mesa defined in the MC spacer. (b)–(d) Atomic force microscopy (AFM) images of the surface profile of three wirelike mesas with nominal widths of 8, 4, and 2 $\mu m$, respectively. The mesa edges expand along the $x||[−1−10]$ direction due to the anisotropic overgrowth. (e) An exemplary AFM profile of the wire in (b) along $y||[−1−10]$ direction. The $w_{y}$, $L_{\text{Left}}$, and $L_{\text{Right}}$ define the full-width half-maximum and interfaces width $L = (L_{\text{Left}} + L_{\text{Right}})/2$, respectively. (f) Dependence of the measured values of $w_{x}$ and $w_{y}$ and $L_{x}$ and $L_{y}$ on the nominal wire width. The values were extracted from plots akin in (e).
FIG. 3. (a) Schematic structure and (b) AFM map of the square-like surface relief arising from the overgrowth of a nominally 4 × 4 µm² mesa defined in the cavity spacer. (c) and (d) Height cross sections of the surface relief in (b) along \( y \parallel [−1\text{−}10] \) and \( x \parallel [−1\text{−}10] \), respectively, showing the effects of the anisotropic overgrowth on the mesa shape. The \( w_x \) and \( w_y \) denote the full-width at half-maximum along \( x \) and \( y \), respectively. \( L_x \) and \( L_y \) are the corresponding interface widths.

spectrometer. The measured sample area contains spatially extended (width \( \approx 40 \text{ µm} \)) nonetched (nER) and etched regions (ER) separated by two narrow (\( \approx 10 \text{ µm} \)) wirelike ER and nER regions. Both the nER and ER areas of the map show pronounced resonances close to the center of the stopband, which covers the spectral range from 1.49 eV to 1.58 eV. The reflectivity spectra of extended nER and ER areas, spatially integrated over their respective regions, are shown in Figs. 4(b) and 4(c), respectively. As expected, the resonances in the ER are blueshifted with respect to the ones in the nER.

Figures 4(d) and 4(e) show momentum-resolved PL spectra recorded at 10 K on extended nER and ER regions, respectively, under nonresonant excitation (\( E_{\text{Exc}} = 1.631 \text{ eV} \)) and low excitation density (0.3 W/cm²). The PL maps of nER and ER regions close to the \( \Gamma \) point (i.e., for in-plane wave vectors \( k_{\text{in-plane}} = 0 \)) are characterized by parabolic signatures typical of the lower and upper MP branches. The emission of the lowest MP branches dominates PL spectra of both regions. The experimental dispersions are well fitted by the solution of the eigenvalue problem for three coupled oscillators representing the bare optical (\( C_i, i = \{\text{nER}, \text{ER}\} \)) mode of the MC as well as the bare heavy-hole (\( X_{\text{HH}} \)) and light-hole (\( X_{\text{LH}} \)) excitonic resonances of the QWs (note that the bare excitonic energies are the same in the nER and ER areas). For the fits, we set the energy for the excitonic resonances to \( X_{\text{HH}} = 1534 \text{ meV} \) and \( X_{\text{LH}} = 1540.6 \text{ meV} \) and varied the Rabi-splitting (\( \Omega_{\text{HH},i}/\Omega_{\text{LH},i} \)) as well as cavity detuning \( \sigma_{C,i} \) in both regions of the sample. The best match between the experiment and calculation was obtained for the parameters listed in Table I. The Hopfield coefficients obtained from the fits were used to determine the effective masses of the lowest polariton branches listed in the last row of the table. Using the results in Table I we can better understand the spectral features of nER and ER spectra shown in Figs. 4(b) and 4(c), respectively. In the nonetched regions, the optical cavity mode mainly couples to \( X_{\text{HH}} \) states—it’s interaction with the \( X_{\text{LH}} \) is weak (\( C_{\text{nER}} \cdot X_{\text{LH}} \approx 12 \text{ meV} > \Omega_{\text{LH},\text{ER}} \)) but still with sufficient oscillator strength to enable the observation of this mode within the stopband. In the etched regions, the cavity resonance energy shifts to higher values, thus leading to comparable light-matter coupling between the \( X_{\text{HH}} \) and \( X_{\text{LH}} \) states.

FIG. 4. (a) Spatially resolved reflectivity of the structured microcavity at 10 K. The horizontal axis corresponds to the orientation of the spectrometer slit along the \( x \parallel [−1\text{−}110] \) direction of the sample surface. The top-view area of the graphic designates the sample surface imaged on the spectrometer slit. (b) and (c) Measured reflectivity spectra (thick black lines) integrated over the nER(A) and ER(B) regions in the top-view part of (a), respectively. Reflectivity spectra of the respective regions calculated by transfer matrix are shown by the thin red curves. (d) and (e) Momentum-space maps of PL of spatially extended nER and ER, respectively. The dashed lines represent bare (uncoupled) dispersion of the heavy-hole (\( X_{\text{HH}} \)) and light-hole (\( X_{\text{LH}} \)) excitons and photonic modes (\( C_{\text{nER}} \) and \( C_{\text{ER}} \)). Thin red lines correspond to the calculated lower branch (LP_{\text{nER/ER}}) and middle-branch (MP_{\text{nER/ER}}) of polariton dispersions.

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TABLE I. Parameters for the polariton states of the nonetched (nER) and etched (ER) spatially extended regions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nonetched region (i = nER)</th>
<th>Etched region (i = ER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{HH}$</td>
<td>1534 meV</td>
<td>1534 meV</td>
</tr>
<tr>
<td>$X_{LH}$</td>
<td>1540.6 meV</td>
<td>1540.6 meV</td>
</tr>
<tr>
<td>$\sigma_{Ci} = C_i - X_{HH}$</td>
<td>($-5.4 \pm 0.2$) meV</td>
<td>($4.3 \pm 0.3$) meV</td>
</tr>
<tr>
<td>$\Omega_{HH}$</td>
<td>($7.6 \pm 0.2$) meV</td>
<td>($6 \pm 0.2$) meV</td>
</tr>
<tr>
<td>$\Omega_{LH}$</td>
<td>($5.6 \pm 0.2$) meV</td>
<td>($4.6 \pm 0.2$) meV</td>
</tr>
<tr>
<td>$m_p^{LP}$</td>
<td>($5.5 \pm 0.3 \times 10^{-5} m_e$)</td>
<td>($2 \pm 0.1 \times 10^{-4} m_e$)</td>
</tr>
</tbody>
</table>

The effect of etching on the optical properties is well reproduced by transfer matrix calculations of the optical reflection using the parameters listed in Table I. Since etching only changes the optical resonance energy $C_i$, the bare excitonic resonances ($X_{HH}$ and $X_{LH}$) remain constant over the sample surface. The same set of parameters was used for nER and ER areas, apart from the spacer thicknesses in nER and ER areas, which determine the bare photon energies $E_{RnER}$ and $E_{RER}$ of the QWs. For that purpose, the heavy-hole (light holes) absorption cross section was modeled by a Lorentzian resonance ($\omega_{ \Gamma}$) of the nonetched (LP$nER$) region and etched areas, respectively. To improve the fitting, the thicknesses of the lower (upper) DBR layers were slightly reduced (increased) by 0.6% (1.2%) with respect to the nominal layer thicknesses to better reproduce the overall shape of the stopband in the reflectivity spectrum. In addition, the difference in the spacer layer thickness of the nonetched and etched areas was set to 14 nm, which is only slightly larger than the intended etching depth of 12 nm.

The numerical simulations reproduce nicely the energies and amplitudes of the measured spectral features of both the etched and nonetched regions. One discrepancy is the larger measured linewidth of the lowest resonance in the nonetched region [Fig. 4(c)]. The latter is an artifact due to the large numerical aperture of NA = 0.28 of the 20× objective used to record the data. Specifically, this NA value corresponds to a collection angle of ±16° with respect to the surface normal (in air), which translates into ±2.15 μm⁻¹ in-plane momentum range. According to Fig. 4(d), the latter yields approximately 3 meV energy range. In contrast, the numerical transfer matrix simulation was done only for the normal incidence. Thus, in the calculated spectrum, the linewidth is given by the cavity quality factor and excitons parameters.

Finally, a close examination of Fig. 4(a) reveals that the polariton states within one area (etched or nonetched) are normally confined to this area. They can, however, tunnel through narrow (10 μm wide) stripes separating two equal (nER or ER) areas.

C. Confined polariton states

The results in Table I show that there is roughly an energy difference $\Delta E_{LP} = LP_{ER} - LP_{nER} \approx 6 \pm 0.5$-meV-wide energy gap at the $\Gamma$ point between the lower polariton (LP) branches of the nonetched (LP$nER$) region and etched (LP$_{ER}$) region. Traps for the quantum confinement of polaritons can then be engineered by sandwiching the nonetched areas between the etched ones. In the following, we investigate the confinement of the lower polariton states by 2D and 3D potentials.

1. Two-dimensional confinement

Figures 5(a)–5(c) display PL maps spatially resolved along the $x||[-110]$ direction of single nER wires with nominal widths of 10, 6.4, and 3.2 μm surrounded by etched barriers. The PL was excited by a focused laser spot (FWHM of 10 μm, $E_{exc} = 1.952$ eV) positioned at the center of the wire. In the figures, the horizontal axes are aligned in parallel with the wire cross sections along the $x||[-110]$ direction, which correspond to the smooth edge profile after the overgrowth (cf. Fig. 2). The images display a series of confined states with increasing energy $E_n$, where $n = 1, 2, \ldots$ denotes the order of the confined states, located between LP$nER$ and LP$_{ER}$. As expected, the energetic splitting between two successive confined levels increases with decreasing wire width. The color-scaled PL intensity modulation yields the profile of the squared MP wave function amplitude $|\Psi_n|^2(x)$ across the wire width $x$. The number of maxima corresponds to the order $n$ of the confined state. The observation of confined states in wires with widths up to 15 μm is a consequence of the very low effective mass $m_p$ of the photoniclike polariton states. As a consequence, the dimensions required to induce quantum confinement increase by a dimensionless factor $A = \sqrt{m_e/m_p}$ relative to the ones

![FIG. 5. Photoluminescence maps of exciton-polaritons confined in wirelike nER structures with nominal widths (w$_{nom}$) of (a) 10 μm, (b) 6.4 μm, and (c) 3.2 μm, measured along x||[-110] direction. The energy of the lower polariton state in the etched region LP$_{ER}$ = 1532.5 meV is taken as the reference energy.](image-url)
modes with barrier height $\Delta E_{LP}$. We determined these energy levels by numerically solving the Schrödinger equation for a square potential with height $\Delta E_{LP}$ and polariton effective mass $m_p$. The calculations were carried out in Fourier space for a periodic supercell containing the wire potential surrounded by wide barriers (i.e., with dimensions comparable to the wire width). The periodic potential was expanded in 64 plane waves—we have checked that the energy of the confined states remains approximately the same if 32 or more plane waves are used. The dashed lines superimposed on the measured data in Fig. 6(a) show the calculated levels $E_n$ for a square potential with a height $\Delta E_{LP} = 5.5$ meV and polariton effective mass $m_p = 5.5 \times 10^{-5} m_e$ from Table I. The solutions given by the dashed lines are valid for integer value of $n$. The model reproduces reasonably well the energy spectra for the larger wires, $w_x = 10, 8$, and 6.4 $\mu m$, but fails in the case of narrower wires.

The discrepancies between the predictions from the square potential model and the experiments are attributed to the rounded shape of the lateral potential barriers discussed in Sec. III A. In order to account for this effect, we have calculated the energy levels assuming a graded interfacial potential $V_i(i)$, where $i = (x, y)$ is the direction index, between the nonetched and etched regions given by

$$V_i(i) = -\frac{\Delta E_{LP}}{2} \left[ \text{Erfc} \left( \frac{x - w_x/2}{\sqrt{2}\delta w_i} \right) + \text{Erfc} \left( \frac{x + w_x/2}{\sqrt{2}\delta w_i} \right) \right],$$

(1)

Here, Erfc($\xi$) is the complementary error function, $x$ is the spatial coordinate in the direction given by $i$, and $\delta w_i$ describes the effective width of the lateral interface between nonetched and etched regions. The solid lines in Fig. 6(a) display the calculated energy levels for the potential of Eq. (1) assuming $i = x |[-110]$, $w_i = w_x = w_{nom} + \Delta w_x$, $\delta w_i = \delta w_x = 0.75 \mu m$ and $m_p = 5.5 \times 10^{-5} m_e$. Here $w_{nom}$ is the nominal wire width and $\Delta w_x = 1 \mu m$ is a small correction factor introduced to account for changes in width due to the anisotropic overgrowth (cf. Sec. III A). The assumed value for $\delta w_x$ yields a length $L_x = 3 \mu m$ for the lateral interface, cf. Fig. 3(d), which is close to the one determined for the $x |[-110]$ direction in Sec. III A. With these assumptions, the potential reproduces very accurately the energy of all confined states for all wire widths.

Figure 6(b) displays the squared wave functions $|\Psi_n(x)|^2$ for the first confined states ($n = 1, 2, 3$) in a nER wire of a width $w_i = w_{nom} + \Delta w_x = 3.2 + 0.5 \mu m$. The calculations yield a spatial extent of $|\Psi_n(x)|^2$ similar to the ones measured in Fig. 5(c). When compared to a square potential, the smooth interfacial profile given by Eq. (1) reduces the spatial extent of $|\Psi_n(x)|^2$ for modes with energy $\Delta E_{LP} < E_n < -\Delta E_{LP}/2$ and increases it for $-\Delta E_{LP}/2 < E_n < 0$. For narrow wires (i.e., with widths comparable to $2\delta w_x$), the shape of the confinement potential $V_i(x)$ as well as the increased penetration into the barriers lead to a spectrum with approximately equidistant energy levels. The confined levels of the narrow wires in Fig. 6(a) follow indeed very closely this behavior. Finally, we note that the finite width of the lateral interfaces substantially reduces the depth of confinement potential for wire widths $<2\delta w_x$. 

FIG. 6. (a) Dependence of the confined energy-levels $\Delta E_n$ on the nominal wire widths (symbols) extracted from spatial PL maps akin to the ones in Fig. 5. The energies are relative to the barrier energy of 1532.5 meV. The wires are oriented along the fast-growing $y|[-110]$ direction (i.e., with cross sections along the fast-growing $x|[-110]$ direction). The dashed lines were calculated using a square infinitely long wire potential of width ($w_x$) with a barrier height of 5.5 meV and polariton effective mass $m_{eff} = 5.5 \times 10^{-5} m_e$, where $m_e$ is the free electron mass. The solid lines were calculated using the potential given by Eq. (1). (b) Squared wave functions $|\Psi_n(x)|^2$ for the first three confined levels in a wire with nominal width of $w_{nom} = 3.2 \mu m$ calculated using the confinement potential defined by Eq. (1).
FIG. 7. Photoluminescence maps of MPs in nonetched mesas: (a) 3.2-µm-wide wire [the same as Fig. 5(c)] and (b) nominally 3.2 × 3.2 µm² square trap. (c) Calculated projections of the squared wave function |ψ₁n(x)|² on the x axis for the square trap in (b). Spatial maps of |ψₙ(x)|² for the first five confined states in (c) with energies (d) E₁ = −4.13 meV, (e) E₂ = −2.74 meV, (f) E₃ = −2.60 meV, (g) E₄ = −1.35 meV, and (h) E₅ = −1.31 meV. The red arrows mark two levels [corresponding to (e) and (f)] with degeneracy lifted by the anisotropic shape of the trap. All energies are relative to the barrier energy of 1532.5 meV.

2. Three-dimensional confinement

Three-dimensional confinement of polaritons is achieved by surrounding a small nonetched area by etched regions. Figures 7(a) and 7(b) compare PL maps of a nominally 3.2-µm-wide wire oriented along the x direction and a nominally 3.2 × 3.2 µm² square trap, respectively. The most apparent difference between the PL maps for the wire and the square trap resides in the PL lineshape. The levels in the wire exhibit a pronounced tail towards high energy due to the normal (i.e., parabolic) MP dispersion along the wire length, corresponding to the absence of confinement. This tail disappears for the 3D confined states of the square traps, leading to spectrally narrow PL lines. We discuss the linewidth of the trap levels in Sec. III E.

As far as the energy levels are concerned, the additional confinement along the y || [−1 − 10] direction in the square trap results in a slightly increased energy of the fundamental state E₁ (by approximately 20%) as well as the energy separation between the confined levels. This behavior contrasts with the expectations for a perfect (no shape anisotropy) square trap surrounded by high barriers, where the energetic separation between consecutive levels should remain the same while the energy of the lowest confined state E₁ should double as compared to a wire with the same width. The discrepancy is attributed to the widening of the lateral interfaces along the x || [−110] direction due to the anisotropic growth, which also breaks the square symmetry of the structure. As a result, the energy shifts due to confinement along x become much smaller than along y.

In order to address the impact of the growth anisotropy on the polariton energies, we have calculated the energy levels and wave functions of a square trap using the numerical model described in the previous section. For the width of the interfaces along x and y direction, we have used δwx = 0.75 µm as in the previous case and δwy = 0.45 µm. Figures 7(d)–7(h) displays |ψₙ(x, y)|² maps for the first five confined levels. The anisotropic shape has a small effect on the fundamental state E₁ in Fig. 7(d), which is nearly isotropic. The anisotropy, however, lifts the degeneracy of levels E₂ and E₃, which have lobes along the x and y directions, respectively.

In order to compare the wave function profiles with the spatially resolved PL maps, we assume that the emission from each of the confined levels has a Lorentzian spectral shape with a FWHM of 0.1 meV. Figure 7(c) displays the calculated spectrum of these levels (vertical axis) as a function of the projection of their |ψₙ(x, y)|² on the x direction (horizontal axis). The calculated projection reproduces very well the measured PL map of Fig. 7(b). In particular, the calculations describe well the lifting of the degeneracy of levels E₂ and E₃, which gives rise to the additional levels indicated by the arrows.

An important consequence of the parabolic-like (quasiequidistant spectrum) confinement potential is the fact that while the lowest energy levels are confined to the physical size of the trap, the upper levels can substantially extend into the barrier, cf. Fig. 6(b). This is an important consideration for designing arrays of interacting polariton traps.
D. Hybridization in lattices of polariton traps

The MBE overgrowth provides a flexible way to fabricate arrays of proximal traps with interacting polaritonic states. We show in this section that an array of traps facilitates hybridized MP wave functions. As an example, we consider a square array of 4 × 5 lattice sites, each containing a square trap with nominal dimensions of $1.6 \times 1.6 \mu m^2$. The lattice constant of the array is equal to 4.8 $\mu m$. Figure 8(a) shows a spectrally and spatially resolved PL image of a line of traps within the array obtained under optical excitation by a laser beam with a rather large diameter of approximately 40 $\mu m$ and excitation power of 30 $\mu W$ ($E_{\text{exc}} = 1.631$ eV). Due to the small lattice period and trap sizes, the lowest levels of the individual traps hybridize to form states with bonding ($s$ character with energy $E_{1s}$) and antibonding ($p$ character with energy $E_{2p}$) properties. While in the former the electronic wave function concentrates on the trap sites, the wave function of the $p$-like states peaks in the region between traps. The character of the trap levels is further evidenced by the momentum-resolved PL image of the same array, measured under the same experiment conditions, cf. Fig. 8(b). Note that both confined levels $E_{1s}$ and $E_{2p}$ dispersions lie below the paraboliclike dispersion of the barrier states. As expected, the $E_{1s}$ level has flat dispersion with the maximum at $\Gamma$ point ($k_x = 0 \mu m^{-1}$). The dispersion of the $E_{2p}$ level has two symmetrical signatures at $k_x \approx \pm 1 \mu m^{-1}$ confirming its $p$ character. In addition, the dispersion of the $E_{2p}$ level is not flat, which is an indication of an emerging band structure. Similar results have been reported for a square array of 2 $\mu m$ large intracavity mesa traps separated by less than 5 $\mu m$ in Ref. [31], and for arrays fabricated by other methods, such as metal islands on the microcavity surface [38], acoustic waves [17], and deep etching of micropillars 1D [39,40] and 2D arrays [41,42].

E. Condensation in a single trap

In this section we show that the traps support MPs condensates. Figure 9(a) shows normalized PL spectra of a nominally $4 \times 4 \mu m^2$ trap recorded at different excitation densities ($P_{\text{exc}}$). In the linear regime (i.e., at low densities), the PL intensity of the confined levels with energies below the barrier has similar values. At larger densities, $P_{\text{exc}} > 12 kW/cm^2$, the PL is dominated by the emission from the lowest confined level. The dependence of the total PL intensity from the lowest confined level and its linewidth (FWHM) on $P_{\text{exc}}$ are summarized in Fig. 9(b). The total PL intensity increases exponentially while the linewidth abruptly reduces to $\sim 50 \mu eV$ (which is the resolution limit of our spectrometer) for $P_{\text{exc}} > 12 kW/cm^2$, thus indicating the formation of a polariton condensate. As expected, the condensation is accompanied by the blueshift of PL levels shown in Fig. 9(a). One could argue that the sharp lines for $P_{\text{exc}}$ above 12 kW/cm$^2$ in Fig. 9(a) arise from photonic lasing rather than from polariton condensation. Note, however,
that the emission energy lies approximately 0.5 meV below the bare cavity resonance in an extended region [dashed horizontal line, see also Fig. 4(d)]. The latter marks a lower limit for the lasing energy, since it neglects the large confinement-induced shift of the lasing modes due to their small effective mass. This proves that the sharp lines arise from polariton condensation in the strong coupling regime rather than from photonic lasing.

Finally, we briefly discuss the linewidth of the trap levels. In the condensed regime, the linewidth drops to less than 50 µeV. Well below the condensation threshold, in contrast, the measured linewidth of the lowest confined state in the square trap is approximately 0.3 meV [cf. Fig. 9(b)]. This linewidth was found to be independent of temperature from 10 to 1.6 K as well as of the excitation density down to a few nW/cm². Therefore, we can rule out effects of phonon-induced broadening and broadening due to the polariton-polariton interactions as well as polariton interactions with the exciton reservoir. Keeping in mind that the QWs remain unaffected by etching and that the size of the trap is only a few µm², we can probably also exclude the inhomogeneous broadening due to the excitonic part of MPs. In addition, the linewidth of the trapped MPs may be limited by the photonic resonances. We suggest that, while the expected quality factor of our cavity is \( Q \approx 5500 \) (Sec. III B) in extended nER regions, the \( Q \) may be reduced in confined areas with smooth optical interfaces between nER and ER.

### IV. CONCLUSIONS

We have investigated polariton quantum confinement in a laterally modulated (Al,Ga)As MC fabricated by etching and MBE-overgrowth. The lateral modulation of the cavity spacer thickness translates into a lateral modulation of the optical mode of the cavity while maintaining unaffected the quantum-well resonances. This results in a purely optical potential landscape for exciton-polaritons. A reduction in thickness of the spacer by 12 nm translates into a 9 meV blueshift of the cavity mode energy. Using optical reflectivity, we observed two types of polaritons appearing in the thinner (etched) and thicker (nonetched) regions of the spacer. In the nonetched regions, the polariton resonances are mostly due to the strong coupling between heavy-hole excitons and the cavity mode, while in the etched region both the heavy- and light-hole excitons couple strongly to the cavity mode.

Spatially resolved photoluminescence spectroscopy gives evidence for the confinement of polaritons within traps formed in nonetched areas surrounded by etched ones. As the width of the nonetched region reduces below approximately 15 µm, discrete confinement levels resulting from the quantization of the low-polariton branch are observed. The 2D confinement in wires and 3D confinement in squarelike traps, as well as in arrays of traps, was demonstrated. The very small polariton effective mass enables us to directly image the confined wave functions and determine the shape of the confinement potential. The latter changes from an approximately squarelike potential for wide traps, widths \( >5 \mu m \), to a smooth-shape one, for narrower structures. This effect is attributed to the diffusion of atoms during the MBE overgrowth process, which tends to smoothen, the shape of the lateral interfaces defined by etching. On one hand, the smooth interface profile leads to stronger confinement of the lowest excited states within the trap. One the other hand, the finite width (of approximately 1 µm) of the lateral interfaces substantially reduces the depth of confinement potential for wire widths less than 2 µm. Well-defined confined states have been observed for effective potential widths down to 1 µm, thus demonstrating that the process can reach small polariton confinement dimensions.

In the case of a squarelike trap, the anisotropic overgrowth results in an elongated rectangular shaped trap, which lifts the confinement degeneracy along the \( x \mid \{−110\} \) and \( y \mid \{−1−10\} \) directions. Finally, we demonstrated the coupling of polariton states in square arrays of small (1.6 × 1.6 µm²) proximal (lattice constant below 5 µm) traps. Upon condensation in a single trap, the PL linewidth reduces from 0.3 meV to 50 µeV (resolution limited). We argue that the linewidth is limited by the deterioration of the cavity quality factor due to the lateral structuring. Due to its single lattice addressability, single level confinement and polariton-polariton interactions via hybridization, the demonstrated system may be suitable for polariton based quantum simulators. The results obtained here provide a solid basis for the design of µm-sized traps as well as lattices with intersite polariton interactions.

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