Edge trapping of exciton-polariton condensates in etched pillars
D. M. Myers, J. K. Wuenschell, B. Ozden, J. Beaumariage, D. W. Snoke, L. Pfeiffer, and K. West

Citation: Appl. Phys. Lett. 110, 211104 (2017);
View online: https://doi.org/10.1063/1.4983832
View Table of Contents: http://aip.scitation.org/toc/apl/110/21
Published by the American Institute of Physics

Articles you may be interested in
Interference-enhanced infrared-to-visible upconversion in solid-state thin films sensitized by colloidal nanocrystals
Applied Physics Letters 110, 211101 (2017); 10.1063/1.4984136

Total internal reflection fluorescence based multiplane localization microscopy enables super-resolved volume imaging
Applied Physics Letters 110, 211102 (2017); 10.1063/1.4983786

High power, higher order ultrafast hollow Gaussian beams
Applied Physics Letters 110, 211103 (2017); 10.1063/1.4983788

Phonon conduction in silicon nanobeams
Applied Physics Letters 110, 213102 (2017); 10.1063/1.4983790

Time-resolved, dual heterodyne phase collection transient grating spectroscopy
Applied Physics Letters 110, 211106 (2017); 10.1063/1.4983716

Athermal synchronization of laser source with WDM filter in a silicon photonics platform
Edge trapping of exciton-polariton condensates in etched pillars

D. M. Myers,¹,a) J. K. Wuenschell,¹,b) B. Ozden,¹ J. Beaumariage,¹ D. W. Snoke,¹
L. Pfeiffer,² and K. West³

¹Department of Physics and Astronomy, University of Pittsburgh, 3941 O’Hara Street, Pittsburgh, Pennsylvania 15260, USA
²Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

(Received 12 January 2017; accepted 3 May 2017; published online 22 May 2017)

In this letter, we present a study of the condensation of exciton-polaritons in large etched pillar structures that exhibit shallow edge trapping. The $\approx 100 \ \text{µm} \times 100 \ \text{µm}$ pillars were fabricated using photolithography and a BCl$_3$/Cl$_2$ reactive ion etch. A low energy region emerged along the etched edge, with the minima $\approx 7 \ \text{µm}$ from the outer edge. The depth of the trap was $0.5–1.5 \ \text{meV}$ relative to the level central region, with the deepest trapping at the corners. We were able to produce a Bose-Einstein condensate in the trap near the edges and corners by pumping non-resonantly in the middle of the pillar. This condensate began as a set of disconnected condensates at various points along the edges but then became a single mono-energetic condensate as the polariton density was increased. Similar edge traps could be used to produce shallow 1D traps along edges or other more complex traps using various etch geometries and scales. Published by AIP Publishing.

[http://dx.doi.org/10.1063/1.4983832]

In the past two decades, many experiments have used polaritons resulting from strong coupling between trapped microcavity photons and quantum well (QW) excitons. These bosonic particles have a very light mass ($\approx 10^{-4} \ \text{m}_e$) due to being partially photonic but also strong particle-particle interactions from being partially excitonic. This combination of a light mass and strong interactions leads to the formation of Bose-Einstein condensates (BECs) at relatively high temperatures ($\approx 10 \ K$). Polaritons provide a promising system for studying bosonic particles at even higher temperatures, and polariton lasing has been observed at room temperature in both GaN and organic systems.

Many methods of confinement have been used to study polariton dynamics in a variety of geometries. Applying stress to a thin ($\approx 100 \ \text{µm}$) GaAs sample can be used to shift the exciton energy, resulting in a harmonic trap. Pumping such a stress trap non-resonantly in the center forms a repulsive barrier and can be used to form a ring geometry. Complex pumping geometries can also be used to confine polaritons, including the use of two or more pump spots in various arrangements or using a ring-shaped pump spot.

More permanent methods of confinement include producing a spacer in certain regions of the cavity during the growth process, using sub-wavelength gratings as the top mirror, depositing metal strips onto the top mirror, and etching the sample after growth to form 1D wires, 2D pillars, and 2D arrays of coupled pillars.

While optically induced trapping potentials have the advantage of being easily reconfigured, etched trapping allows the confinement to be somewhat independent of the pump laser. Post-growth etching also produces much higher potential barriers at the etched edges than the deposition of metal strips, and it is compatible with our existing sample materials and growth methods, unlike sub-wavelength gratings or modulating the cavity spacing mid-growth. In this letter, we present results from etched pillars similar to many of those mentioned above but generally larger in scale ($\approx 100 \ \text{µm} \times 100 \ \text{µm}$). The pillars were fabricated with a relatively simple photolithography process and alternative BCl$_3$/Cl$_2$ reactive ion etch (RIE), as opposed to the more complicated electron beam lithography and HBr RIE used elsewhere. Our pillars exhibit a reduced lower polariton energy near the edges of the pillar independent of the repulsive potential at the location of the pump spot, which has been observed in etched structures similar in scale to the ones presented here. In this paper, we describe the fabrication of these edge traps, the potential-energy landscape, and the formation of a BEC within that landscape.

The microcavity samples used for this study were very similar to those used in previous work. They were grown on a GaAs substrate using molecular beam epitaxy (MBE). A $3\lambda/2$ cavity was formed by two Al$_{0.2}$Ga$_{0.8}$As/AlAs distributed Bragg reflectors (DBRs) with 32 periods in the top DBR and 40 periods in the bottom DBR. Within the cavity were three sets of four coupled GaAs/AlAs QWs, with one set at each antinode of the cavity photon mode. These samples were then etched to a depth of $\approx 4 \ \text{µm}$ using a $\approx 2.7 \ \text{µm}$ photoresist mask. The etching was done with a 20:7 BCl$_3$/Cl$_2$ inductively coupled plasma (ICP) reactive ion etch (RIE) at 3.0 mT chamber pressure, 600 W ICP power, and 75 W RF bias power. This removed the top DBR to form $\approx 100 \ \text{µm} \times 100 \ \text{µm}$ pillars [Figs. 1(a) and 1(b)]. The lower polariton energy at resonance is $\approx 1601 \ \text{meV}$, and the pillars used in this study were at slightly photonic detuning ($\delta = E_{\text{cav}} - E_{\text{ex}} \approx -3 \ \text{meV}$).

Except where noted, the pillar was pumped non-resonantly ($E_{\text{pump}} = 1754 \ \text{meV}$) at an incident angle of approximately $18^\circ$ with a continuous wave (cw) Ti:sapphire pump laser.

---

a)Electronic mail: dmm154@pitt.edu
b)Now at Physical Sciences Laboratory, The Aerospace Corporation, El Segundo, California 90245, USA

0003-6951/2017/110(21)/211104/5/$30.00 Published by AIP Publishing.
The sample was kept at constant temperature in a liquid helium cryostat (5 K). In order to prevent heating, the pump was mechanically chopped with a 1.3% duty cycle at 400 Hz. All reported powers are the peak power of each short pulse. The pump spot was 20 µm FWHM and centered on the pillar. Measurements were taken using a charge-coupled device (CCD) camera on the output of a spectrometer to allow for energy-resolved imaging. We also obtained in-plane momentum information using angle-resolved imaging. Except in the case of the angle-resolved imaging, the collection angle was limited to \(4^\circ\) from normal emission with an aperture at the Fourier plane of the objective lens.

The potential landscape of these pillars at low density was acquired using a defocused pump and collecting energy-resolved slices of the pillar at many locations. The interpolated results are shown in Fig. 1(c), showing the overall effect of the etch process on the ground state energy of the lower polaritons. A low energy region is apparent at all of the edges, with minima \(7 \mu \text{m}\) from the outer etched edge and the overall energy minima appearing at the corners. The depth relative to the flat region in the middle is 0.5–1.5 meV. This is much shallower than the trapping attained from the smaller scale etching or the cavity spacing methods described above but comparable to the depths attained from stress traps. The overall tilt shows the direction of the cavity gradient (approximately 75° from the +x-axis) resulting from a wedge in the cavity thickness. The lifetime of the polaritons was not affected by the etch process to a degree detectable in the energy linewidth using our equipment. As mentioned elsewhere, our spectral resolution (0.1 meV) gives a lower bound on the polariton lifetime that is much smaller than the measured lifetimes around 200 ps.

The potential landscape changed with the addition of a focused pump. The repulsive exciton-exciton interactions formed a new effective potential, with an energy “hill” which is highest at the location of the pump spot [Figs. 1(d) and 2(a)]. This hill became higher at high pump power due to the increase in the exciton density. Figure 2 shows the polariton luminescence of a real space slice across the middle of the pillar containing the pump spot, which is apparent in the center, at several powers. This particular slice follows the y-axis and intersects the origin, using the axes defined in Fig. 1(c). At low pump power, the polariton luminescence was clearly visible at all points across the pillar, but the highest density was at the pump spot [Fig. 2(a)]. The pump spot was even more dominant at higher powers [Fig. 2(b)]. The density distribution underwent a dramatic shift at even higher powers, with the edge regions emitting comparable intensities to the central pump spot [Fig. 2(c)]. The narrow spectral width of the emission from these regions indicates that they contained Bose condensates. This is also consistent with the dramatically increased transport distance, which can be associated with superfluidity that allowed the polaritons to find the local minima of the potential landscape. At the highest powers, the condensates in the edge regions were blue-shifted to higher energies, eventually becoming equal in energy [Fig. 2(d)], consistent with a phase-locked single condensate.

A similar story emerges from the full real-space imaging of the entire pillar at various pump powers [Fig. 3]. The pump spot was prominent at low powers, but polariton luminescence was visible across the whole pillar [Fig. 3(a)].
relatively bright luminescence at the edges and around the pillar was from the bare excitons in the open cavity. As the power was increased [Fig. 3(b)], the pump spot became even more dominant, but the polaritons remained in the non-condensate regime and their diffusion length remained low. At higher powers [Fig. 3(c)], the corners became the dominant features as polaritons flowed long distances to fill in the locations of the energy minima. As the power was increased further [Fig. 3(d)], the polaritons filled a connected region extending along all the edges. The asymmetry relative to the pillar shape was caused by the cavity gradient, with the side closest to \( y = -50 \mu m \) at lower overall energy, and the lower left corner \( (x = -50 \mu m) \) at the lowest point.

Figure 4 shows the angle-resolved polariton luminescence, with the measured angle corresponding to momentum along the direction close to the x-axis defined in Fig. 1(c). These data were collected from a different but nearly identical pillar (in terms of etch parameters, size, detuning, and source sample). The pump in this case was at \( 1759 \text{ meV} \) and at normal incidence. This resulted in considerably different power levels for the same luminescence characteristics, but the overall characteristics were the same. At low pump power [Fig. 4(a)], the polaritons were emitted at many angles fairly evenly, corresponding to the filling of many momentum states. At higher power, high-energy emission emerged from the top of the repulsive “hill” at the pump spot, but the dispersion remained generally the same. Above the condensate threshold power [Fig. 4(c)], the polaritons moved overwhelmingly into a narrow low energy state near \( k_1 = 0 \), which is characteristic of Bose-Einstein condensation. At even higher pump powers [Fig. 4(d)], the parabolic polariton dispersion became nearly undetectable compared to the luminescence at \( k_1 = 0 \), indicating a large condensate fraction. The condensate also exhibited a slight blue shift in energy due to the high polariton density along the edges of the pillar.

To determine the precise threshold power, we plotted the polariton luminescence intensity vs. power at various points along the pillar [Fig. 5]. The positions of each of these points are defined using the same coordinate axes as in Fig. 1(c) but in units of the shortest distance from the origin to the edge trap (\( 41 \mu m \)) [see Fig. 6(b)]. At each position, a linear dependence on intensity was maintained up to the condensate threshold, where a strong nonlinearity emerged. The

FIG. 3. Full real space polariton luminescence intensity near \( k_1 = 0 \) at peak pump powers (the power of each quasi-cw pulse) of (a) 52 mW, (b) 133 mW, (c) 267 mW, and (d) 874 mW. The coordinate axes are the same as those defined in Fig. 1(c). The intensity was normalized separately for each image, so the values are not comparable between images.

FIG. 4. Energy vs. angle of emission at various pump powers. The collection angle was along the direction close to the x-axis defined in Fig. 1(c), but the luminescence was collected from the entire pillar. The pillar was pumped at \( 1759 \text{ meV} \) and at normal incidence, with a threshold power \( (P_{\text{thres}}) \) of \( 86 \text{ mW} \), as defined similarly to those in Fig. 5. The pump powers are (a) \( 0.005P_{\text{thres}} \), (b) \( 0.54P_{\text{thres}} \), (c) \( 1.3P_{\text{thres}} \), and (d) \( 4.7P_{\text{thres}} \). The intensity was normalized separately for each image, so the values are not comparable between images.

FIG. 5. Log-log plot of the intensity of the polariton luminescence at the pillar edges vs. the pump power at various positions. Intensity values were taken by integrating over a small area in spectrally resolved images at the lower polariton energy at the pillar edge in images similar to those in Fig. 2. The vertical lines mark the threshold powers, which are defined by the onset of nonlinearity. Positions are defined according to Fig. 6(b). The threshold powers and positions for each plot are (a) \( P_{\text{thres}} = 138 \text{ mW} \) at point \([0, -1]\), (b) \( P_{\text{thres}} = 166 \text{ mW} \) at point \([0, 1]\), (c) \( P_{\text{thres}} = 159 \text{ mW} \) at point \([-1, -1]\), and (d) \( P_{\text{thres}} = 185 \text{ mW} \) at point \([1, -1]\), and (inset) \( P_{\text{thres}} = 36 \text{ mW} \) at point \([0, 0]\).
A compilation of the threshold powers at various points along the edge is shown in Fig. 6(a). The line of symmetry and overall tilt is oriented along the sample gradient. In general, higher energy points along the gradient had higher threshold powers, as expected, since polaritons from the pump region will generally run downhill and away from the threshold in some cases. The emission eventually saturated and returned to increasing linearly with pump power.

The emission from the pump spot region showed a much less sharp and lower threshold (≈36 mW) [Fig. 5(c) (inset)]. As discussed in Ref. 26, we interpret this behavior at the pump spot as the onset of a quasi-condensate at densities just below true condensation; the momentum distribution is strongly altered, but there is no evidence of superfluidity. At higher density, a true condensate emerges in whatever local energy minimum is available.

A compilation of the threshold powers at various points along the edge is shown in Fig. 6(a). The line of symmetry and overall tilt is oriented along the sample gradient. In general, higher energy points along the gradient had higher threshold powers, as expected, since polaritons from the pump region will generally run downhill and away from these regions. The corners are the obvious exception, since the two shown had the lowest energies of any points on the pillar but noticeably higher threshold powers than the neighboring points on the edges.

The merging of the separated condensates into one, single condensate can be seen clearly in the data of Fig. 7. In this figure, we compare the energy vs. pump power at various separated locations on the pillar. The data were taken at two spatial locations simultaneously by imaging a full slice across the pillar. This removed deviations in the measurements due to pump laser pointing instabilities or small shifts of the pump location. For each location, energy blue-shifting was seen above the threshold power, with the lower energy locations showing larger blue shifts due to higher polariton densities. In all cases, the lower energy locations eventually shifted to the same energy as the higher energy locations, and then their energies were locked together above that power to within out spectral uncertainty (±0.05 meV). This same feature is apparent in Figs. 2(c) and 2(d), which correspond to two pairs of data points in Fig. 7(a). This indicates that the apparently interconnected polariton luminescence at powers well above threshold shown in Fig. 3(d) was from a single mono-energetic polariton condensate.

FIG. 6. (a) Threshold powers [as defined in Fig. 5] at various points on the pillar. The black circles give the actual threshold powers at each point. The surface is there to help guide the eye and is a linear interpolation of the data points. The axes are the same as those in Fig. 1(c). (b) Diagram defining a simple designation for each point, given as the actual position in Fig. 1(c) but in units of the shortest distance from the center to the bottom of the edge trap (≈41 μm).

FIG. 7. Energy vs. pump power at separate locations on the pillar. Data for each pair of locations were taken from a full energy resolved slice across the pillar, similar to and including those in Fig. 2, allowing simultaneous measurement of both locations. The locations are defined according to Fig. 6(b) and are (a) [0, –1], [0, 1], (b) [0, –1], [–1, 0], (c) [0.5, –1], [0.5, 1], and (d) [–0.5, –1], [–0.5, 1], shown as red diamonds and blue squares, respectively. The uncertainty is ±0.05 meV.

The work at the University of Pittsburgh was supported by the Army Research Office (W911NF-15-1-0466). The work at Princeton University was supported by the Gordon and Betty Moore Foundation (GBMF-4420) and by the National Science Foundation MRSEC program through the Princeton Center for Complex Materials (DMR-1420541). D.M.M. also acknowledges the support of the Pittsburgh Quantum Institute.