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Prototype of a bistable polariton field-effect transistor switch

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Microcavity exciton polaritons are promising candidates to build a new generation of highly nonlinear and integrated optoelectronic devices. Such devices range from novel coherent light emitters to reconfigurable potential landscapes for electro-optical polariton-lattice based quantum simulators as well as building blocks of optical logic architectures. Especially for the latter, the strongly interacting nature of the light-matter hybrid particles has been used to facilitate fast and efficient switching of light by light, something which is very hard to achieve with weakly interacting photons. We demonstrate here that polariton transistor switches can be fully integrated in electro-optical schemes by implementing a one-dimensional polariton channel which is operated by an electrical gate rather than by a control laser beam. The operation of the device, which is the polariton equivalent to a field-effect transistor, relies on combining electro-optical potential landscape engineering with local exciton ionization to control the scattering dynamics underneath the gate. We furthermore demonstrate that our device has a region of negative differential resistance and features a completely new way to create bistable behavior.

Encoding and transporting information by the means of light has been shown to have significant advantages over the use of classical electronic transport. Modern fiber technology allows photons to propagate over large distances (typically several kilometers up to hundreds of kilometers) with hardly any losses and optical devices can, in principle, be modulated faster than electric ones with lower energy dissipation¹. However, due to their (truly) bosonic nature it is exceedingly hard to make photons interact with each other².

Exciton-polaritons (polaritons) - hybrid quasi-particles formed by the strong coupling between quantum well excitons and microcavity photons - can, due to their excitonic matter component, be manipulated easily by external forces. Findings of e.g. Bose-Einstein condensation³ and superfluidity⁴ of polaritons have led to a general description as quantum fluids of light⁵. Polariton fluids can be optically manipulated and interfered^{6–8} and they can coherently propagate several tens of micrometers in GaAs based planar and channel structures^{9–11}.

Based on these properties, optical circuits on the basis of polaritons have been discussed^{12,13} and all-optical polariton switches^{14–16} and transistors¹⁷ have been realized. In these implementations, typically a laser creates a local blueshift of the polariton energy due to density-dependent polariton-exciton interactions which offers the possibility to imprint an artificial potential landscape for the propagating polaritons¹⁸.

While steering and switching polaritons with multiple lasers is versatile and reconfigurable, the manipulation via external electric fields is clearly preferable as a significantly more compact and scalable solution. Moreover, the manipulation via external electric fields offers the possibility to investigate fast and reconfigurable manipulation of expanding polariton condensates in channels^{8,10}, electro-optical initialization of dark soliton trains¹⁹ and it gives a dynamical tool to engineer fully reconfigurable potential landscapes for a new generation of electro-optical polariton-lattice based quantum simulators²⁰.

Although initial works have already suggested the feasibility of such an approach²¹, it has only been a recent work that has shown a great potential to manipulate the polariton condensate energy on demand in either red or blue shifted direction by the means of the well-known quantum-confined Stark effect (QCSE) on the one hand and due to the controlled reduction of the Rabi splitting on the other^{22,23}. However, while electrically pumped polariton lasers do exist^{24,25}, an electrically controlled polariton logic device has not been demonstrated yet. In

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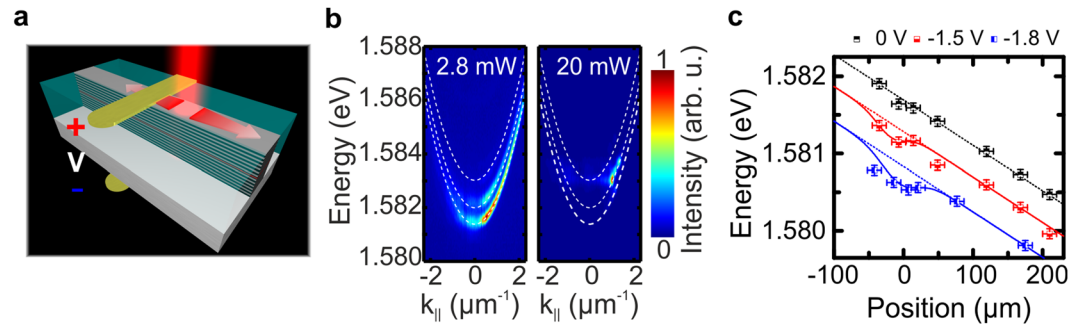


Figure 1. QW-microcavity polariton transistor switch sample and photoluminescence emission features. (a) Schematic image of the processed device consisting of the microwire and the electrical gate on top of the device. The excitation spot is located close to the contact, generating a propagating polariton flow. (b) Momentum resolved photoluminescence measurement at low power (2.8 mW, left) and far above the condensation threshold (20 mW, right) under open circuit conditions. Several lateral modes are visible and fitted by a coupled oscillator model (white dashed lines), yielding an exciton-photon detuning of $\delta = -13.6$ meV for the ground state with respect to the heavy hole exciton. Due to the gold contact, which blocks the PL underneath, the propagation for $k_{||} > 0$ appears much brighter. (c) Spatially resolved PL measurements around zero in-plane wave vector, at low excitation power and several voltages. The reverse bias results in a general redshift of the intrinsic detuning gradient (dotted lines). Furthermore, a local energy minimum evolves underneath the $10\ \mu\text{m}$ wide contact centered at zero position with increasing reverse bias which can be described by an additional Gaussian shaped function (solid line).

addition, the influence of an external electric field on polariton propagation is a completely unexplored field and leads, in our case, to the discovery of a new way to create bistable behavior.

In this work, we implement an electro-optical polariton transistor switch. The prototype is based on a one-dimensional channel to guide a propagating polariton condensate. We show that a local electrical gate can be used to manipulate the propagation of the polaritons via a combination of the QCSE and locally enhanced polariton dissipation.

Results

Implementation. Our polariton device is based on a microcavity composed of AlAs/AlGaAs mirrors with 4 GaAs quantum wells (QWs) integrated into the optical antinode of an intrinsic $\lambda/2$ -thick AlAs cavity layer. The top mirror is carbon doped (p-type), whereas the bottom mirror is n-type doped using silicon to allow electro-optical tuning of the QWs in the microcavity region. The Rabi splitting amounts to $\hbar\Omega_R = (8.7 \pm 0.1)$ meV as determined from low temperature white-light reflectance measurements on the unprocessed wafer (see Fig. S1a in the supplementary material). The Q-factor of the microcavity was previously experimentally determined to exceed $Q \sim 8000$.

In order to generate a one-dimensional polariton channel, microwires with a length of $400\ \mu\text{m}$ and a width of $5\ \mu\text{m}$ were defined via optical lithography and etched deeply into the structure using electron-cyclotron-resonance reactive-ion-etching. In a subsequent step, the sample was planarized with the transparent polymer Benzocyclobutene which serves as a platform for the following contacting steps, but also prevents oxidation of the exposed wire sidewalls. The n-contact on the backside of the substrate is formed by evaporating an AuGe-Ni-Au alloy. Next, the position of the $10\ \mu\text{m}$ wide electrical gate was defined via optical lithography and subsequent evaporation of a $600\ \text{nm}$ thick Au-Ti-layer. A final lift-off step completes the device process (see Fig. 1a).

Power dependent emission features. At first the power dependent photoluminescence (PL) emission of our device was investigated via momentum resolved spectroscopy. The sample is mounted in a helium flow cryostat and is oriented parallel to the entrance slit of the spectrometer. A constant helium flow is cooling the sample down to a temperature of $\sim 5\ \text{K}$. Polaritons are injected close to the contact by a non-resonant continuous wave laser which is tuned to the reflectivity minimum of the first high-energy Bragg mode around $1.664\ \text{eV}$. The Gaussian shaped pump-spot has a diameter of $\sim 5\ \mu\text{m}$. A longpass filter with a cut off energy of $1.653\ \text{eV}$ was placed in front of the spectrometer to filter any scattered light from the laser. Furthermore, a pinhole in the image plane in front of the spectrometer allows us to spatial filter the PL collected from the excited microwire. With an almost completely closed pinhole, we collect luminescence from an approximately $20\ \mu\text{m}$ long region of the microwire. Under moderate power excitation of $2.8\ \text{mW}$ and in the closed pinhole configuration a characteristic set of three parabolic dispersions was observed (see Fig. 1b, left) which we identify as the ground state of the microwire as well as higher order lateral modes^{10,26}. The spectra were fitted using a standard coupled oscillator model by coupling the three lowest lateral cavity modes with the heavy hole exciton, yielding a heavy hole exciton-photon detuning of the ground state of $\delta = -13.6\ \text{meV}$ which is slightly larger than the Rabi splitting. We neglected the light hole exciton in this calculation because at the sample position of interest it lies approximately $50\ \text{meV}$ above the cavity energy and therefore should play no crucial role. With increasing pump power, polariton condensation takes place at $(4.5 \pm 0.5)\ \text{mW}$ (see supplementary material Fig. S1b), which manifests itself in a massive occupation of a distinct energy state (Fig. 1b). The slight asymmetry of the sample perpendicular to

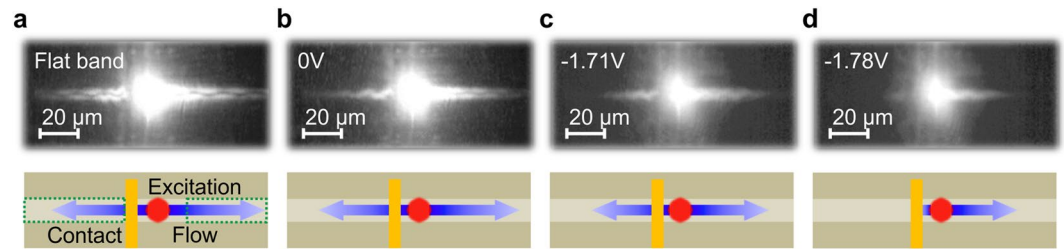


Figure 2. Polariton switching along the wire. Real space images of the studied microwire sample under optical excitation with the center of the pump spot approximately $15\text{ }\mu\text{m}$ away from the center of the $10\text{ }\mu\text{m}$ wide electrical contact (top) and schematic drawings of the experimental configuration (bottom). At the contact a voltage is applied and varied between flat band condition ($U_G = 1.8\text{ V}$) and tilted bands ($U_G = -1.78\text{ V}$). Flat band conditions are reached when the external applied bias has equalized the built-in potential in the pin-doped structure and therefore leading to a nearly flat electronic band structure. Furthermore, tilted band specifies voltages in reverse bias leading to an increased potential and therefore to a strongly tilted electronic band structure. The real space images show the flow for different voltages (a) $U_G = 1.8\text{ V}$, (b) $U_G = 0\text{ V}$, (c) $U_G = -1.71\text{ V}$ and (d) $U_G = -1.78\text{ V}$, respectively, at an excitation power of 20 mW . A clear flow to the right, away from the contact, and to the left, through the contact with respect to the excitation spot, is visible under flat band conditions, while with increasing negative voltage the flow through the contact stops abruptly. The green dashed boxes in the left most schematic drawing mark the integration ranges for the polariton flow through as well as away from the contact, discussed in Fig. 3.

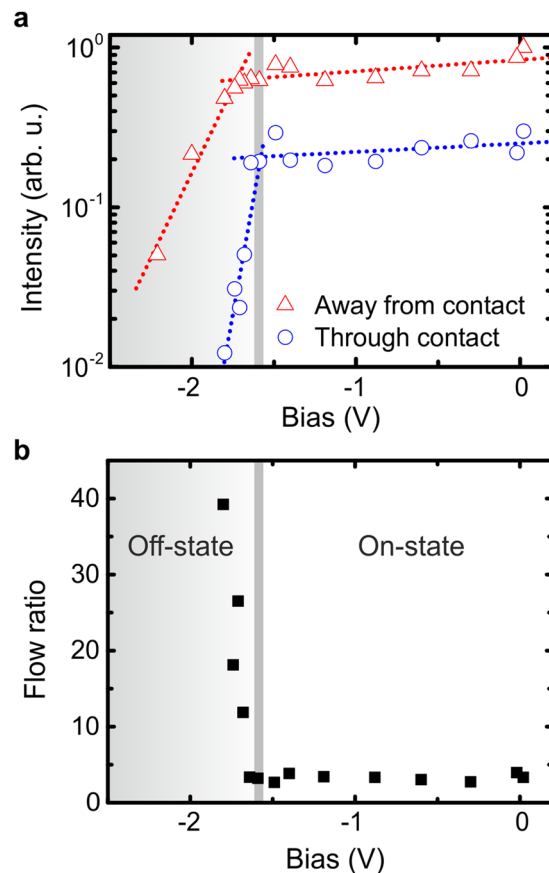


Figure 3. Quantitative analysis of the switching process. (a) Spatially integrated emission of the propagating polariton condensate away from the contact (red triangles) and through the contact (blue circle) for an excitation power of 20 mW . The center of the excitation spot is approximately $15\text{ }\mu\text{m}$ away from the center of the $10\text{ }\mu\text{m}$ wide electrical contact. Dotted lines are guides to the eye. The emission is integrated over a range of $\sim 40\text{ }\mu\text{m}$ along the length of the wire, starting at a distance approximately $20\text{ }\mu\text{m}$ away from the excitation spot, and over the whole width of the wire (cf. schematic drawings in Fig. 2). With increasing negative voltage the flow in both directions decreases continuously. At a voltage of $U_G = -1.60\text{ V}$ the flow through the contact shows a sharp intensity drop, while the flow away from the contact shows a slighter drop at around $U_G = -1.72\text{ V}$. (b) Corresponding ratio between the flow away and through the contact. A sharp increase of the ratio is visible at around $U_G = -1.64\text{ V}$, indicating the 'off-state' of the flow direction.

the direction of the wire combined with an imperfect positioning of the pump spot leads to condensation in the second confined subband. This is a result of the open dissipative nature of the condensate, where the gain profile, the modal losses and the intermode relaxation determine the condensate state²⁷. A detailed estimation of the corresponding exciton density can be found in the supplementary material. Due to the repulsion from the reservoir at the location of the pump laser, the condensate propagates along the wire direction which can be seen in Fig. 1b. The excitation is located close to the contact that blocks the PL signal underneath, such that the propagation away from the contact ($k_{\parallel} > 0$ towards red detuned sample gradient) appears more distinct than the one through the contact ($k_{\parallel} < 0$ towards blue detuned sample gradient) [cf. ref. 28].

Influence of the electrical gate. In order to assess the influence of the local gate on the potential landscape along the microcavity wire, we have carried out spatially resolved PL studies under low excitation conditions and in the closed pinhole configuration while changing the applied reverse bias. As can be seen in Fig. 1c, application of a reverse bias results in a general redshift of the ground state emission energy at zero in-plane wave vector which seems to be independent from the position along the 400 μm microwire. However, one can also observe a local minimum of the emission energy underneath the contact (at positions which were not fully covered by gold) which, as we show in the following, will be sufficient to initiate the switching process. The measured spatial extent (full width at half maximum) of the contact-induced potential dip is strongly dependent on the applied voltage. We find a spreading ranging from zero at zero bias to $\sim 50 \mu\text{m}$ at -1.8 V . Data fitting was performed by using an additional Gaussian shaped function superimposed on the intrinsic, linear detuning gradient along the wire due to the layer thickness gradient occurring during sample growth and due to the general red shift. We believe that the doped DBRs work as an additional capacitor able to affect the depletion zone in the pin-doped structure along the whole microwire leading to the general redshift. Typically, structures for indirect excitons in electrostatic potential traps^{29,30} are ni-doped to avoid this problem and to create sharp local potential patterns. This approach is not readily possible in our case since the intrinsic region needs to be as small as possible to obtain large electric fields that shift the exciton energy distinctly. For reverse bias the QCSE leads to a redshift of the emission and results in a potential minimum underneath the contact of 180 μeV and 300 μeV for $U_G = -1.5 \text{ V}$ and -1.8 V , respectively. The expansion of the condensate along the wire can be directly monitored in an open pinhole configuration by imaging the emission onto a CMOS camera which is mounted in the beam path with a standard optical microscope configuration. The reflection of the excitation laser is filtered out by a longpass filter. Figure 2 depicts real space images of the studied microwire under optical excitation with the center of the pump spot approximately 15 μm away from the center of the 10 μm wide electrical contact (top). Corresponding schematic drawings of the experimental configuration are shown below the microscope images (bottom). At the contact, a voltage is applied which is varied between flat band condition ($U_G = 1.8 \text{ V}$) and strongly tilted bands ($U_G = -1.78 \text{ V}$). Flat band conditions are reached when the external applied bias has equalized the built-in potential in the pin-doped structure and therefore leading to a nearly flat electronic band structure. Furthermore, tilted band specifies voltages in reverse bias leading to an increased built-in potential and therefore to a strongly tilted electronic band structure. The real space images show the flow for different voltages $U_G = 1.8, 0, -1.71$ and -1.78 V , respectively, at an excitation power of 20 mW. Clearly, we can evidence an expansion of the polariton condensate along the wire resulting from the repulsion with the exciton reservoir induced by the pump spot. Under flat band condition a nearly symmetric propagation of the condensate is observed (Fig. 2a). The residual asymmetry in intensity is induced by the already mentioned intrinsic potential gradient in Fig. 1c. It accounts for a soft barrier to the left and thus suppresses the flow in this direction. As we apply a reverse bias, the overall intensity is reduced. More significantly, however, between $U_G = -1.71 \text{ V}$ and -1.78 V the flow to the left, through the contact, is fully blocked, leading to a strongly asymmetric propagation (Fig. 2c and d). It can also be seen in Fig. 2d that the flow to the right, away from the contact, is significantly reduced after the switching as a result of enhanced losses in the device due to carrier tunneling³¹. The tunneling process corresponds to exciton electric field ionization which therefore affects the polariton decay rate. Evidence for increased exciton electric field ionization with increased negative voltage is given by the bias and spatial dependent exciton lifetime measurements in the supplementary material.

In order to assess the capability of our device to switch the polariton flow in a more quantitative manner, the spatially integrated emission from the first subbranches of the visible wire modes from both sides of the pump spot is plotted as a function of the gate voltage in Fig. 3a. The associated excitation conditions are the same as in Fig. 2. That means the center of the pump spot is located 15 μm away from the center of the 10 μm wide gold contact. The spatially integrated emission of the polariton flow away from the contact is represented by the red triangles, whereas the flow through the contact is plotted as blue circles. The emission is integrated over a range of $\sim 40 \mu\text{m}$ along the length of the wire, starting at a distance approximately 20 μm away from the excitation spot, and over the whole width of the wire (cf. schematic drawings in Fig. 2). With increasing negative voltage the flow in both directions decreases continuously due to increasing tunneling losses. At a voltage of $U_G = -1.60 \text{ V}$ the flow through the contact features a sharp intensity drop, which we identify as the threshold from the “on”-state to the “off”-state, while the flow away from the contact shows a more gentle drop at around $U_G = -1.72 \text{ V}$. As our numerical calculations in the discussion below show, the flow is blocked by a soft potential barrier for $U_G < -1.60 \text{ V}$ and fully trapped for $U_G < -1.72 \text{ V}$. Furthermore, the gentler drop of the propagating polariton condensate away from the contact is due to the smaller influence of the enhanced carrier losses underneath the contact (see Fig. S2 in the supplementary material). The integration range for the spatially integrated emission away as well as though the contact start at the edge of the potential dip evolving under the contact. Therefore, a drop of the integrated emission is seen in both cases, first when the polariton flow gets blocked at the transition from the “on”-state to the “off”-state and second when the condensate gets fully trapped. The exact behavior of the trapped polariton condensate cannot be tested directly in this experimental configuration since most of the potential well is covered by the deposited gold contact. However, in our case the spatially dependent polariton

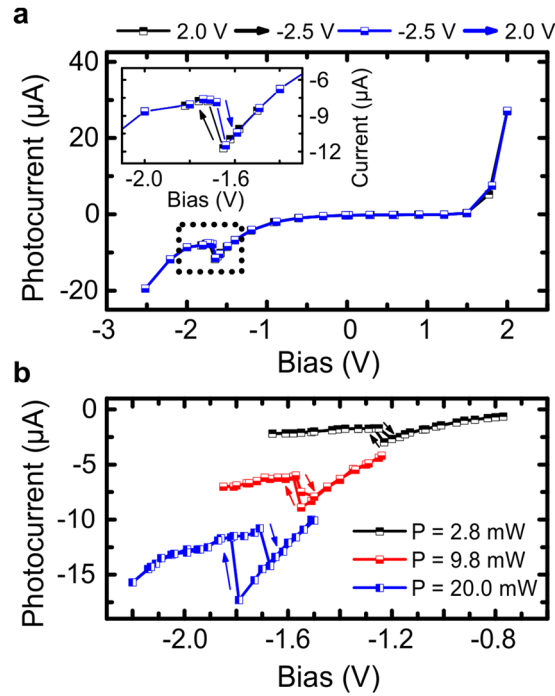


Figure 4. Photocurrent readout and bistable switching. (a) Measured photocurrent in forward as well as in reverse direction for an excitation power of 20 mW, with the pump spot approximately 25 μm away from the center of the contact. The black and blue squares indicate the varied voltage from 2.0 V to -2.5 V as well as from -2.5 V to 2.0 V, respectively. Between -1.62 V and -1.72 V a negative differential resistance is visible in the photocurrent corresponding to the on-/off-state of the device. The inset shows a zoom into the region of negative differential resistance. (b) By moving the pump spot closer to the contact, which means approximately to a distance of 15 μm to the center of the contact, the nonlinearity shows a bistable behavior with upward and downward directed bias. By varying the pump power and therefore the injected carrier density the bistability emerges at 20 mW or vanishes for lower excitation powers.

decay rate, being enhanced underneath the contact, has to be taken into account and the expected increase of the polariton emission for the trapped polariton condensate¹⁶ is not obvious. Considering this, our numerical calculations in the discussion below suggest only a small variation of the trapped polariton emission close to the excitation spot. In order to further visualize the pronounced asymmetry between the spatially integrated emission of the polariton flow away and through the contact, the corresponding ratio is plotted in Fig. 3b. Switching between the ‘on-’ and ‘off-state’ by the local gate is unambiguously verified in this representation.

We can furthermore exploit the electrical contact as a sensitive probe of the carriers which diffuse and propagate along the wire. Therefore, we extracted the photocurrent for various excitation powers by measuring the voltage drop across a series resistance with $R = 1.0$ k Ω . In Fig. 4a, we kept the excitation power at 20 mW and located the pump spot approximately 25 μm away from the center of the contact. While the device features the standard behavior of a diode, between $U_G = -1.62$ V and -1.72 V a marked negative differential resistance is visible which appears at approximately the same applied negative voltage as the threshold where the device switches between the ‘off-’ and the ‘on-’ state. The inset shows a zoom into the region of negative differential resistance. By moving the pump spot closer to the contact, which means to a distance of approximately 15 μm to the center of the contact, a strong bistable behavior evolves as we increase the negative voltage in the device. As we show in Fig. 4b, this hysteresis is a sensitive function of the pump power, and as such, of the injected carrier density.

Discussion

We use a simplified 1D model based on the incoherently driven Gross-Pitaevskii approach^{32,33} to model our findings. Coherent polaritons are described by the order parameter, $\psi(x, t)$, the dynamics of which is given by:

$$i\hbar \frac{d\psi(x, t)}{dt} = \left[-\frac{\hbar^2 \hat{\nabla}^2}{2m} + (\alpha - i\alpha_{NL})|\psi(x, t)|^2 - \frac{i\Gamma(x)}{2} + V(x) + iP(x) \right] \psi(x, t) \quad (1)$$

where m is the polariton effective mass, α is the strength of polariton-polariton interactions and α_{NL} is the strength of nonlinear losses. The polariton decay rate $\Gamma(x)$ is spatially dependent, being enhanced underneath the contact where the applied electric field induces exciton dissociation. The losses in the system are balanced by

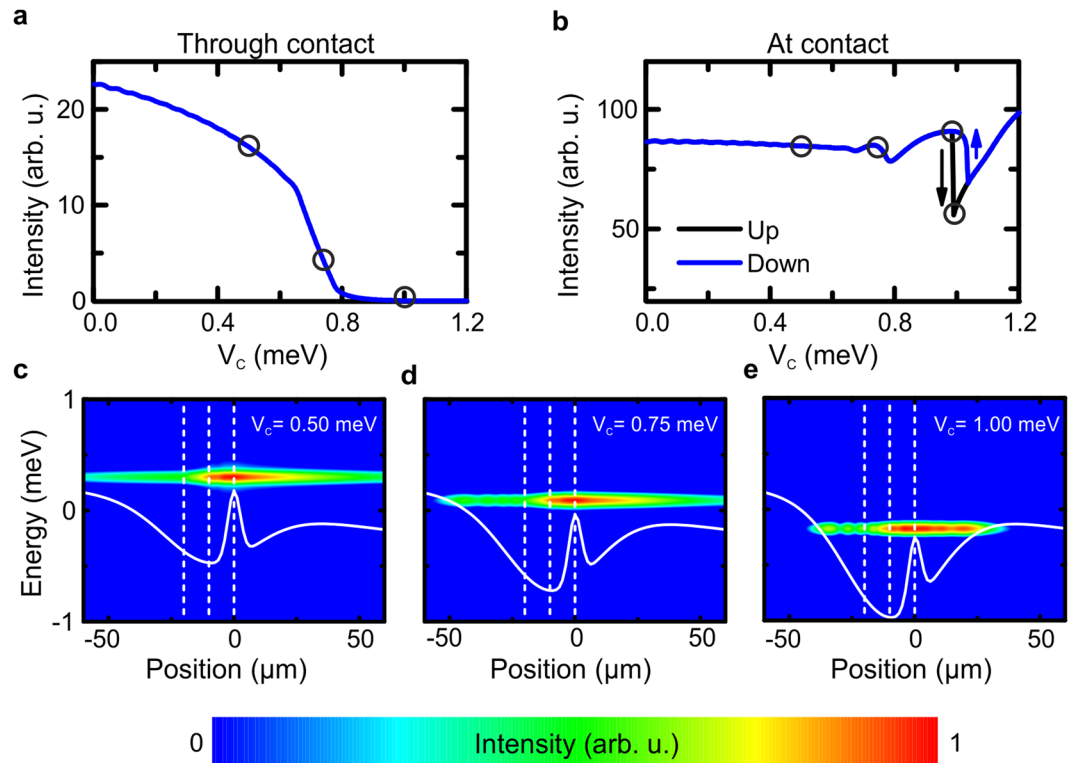


Figure 5. Gross-Pitaevskii model of the experiment. **(a,b)** Total intensity of polaritons that passed the contact **(a)** and before the contact **(b)**. **(c–e)** Potential landscape for the injected polariton flow around the contact for different contact-induced potential depths, V_c . Without an applied potential dip there is a propagation of polaritons through the contact and away from it **(c)**. At a potential depth of ~ 0.75 meV only the polariton flow through the contact is blocked (asymmetric case) **(d)** while the propagation is finally trapped at higher values of V_c **(e)**.

the continuous wave pumping $P(x)$, to form steady states in the system. The effective potential of polaritons $V(x)$ includes the experimentally measured linear potential gradient β . Furthermore, we consider a repulsive potential peak due to the hot excitons excited at the pump position, characterized by constant g , and an additional potential dip at the position of the electrical contact $V_c(x)$, which can be varied in strength:

$$V(x) = \beta x + gP(x) + V_c(x) \quad (2)$$

The spatial distribution of the additional potential dip $V_c(x)$ is chosen in agreement with the experimental values extracted from Fig. 1c.

We solved the driven-dissipative Gross-Pitaevskii equation numerically for a slowly varying contact-induced potential depth V_c , where for each value of V_c the system formed a quasi-stationary state. The polariton intensity spatially integrated beyond the contact (i.e., the total intensity of polaritons that passed the contact) and the polariton intensity spatially integrated over the contact position are shown in Fig. 5a and b as functions of V_c , respectively. We note that we can observe a switching behavior at a potential depth of $\sim V_c = 0.75$ meV. At this point, the polariton flow through the contact is blocked, and the device acts as a switch, analogous to our experimental findings in Fig. 3. Stopping the polariton flow through the contact simultaneously acts on the population underneath the contact which is plotted in Fig. 5b. In fact, this population features the bistable behavior which we have previously probed via the photocurrent. To provide a better understanding of these effects, we plot the expanding polariton cloud for various applied electric fields in Fig. 5c–e. For flat-band condition and small bias, repulsion of polaritons from the incoherent exciton reservoir is the dominating effect³⁴, leading to a nearly symmetric real space pattern (Fig. 5c). In agreement with the experimental observed propagation at flat band conditions (cf. Fig. 1c), the linear potential gradient works as a soft barrier and thus suppresses the propagation. Beyond a threshold (~ 0.75 meV), the effect of the applied electric field becomes dominant and reconfigures the potential landscape in such a way that only propagation away from the contact is possible (Fig. 5d). Larger contact-induced potential depths lead to a full trapping of condensed polaritons (Fig. 5e). Besides the “on”- and the “off”-state this third “trapped”-state regime can also be identified in the experimental data of Fig. 3a where the integrated emitted intensity of the polariton flow away from the contact starts to drop. It is in principle possible for the system of polaritons to demonstrate bistability due to a switching between condensed modes inside the contact-induced trap³⁵. Such a bistability is strongly pronounced in the dependence of the polariton intensity integrated over the contact as a function of increasing or decreasing V_c . The two different stationary states that appear in the bistable region have slightly different energies and spatial structure. Mechanisms of bistable switching based on resonant excitation are well-known^{36–38} in exciton-polariton systems and recently a variety of works

have reported non-resonantly excited bistability, both theoretically^{39,40} and experimentally^{41,42} in particular configurations. However, these mechanisms do not rely on the spatial degree of freedom of polaritons.

The bistability in our device of light appears due to a transition between polariton condensation modes in the presence of the contact-induced trap. The potential trap supports confined polariton modes, which compete with each other as they are fed by the non-resonant pump that injects polaritons on the edge of the trap. The mode favored in the competition is typically the one with largest overlap with the non-resonant pump. As the electric potential is changed, the depth of the potential trap also changes, which allows changes in the mode with greatest overlap with the non-resonant pump. The bistability results near a potential depth where there is a change in the favored confined mode. This is because if a particular mode has been previously populated it experiences enhanced gain due to stimulated scattering processes. This introduces a dependence on the history of the system, where a mode that would normally not win the mode competition can do so if it was previously populated under different conditions. The change in the polariton density affects the (stimulated) relaxation rate of hot carriers and excitons in the system. Therefore the appearance and thus the width of the bistability region is determined on how long the enhanced gain due to stimulated scattering processes compensates the lack of the reduced mode overlap with the non-resonant pump. Accordingly the width of the bistability region is a sensitive function of the carrier reservoir. The corresponding change in its density is directly reflected in the experimentally observed photocurrent response (see Fig. 4b).

Besides the fundamental prospects, namely the trapping of a propagating polariton condensate in an electro-static potential as well as the bistable behavior as a probe for a fundamental gain process, polariton devices offer some advantages compared to conventional silicon based transistor technologies. First, the group velocity, that means the velocity to transport information, as well as switching times had been shown to be at least one order of magnitude higher^{16,17}. Furthermore, activation energies required for the switching process are significantly small (~ 1 fJ)¹⁷. Anyhow, for the construction of complex polariton networks the system needs to satisfy several qualitative criteria¹. The most important criteria are cascability, logic-level restoration, logic level independent of system losses and amplification. Those criteria are discussed in detail in the supplementary material. We believe that by taking advantage of the well-controlled bistability and with the combination of existing work, one can satisfy all of those criteria.

In conclusion, we have implemented a prototype of an electro-optical polariton transistor switch. The functionality of the device, which is the polariton equivalent of a field-effect transistor in its basic definition, is facilitated via local electro-optical potential shaping, giving a dynamic tool to investigate the influence of a static electric field on polariton propagation. We believe that our work represents an important step towards the implementation of compact and densely packed logic gates based on light-matter coupled hybrid particles. As we have already demonstrated electro-optical readout of the population underneath the gate, we suggest implementing similar schemes to probe the transmitted polaritons as a fully electrical readout. In combination with an electrically injected polariton pump^{24,25}, electro-optical interferometers and amplifiers, a full architecture of all-electrical integrated polaritonics is now within reach. In addition to the switching operation, transitions between trapped condensate modes lead to a pronounced negative differential resistance in the photo-current response and a strong bistability which represents a completely new way to create bistable behavior. Furthermore, the accomplished full trapping of a polariton condensate in an electro-static potential yields a flexible tool to engineer fully reconfigurable potential landscapes for polaritons.

Methods

Sample design. The bottom (top) distributed Bragg reflector (DBR) consists of 27 (23.5) AlAs/Al_{0.2}Ga_{0.8}As mirror pairs surrounding a $\lambda/2$ -AlAs cavity with a nominal length of 100 nm. A single stack with four 7 nm wide GaAs-QWs is placed in the field maximum inside the cavity, whereat every QW is separated by 4 nm AlAs barriers. To lower the series resistance of the DBRs, all abrupt AlAs/Al_{0.2}Ga_{0.8}As heterointerfaces have been replaced by 20 nm wide quasi-graded superlattices. Furthermore the bottom (top) mirror is n-doped with silicon (p-doped with carbon) at a doping concentration of $3 \cdot 10^{18} \text{ cm}^{-3}$. The doping is gradually reduced to $1 \cdot 10^{18} \text{ cm}^{-3}$ towards the intrinsic cavity. The topmost mirror pairs in the top DBR are highly C-doped at a concentration of $2 \cdot 10^{19} \text{ cm}^{-3}$ to get a sufficient ohmic contact with an evaporated Au-layer. The whole structure has been grown by molecular beam epitaxy on a Si-doped (001) GaAs substrate.

Experimental setup. A compact low temperature PL setup was constructed, in which both spatially (near-field) and momentum-space (far-field) resolved spectroscopy and imaging are accessible. Photoluminescence was collected through a 0.4 NA microscope objective, and directed into an imaging spectrometer with 1200 grooves/mm grating via a set of lenses, projecting the proper projection plane onto the monochromator's entrance slit. The momentum space coverage in this configuration amounts to $k_{\parallel} = \pm 2.2 \mu\text{m}^{-1}$ with a resolution of $\sim 0.05 \mu\text{m}^{-1}$ ($\sim 0.5^\circ$). The spectral resolution is $\sim 0.05 \text{ meV}$. A nitrogen-cooled Si charge-coupled device was used as detector.

Gross-Pitaevskii model. In solving the Gross-Pitaevskii equation, we took the following parameters: polariton lifetime (away from contact), $\hbar/\Gamma = 10 \text{ ps}$; polariton-polariton interaction strength, $\alpha = 2.4 \cdot 10^{-3} \text{ meV } \mu\text{m}^2$; nonlinear loss, $\alpha_{\text{NL}} = 0.3 \alpha$ ³¹. The effective mass, m , was fitted to the low power dispersion as $2.93 \cdot 10^{-5}$ of the free electron mass. The contact-induced potential was taken with Gaussian width $25 \mu\text{m}$, in agreement with low power spatially resolved experimental spectra. The potential gradient was taken as 2.86 eV/m . The parameter g was chosen such that $gP(0) = 0.6 \text{ meV}$, where $P(0) = 0.33 \text{ meV } \mu\text{m}^{-2}$. The final bistable behaviour was sensitive to a fitting parameter representing the enhanced decay rate beneath the contact, which was allowed to reach 5Γ .

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Author Contributions

C.S. and S.H. initiated the study and guided the work. H.S., S.B. and C.S. designed and fabricated the device. H.S., S.B., M.Kl., M.A. and S.K. performed optical measurements. M. Ka. guided device processing. H.S., S.B., C.S. analyzed and interpreted the experimental data. T.C.H.L., S.B. and C.S. developed the theory. H.S., T.C.H.L., S.K. and C.S., wrote the manuscript, with input from all coauthors.

Additional Information

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