

Bose–Einstein condensation of photons in a vertical-cavity surface-emitting laser

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Many bosons can occupy a single quantum state without a limit. It is described by the quantum-mechanical Bose–Einstein statistic, which allows Bose–Einstein condensation at low temperatures and high particle densities. Photons, historically the first considered bosonic gas, were late to show this phenomenon, observed in rhodamine-filled microcavities and doped fibre cavities. These findings have raised the question of whether condensation is also common in other laser systems with potential technological applications. Here we show the Bose–Einstein condensation of photons in a broad-area vertical-cavity surface-emitting laser with a slight cavity-gain spectral detuning. We observed a Bose–Einstein condensate in the fundamental transversal optical mode at a critical phase-space density. The experimental results follow the equation of state for a two-dimensional gas of bosons in thermal equilibrium, although the extracted spectral temperatures were lower than the device's. This is interpreted as originating from the driven-dissipative nature of the photon gas. In contrast, non-equilibrium lasing action is observed in the higher-order modes in more negatively detuned device. Our work opens the way for the potential exploration of superfluid physics of interacting photons mediated by semiconductor optical nonlinearities. It also shows great promise for enabling single-mode high-power emission from a large-aperture device.

At the beginning of the twentieth century, Albert Einstein extended the statistical theory of Satyendra Nath Bose to describe massive particles and made the pioneering prediction of the Bose–Einstein condensate (BEC) below a critical temperature¹. Such a BEC is characterized by both saturation of occupation in the excited states and condensation in the ground energy state of the system². Seventy years after its theoretical prediction, this macroscopic quantum phenomenon was first observed directly in dilute clouds of atomic gases at temperatures close to absolute zero^{3,4}. The reason for such a low critical temperature is that it is inversely proportional to the mass of the boson. Therefore, a heavy particle gas must be extremely cold to reach the transition point. However, if we consider the mass as the parameter of energy dispersion,

then we can find a bosonic quasiparticle described with a dispersion of large curvature and, hence, with a quite small effective mass, which enables condensation at elevated temperatures. This concept has been realized in a variety of bosonic quasiparticle systems, such as magnons⁵, excitons^{6–8} and plasmons⁹, as well as hybrid excitations of strongly coupled systems of excitons and photons, namely cavity polaritons^{10,11}.

Photons, on the other hand, have been out of the picture for many years because they represent a massless gas with linear energy dispersion and a trivial, null ground state. In principle, the number of particles is not conserved, that is, in a blackbody radiation model in thermal equilibrium, the chemical potential vanishes and, therefore, condensation cannot occur. Nevertheless, over years of research, many

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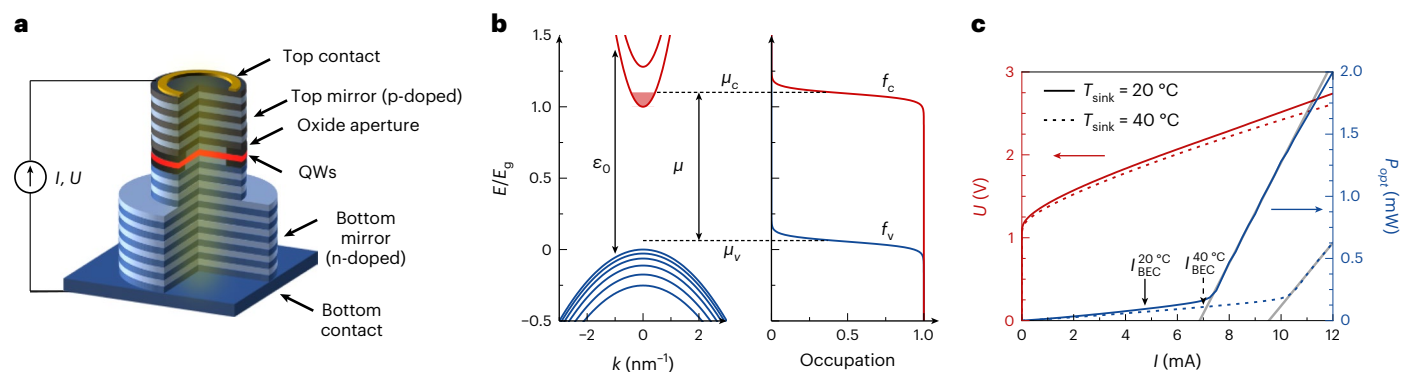


Fig. 1 | Basic properties of a VCSEL. **a**, Scheme of the investigated VCSEL devices, with all main components indicated by arrows. **b**, Left: simplified picture of the energy dispersion E of conduction and valence subbands confined in the QWs of a semiconductor bandgap E_g expressed in the in-plane wavevector. Right: the occupations of the conduction band f_c and the valence band states f_v , expressed with Fermi–Dirac distributions of different quasi-Fermi levels μ_c and μ_v , respectively. ε_0 is the energy of the fundamental cavity mode, which is

larger than the chemical potential μ to ensure below-lasing conditions. **c**, Light-current-voltage (LIV) characteristics of the BEC device measured at two different temperatures of the heatsink $T_{sink} = 20^\circ\text{C}$ (solid line) and $T_{sink} = 40^\circ\text{C}$ (dashed line), where U and I are the voltage and current applied to the device and P_{opt} is the measured optical output power. The points I_{BEC} of critical photon number to achieve BEC are indicated by arrows (see text). The semitransparent grey lines fit the linear part of the optical power curves to extract the laser thresholds I_{th} .

analogies have been drawn between laser physics and atomic BEC physics, yielding a more detailed understanding of these two worlds. Eventually, a system that meets all the requirements of an equilibrium photon BEC was obtained in a laboratory tabletop system of a microcavity filled with a rhodamine solution¹². Remarkably, this system clearly demonstrated many textbook effects of a non-interacting condensate of bosons, from thermodynamic and caloric properties^{13,14} to quantum-statistical effects^{15,16}. Moreover, the driven-dissipative nature of this system beyond equilibrium has been demonstrated^{17,18}, and the phase boundaries between photon BECs and non-equilibrium lasing have been investigated extensively^{19,20}. However, rhodamine-based photon BECs are limited by their weak and slow thermo-optical nonlinearity^{21,22}, which so far has prevented the observation of static or dynamic superfluid effects. Pioneering observations have stimulated the search for BEC conditions in other laser systems, such as fibre cavities²³ and semiconductor lasers^{24–26}, to enable true technological applications outside of the laboratory environment and to find a material system with non-negligible and fast nonlinearities.

Here, we demonstrate a photon BEC in a well-established semiconductor device, a large-aperture electrically driven vertical-cavity surface-emitting laser (VCSEL) diode at room temperature. By testing devices with different energy detunings between the cavity fundamental mode ε_0 and the quantum well (QW) fundamental transition ε_{QW} , defined as $\Delta = \varepsilon_0 - \varepsilon_{QW}$, we found a homogeneous BEC of photons with a thermalized spectrum. This occurred for $\Delta_1 = -5.2$ meV and the standard non-equilibrium laser operation at higher-order modes in another device of the same geometry but with much more negative detuning $\Delta_2 = -14$ meV. In the BEC regime, we found that the photonic gas thermalizes to temperatures below the temperature of the VCSEL, suggesting that it is not fully equilibrated with the optical gain medium. Nevertheless, the extracted temperatures, chemical potentials and photon densities allowed us to experimentally determine the equation of state (EOS), which follows the behaviour of a two-dimensional (2D) Bose gas in thermal equilibrium.

The device under study is an epitaxially grown oxide-confined VCSEL with a large 23- μm -diameter aperture, emitting around 980 nm. The VCSEL is designed for simultaneous high bandwidth, high optical output power and moderate to high wall plug efficiency²⁷ (see Methods for details). The laser device consists of two distributed Bragg reflectors (DBR), p-doped and n-doped, to create a p–i–n junction with the multiple QW active region sandwiched between them (Fig. 1a). Highly resistive oxide apertures are located above and below the cavity layer

in the first nodes of the optical field intensity, providing spatial current confinement in the active region, that is, directing the carrier flow to the centre of the device. The apertures also act on the optical modes, defining the modal distribution in the sample (Supplementary Section I). Photons escape mostly through the top mirror and are detected in our setup. We drive our semiconductor device at room temperature with direct current, by applying a constant voltage across the laser diode (Fig. 1a). This sets the non-equilibrium distribution of carriers in the QW region, as the separation of the quasi-Fermi levels for electrons in the conduction band states μ_c and holes in the valence band states μ_v is proportional to the applied voltage. Due to the subpicosecond relaxation of carriers within the bands²⁸, the electrons and holes are in equilibrium with the device. Hence, both gases can be described with separate Fermi distributions, with different quasi-Fermi levels setting the occupation in both bands (Fig. 1b ref. 29).

Let us assess the essential conditions for obtaining a photon BEC in a VCSEL. In electrically driven semiconductors, excited electrons and holes can recombine, emitting photons. Thus, the condition of chemical equilibrium can be established if the chemical potential of photons is equal to $\mu = \mu_c - \mu_v$, in close analogy to a photochemical reaction³⁰. Another key ingredient is the detailed balance condition between emission and absorption, which was explored in the first demonstrations of photon BECs based on organic laser dyes¹². This condition is also met in semiconductors, where the ratio between emission and absorption rates is expressed as the van Roosbroeck–Shockley relation $R_{abs}(\varepsilon)/R_{em}(\varepsilon) = \exp(\frac{\varepsilon - \mu}{k_B T})$ (Methods)^{29,31}. Hence, the thermalization of light occurs after a few cycles of spontaneous emission and absorption events before the photons escape the cavity through the mirror. This energy exchange with the active medium enables the photon gas to establish both a chemical potential and a temperature. Eventually, it leads to a modified Bose–Einstein (BE) distribution of photons, which can be derived from the laser rate equations (Methods):

$$N(\varepsilon) = \frac{1}{\exp\left(\frac{\varepsilon - \mu}{k_B T}\right) - 1 + \Gamma(\varepsilon)} \quad (1)$$

Here, the correction parameter $\Gamma(\varepsilon) = \gamma(\varepsilon)/R_{em}(\varepsilon)$ represents the ratio of the photon decay rate from the passive cavity γ and the spontaneous emission rate R_{em} to the photon mode at a given energy ε . Consequently, this correction parameter can be treated as a measure of the degree

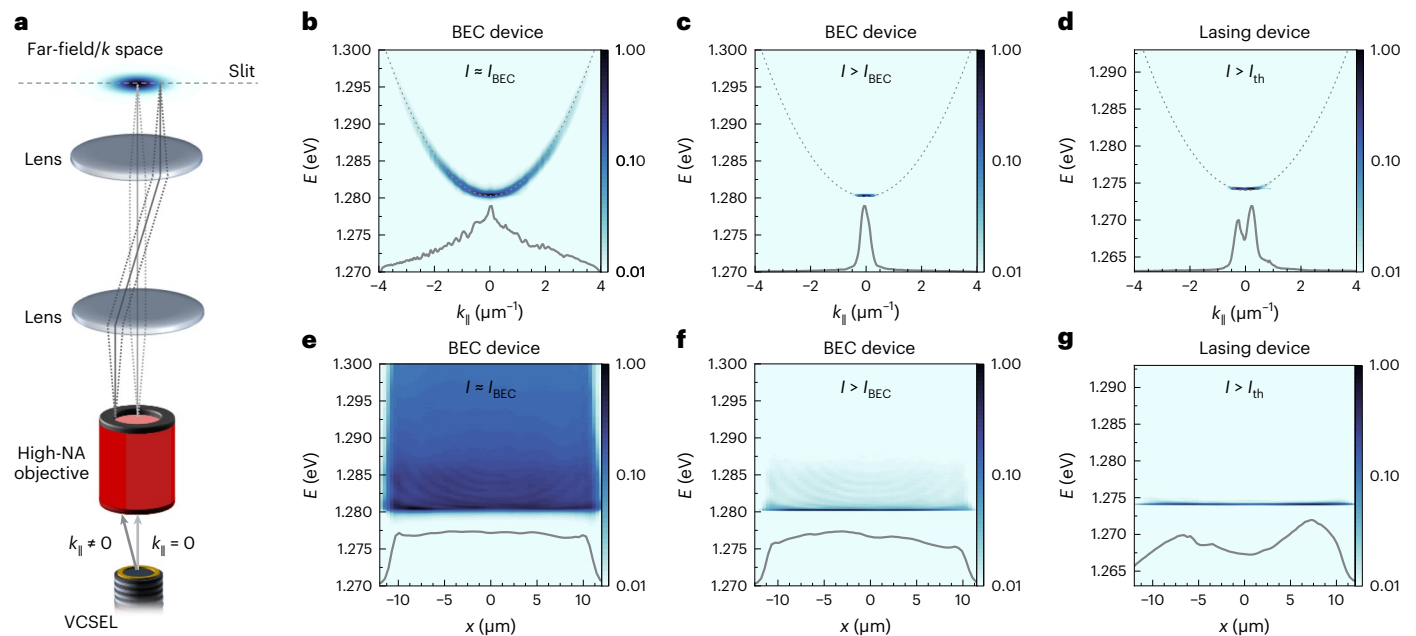


Fig. 2 | Momentum-space and real-space spectra of the BEC and a laser device.

a, Scheme of the experimental setup used for momentum-space imaging. The back focal plane of the microscope objective is imaged onto the entrance slit of the monochromator, and then it is dispersed to the CCD camera, enabling probing of the spectral information at the centre cut of the momentum space. **b**, Momentum-space spectrum (E is the emitted photon energy) of the BEC device around the critical BEC photon number ($I_{\text{BEC}} \approx 5$ mA). **c**, Similar data taken above I_{BEC} , $I = 7.25$ mA showing the narrowing from thermal distribution to the ground

state $k_{\parallel} = 0$. **d**, Momentum-space spectrum of the lasing device in the higher-order mode above the lasing threshold ($I = 6.3$ mA). **e, f**, Real-space spectra of the BEC device around ($I_{\text{BEC}} \approx 5$ mA) and above the threshold ($I = 7.25$ mA) showing homogeneity of the gas. **g**, Real-space spectrum of the lasing device that presents the domination of the higher-order mode. The data are presented for $T_{\text{sink}} = 20$ °C. All colour scales are logarithmic to enhance the visibility of high-energy states. Insets in **b–g** represent the normalized energy-integrated spatial emission of the photon gas in linear scale.

of thermalization. It is expected to be small if many photon emission–absorption cycles occur before the photons escape the cavity. At this limit, equation (1) approaches the BE distribution. Based on our numerical modelling and experimental measurements, we estimated this ratio for the fundamental mode at $\Gamma(\varepsilon_0) \approx 0.008$ (Methods and Supplementary Section IV) ensuring that we obtained a thermalized photon gas in our system.

According to standard semiconductor laser theory, the Bernard–Duraffourg condition³², which is essential for non-equilibrium lasing, is met when the value of the chemical potential exceeds the energy of an optical mode $\mu > \varepsilon$. This creates a positive optical gain at this energy²⁹, so thermalization is expected to dominate below this limit and before reaching the classical lasing threshold I_{th} . Therefore, we probed devices with different cavity–QW gain detunings Δ , that is, with different energies of the cavity mode ε_0 . We used the side effect of epitaxial growth that the resulting layers are not homogeneous throughout the entire wafer and have a tendency to become thinner towards the edge^{33–35}. Phenomenologically, this affects the cavity energy shifts more than the spectral shifts of the gain. Thus, close to the centre of the 3 inch wafer, we probe the device with more negative $\Delta < 0$, which is the standard designed detuning for high-power and high-temperature lasing operation, which we denote as the lasing device. In contrast, close to the edge of the wafer, the detuning becomes close to resonance, and the device is expected to operate in the thermalized BEC regime, which we denote as the BEC device. The relative cavity–QW energy detuning of the probed devices was determined by recording the spontaneous emission from the QW from the side of the laser to determine the spectral position of the QW ground state (Supplementary Section IX).

The electrical and total output power characteristics on the driving current of the BEC device are shown in Fig. 1c, measured at two different heatsink temperatures T_{sink} , whereas the results of the lasing device are summarized in Supplementary Section III. The data show all

the standard features of a semiconductor laser, the electrical characteristics of a diode and the emission threshold current I_{th} . Furthermore, I_{th} shifts to higher values at larger device temperature and the total output power decreases, as expected for this detuning Δ_1 . However, the device is characterized by a substantial spontaneous emission below I_{th} . Therefore, the information contained in the spectral characteristics of the device must be examined to distinguish between a BEC and a lasing state.

To this end, we performed an analysis of the VCSEL spectral features, especially the distribution of occupations in the respective energy states. The investigated devices have large electrical apertures, resulting in a quasi-continuum of transversal optical modes (or in-plane energy states). Thus, photons in the resonator can be described by a parabolic dispersion in the in-plane direction $\varepsilon_k = \varepsilon_0 + \frac{\hbar^2 k^2}{2m_{\text{ph}}}$ with an effective mass m_{ph} . In our device, we find $m_{\text{ph}} \approx 2.75 \times 10^{-5} m_e$, where m_e is the mass of the free electron.

We employed the back focal plane (Fourier space or far-field) imaging technique to directly access the momentum dispersion, as shown schematically in Fig. 2a. The image is directed onto the monochromator slit, allowing for spectral analysis of the momentum dispersions. The resulting momentum dispersion around $I \approx I_{\text{BEC}}$ is shown in Fig. 2b. It shows a thermalized distribution in momentum space, following the expected parabolic dispersion. The most distinguishing feature is observed above the critical BEC threshold $I > I_{\text{BEC}}$ (Fig. 2c), where the fundamental mode at $k_{\parallel} = 0$ dominates the spectrum. This is an unusual behaviour for such a large-aperture resonator, as lasing in higher-order modes is commonplace³⁶. We obtain this standard behaviour in our lasing device with more negative detuning Δ_2 , where lasing in a higher-order mode is detected right above the threshold current, together with a distinctive splitting in the momentum space (Fig. 2d). This crucial difference between the BEC and the lasing devices

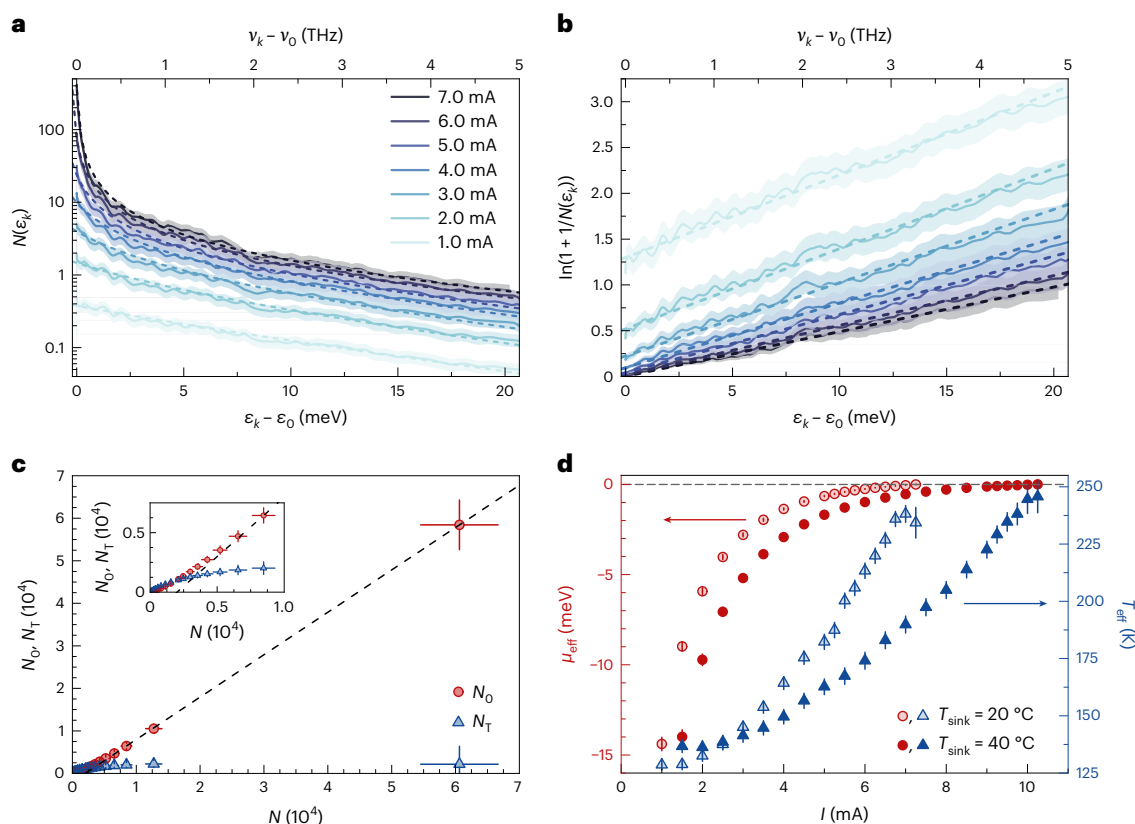


Fig. 3 | Experimental energy distributions and thermodynamic quantities.

a, Solid lines represent energy distributions extracted from the momentum spectra for different driving currents at $T_{\text{sink}} = 20^\circ\text{C}$. **b**, The same data are represented in logarithmic form (see text). In **a** and **b**, the energy scale is expressed with respect to the energy in the ground mode. The dashed lines are the fits of the BE distribution to the experimental data. The error bars are obtained from fits by Lorentzian functions at each $k_{\parallel}$ and are depicted as shaded regions. **c**, Population of the ground state (N_0) and excited states (N_T)

extracted from the experimental spectra at $T_{\text{sink}} = 20^\circ\text{C}$. The dashed line is the linear fit above the condensation threshold to calculate the critical density (N_C). The inset shows the zoom-in into the low-number region of the main plot. **d**, Thermodynamic quantities, effective chemical potential μ_{eff} and temperature T_{eff} extracted from fitting the experimental distributions, as a function of driving current for $T_{\text{sink}} = 20^\circ\text{C}$ (light symbols) and $T_{\text{sink}} = 40^\circ\text{C}$ (full symbols). The error bars in **c** are obtained on the basis of setup calibration uncertainty and in **d** are calculated from fits with the BE distribution.

is confirmed in the spatially resolved spectra in the near field, since in the case of BEC behaviour we are dealing with a spatially homogeneous gas of photons, shown in Fig. 2e,f, where condensation occurs in the fundamental transversal optical mode (ground state) of the system. On the contrary, the lasing device operates in the higher-order mode, which is distributed closer to the aperture perimeter where the current density and optical gain are higher (Fig. 2g)^{36–38}.

We further explore the thermodynamic properties of the photon gas in the BEC device by extracting the occupancies of the respective transversal energy states. Hence, we integrate the momentum-space electroluminescence data taking into account the density of states, the estimated photon lifetimes and the efficiency of the optical setup (see Methods for details). The experimental energy distributions at different driving currents at $T_{\text{sink}} = 20^\circ\text{C}$ are shown in Fig. 3a. All data were successfully fitted with the BE distributions of equation (1) by assuming a negligible Γ . Additional verification of the BE distribution was also carried out, representing the data in logarithmic form, by transforming equation (1) as $\ln[1 + 1/N(\epsilon)] = \epsilon/(k_B T) - \mu/(k_B T)$, which results as a linear function of energy (Fig. 3b). The corresponding data for the lasing device can be found in Supplementary Fig. 4.

The data resemble the textbook behaviour of a Bose condensed gas, such as massive occupation and threshold-like dependency of the ground-state occupancy N_0 as a function of the total number of particles, along with saturation of the excited states N_T . These effects can be seen in the distributions in Fig. 3a. Figure 3c summarizes the corresponding values of N_0 , N_T . However, the thermal tails do not have

the same slopes, which is more evident in Fig. 3b. This implies that, although the photons seem to be equilibrated, the temperature of the gas is not equal at different driving currents. Therefore, we denote the fitting parameters of the BE distribution as an effective chemical potential μ_{eff} and temperature T_{eff} , because these may not be equal to those set by the device conditions. Importantly, the geometry of the device imposes an inhomogeneous current density across the aperture. Therefore, the chemical potential set by the quasi-Fermi levels and the temperature slightly vary spatially. The thermodynamic properties of the photon gas are a result of the spatially averaged overlap of the optical modes with the inhomogeneous QWs active medium³⁹. The results of the fits to the experimental data are shown in Fig. 3d. The effective chemical potential is always negative with respect to the fundamental mode energy and approaches zero when condensation occurs, supporting a BEC behaviour for an ideal gas. On the other hand, the effective temperature is a monotonic function of the driving current and saturates above the condensation transition to $T_{\text{eff}} \approx 234\text{ K}$ at $T_{\text{sink}} = 20^\circ\text{C} = 293\text{ K}$. Importantly, we tested whether the photon gas temperature is related to the device temperature and repeated the experiment at higher temperature $T_{\text{sink}} = 40^\circ\text{C} = 313\text{ K}$. Remarkably, photons condensed in a similar way as before, but at a higher temperature of about $T_{\text{eff}} \approx 246\text{ K}$. Note that the actual temperature of the active region is expected to be even slightly higher due to the heating effects in the device (Supplementary Section I).

Further support of the occurrence of the BEC transition can be extracted from the data in Fig. 3c. We fit the threshold-like N_0

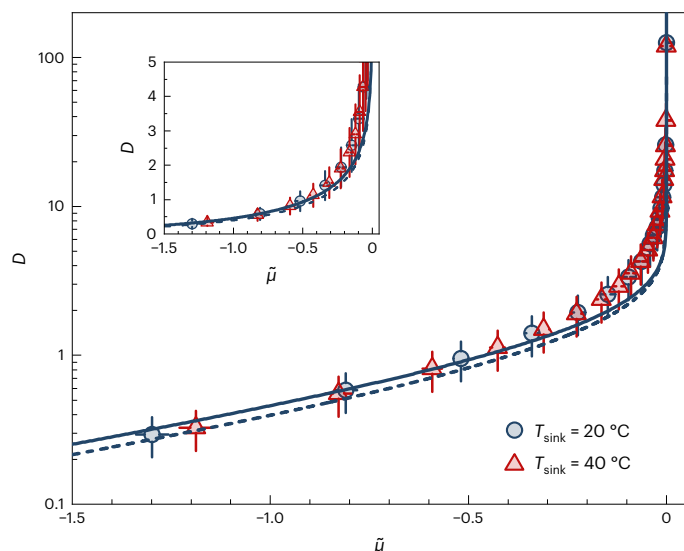


Fig. 4 | Determination of the EOS. Points are extracted from the experimental data based on T_{eff} and μ_{eff} (see the main text). The solid line is the theoretical EOS for a 2D Bose gas in the thermodynamic limit. The dashed line is calculated by taking into account the finite collection angle of the optical setup (cut-off of 20 meV) at $T = 130$ K. The error bars are obtained from fits to the BE distribution and taking into account the setup calibration uncertainty.

dependence on the total particle number N at high values in the condensed state to experimentally extract the critical particle number $N_C^{\text{exp}} = 2,006 \pm 116$ at $T_{\text{sink}} = 20$ °C and $N_C^{\text{exp}} = 2,311 \pm 112$ at $T_{\text{sink}} = 40$ °C. Both critical values N_C occur at currents below the typically defined thresholds of the power–current–voltage (LIV) curves as predicted by recent theory³⁹ (Fig. 1c). Theoretically, the extracted N_C values are expected at photon gas temperatures $T \approx 150 \pm 15$ K and $T \approx 170 \pm 15$ K, which are close to the experimental values extracted from Fig. 3d at the condensation thresholds $T_{\text{eff}} \approx 170$ K and $T_{\text{eff}} \approx 185$ K. Furthermore, the BEC state above the critical density is characterized by a linewidth narrowing and the appearance of spatial coherence (Supplementary Section VII). These features are an additional piece of evidence for the global order parameter in the system accompanying the BEC transition. We also note that the condensed mode is characterized with nearly linear polarization; however, its orientation is always pinned to one direction of the sample, which is a result of small birefringence of the cavity. Therefore, this signature cannot be interpreted as a measure of the order parameter.

The thermodynamic parameters suggest that we are dealing with a photonic gas that is not in full thermal and chemical equilibrium with the reservoir, which is the active region of the device. Equilibration to temperatures lower than the reservoir by stimulated cooling has recently been predicted for driven-dissipative bosonic condensates in the fast thermalization limit in a quantum model taking into account all correlations between states⁴⁰. An experimental indication for the stimulated cooling effect can be seen in our data, as the occupations of the excited states are above unity in the condensed regime according to Fig. 3a. Under such conditions of large occupation numbers, thermalization rates increase strongly due to the bosonic stimulation effect that establishes a thermalized distribution of the gas. Furthermore, there is a saturation of T_{eff} largest currents in Fig. 3d, as predicted in ref. 40. Furthermore, non-perfect thermalization can be an effect of non-vanishing thermalization parameters Γ for the whole spectrum, as discussed in ref. 39. In our case, the monotonic increase of the photon gas temperature towards equilibrium in Fig. 3d can be explained by an increase $R_{\text{em}}(\epsilon)$, that is a decrease of $\Gamma(\epsilon)$ with the current. However, it is impossible to extract the spectrum of $\Gamma(\epsilon)$ from the current experiment.

Therefore, it is interesting to examine what the EOS of the probed photon condensate is and whether it follows the EOS for a 2D Bose gas, despite the non-perfect thermalization. The EOS is written in the thermodynamic limit as

$$D = -\ln[1 + \exp(\bar{\mu})], \quad (2)$$

where $D = n\lambda_T^2$ represents the dimensionless phase-space density and $\bar{\mu} = \mu/(k_B T)$. The photon density is defined by $n = N/(\pi R^2)$ with πR^2 denoting the surface area of the aperture and R being its radius, while the thermal de Broglie wavelength of photons reads $\lambda_T = \sqrt{(2\pi\hbar^2)/(m_{\text{ph}}k_B T)}$. As the EOS is expressed in normalized quantities by D and $\bar{\mu}$, the properties of the 2D bosonic gas are expected to be universal^{41,42}.

The measured EOS, determined from the experimental values μ_{eff} and T_{eff} for two different device temperatures, is shown in Fig. 4. The data follow the equilibrium EOS, with slight deviations from the theoretical expectation. This can be partially explained by the finite collection angle of the collection optics in our setup, which is represented by the numerical aperture (NA) of the microscope objective. We cannot detect energies emitted beyond the maximal angle, which sets the maximal detectable energy at about 20 meV above the ground state. Numerical calculations confirm the observations, as we computed the phase-space density for a finite number of states defined by the NA at the lowest recorded temperature of the gas $T \approx 130$ K, which matches the data at low D . There is a slight deviation at larger D , which could be the result of the imperfect thermalization of our system and the limited experimental accuracy.

We have demonstrated that emission from a slightly detuned VCSEL has the properties of a homogeneous 2D BE condensed gas of photons in a finite system. The measured non-equilibrium nature of the gas can be a signature of reaching the fast, stimulated thermalization limit, because the cavity is characterized by a relatively short photon lifetime. Photon condensation in semiconductor resonators offers the possibility of observing the superfluidity of a weakly interacting Bose gas. Photon interactions are expected to be mediated by semiconductor nonlinearity, which is enhanced by the cavity and has a subpicosecond-order response time^{43,44}. There are no clear indications of such interactions in our data, because the cavity energy shifts are dominated by the current- and temperature-induced changes in the refractive index (Supplementary Section VII). More studies are needed, focused on probing the hydrodynamics of condensed photons directly by perturbing them from the steady state^{45,46}. Additionally, the dissipative nature of the photon gas encourages further studies of phase ordering⁴⁷ and universal scaling in a 2D geometry^{48,49} and signs of non-Hermitian effects⁵⁰.

Another direction for future work is to test the fluctuations of the non-equilibrium BEC and to compare it with the BEC in thermal equilibrium^{51,52} as well as with standard VCSEL operation^{53,54}. The mature technology of semiconductor VCSELs offers the possibility of utilizing the BEC regime to achieve single-mode emission from large-aperture devices characterized by excellent beam quality, without the need for sophisticated design^{55–57}. BEC VCSELs could also be applied in complex lattice geometries, to study topological effects in well-controlled current-operated devices at room temperature⁵⁸.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41566-024-01478-z>.

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Methods

Thermalization of photons in a semiconductor laser

The principles of light absorption and recombination in an excited semiconductor QW, depicted in Fig. 1b, can be described by the following transition rates^{29,39} for emission

$$R_{\text{em}}(\varepsilon) = R(\varepsilon)f_c(\varepsilon_c, T, \mu_c)[1 - f_v(\varepsilon_v, T, \mu_v)] \quad (3)$$

and absorption

$$R_{\text{abs}}(\varepsilon) = R(\varepsilon)f_v(\varepsilon_v, T, \mu_v)[1 - f_c(\varepsilon_c, T, \mu_c)], \quad (4)$$

where $f_{c,v} = \{\exp[(\varepsilon_{c,v} - \mu_{c,v})/(k_B T)] + 1\}^{-1}$ denote the thermalized Fermi–Dirac distributions of electrons in the conduction and holes in the valence bands, respectively. Furthermore, the transition rate $R(\varepsilon)$ at the transition energy $\varepsilon = \varepsilon_c - \varepsilon_v$ takes into account the photonic and electronic density of states, the overlap of the optical modes with the active medium, and the intrinsic properties of the active medium itself³⁹. The natural consequence in semiconductors is the van Roosbroeck–Shockley relation, which appears, after some algebra, from the relation

$$\frac{R_{\text{abs}}(\varepsilon)}{R_{\text{em}}(\varepsilon)} = \exp\left(\frac{\varepsilon - \mu}{k_B T}\right) \quad (5)$$

with $\mu = \mu_c - \mu_v$ (refs. 29,30,39).

Now, the rate equation for the occupation of an optical mode at ε is expressed as

$$\frac{d}{dt}N(\varepsilon) = R_{\text{em}}(\varepsilon)[N(\varepsilon) + 1] - [R_{\text{abs}}(\varepsilon) + \gamma(\varepsilon)]N(\varepsilon), \quad (6)$$

where $\gamma(\varepsilon) = 1/\tau(\varepsilon)$ denotes the decay rate of a photon from an empty cavity at ε . Thus, the resulting steady-state solution gives

$$N(\varepsilon) = \frac{R_{\text{em}}(\varepsilon)}{\gamma(\varepsilon) - [R_{\text{em}}(\varepsilon) - R_{\text{abs}}(\varepsilon)]}. \quad (7)$$

After dividing both numerator and denominator by $R_{\text{em}}(\varepsilon)$ as well as using the van Roosbroeck–Shockley relation (equation (5)), we obtain for $N(\varepsilon)$ the result of equation (1). This amounts to a BE distribution with the correction parameter $\Gamma(\varepsilon) = \gamma(\varepsilon)/R_{\text{em}}(\varepsilon)$.

We estimated this correction parameter $\Gamma(\varepsilon_0)$ for the fundamental mode ε_0 of the device as follows. The decay rate of a photon from an empty cavity follows from the decay time calculated from the realistic numerical model: $\gamma(\varepsilon_0) = 1/\tau(\varepsilon_0) = 1/(3.04 \text{ ps}^{-1}) \approx 0.33 \text{ ps}^{-1}$ (Supplementary Section IV). We are able to determine the value of $R_{\text{em}}(\varepsilon_0) = 42 \pm 3 \text{ ps}^{-1}$ close to the threshold by measuring the linewidth dependence of the ground mode as a function of occupation below the condensation threshold³⁹. With this, we obtain the value $\Gamma(\varepsilon_0) \approx 0.008$ as mentioned above.

Sample

The VCSEL epitaxial structure is designed for high-speed data communication at 980 nm. The epitaxial structure is monolithically grown on an n-doped GaAs substrate. The multi-quantum well active region is composed of five $\text{In}_{0.23}\text{Ga}_{0.77}\text{As}$ QWs and six $\text{GaAs}_{0.86}\text{P}_{0.14}$ barriers centred in an $\text{Al}_x\text{Ga}_{1-x}\text{As}$ cavity graded from $x = 0.38$ to 0.80 with an optical cavity thickness of $\lambda/2$. The cavity is sandwiched by 15.5-pair $\text{GaAs}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ top and 37-pair bottom DBR mirrors. The top and bottom DBRs are C-doped for the p-type and Si-doped for the n-type, respectively. In both mirrors, linearly graded interfaces are incorporated for lower electrical resistance of the structure. Importantly, two 20-nm-thick $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layers are placed to form oxide apertures in the first nodes of the standing wave at the top and bottom of the cavity.

These oxide layers are halfway in the optical cavity and halfway in the first pair of layers in the DBRs.

The VCSELs are processed using standard top-down photolithography. In the first step, the Ti/Pt/Au p-type contact rings are deposited with the use of electron beam deposition (E-beam). The mesa structures are then patterned and etched using inductively coupled plasma reactive-ion etching in a Cl_2/BCl_3 -based plasma. After etching, current confinement apertures are formed by selective wet thermal oxidation of the $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ layers in an oxidation oven in a nitrogen atmosphere with an overpressure of water vapour and at high temperature (420 °C). In the following step, horseshoe-shaped Ni/AuGe/Au n-type contact pads are deposited and annealed in a rapid thermal processing furnace. The structures are then planarized with the use of a spin-on dielectric polymer of benzocyclobutene. The benzocyclobutene layer is patterned with the use of photolithography and reactive-ion etching in a CF_4 -based plasma to selectively open surface areas to subsequently bias the p- and n-type contacts. Finally we deposit ground–signal–ground Cr/Pt/Au contact pads.

Experimental setup

The sample used in this study was a fully processed quarter of the whole 3-inch-diameter epitaxial wafer. The sample was placed on a thermo-electrically cooled plate (Thorlabs PTC1) with a built-in temperature sensor. The temperature of the heatsink was set to 20 °C or 40 °C in our experiments. The temperature-controlled plate was placed on a manual translation stage. The sample was contacted by a microwave probe (GGB Industries Picoprobe 40A) located in an additional manual translation stage. The devices were driven with a direct current by a stabilized precise source/measure unit (Keysight B2901B).

The device emission was collected using an infinity-corrected objective of NA = 0.65 (Mitutoyo M Plan Apo NIR HR 50×). As described in the main text, to measure the momentum spectra (far field), we imaged the back focal plane of the objective with a set of achromatic lenses onto the 0.3-m-focal-length monochromator entrance slit (Princeton Instruments Acton SP-2300i), and the electroluminescence signal was dispersed through a grating (1,200 grooves mm^{-1}) onto an electron-multiplied charge-coupled device (Teledyne Princeton Instruments ProEM-HS:1024BX3). To record the spatially resolved spectra (near field), one of the lenses was removed from the optical path, which enabled projection of the real-space image onto the monochromator slit. This lens was mounted on a flip mount, allowing quick and convenient switching between the two measurement modes of the setup.

Analysis of the momentum space

Taking advantage of homogeneous emission from the BEC device, we determined the thermodynamic properties of the photon gas from the momentum space. We extracted the mean photon occupation distribution by integrating the momentum space emission, using the standard procedure used in cavity-polariton physics^{10,60}.

The mean number of photons collected at a pixel row representing a chosen k state is represented as

$$N_{\text{ph}}(k) = \eta \frac{dN_{\text{CCD}}(k)}{dt} \tau(k), \quad (8)$$

where η is the calibrated collection efficiency of our setup, $dN_{\text{CCD}}(k)/dt$ is the count rate per second on the CCD camera pixel and $\tau(k)$ is the photon lifetime at k . The photon lifetime was estimated from the experiment by extracting the emission linewidth $\Delta\varepsilon_k = \hbar/\tau(k)$ (ref. 61) by fitting a Lorentzian function to the data from a k -state pixel row.

Subsequently, the occupation number at the k state is calculated taking into account the number of states subtended by a pixel at k position in cylindrical coordinates $N_{\text{st}}(k) = k\Delta k\Delta\phi(4\pi/S)^{-1}$, where S is the surface area of the device aperture. The number of states in momentum space was confirmed by numerical simulations of the

optical modes confined in the device (Supplementary Section I). The final expression is

$$N(\varepsilon(k)) = \frac{N_{\text{ph}}(k)}{N_{\text{st}}(k)} = \frac{4\pi^2\eta}{2k\Delta k\Delta\phi S} \frac{dN_{\text{CCD}}(k)}{d\varepsilon} \tau(k), \quad (9)$$

which also considers the spin degeneracy 2 of all states, as our experiment was not polarization resolved. The energy $\varepsilon(k)$ and the photon count (peak area) of the measured k state are extracted from the fitted Lorentzian peak.

Data availability

Data sets generated during the study are available from the corresponding author on reasonable request.

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Author contributions

M.P. conceived this research project. M.P. and A.N.P. conducted the experiments, and M.P. performed the detailed data analysis. J.A.L. designed the epitaxial structure and provided the planar wafer sample. M.G. designed the laser mesa outline and performed all fabrication steps. T.C. performed the numerical modelling of the devices. M.P., A.P., M.W. and T.C. contributed to the theoretical analysis and interpretation of the data. All authors discussed the results. M.P. wrote the manuscript with input from all authors.

Competing interests

The authors declare no competing interests.

Additional information

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