Single SiGe Quantum Dot Emission Deterministically Enhanced in a High-Q Photonic Crystal Resonator

Thanavorn Poempool,1,∗ Johannes Aberl,1 Marco Clementi,2,† Lukas Spindlberger,1
Lada Vukusic,1 Matteo Galli,2 Dario Gerace,2 Frank Fournel,3 Jean-Michel Hartmann,3 Friedrich Schäfler,1 Moritz Brehm,1 and Thomas Fromherz1,‡

1 Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Altenbergerstraβe 69, 4040 Linz, Austria
2 Dipartimento di Fisica, Università di Pavia, Via Bassi 6, 27100 Pavia, Italy
3 University Grenoble Alpes, CEA, LETI, Grenoble, France

We report the resonantly enhanced radiative emission from a single SiGe quantum dot (QD), which is deterministically embedded into a bichromatic photonic crystal resonator (PhCR) at the position of its largest modal electric field by a scalable method. By optimizing our molecular beam epitaxy (MBE) growth technique, we were able to reduce the amount of Ge within the whole resonator to obtain an absolute minimum of exactly one QD, accurately positioned by lithographic methods relative to the PhCR, and an otherwise flat, a few monolayer thin, Ge wetting layer (WL). With this method, record quality (Q) factors for QD-loaded PhCRs up to $Q \sim 10^6$ are achieved. A comparison with control PhCRs on samples containing a WL but no QDs is presented, as well as a detailed analysis of the dependence of the resonator-coupled emission on temperature, excitation intensity, and emission decay after pulsed excitation. Our findings undoubtedly confirm a single QD in the center of the resonator as a potentially novel photon source in the telecom spectral range.

Keywords: high Q photonic crystal resonator; site controlled single SiGe quantum dot; Si integrated photonics

INTRODUCTION

Driven by the rapid growth of the demand in data centers, silicon-based photonic integrated circuits (PICs) have recently witnessed rapid development. They have reached a level of maturity that allowed the implementation of foundry-type fabrication processes.[1, 2] This swift progress was leveraged by utilizing extremely reproducible process steps, originally developed over decades for silicon complementary metal-oxide semiconductor (CMOS) integrated electric circuits to the emerging field of PICs. While for most building blocks of a PIC standard layout libraries are offered by numerous commercial foundries [2], an efficient, Si-based electrically driven light emitter is still missing, mostly due to silicon indirect bandgap. To overcome this hurdle, several methods of heterogeneous integration of III-V semiconductor lasers have been developed.[3] Still, a monolithically integrated emitter would be desirable in terms of production costs and thermal stability. In this respect, promising results on laser emission from strained Ge[4–6], GeSn [7, 8] and SiGe QDs [9] have been reported.

Due to the versatile toolbox available, Si PICs are also highly attractive for possible applications in quantum photonics [10–12]. Complex quantum optical devices integrated on a Si chip have been demonstrated[13]. Similar to classical integrated photonics, also in the quantum domain the indirect bandgaps of Si and Ge pose a major obstacle for the realization of deterministically emitting, monolithically integrated sources of quantum states of electromagnetic radiation. Hybrid integration of highly optimized III-V QDs single photon sources [14] on a Si based integrated quantum optical platform is thus a long standing goal, albeit the most advanced III-V QDs do not emit in the Si transparent wavelength region.[11] Also, defect centers in Si have gained recent attention as single photon sources in the telecom wavelength region.[15] However, site controlled integration of these defects into a PIC platform would be required for prospective scalability but has not been demonstrated, yet.

Thus, despite the spatial separation of electrons and holes confined to SiGe QDs,[16] in addition to the restrictions imposed by the indirect band gaps of Si and Ge, single SiGe QDs as photon emitters remain an active area of research, mainly owing to their anticipated compatibility with CMOS technology,[17] to their natural emission in the telecom wavelength band and, crucially for CMOS compatibility and scalability, to the possibility of perfectly controlling their nucleation site (Ref.[18] and references therein). Several routes to increase the photon emission efficiency of SiGe QDs have been developed, including Ge implantation during QD growth in an MBE reactor [19, 20], annealing and hydrogen diffusion for passivation of recombination centers[21, 22] and radiative lifetime reduction by the Purcell effect [23] in photonic crystal resonators (PhCR)[24–26].

In this work, we concentrate on the enhancement of the emission efficiency by site controlled integration of SiGe QDs into an advanced type of PhCR, providing a large Q-factor via simple design rules [27]. Unlike in previous approaches, in which either more than one QDs

* thanavorn.poempool@jku.at
† Current address: Photonic Systems Laboratory (PHOSL), École Polytechnique Fédérale de Lausanne, Station 11, 1015 Lausanne, Switzerland
‡ thomas.fromherz@jku.at
were present in the photonic structure [24, 25] or all except one QD were removed from the photonic crystal resonator by etching [26]. Here we additionally employ a SiGe QD growth regime, in which \textit{a priori} exactly one QD is nucleating at the center of the PhCR. As a result, we achieve record Q-factor values for PhCR cavities coupled to a QD emitter monolithically fabricated on a Si integrated optical platform. The cavity coupled single QD emission occurs in the telecom wavelength region and is clearly observable up to room temperature.

**EXPERIMENTAL**

**Photonic Crystal Cavities Design and Layout.**

In this work, we use a bichromatic-type PhCR [27] to enhance the emission efficiency of SiGe QDs via the Purcell effect [23]. This effect becomes increasingly efficient for PhCRs with decreasing mode volume (V) and increasing Q-factor (Q), ultimately scaling as the ratio Q/V. [28] In bichromatic PhCRs, both of these requisites can be effectively controlled by straightforward design rules. [27, 29]. A scanning electron micrograph (SEM) of a typical PhCR used in this work is shown in Fig. 1(b). It consists of two main ingredients: a triangular lattice with hole radius \(R\) and PhCR period \(a\), and a line defect made of a row of holes with radius \(r\) and period \(a' < a\). In Fig. 1(b), these four design elements are indicated by white labels. The ratio \(\beta = \frac{a'}{a}\) most significantly determines the Q-factor of this type of PhCR. Since the line defect row has to end with holes centered at positions belonging to the underlying triangular lattice, \(\beta\) can be expressed as \(\beta = \frac{N}{N + 1}\), where \(N\) is the center-to-center distance of outermost holes of the line defect. This distance is then subdivided into \(N + 1\) periods of length \(a'\), i.e. \(N a = (N + 1)a'\). In simulations, \(Q > 10^9\) has been predicted for an ideal Si-membrane PhCR with \(\beta = 0.96\) (\(N = 24\)) [27, 29]. However, due to technological deviations from the ideal design, reported experimental values for such a PhCR were limited to \(Q \sim 1.2 \times 10^6\) in previous reports. [29, 30]

On our chip, we fix \(N = 24\) and \(R = 100\) nm for all PhCRs. The remaining design parameters were varied, resulting in a series of implemented PhCRs with lattice periods covering the range between 330 nm and 430 nm in 10 nm steps. For each \(a\), a subset of PhCRs with varying hole radii \(r\) of the line defect with \(r = 40, 50, 60, 70\) nm was fabricated. The vertical outcoupling efficiency was controlled by a so-called far-field optimization (ff) structure based on the second-order Bragg grating effect [31, 32]. For this purpose, the radius of each square hole around the main cavity [marked in yellow in Fig. 1(b)] was slightly increased by \(\Delta r = 0, 3\) or 6 nm, labeled ff0, ff3, and ff6 in the following. Thus, in total, 132 bichromatic PhCRs, each with a different combination of \(a\), \(r\) and \(\Delta r\) were implemented on one chip. However, since strong optical signals could be observed in our setups already with ff3 PhCRs, including ff6 PhCRs in the experiments reported here turned out to be not required.

**Sample Growth and Fabrication.**

In order to maximize the radiative transition rate between electrons and holes confined into a QD via the Purcell effect, a PhCR has to be fabricated in exact registry with the QD, such that the latter occupies the position of maximum electric field amplitude of the PhCR’s electromagnetic ground mode. To achieve this alignment, we follow the route described in Ref. [26]. In brief, a custom-made silicon-on-insulator (SOI) substrate with reduced background emission in the wavelength range relevant for this work (1.3-1.6 \(\mu\)m) and a 70 nm Si device layer on top of a 2 \(\mu\)m thick buried oxide layer (BOX) was employed as an initial substrate for further growth and PhCR processing. Background emission as described above has recently been observed for commercial SOI substrates even at room temperature [33, 34] and was ascribed to remnants of the hydrogen implantation for the SOI smart-cut process [35]. By a bonding/splitting/thinning/annealing process sequence [36] any potential optical active defects were removed in a similar way as reported in Ref. [33]. In addition, thinning of the device layer to just 70 nm allowed us to vertically center the Ge QDs in the designed slab thickness of 220 nm.

Samples were patterned by electron beam lithography (Methods). A three-mask-level process allows the aligned exposure of the QD positioning mask and the PhCR mask with respect to alignment marks defined in the first lithographic step. The alignment marks were plasma-etched (Methods) into the SOI substrate to a depth of \(\sim 110\) nm. In the second step, a single pit (SP) per PhCR was exposed at a defined position with respect to the alignment marks. This is distinctly different from our previous work [24, 26], where a pit array was defined with all but the center pit in registry with air holes of the PhCR to be defined in the final lithographic layer. The improvements resulting from this modification will be discussed below. These pits were transferred into the SOI substrate by plasma etching at \(-90^{\circ}\)C as described in the Methods section. Theetch depth was adjusted to \(35 \pm 5\) nm as confirmed by atomic force microscopy (AFM). The cross-section of the device layer after pit-etching is schematically indicated by the dotted line in Fig. 1(d). At this point, the SP pre-patterned SOI substrate was ready for the QD growth process.

The QD growth procedure started with cleaning, degassing and buffer layer growth steps that are standard for MBE growth of SiGe layers. They are detailed in the Methods section. A sketch of the surface profile after the buffer deposition is shown in Fig. 1(d) by the dashed line. Next, \(\sim 4\) monolayers (ML) Ge corresponding to \(\sim 5.69\) \(\AA\) were deposited at a growth rate of 0.04 \(\AA/s\) while the substrate temperature was maintained constant at 650\(^{\circ}\)C. Since the total Ge coverage stays below the
critical one for spontaneous Ge QD formation on flat substrate areas (4.2-4.9 ML at 650°C), a two dimensional Ge WL without QDs forms there [18]. On the other hand, QD formation in the pit sets in already at a Ge coverage much smaller than 4 MLs. In addition, at this Ge coverage and the employed growth temperature, the Ge surface diffusion length is much larger than 30 µm [37] so that sufficient Ge for the formation of a QD in a pit reaches one of these sparse pits [18]. We want to emphasize that a pit spacing of 100 µm, as determined in this work by the center-to-center PhCR distance, is the largest for perfectly site-controlled QD formation ever reported. It exceeds previously reported ones by at least a factor ~ 30 [18, 25, 38]. As predicted in Refs. [18, 37], no fundamental limit on the distance of site-controlled SiGe QDs seems to exist under suitable growth condition. Finally, samples intended for QD emission experiments were capped by a 115 nm thick Si layer as described in the Methods section. As a result, the total thickness of grown layers plus original device layer is ~220 nm, with a QD positioned in its center. Note that this total thickness is widely accepted as standard for the SOI integrated optical platform [3], allowing for a straightforward combination of the QD layer stack with device layouts readily available in PIC design libraries. Samples intended for structural characterization by surface scanning methods were grown without the Si cap.

After MBE growth, the samples were prepared for the PhCR mask layer in the same way as for the previous lithographic steps. Due to the large etch depth of the alignment marks, a large fraction of them still shows sufficient contrast for automatized alignment by the e-beam system after the growth of ~ 150 nm Si on top of them. With good alignment marks in place, individual PhCRs could be aligned with ~ 25 nm accuracy relative to the SQD positions [see Fig. 1(b)]. Once again, the PhCRs were transferred into the sample by dry etching as described above. The etch time was adjusted for etching all the way down to the BOX. Compared to our previous work [24, 26], here, no QDs are present at the positions of the PhCRs’ air holes, i.e. in the etch volume. Therefore, a more homogeneous etch rate can be expected, resulting in a tighter etch time control and steeper air hole sidewalls.

Finally, free-standing PhCR membranes as sketched in Fig. 1(c) are implemented by lateral under-etching through the PhCR air holes during a ~ 24 minutes wet chemical etch in 10%-HF. After this etch, the 2 µm thick BOX below the PhCRs is removed. Identically processed, uncapped samples were used to confirm the alignment accuracy by scanning electron microscopy (SEM, LEO Supra 35 from Zeiss).

In addition to SQD samples, reference samples grown on unpatterned SOI substrates were investigated. These
TABLE I. List of SQD and reference samples onto which sets of PhCRs with systematically varying design parameters as described in the text were processed.

| sample ID | emitter     | discussed PhCRs |
|-----------|-------------|-----------------|
| QD        | SiGe SQD, Ge WL | a360 r70 f3 f0  |
| WL        | Ge WL       | a360 r70 f0 f3  |
|           |             | a350 r70 f3 f0  |

reference samples contain the same layer sequence as the SQD samples, including a cap layer. Each layer was grown under nominally identical conditions as its counterpart in the SQD samples. As discussed above, in the absence of pits the deposited Ge forms a homogeneous two-dimensional layer of constant thickness without QDs.

In the following, we refer to this type of reference sample as a wetting layer (WL) sample. To fabricate reference PhCRs on the WL samples, only the third level electron beam lithography step described above and the HF etch step are required.

RESULTS AND DISCUSSION

Post-Processing Characterization

Figure 1(a) shows the morphology of a SQD that is nucleated on a SP pre-patterned substrate. The SQD is surrounded by a flat area free from randomly nucleated QDs as shown by a 30 × 15 μm² AFM image in Fig. 1(a). This perfect site control for QD nucleation is achieved by adjusting the Ge surface coverage to stay below the supersaturation regime of ~ 4.5 ML [39]. The area shown in Fig. 1(b) corresponds to the area within the red rectangle in Fig. 1(a). Figure 1(b) shows a SEM image of a bichromatic PhCR fabricated to be accurately aligned with the QD, in order to maximize the dipole interaction of the QD with the electric field of the PhCR ground mode. The image was taken on an uncapped control sample, for which the QD is not hidden by the capping layer that is required for optically active QDs. The PhCR and QD are in virtually perfect registry in both horizontal and vertical direction with deviation of less than 25 nm. The remaining misalignment is much smaller than typical QD dimensions. It indicates limitations imposed by the employed fabrication technology in a similar range, as previously reported [25]. The yellow dashed circles in Fig. 1(b) mark photonic crystal air holes with radii slightly modified by Δr. By these holes we are able to control the trade-off between highest Q-factor and ff-coupling efficiency.

We want to emphasize, that the QD-free area covers the whole 100 × 100 μm² unit cell of the pit array outside the pit. Therefore, no secondary QD emitters are present to contribute to the resonant emission (RE) from PhCRs. Such a configuration is in contrast to the work of Zeng et al. [25], where PhCRs overlapping with more than one QD separated by 2 μm QD are reported.

Optical Characterization

The emission properties of the cavity coupled QDs were studied by micro-photoluminescence (μ-PL) spectroscopy (Methods). In Fig. 2, we compare the emission of a SQD at the center of a N24 bichromatic PhCR with results from reference PhCRs fabricated on a WL sample. As a typical example, the emission spectrum of a QD in a PhCR with a = 360 nm (a360) r = 70 nm (r70) and second order out-coupling grating formed by air holes with nominal radius of 103 nm (Δr = +3 nm, f3) is shown in Fig. 2 by the blue line. The emission spectrum is dominated by sharp resonances corresponding to the modes of the photonic structure. At 4 K, the dominant peak (labelled M0) is observed at ~ 1336 nm wavelength (∼ 0.9281 eV photon energy). As shown by the dotted line in Fig. 2, increasing the temperature to 290 K results in a ~ 11 nm red-shift of the M0-resonance as a consequence of the Si refractive index’s increase with temperature. We attribute the M0 resonance in Fig. 2 to the emission of the SQD amplified in weak coupling regime by the ground mode of the PhCR according to the Purcell effect [23]. As shown in the Supplementary Material (Fig. S2), the mode M0 can be tuned in the wavelength range between ~ 1304 nm and ~ 1339 nm by selecting a PhCR period in the range 350 nm ≤ a ≤ 370 nm. For all these different PhCR lattice constants, a strong SQD emission coupled to mode M0 is observed, indicating a broad emission spectrum of a single SiGe QD, in agreement with the results reported in Ref. [38].

To corroborate our conjecture, we note that in the red and gray spectra of Fig. 2 the intense cavity-coupled SQD emission is absent and only faint lines are observed instead in the corresponding spectral region. These two spectra were measured on the WL sample, that contains no QDs. The red spectrum was observed for a PhCR nominally identical to the one corresponding to the spectrum for the SQD sample (blue line in Fig. 2). However, the spectral features of both resonators show distinct differences too large to be attributed to limitations of chip-to-chip PhCR reproducibility. Instead, we rather ascribed to them to unequal Ge distributions within the PhCR for the SQD and the WL samples, and thus, to different effective refractive indices for these two nominally identical PhCRs. This effect can be compensated by a slight spectral tuning of the resonance wavelengths via the PhCR lattice constant a. As shown by the gray line in Fig. 2, reducing the PhCR period a from 360 nm to 350 nm results in resonance wavelengths resembling, up to a small blue-shift, those observed for the SQD sample. Most importantly, also for the spectrally tuned resonator on the WL sample, only a small peak (labelled M0 in Fig. 2) is observed within the spectral range of resonance-
coupled SQD emission shown in Fig. S2 of the Supplementary Material. Therefore, the strong resonance $M_0$ is clearly due to the presence of a QD in the PhCR. More evidence for assigning the emission coupled to the $M_0$ mode to the SQD is obtained from its temperature- and excitation-power-dependence as discussed in upcoming paragraphs.

The origin of the faint resonances that are observed also in the absence of QDs in the spectral wavelength range above 1300 nm is attributed to residual WL emission and/or emission associated with defects either in the SOI substrate [40] or in the MBE grown Si. The main contribution of the WL sets in at wavelengths shorter than 1290 nm, indicated by the broad background emission originating from photonic crystal regions outside the actual PhCR with superimposed resonances from WL regions inside the PhCR shown in Fig. 2. In this broad spectral region, for all PhCRs compared in Fig. 2 rather similar mode intensities are observed (note the different scaling factors for the blue, red, and gray spectra). This is especially true for the two PhCRs with different lattice constants $a$ on the WL sample, where the residual intensity differences are tentatively assigned to different Q-factors and outcoupling efficiencies of the various modes. For the SQD sample, the WL is thinner, since Ge from the WL is consumed during QD formation [37, 41], thus, more dissimilarity to the WL-only samples can be expected.

The inset in Fig. 2 shows the spectral profile of the $M_0$ resonance as observed at room temperature in a cross-polarized resonant scattering (RS) experiment [42]. A tunable laser with a spectral resolution better than 1 pm provided by a fiber-based reference Fabry-Perot cavity [29] was scanned through the resonance of the PhCR (blue dots). The peak position of the RS signal is in agreement with the emission maximum of the $M_0$ mode.
observed at $T = 290 \text{K}$. The RS signal is fitted to a Fano-resonance as described in Ref.[42] (red line in inset) and a very high Q-factor close to 53500 is obtained. We want to emphasize, that this value is limited by the effects of out-coupling structure (ff3) included in the respective PhCR layout. Omitting this structure (ff0) while leaving all other parameters of the PhCR unchanged (a=360 nm, r=70 nm, N=24) results in an even larger Q-factor as shown in the inset of Fig. 3 by the blue dots and the fitted Fano-resonance (red line). In this case, we observe $Q \sim 104,000$, which is the largest Q-factor so far reported for a SOI based PhCR loaded with a QD emitter [25, 26, 43–46]. We ascribe this huge improvement of the Q-factor as compared to previous works [25, 26, 43–46] mainly to our novel pit-pattern layout, together with the perfectly site-controlled QD growth technique, that allows restricting the number of QDs per PhCR to exactly the one centered within the cavity. With this layout, we avoid Q-factor degradation as a consequence of secondary QDs in the cavity that possibly act as photon scatterers or absorbers. In addition, via the differences in the etch rates of Si and SiGe for the employed plasma etching recipe, secondary QDs degrade the etch homogeneity and induce additional structural deviations from the ideal PhC structure. Again, we observe the RS resonance shifted to a larger wavelength by $\sim 11 \text{nm}$ due to the different temperatures for PL and RS experiments. It is interesting to note that for the ff0-design the $M_0$ resonance is observed at 5 nm longer wavelength as compared to the ff3-design. This finding is in agreement with a slightly smaller effective index of refraction in the ff3-design due to its smaller Si volume as a consequence of the enlarged air holes forming the ff structure. Further evidence for the distinctly different nature of the emission sources coupled to the modes $M_0$, $M_3$ and $M_0^{\text{ref}}$ of the PhCRs shown in Fig. 2 is provided by their different quenching behavior as the temperature rises from cryogenic to room temperature. Figure 4(a) shows Arrhenius plots of observed mode intensities integrated over the line shapes for modes $M_0$ (blue symbols), $M_3$ (red symbols) of the PhCR aligned to a SQD and for mode $M_0^{\text{ref}}$ (green symbols) of the PhCR on the WL sample. The data were fitted to the simplest quenching function given by [47]

$$I(T) = \frac{I_0}{1 + A \exp \left( \frac{E_a}{kT} \right)}.$$  

Fitting results and extracted activation energies, $E_a$, are shown as dotted lines and labels in Fig. 4(a). The largest activation energy ($E_a = 119.6 \pm 10.8 \text{meV}$) is obtained for the $M_0$ resonance that we assigned to be fed by the SQD emission. Again we observe a distinctly different behavior for the $M_0^{\text{ref}}$ mode, for which we observe a more than 10 times reduced value for the activation energy of only $E_a = 12.9 \pm 3.3 \text{meV}$. The difference in the activation energies can be naturally understood by presence and absence of a QD in the PhCR’s center on the SQD and WL sample, respectively.

As shown in Fig. S3 of the Supplementary Material, for the $M_0$ mode intensity of the a360r70ff0 design, we observe an activation energy identical within experimental errors to the one assigned to the QD emission in the previous paragraph. Thus, we have strong evidence that a QD is present also in the center of the a360r70ff0 PhCR. Nevertheless, only a small PL intensity is detected for the $M_0$ mode of this PhCR as shown in the main panel of Fig. 3, as a consequence of a reduced coupling to radiating modes for to the ff0 design. In turn, this reduced coupling manifests itself also in the large Q-factor for this design discussed in a previous paragraph.

For the WL emission into mode $M_3$ of the PhCR on the SQD sample occurring at $\sim 1220 \text{nm}$ in Fig. 2, we observe an activation energy of $E_a = 39.2 \pm 3.9 \text{meV}$, intermediate to the values reported for modes $M_0$ and $M_0^{\text{ref}}$ in a previous paragraph. In the same spectral range, very similar $E_a$-values are obtained for the emission peaks of the WL reference sample, as shown in Fig. S4 of the Supplementary Material.

Also measurements of the emission intensity in the various PhCR modes $I_{\text{mode}}$ as functions of the excitation intensity $I_{\text{exc}}$ are in agreement with our source assignments. In the double logarithmic plot shown in Fig. 4(b), individual results for modes $M_0$, $M_3$ and $M_0^{\text{ref}}$ as labelled in Fig. 2 are shown by blue, red and green symbols, respectively. For a characterization, we use the

![FIG. 3. Resonantly enhanced PL emission spectrum of the SQD centered in a N24 bichromatic PhCR with parameters a360 r70 without far-field optimization (ff0) as measured at 4K. The inset shows the resonant scattering spectrum of the same cavity measured at room temperature (blue symbols). The data were fitted to the Fano function [42] plotted in red. From the fit, a resonance wavelength of 1350.95 nm, a FWHM of 13.0 pm, and thus, a Q-factor of $\sim 104000$ were obtained for the $M_0$ resonance.](image-url)
exponent \( m \) of the commonly employed empirical relation \( I_{\text{mode}} \propto (I_{\text{exc}})^m \). As shown in Fig. 4(b), for \( M_0 \) we obtain \( m \approx 1 \) for low and \( m \approx 2/3 \) for intermediate excitation power, with a transition region between 30 and 70 \( \mu \text{W} \). Such a behaviour is typically observed for QD emitters, with the \( m = 1 \) region indicating dominant electron (e) hole (h) pair recombination and the \( m = 2/3 \) region Auger-recombination involving three particles (for example two e and one h) [48, 49]. At even higher excitation, additional e-h recombination paths result in a further decrease of \( m \). On the other hand, for the \( M_3 \) mode we obtain \( m \approx 1.9 \), typically for WL emission [48], where the carrier lifetime is limited by Shockley-Read-Hall recombination over trap states. For this recombination process, \( m = 2 \) is expected [50]. Due to e, h localization in QDs, the trap states do not influence the carrier lifetime in QDs as long as they are not close to a QD. Thus, they are much more efficient for extended QW states. For mode \( M_0^{\text{ref}} \) of the a350 r70f3 PhCR on the WL reference sample, we observe \( m = 0.88 \), indicating e-h pair as the dominant recombination channel in this spectral region of the WL emission.

The decay dynamics of the \( M_0 \) emission was characterized by TCSPC experiments. The results of two measurements at different average laser power are shown in Fig. 5. For an average excitation power of 33.2 \( \mu \text{W} \), an initial fast decay component with a decay time of \( \tau \approx 0.65 \text{ ns} \) is observed, followed by a slower decay with a time constant \( \tau \approx 3.9 \text{ ns} \). For a lower average excitation power of 5 \( \mu \text{W} \), a single exponential decay with a time constant \( \approx 3.7 \text{ ns} \) close to the slow component at larger excitation is measured. According to Ref. [49], the observed decay characteristics is expected for QDs excited to more than one e-h pair. In this case, more combinatorial recombination paths for e-h pair recombination as well as Auger processes become effective, resulting in a reduced life time of the e-h density in the QD. Eventually, after the rapid initial decay only one e-h pair will be present in the QD, resembling the situation after weak excitation. Therefore, the slowest decay constants are expected to be equal for intense and weak excitation, in agreement with the experimental results shown in Fig. 5.

CONCLUSION

In this work we used CMOS compatible lithographic alignment to position single SiGe QDs at the electric field maxima of bichromatic PhCRs’ ground modes. Due to the high reproducibility of the alignment process, we were
able to produce a large set of resonators with varying lay-outs, each one centered with respect to its single QD. By this lithographic tuning we could identify the cavity lay-out best matching the emission maximum of the coupled QD. The bichromatic cavity design provides very large Q-factors but requires extremely accurate alignment of QD and cavity, due to its narrow Si region at the cavity center. By reducing the amount of Ge within the resonator and the surrounding photonic crystal to a minimum of exactly one QD on its associated WL, we improve the resonators’ structural quality by improving the etching homogeneity for the fabrication process. In addition, by these measures we avoid light scattering out of the resonator due to secondary QDs. As a consequence, we were able to demonstrate a Q-factor in excess of $10^5$ for a QD-coupled resonator mode. This value represents the largest Q-factor reported so far for QD-loaded photonic crystal resonators realized in a SOI integrated optics platform [25, 26, 43–46]. The dependence of mode emission intensities on temperature, excitation power, and time after pulsed excitation was carefully analyzed and compared to results from cavities fabricated on samples containing a WL without QDs. By this analysis we were able to identify PhCRs for which the emission coupled to the high Q ground mode is associated with optical transitions within the SiGe QD. As these transitions occur in the relevant telecom wavelength band, the nano-optical system investigated in this work is of high relevance as a potential quantum optical source for a future SOI based integrated quantum photonic platform compatible with existing fiber networks. With respect to the latter aspect, the results of time resolved PL decay indicate that photon emission at a level of a single e-h pair is within reach.

[1] X. Chen, M. M. Milosevic, S. Stanković, S. Reynolds, T. D. Bucio, K. Lü, D. J. Thomson, F. Gardes, and G. T. Reed, The emergence of silicon photonics as a flexible technology platform, Proceedings of the IEEE 106, 2101 (2018).
[2] S. Y. Siew, B. Li, F. Gao, H. Y. Zheng, W. Zhang, P. Guo, S. W. Xie, A. Song, B. Dong, L. W. Luo, C. Li, X. Luo, and G.-Q. Lo, Review of silicon photonics technology and platform development, Journal of Lightwave Technology 39, 4374 (2021).
[3] D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J.-M. Fédéli, J.-M. Hartmann, J. H. Schmid, D.-X. Xu, F. Boeuf, P. O’Brien, G. Z. Mashanovich, and M. Nedeljkovic, Roadmap on silicon photonics, Journal of Optics 18, 073003 (2016).
[4] R. E. Camacho-Agüilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, and J. Michel, An electrically pumped germanium laser, Optics Express 20, 11316 (2012).
[5] R. Koerner, M. Oehme, M. Gollhofer, M. Schmid, K. Kostecki, S. Bechler, D. Widmann, E. Kasper, and J. Schulze, Electrically pumped lasing from Ge Fabry-Perot resonators on Si, Optics Express 23, 14815 (2015).
[6] F. T. A. Pilon, A. Lyasota, Y.-M. Niquet, V. Reboud, V. Calvo, N. Pauc, J. Widiez, C. Bonzon, J. M. Hartmann, A. Chelnokov, J. Faist, and H. Sigg, Lasing in strained germanium microbridges, Nature Communications 10 (2019).
[7] A. Elbaz, D. Buca, N. von den Driesch, K. Pantzas, G. Patriarche, N. Zerouman, E. Herth, X. Checoury, S. Sauvage, I. Sagnes, A. Foti, R. Ossikovski, J.-M. Hartmann, F. Boeuf, Z. Ikonic, P. Boucaud, D. Grützmacher, and M. E. Kurdi, Ultra-low-threshold continuous-wave and pulsed lasing in tensile-strained GeSn alloys, Nature Photonics 14, 375 (2020).
[8] Y. Zhou, S. Ojo, C.-W. Wu, Y. Miao, H. Tran, J. M. Grant, G. Abernathy, S. Amoash, J. Bass, G. Salamo, W. Du, G.-E. Chang, J. Liu, J. Margetis, J. Tolle, Y.-H. Zhang, G. Sun, R. A. Soref, B. Li, and S.-Q. Yu, Electrically injected GeSn lasers with peak wavelength up to 2.7 µm, Photonics Research 10, 222 (2021).
[9] M. Grydlik, F. Hackl, H. Groiss, M. Glaser, A. Halilovic, T. Fromherz, W. Jantsch, F. Schäffler, and M. Brehm, Lasing from glassy Ge quantum dots in crystalline Si, ACS Photonics 3, 298 (2016).
[10] J. W. Silverstone, D. Bonneau, J. L. O’Brien, and M. G. Thompson, Silicon quantum photonics, IEEE Journal of Selected Topics in Quantum Electronics 22, 1–13 (2016).
[11] J. C. Adcock, J. Bao, Y. Chi, X. Chen, D. Bacco, Q. Gong, L. K. Oxenløwe, J. Wang, and Y. Ding, Advances in silicon quantum photonics, IEEE Journal of Selected Topics in Quantum Electronics 27, 1 (2021).
[12] L. Lu, X. Zheng, Y. Lu, S. Zhu, and X.-S. Ma, Advances in chip-scale quantum photon technologies, Advanced Quantum Technologies 4, 2100068 (2021).
[13] J. Wang, F. Sciarrino, A. Laing, and M. G. Thompson, Integrated photonic quantum technologies, Nature Photonics 14, 273 (2019).
[14] P. Senellart, G. Solomon, and A. White, High-performance semiconductor quantum-dot single-photon sources, Nature Nanotechnology 12, 1026 (2017).
[15] A. Durand, Y. Baron, W. Redjem, T. Herzig, A. Benali, S. Pezzagna, J. Meijer, A. Y. Kuznetsov, J.-M. Gérard, I. Robert-Philip, M. Abbarchi, V. Jacques, G. Cassabois, and A. Dréau, Broad diversity of near-infrared single-photon emitters in silicon, Phys. Rev. Lett. 126, 083602 (2021).
[16] O. G. Schmidt, K. Eberl, and W. Redjem, Strain and band-edge alignment in single and multiple layers of self-assembled Ge/Si and Ge/Si/Si islands, Physical Review B 62, 16715 (2000).
[17] L. Tsybeskov and D. Lockwood, Silicon-germanium nanostructures for light emitters and on-chip optical interconnects, Proceedings of the IEEE 97, 1284 (2009).
[18] M. Grydlik, G. Langer, T. Fromherz, F. Schäffler, and M. Brehm, Recipes for the fabrication of strictly ordered Ge islands on pit-patterned Si(001) substrates, Nanotechnology 24, 105601 (2013).
[19] M. Grydlik, M. T. Lusk, F. Hackl, A. Polimeni, T. Fromherz, W. Jantsch, F. Schäffler, and M. Brehm, Laser level scheme of self-interstitials in epitaxial ge dots
encapsulated in silicon, *Nano Letters* **16**, 6802 (2016).

[20] F. Murphy-Armando, M. Brehm, P. Steindl, M. T. Lusk, T. Fromherz, K. Schwarz, and P. Blaha, Light emission from direct band gap germanium containing split-interstitial defects, *Physical Review B* **103**, 085310 (2021).

[21] L. Spindlberger, J. Aberl, A. Polimeni, J. Schuster, J. Horschläger, T. Truglas, H. Groiss, F. Schäffler, T. Fromherz, and M. Brehm, In-situ annealing and hydrogen irradiation of defect-enhanced germanium quantum dot light sources on silicon, *Crystals* **10**, 351 (2020).

[22] L. Spindlberger, M. Kim, J. Aberl, T. Fromherz, F. Schäffler, F. Fournel, J.-M. Hartmann, B. Hallam, and M. Brehm, Advanced hydrogenation process applied on Ge on Si quantum dots for enhanced light emission, *Applied Physics Letters* **118**, 083104 (2021).

[23] E. M. Purcell, B10. Spontaneous emission probabilities at radio frequencies, in *Proc. of the APS* (1946) p. 681.

[24] R. Jannesari, M. Schatzl, F. Hackl, M. Glaser, K. Hingerl, T. Fromherz, and F. Schäffler, Commensurate germanium light emitters in silicon-on-insulator photonic crystal slabs, *Opt. Express* **22**, 25426 (2014).

[25] C. Zeng, Y. Ma, Y. Zhang, D. Li, Z. Huang, Y. Wang, Q. Huang, J. Li, Z. Zhong, J. Yu, Z. Jiang, and J. Xia, Single germanium quantum dot embedded in photonic crystal nanocavity for light emitter on silicon chip, *Optics Express* **23**, 22250 (2015).

[26] M. Schatzl, F. Hackl, M. Glaser, P. Rauter, M. Brehm, L. Spindlberger, A. Simbula, M. Galli, T. Fromherz, and F. Schäffler, Enhanced telecom emission from single group-IV quantum dots by precise cmos-compatible positioning in photonic crystal cavities, *ACS Photonics* **4**, 665 (2017).

[27] F. Alpeggiani, L. C. Andreani, and D. Gerace, Effective bichromatic potential for ultra-high q-factor photonic crystal slab cavities, *Applied Physics Letters* **107**, 261110 (2015).

[28] L. C. Andreani, G. Panzarini, and J.-M. Gérard, Strong-coupling regime for quantum boxes in pillar microcavities: Theory, *Phys. Rev. B* **60**, 13276 (1999).

[29] A. Simbula, M. Schatzl, L. Zagaglia, F. Alpeggiani, L. C. Andreani, F. Schäffler, T. Fromherz, M. Galli, and D. Gerace, Realization of high-Q/V photonic crystal cavities defined by an effective Aubry-André-Harper bichromatic potential, *APL Photonics* **2**, 056102 (2017).

[30] M. Clementi, A. Barone, T. Fromherz, D. Gerace, and M. Galli, Selective tuning of optical modes in a silicon comb-like photonic crystal cavity, *Nanophotonics* **9**, 205 (2020).

[31] N. V. Q. Tran, S. Combré, and A. D. Rossi, Directive emission from high-Q photonic crystal cavities through band folding, *Physical Review B* **79** (2009).

[32] S. L. Portalupi, M. Galli, C. Reardon, T. Krauss, L. O’Faolain, L. C. Andreani, and D. Gerace, Planar photonic crystal cavities with far-field optimization for high coupling efficiency and quality factor, *Optics Express* **18**, 16064 (2010).

[33] N. Hauke, A. Tandaechanurat, T. Zabel, T. Reichert, H. Takagi, M. Kaniber, S. Iwamoto, D. Bougeard, J. J. Finley, G. Abstreiter, and Y. Arakawa, A three-dimensional silicon photonic crystal nanocavity with enhanced emission from embedded germanium islands, *New Journal of Physics* **14**, 083035 (2012).

[34] A. Shakoor, R. L. Savio, P. Cardile, S. L. Portalupi, D. Gerace, K. Welna, S. Boninelli, G. Franzò, F. Priolo, T. F. Krauss, M. Galli, and L. O’Faolain, Room temperature all-silicon photonic crystal nanocavity light emitting diode at sub-bandgap wavelengths, *Laser & Photonics Reviews* **7**, 114 (2012).

[35] C. Maleville, B. Aspar, T. Poumevol, H. Moriceau, M. Bruel, A. Auberton-Hervé, and T. Barge, Wafer bonding and H-implantation mechanisms involved in the smart-cut® technology, *Materials Science and Engineering: B* **46**, 14 (1997).

[36] H. Moriceau, F. Fournel, O. Rayssac, A. M. Cartier, C. Morales, S. Pocas, M. Zussy, E. Jalaguier, B. Biasse, B. Bataillou, A. M. Papon, C. Lagahe, B. Aspar, C. Maleville, F. Leterte, B. Ghyselen, and T. Barge, Overview on some recent advances in wafer bonding technologies, in *Proceedings of the Sixth International Symposium on Semiconductor Wafer Bonding: Science, Technology, and Applications*, Vol. 27 (2001) p. 1.

[37] M. Grydlik, M. Brehm, F. Hackl, F. Schäffler, G. Bauer, and T. Fromherz, Unrolling the evolution kinetics of ordered SiGe islands via Ge surface diffusion, *Phys. Rev. B* **88**, 115311 (2013).

[38] M. Grydlik, M. Brehm, T. Tayagaki, G. Langer, O. G. Schmidt, and F. Schäffler, Optical properties of individual site-controlled Ge quantum dots, *Applied Physics Letters* **106**, 251904 (2015).

[39] M. Brehm, F. Montaleti, M. Grydlik, G. Vastola, H. Lichtenberger, N. Frauda, M. J. Beck, T. Fromherz, F. Schäffler, L. Miglio, and G. Bauer, Key role of the wetting layer in revealing the hidden path of Ge/Si(001) Stranski-Krastanow growth onset, *Physical Review B* **80**, 205321 (2009).

[40] R. Lo Savio, S. L. Portalupi, D. Gerace, A. Shakoor, T. F. Krauss, L. O’Faolain, L. C. Andreani, and M. Galli, Room-temperature emission at telecom wavelengths from silicon photonic crystal nanocavities, *Appl. Phys. Lett.* **98**, 201106 (2011).

[41] J. Schuster, J. Aberl, L. Vukašić, L. Spindlberger, H. Groiss, T. Fromherz, M. Brehm, and F. Schäffler, Photoluminescence enhancement by deterministically site-controlled, vertically stacked SiGe quantum dots, *Scientific Reports* **11**, 20597 (2021).

[42] M. Galli, S. L. Portalupi, M. Belotti, L. C. Andreani, L. O’Faolain, and T. F. Krauss, Light scattering and fano resonances in high-Q photonic crystal nanocavities, *Applied Physics Letters* **94**, 1 (2009).

[43] K. Kuruma, Y. Ota, M. Kakuda, S. Iwamoto, and Y. Arakawa, Strong coupling between a single quantum dot and an L4/3 photonic crystal nanocavity, *Applied Physics Express* **13**, 082009 (2020).

[44] A. Schwagmann, S. Kallikatos, D. J. P. Ellis, I. Farrer, J. P. Griffiths, G. A. C. Jones, D. A. Ritchie, and A. J. Shields, In-plane single-photon emission from a L3 cavity coupled to a photonic crystal waveguide, *Optics Express* **20**, 28614 (2012).

[45] M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota, and Y. Arakawa, Photonic crystal nanocavity laser with a single quantum dot gain, *Optics Express* **17**, 15975 (2009).

[46] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Guido, S. Fütt, E. L. Hu, and A. Imamoğlu, Quantum nature of a strongly coupled single quantum dot–cavity system, *Nature* **445**, 896 (2007).
[47] M. Wachter, F. Schäffler, H.-J. Herzog, K. Thonke, and R. Sauer, Photoluminescence of high-quality SiGe quantum wells grown by molecular beam epitaxy, Applied Physics Letters 63, 376 (1993).

[48] R. Apetz, L. Vescan, A. Hartmann, C. Dieker, and H. Lüth, Photoluminescence and electroluminescence of SiGe dots fabricated by island growth, Applied Physics Letters, 445 (1995).

[49] J. Julsgaard, P. Balling, J. L. Hansen, A. Svane, and A. N. Larsen, Auger-decay dynamics of germanium nanoislands in silicon, Nanotechnology 22, 435401 (2011).

[50] A. Shklyaev, A. Latyshev, and M. Ichikawa, Excitation dependence of photoluminescence in the 1.5-1.6μm wavelength region from grown dislocation-rich Si layers, Physics Procedia 32, 117 (2012).

[51] H. Caro, Zur Kenntniss der Oxydation aromatischer Amine, Zeitschrift für angewandte Chemie 11, 845–846 (1898).

[52] W. Kern and D. A. Puotinen, Cleaning solutions based on hydrogen peroxide for use in silicon semiconductor technology, RCA Review 31, 187 (1970).

[53] Z. Zhong, A. Halilovic, T. Fromherz, F. Schäffler, and G. Bauer, Two-dimensional periodic positioning of self-assembled Ge islands on prepatterned Si (001) substrates, Applied Physics Letters 82, 4779 (2003).

[54] M. Brehm, M. Grydlik, H. Groiss, F. Hackl, F. Schäffler, T. Fromherz, and G. Bauer, The influence of a Si cap on self-organized SiGe islands and the underlying wetting layer, Journal of Applied Physics 109, 123505 (2011).

[55] F. Hackl, M. Grydlik, P. Klenovský, F. Schäffler, T. Fromherz, and M. Brehm, Assessing carrier recombination processes in type-II SiGe/Si(001) quantum dots, Annalen der Physik 531, 1800259 (2019).
**METHODS**

**Lithographic sample patterning**

Sample patterning was performed by electron beam (e-beam) lithography using a Raith eline plus system. Prior to spin-coating the sample surface with a positive polymethyl methacrylate (PMMA) resist purchased from Allresist (Allresist 679.04), it was cleaned by dipping it into Acetone, Methanol and 10% hydrofluoric (HF) acid for 30 s each. The HF dip promotes the adhesion of the e-beam resist. After exposure, the resist was developed for 60 s. The Raith eline plus system allows automated alignment of a mask layer to reference marks by a pattern recognition algorithm.

**Pattern transfer**

The pattern of the lithographic mask was transferred to the Si layer of the sample by reactive ion etching in an inductively coupled plasma setup (ICP-RIE) from Oxford Instruments (Plasmalab 100). To minimize lateral etching, we used a cryo-process, for which the sample was cooled to 183 K by liquid $\text{N}_2$ cooling. A mixture of SF$_6$ and O$_2$ at flow rates of 5 sccm and 3 sccm, respectively, and an etch-chamber pressure of 15 mTorr was used as etch medium. The etch depths were verified ex-situ by surface scans using a Digital Instruments Veeco Dimension 3100 atomic force microscope with a Nanoscope IV controller.

**MBE growth**

After cleaning the substrates in piranha solution [51] as well as by a RCA sequence, [52] and finally by a dip in 5%-hydrofluoric acid (HF) to remove the native oxide, they were transferred into a solid-source MBE (Riber Siva 45) chamber for site-controlled SiGe QD growth in the etched pits [18, 53]. As first step, an in-situ degassing at 650°C for 15 minutes was performed. Then, a 34 nm thick Si buffer was grown at a growth rate of 0.7 Å/s while ramping the substrate temperature from 450°C to 550°C. The buffer layer buries potential surface defects and remaining contaminations and flattens the pit sidewalls by exposing $\{1,1,n > 7\}$ low-surface-energy Si facets that enable site-controlled Ge QD nucleation [18] at the pit center. The growth methods for realizing perfectly ordered SiGe QDs in very sparse regular arrays are central to this work. Thus, they are described in the main text. If required, a ~115 nm thick Si cap was grown as final layer. As indicated in the inset of Fig. 1(d), during the growth of the first ~38 nm of this cap the substrate temperature was ramped up from 500-700°C to minimize Si/Ge intermixing [54]. The elevated growth temperature in the late state of the ramp is beneficial to achieving low defect densities in the Si capping layer. The remaining 77 nm capping layer were then grown at 700°C as well.

**Optical characterization**

The emission properties of the cavity coupled QDs were studied in a micro-photoluminescence ($\mu$-PL) setup described in details elsewhere [55]. For optical excitation, a continuous-wave (CW) diode laser emitting at 442 nm wavelength (PicoQuant LDH-D-C-440) was focused via a microscope objective with numerical aperture NA=0.7 (Mitutoyo M Plan Apo NIR HR 100×) to a PhCR. The sample was mounted on the cold finger of a liquid He cryostat (CryoVac Konti Mikro X/Y), allowing to cool the sample to less than 10 K. Via x-y translation stages mounted in the isolation vacuum chamber of the cryostat, cold finger and sample can be positioned with ~100 nm accuracy over ~1 cm travel range. The PL emission was collected through the same objective and coupled to either a single- or a multi-mode fiber after filtering out the excitation laser. The multi-mode fiber was connected to an Acton SpectraPro 300i grating spectrometer with 300 nm focal length, NA=0.25, equipped with 300 or 600 grooves/mm gratings at blaze wavelengths of 1 or 1.6 µm, respectively. We detect the dispersed signal with a liquid-N$_2$-cooled InGaAs line detector (Princeton Instruments OMA V), containing 1024 pixels at 25 µm pitch. A single-mode fiber and superconducting single photon detector (Single Quantum ) operated in time-correlated photon counting (TCSPC) mode using a PicoHarp 300 time tagging electronics were used for time-resolved PL decay experiments.

**DATA AVAILABILITY**

The main data supporting the findings of this study are available within the article and its Supplementary Information. Extra data are available from the corresponding authors upon reasonable request.

**ACKNOWLEDGEMENTS**

The authors acknowledge Alma Halilovic and Stephan Bräuer for cleanroom and other technical supports, as well as Lucio C. Andreani and Jeffrey Schuster for fruitful discussions. This work was supported by the project CUSPIDOR that has received funding from the QuanTERA ERA-NET Cofund in Quantum Technologies implemented within the European Union’s Horizon 2020, cofunded by the Italian Ministry of University and Research (MUR) and the Austrian Science Foundation FWF under Project I 3760-N27. Additional funding by the FWF under Projects FWF_30564NBL (co-founded by the province of Upper Austria), Y1238-N36 and by
the Linz Institute of Technology (LIT): Grant No. LIT-2019-7-SEE-114 is acknowledged. The Department of Physics of the University of Pavia is supported from MUR through the “Dipartimenti di Eccellenza Program (2018-2022)”.

AUTHOR CONTRIBUTIONS

T.P., M.C., D.G., M.G., M.B. and T.F. designed the experiment. T.P., L.S., M.C., and M.G. carried out the experiment. J.A., L.V., F.S. and M.B. optimized the QD growth and provided the samples. F.F. and J.-M. H. adapted the SOI substrates. T.P. and T.F. analyzed the raw data and wrote the manuscript. All authors interpreted and discussed the paper’s content and contributed to the final manuscript. T.F. supervised the project.

ADDITIONAL INFORMATION

- The authors declare no competing interests.
- Supplementary material is provided on the following page.
- Correspondence and request for materials should be addressed to Thanavorn Poempool or Thomas Fromherz
Supplementary Information:
Single SiGe Quantum Dot Emission Deterministically Enhanced in a High-Q Photonic Crystal Resonator

Thanavorn Poempool,1,* Johannes Aberl,1 Marco Clementi,2,† Lukas Spindlberger,1 Lada Vukušić,1 Matteo Galli,2 Dario Gerace,2 Frank Fournel,3 Jean-Michel Hartmann,3 Friedrich Schäffer,1 Moritz Brehm,1 and Thomas Fromherz1,‡

1Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Altenbergerstraße 69, 4040 Linz, Austria
2Dipartimento di Fisica, Università di Pavia, Via Bassi 6, 27100 Pavia, Italy
3University Grenoble Alpes, CEA, LETI, Grenoble, France

I. PHOTOLUMINESCENCE SPECTRA OF QD ENSEMBLE

Figure S1 compares the ensemble PL emission of densely (∼1.5 × 10^8 cm⁻²) ordered QDs as observed on a sample without PhCR with the emission of the WL without QDs. Due to the large density of the QDs, their PL emission is clearly observed also in the absence of a PhCR. Thus, the full emission spectrum of the QDs without the amplification due to the PhCR resonances can be observed. By comparing this spectrum with the spectrum measured in sample regions without pit-patter (red line in Fig. S1), and, thus, without QDs, we can clearly identify the spectral range between ∼1300 nm and ∼1450 nm as being dominated by QD emission.

II. LITHOGRAPHIC TUNING OF RESONATOR-COUPLED QD EMISSION

Figure S2 shows the PL emission of three bichromatic cavities with different periods a but otherwise identical design parameters (r = 70 nm, ff=+3 nm), excited with the same excitation power (2.2 mW). The M₀ mode systematically shifts from ∼1304 nm for a = 350 nm (black line) over ∼1336 nm for a = 360 nm (red line) to ∼1369 nm for a = 370 nm (blue line). For all these resonance wavelengths, we observe a variation of the M₀ mode intensity by approximately a factor 3. In the main paper, the M₀ emission was assigned to optical QD transition for the a360r70ff3 PhCR design. From this small variation, we exclude a spectrally narrow emission spectrum of the QD in the center of the cavity, at least at the excitation intensities employed in this work. Our interpretation is in agreement with Ref. [1], where a broad PL emission of a single SiGe QD outside a PhCR is observed.

III. ACTIVATION ENERGY OF THE M₀ RESONANCE FOR A QD COUPLED PHCR WITHOUT FAR-FIELD OPTIMIZATION (FF0)

Due to the absent far-field optimization, the observed M₀ mode intensity shown in Fig. 3 of the main paper for a QD coupled to a a360r70ff0 PhCR is small. In fact, its intensity is comparable to the intensities observed for the M₀ref emission of the WL reference samples shown in Fig. 2 of the main paper. Thus, a priori it can not be ruled out, that no QD nucleated in the pit and only

* thanavorn.poempool@jku.at
† Current address: Photonic Systems Laboratory (PHOSL), École Polytechnique Fédérale de Lausanne, Station 11, 1015 Lausanne, Switzerland
‡ thomas.fromherz@jku.at
a WL is present instead of the QD. In turn, the absent QD could possibly be the reason for the large Q-factor ($>10^5$) of the $M_0$ resonance reported for this PhCR design in the main paper. However, the thermal quenching behavior for the $M_0$ mode of this PhCR shown in the Arrhenius plot Fig. S3 yields an activation energy $E_a = 129.2 \pm 39.1$ meV, equal within the experimental error to the activation energy of a single QD coupled to the PhCR a360r70ff3 as found in the main paper. In addition, this activation is significantly larger than the activation energies obtained for any of the resonances shown in Fig. 2 of the main paper by the gray line for the WL reference sample. The corresponding Arrhenius plots are shown in Fig. S4 and yield activation energies in the range between $\sim 13$ meV and $\sim 37$ meV for the four resonances labeled by their resonance wavelength in Fig. S4. Here the mode shown in magenta corresponds to mode labeled $M_0^{ref}$ in Fig. 2 of the main paper. These findings give strong evidence, that a QD is present in the center of the a360r70ff3 PhCR and still Q-factors in excess of $10^5$ are feasible.

For completeness we want to add, that for extracting activation energies $E_a$, the logarithm of the observed mode intensities was fitted to the logarithm of the right-hand side of Eq. (1) given in the main paper. Such a fitting strategy is routinely employed in Arrhenius fits and emphasizes the significance of small experimental values that provide most information on a temperature induced quenching behavior.

![FIG. S2.](image2)

**FIG. S2.** PL spectra of single QDs coupled to bichromatic cavities with the different periods $a$ given by the line labels, but otherwise equal design parameters ($r = 70$ nm, $f = +3$ nm). The spectra were measured at the same excitation power (2.2 mW) and are offset vertically for clarity. The mode $M_0$ systematically shifts from $\sim 1304$ nm over $\sim 1336$ nm to $\sim 1339$ nm for $a = 350, 360, 370$ nm, respectively. For all $a$, the mode $M_0$ is comparably intense (within a factor 3), indicating a broad QD emission spectrum, in agreement with the results of Ref. [1].

![FIG. S3.](image3)

**FIG. S3.** Thermal quenching behavior for the $M_0$ mode PL intensity for a bicromatic PhCR without far-field optimization (a360r70ff0). The corresponding low-temperature PL spectrum is shown in Fig. 3 of the main paper. The activation energy $E_a$ as given in the plot is typical for optical QD transitions coupled to the PhCR and strongly indicates the presence of a QD in the PhCR center.

![FIG. S4.](image4)

**FIG. S4.** Thermal quenching behavior of the mode intensities observed in PL for the a350r70ff3 bichromatic PhCR design fabricated on a WL reference sample. The corresponding PL emission spectrum is shown by the gray line in Fig. 2 of the main paper. The different traces are labelled according to their resonance wavelength shown therein. Therefore, data shown in magenta correspond to the mode labeled $M_0^{ref}$ in Fig. 2 of the main paper. At each resonance wavelength, the fitted activation energies $E_a$ for WL PL quenching are much smaller than the one shown for the QD PL quenching in Fig. S3 and in main-paper Fig. 4 by the blue line.
[1] M. Grydlik, M. Brehm, T. Tayagaki, G. Langer, O. G. Schmidt, and F. Schäffler, Optical properties of individual site-controlled Ge quantum dots, Applied Physics Letters 106, 251904 (2015).