

## Silicon photonic bowtie cavities with atomic-scale dimensions

Babar, Ali Nawaz; Weis, Thor August Schimmell; Tsoukalas, Konstantinos; Kadkhodazadeh, Shima; Arregui Bravo, Guillermo; Vosoughi Lahijani, Babak; Stobbe, Søren

Published in: Proceedings of SPIE

Link to article, DOI: 10.1117/12.3001866

Publication date: 2024

Document Version Publisher's PDF, also known as Version of record

## Link back to DTU Orbit

Citation (APA):

Babar, A. N., Weis, T. A. S., Tsoukalas, K., Kadkhodazadeh, S., Arregui Bravo, G., Vosoughi Lahijani, B., & Stobbe, S. (2024). Silicon photonic bowtie cavities with atomic-scale dimensions. In *Proceedings of SPIE* Article 128960F SPIE - International Society for Optical Engineering. https://doi.org/10.1117/12.3001866

#### **General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# Silicon photonic bowtie cavities with atomic-scale dimensions

Ali Nawaz Babar<sup>a,b</sup>, Thor August Schimmell Weis<sup>a</sup>, Konstantinos Tsoukalas<sup>a</sup>, Shima Kadkhodazadeh<sup>b,c</sup>, Guillermo Arregui<sup>a</sup>, Babak Vosoughi Lahijani<sup>a,b</sup>, and Søren Stobbe<sup>a,b</sup>

<sup>a</sup>Department of Electrical and Photonics Engineering, DTU Electro, Technical University of Denmark, Building 343, DK-2800 Kgs. Lyngby, Denmark.

<sup>b</sup>NanoPhoton - Center for Nanophotonics, Technical University of Denmark, Ørsteds Plads 345A, DK-2800 Kgs. Lyngby, Denmark.

<sup>c</sup>DTU Nanolab, Technical University of Denmark, Building 307, DK-2800 Kgs. Lyngby, Denmark.

## ABSTRACT

Recent progress in photonics has highlighted the importance of miniaturization, particularly in achieving dielectric bowtie cavities with small mode volumes, which were previously limited to plasmonics. This study presents a novel method that combines top-down nanopatterning and bottom-up self-assembly to fabricate photonic cavities with atomic-scale dimensions. By utilizing surface forces, we demonstrate waveguide-coupled silicon photonic cavities with high quality factors, confining light to atomic-scale air gaps with an aspect ratio above 100, corresponding to mode volumes more than 100 times below the diffraction limit. These cavities exhibit unprecedented figures of merit for enhancing light-matter interaction and enable charting hitherto inaccessible regimes of solid-state quantum electrodynamics.

**Keywords:** nanocavities, photonic crystals, atomic-scale confinement, nanophotonics, nanofabrication, self-assembly

#### 1. INTRODUCTION

Enhancing the strength of the interaction between light and matter is crucial for nanophotonics research as it is necessary for building new generations of photodetectors, nanolasers, optical interconnects, and quantum light sources.<sup>1</sup> An optical nanocavity with a high quality factor and a small mode volume strongly enhances the interaction between light and matter due to the spatial confinement and temporal storage of electromagnetic field.<sup>2</sup> Dielectric photonic crystal nanocavities have seen remarkable progress in recent decades due to their ability to increase the light-matter interaction by trapping light for a long time, achieving large quality factors up to a few million.<sup>3</sup> The mode volume in dielectric cavities was previously considered to be diffraction-limited,<sup>4</sup> but it is now understood that dielectric nanocavities with a bowtie feature can provide deep subwavelength confinement.<sup>5,6,7,8</sup> Dielectric bowtie nanocavities confine light below the diffraction limit by exploiting the electromagnetic-field boundary conditions at material interfaces.<sup>9</sup> The mode volume of a dielectric bowtie nanocavity is proportional to the size of the bowtie bridge (solid or void); therefore, it is limited by nanofabrication.<sup>10</sup> Recent developments in nanophotonics involve the experimental demonstration.<sup>11</sup> of a topology-optimized nanocavity with a bowtie width of 8 nm and an aspect ratio of 30. Further reduction of the mode volume and, thus, enhancement of the light-matter interaction therefore requires fabricating bowtie dimensions approaching the atomic scale, which seems impossible with the current nanofabrication technology.

Photonic and Phononic Properties of Engineered Nanostructures XIV, edited by Ali Adibi, Shawn-Yu Lin, Axel Scherer, Proc. of SPIE Vol. 12896, 128960F © 2024 SPIE · 0277-786X · doi: 10.1117/12.3001866

Author information: Send correspondence to Ali Nawaz Babar and Søren Stobbe.

Ali Nawaz Babar: E-mail: anaba@dtu.dk, Søren Stobbe: E-mail: ssto@dtu.dk



Figure 1. Design of a self-assembled bowtie nanobeam cavity. **a**, Schematic of the bowtie nanobeam cavity. **b**, The normalized electric field of the fundamental cavity mode,  $|\mathbf{E}|$ , with a logarithmic color map. **c**, Schematic of a single bowtie unit cell with the following design parameters: lattice constant, *a*, bowtie angle,  $\varphi$ , bowtie width,  $W_{\rm b}$ , nanobeam width, *H*, silicon membrane thickness, *t*, and a bowtie width, *g*, of 2 nm. **d**, The normalized electric field of the fundamental cavity mode at the central bowtie unit cell with a linear color map. The electric field is tightly confined around the 2 nm air void at the bowtie center.

#### 2. METHODS

The two main techniques for fabricating nanostructures are top-down nanopatterning and bottom-up selfassembly. Top-down nanopatterning has been driving Moore's law for many decades as it offers precise control of pattern placement and scalability, but it is limited in achieving the smallest feature sizes.<sup>12</sup> On the other hand, bottom-up self-assembly is widely present in nature, e.g., DNA and proteins in our body self-assemble into complex shapes. Self-assembly involves building blocks organizing themselves into functional structures through various interactions, offering atomic-scale resolution but less geometric freedom and production yield.<sup>13</sup> Combining the best of both approaches would be of great value to science and technology, especially nanophotonics, because, on the one hand, light confinement is limited by the size of the smallest feature that can be fabricated<sup>10,11</sup> and, on the other hand, the potential of photonic technologies rely on the reliable fabrication of large-scale circuits.<sup>14</sup> One of the challenges to confining light to unprecedented levels in air bowties is to make reliable void features well below the resolution limit of the nanofabrication while at the same time obtaining high aspect ratios, e.g., > 100.<sup>7</sup> We report on a new method that combines the atomic-scale resolution of self-assembly with the scalability and components of planar photonic circuits.<sup>15</sup> We use surface forces, including Casimir-van der Waals interactions,<sup>16</sup> to self-assemble structures patterned only through lithography and etching.<sup>15</sup>

### 3. RESULTS

To demonstrate our method of integrating planar technology with self-assembly, we first design a cavity that includes dimensions well below the resolution limit of the current nanofabrication technology.<sup>17</sup> The geometry and normalized electric field of the fundamental optical mode of our cavity are shown in Figs. 1a and 1b. We consider the constraints of our nanofabrication process for the cavity design,<sup>11, 15</sup> except for a 2 nm air void at the bowtie centers. The fundamental cavity mode has a resonance wavelength of  $\lambda = 1524$  nm, a quality factor of  $Q = 5 \times 10^4$ , and a mode volume of  $V = 3.4 \times 10^{-4} \lambda^3$ . The extremely small mode volume stems from light confinement to a 2 nm air bowtie (Figs. 1c and 1d). We fabricate the designed air-bowtie nanobeam cavities on silicon-on-insulator wafers by self-assembling two nanobeam halves initially separated by a gap  $g_f$  (Figs. 2a and 2b) and suspended by two folded guided cantilevers. The two halves also consist of 22  $\mu$ m of unpatterned halfbeams on each side of the photonic-crystal bowtie cavity to increase the surface forces and aid the self-assembly. The geometry parameters of the device lie deep within the parameter space that leads to surface-force-assisted



Figure 2. Fabrication and optical characterization of self-assembled bowtie cavities. **a**, Top-view scanning electron microscope (SEM) image of a bowtie nanobeam cavity before self-assembly. **b**, Top-view SEM image of a single bowtie unit cell before self-assembly, with a fabricated gap,  $g_{\rm f}$ , and a bowtie gap,  $g_{\rm b}$ . **c**, Tilted (20°) SEM image of a bowtie unit cell after self-assembly with an approximate bowtie width of 2 nm. **d**, Top-view high-resolution transmission electron microscope image of the central region of the bowtie with an approximate 2 nm gap. **e**, Tilted (20°) SEM image of a self-assembled bowtie nanobeam cavity. **f**, A scattered far-field spectrum of a self-assembled nanobeam cavity measured using cross-polarized optical microscopy. Fundamental cavity resonance is extracted by fitting a Fano lineshape to the resonance. **g**, Tilted (20°) SEM image of a self-assembled bowtie nanobeam cavity. Fundamental cavity resonance is extracted by fitting a Fano lineshape to the resonance. **g**, Tilted (20°) SEM image of a self-assembled bowtie nanobeam cavity. Fundamental cavity resonance is extracted by fitting a Fano lineshape to the resonance. **g**, Tilted (20°) SEM image of a self-assembled bowtie nanobeam cavity integrated with a waveguide circuit using air-trenched waveguide-to-waveguide couplers, suspension springs, and tapered waveguide sections. **h**, The transmission spectrum of a self-assembled nanobeam bowtie cavity. Fundamental cavity resonance is extracted by performing a Lorentzian fit to the resonance. The grating couplers are placed orthogonally in order to minimize the specular reflection in cross-polarized microscopy.

collapses.<sup>15</sup> Therefore, when the buried-oxide layer is selectively etched away, the two halves and springs are released, and the surface forces cause a deterministic collapse to form a 2 nm bowtie gap, as shown in Fig. 2c. The resolution of the nanofabrication limits the absolute value of  $g_f$ . However, the relative distance between  $g_b$  and  $g_f$  is not limited by the resolution, and, thus, the bowtie width, g, in the final device is limited only by surface roughness, enabling the realization of bowties with atomic-scale features (see high-resolution transmission electron microscope image in Fig. 2d). A systematic variation of the relative difference between  $g_b$  and  $g_f$  in the electron-beam lithography mask determines the size of the bowtie gap after self-assembly. The SEM image of the full self-assembled nanobeam cavity is shown in Fig. 2e. Figure 2f shows the scattered far-field spectrum of a self-assembled cavity obtained with cross-polarized optical microscopy and its resonance fitted with a Fano lineshape<sup>18</sup> to extract the resonance wavelength and quality factor. We measure quality factors up to  $4.2 \times 10^4$  for our self-assembled cavities designed for far-field scattering measurements.

Finally, we address the challenge of integrating self-assembled devices with photonic circuitry, such as waveguides and grating couplers, as efficient coupling to the cavity is critical for many applications. For photoniccrystal nanobeam cavities, the most well-known approaches of efficient coupling to and from the cavity are either evanescent side-coupling<sup>19</sup> or (in-line) direct coupling.<sup>20</sup> For self-assembled devices, these two methodologies are not straightforward to implement since they call for an effective coupling between mechanically isolated self-assembled parts, like a self-assembled nanobeam cavity, and non-self-assembled regions, such as suspended waveguides and grating couplers. We therefore use a recently invented topology-optimized photonic component that enables a broadband waveguide-to-waveguide transmission window across a 100 nm air trench and provides mechanical isolation.<sup>21</sup> This allows the use of the self-assembly method by fabricating one of the sides of the topology-optimized photonic component across the trench in two halves, which self-assembles at the same time as the nanobeam cavity and the other half is attached to the waveguide. The self-assembled nanobeam cavity with air-trenched waveguide-to-waveguide couplers, suspended springs, and tapered waveguide section is shown in Fig. 2g. Some out-of-plane bowing is observed, which could readily be avoided using stress-release management or adding more springs to the nanobeam. Compared to the cavity shown in Fig. 1 and Fig. 2e, the cavity for on-chip transmission experiments, which is shown in Fig. 2g, has a more extended defect region to reduce outof-plane radiation losses and a smaller number of mirror unit cells to facilitate efficient transmission through the cavity. The photonic circuits beyond the crossings include two orthogonally oriented free-space grating couplers that allow measuring the circuit transmission through spatially resolved and cross-polarized spectroscopy<sup>22</sup> as shown by the dark-field optical microscope image in the inset of Fig. 2h. The cavity transmittance is obtained by normalizing the measured transmitted power to that measured in a self-assembled suspended waveguide of equivalent length, i.e., all optical elements on the chip and in the optical setup are factored out. The transmission spectrum of the waveguide-coupled self-assembled cavity is shown in Fig. 2h, with the cavity mode highlighted. By fitting a Lorentzian lineshape to the cavity resonance, we obtain a loaded Q-factor of  $1.5 \times 10^4$ .

#### 4. CONCLUSION

Our approach showcases the potential of integrating top-down nanopatterning with bottom-up self-assembly to realize photonic nanocavities with atomic-scale confinement.<sup>15</sup> Our concept can be applied to any material platform due to the ubiquitous nature of the surface forces,<sup>23</sup> and devices can be further functionalized by depositing novel materials using atomic-layer deposition before self-assembly. Our method bypasses the resolution limit of lithography and results in dielectric cavities with unprecedented dimensions, confining light in air gaps with widths of about a few silicon atoms. Such levels of field confinement may impact potential applications such as surface-enhanced Raman spectroscopy,<sup>24</sup> nonlinear optics,<sup>7</sup> biosensing,<sup>25</sup> and quantum technologies.<sup>1,26</sup> Our waveguide-coupled self-assembled bowtie cavity features a mode volume  $100 \times$  below the diffraction limit while exhibiting a loaded quality factor of  $1.5 \times 10^4$ . The smallest dimension of devices obtainable with this new method is only limited by structural disorder.<sup>22</sup> Although the self-assembly of photonic cavities with fewto-sub-nanometer confinement is the focus of our work, a much more comprehensive range of research and technology may benefit from our technique. Our work generally provides avenues for investigating novel domains in photonics, electronics, and mechanics at the atomic scale while facilitating self-aligned and scalable integration with large-scale chip architectures.

#### ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the Villum Foundation Young Investigator Programme (Grant No. 13170), Innovation Fund Denmark (Grant No. 0175-00022 – NEXUS and Grant No. 2054-00008 – SCALE), the Danish National Research Foundation (Grant No. DNRF147 – NanoPhoton), Independent Research Fund Denmark (Grant No. 0135-00315 – VAFL), the European Research Council (Grant. No. 101045396 – SPOTLIGHT), the European Union's Horizon 2021 research and innovation programme under a Marie Sklodowska-Curie Action (Grant No. 101067606 – TOPEX), and the European Union's Horizon research and innovation programme (Grant No.101098961 – NEUROPIC).

#### REFERENCES

- Lodahl, P., Mahmoodian, S., and Stobbe, S., "Interfacing single photons and single quantum dots with photonic nanostructures," *Rev. Mod. Phys.* 87(2), 347 (2015).
- [2] Akahane, Y., Asano, T., Song, B.-S., and Noda, S., "High-Q photonic nanocavity in a two-dimensional photonic crystal," *Nature* 425(6961), 944–947 (2003).
- [3] Asano, T., Ochi, Y., Takahashi, Y., Kishimoto, K., and Noda, S., "Photonic crystal nanocavity with a Q factor exceeding eleven million," Opt. Express 25(3), 1769–1777 (2017).
- [4] Khurgin, J. B., "How to deal with the loss in plasmonics and metamaterials," Nat. Nanotechnol. 10(1), 2–6 (2015).
- [5] Gondarenko, A. and Lipson, M., "Low modal volume dipole-like dielectric slab resonator," Opt. Express 16(22), 17689–17694 (2008).
- [6] Gondarenko, A., Preble, S., Robinson, J., Chen, L., Lipson, H., and Lipson, M., "Spontaneous Emergence of Periodic Patterns in a Biologically Inspired Simulation of Photonic Structures," *Phys. Rev. Lett.* 96(14), 143904 (2006).
- [7] Choi, H., Heuck, M., and Englund, D., "Self-Similar Nanocavity Design with Ultrasmall Mode Volume for Single-Photon Nonlinearities," *Phys. Rev. Lett.* 118(22), 223605 (2017).
- [8] Hu, S. and Weiss, S. M., "Design of photonic crystal cavities for extreme light concentration," ACS Photonics 3(9), 1647–1653 (2016).
- [9] Almeida, V. R., Xu, Q., Barrios, C. A., and Lipson, M., "Guiding and confining light in void nanostructure," Opt. Lett. 29(11), 1209–1211 (2004).
- [10] Albrechtsen, M., Vosoughi Lahijani, B., and Stobbe, S., "Two regimes of confinement in photonic nanocavities: bulk confinement versus lightning rods," *Opt. Express* **30**(9), 15458–15469 (2022).
- [11] Albrechtsen, M., Vosoughi Lahijani, B. V., Christiansen, R. E., Nguyen, V. T. H., Casses, L. N., Hansen, S. E., Stenger, N., Sigmund, O., Jansen, H., Mørk, J., et al., "Nanometer-scale photon confinement in topology-optimized dielectric cavities.," *Nat. Commun.* 13(1), 6281 (2022).
- [12] Hah, J. H., Mayya, S., Hata, M., Jang, Y.-K., Kim, H.-W., Ryoo, M., Woo, S.-G., Cho, H.-K., and Moon, J.-T., "Converging lithography by combination of electrostatic layer-by-layer self-assembly and 193 nm photolithography: Top-down meets bottom-up," J. Vac. Sci. Technol. B 24(5), 2209–2213 (2006).
- [13] Min, Y., Akbulut, M., Kristiansen, K., Golan, Y., and Israelachvili, J., "The role of interparticle and external forces in nanoparticle assembly," *Nat. Mater.* 7(7), 527–538 (2008).
- [14] Xiang, C., Bowers, S. M., Bjorlin, A., Blum, R., and Bowers, J. E., "Perspective on the future of silicon photonics and electronics," *Appl. Phys. Lett.* **118**(22) (2021).
- [15] Babar, A. N., Weis, T. A. S., Tsoukalas, K., Kadkhodazadeh, S., Arregui, G., Vosoughi Lahijani, B., and Stobbe, S., "Self-assembled photonic cavities with atomic-scale confinement," *Nature* 624(7990), 57–63 (2023).
- [16] Klimchitskaya, G., Mohideen, U., and Mostepanenko, V., "The Casimir force between real materials: Experiment and theory," *Rev. Mod. Phys.* 81(4), 1827 (2009).
- [17] Aoyama, H. et al., "The International Roadmap For Devices And Systems (IEEE, 2022); https://irds. ieee.org/images/files/pdf/2022/2022IRDS\_Litho.pdf."
- [18] Galli, M., Portalupi, S., Belotti, M., Andreani, L., O'Faolain, L., and Krauss, T., "Light scattering and Fano resonances in high-Q photonic crystal nanocavities," *Appl. Phys. Lett.* 94(7), 071101 (2009).

- [19] Afzal, F. O., Halimi, S. I., and Weiss, S. M., "Efficient side-coupling to photonic crystal nanobeam cavities via state-space overlap," JOSA B 36(3), 585–595 (2019).
- [20] Quan, Q., Deotare, P. B., and Loncar, M., "Photonic crystal nanobeam cavity strongly coupled to the feeding waveguide," Appl. Phys. Lett. 96(20), 203102 (2010).
- [21] Vosoughi Lahijani, B., Albrechtsen, M., Christiansen, R., Rosiek, C., Tsoukalas, K., Sutherland, M., and Stobbe, S., "Electronic-photonic circuit crossings." Preprint at https://arXiv:2204.14257 (2022).
- [22] Rosiek, C. A., Arregui, G., Vladimirova, A., Albrechtsen, M., Vosoughi Lahijani, B., Christiansen, R. E., and Stobbe, S., "Observation of strong backscattering in valley-Hall photonic topological interface modes," *Nat. Photon.*, 1–7 (2023).
- [23] Mastrangeli, M., Abbasi, S., Varel, C., Van Hoof, C., Celis, J.-P., and Böhringer, K. F., "Self-assembly from milli- to nanoscales: methods and applications," J. Micromech. Microeng. 19(8), 083001 (2009).
- [24] Luo, S., Mancini, A., Wang, F., Liu, J., Maier, S. A., and de Mello, J. C., "High-Throughput Fabrication of Triangular Nanogap Arrays for Surface-Enhanced Raman Spectroscopy," ACS Nano (2022).
- [25] He, Q. and Tang, L., "Sub-5 nm nanogap electrodes towards single-molecular biosensing," Biosens. Bioelectron., 114486 (2022).
- [26] Wang, J., Paesani, S., Ding, Y., Santagati, R., Skrzypczyk, P., Salavrakos, A., Tura, J., Augusiak, R., Mančinska, L., Bacco, D., et al., "Multidimensional quantum entanglement with large-scale integrated optics," *Science* **360**(6386), 285–291 (2018).