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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.[1] 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.[2] 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.[3] The mode volume in dielectric cavities was previously considered to be diffraction-limited,[4] but it is now understood that dielectric nanocavities with a bowtie feature can provide deep subwavelength confinement.[5,6,7,8] Dielectric bowtie nanocavities confine light below the diffraction limit by exploiting the electromagnetic-field boundary conditions at material interfaces.[9] 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.[10] Recent developments in nanophotonics involve the experimental demonstration[11] 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.

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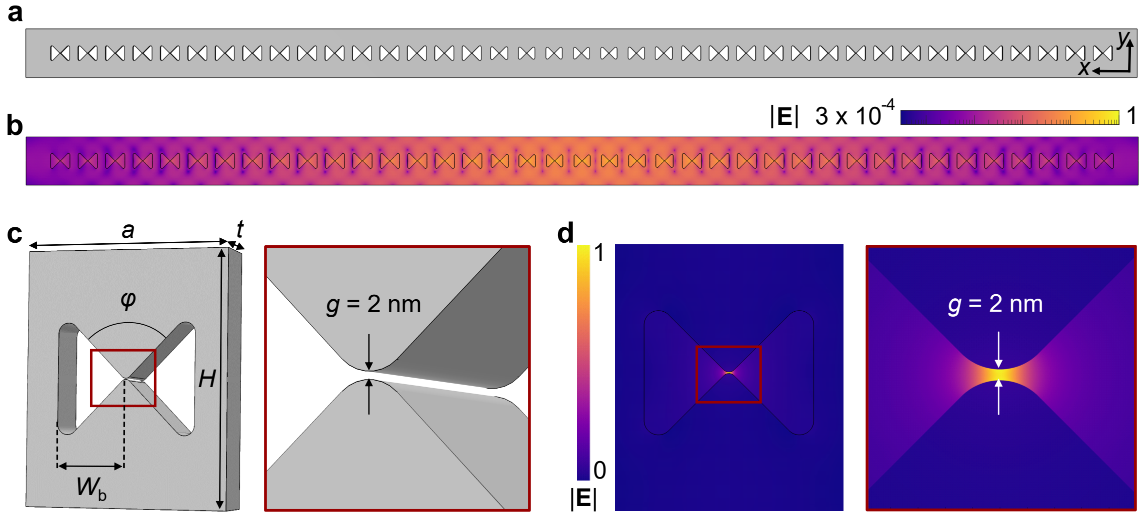

Figure 1. Design of a self-assembled bowtie nanobeam cavity. **a**, Schematic of the bowtie nanobeam cavity. **b**, The normalized electric field of the fundamental cavity mode, $|\mathbf{E}|$, with a logarithmic color map. **c**, Schematic of a single bowtie unit cell with the following design parameters: lattice constant, a, bowtie angle, φ, bowtie width, W_{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 self-assembly. 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.[12] 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.[13] 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[10,11] and, on the other hand, the potential of photonic technologies rely on the reliable fabrication of large-scale circuits.[14] 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.[7] We report on a new method that combines the atomic-scale resolution of self-assembly with the scalability and components of planar photonic circuits.[15] We use surface forces, including Casimir-van der Waals interactions,[16] to self-assemble structures patterned only through lithography and etching.[15]

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.[17] 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,[11,15] 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 μm of unpatterned half-beams 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

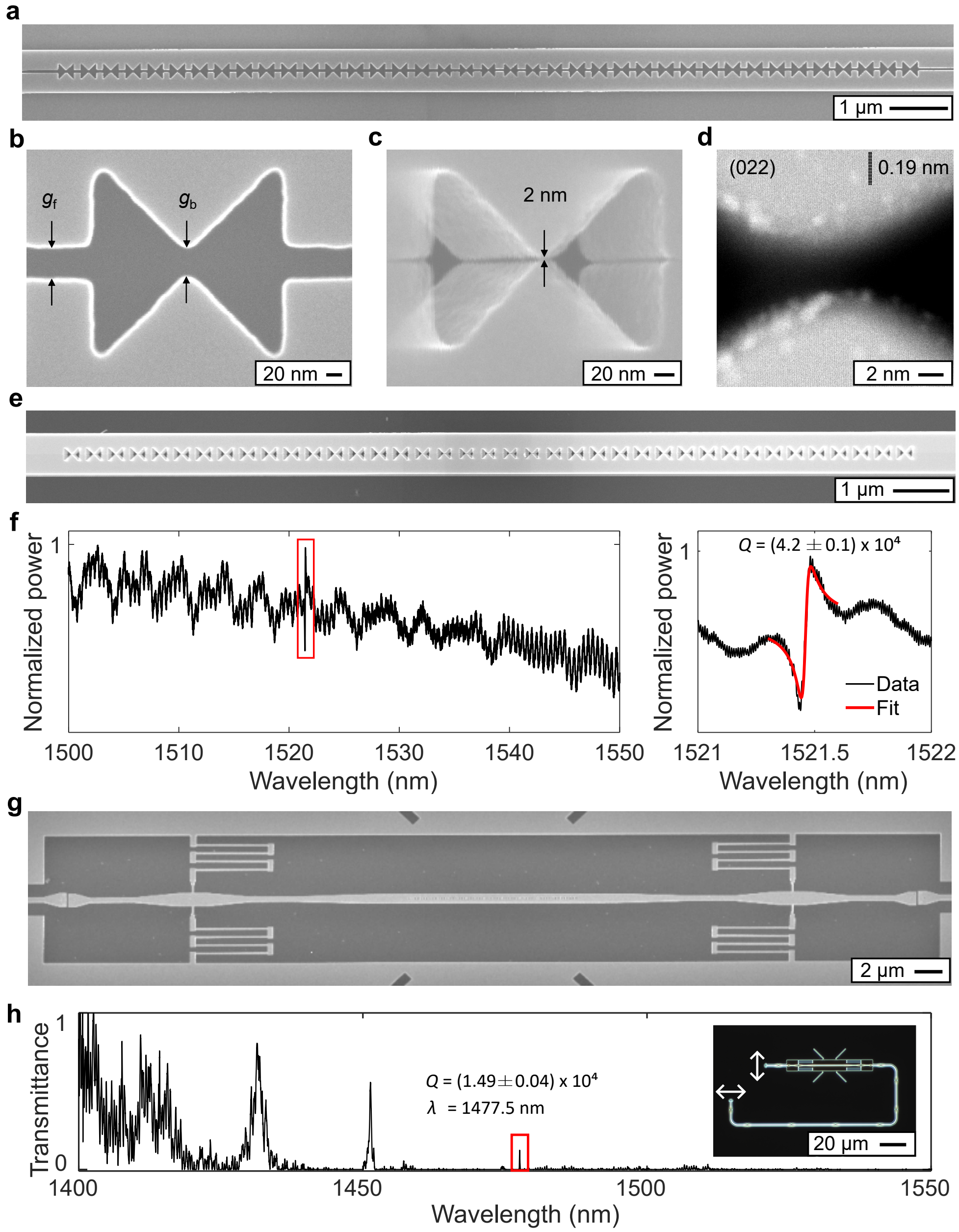

Figure 2. Fabrication and optical characterization of self-assembled bowtie cavities. **a**, Top-view scanning electron microscope (SEM) image of a bowtie nanobeam cavity before self-assembly. **b**, Top-view SEM image of a single bowtie unit cell before self-assembly, with a fabricated gap, g_f, and a bowtie gap, g_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 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.[15] 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[18] to extract the resonance wavelength and quality factor. We measure quality factors up to 4.2×10^4 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 photonic-crystal nanobeam cavities, the most well-known approaches of efficient coupling to and from the cavity are either evanescent side-coupling[19] or (in-line) direct coupling.[20] 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.[21] 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 out-of-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[22] 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 1.5×10^4.

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.[15] Our concept can be applied to any material platform due to the ubiquitous nature of the surface forces,[23] 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,[24] nonlinear optics,[7] biosensing,[25] and quantum technologies.[1,26] Our waveguide-coupled self-assembled bowtie cavity features a mode volume $100\times$ below the diffraction limit while exhibiting a loaded quality factor of 1.5×10^4. The smallest dimension of devices obtainable with this new method is only limited by structural disorder.[22] Although the self-assembly of photonic cavities with few-to-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.

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