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An improved surface-plasmonic nanobeam cavity for higher *Q* and smaller *V*

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We demonstrate a high-Q hybrid surface-plasmon-polariton-photonic crystal (SP3C) nanobeam cavity. The proposed cavities are analyzed numerically using the three-dimensional finite difference time domain (3D-FDTD) method. The results show that a Q-factor of 2076 and a modal volume V of $0.16(\lambda/2n)^3$ can be achieved in a 50 nm silica-gap hybrid SP3C nanobeam cavity when it operates at telecommunications wavelengths and at room temperature. V can be further reduced to $0.02(\lambda/2n)^3$ when the silica thickness decreases to 10 nm, which leads to a Q/V ratio that is 11 times that of the corresponding plasmonic-photonic nanobeam cavity (without silica). The ultrahigh Q/V ratio originates from the low-loss nature and deep sub-wavelength confinement of the hybrid plasmonic waveguide, as well as the mode gap effect used to reduce the radiation loss. The proposed structure is fully compatible with semiconductor fabrication techniques and could lead to a wide range of applications.

optical cavity, surface plasmon polariton, *Q*-factor, modal volume, slot waveguide

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Considerable efforts are currently focused on exploring ways to increase the quality factor Q and decrease the modal volume V of optical microcavities, because of their significant roles in many fundamental physics studies, including light-matter interactions and device physics [1]. A higher Q value indicates a very long photon lifetime, while a small V means that the cavity can localize the photon in a small spatial volume. Over the last decade, various types of optical microcavities were proposed and investigated, including whispering-gallery microcavities, Fabry-Perot microcavities, and photonic crystal microcavities [2]. Among these cavities, the nanobeam photonic crystal microcavity [3–11] provides not only a very high Q value, but also an ultrasmall V and an ultracompact footprint. Nanobeam photonic crystal microcavities with Q values even higher than 10^9 were demonstrated [12]. Although Q values have been raised considerably by sophisticated designs, the smallest achievable V in a conventional dielectric cavity is bound to the diffraction limit, i.e. it is of the order of several times $(\lambda/2n)^3$ [13]. However, in some cases, an ultrasmall V is more important than a higher Q. For example, when the cavity's resonance linewidth is smaller than the emission linewidth of the emitter, decreasing the effective modal volume is the only way to increase the spontaneous emission rate [14].

New microcavity schemes were designed to further decrease V. For example, microcavities based on slot waveguides were proposed [14–18]. Microcavities using surface plasmon polaritons (SPPs) were also studied extensively [19,20]. SPPs are electron density waves excited at and propagating along metal-dielectric interfaces [21,22]. Because of their sub-wavelength confinement of optical fields, they are promising candidates for realization of ultrasmall-V nanocavities. However, the reported Q values of SPP cavities thus far are very small and high Q values were only predicted at cryogenic temperatures [23]. The intrinsic high loss caused by metallic absorption and the low temperature requirements for high Q limit the practical applications. A

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high Q (theoretically ~1800) plasmon whispering-gallery microcavity at room temperature was realized [24], but the modal volume of this cavity was very large (30–50 μm^3) compared with that of a conventional dielectric photonic crystal cavity. Recently, surface-plasmonic nanobeam cavities formed by bonding nanobeam photonic crystal cavities to a silver substrate were proposed [25]. These cavities are ultracompact and are expected to obtain sub-wavelength confinement and thus smaller V values, whereas the reported total Q is still at a value of several hundred (<400).

In this paper, we propose an improved surface-plasmonic nanobeam cavity, called a hybrid SPP-photonic crystal (SP3C) nanobeam microcavity. This hybrid SP3C nanobeam microcavity can be formed by oxidizing the lower surface of a conventional silicon photonic crystal nanobeam cavity and then bonding it to a silver substrate (Figure 1). Compared with a previously proposed nanobeam cavity [25], our hybrid SP3C includes an additional low-index silica layer between the silicon nanobeam and the silver substrate. The three-dimensional finite difference time domain method (3D FDTD) is used to investigate the characteristics of the proposed cavity. For the convenience of normalizing V with respect to $(\lambda/2n)^3$, we calculate V using the following equation [13,14,24,26]:

$$V=\frac{\int \varepsilon(\vec{r})\,|\,\vec{E}(\vec{r})^2\,|\,\mathrm{d}^3 r}{\varepsilon(\vec{r}_{\max})\max[|\,\vec{E}(\vec{r})^2\,|]}\left(\frac{2n(\vec{r}_{\max})}{\lambda}\right)^3, \qquad (1)$$

where $\vec{r}_{\max}$ is the location of the maximum square field. The effective dielectric constant of silver is obtained by considering the dispersion property of the metal [23], $\varepsilon_{\mathrm{eff}}=\mathrm{Re}[\mathrm{d}(\omega\varepsilon(\omega))/\mathrm{d}\omega]$.

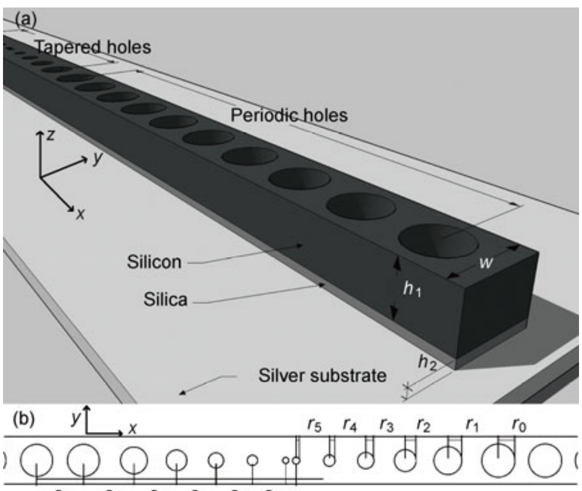

Figure 1 Schematic of the hybrid SPP-photonic crystal nanobeam cavity. a_0, r_0, S, w, h_1, and h_2 are the lattice constant, radius of the periodic holes, center hole spacing, width of the nanobeam, and the heights of the silicon and silica layers, respectively. a_1–a_5 are the five linearly tapered lattice constants from 440 to 320 nm, and the corresponding hole radii r_1–r_5 linearly decrease from $0.3a_i$ to $0.1a_i$.

Figure 1 shows a schematic diagram of the hybrid SP3C cavity. Detailed parameters are marked in the figure, and their corresponding meanings are given in the figure caption. We start our design by choosing the optimized nanobeam sizes (w=450 nm, h_1=300 nm) for low loss operation at communication wavelengths [27]. The lattice constant a_0 and the hole radius r_0 are set to 450 nm and $0.35a_0$, respectively, to open a hybrid TM band gap near 1500 nm for a 50 nm silica layer (h_2=50 nm) hybrid SP3C crystal. The lattice constant and the hole radius remain constant in the following investigation. Because a previous study indicated that decreasing h_2 would widen the band gap [18], these cavities can still provide good confinement of the hybrid cavity modes. In the center section of the cavity, tapering of both the lattice constant and the air hole radius (Figure 1(b)) was implemented for lower radiation losses [28].

Typical cavity mode profiles are shown in Figure 2. The field distribution along the z direction in Figure 2(c) indicates the distinct hybrid plasmon-photonic origin [29] of these cavity modes. In contrast to the plasmonic-photonic crystal nanobeam cavities [25] (Figure 2(e) and (f)), the hybrid SP3C nanobeam cavities (Figure 2(b) and (c)) show stronger field confinement in their narrow silica regions. Their maximum electric fields move to the boundary between the silica and the silicon, instead of the original location at the interface between the silver and the silicon. Because of this change in the mode profiles, the energy ratio of the silver layer decreases and the corresponding absorption loss declines. As shown in Figure 2(c) and (f), the hybrid SP3C nanobeam cavity with h_2=50 nm shows nearly the same value of V with a more than five-fold enhancement of Q compared with that of the plasmonic-photonic crystal nanobeam cavity (h_2=0 nm).

The values of Q calculated as a function of the silica thickness h_2 are plotted in Figure 3. As we may expect from the low-loss properties of the hybrid-plasmonic waveguide, a substantial increase in the total Q_{tot} ($Q_{\mathrm{tot}}^{-1}=Q_{\mathrm{abs}}^{-1}+Q_{\mathrm{rad}}^{-1}$) can be observed with increasing silica thickness. Over the investigated silica layer thickness range, the value of Q_{tot} nearly approached the absorption quality factor (Q_{abs}), which is limited by the ohmic loss of silver. This also indicates the positive effects of implementing tapered holes, which benefit from the mode gap effect [30] and result in

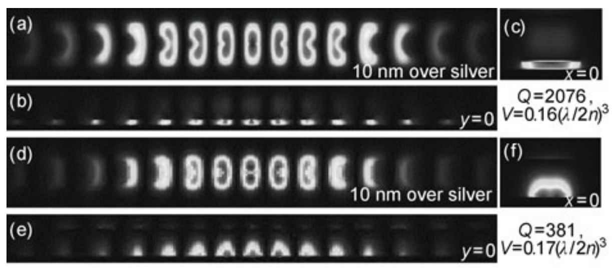

Figure 2 Mode profiles (E_z) of hybrid SP3C nanobeam cavities with h_2=50 nm ((a)–(c)) and h_2=0 nm ((d)–(f)).

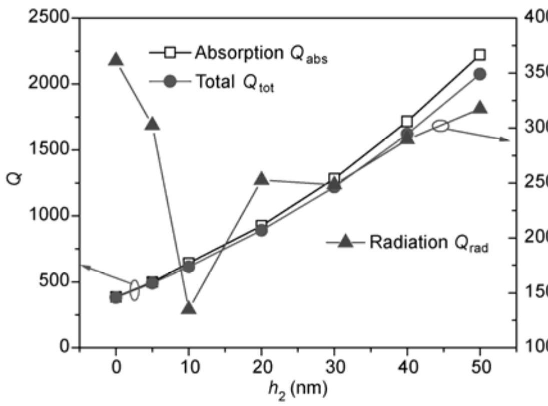

Figure 3 Quality factors for radiation (Q_{rad}), absorption (Q_{abs}) and total (Q_{tot}) as a function of h_2. The two-hole center spacing S is 100 nm.

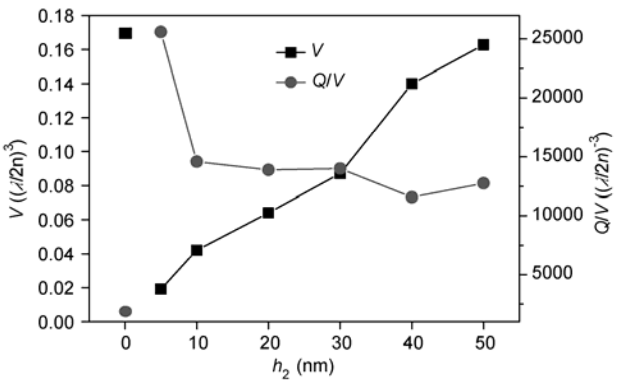

Figure 4 Modal volume V and figure of merit (Q/V) as a function of h_2. The two-hole center spacing S is 100 nm.

higher radiation Q_{rad}. The radiation loss is very sensitive to the silica thickness h_2 and the hole center spacing S. Q_{rad} has a minimum value of 13479 at h_2=10 nm, which is sufficient to approach Q_{abs} according to the relationship given above. Also, further increases in Q_{rad}, and therefore in Q_{tot}, can be obtained by adjusting S. For example, the initial Q_{tot} of 2076 for h_2=50 nm can increase to a maximum value of 2193 when S shifts from 100 nm to 60 nm. It should be noted that increasing S will slowly increase the modal volume V, but this is only a very weak linear dependence [18].

Using the definition of V from eq. (1), we consider a cavity with an infinitesimal silica layer. Recalling from Maxwell's equations that across the boundary of silica and silicon [31] $\varepsilon_{SiO_2} E_{SiO_2} = \varepsilon_{Si} E_{Si}$, we can rewrite eq. (1) as:

$$V' = \frac{\int \varepsilon(\vec{r}) \, |\vec{E}(\vec{r})^2| \, \mathrm{d}^3 r}{\varepsilon_{SiO_2} \, | \varepsilon_{Si} / \varepsilon_{SiO_2} E_0 |} \left(\frac{2n_{SiO_2}}{\lambda} \right)^3, \qquad (2)$$

where E_0 is the maximum value at the boundary between silver and silicon before introducing the silica layer (h_2=0 nm). The infinitesimal silica layer has a negligible effect on the numerator. Therefore, eq. (2) predicts a 40-fold decrease in V ($V'/V = (\varepsilon_{SiO_2}/\varepsilon_{Si})^{5/2} \approx 1/40$). Figure 4 shows the dependences of V and the figure of merit (FOM=Q/V) on the silica thickness h_2. Introduction of a silica slot layer greatly enhances the FOM, because of the simultaneous decrease in V and increase in Q. When the thickness of the silica layer increases to 50 nm, V nearly reaches the same level as that of the plasmonic-crystal cavity (h_2=0 nm). The FOM increases substantially with the decrease in h_2 and reaches a maximum value of 25590 $(\lambda/2n)^3$ within the h_2 range studied, which is more than 11 times the value at h_2=0 nm.

In conclusion, an improved surface-plasmonic nanobeam cavity called the hybrid SP3C nanobeam cavity was proposed and analyzed. Compared with a typical plasmon-photonic crystal nanobeam cavity, the hybrid SP3C nanobeam cavity provides not only a decrease in V but also an increase in Q, and therefore provides a substantial enhancement of the FOM. A high Q of 2076 and an ultrasmall V of the order of $10^{-2}(\lambda/2n)^3$ were achieved when the cavity was operated at room temperature and at telecommunications wavelengths. The proposed structure is fully compatible with semiconductor fabrication techniques and could lead to numerous applications. We also propose to replace the silica layer with an air slot or with other low index materials (such as gain materials), which will open possibilities for realization of low-threshold nanolasers, and high-sensitivity opto-mechanical systems and sensors.

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