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Design and Optical Properties of Electromechanical Double-Membrane Photonic Crystal Cavities

Leonardo Midolo and Andrea Fiore

Abstract—We discuss relevant design considerations for the fabrication of electromechanically tunable photonic crystal cavities based on double semiconductor slabs. A simple optical and electromechanical model of the device based on coupled-mode theory and electrostatics is discussed and used jointly with 3-D finite-element calculations of optical cavity modes to extract the tuning-range dependence on geometrical parameters. A design rule, which avoids the sticking of membranes due to capillary forces and keeps a large tunability, is defined. The details of the fabrication process and a summary of the experimental results on GaAs and InGaAsP/InP material systems are given. We also address the problem of nonsymmetric devices, where the thicknesses of the membranes are not exactly the same, resulting in an imbalanced power emission of coupled modes.

Index Terms—Microelectromechanical devices, quantum dots, fabrication.

I. INTRODUCTION

CONTROLLING the spectrum of a photonic crystal cavity (PCC) has been an active field of research during the last decade, due to the numerous applications of these devices in nanophotonics and in solid-state cavity quantum electrodynamics with quantum dots (QDs). In this direction, the ability to manipulate the local density of optical states (LDOS) through a frequency-tunable cavity at the nanoscale is extremely attractive, as it opens up novel opportunities for scalable Purcell-enhanced single-photon generation within integrated optical chips [1]. The methods presented so far in the literature address the problem of tuning in two ways: through a physical alteration of the refractive index of the materials involved, as in thermo-optic tuning [2], [3], liquid infiltration [4], gas condensation on the surface [5], carrier injection [6]–[9], Kerr non-linearities [10] or through a spatial reconfiguration of the dielectric environment [11]–[13]. Recently, the latter method has proven to be particularly useful for integrated devices when implemented through micro-opto-electromechanical systems (MOEMS), where the mechanical displacements are obtained with capacitive actuation using compact and scalable architectures [14]–[17]. Micro-mechanical devices usually feature stable operation over a

Fig. 1. Sketch of the double membrane MOEMS for the electromechanical tuning of a PCC. When reverse-biasing the p-i-n diode an electrostatic force builds up across the air gap between the membranes, resulting in a displacement of the upper slab. The tuning can be reversed by reducing the bias due to the restoring elastic forces.

wide range of temperatures and low susceptibility to environmental vibrations due to their high resonant frequencies (>100 kHz). Our group recently developed wavelength-tunable PCCs based on double membranes with the goal of improving the QD-PCC system for applications in quantum information processing [18]. In this article we present the design and the fabrication of our electromechanical PCCs. We derive a simple design rule in the case of pull-in-limited tuning and discuss the factors which restrict the tuning range. We briefly report the most important experimental results and study the effect of the membranes' asymmetry to explain the measured spectra.

II. THE DOUBLE-MEMBRANE MOEMS

Etching PCCs on two closely spaced parallel membranes and controlling the distance between them electromechanically provides a large tuning without affecting the quality factor (Q). The idea, theoretically proposed by Notomi *et al.* [19], provides an attractive and feasible implementation of a widely tunable PCC with embedded QDs. The biggest difference in double membranes as compared to existing electromechanical methods is to realize a vertical, rather than an in-plane, displacement, similar to what has been done with tunable vertical cavity surface emitting lasers [20]. The structure is ideal for epitaxial growth using III/V materials as several active and doped regions can be stacked on top of each other and separated in the vertical direction. Additionally, a large electrostatic force is easily applied due to the relatively large area of the membranes. Fig. 1 shows a sketch of the

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proposed double-membrane MOEMS. The mechanical motion is achieved electrically introducing two doped layers located in the membranes to form a p-i-n junction and operating it under reverse bias.

The principle of operation of the device is based on the alteration of the effective refractive index in a two-dimensional (2D) PCC. If two identical parallel membranes are brought at small distances, such that the evanescent tail of each guided mode tunnels into the other slab, they form a coupled system. When PCCs are defined by patterning holes in both membranes, they also become coupled, resulting in a frequency splitting and field delocalization across the two membranes. These modes are called symmetric and anti-symmetric from the profile of their electric (or magnetic) field. The origin of these modes can be explained with the formalism of coupled mode theory (CMT) introduced by Haus *et al.* [21].

The temporal coupled mode equation in matrix form reads:

$$\frac{d}{dt} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} = i \begin{pmatrix} \omega_1 & \mu \\ \mu & \omega_2 \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} \quad (1)$$

where $\Psi_{1,2}(t)$ are the amplitudes of the uncoupled cavity eigenmodes with resonant frequencies $\omega_{1,2}$ whose spatial field profile is denoted as $\mathbf{E}_{1,2}(\mathbf{r})$. The coupling μ can be derived from variational principles. When a small, positive perturbation ($\delta\epsilon > 0$) is added to the dielectric constant the field tends to re-distribute to reduce the energy of the mode. μ can be written as [22]:

$$\mu_{1,2} = -\frac{\omega_1}{2} \frac{\int \delta\epsilon_{1,2} \mathbf{E}_1^* \mathbf{E}_2 dV}{\int \epsilon_1 |\mathbf{E}_1|^2 dV} \quad (2)$$

where the subscripts refer to the perturbation “seen” by mode 1 due to mode in slab 2. We assume that the total energy of the system is conserved so that no loss is introduced by the coupling. This implies that $\mu_{1,2} = \mu_{2,1}^* = \mu$ [21]. The diagonalization of the coupling matrix (1) yields a new set of eigenmodes whose field profiles are

$$\mathbf{E}_s = \alpha \mathbf{E}_1(\mathbf{r}) + \beta \mathbf{E}_2(\mathbf{r}) \quad (3)$$

$$\mathbf{E}_{as} = \alpha \mathbf{E}_1(\mathbf{r}) - \beta \mathbf{E}_2(\mathbf{r}) \quad (4)$$

with eigenfrequencies:

$$\omega_{s,as} = \bar{\omega} \pm \sqrt{\left(\frac{\Delta\omega}{2}\right)^2 + \mu^2} \quad (5)$$

where the subscript s and as denote the symmetric and the anti-symmetric modes, respectively, $\bar{\omega}$ is the average frequency of the two uncoupled cavities and $\Delta\omega$ is the relative detuning. The resulting modes are thus the in-phase and anti-phase sum of the decoupled modes. The vectors (α, β) and $(\alpha, -\beta)$ are the normalized eigenvectors of the coupling matrix. Assuming two identical slabs of equal thickness and dielectric constant and two identical PCCs ($\omega_1 = \omega_2 = \omega_0$) then (5) is simplified to $\omega_{s,as} = \omega_0 \pm \mu$ and $\alpha = \beta = 1/\sqrt{2}$.

The equations discussed so far are valid in general for any system of coupled cavities. For a cavity mode in a two-dimensional photonic crystal slab, the field can be approximately rewritten as the product of an in-plane component

and an out-of-plane component, assuming transverse-electric polarization:

$$\mathbf{E}(\mathbf{r}) \simeq \mathbf{E}(x, y) \phi(z) \quad (6)$$

where $\phi(z)$ is one of the guided mode profiles and the z -axis is normal to the membranes. The guided modes $\phi(z)$, obtained by imposing boundary conditions at the slab-air interfaces, result in a modified dispersion relation where the wave phase velocity is reduced, compared to vacuum, by an *effective refractive index* n_{eff} [23]. Since the coupling occurs along the z direction and assuming that $\delta\epsilon(\mathbf{r})$ can be factorized in $\delta\epsilon(x, y)\delta\epsilon(z)$, the dependence of μ on the distance d between the membranes can be calculated with the overlap integral, weighted on the dielectric constant, of the out-of-plane profiles. It is reasonable to expect a stronger coupling when the evanescent tail of one mode penetrates the other slab to a larger extent, i.e. when the inter-membrane distance d is reduced. To a good approximation, the coupling depends exponentially on d with the same decay constant as the evanescent field. The expression of the coupling as a function of the distance can be approximately written as [23]:

$$\mu \simeq A e^{-\gamma d} \quad (7)$$

where $\gamma = k_0 \sqrt{n_{eff}^2 - 1}$ is the spatial decay (or tunneling constant) of the evanescent mode in the gap region and A is the result of the overlap integral with the contribution of the in-plane profile. For a given in-plane mode profile and slab thickness, A can be calculated numerically. Its value will be higher for modes whose electric field sits predominantly in the high index medium (see (2)). This feature highlights one of the benefits of double membranes as compared to other systems, especially for spontaneous-emission control of quantum dots where a good spatial overlap between the cavity field and the emitter is essential. For modes strongly localized in the dielectric $A/2\pi$ is in the range 10–30 THz (corresponding to 150–200 nm wavelength shift in the near infrared). Equation 5 with the coupling defined as in (7) is plotted in Fig. 2a (converted to wavelength) as a function of the distance d (dashed lines). The tuning is compared to three-dimensional (3D) finite-element simulations (solid lines) of an L3 cavity mode (see section II-B) showing a good agreement for $d > 200$ nm and deviations at smaller separation, where (2) is no longer valid.

The CMT formalism presented here is the standard, first-order perturbative approach, which works quite well to describe the spectral behavior of double membranes. However the cavities considered so far have been regarded as loss-free. Losses are not easily included in the CMT especially for strongly coupled systems. Assuming two cavities with an equal loss rate κ_0 (or same Q), it is expected intuitively that the coupled modes exhibit the same loss rate as the decoupled ones ($\tilde{\omega}_{s,as} = \omega_0 \pm \mu + i\kappa_0$). However the loss mechanism in a single (or multiple) slab PCC is related to the amount of k components (obtained by the Fourier transform of the fields) lying inside the light cone. As the frequency of the coupled system shifts, a fraction of these components may fall in or out the light cone resulting in a change of Q. Fig. 2b shows the 3D finite element calculation of Q factors for the symmetric and

Fig. 2. (a) Wavelength tuning of an L3 cavity mode calculated by 3D finite elements (solid lines) and coupled mode theory (dashed lines). The coupling strength is estimated via the overlap integral. (b) Q factor, calculated with 3D finite elements, as a function of separation for symmetric and anti-symmetric modes. The fluctuations are due to the variation of Fourier components inside the light cone and to interference effects. (c) Lumped model of a double-membrane capacitive electrostatic actuator.

anti-symmetric modes of a L3 cavity mode as a function of the membrane separation. The values differ significantly due to the aforementioned effect and particularly the anti-symmetric mode decreases strongly for decreasing separation, due to the increasing Fourier components entering the light cone. Additionally a modulation due to interference effects (see for example Le Thomas *et al.* [24]) is visible for the symmetric mode which prevents the Q to raise further at small separations despite the frequency red-shift which pushes components away from the light cone. Interference effects strongly depend on the far-field profile of the cavity mode under consideration. However they can be highly suppressed optimizing the cavity design, for example to reduce small- k components [25]. This is the main reason for the difference between this work and the theoretical Q factors calculated by Notomi *et al.* [19] where a high Q cavity (and thus less sensitive to frequency shifts) has been used instead, showing little dependence of Q on the inter-membrane distance. We stress that, in any case, for small tuning ranges (<30 nm) and even for non-optimized cavities,

the Q factor shift is just a fraction of percent and it can be thus neglected.

A. Pull-In Limited Tuning

The large tuning range predicted by CMT when the full travel of the membrane is considered reduces significantly when using electrostatic actuation as a result of the pull-in effect. A simple but comprehensive model to describe an electrostatic, or *capacitive*, actuator can be derived from a lumped one-dimensional massless capacitor with area S whose plates are attached to springs (Fig. 2c). Assuming the general case where the spring constants, k_1 and k_2 , are different for each plate, the total potential energy of the system under a voltage U can be written:

$$\mathcal{E} = -\frac{\epsilon_0 S U^2}{2(z_2 - z_1)} + \frac{k_1 z_1^2 + k_2 (z_2 - z_0)^2}{2} \quad (8)$$

where z_1 and z_2 are the coordinates of the plates and z_0 is the distance at rest. Since the electrostatic force is applied equally to both plates and depends only on the distance, the two spring forces must also be equal at equilibrium

$$k_1 z_1 = k_2 (z_0 - z_2). \quad (9)$$

The problem can be reduced to one degree of freedom by introducing the inter-membrane distance $z \equiv z_2 - z_1$. Substituting z in (9) yields the two position variables as a function of the distance z :

$$z_1 = -\frac{k_+}{k_1}(z - z_0) \quad z_2 = k_+ \left(\frac{z_0}{k_1} + \frac{z}{k_2} \right) \quad (10)$$

where $k_+ = k_1 k_2 / (k_1 + k_2)$ denotes the stiffness of the two springs in series. Equation 8 is then rewritten as

$$\mathcal{E} = -\frac{\epsilon_0 S U^2}{2z} + \frac{k_+ (z - z_0)^2}{2}. \quad (11)$$

The static solution is obtained solving for the equilibrium condition ($\partial \mathcal{E} / \partial z = 0$)

$$z^3 - z^2 z_0 = -\frac{\epsilon_0 S U^2}{2k_+}. \quad (12)$$

The left hand side (lhs) of (12) is independent of the applied voltage and the stiffness of the system. Its value is always negative and it has a minimum, implying that not all values of U will provide a valid solution. When the voltage increases above a certain threshold, defined as the *pull-in* voltage, the electrostatic forces (proportional to z^{-2}) win over the restoring elastic forces ($\propto z$) and no minima are found to $\mathcal{E}$ (see (11)). The z value which provides the minimum of the lhs of (12) is called pull-in distance and has the value

$$z_{PI} = \frac{2z_0}{3}. \quad (13)$$

This is a characteristic result of capacitive electrostatic actuators and states that no matter what design is chosen for the plates, the maximum travel is limited to 1/3 of the original gap. Substituting in (12) yields the pull-in voltage

$$U_{PI} = \sqrt{\frac{8}{27} \frac{k_+ z_0^3}{\epsilon_0 S}}. \quad (14)$$

The device should be operated far from the pull-in as this instability may lead to damage or to unrecoverable surface adhesion [26]. As the pull-in distance and voltage depend on z_0 and k_+ , the gap at rest and the stiffness are fundamental design parameters for the device. The choice of z_0 defines the maximum tuning range of the PCC.

From the coupling factor μ (see (7)) it is possible to extract the maximum tuning achievable when pull-in is the only limiting factor. For the symmetric mode we have

$$\Delta\omega_{PI} = \omega(2z_0/3) - \omega(z_0) = A \left(e^{-\gamma 2z_0/3} - e^{-\gamma z_0} \right). \quad (15)$$

The range can be maximized when the distance at rest is

$$z_0 = \frac{3}{\gamma} \ln \left(\frac{3}{2} \right) = \frac{3\lambda_0}{2\pi\sqrt{n_{eff}^2 - 1}} \ln \left(\frac{3}{2} \right), \quad (16)$$

corresponding to a range of $\Delta\omega_{PI} = 4A/27$. This means that optimum gap at rest on pull-in limited actuators depends only on the free-space wavelength and the effective index n_{eff} of the single membrane and not on the coupling strength A . Assuming $n_{eff} = 2.5$ for a 180-nm-thick GaAs membrane and $\lambda_0 = 1300$ nm then $z_0 \approx 110$ nm, corresponding to a wavelength tuning of 20–40 nm.

B. Finite Element Modeling of PCCs

The analytical model derived from coupled mode theory (CMT) provides only an approximate solution to the wavelength shift of vertically coupled PCCs. To extract the profile of the modes, their wavelengths, quality factors and the effective tuning (taking into account material dispersion and membrane thicknesses), a full three-dimensional (3D) solution of Maxwell equations is needed.

The relevant quantity to evaluate light-matter interaction in a cavity-QD system is the local density of optical states LDOS [27]. The approach used in this work to calculate the *relative* LDOS is based on the calculation of the variation of spontaneous emission rate using classical electrodynamics [28]. The spontaneous emission rate $\Gamma_{cav}(\mathbf{r}, \omega)$ has a classical analog in the radiated power P_{cav} (or energy emission rate) of a small ($d \ll \lambda$) dipole antenna surrounded by a dielectric environment (i.e. $P_{cav}(\mathbf{r}, \omega)$ scales as $\hbar\omega\Gamma_{cav}(\mathbf{r}, \omega)$). The amount of radiated power can be calculated numerically by integrating the time-averaged Poynting vector on any surface surrounding the dipole. Dividing this quantity by the power radiated by an antenna in the homogeneous material yields a relative enhancement (or suppression) which can be related to the decay rate

$$\frac{\Gamma_{cav}(\mathbf{r}, \omega)}{\Gamma_{hom}(\omega)} = \frac{P_{cav}(\mathbf{r}, \omega)}{P_{hom}}. \quad (17)$$

This formula has been derived rigorously by Xu *et al.* [28] and it is based on the fact that the quantum and classical calculations of the radiated power differ only by a constant factor. The calculation of the relative LDOS and the mode profiles of PCCs have been carried out using a 3D finite element (FE) software [29]. The code provides a general-purpose FE discretization algorithm and Maxwell-equation solver.

Fig. 3. Geometry used to simulate double membrane photonic crystal cavities (an L3 cavity is shown in the figure). Three symmetry planes have been used (two of which are indicated in the figure). The perfectly matched layer (PML) region is 700 nm thick and the distance from the membrane is 1.7 μm .

To simulate a PCC structure on a double membrane, a 3D geometry has been drawn as shown in Fig. 3. Since the full geometry has three symmetry planes, orthogonal to x , y and z axes and passing through the origin, only one octant of the device is drawn and boundary conditions are imposed on the symmetry planes. In double membranes, the z -plane can be set to a perfect electric conductor or to perfect magnetic conductor depending whether an anti-symmetric or a symmetric mode is required. The dipole source, placed in the center of the membrane to simulate the QD, is approximated by a horizontal 10-nm-long line where an oscillating current is flowing tangentially. Open boundaries, such as the slab and the surrounding air domains, are terminated using perfectly matched layers (PML). A spectrum as the one obtained in photoluminescence experiments, when the structure is fed by a spectrally broad emitter, can be obtained sweeping the dipole frequency with an adaptive-step algorithm to resolve sharp peaks in the LDOS.

A three-period-long line defect cavity, the so-called L3 cavity, has been chosen in this work as a test for almost every tuning experiment. The reason for this choice is that the L3 provides a mode with a moderately high Q factor and a clearly recognizable spectrum. The L3 spectrum, obtained by FE simulation of a double membrane, is shown in Fig. 4. It contains three Y-polarized modes (Y1, Y2 and Y3), and two X-polarized modes (X1 and X2) at the bandgap center [30]. Each mode appears twice in the spectrum as a result of the mode splitting in symmetric (s) and anti-symmetric (as) profiles. The lowest energy mode, labeled Y1, has a nominal Q of ~ 3100 (s) and ~ 1600 (as) and an energy splitting of 38.2 meV (53 nm in wavelength). The large difference in Q factor from symmetric to anti-symmetric modes is attributed to the different amount of components in the light cone as discussed above. The wavelength and Q-factor of Y1 modes as a function of the inter-membrane separation is shown in fig. 2a and 2b, respectively. The other modes have lower Q factor (<1000) and lower energy splitting (<30 meV).

III. DEVICE FABRICATION AND DESIGN

The samples have been fabricated on two material systems: InP and GaAs for operation in the two telecom

Fig. 4. 3D FE calculated spectrum of an L3 cavity on a double GaAs membrane with a thickness of 160 nm for each slab and a gap of 200 nm. The lattice constant is $a = 390$ nm and the holes have a radius $r = 0.31a$. The source dipole is located near the cavity center, in the middle of the upper membrane, with a 100 nm x -offset to excite modes with different symmetries. Each mode's in-plane profile (electric field norm $|E|^2$) is plotted above the spectrum. Some of the peaks are barely visible since they are hidden by other modes or they radiate very little. The simulation is compared to the experimental data (black line above) obtained by micro-photoluminescence (μ PL) experiments. The dashed vertical line indicates the band edge of the anti-symmetric mode.

spectral windows around 1550 nm and 1300 nm, respectively. Additionally the GaAs sample has been used to study the coupling to single QDs. The fabrication approach is based on a combination of surface and bulk micromachining. The structural and sacrificial layers are defined initially, during the epitaxial growth of the sample, taking advantage of the mutual selectivity of certain III/V alloys to wet etching. Then, surface micromachining techniques are used to define structures (cantilevers, bridges...) which are subsequently transferred to the bulk by front side etching [31], [32]. This approach, although somewhat limited if compared to polysilicon technology, offers the possibility to create simple free-standing micro and nano structures which combine the optical properties of III/Vs with micromechanical functionalities. The integration of small scale optoelectronic devices with electromechanical systems forms a novel class of devices commonly denoted as micro or nano opto electromechanical systems (MOEMS and NOEMS).

The epitaxial growth of III/V wafers is performed by molecular beam epitaxy (GaAs) or metal-organic chemical vapor deposition (InP). The sample growth starts with an undoped (100) substrate. A thick (1–1.5 μ m) sacrificial layer is initially deposited to separate the double-membrane structure from the substrate. Then, two structural membrane layers (GaAs or InGaAsP with a gap energy corresponding to $\lambda = 1.25 \mu$ m) having the same thickness and an inter-membrane sacrificial layer are grown. The upper membrane contains a layer of low-density self-assembled InAs quantum dots, emitting at 1.3 μ m or 1.55 μ m for GaAs and InP substrates, respectively. To realize the electrostatic actuator, parts of the membranes are doped to form a p-i-n junction. The top 50 nm of the lower membrane are p-doped and the bottom 50 nm of the upper membrane are n-doped. The doping concentration is kept low enough to avoid diffusion of dopants or excessive optical

Fig. 5. Process flow for the fabrication of the diode and the photonic crystal MOEMS.

absorption. The nominal value is $n = p = 1 \cdot 10^{18} \text{ cm}^{-3}$. Since the QDs are situated above the junction, they are not affected by the electrostatic field. On InP, a final capping layer is added to terminate the growth. This layer has to be removed before starting the fabrication process.

A. Nanofabrication Process

The complete fabrication process can be separated into two main parts: the *diode fabrication* and the *photonic crystal fabrication*. The generic (material independent) process for the diode fabrication is summarized in the following steps, graphically shown in Fig. 5.

- 1) The vias for the p-contacts are defined with optical lithography and transferred by CHF_3/O_2 reactive ion etching (RIE) to a 50-nm-thick SiN mask and subsequently into the membrane and the sacrificial layer by wet or dry etching. At the end the SiN is removed in HF 1%. During this step, the (negative) shape of the movable part is also defined.
- 2) The n-via is defined with a similar process (50 nm SiN mask and optical lithography) and etched down to the n-doped layer. Since no selectivity is available between intrinsic and n-doped layers, the etching times are carefully optimized to stop exactly at the n-layer interface.
- 3) The p and n metal contacts are defined with two separate lithographic steps by evaporation and lift off of Ti/Au (50/200 nm).

At the beginning of the process and at the end of each lithographic step the sample is cleaned by O_2 plasma and deoxidized in a diluted hydrochloric or phosphoric acid solution. The process continues with the fabrication of the photonic crystal:

- 4) A thick (400 nm) SiN layer is deposited on the sample and then coated with ZEP 520A (e-beam resist). The PCC patterns are exposed, aligned to the existing structures, by electron beam lithography (EBL). After development, the holes are etched in the SiN mask by

RIE with pure CHF_3 for approximately 20 minutes. The residual resist is stripped off with O_2 plasma. From the hard mask, the PCC is etched into both membranes (and the inter-membrane sacrificial layer) with inductively coupled plasma (ICP) for 2.5 minutes.

- 5) The sacrificial layers are etched using a selective hydrochloric acid solution without removing the SiN mask. After the sample has dried, the SiN mask is removed in a barrel etcher with CF_4 plasma.

There are a few differences, outlined in the following, related to the two material systems used:

- The diode vias are etched using CH_4/H_2 RIE for InGaAsP and InP [33] whereas a wet etching, based on citric acid/peroxide ($\text{C}_6\text{H}_8\text{O}_7$ monohydrate mixed 1:1 with water by weight), has been used on GaAs [34]. A citric acid/peroxide 40:1 solution is prepared to etch n-vias (with a controlled etching rate of 80 nm/min) and a 10:1 solution for p-vias (rate 150 nm/min) [35]. $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ is removed by HF 1%.
- The holes are etched by ICP in a $\text{Cl}_2/\text{Ar}/\text{H}_2$ chemistry for InGaAsP/InP and in Cl_2/N_2 chemistry for GaAs/AlGaAs [36].
- The undercut of the membranes is done in $\text{HCl}/\text{H}_2\text{O}$ (4:1) for InP sacrificial layers [37] and in pure HCl (36 %) for $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layers [38]. In both cases the temperature of the solution is lowered to 1 °C to improve the selectivity. Instead of etching $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ in HF, as normally done on single membrane PhCs [39], HCl is used to avoid dissolving the SiN mask.

One of the most challenging steps in micromechanical system manufacturing is the release of free-standing structures after the wet etching of a sacrificial layer. Once the acid has been replaced by de-ionized (DI) water, a liquid bridge forms in the interstitial spaces left by the sacrificial material and a strong capillary pressure arises due to the surface tension of the droplet which may lead to a sticking of the membranes upon drying. Stiction is usually avoided using critical point drying [40]. In this work, however, supercritical drying has not been used. Instead, a technique has been developed to reduce stiction by stiffening the membranes with the nitride mask layer, a method partly inspired by the photoresist-assisted release of micro-mechanical structures [41]. As the deposition of the mask is conformal, it supports the free-standing parts from the top and from the sides during the wet etching and the drying (Fig. 6a). The result is an increased stiffness which reduces the elastocapillary number of the structure [42]. To remove the nitride, a CF_4 plasma in a barrel etcher can be used, which does not involve any liquid. Examples of the final released MOEMS are shown in Fig. 6b and 6c for GaAs and InGaAsP/InP, respectively.

B. Device Geometry Design

The device design and the choice of the geometrical parameters are now discussed in the light of the foregoing. The elastocapillary number sets a lower bound for the stiffnesses k_1 (bottom membrane), k_2 (upper membrane) and the gap z_0 . Using our anti-stiction technique, the release of structures

(a)

(b)

(c)

Fig. 6. (a) The anti-stiction method used in this work. The upper membrane is stiffened by the SiN mask. The water droplet with volume V_l , contact angle θ_c and surface tension γ_l produces a capillary pressure q which is responsible of stiction. Using a thick conformal nitride layer on top of the membrane its movement is restricted and the risk of collapse is reduced. The bottom membrane is still free to move, imposing lower bounds on the thickness t and gap at rest z_0 . After the sample has dried, the SiN is removed by CF_4 plasma etching. (b) A scanning electron microscope (SEM) picture of a free-standing GaAs slotted bridge. (c) SEM image of a spiral-shaped 4-arms cantilever on InGaAsP membranes.

is limited only by the flexibility of the lower membrane (see Fig. 6a). In other words we are in the situation where the bottom membrane can collapse on the upper membrane by capillary forces even if the latter is very stiff ($k_2 \gg k_1 \simeq k_+$). The lower slab cannot be made arbitrarily stiff as k_1 ultimately depends on the geometrical properties of the PCC (thickness and area). The thickness of each membrane should be small enough to avoid high-order coupled modes ($t < 250$ nm), but large enough to fit doped layers and QDs ($t > 100$ nm). The area of the device has to accommodate a PCC with at least 10-12 holes around the defect. Long structures (with aspect ratio length/width $\gg 1$) suffer from large internal stresses after undercut leading to buckling effects. It is thus better to use square structures in order to limit this phenomenon. We have assumed a device area of $11 \times 11 \mu\text{m}^2$ and $14 \times 14 \mu\text{m}^2$ for GaAs and InGaAsP respectively. The elastocapillary number for square plates [42], neglecting the holes and the internal residual stress is

$$N_{EC} = \frac{25Yt^3z_0^2}{(1-\nu^2)\gamma_l \cos \theta_c L^4} \left(1 + \frac{5z_0^2}{12t^2} \right) \quad (18)$$

where Y is the Young modulus (86 GPa and 65 GPa for GaAs and InGaAsP respectively), ν the Poisson ratio (0.31), L the width of square, θ_c the contact angle of the water droplet between the membranes (we assume the worst case $\theta_c = 0$) and γ_l the surface tension of water (72 mN/m) (see fig. 6a).

To define a design rule, the pull-in limited tuning range of a Y1 mode (fig. 4) of the L3 cavity is used as a figure of merit for the optimization of the geometrical parameters. Operation around 1300 nm and 1550 nm is considered here for GaAs and InGaAsP, respectively. The contour plots in Fig. 7a and 7b show such a tuning range as a function of thickness t and the gap z_0 as well as the line $N_{EC} = 1$ which sets the limit of device design for both GaAs and InGaAsP. Indeed, N_{EC} should be larger than 1 to minimize the risk of stiction during the drying. For a given pair of parameters, the InGaAsP material system is expected to provide a larger pull-in limited tuning due to the longer wavelength operation whereas the GaAs system provides a higher elastocapillary number due to the higher Young modulus. It is quite clear that the optimum value of z_0 obtained from (16) (thin red dashed line) cannot be reached using our fabrication method due to stiction. Critical point drying would be advantageous to completely eliminate the capillary forces and to reach an optimum design. In this case, however, a more accurate model is needed to keep into account the effects of strain and techniques to control buckling should be implemented [43]. To be on the safe side, conservative values of $t = 180$ nm and $z_0 = 240$ nm have been chosen for InP devices and $t = 160$ nm and $z_0 = 200$ nm for GaAs (red boxes in Fig. 7). These values provide a maximum tuning of 10–20 nm which is definitely enough for most CQED experiments.

After the supporting SiN has been removed the lower membrane is too stiff to be bent. The capillary pressure is usually much higher than the electrostatic pressure achievable with reverse biased p-i-n junctions. However the upper slab can be trenched and shaped to lower its stiffness (k_2), so that after release $k_1 \gg k_2 \simeq k_+$.

The largest impact on the stiffness k_2 is given by the fraction of boundary clamped to the bulk. For example a cantilever (one-side clamp) is much more flexible than a doubly-clamped bridge. It is possible to engineer the shape of the structures to achieve a range of stiffnesses per unit area k_2/S between 1 and 1000 Pa/nm. This range has been experimentally found to be safe for most structures. Nevertheless, statistically, it is still possible to find collapsed structures especially for stiffnesses below 100 Pa/nm.

IV. EXPERIMENTAL RESULTS

The devices have been fabricated and measured using InP and GaAs as substrates for the operation at 1550 nm and 1300 nm, respectively. The results have been reported in previous publications [44] and [45]. Here we summarize some of the main features of the devices and discuss some open issues related to both material systems. The geometrical device parameters, photonic crystal parameters and the corresponding tuning plots are listed in Table I.

Fig. 7. Contour map of the pull-in limited tuning of an L3/Y1 mode for (a) InGaAsP and (b) GaAs membranes. The labels on each curve indicate the total tuning in nanometers calculated using the effective index approximation. The curve $N_{EC} = 1$ (blue dashed line) is shown as a threshold below which stiction during fabrication may occur with high probability. The maximum theoretical tuning from (16) as a function of z_0 is also shown. The red box indicates a “safe” area in the parameter space used as a target in sample design.

A. InGaAsP/InP Devices

The sample has been grown by metal-organic chemical vapor deposition on an undoped (100) InP substrate. The material of the slab is the quaternary $\text{In}_{(1-x)}\text{Ga}_x\text{As}_y\text{P}_{(1-y)}$ ($x = 0.26$, $y = 0.57$, 1.25 μm bandgap) alloy whereas InP is used as a sacrificial material. We used a thickness of 180 nm for both membranes and a gap at rest $z_0 = 240$ nm according to the design in Section III. The contacts used are Ti/Au or Ti/Pt/Au deposited without annealing and both p-type and n-type contacts showed good ohmic behavior.

TABLE I
DEVICE PARAMETERS USED IN THE EXPERIMENTS

Material	Gap z_0	Thickness t	Spacing a	Radius r	Cavity Plot
InGaAsP	240 nm	180 nm	500 nm	155 nm	L3 Fig.8(a)
	240 nm	180 nm	530 nm	165 nm	H1 Fig.8(b)
GaAs	200 nm	160 nm	370 nm	115 nm	L3 Fig.8(c)

Fig. 8. (a) Photoluminescence of symmetric and antisymmetric modes of an L3 cavity on InGaAsP obtained sweeping the reverse DC bias. (b) Peak shift of a H1 dipole symmetric mode on InGaAsP. (c) Tuning of an anti-symmetric L3/Y1 mode on GaAs slotted bridges. The data is taken from [45].

Sheet resistances up to 10 k Ω /square have been measured by the transfer line method [46] for the 50 nm p-layer. The n-layer sheet resistance, on the other hand, is 200 Ω /square, much lower than p-doped InGaAsP due to the higher mobility of electrons. These values are in good agreement with the resistivity derived from the doping concentration ($n = p = 1 \cdot 10^{18}$ cm $^{-3}$) and the carrier mobility.

A room temperature micro-photoluminescence (μ PL) setup integrated with a probe station has been used to characterize the fabricated devices. The measurements are performed by acquiring PL spectra (integration time ~ 10 s) from each device without bias and then gradually increasing the input reverse bias voltage. Fig. 8a shows the PL spectra of an L3 cavity with lattice constant $a = 500$ nm and radius $r = 155$ nm as a function of the applied reverse bias. The presence of both symmetric and anti-symmetric modes and the fact that they tune in different directions (up to 4.5 nm) when the device is biased, clearly indicate the mechanical

origin of the tuning [44]. The zero-bias mode splitting energy is 14.1 meV (25.6 nm) from which a distance at rest of $z(U = 0V) = 310$ nm is calculated. The zero-voltage membrane spacing is much higher than the one expected from the design (240 nm). This can be explained from the residual strain which is sometimes observed on the released membranes. This is an issue which has been observed in most double-membrane MOEMS and which does not allow to predict the initial coupling strength and the wavelength of the modes. Techniques to control the buckling should therefore be investigated to improve the repeatability of devices [43]. The Q factor of both modes is not as high as expected from simulations. The lower Q (around 1500) is attributed to imperfections in the fabrication such as the damage due to CF $_4$ plasma during the removal of the SiN mask. A small degradation of the Q is observed (around 10%) as the bias is increased and it's most likely due to small fluctuations in the driving electronics. The electrostatic actuation is limited, in this device, by the breakdown of the p-i-n junction under reverse bias. The breakdown voltage varies significantly across the wafer due to fabrication imperfections and different actuator geometries. In devices where breakdown occurs at higher voltages we have observed a larger wavelength tuning. Fig. 8b shows 10 nm tuning of the dipole mode (symmetric, red-shifting) of a H1 (one hole missing, $a = 530$ nm, fill factor 35 %) cavity when the reverse DC bias is increased in small steps up to 5.8 V. At higher voltages, the pull-in effect occurs and the cavity mode disappears due to collapse of the membranes. Again, the theoretical tuning values discussed in section III have not been reached due to buckling effects which shift the distance at rest to much higher values.

Additional proofs of the mechanical origin of the tuning, such as the pull-in phenomenon and mechanical resonances under a sinusoidal drive, have been also observed [44].

B. GaAs Devices

GaAs has been adopted mainly due to the fact that single InAs QDs in this system have been widely studied and well characterized in the past [47]. Moreover single photon sources and spontaneous emission enhancement at telecommunication wavelengths based on self-assembled InAs QDs embedded in GaAs have been already demonstrated [48]–[50]. The samples have been grown by molecular beam epitaxy using AlGaAs (70%) as sacrificial material. Compared to InGaAsP devices, the diode presents a much more ideal characteristic, probably due to the fact that Zn (the p-dopant used for quaternary alloys) diffuses much more easily in the sacrificial layers than Be (p-dopant used for GaAs). Ti/Au on n-doped GaAs forms Schottky barriers as verified by transfer line method measurements. However the operation of the device at room and low temperatures is not affected and forward currents are still measurable (up to several hundreds of μ A at 1.5V) [45]. As we do not operate in forward bias we did not further optimize the Schottky contacts. Ohmic contacts may be necessary when investigating the dynamic properties of the device, as the p-i-n junction using our contact layers cannot be driven faster than few hundred Hz due to charging effects.

Fig. 9. (a) Ratio between the symmetric and anti-symmetric power emitted by a L3/Y1 mode (see fig. 4). The total power P_{TOT} and the powers collected above $P_{\uparrow}$ and below $P_{\downarrow}$ the membranes are plotted as a function of the thickness asymmetry. The sketches indicate the two membranes, their thickness and the position of the QDs (dotted line). (b–c) Time-averaged power flow (in arbitrary units) normal to the surfaces located $1 \mu\text{m}$ above and below the double membrane slabs for the (b) symmetric and (c) anti-symmetric L3/Y1 mode. The upper membrane is 155-nm-thick whereas the lower one is 165-nm-thick. A clear asymmetry in the near-field emission is observed.

L3 cavities have been fabricated on stiffer cavities as compared to the InP case. A smaller area is used ($11 \times 11 \mu\text{m}^2$) and slotted bridges have been adopted instead of cantilevers. This allowed us to design cavities with accurate resonant wavelengths as a result of the reduced buckling effects. Fig. 4 compares the L3 spectrum of a GaAs cavity to the simulated one. Each peak is clearly recognizable and almost every mode can be identified.

The anti-symmetric mode, which is here brighter than the symmetric one, has been used to control the spontaneous emission lifetime of single QDs by controlling the wavelength detuning up to 13 nm (not limited by pull-in and in good agreement with the theoretical values of Fig. 7b) [45]. The wavelength tuning of such a mode, is shown in Fig. 8c. Moreover, no evident change of Q as a function of the applied voltage has been observed. The use of an anti-symmetric mode is, in general, unfavorable as it normally provides lower Q compared to the symmetric mode. On the other hand anti-symmetric modes lie into both symmetric and anti-symmetric bandgaps, making the determination of spontaneous emission enhancement easier.

V. EFFECT OF ASYMMETRY IN THE MEMBRANES' THICKNESS

All experiments involving the measurement of μPL spectra from double membranes have shown a large imbalance between the emission originating from symmetric and anti-symmetric modes. Since the QDs are located to a good approximation in the middle of the upper cavity, an equal dot-mode coupling is expected for both modes as their profile has a maximum at the membranes' center. As calculated from FE simulations, the spontaneous emission rate is typically higher for the symmetric than for the anti-symmetric modes in perfect double membranes due to the difference in Q factor (Fig. 2b). This is in contrast with the results obtained on GaAs, where the symmetric mode is just barely visible and the anti-symmetric mode is highly enhanced. Moreover no significant

difference between the symmetric and anti-symmetric angular emission has been found theoretically which could justify a better collection of one of the two modes by the μPL objective (numerical aperture 0.4).

The origin of the imbalance should thus be ascribed to a lack of symmetry in the double membrane itself. If one of the two slabs is slightly thinner than the other, the double membrane can still be treated as a coupled system but with asymmetric vertical profiles [51]. The symmetric (asymmetric) mode tends to localize on the thicker (thinner) membrane. It is therefore expected that, if the dots are located on the thinner membrane, they will couple better to asymmetric modes and vice versa.

To verify this assumption a full 3D FE simulation of the GaAs double membrane is carried out, using symmetry planes on the $x = 0$ and $y = 0$ planes only. An L3 cavity is used with a reduced number of holes around it to reduce memory requirements yet keeping sufficiently high in-plane Q. In the following, the quantities referring to the upper part (i.e. on the objective side) are indicated with the symbol $\uparrow$ whereas those referring to the bottom part (the substrate) are denoted with $\downarrow$. Only the Y1 mode is considered.

The asymmetry is introduced varying the thickness of one of the membranes keeping the inter-membrane distance ($z_0 = 200 \text{ nm}$) and the sum of the two thicknesses ($t_{\uparrow} + t_{\downarrow} = 320 \text{ nm}$) fixed. The normalized powers are calculated as explained in Sec. III at the peak wavelength (obtained with an adaptive step algorithm). Additionally, the power radiating through the top face $P_{\uparrow}$ and the one through the bottom face $P_{\downarrow}$ of the computational domain have been extracted from simulations to distinguish possible asymmetries in the emission direction.

Fig. 9a shows the ratio between the symmetric and anti-symmetric peak powers as a function of the thickness difference $t_{\downarrow} - t_{\uparrow}$. When the membranes have equal thickness, the total power (equivalent to the relative LDOS) is higher for the symmetric mode. Moreover, as the two modes radiate equally towards the top and the bottom, the power ratios collected from the top and the bottom are the same as the ratio of

the total power. As the thickness of the upper membrane is reduced, (right side of fig. 9a) the source couples better to the anti-symmetric mode and the total power ratio P_{TOT} (blue circles) decreases. The ratio between the powers collected above the membranes $P_{\uparrow}$ (green upward-pointing triangles) also reduces but at a higher rate as compared to the total power. The anti-symmetric mode thus not only couples better to the thinner membrane, but it also radiates mostly towards the top surface, where the objective is located. The reason of this higher intensity asymmetry stems most probably from interference effects which affect the coupling to the free-space radiating modes [24].

Fig. 9b and 9c show the out-flowing power through planes located $1 \mu\text{m}$ above and below the membranes for the symmetric and anti-symmetric modes, respectively, in the case where the upper membrane is 10 nm thinner than the lower one. A clear imbalance in the power emission is visible. From this simulation a rule can be extracted which states that the symmetric modes tend to radiate mostly in the direction of the thicker membranes and vice-versa.

The simulated data allow us to give an interpretation to the spectrum of Fig. 4. The upper membrane is probably thinner than the lower membrane (by few tens of nanometers) enhancing the emission of anti-symmetric modes. We attribute this thickness difference to the poor selectivity of CF_4 plasma to GaAs. This is not observed on the InP spectra (fig. 8), where the symmetric mode intensity is approximately 5 times higher, suggesting that the membranes have a better symmetry.

This result clearly shows that the simultaneous visibility of the two modes is strictly related to the quality of the epitaxial growth and fabrication. Asymmetric membranes also limit the total tunability of the modes as the influence of the thinner membrane is reduced. However, if the asymmetry is small, the far-field of one mode can be engineered to preferentially emit in one direction instead of the other, keeping a reasonable tuning range. In this way an enhancement of collection can be obtained also compared to single membrane cavities, which necessarily emit equally in both directions.

VI. CONCLUSION

In this article, the design and fabrication of a nanophotonic device for the electromechanical wavelength tuning of PCC resonances has been discussed. III/V micromechanical devices, photonic bandgap structures and semiconductor QDs have been successfully combined together to form a prototype of a micro-opto-electromechanical cavity quantum electrodynamics system. Free-standing membranes have been realized without resorting to supercritical drying. The fabrication limits due to stiction are taken into account using the theory of adhesion under capillary forces. A “safe” design rule which maximizes the pull-in limited tuning range has been defined. A maximum tuning range of 13 nm has been demonstrated on GaAs, limited by pull-in. The use of more ambitious designs, together with supercritical drying, should allow reaching a tuning range above 20 nm, corresponding to the wavelength distribution of self-assembled QDs. Finally, the effect of asymmetry in the membranes’ thickness is discussed. It explains why symmetric

modes are often less visible than anti-symmetric modes in photoluminescence experiments: the asymmetry changes the coupling of the two modes in the QD layer and to the far field, enhancing or inhibiting the emission towards the objective.

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REFERENCES

- [1] A. J. Shields, “Semiconductor quantum light sources,” *Nature Photon.*, vol. 1, no. 4, pp. 215–223, 2007.
- [2] B. Wild, R. Ferrini, R. Houdré, M. Mulot, S. Anand, and C. J. M. Smith, “Temperature tuning of the optical properties of planar photonic crystal microcavities,” *Appl. Phys. Lett.*, vol. 84, no. 6, p. 846, 2004.
- [3] A. Faraon and J. Vučković, “Local temperature control of photonic crystal devices via micron-scale electrical heaters,” *Appl. Phys. Lett.*, vol. 95, no. 4, p. 043102, 2009.
- [4] F. Intonti *et al.*, “Tuning of photonic crystal cavities by controlled removal of locally infiltrated water,” *Appl. Phys. Lett.*, vol. 95, no. 17, p. 173112, 2009.
- [5] S. Mosor *et al.*, “Scanning a photonic crystal slab nanocavity by condensation of xenon,” *Appl. Phys. Lett.*, vol. 87, no. 14, p. 141105, 2005.
- [6] F. Raineri *et al.*, “Tuning a two-dimensional photonic crystal resonance via optical carrier injection,” *Opt. Lett.*, vol. 30, no. 1, pp. 64–66, 2005.
- [7] Y. Tanaka, J. Upham, T. Nagashima, T. Sugiyama, T. Asano, and S. Noda, “Dynamic control of the Q factor in a photonic crystal nanocavity,” *Nature Mater.*, vol. 6, no. 11, pp. 862–867, 2007.
- [8] I. Fushman, E. Waks, D. Englund, N. Stoltz, P. Petroff, and J. Vuckovic, “Ultrafast nonlinear optical tuning of photonic crystal cavities,” *Appl. Phys. Lett.*, vol. 90, no. 9, p. 091118, 2007.
- [9] T. Tanabe, M. Notomi, H. Taniyama, and E. Kuramochi, “Dynamic release of trapped light from an ultrahigh-Q nanocavity via adiabatic frequency tuning,” *Phys. Rev. Lett.*, vol. 102, no. 4, p. 043907, 2009.
- [10] G. Ctistis *et al.*, “Ultimate fast optical switching of a planar microcavity in the telecom wavelength range,” *Appl. Phys. Lett.*, vol. 98, no. 16, p. 161114, 2011.
- [11] I. Märki, M. Salt, and H. P. Herzig, “Tuning the resonance of a photonic crystal microcavity with an AFM probe,” *Opt. Exp.*, vol. 14, no. 7, pp. 2969–2978, 2006.
- [12] S. Mujumdar, A. Koenderink, R. Wuest, and V. Sandoghdar, “Nano-optomechanical characterization and manipulation of photonic crystals,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 2, pp. 253–261, Mar. 2007.
- [13] F. Intonti *et al.*, “Spectral tuning and near-field imaging of photonic crystal microcavities,” *Phys. Rev. B*, vol. 78, no. 4, p. 041401, 2008.
- [14] M.-K. Kim, I.-K. Hwang, M.-K. Seo, and Y.-H. Lee, “Reconfigurable microfiber-coupled photonic crystal resonator,” *Opt. Exp.*, vol. 15, no. 25, pp. 17241–17247, 2007.
- [15] R. Perahia, J. D. Cohen, S. Meenehan, T. P. M. Alegre, and O. Painter, “Electrostatically tunable optomechanical ‘zipper’ cavity laser,” *Appl. Phys. Lett.*, vol. 97, no. 19, pp. 191112-1–191112-3, 2010.
- [16] I. W. Frank, P. B. Deotare, M. W. McCutcheon, and M. Loncar, “Programmable photonic crystal nanobeam cavities,” *Opt. Exp.*, vol. 18, no. 8, pp. 8705–8712, 2010.
- [17] M. Winger *et al.*, “A chip-scale integrated cavity-electro-optomechanics platform,” *Opt. Exp.*, vol. 19, no. 25, pp. 24905–24921, 2011.
- [18] L. Midolo *et al.*, “Electromechanical tuning of vertically-coupled photonic crystal nanobeams,” *Opt. Exp.*, vol. 20, no. 17, pp. 19255–19263, 2012.
- [19] M. Notomi, H. Taniyama, S. Mitsugi, and E. Kuramochi, “Optomechanical wavelength and energy conversion in high-Q double-layer cavities of photonic crystal slabs,” *Phys. Rev. Lett.*, vol. 97, no. 2, p. 023903, 2006.

- [20] C. Chang-Hasnain, "Tunable VCSEL," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 978–987, Dec. 2000.
- [21] H. Haus, W. Huang, S. Kawakami, and N. Whitaker, "Coupled-mode theory of optical waveguides," *J. Lightw. Technol.*, vol. 5, no. 1, pp. 16–23, Jan. 1987.
- [22] J. D. Joannopoulos, *Photonic Crystals: Molding the Flow of Light*, 2nd ed. New York, NY, USA: Princeton Univ. Press, 2008.
- [23] R. Syms and J. Cozens, *Optical Guided Waves and Devices*. New York, NY, USA: McGraw-Hill, 1992.
- [24] N. Le Thomas and R. Houdré, "Inhibited emission of electromagnetic modes confined in subwavelength cavities," *Phys. Rev. B*, vol. 84, no. 3, p. 035320, 2011.
- [25] Y. Akahane, T. Asano, B.-S. Song, and S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," *Nature*, vol. 425, no. 6961, pp. 944–947, 2003.
- [26] R. Maboudian and R. T. Howe, "Critical review: Adhesion in surface micromechanical structures," *J. Vac. Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 15, no. 1, pp. 1–20, 1997.
- [27] P. Lodahl and S. Stobbe, "Solid-state quantum optics with quantum dots in photonic nanostructures," *Nanophotonics*, vol. 2, no. 1, pp. 39–55, 2013.
- [28] Y. Xu, J. Vučković, R. K. Lee, O. J. Painter, A. Scherer, and A. Yariv, "Finite-difference time-domain calculation of spontaneous emission lifetime in a microcavity," *J. Opt. Soc. Amer. B*, vol. 16, no. 3, pp. 465–474, 1999.
- [29] *COMSOL Multiphysics 3.5a*, Comsol AB, Stockholm, Sweden, 2008.
- [30] A. R. A. Chalcraft *et al.*, "Mode structure of the L3 photonic crystal cavity," *Appl. Phys. Lett.*, vol. 90, no. 24, p. 241117, 2007.
- [31] C. Seassal, J. L. Leclercq, and P. Viktorovitch, "Fabrication of InP-based freestanding microstructures by selective surface micromachining," *J. Micromech. Microeng.*, vol. 6, no. 2, p. 261, 1996.
- [32] J.-L. Leclercq, M. Garrigues, X. Letartre, C. Seassal, and P. Viktorovitch, "InP-based MOEMS and related topics," *J. Micromech. Microeng.*, vol. 10, no. 2, p. 287, 2000.
- [33] K. Srinivasan, P. E. Barclay, O. Painter, J. Chen, and A. Y. Cho, "Fabrication of high-quality-factor photonic crystal microcavities in InAsP/InGaAsP membranes," *J. Vac. Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 22, no. 3, p. 875, 2004.
- [34] G. C. DeSalvo, W. F. Tseng, and J. Comas, "Etch rates and selectivities of citric acid/hydrogen peroxide on GaAs $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, and InP," *J. Electrochem. Soc.*, vol. 139, no. 3, p. 831, 1992.
- [35] J.-H. Kim, D. H. Lim, and G. M. Yang, "Selective etching of AlGaAs/GaAs structures using the solutions of citric acid/ H_2O_2 and de-ionized H_2O /buffered oxide etch," *J. Vac. Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 16, no. 2, pp. 558–560, 1998.
- [36] R. Braive *et al.*, "Inductively coupled plasma etching of GaAs suspended photonic crystal cavities," *J. Vac. Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 27, no. 4, pp. 1909–1914, 2009.
- [37] F. Fiedler, A. Schlachetzki, and G. Klein, "Material-selective etching of InP and an InGaAsP alloy," *J. Mater. Sci.*, vol. 17, no. 10, p. 2911, 1982.
- [38] X. Sun *et al.*, "Selective wet etching of $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer in concentrated HCl solution for peeling off GaAs microtips," *Solid-State Electron.*, vol. 53, no. 9, pp. 1032–1035, 2009.
- [39] M. Francardi *et al.*, "Quantum dot photonic crystal nanocavities at 1300 nm for telecom-wavelength single-photon sources," *Phys. Status Solidi (c)*, vol. 13, no. 11, pp. 3693–3696, 2006.
- [40] G. L. Weibel and C. K. Ober, "An overview of supercritical CO_2 applications in microelectronics processing," *Microelectron. Eng.*, vol. 65, nos. 1–2, pp. 145–152, 2003.
- [41] D. Kobayashi, C.-J. Kim, and H. Fujita, "Photoresist-assisted release of movable microstructures," *Jpn. J. Appl. Phys.*, vol. 32, no. 11A, pp. L1642–L1644, 1993.
- [42] C. Mastrangelo and C. Hsu, "Mechanical stability and adhesion of microstructures under capillary forces. I. Basic theory," *J. Microelectromech. Syst.*, vol. 2, no. 1, pp. 33–43, 1993.
- [43] E. Iwase *et al.*, "Control of buckling in large micromembranes using engineered support structures," *J. Micromech. Microeng.*, vol. 22, no. 6, p. 065028, 2012.
- [44] L. Midolo, P. J. van Veldhoven, M. A. Dündar, R. Nötzel, and A. Fiore, "Electromechanical wavelength tuning of double-membrane photonic crystal cavities," *Appl. Phys. Lett.*, vol. 98, no. 21, p. 211120, 2011.
- [45] L. Midolo *et al.*, "Spontaneous emission control of single quantum dots by electromechanical tuning of a photonic crystal cavity," *Appl. Phys. Lett.*, vol. 101, no. 9, p. 091106, 2012.
- [46] G. Reeves and H. Harrison, "Obtaining the specific contact resistance from transmission line model measurements," *IEEE Electron Device Lett.*, vol. 3, no. 5, pp. 111–113, May 1982.
- [47] B. Alloing *et al.*, "Growth and characterization of single quantum dots emitting at 1300 nm," *Appl. Phys. Lett.*, vol. 86, no. 10, p. 101908, 2005.
- [48] C. Zinoni *et al.*, "Time-resolved and antibunching experiments on single quantum dots at 1300 nm," *Appl. Phys. Lett.*, vol. 88, no. 13, pp. 131102-1–131102-3, 2006.
- [49] L. Balet *et al.*, "Enhanced spontaneous emission rate from single InAs quantum dots in a photonic crystal nanocavity at telecom wavelengths," *Appl. Phys. Lett.*, vol. 91, no. 12, p. 123115, 2007.
- [50] T. B. Hoang *et al.*, "Widely tunable, efficient on-chip single photon sources at telecommunication wavelengths," *Opt. Exp.*, vol. 20, no. 19, pp. 21758–21765, 2012.
- [51] H. Chang and J.-M. Jeong, "A modified coupled-mode analysis for asymmetric coupled waveguides," *Microw. Opt. Technol. Lett.*, vol. 13, no. 5, pp. 277–280, 1996.

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