Monolithic integration of self-aligned nanoisland laser with shifted-air-hole waveguide

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Abstract: We report a novel scheme for monolithic integration of a nanoisland laser with a shifted-air-hole waveguide by employing selective etching techniques. An active L3 laser cavity and passive shifted-air-hole waveguide are simultaneously formed through a single fabrication step. In the shifted-air-hole waveguide, the air-hole position is adjusted to be compatible with selective etching. The spectral overlap between the L3 laser resonance and guided mode is achieved by introducing small air holes at the nodes of the shifted-air-hole waveguide. Experiments show that >60% of the light is coupled from the nanoisland laser to the end of the 12-μm-long waveguide.

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1. Introduction

In recent years, photonic integrated circuits have been intensively studied for big data communication. Light does not suffer from Joule losses even at high frequencies and data can be carried by many different wavelengths through a single transmission channel. However, optical communication requires a certain amount of energy to modulate a laser, which mainly relies on the size of the gain medium. The development of smaller lasers such as vertical-cavity surface-emitting lasers (VCSEL), has led to industrial applications in optical interconnects for rack-to-rack and board-to-board communications [1–3]. Furthermore, for chip-to-chip or on-chip communications, the advantages of light are yet to be addressed in a convincing manner. In order to implement a chip-scale optical communication that would require even smaller active medium to compete with electrical counterparts [4, 5], wavelength-scale quantum-well (QW) active region has been recently introduced [5, 14].

One of the challenges in the practical application of such smallest lasers for chip-scale optical communication is an efficient coupling of the laser output into passive waveguides. In standard processes, it is nontrivial to integrate both active and passive devices on a single III–V membrane, on which the active quantum-well (QW) layer covers a whole wafer non-selectively. For example, if the waveguide region of a photonic integrated circuit is filled with absorptive QWs, propagation losses become significant.

In order to overcome this issue, various studies have been performed, including a selective QW regrowth [5–9] and quantum well intermixing [10–12]. In these methods, active and passive regions are lithographically defined; the active QW exists only inside a laser cavity, and the waveguide region is made transparent by an epitaxial re-growth or band-gap engineering. However, when the device size becomes smaller, the whole process becomes more sensitive to fabrication imperfections.

Previously we reported photonic crystal (PhC) nanoisland lasers [13, 14] by employing selective QW etching processes [15]. In this case, the active medium is formed in a self-aligned manner without complex fabrication processes. However, the laser output was directed into the vertical free space. In order to apply this laser to planar photonic circuits, the output light from the nanoisland laser needs to be funneled into in-plane transparent waveguides.

In this study, we monolithically integrate PhC nanoisland lasers and transparent waveguides through a single selective QW etching step. The QW is self-aligned in the PhC cavity, while the adjacent air-hole-introduced waveguide simultaneously becomes a passive waveguide. For a compatibility with selective QW etching, we identified the waveguide requirements, and proposed a shifted-air-hole waveguide. A coupling efficiency larger than 60% is experimentally confirmed with a computational analysis.
2. Integrated device structure

The laser cavity–waveguide integrated structure is investigated using a standard wafer, which contains two InGaAsP QWs between a pair of 140-nm-thick InP slabs [13]. Selective QW etching techniques are employed to remove the QW material, except that in the middle of the laser resonator region [14]. For in-plane light extraction, a shifted-air-hole waveguide is connected with an L3 resonator. The interface of the two structures is represented as a yellow dotted line in Figs. 1(a) and 1(b). As illustrated in Fig. 1(a), in the vicinity of the laser cavity, an elongated rectangular QW remains unetched after the selective wet-etching process. The upper and lower InP slabs in all other regions, where the QW is completely removed, become free-standing with a thin air gap in-between them. However, in practice, these two free-standing slabs tend to stick together. In the region between the unetched QW and collapsed InP slabs, an air pocket is formed. The air pocket is outlined by the blue region; the black dotted line indicates the points where the InP slabs are attached [Fig. 1(a)].

![Fig. 1. (a) Schematic of the L3 resonator coupled with a shifted-air-hole waveguide. Even after a selective etching, the QW remains unetched in the resonator. An air pocket is formed around the QW, represented in blue. (b) Triangular air pocket is assumed. The upper and lower InP slabs stick together outside the air pocket region.](image)

2.1 L3 resonator

A PhC L3 cavity is employed as a laser resonator. The L3 cavity is formed in a triangular lattice \((a = 450 \text{ nm})\) of air holes (radius of 0.31\(a\)) with three missing air holes. The four air holes in each side of the L3 cavity are graded to reduce radiation losses [16, 17]. Through selective wet-etching processes, a QW nanoisland with a size of \(1,600 \times 150 \times 35 \text{ nm}^3\) is formed in a self-aligned manner. After the drying process, a triangular air pocket is naturally formed next to the QW [Fig. 2(a)]. The air pocket is approximated as a triangle with a floating length of \(L\), which is the distance from the end of the QW to the collapsed InP slabs. The total thicknesses of the nanoisland region and collapsed region are 315 nm and 280 nm, respectively.

Based on three-dimensional finite-difference time-domain (3D-FDTD) simulations, we focus on the 0th mode (1,551 nm) and 1st mode (1,528 nm) in the vicinity of the spectral region of interest. In the simulation, the refractive indices of InP and InGaAsP are 3.17 and 3.4, respectively. The influence of the air pocket size on the quality factor \((Q)\) and confinement factor \((\Gamma)\) are analyzed as a function of \(L\), as summarized in Fig. 2(a). In the graph, the \(Q\) of the resonant modes decrease at certain value of \(L\). Here optical loss increases due to the vertical scattering loss caused by the collapsing of InP slabs. The \(Q\) and \(\Gamma\) values of the 0th mode are higher than those of the 1st mode in all cases. When \(L = 520 \text{ nm}\), \(Q\) and
$\Gamma$ of the 0th mode are 207,000 and 1.6%, respectively, while those of the 1st mode are 14,700 and 1.4%, respectively. As shown in Figs. 2(b) and 2(c), the electric field intensity $|E|^2$ of the 0th mode overlaps well with the rectangular nanoisland region. Accordingly, we chose the 0th mode of the L3 cavity as the laser mode.

Fig. 2. (a) Quality factor $Q$ and confinement factor $\Gamma$ of the 0th and 1st modes as a function of $L$. (b) $|E|^2$ field profiles of the 0th- and 1st-order modes with $L = 520$ nm. The white rectangle represents the QW nanoisland. (c) $|E|^2$ field profile of the 0th mode in the XZ-plane.

2.2 Shifted-air-hole waveguide

In the beginning, a collapsed W1 waveguide (non-air-hole waveguide, NAW) is studied as a coupler of the L3 resonator. Once the selective chemical etching is properly preformed, the QW in the cavity region survives, while that in the PhC region is completely removed. However, the absorptive QW in the waveguide remains unetched, as the width is equal to that in the cavity. The unetched QW introduces a significant inter-band absorption, and attenuates the wave propagating in the waveguide, as illustrated in Fig. 3(a). Therefore, it is required to remove the QW in the waveguide region faster than that in the laser cavity.

Small air holes (radius $r_w$ of 0.15$a$) can be introduced at the center of the NAW, as shown in Fig. 3(b), leading to a structure referred to as central-air-hole waveguide (CAW). Through the additional small air holes in the middle of the waveguide, the liquid etchant finds additional routes to attack the target QW in the waveguide, and removes it faster than that in the cavity region. When the air holes are formed at anti-node positions, the whole dispersion curve tends to blue-shift, as shown in Fig. 3(d). This spectral shift introduces an unwanted spectral decoupling between the shifted guided mode and L3 cavity resonance.

In order to overcome this problem, we shift the center air holes ($r_w = 0.15a$) by half of the lattice constant, 0.5$a$, leading to a structure referred to as shifted-air-hole waveguide (SAW), as illustrated in Fig. 3(c). The 0.5$a$-shifted air hole overlaps with the node of the guided modes in the vicinity of the band edge. In other words, the additional small air holes are nearly invisible to the guided modes. Therefore, as one can notice in Figs. 3(d) and 3(e), the SAW cut-off frequency remains almost unaffected and similar with that of the NAW structure. The shift enables a comfortable spectral overlap between the L3 cavity resonance and propagating modes available in the SAW.
The proposed SAW has two advantages: insensitivity to fabrication errors and wider guiding bandwidth. The effect of the small air hole size is compared for \( r_w = 0a, 0.1a, 0.15a, \) and \( 0.2a \). Figure 4(a) reveals that the CAW cut-off frequency changes with the radius \( r_w \). In contrast, the SAW cut-off frequency is almost unaffected until the radius \( r_w \) becomes larger than \( 0.2a \) (see Fig. 4(b)), as the SAW air hole overlaps with the node of the guided mode. Therefore, the dispersion near the band edge is less sensitive to the air hole size and fabrication imperfections. The SAW dispersion for \( r_w = 0.15a \) is represented with the red curve, and its guiding bandwidth is outlined with the yellow rectangle. The SAW bandwidth is much broader than the CAW bandwidth. Note that the CAW dispersion blue shifts as a whole. In comparison, the SAW waveguide modes far away from the band edge shift more than those near the band edge where the wave vector is \( 0.5(ka/2\pi) \).

We set the lower and upper bounds of \( r_w \) to \( 0.1a \) and \( 0.2a \), respectively. When the air hole size \( r_w \) is larger than \( 0.2a \), the SAW cut-off frequency becomes too close to the L3 cavity resonance. If \( r_w \) is too small, more time is required to remove the QW in the waveguide, which imposes constraints on the size of the QW nanoisland. With the decrease of the width of the nanoisland, the total available gain decreases, and simultaneously, the surface recombination losses at the QW boundary increase. Experimentally, we are able to observe lasing signals until \( r_w = 0.1a \), where the remaining QW nanoisland’s width is \( \sim 100 \) nm. We
believe that the $r_w = 0.1a$ condition is close to the lower bound, which barely satisfies lasing threshold conditions. For practical reasons, we chose a value of $r_w = 0.15a$ owing to possible fabrication imperfections.

Fig. 4. Dispersion curves of the (a) CAW and (b) SAW with $r_w = 0a$, $0.1a$, $0.15a$, and $0.2a$. The green dashed line represents the resonant frequency of the 0th mode. The orange rectangular area indicates the guiding bandwidth, $r_w = 0.15a$. The $|E|^2$ profile of each waveguide mode at the cut-off frequency is obtained with $r_w = 0.15a$.

2.3 Waveguide-coupled cavity

A schematic of the coupled structure is shown in Fig. 5(a). The gray and darker gray areas represent the cavity and SAW, respectively. We refer to the air hole at the end of the cavity and that at the entrance of the SAW as the exit and entrance holes, respectively. The number of air holes between the nanoisland and exit hole is referred to as a separation $N$. For example, when $N = 4$, the exit hole radius is $0.31a$, and the separation between the exit and entrance holes becomes $0.04a$. Two adjacent holes tend to merge into one large hole after the completion of the fabrication processes. In order to overcome this issue, we reduce the radius of the exit hole from $0.31a$ to $0.15a$, equal to that of the entrance hole. In the design, the radius of the exit hole is fixed at $0.15a$, and the exit hole is placed $0.5a$ away from the entrance hole.

The coupling efficiency of the SAW-coupled cavity is investigated as a function of the separation $N$, as shown in Fig. 5(b). In the simulation, we collect total output power ($P_t$) with plane monitors which enclose the cavity-waveguide coupled structure. $P_t$ contains emitting power from the cavity ($P_v$) and propagating power through the waveguide ($P_w$). The coupling efficiency ($\eta$) is calculated by $P_w/P_t = Q_t/Q_w$, and $P_v/P_t = Q_v/Q_w$, respectively. In the graph, $1/Q_v$, $1/Q_w$, and $1/Q_t$ represent the cavity energy loss rates into the air, waveguide, and all space ($1/Q_t = 1/Q_w + 1/Q_v$), respectively. The loss rate into the waveguide $1/Q_w$ is proportional with the coupling strength between the cavity and SAW, and increases with $N$, as expected. However, the energy loss rate into the air ($1/Q_v$) remains almost unchanged. The stored energy flows mainly into the SAW (see Fig. 5(c)), where the coupling efficiency $\eta$ is computed to be >80%.
Fig. 5. (a) Design of the coupled device \((N = 4)\). (b) Quality factor and coupling efficiency as a function of \(N\). (c) Calculated log|\(E|^2\) field profiles for \(N = 1\) and 4.

3. Fabrication

PhC patterns are defined on PMMA using e-beam lithography followed by a Cl\(_2\)-assisted argon-ion-beam etching. A selective QW etching is performed at 4 °C with a mixture of H\(_3\)PO\(_4\), H\(_2\)O\(_2\), and H\(_2\)O, as briefly explained in Fig. 6(a). The liquid solution etches both InGaAsP QW and InGaAs sacrificial layer. During the etching process, the InGaAs layer is etched faster than the InP and InGaAsP QW, and a free-standing structure is obtained. The PMMA layer is then removed by O\(_2\)-plasma etching. The fabricated free-standing InP/InGaAsP structure is shown in Fig. 6(b). For an optical characterization, a vertical coupler is introduced at the end of the SAW to collect the light escaping from the horizontal waveguide [18]. The coupler is composed of a single ring floating in the air. The position and width of the ring are designed for an optimal light collection with an objective lens.

The boundary of the nanoisland (1,600 \(\times\) 150 nm\(^2\)) in the cavity appears fuzzy owing to weak secondary electrons originating from the 35-nm-thick QW through the 140-nm-thick upper InP slab. In order to enhance the visibility of the nanoisland boundary, the image is post-processed by adjusting contrast and brightness. As shown in Fig. 6(c), the typical QW shape becomes an elongated rectangle. In the tilted view in Fig. 6(d), an air gap can be observed. The unetched QW nanoisland prevents a collapse of the upper and lower InP slabs. Furthermore, at the second row of holes at the bottom, the two InP slabs are merged. The measured triangular floating length \(L\) is 480–560 nm. In the computational analysis, we set \(L\) to 520 nm, which is the medium value.
4. Optical characteristics

For the optical characterization, a 980-nm laser diode (pulse duration: 50 ns, duty: 5%) is used as a pump source. A 50 × objective lens (numerical aperture (NA) = 0.85) focuses the pump laser beams and simultaneously collects the laser output from the top. The emitted light is captured by an infrared charge-coupled device (CCD) and spectrometer.

For the CAW-coupled laser cavity, the light emerging directly from the cavity region is dominant, as shown in Fig. 7(a). In this case, a coupling into the CAW is spectrally forbidden, which is confirmed by independent Poynting vector (Pz) analyses. In contrast, when the laser cavity is coupled with the SAW, where the air holes are shifted by 0.5a, a bright emission is observed from the vertical coupler at the end. The calculated Pz exhibits a strong vertical scattering at the vertical coupler, as shown in Fig. 7(b).

The two laser outputs escaping vertically from the laser cavity (PC) and horizontally into the waveguide, and scattered at the vertical coupler (PVC), are measured as a function of the pump power for cavity–waveguide separations N of 1 and 4. The cavity–waveguide surface is imaged on the entrance slit of the spectrometer, which also functions as a spatial filter. In Fig. 7(c), the brightest vertical emission PVC is observed at the vertical coupler with a separation of N = 1. The lasing wavelength is 1,533 nm, while the absorbed threshold power is 8.5 μW. The inset, in Fig. 7(c), represents normalized spectrums which are measured at the incident power below and above the threshold, respectively. The output power from the cavity is measured with a power meter at the input slit of the spectrometer. At the incident peak pump power of 700 μW, 60 nW is measured (duty: 5%). For a larger separation N, PVC becomes weaker than PC, as shown in Fig. 7(d).

In order to estimate the absorbed power in the nanoisland, the spatial overlap between the pump beam and nanoisland is calculated. The diameter of the pump beam is 1.2 μm, while the lateral dimensions of the nanoisland are 1,600 nm × 150 nm. 20% of the total pump power is incident on the nanoisland region; 16% of the incident power is absorbed in the nanoisland (the absorption coefficient is 14,000 cm⁻¹ at 980 nm).
The effects of the cavity–waveguide separation \( N \) are investigated for five different samples. An isolated L3 cavity with \( N = \infty \) is included as a reference in Fig. 8. The laser threshold tends to decrease with the increase of the separation \( N \), as expected. For a comparison, a measured power ratio \( P_{VC}/P_C \) is defined at a fixed pump power of 0.44 mW, which is above the lasing threshold. Figure 8(b) shows that the power ratio increases with the decrease of the separation \( N \), as expected, and more photons flow into the SAW. In Fig. 8(b), the theoretical power ratios \( P_{TVC}/P_{TC} \), obtained by 3D-FDTD simulations, are represented with the connected black dots. The theoretical output lights captured above the cavity \( (I_C) \) and vertical coupler \( (I_{VC}) \) are illustrated in Fig. 8(c). In addition, far-field patterns above the cavity and vertical coupler are obtained to estimate the spatial collection efficiency \( (\eta_C, \eta_{VC}) \). The collection efficiency represents the power that incidents within the solid angle of the objective lens divided by the total power. We obtain the theoretical power ratio as \( P_{TVC}/P_{TC} = (I_{VC}/\eta_{VC})/(I_C/\eta_C) \). For a separation larger than 1, the measured power ratio is consistent with the theoretical power ratio. However, for a separation \( N = 1 \), the measured power ratios are smaller than the theoretical power ratio. The measured values imply increased vertical losses \( P_C \) in the vicinity of the low-\( Q \) cavity region. In our structure, the transition between the cavity and SAW waveguide is rather abrupt. The scattering losses become sensitive to the size and position of the holes. We believe that the fabrication imperfection at the connection part perturbed the evanescent tail of the resonant mode, which leads to the increased scattering losses into the air. These scattering losses are larger for \( N = 1 \), since the field of the resonant mode in the transition region is stronger than that of the larger \( N \).

The coupling efficiency \( \eta \) is estimated using the measured power ratio \( P_{VC}/P_C \). First, the coupling efficiency \( \eta \) is plotted as a function of the theoretical power ratio \( P_{TVC}/P_{TC} \) in Fig. 8(d), where the intermediate \( \eta \) values are linearly interpolated. Using the measured power ratio of 6.8, smaller than the theoretical value for \( N = 1 \), we estimate that the coupling efficiency \( \eta \) is in the range of 60–88%. In our cavity–waveguide coupled design, for
simplicity, the exit hole is fixed at $0.5a$ away from the entrance hole. This constraint could generate unwanted scattering losses at the junction. We believe that the coupling could be further improved through a position and size control of the exit hole.

Fig. 8. Measured (a) thresholds and (b) power ratios for 5 different samples. The infinity value of $N$ corresponds to a stand-alone cavity. The threshold represents the absorbed peak pump power. The theoretical power ratio is represented with the black curve. (c) Illustration of the theoretical power ratio employed in the 3D-FDTD simulation. (d) Coupling efficiency $\eta$ as a function of the theoretical power ratio. The red dashed line represents the expected $\eta$ when the measured power ratio is 6.8.

5. Conclusion

In summary, we monolithically integrated PhC nanoisland lasers and transparent waveguides through a single selective QW etching step. The active QW was self-aligned in the PhC cavity, while the adjacent waveguide with small central air holes simultaneously became a passive waveguide. We identified the waveguide requirements, and proposed the SAW structure, which was compatible with the selective QW etching technique. The unique design of the SAW, where central air holes were placed at the nodes, was robust against fabrication imperfections. In addition, the shifted air holes widened the bandwidth of available guided modes, and enabled a considerable spectral overlap with the laser resonance. A coupling efficiency larger than 60% was estimated by comparing the measured power ratio with the values obtained using FDTD simulations. The inherent self-aligning nature of the selective QW etching technique is expected to pave an alternative way for a cost-effective photonic integration.

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