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Low-loss silicon nitride Kerr-microresonators fabricated with metallic etch masks via metal lift-off

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Stoichiometric silicon nitride has emerged as a widely used integrated photonic material owing to its high index of refraction, nonlinear optical properties, and broad transparency window spanning visible to mid-IR frequencies. However, silicon nitride is generally more resistant to reactive ion etching than are typical etch masks made of polymer-based resist. This necessitates resist layers that are significantly thicker than the silicon nitride and results in mask patterns which are tall and narrow. These high-aspect-ratio patterns inhibit the plasma transport of reactive ion etching, which leads to difficulties in accurately reproducing dimensions and creating well-defined, vertical waveguide sidewalls. In this work, we overcome these challenges by developing a metallic etch mask deposited via metal lift-off that provides a 30 : 1 nitride-to-metal etch rate ratio, representing a near 45-fold reduction in the required mask thickness. We demonstrate the validity of this technique by etching microring resonators with near-vertical waveguide sidewalls and intrinsic quality factors of over 1 million. Leveraging the low optical loss of our resonators, we generate optical frequency combs with more than an octave of bandwidth and dual dispersive waves. These results establish metal lift-off as a viable and easy-to-implement technique capable of producing low optical loss waveguides.

Keywords Silicon nitride, Frequency combs, Photonic integrated circuits, Kerr-microresonators, Microfabrication, Etching

Developing photonic integrated circuits to replace tabletop optics analogs represents a compelling new direction in many sectors of scientific research, including next-generation timing and navigation^{1–3}, optical computation^{4–6}, and chip-scale quantum computers^{7–9}. Similar to the integrated circuit (IC) revolution of the 20th century, the past two decades have seen rapid innovation in photonic integrated circuits (PICs), often aided by existing IC fabrication expertise. However, unlike their electronic antecedents, bulk commercial availability of PICs is in its infancy¹⁰. In order to move this technology from the lab to the market, optical scientists and engineers often must adapt specialized processes developed in academic cleanrooms for the standard tools of IC- and MEMS-based commercial-scale foundries^{11,12}.

A good illustration of the difficulty of translating PIC fabrication to foundry processes is the on-chip waveguide. Waveguides are ubiquitous in PIC design as the main way of porting photons from device to device. Waveguides can also be formed into resonators^{13,14}, couplers and splitters¹⁵, dichroic elements^{16,17}, gratings^{18,19}, and electro-optic components²⁰. They are generally made of a material that is transparent within the spectrum of interest and are thus typically formed in dielectrics with large band gaps. A typical scheme for waveguide fabrication involves depositing a layer of photo- or electron resist on top of a layer of the dielectric, lithographically defining a pattern in the resist to serve as a protective mask, and removing the dielectric not protected by the mask through reactive ion etching (RIE)^{21–27}.

However, commonly used dielectrics such as silica (SiO₂), silicon nitride (Si₃N₄), aluminum nitride (AlN), and lithium niobate (LiNbO₃) are resistant to the physical and chemical etching of RIE. In fact, the ratio of the etching rate of the dielectric compared to that of the resist mask, the etch selectivity, is often less than 1 : 1²⁸. This creates challenges for fabrication, as the protective masks must be thicker than the dielectric to outlast the etching. These thick masks with tall, narrow features exhibit inhibited plasma transport and increased etch

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by-product redeposition as a function of feature size²⁹. This can lead to non-uniform etching rates between features of varying sizes, sidewalls with non-vertical and/or bowed profiles, and deviations in device dimensions from the intended design. For applications that require deterministic control of properties that depend on accurate geometries and dimensions, such as resonator dispersion and coupler efficiency, etch masks of thick resist represent a significant problem. These complications can be partially alleviated with harder, more resistant masks such as hydrogen silsesquioxane (HSQ)³⁰, but post-etch removal of HSQ necessitates the use of strong acids which may also etch the dielectric. An alternative approach consists of depositing Si_3N_4 into pre-etched SiO_2 trenches; this method is particularly suited to creating thick waveguides while avoiding tensile stress and cracking. However, the SiO_2 preform etching is still subtractive, and thus the problems of sloped sidewalls and inaccurate dimensions persist^{31,32}.

In this work, we develop a process for the subtractive fabrication of silicon nitride microring waveguides using a metal-lift-off-based mask and subsequent subtractive etching. Metal lift-off is a common MEMS process that can be found in most commercial foundries. Metal lift-off's suitability for patterning small features in a scalable manner makes it a particularly good candidate for patterning photonic etch masks^{33,34}. The metal mask in our work demonstrates improved etch selectivity of 30 : 1, allowing thin layers of metal to protect and template thick layers of silicon nitride. Our results show vertical sidewall angles, minimal RIE lag, and predictable etch dimensions. We optically characterize ring resonators to demonstrate reasonably low optical loss and good resonator quality factors. Furthermore, we investigate our leading sources of loss and identify paths towards improvement in the case when ultra-low loss is necessary. Finally, we demonstrate the viability of our process by generating optical frequency combs with more than an octave of bandwidth, as well as creating long-lived optical soliton states in our microring resonators.

Fabrication process

The waveguides under study are fabricated on chiplets cut from stoichiometric Si_3N_4 (hereafter SiN) deposited in-house on oxidized silicon wafers. The SiN layer is deposited on top of 3 μm of SiO_2 via low-pressure chemical vapor deposition (LPCVD) in a two-stage deposition process for a total thickness of 620 nm.

The full fabrication flow from unpatterned SiN chiplet to final optical device is illustrated in Fig. 1. We start with electron-beam lithography (EBL) using a JEOL JBX6300-FS to write the negative of our waveguide design in a layer ma-N 2403 negative-tone EBL resist. The inherent polymer cross-linking in developed negative-tone resist provides relatively high resistance to thermal deformation during metal deposition (Fig. 1c), while still remaining soluble during lift-off (Fig. 1d)³⁶. A 50 nm blanket layer of chromium (Cr) is deposited over top of the developed pattern via electron-beam physical vapor deposition (EBPVD) for a 5 : 1 resist-to-metal ratio. Lift-off is achieved with a 12-hour soak in *N*-Methyl-2-pyrrolidone (NMP) followed by an acetone and isopropyl alcohol (IPA) rinse. After lift-off, etching is performed using an inductively coupled plasma-reactive ion etch (ICP-RIE) tool (PlasmaTherm SLR) with a $\text{CF}_4/\text{O}_2/\text{Ar}$ chemistry. We achieve a SiN etch rate of about 210 nm/min compared to an etch rate of about 7 nm/min for Cr, for an estimated etch selectivity of 30 : 1. Following the etch, the remaining chromium mask is removed in a wet chromium etchant (CR-7). In order to facilitate edge-on optical coupling to the bus waveguides, a final etch is performed through the edges of the sample to form the coupling facets.

The SEM micrographs in Fig. 2 show a typical microring resonator fabricated with our metallic mask process. The left panel of Fig. 2a shows a top-down view of the devices under study which consist of a 46.6 μm diameter ring resonator and coupling (or “bus”) waveguide etched in 620 nm of SiN. The right panel of Fig. 2a shows a higher magnification view of the coupling region where light evanescently couples across a small air gap into- and out-of- the ring. Fig. 2b shows an angled view looking through this coupling region in order to highlight the clean and uniform etching of the small coupling gap (roughly 400 nm wide for the device shown). Some sidewall roughness, presumably transferred from the metallic mask during the etch, is evident in the ring sidewall in Fig. 2c. The thin chromium mask results in near-vertical waveguide sidewall angles as shown in the cleaved cross section of the bus waveguide in Fig. 2d.

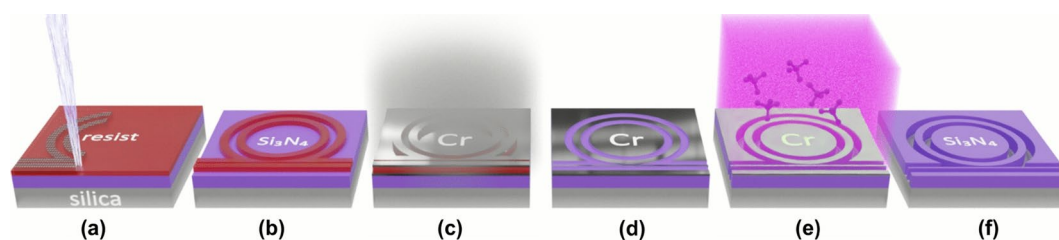


Fig. 1. Illustration of the process for fabricating waveguides using metal lift-off. **(a)** Electron-beam lithography (EBL). The process begins by coating the SiN sample with resist and writing the inverse pattern using EBL. **(b)** Resist development. After developing the patterned resist, the exposed (negative-tone) resist is left behind. **(c)** Metal deposition. A uniform layer of metal is deposited on the surface via electron beam evaporation. **(d)** Metal lift-off. A solvent soak/rinse removes the resist and overlaying metal to leave behind a protective etch mask. **(e)** ICP-RIE etching. The etch mask pattern is transferred to the SiN. **(f)** Mask removal. The final device is a SiN microring resonator with evanescent coupling to a bus waveguide. (CF_4 crystal structure in **(e)** is modified from PubChem database³⁵).

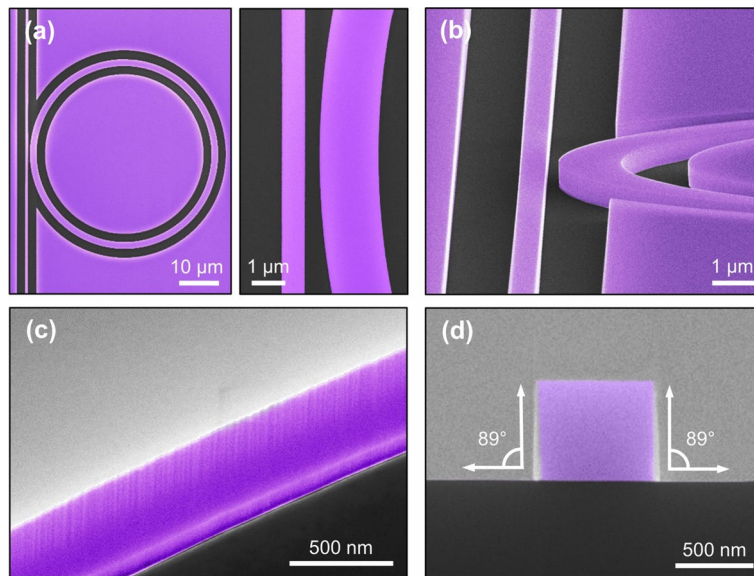


Fig. 2. SEM micrographs of etched waveguides with false coloring of SiN (purple) and SiO₂ (dark gray). **(a)** Top-down view of a microring resonator and bus waveguide (left) with zoomed in view of coupling gap region (right). **(b)** Angled view looking through the coupling region. **(c)** High magnification SEM of etched ring resonator sidewall roughness and remaining Cr mask overtop (silver). **(d)** Cleaved cross section of the coupling waveguide showing near-vertical sidewall angles. (Charging during SEM imaging adds some uncertainty to our angle measurement.).

Optical loss

Optical losses in photonic waveguides, specifically propagation losses, are classified into two sub-groups. First is loss due to optical absorption of the propagating photons by the waveguide material. SiN deposition by LPCVD produces films with residual N-H bonds, which increase absorptive losses in the telecom C-band. We minimize absorption due to N-H bonds with a high-temperature post-deposition anneal²⁵. The second type of propagation loss is connected to waveguide geometry and includes scattering at the core/cladding interface (sidewall scattering) and reduction of total internal reflection due to tight bending. These two effects are linked, as a tighter waveguide bending radius will cause increased overlap between the optical mode and the sidewall, enhancing sidewall scattering. Loss due to sidewall scattering is commonly attributed to fabrication-induced roughness, often originating from an uneven etch mask edge. In our work, the smoothness of the etch mask is primarily determined by two process steps, e-beam lithography and metal deposition/lift-off. Pattern roughness in electron-beam lithography is related to the pixelation of the pattern to the machine's grid. Both the diameter of the electron beam (controlled by the beam current) and the pixel separation (shot pitch) can influence the roughness of the resist sidewall based on the degree of overlap. Since the resist serves as the template for metal deposition, this roughness can be transferred to the metal mask edge. The metal mask may acquire additional roughness based on the details of the EBPVD step, including the chamber base pressure and the evaporation rate of the metal.

In order to investigate the optical losses induced by our process, we pattern a series of waveguide-coupled microring resonators and directly measure the optical quality (Q) factor of the resonance modes. The Q factor is defined in terms of the the optical loss according to

$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}} = \frac{\nu_o}{\Delta\nu_{\text{FWHM}}}, \quad (1)$$

where ν_o is the center frequency and $\Delta\nu_{\text{FWHM}}$ is the full-width-at-half-maximum (FWHM) of the resonance³⁷. While our resonators are capable of supporting either transverse-electric (TE) or transverse-magnetic (TM) spatial modes, we choose to characterize the fundamental TE modes (TE₀₀) whose electric field lie in the plane of the ring resonator and whose intensity more strongly samples the sidewall. Optical measurement of Q is performed via a laser frequency sweep across many TE modes of the resonators (see Section I of the Supplementary Information and Supplementary Fig. S1a for details). To do this, we use a tunable continuous wave (CW) external cavity diode laser to probe the resonance modes between 1510 and 1630 nm. The FWHM of the resonance is converted to frequency with a calibrated Mach-Zehnder interferometer (MZI).

The total, or loaded, quality factor as described in equation (1) captures the optical energy loss per cycle due to a variety of contributions that we broadly classify as out-of-resonator/external (such as the bus-to-resonator coupling) and intrinsic (such as intra-resonator absorption and scattering). In the weak coupling regime, the total, or loaded, quality factor can be separated into the external and intrinsic loss contributions:

$$Q_{\text{loaded}} = \left[\frac{1}{Q_{\text{ext}}} + \frac{1}{Q_{\text{int}}} \right]^{-1}, \quad (2)$$

where Q_{ext} and Q_{int} are the external and intrinsic quality factors, respectively³⁸. We can extract Q_{int} from our measurement of Q_{loaded} :

$$Q_{\text{int}} = \frac{2 Q_{\text{loaded}}}{1 - \sqrt{T}} \quad (\text{overcoupled}) \quad \text{or} \quad Q_{\text{int}} = \frac{2 Q_{\text{loaded}}}{1 + \sqrt{T}} \quad (\text{undercoupled}), \quad (3)$$

where T is the measured transmission on resonance³⁹. We determine whether a device is overcoupled ($Q_{\text{int}} > Q_{\text{ext}}$) or undercoupled ($Q_{\text{int}} < Q_{\text{ext}}$) by investigating a range of bus-to-resonator gaps and determining where the transmission goes to zero (“critical” coupling, where $Q_{\text{int}} = Q_{\text{ext}} = 2 Q_{\text{loaded}}$). Q_{ext} can then be determined from equation (2). (The derivation of equations (3) is described in further detail in Section I of the Supplementary Information.)

Results

Quality factors

Figure 3 demonstrates the intrinsic optical loss of typical resonators fabricated with our metal lift-off process. We fabricate a series of four waveguide-coupled resonators with sequentially increasing bus-to-ring coupling gaps between 300 and 700 nm on a single chiplet. For enhanced mode sampling of the sidewall, resonators are designed with a small radius of 23.3 μm corresponding to a free spectral range of 1 THz. The resist layer was patterned with a 0.2 nA beam current (~ 5.8 nm beam diameter) and a shot pitch of 2 nm (the smallest our machine will allow). The metal layer was deposited with an evaporation rate of 0.3 $\text{\AA}/\text{s}$ and a chamber base pressure of $4\text{E}-7$ Torr. In Fig. 3a, we show Q_{loaded} as a function of the bus-to-ring coupling gap for both single peak (singlet) and split (doublet) fundamental TE resonance modes. (More details of this measurement and example resonance lineshapes are included in Supplementary Fig. S1b and c.) By identifying the critical coupling point from the measured transmission vs. coupling gap in Fig. 3b and applying the appropriate form of equation (3), we calculate Q_{int} and Q_{ext} in Fig. 3c. While Q_{ext} increases with gap, we expect Q_{int} to remain relatively constant, independent of coupling gap. We find $\langle Q_{\text{int}} \rangle = 900\text{k} \pm 70\text{k}$ with a standard deviation of 290k for the 19 singlet modes measured. In determining average Q_{int} , we exclude the doublet modes from our calculation but consider the implications of their presence and measured splitting in the next section.

We next consider the possible effect of the EBL parameters on the optical quality factor by fabricating the same series of rings, but with varying beam current and shot pitch. The results in Fig. 4a and b show the effect of increasing the shot pitch from 2 nm (Fig. 3 results) to 6 and 8 nm with a common 0.2 nA beam current. The resonances in the 6 nm shot pitch devices yield $\langle Q_{\text{int}} \rangle = 1.10\text{M} \pm 70\text{k}$ with a standard deviation of 250k, while the 8 nm shot pitch devices show a slightly lower $\langle Q_{\text{int}} \rangle = 920\text{k} \pm 60\text{k}$ with a standard deviation of 250k; we consider both of these consistent with $\langle Q_{\text{int}} \rangle = 900\text{k} \pm 70\text{k}$ for the 2 nm shot pitch devices. To remove any ambiguity, we only report singlet modes without discernible doublet splitting.

We further explore the effect of shot pitch for a given beam size in Fig. 4c and d by increasing beam current to 1.0 nA, giving an increased beam diameter of ~ 7.5 nm. At 1.0 nA, using a 6 nm shot pitch yields $\langle Q_{\text{int}} \rangle = 1.0\text{M} \pm 0.1\text{M}$ with a standard deviation of 500k, while increasing the shot pitch to 8 and 12 nm results in $\langle Q_{\text{int}} \rangle = 710\text{k} \pm 90\text{k}$ (standard deviation of 370k) and $\langle Q_{\text{int}} \rangle = 980\text{k} \pm 50\text{k}$ (standard deviation of 230k), respectively. We do not see evidence that the coarser shot pitch (and the significant difference between shot pitch and beam diameter for the 1.0 nA, 12 nm sample) leads to more sidewall loss. (There is a slight but potentially significant reduction in Q for the intermediate 8 nm shot pitch. However, this significance is small, and this data set is dominated by measurements in the smallest gap devices, where the coupling gap was measured to be close to the minimum writeable critical dimension. Additionally, the intrinsic Q of overcoupled resonators can display larger variance due to a variation in measured transmission than larger gap devices; see Supplementary Section I, Supplementary Fig. S2, and Supplementary Table S1 for a detailed explanation of this effect. Due to this and due to the lack of a monotonic trend with shot pitch, we tentatively report the average

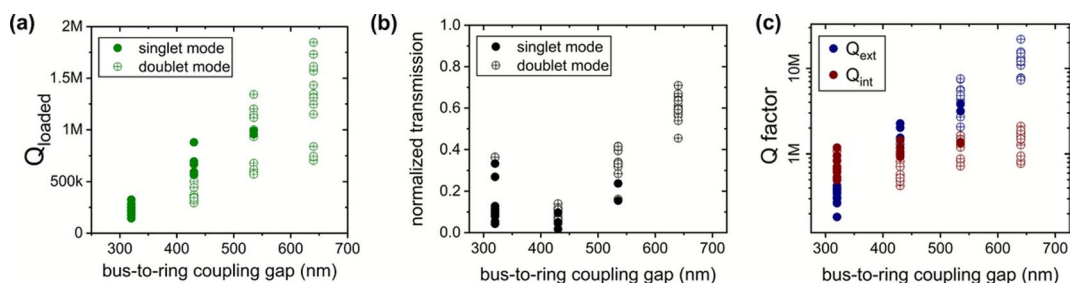


Fig. 3. Extracting optical quality factors for our resonators. (a) Loaded quality factor vs. coupling gap for resonance modes between 1510 and 1630 nm. Split modes (doublets) are indicated by open circles with crosses. (b) Measured on-resonance transmission vs. gap. (c) Q_{ext} and Q_{int} extracted from Q_{loaded} based on the coupling behavior in (b).

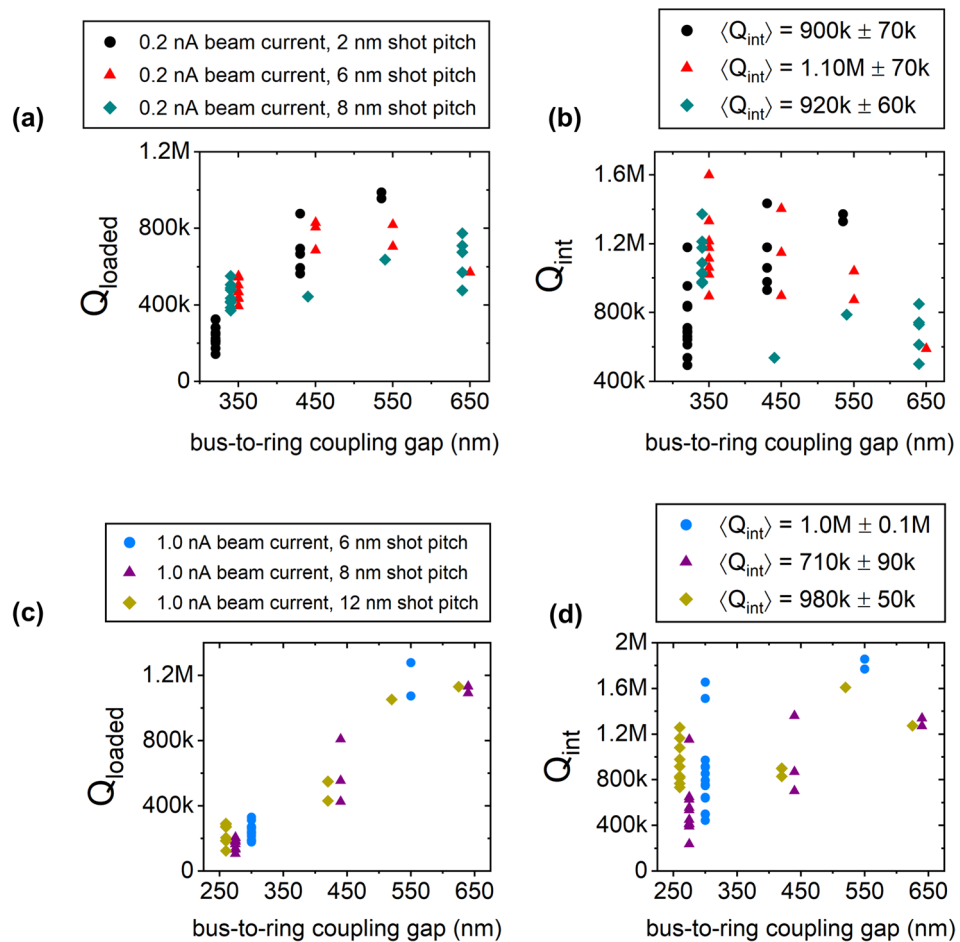


Fig. 4. (a) Loaded Q and (b) intrinsic Q vs. bus-to-ring coupling gap for resonance modes of rings patterned with 2, 6, and 8 nm shot pitches at 0.2 nA beam current. (c) Loaded Q and (d) intrinsic Q for 6 and 12 nm shot pitches at 1.0 nA beam current.

intrinsic loss to be similar for all three conditions.) As with the results at 0.2 nA, the overall trend at 1.0 nA suggests that increasing the shot pitch has little effect on the average Q.

We investigate the influence of beam current on optical loss by comparing the data in Fig. 5 for varying beam currents and common shot pitch. As seen in Fig. 5a and b for the 6 nm shot pitch, the 0.2 nA beam current results in $\langle Q_{\text{int}} \rangle = 1.10\text{M} \pm 70\text{k}$ (standard deviation of 250k) while the 1.0 nA produces $\langle Q_{\text{int}} \rangle = 1.0\text{M} \pm 0.1\text{M}$ (standard deviation of 500k). We find similar results holding 8 nm shot pitch constant (Fig. 5c and d); 0.2 nA beam current results in $\langle Q_{\text{int}} \rangle = 920\text{k} \pm 60\text{k}$ (standard deviation of 250k), and 1.0 nA beam yields $\langle Q_{\text{int}} \rangle = 710\text{k} \pm 90\text{k}$ (standard deviation of 370k). Overall, the Q factors at either beam current suggest there is little influence of the beam current on the optical loss of our devices.

Finally, we consider the influence of the parameters used in depositing the metal mask layer starting with the metal deposition rate. We again pattern the same set of rings in EBL resist with our standard 0.2 nA beam current and 2 nm shot pitch and start by increasing the rate of the chromium mask deposition. The deposition rate is monitored in real time by a Quartz Crystal Microbalance (QCM) which provides a feedback signal for controlling the rate throughout the deposition process. Figures 6a–b show the results of increasing the rate by a factor of 4 from our standard 0.3 Å/s to 1.2 Å/s. We observe that increasing the deposition rate results in a significant decrease in the intrinsic Q from $\langle Q_{\text{int}} \rangle = 1.14\text{M} \pm 80\text{k}$ to $\langle Q_{\text{int}} \rangle = 800\text{k} \pm 60\text{k}$ with standard deviations of 250k and 240k, respectively. Of all the fabrication parameters investigated, we observe that the metal deposition rate has the clearest influence on Q.

The metal deposition is performed in a high vacuum environment, with the starting base pressure controlled by the pump-down time allowed between loading and the start of deposition. Here, we explore two extremes of this pump-down time, 20 minutes (reaching 7E–7 Torr base pressure) and 14 hours (reaching 7E–8 Torr base pressure) before starting deposition. Since the chamber continues to pump down throughout the deposition process, we choose to use a slightly faster deposition rate of 0.5 Å/s to minimize the further reduction of the pressure throughout the ~20 minute process. As seen in Fig. 6c and d, reducing the base pressure by a factor of ten results in a reduction of $\langle Q_{\text{int}} \rangle$ by nearly half. We do not as of yet have a physical explanation for this trend. (It should be noted the statistics in this data are also dominated by devices with coupling gaps near our fabrication limit.)

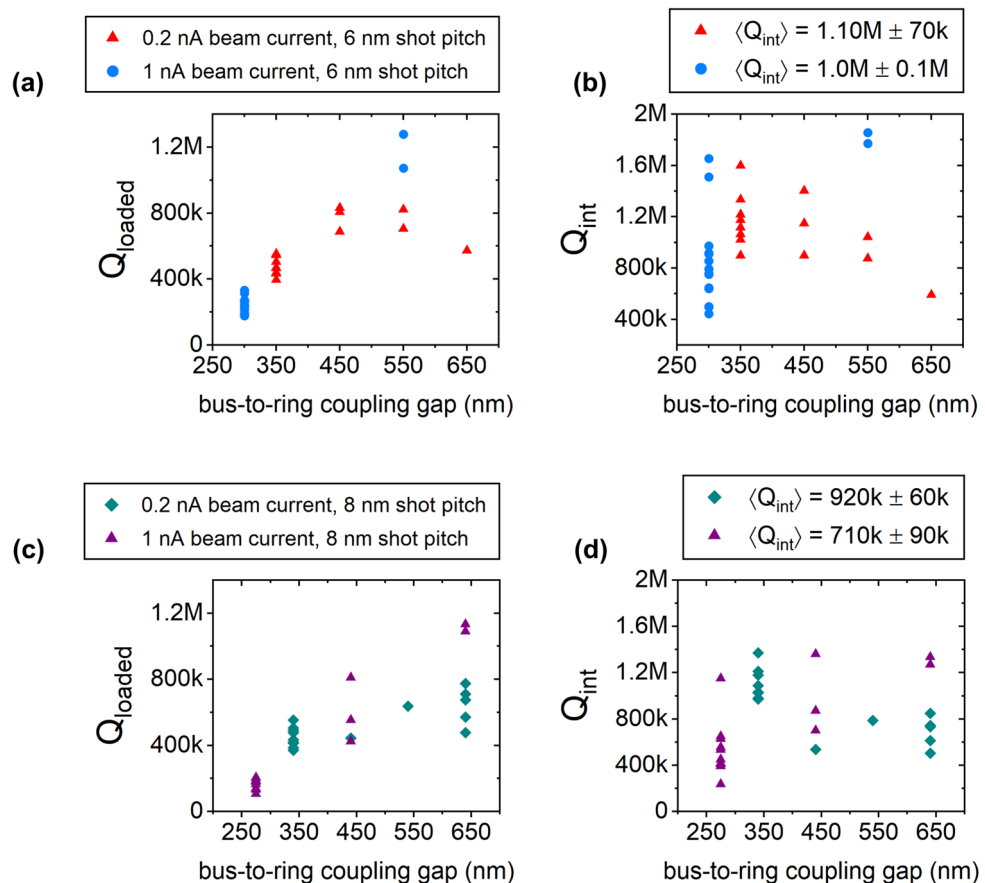


Fig. 5. (a) Loaded Q and (b) intrinsic Q vs. bus-to-ring coupling gap for resonance modes of rings patterned with a 6 nm shot pitch. (c) Loaded Q and (d) intrinsic Q for an 8 nm shot pitch at both 0.2 and 1.0 nA beam currents.

Resonance splitting

As indicated in Fig. 3, we observe a number of modes whose resonance peaks are split, which can hinder their use in applications requiring the large intracavity intensities provided by high-Q singlet microresonator modes. The origin of doublet resonance splitting is rooted in the fabrication-induced sidewall roughness of the microresonator waveguide^{39,40}. The connection between the doublet splitting and degree of sidewall roughness originates in the strength of the back-scattered field and its coupling to the forward-propagating mode. This coupling strength is directly proportional to the back-scattered reflectivity, which itself is dependent on both the degree of sidewall roughness and the physical cavity length. Since our ring resonators are nominally the same dimensions in radius (as well as cross-section), we assume the physical path length is equivalent, and thus a measure of the resonance splitting gives us insight into the relative degree of fabrication-induced sidewall roughness.

Table 1 summarizes the measured doublet splitting as well as the prevalence (% of modes that are doublets) for the same samples used in the optical loss study. In Samples A-C, we consider the effects of varying shot pitch at 0.2 nA beam current. Increasing the shot pitch from 2 to 8 nm, we see a slight increase in the average doublet splitting from $280\text{ MHz} \pm 20\text{ MHz}$ to $320\text{ MHz} \pm 20\text{ MHz}$ suggesting a slight improvement in sidewall roughness for the 2 nm condition. In the 1.0 nA Samples D-F, we see a similar trend where increasing the shot pitch from 6 to 12 nm shows an increase in the splitting from $230\text{ MHz} \pm 20\text{ MHz}$ to $320\text{ MHz} \pm 30\text{ MHz}$ with little difference between the 8 and 12 nm devices. This suggests there may be an improvement in sidewall roughness, albeit minimal, for the finer shot pitch of 6 nm, potentially due to the slight overlap of adjacent shots.

Next, we compare the effects of increasing beam current (and thus the beam size) at constant shot pitch, starting with Samples B (0.2 nA) and D (1.0 nA) at 6 nm shot pitch. There is a noticeable increase in the doublet splitting for the Sample B, where again the shot pitch is on-par with the beam diameter, compared to Sample D, where the beam diameter exceeds the shot pitch. Overall, based on the relative similarity of doublet splitting and prevalence across all of these samples, we conclude that the shot pitch and beam current parameters are not the main influence on sidewall roughness in our devices.

Shifting our focus to the next major process in the fabrication flow, we consider the influence of the parameters of the metal deposition process. Samples G and H compare the results for variation in starting base pressure; Sample G (7E-7 Torr base pressure) was measured to have an average doublet splitting of $260\text{ MHz} \pm 30\text{ MHz}$, a slight increase over the $220\text{ MHz} \pm 10\text{ MHz}$ splitting in Sample H (7E-8 Torr), while the doublet prevalence

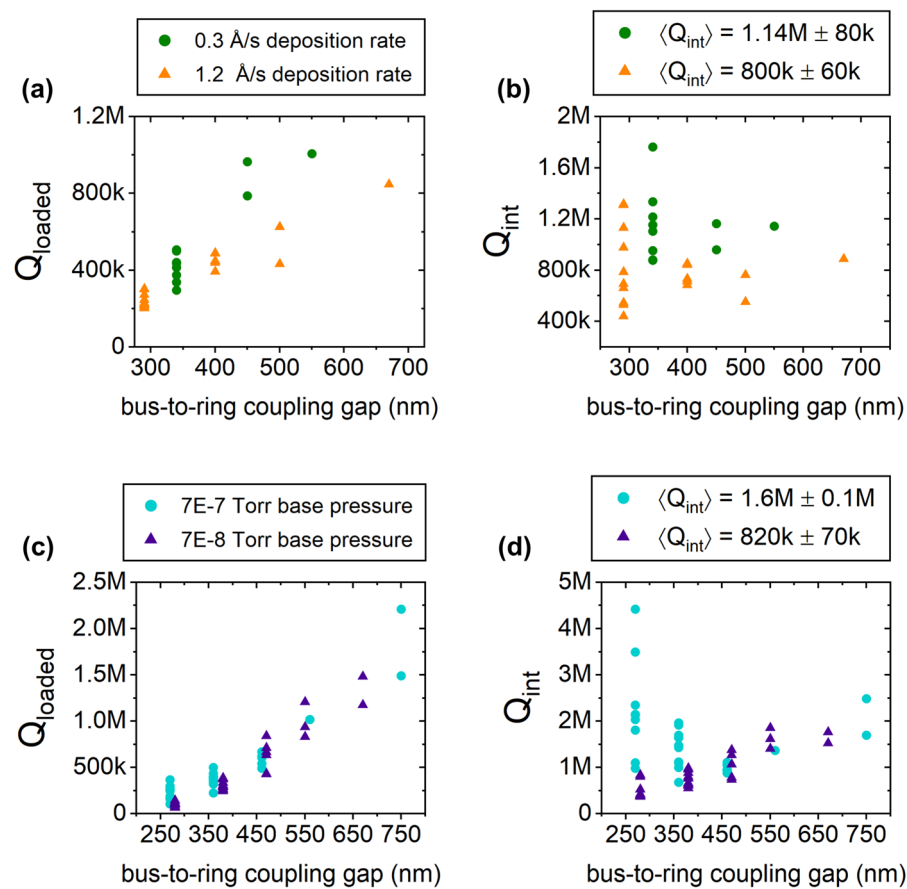


Fig. 6. (a) Loaded Q and (b) intrinsic Q vs. bus-to-ring coupling gap for resonance modes of rings with chromium mask deposited at 0.3 Å/s and 1.2 Å/s at 4E–7 Torr base pressure. (c) Loaded Q and (d) intrinsic Q compare the results for rings patterned at 0.5 Å/s with 7E–7 and 7E–8 Torr base pressure.

Sample	beam current	shot pitch	PVD rate	PVD base pressure	average doublet splitting	std. dev.	SE of mean	doublet: singlet ratio	prevalence
	nA	nm	Å/s	Torr	MHz	MHz	MHz	-	%
A	0.2	2	0.3	4E-7	280	110	20	32:20	62
B	0.2	6	0.3	4E-7	300	140	20	41:14	75
C	0.2	8	0.3	4E-7	320	120	20	35:21	63
D	1.0	6	0.3	4E-7	230	90	20	26:16	62
E	1.0	8	0.3	4E-7	300	170	40	25:17	60
F	1.0	12	0.3	4E-7	320	150	30	39:19	65
G	0.2	2	0.5	7E-7	260	170	30	33:30	52
H	0.2	2	0.5	7E-8	220	80	10	33:36	48
I	0.2	2	0.3	4E-7	240	110	20	20:11	65
J	0.2	2	1.2	4E-7	390	170	30	29:20	60

Table 1. Table of EBL and metal deposition parameters and associated doublet splitting with samples labeled alphabetically and color coded according to their varied parameters. Slight differences in the number of modes used in the averaging vs the doublet:singlet ratio exist as some modes were recorded as doublets, but the splitting was minimal and peak centers could not be determined reliably. These modes were still recorded as doublets due to the observable, but unmeasurable splitting.

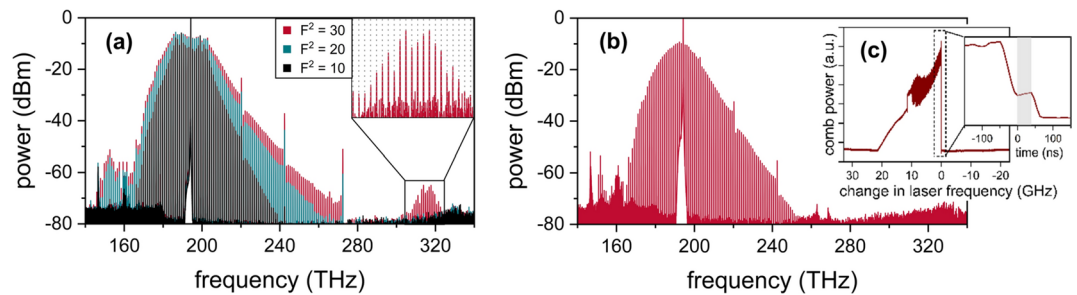


Fig. 7. (a) Comb spectra for three different optical pump powers: black - 65 mW ($F^2 = 10$), turquoise - 130 mW ($F^2 = 20$), and red - 195 mW ($F^2 = 30$). The emergence of dual dispersive waves extend the spectral bandwidth over an octave. The inset zooms in on the short-wavelength dispersive wave and compares it to a grid of the comb mode spacing extrapolated and continuously extended from the central comb modes (gray dashed lines). (b) Optical soliton spectrum for a long-lived soliton obtained at $F^2 = 30$, using the pump frequency sweeping method to stabilize the soliton state after generation. (c) The short-lived soliton step, lasting for roughly 40 ns, observed in the total comb power during an adiabatically slow laser frequency sweep across the resonance. (This is the same soliton state stabilized in (b).)

is essentially the same. These results suggest that samples patterned at the lower base pressure have a slightly lower degree of sidewall roughness; this may disagree with the results of Fig. 6d, which may further indicate a fabrication issue with gaps much smaller than 300 nm. (For completeness, we report observation of defects from the metal lift-off in Sample H, mainly in the coupling region of the ~ 300 and ~ 400 nm gap devices, while Sample G was clear of defects. Despite these defects, there is no major effect on the number of doublets in the ~ 300 and ~ 400 nm gap devices. Section II of the Supplementary Information and Supplementary Fig. S3 provide more details on common defects associated with metal lift-off.)

Finally, we explore the influence of the metal deposition rate in Samples I and J where the deposition rate is increased respectively from 0.3 to 1.2 Å/s at a comparable starting base pressure. Increasing the deposition rate results in an increase in the average doublet splitting from $240 \text{ MHz} \pm 20 \text{ MHz}$ to $390 \text{ MHz} \pm 30 \text{ MHz}$, while the doublet prevalence is comparable for both devices. Additionally, with both samples free of the lift-off defects observed in other samples, we take this large increase in the average splitting to indicate that the deposition rate is the main driver of roughness in the metallic mask and also the sidewall roughness transferred from the mask during the etch process. This is consistent with our findings linking metal deposition rate to optical loss.

Frequency comb generation

Intrinsic quality factors near 1 million in our THz-rate resonators suggest that they are sufficient to support broadband frequency comb generation²². Optically pumping a high-Q, critically coupled mode of Sample A, we observe a threshold for nonlinear four-wave mixing of 6.5 mW in the bus waveguide and generate optical frequency combs at three different multiples of this threshold power (Fig. 7a). Here the CW pump power in the waveguide is reported in units of the threshold power, $F^2 \equiv P_{\text{pump}}/P_{\text{threshold}}$. These three comb spectra represent low-coherence chaotic states where the comb is formed as the result of cascaded four-wave mixing in the resonator. As CW pump power increases, the comb power and the bandwidth increase. We purposefully design our resonator dimensions to achieve dual dispersive wave, octave-bandwidth frequency combs, a feat which requires precise control over the fabricated dimensions and geometry. For a pump powers of $F^2 = 20$ and $F^2 = 30$, we observe a dispersive wave centered around 152 THz (1965 nm). At the largest pump power ($F^2 = 30$), we observe the emergence of a second dispersive wave near 315 THz (950 nm). Together, these dispersive waves extend the overall bandwidth of our comb to over an octave.

While we find chaotic combs helpful indicators of resonator dispersion, many applications benefit from the high coherence and smooth spectral envelope of soliton pulsed operation⁴¹. The transformation from chaos to soliton can be observed as a sharp drop in the intracavity power to a steady level when sweeping the pump frequency across the resonant mode⁴². The transition to soliton operation and associated reduction in power is illustrated Fig. 7c, which shows the intracavity power during a slow adiabatic sweep (roughly 1 GHz/μs at a moderate optical power of $F^2 = 12$ in the waveguide) of the laser frequency across the resonance. We observe a build-up of the comb power as the intracavity field develops through the noisy chaotic comb regime on the rising edge. The comb power reaches a maximum at which point the laser crosses the peak of the resonance and falls into the soliton regime indicated by a short step of 40 ns duration (highlighted gray region in the inset). Stabilizing the soliton state for extended operation requires compensating for the dramatic thermal shifts involved with the chaotic comb-soliton transition. We achieve this with a fast pump frequency sweep method that allows us to sweep multiple orders of magnitude faster than the piezo modulation limit of our laser⁴³. (See Section III of the Supplementary Information and Supplementary Fig. S4 for further details on comb generation in our resonators.)

Utilizing this method, we successfully create a long-lived soliton pulse in our devices, with resulting spectrum shown in Fig. 7b for $F^2 = 30$. Although our microrings were designed to support octave-bandwidth spectra, we did not optimize the bus waveguide-resonator coupler for broadband extraction, instead opting for a point coupler (straight bus waveguide) which allowed for simpler resonator mode analysis. We believe that with

improved coupler design, we can generate and extract soliton combs with dual dispersive waves at sufficient power for f-2f self referencing^{41,44–46}.

Conclusions and discussion

In this work, we have demonstrated that subtractive fabrication utilizing an etch mask formed by metal lift-off is a viable technique for realizing photonic waveguides in thick, etch-resistant dielectric films. With this method we achieve Q_{int} values close to 1 million in THz-rate ring resonators with near-vertical sidewalls and well defined high-aspect-ratio features. Through careful investigation of our fabrication process parameters, we identify the metal deposition, specifically the deposition rate, is currently the predominant factor influencing our sidewall loss, more so than electron beam lithography parameters. We believe that adjusting the metal choice and deposition details will result in further reduction in optical loss.

As the field of photonics continues to expand, new thresholds for performance, widened scope in applications, and advances in integration will place ever-increasing demands on the fabrication of photonic devices. To meet these demands, robust solutions to fabricating complex, high-aspect-ratio designs in a variety of hard-to-etch photonic materials will be of great use. In addition, the progressive efforts to translate photonics research from the lab to integrated devices in the field and commercial sphere require techniques that can be applied by anyone from the novice researcher working in a small research cleanroom to experienced technicians in high-throughput commercial foundries. The results of this work highlight that metallic etch masks formed by metal lift-off can serve this purpose as a widely applicable and easy-to-implement technique that meets all of these requirements. With just a few steps added to the typical fabrication flow, minimal optimization, and the use of standard tools found in most CMOS foundries, this method is capable of producing high quality photonic devices such as the high-Q microresonators presented in this work. With further improvement, we speculate that microresonators formed with this method could reach the quality factors attainable with more complex techniques, with fewer trade-offs and limitations in device design.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

The contributions of the authors to this research are as follows: G.M.C. conceptualized this study, developed the fabrication process, performed fabrication and characterization experiments, analyzed the results, and wrote the manuscript. L.R. and F.B. performed characterization experiments and data analysis. L.R. contributed to process development and study conceptualization. T.E.D. conceptualized this work and provided guidance, training, and oversight. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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