Development of metal etch mask by single layer lift-off for silicon nitride photonic crystals

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Abstract

We present a method for fabrication of nanoscale patterns in silicon nitride (SiN) using a hard chrome etch mask formed by metal liftoff with a negative ebeam resists (maN-2401). This approach enables fabrication of a robust etch mask without the need for exposing large areas of the sample by electron beam lithography. We demonstrate the ability to pattern structures in SiN with feature sizes as small as 50 nm. The fabricated structures exhibit straight sidewalls, excellent etch uniformity, and enable patterning of nanostructures with very high aspect ratios. We use this technique to fabricate two-dimensional photonic crystals in a SiN membrane. The photonic crystals are characterized and shown to have quality factors as high as 1460.

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1. Introduction

The ability to pattern dielectric structures with high resolution electron beam lithography has enabled a broad range of photonics device applications. One important example is the fabrication of photonic crystal (PC) devices that exploit Bragg reflection in multiple dimensions to achieve strong confinement of electromagnetic fields [1,2]. The engineering of photonic devices has mostly focused on high index materials such as silicon (Si) or Gallium Arsenide (GaAs) that typically operate at infrared wavelengths. Recently there has been great interest in extending these devices into the visible and ultraviolet (UV) wavelengths. Silicon nitride (SiN) is an ideal material for these applications due its large transparency bandwidth that spans the entire visible and part of the UV spectrum. SiN has already been used to develop low loss optical waveguides [3,4], one-dimensional resonant tunneling structures [5–7], and two-dimensional PCs [8–10] for studying cavity quantum electrodynamic (QED). SiN also exhibits a large nonlinear coefficient [11] and is CMOS compatible, making it useful for on-chip nonlinear optical devices such as multiple-wavelength oscillators [12].

The fabrication of these devices in a SiN material system has relied on direct patterning of a polymer etch mask from ebeam resist, followed by dry etching using fluorine chemistry. However, SiN generally exhibits poor etch selectivity relative to ebeam resist under dry etching, which results in significant degradation of the mask pattern. This degradation typically results in sloped sidewalls that greatly reduce the quality (Q) factor of the device [9]. One method to improve the sidewall profile of the structures is to use a hard etch mask that does not degrade under dry etching. Hard etch masks based on silicon dioxide (SiO₂) have been demonstrated in GaAs and indium phosphide (InP) systems [13,14]. However, the etching rate ratio of SiN to SiO₂ has been reported to be only 2.3 using standard fluorine chemistry [15], which significantly limits the etch depth. Metallic masks such as chrome (Cr) and nickel (Ni) would have the advantage of much higher selectivity. Such metals are usually patterned by a liftoff technique where the metal is deposited on a patterned resist mask that is subsequently removed. The majority of work on high resolution metal liftoff utilizes positive tone resists such as polymethyl methacrylate (PMMA) [16,17]. But in many photonics applications (such as PCs) the device must be patterned on thin suspended membranes. In these cases the use of positive tone resist would require exposing the negative pattern of the device, which necessitates exposure of an extremely large area in order to support the membrane structures. This disadvantage makes the use of positive tone resists impractical for patterning of such devices.

Methods for patterning of metallic structures with negative tone resists have been reported in previous works. In particular, high resolution liftoff using Hydrogen Silses Quioxane (HSQ) negative tone resist has been previously demonstrated to pattern germanium and platinum [18]. HSQ has the advantage of very high spatial resolution, but is difficult to liftoff resulting in pattern irregularities. To overcome this problem, an HSQ/PMMA bilayer technique has been employed [19] to improve the ease of liftoff. However, the bilayer liftoff method can result in significant distor-
tion of the pattern when transferred from resist to the metal mask by dry etching.

In this paper, we report an approach for fabrication of nanoscale patterns on SiN using a hard Cr mask. The mask is deposited by single layer metal liftoff of ma-N 2401 negative tone ebeam resist. A variant of this resist, maN-2410, has previously been used to pattern gold structures with feature sizes as small as 200 nm [20,21]. Here we use maN-2401 to fabricate a robust Cr etch mask for ebeam lithography. Using this approach we demonstrate the ability to fabricate feature sizes as small as 50 nm, which are then transferred to a 200 nm thick SiN membrane. The fabricated structures exhibit straight sidewalls, superb pattern regularity, and very high aspect ratios. The fabrication technique we demonstrate is ideally suited for patterning PCs due to its high spatial resolution and the fact that we are patterning the negative tone, enabling us to pattern structures that can be undercut to form membranes. As a demonstration, we fabricate a PC cavity on a thin SiN membrane that exhibits straight sidewalls and Q factors as high as 1460.

2. Fabrication procedure

Fig. 1 illustrates our fabrication procedure for patterning of the metal Cr mask and subsequent transfer to SiN. The initial substrate is composed of a 200 nm thick SiN layer grown by low pressure chemical vapor deposition (LPCVD) on a 500 μm thick silicon wafer. After the LPCVD process, the wafer is cleaned with standard acetone, methanol, iso-propanol and de-ionized water rinse. The

![Fig. 1. Sketch of the fabrication process.](image-url)
negative tone ebeam resist, ma-N 2401 (Micro Resist Technology), is then spin coated at 3000 rpm for 60 s and baked on a hot plate at 90 °C for 2 min. The thickness of resist after spin coating was measured to be approximately 100 nm with a surface profilometer (Tencor TP-20). The resist layer is then patterned by ebeam lithography. After ebeam exposure the resist is developed (MF CD-26, Microposit) to form the negative mask pattern. A 20 nm Cr film is then deposited onto the sample by using an ebeam evaporator. After Cr deposition, a metal mask is obtained by lifting off the resist layer with acetone assisted by ultrasonic agitation for 1 h. Once the Cr etch mask is formed, the pattern is transferred to the SiN layer using reactive ion etching (RIE). For samples requiring suspended structures, the sacrificial Si layer is etched for 5 min at 80 °C in a solution of 20 g of solid KOH in 300 ml DI water. Once the structure is finalized, the Cr mask can be removed by chemical etchant (Ceric Ammonium Nitrate and Nitric Acid).

3. Characterization of fabrication

We have carried out the fabrication procedure described in the previous section and examined the resulting structures. Fig. 2 shows several scanning electron microscope (SEM) images of the fabrication results taken at various steps in the process. Fig. 2(a–d) were taken after completion of the steps illustrated in panels (c), (d), (f) and (g) of Fig. 1. Fig. 2a shows an angle view of cylindrical negative resist patterns on a SiN layer defined by ebeam lithography (RAITH E-Line at 30 kV acceleration voltages). After development, a 20 nm Cr layer was deposited on the sample, followed by liftoff. Fig. 2b shows a top view image of the Cr mask on SiN after liftoff, showing that the written pattern has been cleanly transferred to the Cr mask. Every hole was successfully lifted off from the structure, and the mask exhibits superb regularity. Fig. 2c shows a cross section of patterned SiN membrane after RIE and undercut, but prior to removal of the Cr mask. The circular patterns on the Cr etching mask have been transferred through the SiN layer using an RIE dry etching process. The cross cut shows a straight side wall profile and well defined bottom edge of etched air holes. In Fig. 2d, an SEM image of a final structure after Cr removal is shown, where the image is taken at a 30° tilt angle. Gold particles were applied on the surface to enhance the SEM image quality, resulting in a rough surface appearance.

Using this technique we fabricated a series of test patterns of different sizes to determine the resolution limit of the fabrication process. Fig. 3a shows an array of air holes etched into the SiN layer with varying sizes. The 4 × 4 array consists of groups of air holes with varying sizes ranging from 250 nm (top left) down to 60 nm (bottom right) in diameter. Lift-off was successful for every hole in the structure, including the smallest one. These results demonstrate that lift-off can be reliably applied to structures with many different disconnected features in a highly repeatable way.

In order to determine the sidewall profiles, we fabricated a series of trenches. Fig. 3b shows the cross sectional profile of the trenches, obtained by imaging the cleaved edge of the fabricated sample. The trenches are measured to have widths ranging from 80 nm on the left down to 50 nm on right. The vertical side wall of the trenches are found to be very straight, even for the thinnest trenches that are only 50 nm in width, exhibiting a very small aspect ratio. Such aspect ratios would be very challenging to achieve using only a soft polymer resist mask.

4. Design and fabrication of photonic crystals in silicon nitride

To demonstrate that this procedure can be used to fabricate real photonic devices, we fabricated a PC optical resonator. The design of the resonator, illustrated in Fig. 4a, is based on a three holes defect L3 cavity structure [22]. The Q factor of the device was numerically optimized by sequentially shifting three groups of air holes (labeled A, B, and C in Fig. 4a) and performing Finite Difference Time Domain (FDTD) simulations. The thickness of the membrane was set to \( t = 200 \text{ nm} \) while the refractive index of SiN was set to \( n = 2.01 \). The optimal device was attained when the radius of air holes and lattice constant were set to \( r = 70.2 \text{ nm} \) and
$a = 250.9 \text{ nm}$, respectively. A maximum $Q$ of 3280 was attained at a wavelength of $\lambda = 620 \text{ nm}$ when the hole shifts for groups A, B and C were displaced by a distance of $0.07a$, $0.04a$ and $0.24a$, respectively. Fig. 4b plots the $y$-component of the electric field of the cavity mode that achieves the optimal $Q$.

The optimized PC design was fabricated onto a SiN membrane using the described fabrication procedure. An SEM image of the fabricated structure is shown in Fig. 4c. To characterize the repeatability and degree of disorder of the fabrication, we measured the radius of all 122 air holes shown in the panel. The average radius was found to be 69.9 nm, which is very close to the target value of 70.2 nm, while the standard deviation was only 1.5 nm. Thus, the fabricated structure comes very close to the targeted design and exhibits superb hole regularity along the entire PC structure. After fabrication photoluminescence (PL) measurements of the fabricated SiN PCs were carried out using a confocal microscope setup. The SiN substrate was pumped with a 532 nm laser at 30 mW pumping power, producing a weak broadband PL emission that is filtered by the cavity mode. This emission was collected by an objective lens with a numerical aperture of 0.7 and spatially filtered by a 250 μm pinhole to eliminate unwanted background emission from the surrounding material. After spatial filtering, the collected light was sent to a high resolution grating spectrometer (Princeton Instrument SpectraPro 2750) for spectral measurements.

Fig. 4d plots a typical cavity spectrum from a fabricated SiN PC device. The mode resonance peak is centered at a wavelength of...
678.39 nm. The full width half maximum (FWHM) linewidth is calculated by numerically fitting the peak to a Lorentzian lineshape, and is given by 0.462 nm. The Q factor, defined as the center wavelength divided by the FWHM linewidth, is calculated to be 1460. The measured Q factors are lower than those calculated by FDTD simulations due to a number of practical imperfections such as air hole roughness and material losses. The optical spectrum alone does not provide enough information to determine which of these factors is the most significant source of reduction in Q. From Fig. 3b we see that the fabricated sidewalls are very straight, while the standard deviation in hole radii for the fabricated structure in Fig. 4c is only 1.5 nm, which is comparable to hole regularities seen in GaAs and SiPCs. These numbers suggest that cavity Q is likely not limited by fabrication, and that material losses potentially play a major role in determining the cavity linewidth. One way to investigate this possibility, and simultaneously improve the cavity Q, is to use stoichiometric SiN instead of the low-stress SiN used in this work. Stoichiometric SiN exhibits lower losses which should result in optical devices that perform much closer to the ideal limit.

5. Conclusion

In conclusion, we have demonstrated a method to fabricate a hard Cr mask for nanofabrication using metal liftoff with negative tone ma-N 2401. The spatial resolution of this technique was demonstrated to be as small as 50 nm. The Cr mask enabled transfer of the mask pattern into 200 nm of SiN, enabling fabrication of structures with very high aspect ratios. The fabrication procedure was used to etch PC cavities into SiN that exhibited Q factors as high as 1460. Although we focused on patterning of SiN, the proposed fabrication procedure should be compatible with virtually any material substrate and most types of deposited metals. It thus provides a very versatile technique for high aspect ratio nanofabrication for broad range of applications in photonics.

References