Reducing redeposition on KYW waveguides through hard mask engineering

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The deeper a waveguide needs to be etched, the thicker the mask needs to be. However, a thick mask causes problems including redeposition and low resolution. This becomes especially problematic when using physical etching rather than chemical etching, as the selectivity is inherently lower and the mask must be thicker. In this work, we investigate a number of potential mask materials. We evaluate their performance in etching, as well as other properties that affect their use. We find a tradeoff between performance and convenience: Photoresist is deposited and patterned in a single step, but has low selectivity. Carbon etches four times slower, but is extremely fragile.

Introduction

$KY(WO_4)_2$ (KYW) is highly attractive in integrated optics, both as a host material for lanthanide ions and for its good nonlinear properties. However, fabrication is challenging as KYW is chemically inert and can only be structured by physical sputter etching.

Sputter etching with Ar ions is relatively non-selective compared to reactive ion etching with a chemical component. Therefore, the mask thickness must be similar to the height of the final structure or even thicker. This causes problems because of redeposition, where etched material adheres to feature sidewalls[1]. Redeposition makes the structure wider, which introduces a sidewall slope and reduces the attainable aspect ratio. Furthermore, redeposited material is amorphous, and in the case of compound materials non-stochiometric, and will cause losses. Redeposition naturally becomes more of a problem for deeper etching, as a tall sidewall will have a larger area to be targeted.

Traditional mask materials like photoresist sputter quickly and are often considered unsuitable for sputter techniques like ion beam and argon reactive ion etching. Popular alternatives include metals. While metals are often sufficiently hard, the residues can cause absorption losses in waveguides, and metals are often banned from etching machines in multiuser cleanrooms.

We attempt to develop a mask that will etch significantly slower than KYW. The compared materials are photoresist, silicon oxide, chromium oxide, silicon rich nitride and amorphous carbon.

Etching

The etching was performed using an Adixen AMS100 DE ICP-RIE system. The process pressure was 5e-3 mbar, with an argon flow of 150 sccm. ICP power was 1500 W and CCP RF power was 150 W. This resulted in a bias voltage of 175 V. The table temperature was -10 °C. The results of the etching, namely the etching rate and selectivity between mask and KYW are shown in Table 1.

Table 1: Rates for argon etching of different materials, and selectivity to KYW.

Material	Rate [nm/min]	Selectivity
KYW	33	1
SiRN	60	0.6
SiO_2	56	0.6
Resist	35	1
Cr_2O_3	28	1.2
Carbon	8	4.2

$KY(WO_4)_2$

As the target material, KYW acts as a baseline for the testing. A KYW sample was coated with 5 µm of PECVD SiO_2 for use as a hard mask. Deposition was performed in an Oxford Instruments Plasmalab 80 Plus. The sample was patterned with ridges using photolithography and a SiO_2 etch in the Adixen etcher.

After patterning, resist stripping and one hour of argon etching, the sample was imaged in a FEI Nova 600 FIB/SEM. The structure is shown in Figure 1. The sidewalls are notably sloped at 60°, and the redeposited layer is as high as the residual mask.

After imaging, HF was used to strip the residual SiO_2 mask and the ridge height was measured with a Veeco Dektak 8 profilometer. The waveguides were measured to be 2 µm tall, corresponding to an etch rate of 33 nm/min.

Photoresist

The Olin Oir series of photoresists were used, as they are the standard in the MESA+ cleanroom. The resist thickness was measured with a Filmetrics F50 reflectometer. This method of measurement is quick and easy, enabling convenient verification of the mask thickness.

As the available resists can be tuned between 1 µm and 4 µm, photoresist is a simple solution for deep etched waveguides. However, redeposition is a problem with such thick masks, and achieving consistent sub-µm resolution is challenging.

Silicon oxide

As a convenient benchmark, silicon oxide samples were used alongside all the other etch tests. The samples consisted of 1 µm thick PECVD SiO_2 on Si.

In addition to the high etch rate, silicon oxide is problematic because of stress. Film cracking and peeling has been observed when depositing the thick (5 µm) layers necessary for effective use as a hard mask. This may be alleviated by using a pulsed LF/RF deposition method, which will balance out tensile and compressive stress in a stack of sub-10 nm thick layers.

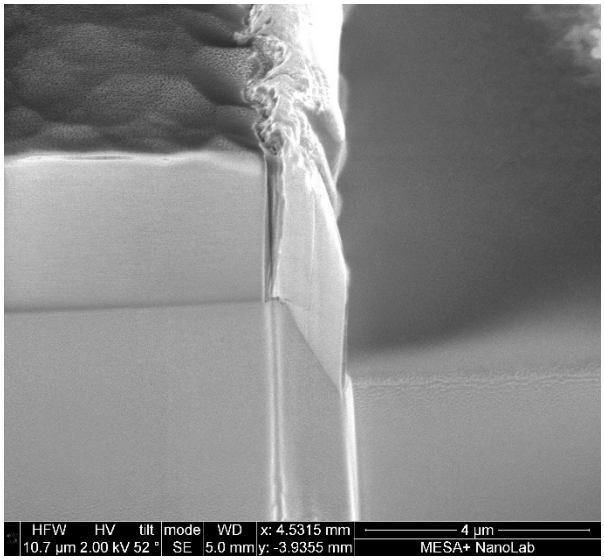

Figure 1: Severe redeposition above and on the sidewall of a KYW ridge. The thick slab on top is the residual SiO_2 cladding, which was not removed before imaging.

Si-rich nitride

Silicon rich nitride can be grown quickly and conveniently by PECVD, and was thus a natural candidate for use as a mask. However, the rate of deposition is lower than that of SiO_2 and the performance as a mask is worse.

Chromium oxide

Chromium oxide (Cr_2O_3) was evaporated in a BAK600 e-beam evaporator. Film thickness measurements could be conveniently performed using a J.A. Woollam M-200UI ellipsometer with good correspondence between material models and profilometric step measurement.

The deposition of chromium oxide is somewhat time consuming, as evaporation happens at a few hundred nm/h. The selectivity is also not much better than resist. However, any deposited mask has the major advantage over resist in that it can be patterned using electron beam lithography. This can be used for high resolution, deeply etched features.

Carbon

Carbon is well known as a very hard mask material[2]. This image was reinforced by our testing, where a selectivity of 4.2 was measured. This should enable very thin masks, on the order of 500 nm for a 2 µm tall waveguide.

Unfortunately, the material is difficult to handle. Evaporation has been found to produce low quality films with severe cracking and high roughness, and carbon CVD is not available at MESA+. This leaves sputter deposition. However, along with the desirable low sputter rate for etching comes an undesirable low sputter rate for deposition. In the current process, deposition happens at a rate of approximately 1 nm/min, which has kept us from experimenting with films thicker than 100 nm.

Furthermore, amorphous carbon is extremely brittle and suffers from poor adhesion to KYW. Therefore, it has been necessary to deposit a SiO_2 or Si adhesion layer, as well as two capping layers. The top capping layer, SiO_2, is opened with a selective dry etch after photolithography. Next, the resist is stripped in organic solvents. Afterward, the top layer acts as a hard mask while the bottom capping layer, Si, is opened. The carbon can then be etched with an oxygen based ICP-RIE process. Using only one capping layer would expose the fragile carbon film to liquids that would wash it away. Stripping the resist with the same etch process that removes the carbon is not an option, as Olin Oir series resists are partially inorganic and will leave powdery residues after plasma ashing.

Yet another problem with carbon is measuring the mask thickness. Ellipsometry has not been found to be useful, as the color of the film remains brown regardless of thickness. The only reliable method for determining the film thickness has been to cover half of a sample with a shadow mask, oxygen plasma etching away the exposed area and measuring the step by profilometer.

While the complexity of the carbon process is undoubtable, the engineering challenges when combined with photolithography must be recognized. In combination with EBL it may be significantly easier, as PMMA oxidizes to CO_2 and H_2O with no solid residue.

Conclusion

We have evaluated photoresist, SiO_2, SiRN, Cr_2O_3, and C for use as hard masks for KYW. Only C and Cr_2O_3 have been found to sputter etch significantly slower than photoresist. However, it is very fragile when exposed to other things than high powered plasma, and requires many processing steps. The use of amorphous carbon as a mask is only recommended for very demanding structures.

Acknowledgements

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