Optimization of a single-step reactive ion etching process for InP photonic integration

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In this contribution we present a novel single-step reactive ion etching process based on CH_4/H_2 chemistry. Unlike the traditional RIE process, the single-step process does not require cycles iterated with O_2 plasma to control the polymerization. The optimization is achieved by balancing the isotropic and the vertical anisotropic etching. The final process provides high selectivity, smooth etched profiles and small sidewall angles, and can be a perfect solution for etching InP membrane waveguides.

Introduction

The reactive ion etching (RIE) technology has become an indispensable tool in the fabrication of integrated photonic devices due to the high demand for precise and uniform dry etching. As higher etch rates and better anisotropy was required, updated versions such as electron cyclotron resonance (ECR) RIE and inductively coupled plasma (ICP) RIE were developed [1]. However the original RIE technique still has advantages such as a low cost, simple and robust configuration. More importantly, the RIE process is preferred over ICP and ECR in many applications especially in the area of integrated photonics, due to the higher selectivity and lower physical damage to the sample surface from RIE [2].

In the area of InP based integrated photonics, the CH_4/H_2 chemistry is widely used due to its low surface damage after etching [1], as compared to Cl_2 chemistry. During the CH_4/H_2 based RIE process, the CH_3 and H radicals in the reactive plasma will react with InP and its ternary and quaternary compounds [1]. The CH_3 radicals will extract the In from the material and form $In(CH_3)_3$. The H radicals removed the residual P and form PH_3. The etching principle for Ga and As elements in compound material is similar to In and P respectively. During this reaction process, excess polymer can form due to the interaction between CH_3 radicals or etch products [1]. The polymer formation on one hand can help to protect the hard mask and increase the selectivity, but on the other hand will influence the etching process thus the etched profile. The traditional method to control the polymer formation is to interrupt the etching process with a short O_2 plasma descum step [3]. This method increases the process time, introduces horizontal roughness on the sidewall [2] and forbids the direct use of resists as etching mask. Another promising method is based on a single-step etching scheme, where polymer formation can be suppressed or even eliminated [2]. By using this single-step process, horizontal roughness due to the O_2 plasma iteration can be avoided and the process can be more time efficient than its cyclic counterpart. The disadvantage is the relatively large sidewall tilt. Since there is no polymer formation during etching, the already etched sidewall will have no polymer layer protection. Thus the isotropic etch will play an important role and attack the already etched part underneath the hard mask. As a result there will be an undercut beneath the hard mask and the sidewall angle is relatively poor (84-85° [2]).

In this contribution we focus on the improvement of the single-step RIE process with CH_4/H_2 chemistry. We present a novel process recipe which can improve the etched profile (i.e., sidewall angle) in the single-step process, by balancing the isotropic and the vertical anisotropic etching. The result shows that this process can provide high selectivity, smooth etched profiles and small sidewall angles, and can be a perfect solution for etching InP optical waveguides.

Process parameters

The parameters in this novel process deviate from the polymer-free condition as suggested in [2]. Since the isotropic etching results in smoother surfaces as compared to the anisotropic vertical etching, the process is tuned to increase the isotropic etching. This can be achieved by increasing the chamber pressure and the RF power. The chamber pressure can have a significant influence on the kinetic energy of the radicals as well as the polymer formation rate. Higher chamber pressures will result in a smoother etched surface and higher polymer deposition. The RF power directly determines the density of the plasma. It can also influence the verticality of the reactive radicals as has been observed experimentally in our etchings. Gas composition and the ratio between ingredients are also important to the process. Literature suggest that the CH_4/H_2 ratio should be kept within ½ and ¼ [2]. Excessive H_2 is commonly employed to dilute the CH_4 concentration. It can efficiently remove the P from the surface depleted from In due to reaction with the CH_3 radicals. This avoids spontaneous micro-masking due to polymer formation on the surface. Nevertheless, Ar is often added into the gas mixture to increase the vertical physical etching in the CH_4/H_2 based RIE process. It is also reported that Ar can help to reduce the amount of polymer during etching [2]. However too much Ar creates roughness on the etched surface. The plate temperature underneath the sample has less impact on the result, since the etch products in the CH_4/H_2 process are very volatile and the heating effect due to the physical bombarding of the plasma is much lower than in an ICP process.
Based on the above analysis, the process parameters were determined as shown in Table. 1.

Table. 1 Process parameters

Process parameter	Value
Chamber pressure	75 mT
RF power	100 W
Gas flow $CH_4/H_2/Ar$	30/70/30 sccm
Platen temperature	50 °C

Prior to the actual device etching, the chamber is pre-conditioned by running the process recipe for 5 min. An O_2 plasma descum is only necessary afterwards, to remove the polymer deposited during the etching.

Etching result

A scanning electron microscope (SEM) picture of an etched waveguide structure (~ 1 μm deep) on InP substrate is shown in Fig. 1(a). The hard mask pattern for etching is a 50 nm thick SiN_x layer deposited by plasma enhanced chemical vapour deposition (PECVD). As can be seen from the picture, both a vertical sidewall and a smooth etched surface can be achieved using the process parameters from Table. 1. As a result the proposed process recipe can etch waveguides on InP with an etch rate of 45 nm/min, a sidewall angle of 87.5° and a selectivity to the SiN_x hard mask of about 120.

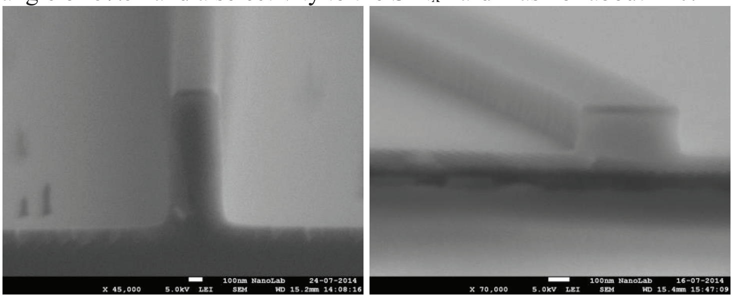

Fig. 1 (a) SEM picture of a 1 µm deep etched waveguide structure (b) SEM picture of the etched waveguide on InP membrane.

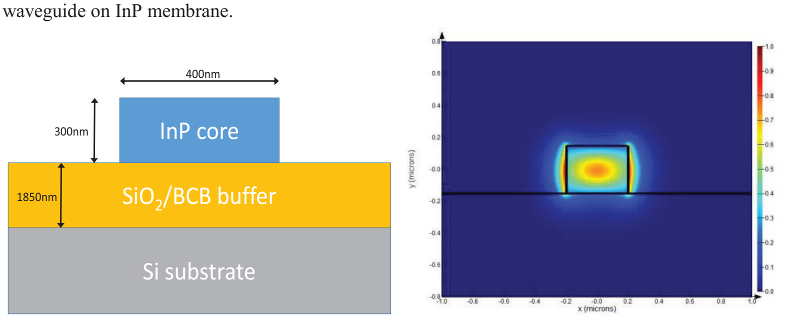

Fig. 2 (a) The schematic diagram of a single-mode IMOS waveguide. (b) The TE mode profile in the waveguide.

To investigate the impact of the etched roughness on the sidewall on the scattering of optical mode in waveguide, straight waveguides were fabricated on an InP membrane on Si (IMOS) platform [4] to verify the propagation loss. The cross-section diagram of the single-mode waveguide on IMOS is shown in Fig. 2(a). The high-index-contrast IMOS waveguides with sub-micron dimensions are the best test structures to examine the impact of sidewall roughness due to the strong interaction between the optical mode (TE) and the etched sidewall, as shown in Fig. 2(b). The 300nm thick InP waveguide layer was adhesively bonded on a Si carrier wafer using BCB polymer [5]. Two electron beam lithography (EBL) steps were performed with C_{60}/ZEP resist [6] and a 50nm SiN_x layer to etch waveguides of 400nm width and 280nm height, and fiber coupling gratings with 100nm depth. The SEM picture of a fabricated IMOS waveguide (with SiN_x mask on top) is shown in Fig. 1(b).

The measurement of the waveguide loss utilizes a commercial laser at 1550 nm wavelength with an output power in fiber of 6 dBm. The laser light is coupled to the waveguide through an input grating coupler using a single-mode fiber tip. The transmitted light from the output grating coupler is collected by another fiber. Both fibers are placed at 10 degrees from surface normal of the chip. The output optical power is measured with a power meter. The measurement result of the insertion loss of the fabricated waveguides as a function of the waveguide length, is shown in Fig. 3. The measured data is fitted with a linear function. The result indicates a propagation loss of 2.5 dB/cm and a fiber-grating coupling loss is 5.7 dB/coupling. This result is slightly better than our previous loss experiments [6] which implies an improved sidewall roughness.

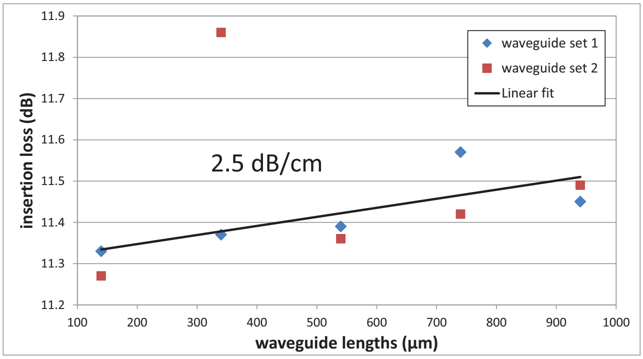

Fig. 3 The measurement results of single-mode IMOS waveguides fabricated using the proposed RIE process.

Conclusion

In conclusion a single-step RIE process based on CH_4/H_2 chemistry has been optimized for fabrication of InP optical waveguides. The proposed etching process has balanced the isotropic etching and the anisotropic etching, thus provides a combination of a smooth etched surface and a vertical sidewall. The other advantages of this process include the high selectivity to the etching mask, freedom of using polymer masks and high time efficiency. Record low loss of 2.5 dB/cm on the IMOS waveguides fabricated using this process confirms a low sidewall roughness from this process.

References

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