C60-assisted electron-beam lithography for loss reduction in InP membrane waveguides

C_{60}-assisted electron-beam lithography for loss reduction in InP membrane waveguides

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In this contribution we present a method to prepare a mixed material composed of a positive electron-beam resist (ZEP520A) and C_{60} fullerene. The addition of C_{60} to the ZEP resist changes the material properties under electron beam exposure significantly. This mixed material has shown an increased clearance dose as well as an increased reflow temperature. An improvement of the mixed material on the thermal resistance has been demonstrated by fabricating multimode interference couplers and coupling regions of micro-ring resonators. This shows improvement with respect to the same structures fabricated with normal ZEP resist. An improvement on the propagation loss of the InP membrane waveguides from 6 to 3 dB/cm using this mixed material is shown.

Introduction

The ever-growing demand for high-speed chip-scale data transport in computers has inspired the development of on-chip optical interconnects [1], among which the InP membrane on Si (IMOS) technology [2] is a novel concept for realizing such a photonic interconnect layer on top of a conventional complementary metal oxide semiconductor (CMOS) circuit. Compared to other concepts such as III-V bonded on silicon-on-insulator (SOI) or Si/Ge, the major advantage of the IMOS technology is the potential to realize monolithic III-V active-passive integration with both compact passive photonic devices and high-performance active devices.

The IMOS passive waveguides and devices can be fabricated using electron-beam lithography (EBL) with ZEP520A resist. During the characterization of those devices we have observed a relatively high propagation loss of the InP membrane waveguides. The average propagation loss is around 10-15 dB/cm with a best result of 6 dB/cm. It is suspected to be mostly caused by the sidewall roughness on the ZEP resist pattern after exposure and development. Furthermore the erosion on the resist pattern when using it as plasma etching mask increases the roughness. Such high propagation loss will significantly limit the performance of both active and passive InP membrane devices. Therefore it is crucial to develop an improved electron-beam resist with reduced roughness.

One of the practical approaches to loss reduction is to use the so-called fullerene-assisted resist system [3]. The incorporation of fullerene in a resist system can improve the material strength during physical etching (e.g., reactive ion etching (RIE)) as well as wet chemical etching (e.g., developer solution) [3]. As a result a reduced sidewall roughness of the resist pattern can be obtained. The reduction of waveguide propagation loss has been experimentally demonstrated for Si wire waveguides [4] and InGaAsP wire waveguides [5] by incorporating C_{60} (one of the fullerene types) into ZEP resist.

In this contribution we will present the preparation of such C_{60}-assisted ZEP resist and use it in the EBL process for realizing InP waveguides. We will show the change of the resist properties due to the C_{60} material. Finally we will demonstrate the reduction of waveguide propagation loss using this mixed resist.

Resist preparation

The preparation procedure of the C_{60}/ZEP mixed resist is similar to what has been described in [3]. The C_{60} powder is first dissolved in anisole (solubility is about 5.6 g per liter [6]) and then mixed with ZEP520A resist solution by magnetic stirring. The mass ratio between C_{60} and ZEP material is 1:9. The final mixed solution will appear black due to the presence of C_{60}, instead of transparent as for normal ZEP resist.

Since additional amount of anisole is added as solvent into the mixed resist solution, the concentration of ZEP material will decrease. As a result the thickness of the mixed resist after spin-coating will be less than that of the normal ZEP resist. For instance, the thickness of the mixed resist at a spin speed of 2000 rpm is about 100 nm, while the thickness of the normal ZEP resist at 4000 rpm is 300 nm.

Resist properties

The addition of C_{60} material in the ZEP resist changes significantly the properties of the resist system regarding the clearance dose during EBL and the thermal behaviour. It is found that in the Raith 150-2 EBL system with 20 kV voltage and 10 μm aperture settings, the clearance dose of the mixed resist has increased to 48 μC/cm^2 while the normal ZEP resist has a clearance dose of 38 μC/cm^2.

A post-exposure bake is crucial for obtaining a smooth resist sidewall. The bake temperature is chosen close to the reflow temperature, so that the roughness on the sidewalls can be smoothened during controlled reflow. After mixing with C_{60}, the reflow temperature of the mixed resist has increased from 154 ℃ for normal ZEP to 170 ℃. This is due to the increased thermal strength provided by the C_{60} material. Furthermore, the mixed resist also shows much less deformation after 170 ℃ baking compared to the normal ZEP resist after 154 ℃ baking. As can be seen from Fig. 1(a), the corners in the MMI coupler structure are all rounded due to the reflow of the normal ZEP resist at 154 ℃. This might increase fabrication errors of the devices. On the other hand after 170 ℃ baking, the mixed resist still shows relatively sharp, as designed corners (see Fig.1(b)).

The improved thermal resistance of the mixed resist also helps to realize structures with

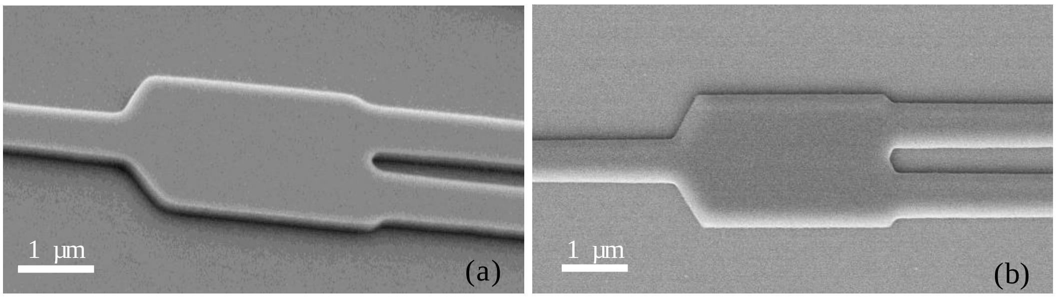

Fig. 1 (a) The MMI coupler structure fabricated by using nornal ZEP resist. (b) The MMI coupler structure fabricated by using the mixed resist.

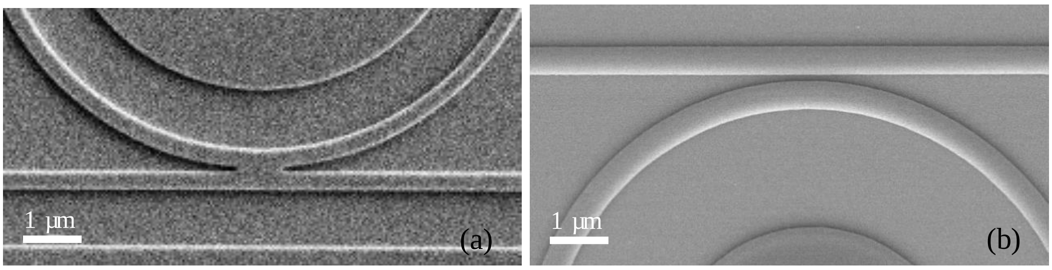

Fig. 2 (a) The coupling region of MRRs fabricated by using nornal ZEP resist. (b) The coupling region of MRRs fabricated by using the mixed resist.

narrow gaps. For instance the coupling regions of micro-ring resonators (MRRs) are fabricated using both mixed resist and normal ZEP, and baked at 170 ℃ and 154 ℃, respectively. It can be clearly seen from Fig. 2(a) and (b) that the gap in the coupling region fabricated with normal ZEP resist has already closed due to the deformation of the material. On the other hand, the gap fabricated with the mixed resist survivs after baking. Thus it is obvious that the IMOS photonic devices can benefit more fabrication accuracy from this enhancement of the thermal resistance in the mixed resist.

Loss reduction

Straight IMOS passive waveguides of different lengths are fabricated using the mixed resist for loss measurement. The fabrication starts by depositing a 1850 nm thick SiO_2 layer on top of a Si wafer and a 50 nm SiO_2 layer on top of an InP wafer by using plasma enhanced chemical vapor deposition (PECVD). The InP wafer contains a 250 nm-thick InP membrane layer as the future waveguiding layer and a 300 nm-thick InGaAs sacrificial layer between the membrane layer and the substrate. The Si wafer and the InP wafer are adhesively bonded using 50 nm-thick DVS-BCB (divinylsiloxane-bisbenzocyclobutene) material [7]. After wet-chemically removing the InP substrate and the InGaAs sacrificial layer, the 250 nm-thick InP membrane is tightly bonded on top of the SiO_2/Si carrier wafer. The fabrication requires two steps of EBL. Both steps utilize a 50 nm-thick PECVD-deposited SiN_x layer on top of the InP membrane as the hard mask. The 100 nm-thick mixed resist material is spin-coated on top of this SiN_x layer, and the designed patterns are written on the resist layer by EBL with 20 kV voltage and 10 μm aperture settings. After development, the patterns on the resist layer are transferred to the SiN_x layer by means of CHF_3/O_2 RIE. Finally the patterns are formed in the InP membrane layer using CH_4/H_2 InP RIE. The first EBL step prints all the waveguide designs as well as the local markers for alignment of the next EBL. The final InP waveguide will have a width of 400 nm and an etch depth of 220 nm. The second EBL step prints the grating couplers for coupling light between optical fibers and the waveguides. The gratings will have a etch depth of 100 nm. The processing procedure is the same as for the standard IMOS passive processing [2], [8], except for the change of the resist material from normal ZEP to the mixed resist. The fabricated membrane waveguides have five different lengths from 140 μm to 940 μm, with 200 μm increment.

The measurement of the waveguide loss is performed by using a commercial laser with the wavelength of 1550 nm with an output power in fiber of 12 dBm. The laser light is coupled to the input grating coupler by means of a single-mode fiber with a cleaved facet. 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

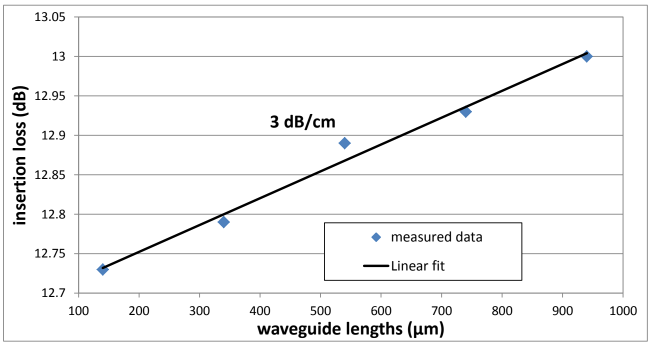

Fig. 3 The measured insertion loss of the IMOS passive waveguides as a function of waveguide length.

power is measured with a power meter. The measurement result of the insertion loss (including both propagation loss and grating coupling loss) of the five waveguides, as a function of the waveguide length, is shown in Fig. 3. The measured data is fitted with a linear function from which a propagation loss of 3 dB/cm and a fiber-grating coupling loss of 6.4 dB/coupling are extracted. Compared to the propagation loss of more than 10 dB/cm in average by using the normal ZEP resist, the measured 3 dB/cm propagation loss by using the mixed resist proves that a significant loss improvement is achieved by the assistance of C_{60} material.

Conclusion

In this contribution we have presented a method to prepare a mixed material composed of ZEP520A resist and C_{60} fullerene. Compared to the normal ZEP resist, the mixed resist has shown an increased clearance dose and an enhanced thermal resistance. The IMOS MMI couplers and the coupling regions of MRRs are fabricated using both mixed resist and normal ZEP. The comparison between two resists has indicated an improvement on the fabrication accuracy by using the mixed resist. Loss measurement on the IMOS passive waveguides also demonstrated a significantly reduced propagation loss (3 dB/cm) with the mixed resist.

Acknowledgements

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