Benzocyclonbute (BCB) Process Development and Optimization for High-Speed GaAs VCSELs and Photodetectors

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Abstract

The RIE dry etching of Benzocyclobutene are studied to develop a compatible process for high-speed VCSEL and PD fabrications. SF6, O2 and N2 are selected as the process gases with their functions in the dry etching process explained. Optimal gas ratio of SF6 to O2 is 1:4. Controlled experiments are performed to identify the optimal power and pressure configurations for a new RIE system. The main problem is pointed out to be excessive physical sputtering from experiments. A clean etching recipe is finally developed to produce ideal etching results.

INTRODUCTION

Benzocyclobutene (BCB) based polymers are commonly used in microelectronic processing as dielectric materials for their low dielectric constant, negligible RF loss and high DC resistivity. In that case, a dry etching process to selectively remove BCB is necessary to shape the device structure such as opening vias for metal interconnect. A well-calibrated etching process is expected to create a smooth etch surface with minimum residue. BCB plasma etching is more complicated than common polymer or semiconductor etching in that BCB based polymer contains both organic materials and Si. Both must be removed simultaneously to achieve a smooth etching surface. In this work, we start from a recently implemented and unfamiliar RIE tool and design experiments to develop RIE etching process to improve the BCB surface morphology. Experimental results are shown to illustrate the effects of temperature, pressure, gas ratio in the process of polymer plasma etching.

EXPERIMENT TARGETS

The BCB etching process of this work is developed for high-speed GaAs vertical-cavity surface-emitting lasers (VCSEL) [1] and photodetectors (PD). The epitaxial materials of VCSELs and PDs are first grown with MOCVD or MBE tools to pre-define the P-i-N diode structure. And the following fabrication process mainly focuses on shaping the physical device structure. It usually starts with an ICP/RIE etching process to define the mesa structure and exposed the

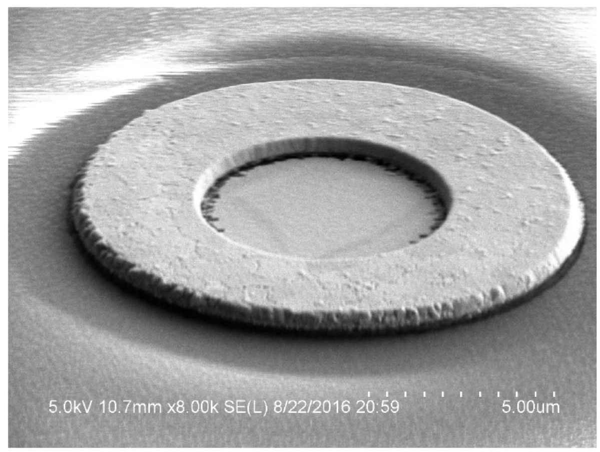

Fig. 1. VCSEL devices with BCB residue covering the aperture.

N-doped semiconductor layer. Contact metal is subsequently deposited onto the P- and N-doped layers. The samples are then planarized with BCB before selectively removing the BCB to reveal N- and P- contact. The last step is to deposit top metal contact which forms tapered GSG or GS waveguide. The BCB in this process has three main functions: planarization, DC isolation and RF signal carrying. VCSELs commonly have around 20 pairs of P-DBR structure in the P-doped region to confine the optical field. This will result in a height difference of up to 4 μm after defining the mesa structure. To allow for good interconnect to the large probing pad, the device must be planarized first. Apart from planarization, the co-planar waveguide structure to couple the RF signal into/out of the devices requires a low-loss dielectric to isolate DC coupling and carry the RF signals. Absence of dielectric material beneath the metal pads of the waveguide will cause the RF signal to leak into the substrate before reaching the devices. BCB is an ideal dielectric material for having high breakdown voltage, small dissipation factor and dielectric constant.

The experiments discussed in this work are focused on two major goals to be compatible to the fabrication process. The first target is to expose a clean semiconductor aperture in the BCB etch-back process so that optical output uniformity is not affected by the BCB residue of random shapes and sizes as shown in Fig. 1 [2]. The second target is to ensure the smoothness of the BCB surfaces after etching to maximize adhesion to the top metal contact layer. Poor adhesion may result in metal peeling off during probe testing and wire bonding.

Reactive ion etching Process of BCB

The BCB-based resin discussed in this work are Dow CYCLOTENE™ 3022 series resins which contains silicon in its backbone polymer. It is a common practice to selectively removed BCB material through reactive ion etching (RIE). An RIE process chamber consists of a grounded shower head and a bottom electrode with negative self-bias. Plasma is generated in the process chamber and reactive ions species are attracted to the bottom electrode where processing wafers are placed. The etching is realized with both chemical reaction and physical sputtering.

Process gases used for BCB plasma etching are SF6, O2 and N2 [3]. Fluorine ions in SF6 are aimed to remove Si and O2 serves as the main reactant to burn away other organic polymers. Insufficient SF6 will results in the formation of SiO2 in a O2 rich environment. The nonvolatile product SiO2 can only be removed through further reactions with fluorine ions. It is more likely to accumulate in random shapes and block further etching, producing in a rough etching surface. On the other hand, abundant SF6 will cause the lack of main reactant O2 and induce uniformity issues due to a slow etching rate. Previous works [3] have shown that the optimal ratio of SF6 to O2 is approximately 1:4 which should apply universally in most properly designed RIE systems. The third process gas N2 does not react with either polymer or silicon. However, it will participate in the phsycial etching process instead of simply diluting the reactive process gases. It is theorized to remove silicon through physical bombardment and create active centers to assist in the reactive etching process. Consistent increase in the etching rate is observed in our experiments by adding a small amount of N2 in addition to SF6 and O2.

Besides gas ratios, the remaining factors affecting the dry etching process are mainly temperature, plasma power and pressure. Temperature is mostly a problem of process control. Lacking temperature control will let heat buildup on processing wafer, causing the drifting of the etching rate and surface profile. High temperature will also favor formation of SiO2 which may cause a similar case as lack of fluorine ions. Modern RIE system has helium backside cooling to assist in the temperature control. The plasma power will determine the bias between the grounded showerhead and the self-biased lower electrode which attracts the process ions. Higher power will induce stronger electric field and physical bombarding effect. Pressure affects the process in a similar mechanism. Molecules having longer mean free path under lower pressure accelerates for a longer period in the electric field. As a result, the ions will carry higher energy when bombarding the wafer. The optimal configurations of pressure, power and temperature could vary drastically with different designs and conditions of the process chamber. The following experiments will focus on methods to locate the optimal process windows of an unfamiliar RIE tool.

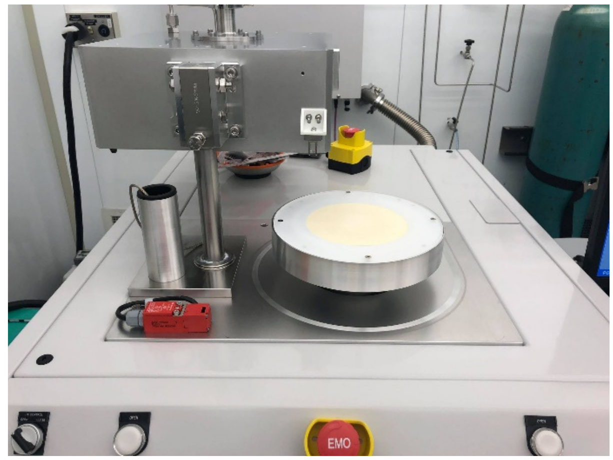

Fig. 2. Oxford PlasmaPro 80 RIE system with alumina carrier wafer installed on the lower electrode.

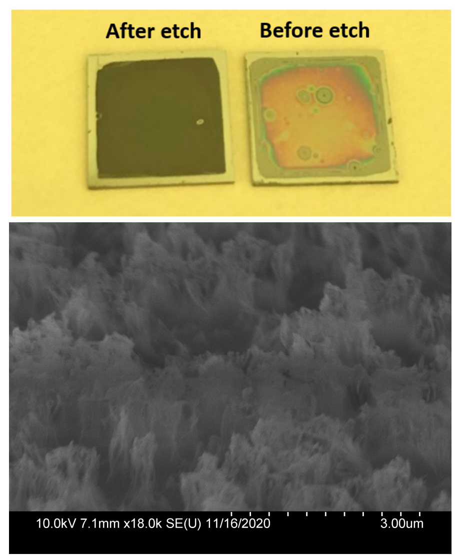

Fig. 3. (a) BCB sample before etching and after etching. (b) SEM picture of etched BCB surfaces with server roughness.

Experimental Results & analysis

Samples for experiments are prepared by spin coating BCB solvent (Dow CYCLOTENE™ 3022 series resins) on 1.2x1.2cm N-doped GaAs wafer pieces. The coated samples are then cured in oxygen free oven for three hours at 250 °C.

The solidified BCB thickness after cure is 3.1 µm. Etching experiments are carried out with Oxford PlasmaPro 80 RIE system as shown in Fig 2. while varying the setup and configurations. The RIE system is designed for whole wafer processing. For small wafer pieces in our case, 6-inch alumina wafers are initially chosen as the carrier wafer.

The experiments start with a recipe transferred from a different RIE tool. 10 sccm SF6 and 40 sccm O2 are used as the process gases. The RF power and pressure are set to be 60 W and 50 mT. The initial results are shown in Fig. 3. After a 2 µm BCB etch, the semi-transparent BCB thin film turns completely black, indicating a macroscopic roughness issue. In this case, MProbe can be used for quickly analysis. MProbe is a reflectance spectroscopy tool for thin film thickness measurement. A smooth thin film surface will reflect most of the light power back to the detector while a rough surface diffuses some of the light in random directions. A comparison is shown in Fig. 4(a) and 4(b). The light spot from an etched sample observable with naked eyes indicates beam diffusion from rough surfaces. The surface roughness can therefore be estimated based on the compression ratio of the measured spectrum as compared to the calculated results. An example is illustrated in Fig. 4(c) where the red measurement curve shows the measured spectrum, and the blue curve shows the theoretical calculations. The peak-to-peak amplitude can be used to characterize roughness while the alignment of peaks and valleys identifies the thin film thickness.

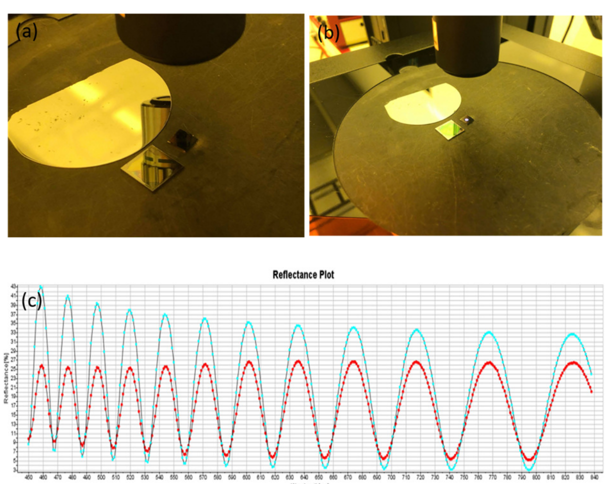

Fig. 4. (a) BCB surface before etching placed under light beam showing no light diffusion. (b) An etched BCB film diffuses light beam. (c) Measured reflectance spectrum of a thin film with rough surface.

The DOE experiments to improve surface condition starts from the tuning of RF power. After reducing the power from 60 W to 20 W, the etching surface condition improves significantly. The reflectance measurement can no longer detect any roughness. However, nano-scale residues remain if observing using scanning electron microscopy (SEM). The results are displayed in Fig. 5. The SEM picture focuses on the edge of a circular GaAs mesa structure resembling the case of a VCSEL device aperture. The mesa structure was originally covered with ~1 µm BCB. After etching to expose the circular mesa, dense residues are found on top of both the semiconductor and BCB surface. The residue size is measured to be 40-60 nm. Further reducing the RF power does not improve the residue condition which makes 20 W the optimized power setting.

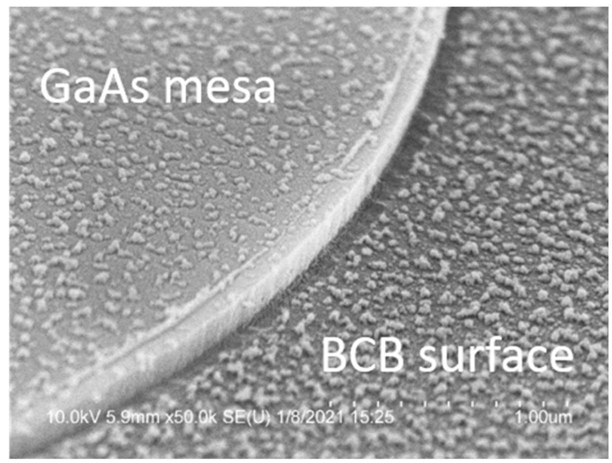

Fig. 5. Improvement from macroscopic roughness to nano-scale residues after reducing power from 60 W to 20 W.

We then start varying the chamber pressure while keeping the RF power constant at 20 W. 30 mT, 50 mT and 90 mT have been tried separately to etch 1.4 µm BCB. The results are observed with SEM and the residue scales are measured at 200K magnification. As shown in Fig. 6, 50 mT process produces dense 40-60 nm residues. Reducing the pressure to 30 mT will cause more sever intertwined residues while increasing the pressure to 90 mT reduces the residue sizes to 20-40 nm. The distribution of the residues is also sparser in comparison to the previous cases.

Since lower power and higher pressure both improves the surface condition, the roughness and residue are hypothesized to be caused by excessive physical sputtering. However, optimal RF power window has been determined and 90 mT pressure has reached the upper limit supported by the turbo pump. To further reduce the sputtering effect and residues, a 6-inch conducting silicon wafer is used in place of the insulating alumina wafer as the carrier. Small wafer pieces placed on top of insulating carrier may accumulate negative charges during process, resulting in higher local field and stronger sputtering effects. This is also supported by fact that the displayed DC bias increases from 33V to 44V with 20 W RF power after switching to the silicon carrier. It suggests the insulated process wafer surface potentially has a lower potential than the lower electrode. The expected improvement is displayed in Fig. 6 (d) where the particle size on BCB etching surfaces further reduces to < 20 nm.

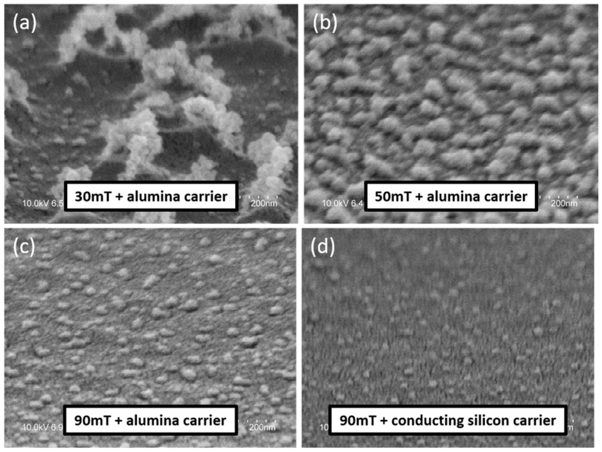

Fig. 6. (a)(b)(c) BCB surface under SEM at 200K magnification after 1.4 μm BCB etch down with 20 W RF power and pressure varying from 30 mT to 90 mT. Alumina wafer is used as the carrier (d) Improved surface condition after switching to a conducting silicon carrier.

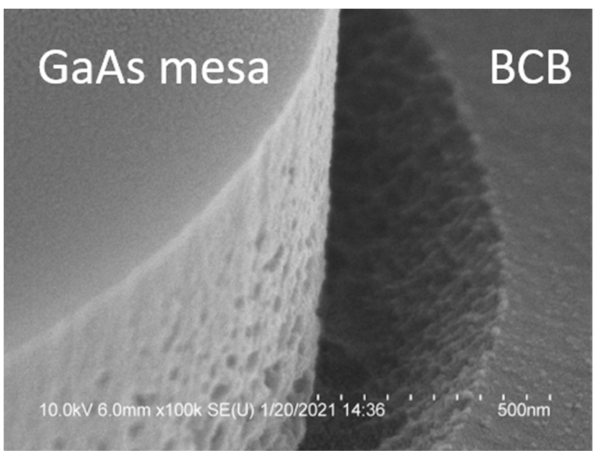

Fig. 7. Clean semiconductor mesa surface and smooth BCB surface after etching with optimized recipe.

The final optimized recipe is therefore set to be 20 W RF power, 90 mT pressure with conducting silicon wafer carrier. Gas ratio of SF6 to O2 is kept being 1:4. The mesa sample etching results are shown in Fig. 7. Compared to results in Fig. 5, a clean semiconductor surface and a smooth BCB surface are simultaneously achieved.

Conclusions

A BCB RIE dry etching process is developed for high-speed VCSEL and PD fabrications. The theory of etching BCB is first explained and DOEs are discussed in detail to identify the optimal process window of an RIE system. The optimized recipe produces smooth etching surfaces with minimum residue.

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Reference

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ACRONYMS

VCSEL: Vertical Cavity Surface Emission Laser
BCB: Benzocyclobutene
SEM: Scanning Electron Microscopy