Reactive Ion Etching of Benzocyclobutene Using a Silicon Nitride Dielectric Etch Mask

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ABSTRACT

The feasibility of patterning a cured polymeric film of benzocyclobutene (BCB) using silicon nitride (SiN_x) as an etch mask was investigated. Due to the carbon- and silicon-containing composition of BCB, a gas mixture with oxygen- and fluorine-containing components is required, which unfortunately also etches SiN_x. Therefore, a reactive ion etching process with high selectivity between the etch rates of the BCB, CYCLOTENE™ 3022-46, and the SiN_x was developed. We have investigated the dependence of the etch rates as a function of the CF_4 content in the O_2/CF_4 gas mixture. The surface morphology and the angle of the etched BCB sidewall were determined using a scanning electron microscope. A process with 37.5% CF_4 content was defined, exhibiting etch rates of 155 and 14 nm/min for the polymerized BCB and the SiN_x, respectively. This yields a selectivity of 11:1. The morphology of the etched BCB surface is smooth. Depending on the shape of the SiN_x etch mask, sidewall angles of the BCB structure between 70° and 80° were obtained. These inclinations allow an effective deposition of a contact metallization. For further technological processing, a residual dielectric SiN_x film can be left on the structure when the BCB layer is etched.

Introduction

Increasing demands for miniaturization, speed, and densification of microelectronic components have led to the necessity of developing new polymeric dielectric materials. Various requirements must be fulfilled by these polymers. Easy processing, good planarization behavior, a low dielectric constant, and good mechanical properties are some of the most important aspects.

Dielectric polymers based on benzocyclobutene (BCB) fulfill these requirements very well.[1-8] These thermoset films are derived from prepolymerized monomers which are dissolved in mesitylene. The polymerization of BCB takes place at a temperature range from 200 to 300°C. Low moisture absorption and excellent stress behavior, as well as good adhesion to metals (such as copper, gold, or aluminum) are additional advantages. These aspects have led to widespread applications of BCB dielectric polymers in the field of multichip modules (MCM) [1,2,5,7] and very large scale integrated (VLSI) circuit fabrication.[3,4,6,8] Because of its outstanding planarization behavior [degree of planarization (DOP) > 90%] and its low dielectric constant ($\epsilon_r = 2.7$), BCB is the favored material for interlayers in multilevel interconnection structures.[4]

BCB dielectric polymers are of great interest in the fabrication of Si and GaAs integrated circuits. These films also offer a wide range of potential applications in the area of optoelectronic integrated circuits (OEICs), where they can be used as light-guiding layers as well as for dielectric interlayers to optimize the high-speed characteristics of optoelectronic components (*e.g.*, laserdiodes, photodiodes).

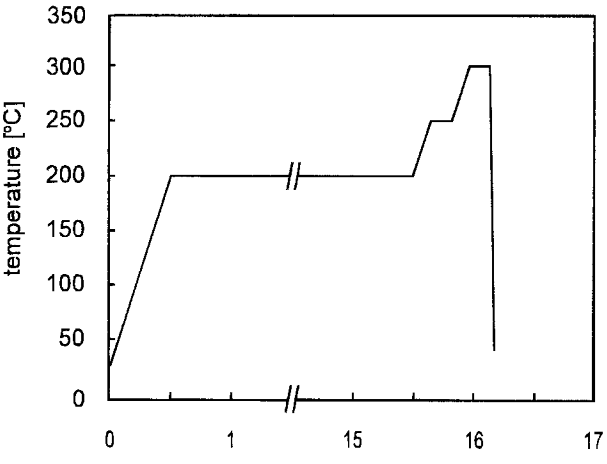

Fig. 1. Temperature ramp used for polymerization of the BCB, CYCLOTENE™ 3022-46.

In all these cases, the challenge is the patterning of the polymerized benzocyclobutene. Unfortunately, cured BCB films exhibit high resistance to wet chemical etching.[1,2,6,8] Therefore, we must use plasma etching techniques to create exact patterns. As previously reported, mixtures of oxygen- and fluorine-containing gases (*e.g.*, CF_4, SF_6) have been successfully employed.[1-3,6,8] Etch rates greater than 1.5 μm/min have been achieved.[8] Although there are numerous publications concerning the patterning of BCB films, the use of a dielectric etch mask (*e.g.*, SiN_x, SiO_2, Al_2O_3) has not yet been investigated in detail. Aluminum and copper films were mostly used as nonerodible masking materials[1,3,6,8] which must be removed after the polymerized BCB layer is etched. The main problem that appears when using dielectric films as the masking material is their relatively high etch rate in fluorine-containing gas mixtures. Therefore, we needed to find etching conditions that combine a high etch rate of the BCB polymer with a simultaneously low etch rate of the dielectric mask.

The intention of the present work was to define a process which makes it possible to pattern a BCB film by reactive

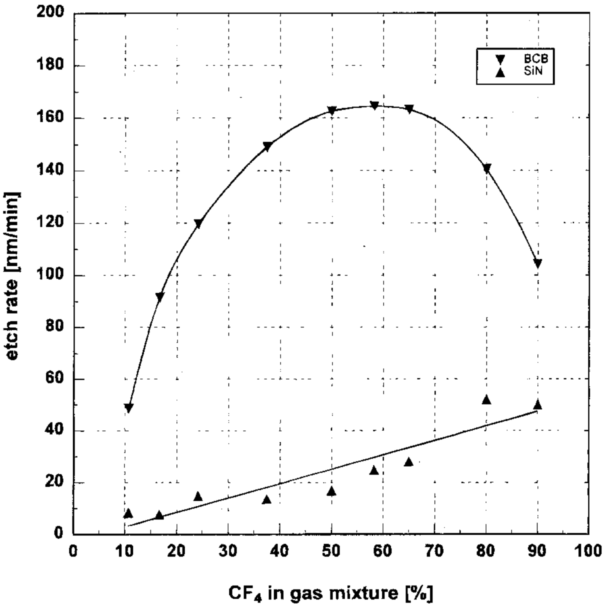

Fig. 2. Etch rates of silicon nitride and cured CYCLOTENE™ 3022-46 as a function of the gas composition. The selectivity of 11:1 is obtained at a CF_4 content of 37.5%.

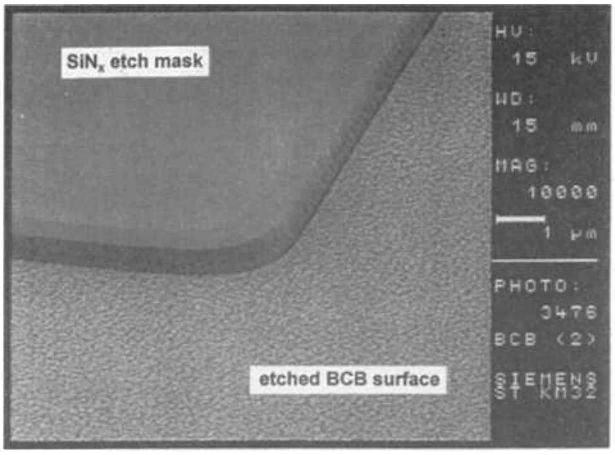

Fig. 3. Rough surface morphology of the benzocyclobutene, obtained at 10% CF_4 content, resulting from a silicon-rich surface layer.

ion etching (RIE), using a dielectric mask that can be left on the device structure for further process steps. The studies were carried out using silicon nitride (SiN_x) as the masking material. The influence of the O_2/CF_4 gas composition on the etch rates of BCB and SiN_x was determined. With these data, an RIE process with high selectivity with respect to the etch rates of the dielectric polymer and the etch mask has been developed.

Experimental

To determine the etch rates of cured BCB and the masking SiN_x, a multilayer test structure on InP substrates was used.

A 200 nm thick silicon nitride layer was deposited onto the InP carrier material by plasma-enhanced chemical vapor deposition (PECVD) at a temperature of 300°C, employing an SiH_4- and NH_3-containing gas mixture. Then, the BCB dielectric was applied to the wafer by spin-on coating. In the present work, the BCB solution, CYCLOTENE™ 3022-46,[9] was employed. At 5000 rpm, a layer 2.3 µm thick was obtained. The curing was carried out using a resistance heated molybdenum plate and the temperature was controlled with a calibrated thermocouple element which has been welded to the lower side of the plate. Figure 1 shows the temperature schedule used to polymerize the BCB film under argon atmosphere. In a first step, the wafer was heated with a ramp of 6°C/min from room temperature to 200°C. Then, the temperature was kept constant for 15 h. After that time, the temperature was raised with the same gradient to 250°C for 10 min and up to 300°C, also for 10 min. After cooling, the cured BCB film was coated with a 300 nm thick PECVD silicon nitride layer. A test pattern was defined in this SiN_x top layer using conventional contact lithography and wet chemical etching. Eventually, the photoresist was removed with acetone.

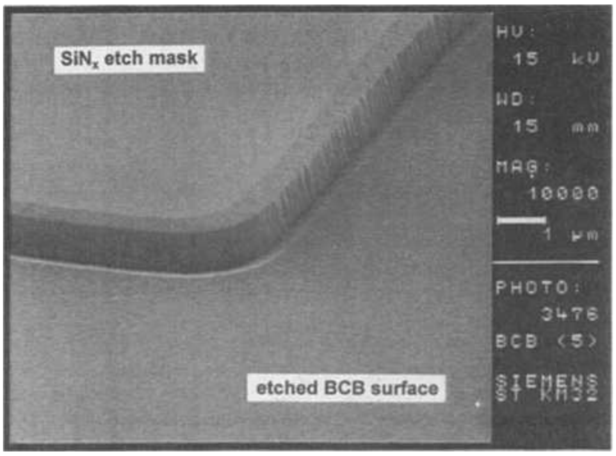

Fig. 4. Surface morphology of the benzocyclobutene when etched with 37.5% CF_4.

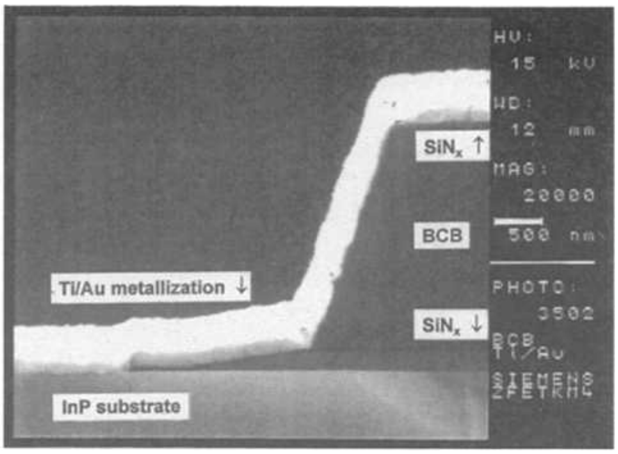

Fig. 5. SiN_x (200 nm)/BCB (2.5 µm)/SiN_x (300 nm) sandwich structure. The angle (70°) of the etched step is well suited for vertical evaporation of the contact metallization (60 nm Ti/500 nm Au).

The RIE studies were carried out using a Leybold Z 401 S parallel-plate reactor and an O_2/CF_4 gas mixture. The thickness of the residual SiN_x etch mask and the depth of the etched pattern in the BCB were measured with a Tencor alpha-step 200™. The dependence of the etch rates of the polymerized CYCLOTENE™ 3022-46 and the silicon nitride masking material on the gas composition were investigated and the selectivity was determined. The CF_4 content in the gas mixture was varied from 10 to 90%. The RF power and operating pressure remained constant at 50 W and 0.02 mbar, respectively. Using a scanning electron microscope, the morphology of the treated BCB surface and the inclination of the sidewall of the etched BCB pattern have been controlled.

Results and Discussion

The etch rates of the cured CYCLOTENE™ 3022-46 and the silicon nitride masking material as a function of the CF_4 percentage in the gas mixture are shown in Fig. 2. In the region of 55 to 60% CF_4 content, the etch rate of the BCB has its maximum value of about 165 nm/min. Above and below this region, the etch rate decreases significantly. This maximum seems to be due to at least two competing mechanisms. We relate this to the composition of the CYCLOTENE™ 3022-46 which contains considerable amounts of carbon and silicon.[1,2,4,5,7] For low CF_4 content, Si cannot be completely transformed into the volatile compound SiF_4, leading to a silicon-rich surface layer which is removed at a low etch rate. As shown in Fig. 3 and 4, another indication of this effect is an increasing roughness of the morphology of the etched BCB due to micromasking caused by the higher Si content atop the surface. For too high CF_4 percentages, however, the gas mixture lacks oxygen, required to oxidize the carbon content, leading also to a decrease in the etch rate.

The etch rate of the masking dielectric SiN_x steadily rises from 8 nm/min at a CF_4 fraction of 10% (physical etching dominates) up to 52 nm/min at 90% CF_4 in the gas mixture (chemical etching dominates). The highest selectivity combined with a smooth surface morphology and a suitable etch rate for the cured BCB material was found at a gas composition containing approximately 37.5% CF_4. At this fraction, the etch rates for BCB and SiN_2 are 155 and 14 nm/min, respectively. The corresponding selectivity is 11:1. This is sufficient to apply a silicon nitride layer <300 nm thick for pattern definition in a 3 µm thick polymeric film.

The inclination of the etched step in the BCB primarily depends on the angle of the sidewall of the silicon nitride etch mask. This angle in the SiN_x is influenced mainly by the process used to define the pattern in the etch mask. In our case, wet chemical etching was employed, leading to sidewall angles of about 30°. Because the silicon nitride mask is etched while patterning the BCB, this sidewall angle is transferred into the BCB approximately as the ratio of the etch rates of SiN_x and BCB. We obtained a final inclination angle in the CYCLOTENE™ 3022-46 layer in the range of 70° to 80° as shown in Fig. 5. This figure shows a 2.5 μm thick patterned BCB film which was spun onto a 300 nm thick SiN_x layer. On top of the BCB, the residual 200 nm thick silicon nitride etch mask can be seen. After the BCB was patterned, a contact metallization consisting of a 60 nm thick titanium layer and a 500 nm thick gold layer was evaporated vertically onto the SiN_x/BCB/SiN_x sandwich structure. As the micrograph clearly shows, the sidewall angle of the etched BCB layer is well suited for applying metallization layers.

Conclusion

Dielectric polymers derived from BCB are promising materials in advanced chip fabrication. We have reported here on the feasibility of patterning polymerized benzocyclobutene with silicon nitride as the dielectric masking material. RIE with an O_2/CF_4 gas mixture was employed. The etch rates of the BCB, CYCLOTENE™ 3022-46, and the silicon nitride were determined as a function of the gas composition. With increasing CF_4 content, the etch rate of SiN_x rises steadily, whereas the etch rate of the polymeric dielectric shows a maximum value of 165 nm/min between 55 and 60% CF_4 fraction. A process with a high selectivity of 11:1 between the etch rates was developed using a CF_4 content of 37.5%. It creates a smooth surface in the etched BCB and a sidewall angle between 70° and 80°. It has been shown that this angle is suitable for subsequent deposition of a contact metallization by vertical evaporation.

This process offers a further possibility of employing BCB in OEICs for dielectric interlayers. A further improvement in the selectivity of the etching process may be obtained by the use of different dielectric films. For example, SiO_2 or Al_2O_3 empirically have smaller etch rates than silicon nitride when exposed to an oxygen- and fluorine-containing RIE process. But above all, the masking material must fulfill the requirements of the applied device technology.

Acknowledgment

The author thanks G. Franz for valuable discussions as well as G. Baumeister and Ch. Lauterbach for technical assistance. This work has been supported partly by the RACE Program R 2070 MUNDI.

Manuscript submitted Feb. 14, 1995; revised manuscript received May 31, 1995.

Siemens AG asissted in meeting the publication costs of this article.

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