Microelectronic Engineering 161 (2016) 63–68

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Research paper

Benzocyclobutene dry etch with minimized byproduct redeposition for application in an InP DHBT process

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ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 3 March 2016
Accepted 10 March 2016
Available online 8 April 2016

Keywords:
InP
BCB
RIE
ICP
Dry etch
Redeposition
SF_6
O_2
Al_2O_3

ABSTRACT

In this article we report on the reduction of redeposition during inductively coupled plasma (ICP) etching of benzocyclobutene (BCB) with a soft mask in a sulfur hexafluoride/oxygen (SF_6/O_2) plasma. We have developed an anisotropic ICP recipe to fabricate vertical interconnects through BCB for our indium phosphide (InP) transferred-substrate DHBT technology. In this context the new recipe has an etch inhomogeneity on 3 in. wafer of <1% 3-sigma based on the total BCB thickness. The origin of residuals post resist ashing consisting of Al, F, and O was traced back to reactor chamber parts made from Al_2O_3. The amount of redeposition appears to be minimized with lower chamber pressure. We saw an impact of different substrate carrier materials on the amount of redeposition, etch rate, and bias. Remaining deposits could be removed in a wet chemical final rinse, which was based on diluted tetramethylammonium hydroxide (TMAH). With the new high density plasma recipe the BCB etch rate could be increased fivefold while maintaining excellent lateral structure fidelity and minimizing etch byproduct redeposition.

1. Introduction

Terahertz (THz) technology has been at the center of attention in recent years [1], for applications in medicine and biology [2], high resolution radar, communication, terahertz imaging, standoff chemical agent detection, astrophysics, and many more [3]. InP double heterojunction bipolar transistors (DHBTs) are of particular interest for THz applications due to their high cutoff frequencies paired with high RF output power density. The best reported InP DHBTs reach cutoff frequencies of f_t/f_{max} 404/901 GHz, respectively [4].

Extrinsic base-collector feedback capacitance related to classic triple mesa HBTs is avoided in our transferred-substrate (TS) technology, as illustrated in Fig. 1. The full integration includes InP DHBTs in single- and multifinger geometry with 0.8 μm emitter width, three layers of electroplated gold interconnect, as well as thin-film resistors and capacitors for realization of monolithic microwave integrated circuits (MMICs). The $0.8 \times 6\ \mu m^2$ single-finger InP DHBT biased at VCE = 1.5 V draws a collector current of 28 mA and exhibits f_t/f_{max} 360/330 GHz, respectively [5].

Many InP DHBT circuit integration schemes rely on BCB for planarization and as an interlayer dielectric. In our case, we also use BCB for adhesive wafer level bonding in the transfer substrate process. Divinyl siloxane bis-benzocyclobutene (DVS-bis-BCB) is a low-*k* dielectric which is well-suited for THz applications due to its low loss tangent of 7×10^{-3} at 1 THz [6]. Furthermore, BCB offers a high breakdown field of 5.3×10^6 V/cm, low leakage current of 6.8×10^{-10} A/cm², and low moisture absorption of <0.2%. Its low processing temperature (full cure can be achieved in less than one hour at 250 °C) makes BCB very suitable for InP device applications. BCB starts reflowing at 350 °C, allowing for a wide temperature process window [7].

In our InP DHBT process we need at least 21 lithography process steps to fabricate the complete MMIC. At first we deposit metallic contacts to the emitter (E) and base (B), after which the emitter-base-diode is encapsulated and planarized with BCB as shown in Fig. 1. The emitters are electrically connected using an electroplated gold layer (GD) which also functions as a heat sink. Subsequently, the wafer is planarized again and bonded to an aluminium nitride (AlN) [8] or to a fully processed BiCMOS wafer [9] using adhesive wafer bonding. Post wafer bonding, the InP substrate is removed, the collector contact metal is added (C) and used as an etch mask for collector mesa definition. After collector planarization with BCB, vertical interconnects (vias) to the base (V1), the emitter ground plane (VG) and to the AlN transfer substrate (VX) are etched. The via (VX) couples the electroplated RF ground plane thermally to the AlN transfer substrate. Following via fabrication, the bottom plates of the capacitors are formed, and a second gold interconnect (G1) is electroplated. A BCB layer again planarizes the subjacent layers. A two-step BCB etch (V2) forms the capacitor and provides access to the previous electroplated

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http://dx.doi.org/10.1016/j.mee.2016.03.024
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layer. Finally, the capacitor dielectric is deposited and a third electroplated gold layer (G2) provided.

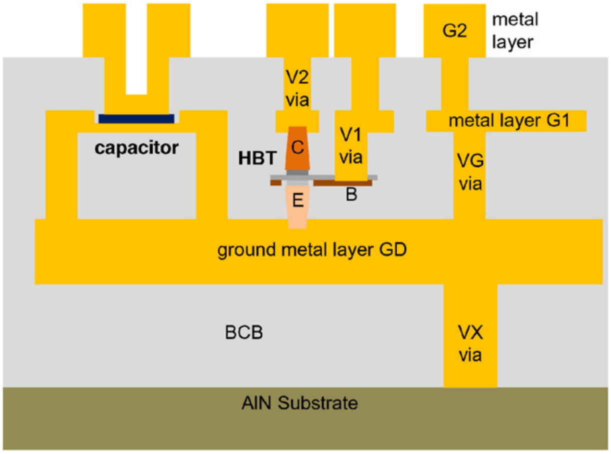

Fig. 1. Cross section of our InP DHBT process with aluminium nitride transfer wafer.

In our InP DHBT transfer substrate process there are planarization, via and trench etch processes which require a total of 25 μm BCB removal on each wafer. With the usual RIE process we achieved an etch rate of only 60 nm/min which turns into a bottleneck due to the number of needed etch steps in single-wafer processing. In this article we report on the development of a ICP etch process as a replacement for the reactive ion etching RIE process. Additional focus of this report is the identification of plasma by-products and their removal.

2. Experimental

The landing pad material of a contact hole etch in an InP HBT process usually consists of electroplated or evaporated gold. In our mechanical model system an evaporated layer stack of 30 nm titanium (Ti), 40 nm palladium (Pd) and 20 nm Ti was used, as shown in Fig. 2. Ti acts as an adhesive layer to both, silicon and BCB. The Pd acts as a reliable etch-stop. Two BCB formulations (CYCLOTENE 3022-35 and -46) with 2.5 μm and 4 μm thickness, were used for planarization and shallow via etching, respectively. BCB was cured at 240 °C for 90 min in nitrogen (N_2) atmosphere in a dedicated BCB curing oven (YES-PB6-2P-CP). Experiments concerning etch uniformity were performed without an etch mask. Photoresist (AZ nLOF 2035, MicroChemicals GmbH) with a thickness of 5.5 μm exposed in an i-line step-and-repeat lithography tool (Nikon i12) was used as an etch mask for shallow via etching. BCB dry etching was performed using an ICP-RIE plasma etcher (SI 500, Sentech Instruments GmbH) and an RIE plasma etcher (SI 591, Sentech Instruments GmbH). In-situ process control was performed with a laser interferometer (NANOMES, GFMesstechnik GmbH). For scanning electron microscopy (SEM) we used a Hitachi S4800. BCB layer thickness was measured using an ellipsometer (SE400adv, Sentech Instruments GmbH) and a reflectometer (RM2000, Sentech Instruments GmbH). Material analysis was performed using an SEM (Zeiss Ultra+) with energy-dispersive X-ray spectroscopy (EDX).

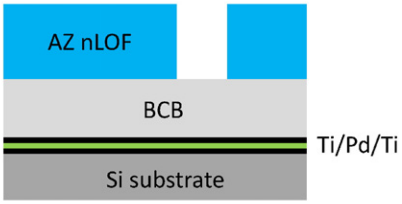

Fig. 2. Cross section of our mechanical model system for the experimental setup.

3. Basic principles for BCB dry-etching

The most prevalent method of BCB structuring is reactive ion etching, used with either soft [10,11] or hard masks [12,13]. Dielectrics such as Si_xN_y or Si_xO_y, as well as metal films are considered hard masks [14–16], photo resists are referred to as soft masks [17]. While hard masks are superior to soft masks in etch selectivity [18], they need at least one additional process step for their application since the lithographic resist pattern must be transferred into the hard mask material. A further drawback is the necessary chemical process compatibility of the hard mask itself, and of the hard mask stripping agents, such as acids or bases used for metal mask removal, or hydrofluoric acid used for SiO_2 and Si_3N_4 mask stripping. Also, the removal of a hard mask layer is more work intensive compared to photoresist. It is recommended to etch BCB in oxygen and fluorine plasma due to the presence of silicon in DVS-bis-BCB. Suggested gas mixtures for BCB dry etching by the manufacturer are fluorine radical generating gases such as CF_4, C_4F_6, C_4F_8, SF_6, and NF_3, mixed with O_2 [7]. The effects of power, pressure and etch gas composition were evaluated in [10–22]. Common gas compositions are O_2 with CF_4 or SF_6 with a 4:1 and 5:1 ratio, respectively. RIE power settings of 50 W to 550 W combined with pressures of 50–500 mTorr resulting in etch rates of 0.25 μm/min to 1.6 μm/min. Increasing the concentration of SF_6 to >10% SF_6 in O_2 leads to a decrease in etch rate. At the same time, however, the anisotropic nature of the etching is maintained [10,12,14]. An increase in pressure towards 200 mTorr leads to significantly higher etch rates, in this case a strong reduction in anisotropy is observed. Both anisotropy and etch rate can be enhanced by increasing the RIE power, which also results in a higher etch bias [12].

4. Results and discussion

4.1. Shallow BCB via etching

The approach outlined above was chosen for the development of a new etching recipe. We used a gas ratio of O_2:SF_6 of 4:1, a pressure of around 7.5 mTorr (see Table 1) and RIE power between 100 W and 200 W. An increase in the RIE power caused an increase in the etch rate, a higher anisotropy, and higher bias against the bottom electrode (substrate). The bias was continuously monitored to be kept as low as in the reference process (350 V) to avoid additional bias induced damage [23].

As shown in Table 1, the top recipe was very similar to the existing reference RIE recipe (BCB etch rate of 60 nm/min at 100 W RIE power, 7.5 mTorr, 3 sccm SF_6 and 7 sccm O_2). The gas flows were increased. The observed etch rate of 75 nm/min at 100 W RIE power was comparable to the reference RIE etch rate of 60 nm/min. In order to increase the etch rate, we added ICP power via the antenna located on top of the etch chamber. The ICP excitation frequency was 13.56 MHz. Satisfying anisotropy is achieved by keeping the ICP:RIE (inductively coupled to capacitive coupled) power ratio below 1:2. High etch rates of 300 nm/min and acceptable bias of 350 V were achieved with 100 W ICP power, 200 W RIE power and an SF_6/O_2 gas flow ratio of 5 sccm:

Table 1
ICP recipe variations for BCB dry etching.

SF_6 [sccm]	O_2 [sccm]	ICP [W]	RIE [W]	Pressure [mTorr]	Etch rate [nm/min]	Bias [V]
5	20	0	100	7.5	75	200
5	20	0	200	7.5	120	350
5	20	50	100	7.5	120	235
5	20	100	100	7.5	220	230
5	20	100	200	1.5	300	340
5	20	100	200	3.7	300	350
5	20	100	200	7.5	300	350