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Inductively coupled plasma reactive ion etching of sapphire using C_2F_6- and NF_3-based gas mixtures

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Inductively coupled plasma reactive ion etching (ICP-RIE) of sapphire wafers using C_2F_6- and NF_3-based plasma was investigated as a function of ICP power, bias power, pressure, and plasma chemistry. Etch rate of about 150 nm/min in the case of C_2F_6 plasma and about 260 nm/min in the case of NF_3 plasma was obtained at the optimum condition, with anisotropic profiles and smooth surfaces. No chamber corrosion was observed after the etching, indicating that ICP-RIE using the fluorine-related gases is a promising technique for sapphire patterning.

1. Introduction

Sapphire (Al_2O_3) wafers are widely used as the substrate material to grow epitaxial thin films for optoelectronic devices, such as III-nitrides and ZnO. It is often necessary to etch and pattern the sapphire substrate surface to grow hetero-epitaxial films with low defect density. For example, it has been reported that density of the mismatch dislocations can be significantly reduced utilizing the lateral epitaxial patterned sapphire technique [1–3], in which pre-patterned substrates are used to induce lateral growth of the GaN layer.

As sapphire (Al_2O_3) is inert to most of the chemical solutions, it is inevitable to utilize dry etch techniques to pattern the material. Most of the recent studies on the dry etching of sapphire utilizes inductively coupled plasma (ICP) reactive ion etching (RIE), as this technique provides high etch rate, clean and low-damage surfaces, and vertical profile, due to highly directional ion flux with low and controllable ion energies at low pressure [4–9].

So far, systematic studies on ICP-RIE of sapphire have been only reported using chlorine-related chemistry [4–9]. It is desirable to use fluorine gases for the etch in many cases; however, the chlorine-related plasma is toxic and often causes corrosion of the chamber and vacuum pumps. In this paper, ICP-RIE characteristics of sapphire films were investigated as a function of various process variables, using C_2F_6- and NF_3-based gases. These gases are widely used for dry etching of Si, due to their low PFCs emission characteristics compared to conventional CF_4 and SF_6 gases.

2. Experimental

The ICP reactor used in this study was a home-made instrument, utilizing a 13.56 MHz RF power sources for the ICP power and a separate 13.56 MHz supply for the bias application. Experiments were performed on lower (sample) electrode of 10-in diameter in the main chamber and the samples were loaded through a pre-chamber.

Samples used in this study were 2 in (0 0 0 1) sapphire wafers. Etch characteristics were studied as a function of ICP power (800–1100 W), bias power (100–400 W), and chamber pressure (4–16 mTorr) with total gas flow fixed at 35 sccm. Experiments were performed using a 0.35-μm thick Cr etch mask, deposited by an RF magnetron sputter and patterned using the conventional lift-off technique.

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A scanning electron microscope (SEM, Hitachi S-4700) and an atomic force microscope (AFM, Digital Instrument Multimode SPM) were used to observe etch profile and surface roughness. The etch depth was measured using cross-sectional SEM photographs imaged from a vertical angle, which give more precise numbers than the side-view images shown in Fig. 1. An X-ray photoelectron spectroscope (XPS, ESCALAB 250) was also employed to measure the surface contamination.

3. Results and discussion

Figs. 1 and 2 show effects of various process variables on the etch characteristics of the C_2F_6 and the NF_3 ICP-RIE. All samples in this experiment were processed at 1100 W ICP power and 8 mTorr pressure except for the process variable under discussion. Bias power applied for the experiment was 400 W in the case of C_2F_6 and 250 W in the case of NF_3. It is observed that etch rate and roughness of the etched surface increase with increasing ICP source power (Figs. 1a and 2a) and increasing bias power (Figs. 1b and 2b). In the case of process pressure (Figs. 1c and 2c), etch rate and surface roughness slightly decrease with increasing pressure. Data points in Figs. 1 and 2 represent three to five separate etching experiments. Very similar results were obtained among the samples, as noticed by the small error bars.

It is believed that the etch rate is enhanced with increasing ICP power as the density of radicals and ions within the plasma increases. With increasing bias power, self-bias applied to the samples and kinetic energy of the impinging ions increase, resulting in higher etch rate [10,11]. Etch rate decreases with process pressure because the mean free path of the radicals and ions and their kinetic energy decrease due to frequent scattering [10,11].

It is observed that the etched surface morphology becomes rougher at higher ICP power and higher bias power (Figs. 1 and 2). It has been suggested that rough surfaces result from several factors during dry etching, such as energy of incident ions, difference in the removal rates of substrate components (Al and O) and etch products, and/or size of the atomic cluster removed from the surface [11,12]. It is believed that rougher surface is obtained as the ion energy and the etch rate increase with increasing ICP and bias power. It has been reported that, the fluorine-based, plasma fluorinates the aluminum oxide surface layer through the particle bombardment activated reaction, producing etch products in the form of AlF_3 or AlO_xF_y, which is nonvolatile but has a higher sputtering yield than aluminum oxide [13]. It is believed that the presence of the nonvolatile fluorine and carbon residues may have been accentuated the roughening of the etched surface.

Fig. 3(a and b) shows a SEM image and an AFM image of a sapphire mesa etched in C_2F_6 plasma at 1100 W CP power, 400 W bias power (−770 V dc bias), and 8 mTorr chamber pressure, for 5 min. Etch rate of about 150 nm/min was obtained, with anisotropic profiles (sidewall angle ~80°) and very smooth surfaces. The AFM measurement indicated ~0.4 nm root-mean-square (RMS) value after RIE, comparable with that of the bare wafer (~0.2 nm). Much higher etch rate of about 260 nm/min is observed in the case of samples etched in NF_3 plasma at 1100–250 W (−400 V dc bias)–8 mTorr (Fig. 3c and d), with anisotropic profiles (sidewall angle ~80°) and slightly rougher surfaces (AFM RMS ~4.1 nm). Application of higher bias power (Fig. 4) resulted in higher etch rates, ~200 nm/min in the case of 600 W in C_2F_6 (Fig. 4a) and ~400 nm/min in the case of 400 W in NF_3 (Fig. 4b), but the mask was severely eroded, resulting in sloped mesas with rough surfaces.

It has been reported that ICP-RIE using chlorine-related gas plasma results in etch rate of 100–200 nm/min at 600–700 W ICP power and −150~−250 V bias voltage in $BCl_3/Cl_2/(Ar)$ gas mixtures [4,5,7], ~360 nm/min at 800 W and −300 V bias in $BCl_3/Cl_2/Ar$ [8], and ~550 nm/min at 1400 W ICP power and −800 V bias in $BCl_3/HBr/Ar$ [9]. Considering these reports, it is seen that etch rates reported in this work are generally lower than the etch rates previously reported using the chlorine-related gases [4,7–9]. It is emphasized, however, that the etch rate obtained in this work using the fluorine plasma, 150–260 nm/min, is high enough for most of the semiconductor processing application. It is mentioned that

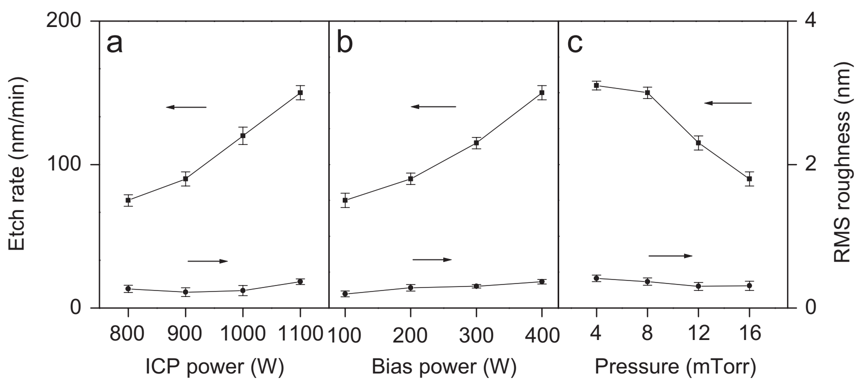

Fig. 1. Effects of process variables on the etch characteristics of sapphire mesas in C_2F_6 ICP-RIE, etched at 1100–400 W–8 mTorr, except for the process variable under discussion.