ECR Based Chemically Assisted Plasma Etching Of GaAs

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Abstract

Etching of GaAs, when plasma of Ar gas is used and CF_4 /O_2 is directed fall on the wafer from another port in Electron Cyclotron Resonance (ECR) source in Chemically Assisted Ion Beam Etching (CAIBE) has been carried out. The plasma source was 2.45 GHz microwave source superimposed with mirror type magnetic field configuration to have resonance. Effect of $CF_4/O_2/Ar$ ratio and substrate bias on etching rate of GaAs and anisotropy of etched profile has been investigated. Etching processes consists of many etching parameters such as the component of radicals and ions in plasma flow of gases, source power, pressure, substrate bias etc. Get maximum high etch rate with use specific ratio of gases CF_4 /O_2 and Ar, pressure $4x10^{-4}$ Torr, source power 700 W, substrate bias –30 V. Etched samples were characterized with Scanning Electron Microscope (SEM) and Dektek 3030ST from Veeco U.S.A.

INTRODUCTION

The effort to reduce the minimum feature size and access higher operating devices frequencies necessitates the use of high-density plasma technology for high resolution, low damage; etch processes in III-V device fabrication. The demand of high-density plasma has been generated by the potential for achieving high etches rates and excellent anisotropy with low substrate damage. [1-3] These etch properties are achieved as a consequence of low operating pressure (< 0.4 mTorr), high plasma density (> 10^{11} cm^{-3}) and the ability to control ion energy and ion density with relative independence typically ECR (Electro Cyclotron Resonance) or ICP (Inductively Coupled Plasma) source have been employed. Etch process based on ECR and ICP plasma generation have been systematically evaluated for GaAs and other III – V semiconductor device development (4-6). However, the use of ECR high-density plasma in the fabrication process for III-V semiconductor materials has been more significantly than other plasma systems because the beneficial features of the ECR plasma are the generation of high-density plasma at low pressure (~10^{-4}/10^{-5}) Torr and low energy ions. [7]

The development of Reactive Ion Etching (RIE) & Chemically Assisted Ion Beam Etching (CAIBE) both modes has achieved very good maturity for etching of silicon and silicon related materials but however some improvement in etching is always been carried out mainly by trial and error on the work front.

RIE has its own specific problems [8]. It give very slow etch rate and acquire unusually high ion energies [9-12] because of self biasing, which varies from few electron volts (50 ev) to few hundred electron volts (500ev)[13] depending upon operational parameters of machine. This results in ion bombardment and finally damage wafer surface, tendency toward the over cut etch profiles & trenching effects familiar in ion dominated dry etching processes. A very attractive alternative is Chemically Assisted Ion Beam Etching (CAIBE), which is equally competitive dry etching technique with many advantageous factors than RIE like high etch rate [14], low ion energy for etching Silicon [15,8,16], SiO_2 [17,18] and semiconductor compound like InP & InSb [19], InAS [20], GaN [14,21,22-25,26,27], GaAs & GaSb [28] and AlGaAs [29].

In ECR plasma there is no self-biasing of the wafer and therefore etching experiments are carried out in Chemically Assisted Plasma Etching (CAPE) mode. However, precise control of ion energy is carried out by additional biasing of the substrate either by rf or dc [13].

In this study, we are investigating use of CF_4 and Ar gas to find out suitable conditions for etching of GaAs in ECR plasma. We choose CF_4 because F based chemistry is necessary for achieving high etch rate [15] and Ar was selected as primary buffer gas, which is used in many applications [30]. This mixture of CF_4 and Ar are used in plasma etching of Silicon [31-33].

As we know etching depends upon various parameters like component of radicals, ions in plasmas, flow of gases and dc bias, so it is more difficult to select the most suitable conditions for various etching processes. Therefore, it becomes more necessary to understand the effect above parameters on etching performance and hence this study. Effect of % Ar, bias on etch rate and anisotropy of etched profile has been carried out.

EXPERIMENT

In this experiment we proposed to use ECR plasma in unconventional fashion. In which reactive gases are spread straight on the wafer to be etched, while Ar is introduced into ECR cavity. The ionic species of Ar (electron & positive ion) move along the line of force of magnetic field and shared their energy/momentum with reactive gases on the top of the wafer. The energy of the reactive gas after the collision is less than or equal to that of curable Ar ions (depending upon elastic or inelastic collision) and therefore may not have the same energy assemble as in the case where reactive gas passed through resonance cavity. So in this case the energy damage impact will be lowered and etching rate will improve. The schematic layout of experiment is shown in the Figure 1.

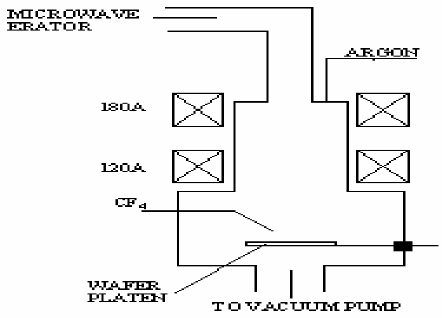

Figure 1 Schematic of Chemically Assisted Plasma Etching (CAPE) mode.

In ECR illuminating a magnetized region with high-power microwave radiation created plasma. At a magnetic field of about 875 Gauss, the electron Larmor frequency is equal to the microwave frequency of 2.45 GHz (it is the microwave oven frequency). At low enough pressures, electrons gain energy on each circuit around the field lines; this field allows both confinement and efficient electron heating. ECR sources can achieve densities around $10^{12}/cm^3$ ions at pressures of a few mTorr (this is several percent ionization). The ECR has very low energy plasma potential. In order to achieve significant sputtering rates at the wafer, it is necessary to apply a bias, and has been carried out by dc bias.

The vacuum system includes Varian mechanical pump, model SD-300 capacity 300 liters per minute and Varian cryopump model Cryostack-8 capacity 1500 lts/sec. The pressure of the gas is measured with two gauges, ionization gauge for measuring pressure in the range of 10^{-3} Torr and below, capacitance diaphragm gauge from Vacuum General model CMH-01 for pressure range of 10^{-4} to 1Torr. Alphagaz mass flow controller controlled the gas flow. The microwave power was generated by a continuously variable microwave power supply from M/s ASTeX, USA (50 to 1000 watts at frequency 2.45 GHz). Microwave in TM_{01} mode was launched in the source region through quartz window. A three-stub tuner is used to tune the reflected power to the minimum value. A set of two-solenoid coils surround's the cavity, where the plasma is produced. Each coil is powered by two EMS power supply model EMS 20-125-2D and EMS 27-185-2D. The entrance coil is powered by 180 Amp, 27 Volts supply while exit coil is powered by 120 Amp, 20V. The independent powered coils provide a static magnetic field of the order of 1.25 KGauss by entrance coil and 0.87 KGauss by exit coil. The two together create the resonance condition for efficient microwave absorption in the source [13].

In the ECR machine, the plasma excited by a microwave field in the presence of a dc magnetic field of the correct magnitude to cause the electrons to gyrate at the microwave field frequencies thus increasing the probability of ionization. The potential advantage of the ECR in this separation of the fields, which is first create the plasma and then impart energy to the ions. In general, two main advantage of dry etching are (i) the use of highly directed ions results in a profile of the etched material, which can be anisotropic, (i.e. vertical walls can be formed) and (ii) it is possible to obtain better uniformity over the wafer. This investigation on the use of CF_4, O_2 and Ar as posses gases, where AR was used aid in an isotropic and O_2 in reduction of residual surface polymers.

RESULT AND DISCUSSION

The etch rate of GaAs, at a pressure of 0.4 mTorr, 700 W input power and negative 30V bias as a function of flow of $CF_4 + O_2$ gases at different Argon (Ar) flows (20, 10 & 0 SCCM). in figure. 2 It has been observed that in last two cases, etch rate increases till the flow of CF_4 equals that of Ar flow and there after etch rate decreases. Maximum etch rate achieved are 190 A^0/min, 130 A^0/min were at 10, 20, SCCM of Ar flows respectively. With no Argon flow in cavity, the etch rate increase from 70 A^0/min to 107 A^0/min and then saturate but there is no peaking in etch rate.

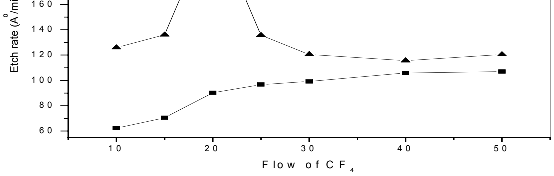

Figure 2 Plot between Etch rate (A^0/min) and CF_4 /O_2at constant Ar 0,10,20 SCCM.

20 SCCM of Ar is made to flow into ECR cavity while CF_4 gas is varied from 0 - 50 SCCM in case 1. Ar gas under goes following transformation in ECR cavity.

$$Ar + e^- \longrightarrow Ar^+ + 2e^- \quad (1)$$

Electrons and Argon ions move down the cavity towards the wafers where CF_4 molecules sprayed on the wafer. The ions are further accelerated near the wafer by the negative bias, these Ar ions and secondary electrons then ionize some of the CF_4 molecules and produces free atoms and CF_4 radicals. As the CF_4 increased further, the probability of secondary electrons and ions striking CF_4 molecules increases and increasing free F atoms. This increases F/Argon atoms ratio striking the silicon wafer and this leads to increase in etch rate [32]. These trends continue, till the volume of CF_4 equals that of constant flow of Argon (i.e. 20 SCCM) in the cavity. This trend is reversed when the flow of CF_4 is increased beyond 20 SCCM and etch rate of GaAs start decreasing. These characteristics may be due to the facts that the probability of getting reaction on the GaAs surface producing non volatize product increases beyond 50 % of CF_4 flow and leads to decrease in etching rate [35]. Abundance of CF_4 beyond 50% over silicon wafer, decreases the ratio of active species (fluorine atoms) to neutrals [36,37] reaching the wafer and thereby decreasing the etch rate. Another reason may be that beyond 50 % flow of CF_4 (i.e. > 20 SCCM) the probability of getting CF_4 ionized decreases even for best efficiency of ionization in ECR cavity and thereby decreasing active species to neutral ratio. This lead to increase in amount of neutrals or molecules, which are not useful in etching. These neutrals and molecules get adsorbed on the silicon surface and inhibit etching and decrease etching rate[36, 37]. Maximum etch rate (190 A^0/min) is achieved for 10 SCCM of Argon in cavity with 10 SCCM of CF_4 on silicon wafer. This may be due to decrease in active fluorine to neutral ratio over the silicon wafer & will result in decrease in etching rates. Efforts were also made for etching study at 5 SCCM of Ar flow in the ECR cavity and 5 SCCM of CF_4 flow on the wafer surface. It was noticed that the reflected power in this case was more than 50% and was not tunable with three stub tuner and therefore detail studies of etching at these flows was not carried out.

It has been observed that, where no Ar is given in the ECR cavity and CF_4 neutral are spread on the wafer, the etching characteristics are totally different from above observation and are of the order of 5-10 A^0/min only [38]. In our experiment with no argon in the cavity we observed that the curves do not pass through maxima. Etch rate increases from 70 A^0/min to 107 A^0/min with increase in CF_4 & then saturate. This may be due to the absence of ions & secondary electron of argon from the ECR cavity. However etching of Si is not because of neutrals of CF_4 which is of the order of 5-10 A^0/min, but because of diffusion of CF_4 into ECR cavity and then providing actives species for etching, which are then transported back to wafer surface. Marginal increase in etching may be due initial increase of active species with increase of CF_4 flow.

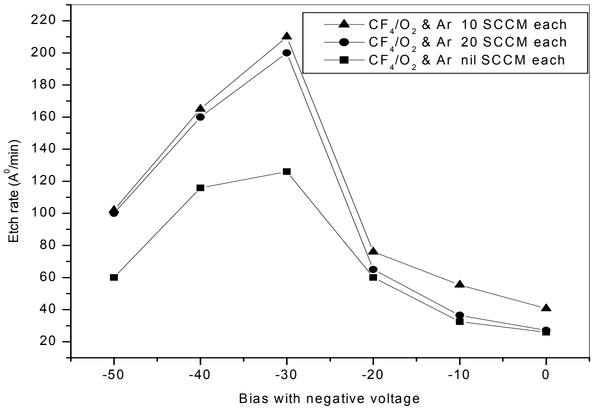

Figure 3 Variation of Etch rate (A^0/min) with bias in CAPE mode at constant flow of CF_4/ O_2 and Ar at 10,20, & nil SCCM each.

The ECR has low plasma potential. In order to control bias, it is necessary to apply separate power supply. Figure 3 represent etch rate versus bias characteristics at 0.4 mTorr pressure, 700 watts input power. Where DC power supply has been used to vary the voltage from 0 to – 50 volts. It has been observed that the Etch rate increase from 0 to - 30 volts (102 A^0/min to 210 A^0/min) and then beyond - 30 volts it decreases (210 A^0/min to 40 A^0/min). The increase in etch rate can be attributed the fact that Ar ions and electrons from the cavity has a very small energy, as these approaches the wafer, the positive ions encounter negative electric field, & gets accelerated and its energy is increased. This enhanced energy of Ar ions leads to increase in ionization of CF_4 neutrals which is between 5-10 % [39] and thereby producing more active etching radicals (CF_3, CF_2 and C). This leads to the increase etch rate. The decrease in etch rate beyond –30 volts bias, may be because of a few reasons. One of them is formation of passivation layer $nCF_{2(s)}$ on Si wafer; beyond certain % of CF_4, which resist to etching on the wafer [40]. Other reason for decrease in etching rate may be that because of DC bias; there may be charge accumulation on the wafer, which do not get neutralized as in the case of RF. The charge accumulation can scatter active species thereby leading to reduction in etch rate on the Si wafer. Another reason may be due to sputter redeposition or other reactant etch species, given the inherent competition in etch process between sputter removal and redeposition of reactants.

Figure 4 is the scanning electron micrographs of the trench for study of anisotropy, which is defined as [41].

$A = 1- V_h/V_v$

Where V_h is the horizontal etch rate and V_v is the vertical etch rate. These micrograph of GaAs is taken at 0.4 mTorr pressure, 700 watts input power and negative 30 volts bias with CF_4 & Ar flow 10 SCCM each. It has been observed that the anisotropy in figure 4 is 0.8. The reason for good anisotropy at low CF_4/Ar flow may be attributed to the many facts. First the presence of energetic electron along with availability of CF_4 molecule in abundance leads to following reaction.

$$CF_4 + e^- \rightarrow CFx^+ + CFxo + F^o + e^- \quad (2)$$

$$CFxo \rightarrow nCF_2(ads) \rightarrow nCF_2(s) \quad (3)$$

$$nCF_{2(s)} + F^o \rightarrow \text{ion energy} \rightarrow CF_{x(ads)} \rightarrow CF_{x(g)} \quad (4)$$

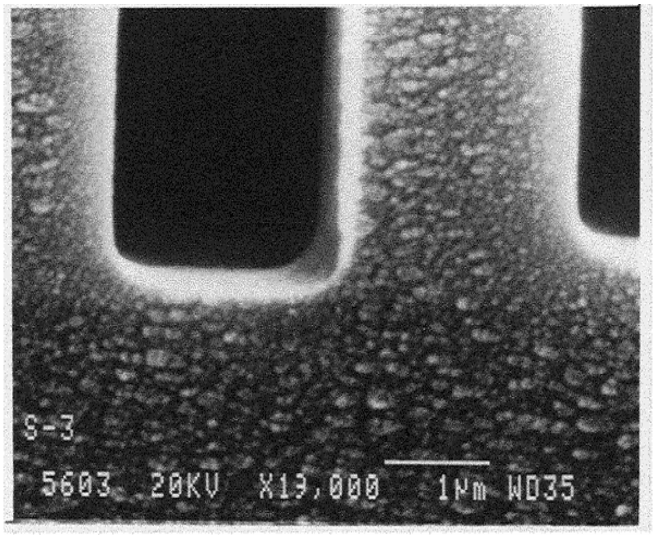

Figure 4 Micrograph of etching profile in Chemically Assisted Plasma Etching (CAPE) mode of GaAs are taken at 0.4 mTorr pressure, 600 watts input power and negative 30 volts bias with CF_4 /O_2& Ar flow 10 SCCM each.

This lead to formation of passivating layer on all the surface of the trench as indicated in equation (4). With higher CF_4 flow, the probability of formation of passivation layer may be earlier than lower CF_4 flow because of abundance of CF_4 molecules. The passivating layer $nCF_{2\,(s)}$ inhibit further etching of the Si from the sidewall as well as trench surface (2) and thereby leading to decrease in etching rate and anisotropy. This process can be reversed by the application of energetic ions on the passivating layer $nCF_{2\,(s)}$ indicated in equation (4). However in case of DC bias, because of charge accumulation and surface sparking, this process could not be carried out. So Judicious chemistry selection is very difficult to finely control this balance between etching and the deposition.

Conclusion

In ECR plasma source with a mirror type magnetic field configuration system, anisotropy & etch rate of GaAs in CAPE mode was evaluated with % of CF_4, flow of gases, and bias. Following conclusion from the investigation has been drawn.

(a) In CAPE mode with CF_4/Ar plasma, etch rate increase with increase CF_4 for GaAs and trend was reversed after increase CF_4 greater than 50%.
(b) The etch rate of GaAs increased (102 A^0/min to 210 A^0/min) with negative bias it was maximum around – 30 volts.
(c) The formation of passivating layer $nCF_{2\,(s)}$, which inhibit further etching, is more beyond 50% flow of reactive gases.

This study demonstrates the viability of ECR high-density plasma for low damage and high etching in the fabrication of III-V devices. This is a good application for this technology , which allows for the development of low cost, high throughput production process for devices requiring sub micron critical dimension.

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ACRONYMS

ECR: Electron Cyclotron Resonance