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Influence of chloropentafluoroethane inductively coupled plasma parameters on the rate and characteristics of gallium arsenide etching

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In paper the influence of parameters of inductively coupled chloropentafluoroethane plasma on the rate and characteristics of gallium arsenide etching was studied. Etched GaAs profiles by white light interferometry and scanning electron microscopy were investigated. It turned out that the process rate does not depend on freon flow, but forward and inductive power, as well as pressure determined. In this case, when the power of the plasma generator increase, the surface morphology changes significantly, that manifests itself in roughness increase and the detection of defects on GaAs and mask. Carrying out a process at low pressure leads to the deposition of single large inhomogeneities on the substrate. The transition from pulsed to continuous etching is accompanied by deterioration in the anisotropy of a process due to the polymer layer deposition on side walls.

Keywords: chloropentafluoroethane, plasma-chemical etching, inductively coupled plasma, gallium arsenide.

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1. Introduction

Gallium arsenide is direct-gap semiconductor with high mobility of charge carriers, on the basis of which devices are manufactured that are resistant to radiation defects and operate under high loads [1]. One of such devices is a GaAs-based vertical field-effect transistor with control $p-n$-junction [2]. There are a number of requirements for the methods of manufacturing such a transistor, in particular, it is necessary to form a vertical channel in GaAs. Conventional liquid etching is not suitable in this case due to the presence of large lateral undercut under the mask. Anisotropic etching can be carried out by the plasma-chemical method; however, if chemically active gases, such as chlorine [3–6], are used as a reagent, this can lead to the stoichiometry violation of near-surface layer. As a result, many further processes of structure formation (including metal-organic vapor-phase epitaxy) will become impossible. In this regard, it is necessary to choose plasma-forming gases with minimal effect on the surface during etching. One such substance is chloropentafluoroethane (C_2F_5Cl). This reagent can act both as the main etchant for GaAs and as a passivating agent. In our previous works the possibility of „soft“ gallium arsenide etching in C_2F_5Cl plasma under a metal mask [7], as well as the influence of the addition of the above freon to gaseous chlorine on this process [8], was shown. In this work, the direct influence of the parameters of inductive-connected one-component plasma C_2F_5Cl on the rate and characteristics of gallium arsenide etching is studied.

2. Experimental procedure

The processes of plasma-chemical etching of GaAs in C_2F_5Cl plasma with different operating parameters were carried out. The freon flow (f), reactor pressure (p), capacitive power (Radio Frequency Power, RF_p), inductive power (Inductively Coupled Plasma Power, ICP_p) and cycle time (t_c) were varied. Etching was carried out in a pulsed mode (system inactivity time 40 s) on an Oxford Plasmalab80 installation (Oxford Instruments, UK) with source of inductive connected plasma with frequency of 13.56 MHz. To prevent overheating of the sample, it was placed on a sapphire substrate with vacuum lubricant, to which gaseous helium was supplied from below with a flow of 30 cm^3/min. Gallium arsenide with orientation (001) was used. The substrate orientation was determined using the D8 Discover X-ray diffractometer (Bruker, Germany). The pattern on the GaAs surface was formed by explosive photolithography in combination with the deposition of two-layer V/Ni metal mask (75 nm each) by electron beam deposition on Amod 206 system (Angstrom Engineering, Canada). The choice of the mask is determined, on the one hand, by the plasma resistance of nickel, and, on the other hand, by the good adhesion of vanadium to GaAs. Etching rate (r) and gallium arsenide surface parameters (roughness S_q, presence of defects), as well as the obtained profile, were studied by white light interferometry methods (optical measuring system Talysurf CCI 2000, Taylor & Hobson, UK) and scanning electron microscopy (microscope EVO 10, Carl Zeiss, Germany).

3. Results and discussion

With a value of $f = 10\,\mathrm{cm^3/min}$ and a low capacitive discharge power (10 W), the etching rate is $\sim 6\,\mathrm{nm/min}$. In this case, the GaAs sample in the area of $100\,\mu\mathrm{m}^2$ is characterized by a uniform smooth surface with $S_q = 0.7\,\mathrm{nm}$ (Fig. 1). Increase in freon flow by 8 times (up to $80\,\mathrm{cm^3/min}$) does not lead to the increase in the process rate. Obviously, this is due to the structure of molecule of the chloropentafluoroethane as a result of the dissociation of which particles are formed, both participating in etching and contributing to surface passivation [7]. It should be noted that the etching surface of gallium arsenide at a high freon flow was smooth, without any-or obvious defects.

Increase in the capacitive power from 10 to 75 W leads to r increase by a factor of 10 (up to 60 nm/min) due to increase in the concentration of chlorine-containing particles in the plasma (under the influence of the high generator power, more intense rupture C−Cl bonds in the chloropentafluoroethane molecule) and the predominance of the etching process over passivation. At $RF_p = 150\,\mathrm{W}$, the etching rate increases even more — up to 125 nm/min. However, in this case, a layer of passivation products with uneven contours appears on the wall of the etched GaAs profile. In addition, the entire surface of the mask is covered with defects in the form of small round-shaped formations.

Turning off the ICP generator leads to a decrease in the etching rate by more than a factor of 2.5. At the same time, the surface roughness increases to 1.4 nm, and „edges“ appear around the etched elements. The surface of the mask after etching is covered with inhomogeneities in the form of irregularly shaped flakes (Fig. 2). In all likelihood, these are traces of the remaining polymer, which was not completely etched from-due to the low concentration of bombarding ions in the plasma in the absence of inductive power. As ICP_p decreases from 250 to 150 W r decreases slightly (within 10%). There are practically no defects on the surface of the metal mask and on the bottom of the etched elements; however, this mode cannot be considered optimal due to the presence of a polymer layer on the walls of narrow grooves.

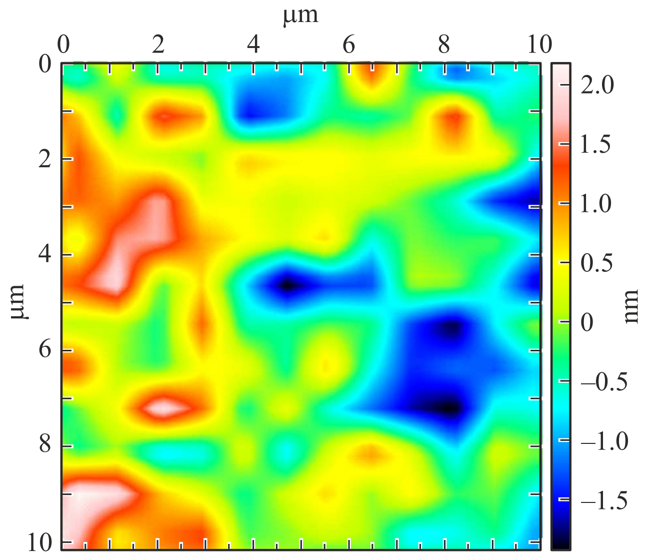

Figure 1. White light interferometer image of GaAs etching surface in inductively coupled plasma C_2F_5Cl at $RF_p = 10\,\mathrm{W}$ and $t_c = 30\,\mathrm{s}$. Here and below $f = 10\,\mathrm{cm^3/min}$, $p = 11\,\mathrm{mTorr}$. (A color version of the figure is provided in the online version of the paper).

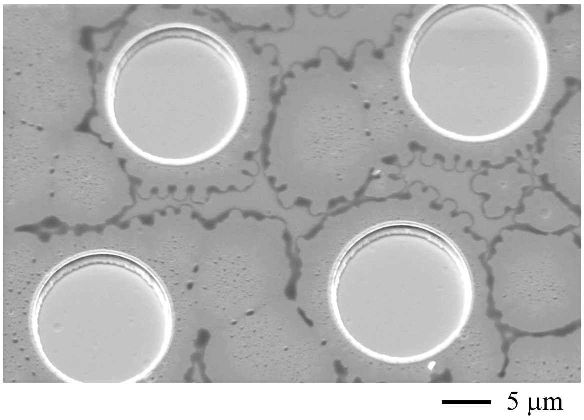

Figure 2. Electron microscope image of the GaAs etching profile in C_2F_5Cl plasma with the generator ICP turned off ($RF_p = 150\,\mathrm{W}$, $t_s = 30\,\mathrm{s}$).

The dependence of the gallium arsenide etching rate in C_2F_5Cl plasma on pressure is non-linear. Thus, when p is increased from 5 to 11 mTorr r decreases by a factor of 1.2; and with a 6-fold increase p (up to 30 mTorr), the rate of the process decreases only by a factor of 2.5. Decrease in the etching rate with increasing pressure can be explained by decrease in the energy of particles due to a reduction in their mean free path. At low pressure during gallium arsenide etching, single large inhomogeneities fall on the substrate surface, which fall on both the mask and the etched elements. At high values of p, the GaAs etching surface remains smooth, but „ledges“ are formed along the contour of the elements, similar to those observed earlier when the ICP generator was turned off.

When the cycle time is reduced by a factor of 2 (from 30 to 15 s), the etching rate slightly decreases (by $\sim 11\%$), while the total process time increases significantly. Conducting etching in a continuous mode has a much greater influence on the nature of the process. First of all, this concerns the deterioration of the degree of anisotropy. For example, for the groove $9\,\mu\mathrm{m}$ wide, the degree of anisotropy is 3 : 1, which is 2 times less than the etching anisotropy for the groove of identical size obtained in the pulsed mode. It should be noted that, in the continuous mode, significant polymer deposition is observed on the side walls of the etching profile (Fig. 3), and to much greater extent than during pulsed etching, which ultimately affects the anisotropy. This is probably due to the fact that, with the continuous flow of the process, the passivation products

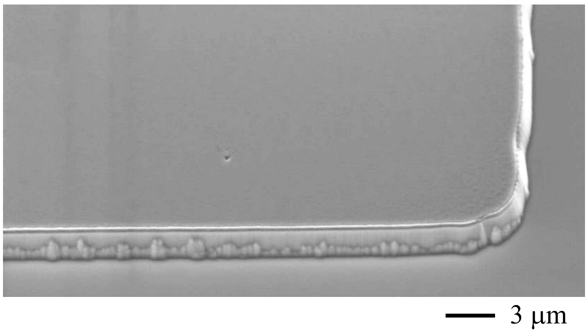

Figure 3. Electron microscope image of GaAs etching profile (continuous mode) in inductively coupled plasma C_2F_5Cl at $RF_p = 150\,W$ and $ICP_p = 250\,W$.

do not have time to completely leave the etching surface and remain on it in the form of polymer layer.

4. Conclusion

As a result of the studies performed, it was shown that the increase in the flow of chloropentafluoroethane does not lead to the change in the etching rate of gallium arsenide. Increase in capacitive power contributes to an increase in the process speed by several times, however, a layer of passivation products with uneven contours appears on the walls of the etching profile. With decrease in inductive power, the etching anisotropy decreases, and the complete shutdown of the ICP generator contributes to the development of surface roughness and the appearance of inhomogeneities in a form of „flakes“ on the mask. With increase in pressure in the reactor, the etching rate decreases due to decrease in the free path of the reaction plasma particles. Under reduced pressure, single large inhomogeneities fall on the surface of the substrate, which occur both on the mask and on the etched elements. Etching GaAs in a continuous mode significantly worsens the degree of anisotropy compared to pulsed mode etching.

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Conflict of interest

The authors declare that they have no conflict of interest.

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