Gate recessing optimization of GaAs/Al_{0.22}Ga_{0.78}As heterojunction field effect transistor using citric acid/hydrogen peroxide/ammonium hydroxide for power applications

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The etching characteristics of GaAs and Al_{0.22}Ga_{0.78}As in citric acid/hydrogen peroxide/ammonium hydroxide etching solution were studied. The selectivity of GaAs to Al_{0.22}Ga_{0.78}As was as high as 200 at 20 °C (510 at 0 °C) by optimizing the pH and citric acid/hydrogen peroxide ratio. To our knowledge, this is the best result. The etch rate of GaAs is 1000 Å/min and permits a good control of the etched depth. The effects of the etching solution temperature and the doping level of GaAs on the selectivity were determined. The solution stability study over the time proves that the process is very reliable. This wet etching was applied to the gate recess etching of a heterojunction field effect transistor (HFET). Observations and measurements by electron beam microscopy are presented for short gate lengths. They show a very good surface morphology and that the gate recess width is independent of the gate length. It only depends on the etching time. The breakdown voltage value can be adjusted by the gate recess width. The possibilities of this wet etching are consequently demonstrated to be particularly appropriate to the realization of millimeter power HFETs. © 1998 American Vacuum Society. [S0734-211X(98)05205-6]

I. INTRODUCTION

Selective etching of semiconductors plays a vital role in the fabrication of many devices such as heterostructure field effect transistors (HFETs), light emitting diodes, and lasers. For power applications, we need the maximum of drain current and breakdown voltage. A great control of the recess prevents damage due to over etching, characterized by a drain current decrease, and permits a high breakdown voltage value.

Many efforts have been devoted to search for a highly selective etching for GaAs/AlGaAs. Selective reactive ion etching has been a good candidate for gate recessing, but the degradation due to the ion beam is not negligible.¹ On the other hand, selective wet etching is a nondamaging process.

It has been reported that succinic acid/hydrogen peroxide solutions have a selectivity better than 100^{2,3} for an Al mole fraction of 40%. In our application, we need the maximum of aluminum to obtain a good electron confinement in the channel and a high barrier height.⁴ But if the aluminum concentration is too important some problems appear due to DX centers.⁵⁻⁷ We have chosen an Al mole fraction of 22% to minimize this problem, so we cannot use this selective wet etching.

The peroxide-alkaline system of H₂O₂/NH₄OH is a common etchant for GaAs and AlGaAs.^{8,9} But the selectivity is very low (30) and the solution attacks electronic resists.

Lee *et al.* have obtained a selectivity of 100 for an aluminum concentration of 15% in citric acid/hydrogen peroxide solution at 0 °C and a selectivity of 30 at room temperature.¹⁰ A lot of people have used this solution¹¹⁻¹³ and high selectivity (100) is available at room temperature,

but for an aluminum concentration of 30%. When the Al mole fraction decreases, the selectivity decreases rapidly.² Consequently, for an Al mole fraction of 22%, the selectivity obtained at room temperature is insufficient for us.

Recently, Kitano and co-workers have developed a new selective wet etching using a solution of citric acid/hydrogen peroxide and ammonium hydroxide.^{14,15} At room temperature, they obtained a selectivity of 80 and better than 100 for an Al mole fraction of 15% and 30%, respectively. It was the best result published in the literature.

The first part of our study consists in an optimization of citric acid/H₂O₂ ratio and pH value to obtain a very high selectivity value. In the second part, this wet etching has been successfully applied to the gate recess etching of a HFET with high control of the recess width and minimization of the over etching. Measurements of recess depth and width are presented for 0.1, 0.2, and 0.3 μm openings. For a drain-source distance of 1.3 μm with a 0.2 μm centered gate in a single 0.6 μm wide recess, we have obtained a breakdown voltage of 20 V in diode configuration.

II. CHARACTERISTICS OF CITRIC ACID/HYDROGEN PEROXIDE/AMMONIUM HYDROXIDE SOLUTION

A. Experiment

The GaAs and Al_{0.22}Ga_{0.78}As materials used for etch rate and selectivity measurements were grown on a GaAs substrate using solid source molecular beam epitaxy. The epitaxial layers were about 7000 Å thick with different Si doping levels for GaAs (3.5×10¹⁷, 1.5×10¹⁸, and 4×10¹⁸ cm⁻³) and with an Al mole fraction of 22% for AlGaAs. An undoped GaAs substrate was also used. The dop-

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FIG. 1. (a) Evolution of GaAs and Al_{0.22}Ga_{0.78}As etch rates vs pH. (b) Evolution of GaAs/Al_{0.22}Ga_{0.78}As selectivity vs pH.

ing concentration and aluminum composition were determined by Hall effect and photoluminescence, respectively. Wafers were patterned using standard photoresist process with Shipley 1400-27 photoresist. The pattern's dimensions were 50×100 μm to perform easy measurements by profilometer (Alpha Step P10 TENCOR).

The citric acid was prepared by dissolving monohydrate citric acid with deionized water H₂O at the ratio of 1.5 g:100 ml. The pH of citric acid solution was adjusted by addition of ammonium hydroxide NH₄OH (30%). Finally, the solution was mixed with hydrogen peroxide H₂O₂ (30%). Before etching, realized without stirring, wafers were deoxidized with a solution of sulfuric acid and deionized water at the ratio of 10 ml H₂SO₄:80 ml H₂O for 1 min and blown dry with N₂. The etching time varied from 1 min to 1 h depending on the material etch rate. Etching was stopped by rinsing in DI H₂O for 1 min. The photoresist mask was removed in acetone and blown dry with N₂. The etched depth was measured at different locations across the wafer. The selectivity is defined as the ratio of GaAs to AlGaAs etch rates.

B. Results and discussion

Figure 1 shows the etch rates and selectivity of GaAs and Al_{0.22}Ga_{0.78}As as a function of pH and for a hydrogen peroxide concentration of 2%, at 20 °C. The selectivity increases rapidly for pH values of 6–6.8. The selectivity reaches 205 for a pH value of 6.2. The selectivity increases with the aluminum concentration,^{2,14} so it is easier to have a good selectivity with high Al mole fraction. Our result, ob-

FIG. 2. (a) Evolution of GaAs and Al_{0.22}Ga_{0.78}As etch rates vs H₂O₂ concentration. (b) Evolution of GaAs/Al_{0.22}Ga_{0.78}As selectivity vs H₂O₂ concentration.

tained for only 22% aluminum is better than others' results obtained for 30% (120).¹⁵ This is the best result to our knowledge. The GaAs etch rate is 1000 Å/min and permits a good depth etched control.

The etch rates and selectivity of GaAs and Al_{0.22}Ga_{0.78}As are plotted in Fig. 2 for various citric acid/hydrogen peroxide solution ratio at 20 °C and for a pH value of 6.2. The selectivity strongly increases with H₂O₂ concentration contrary to a previous publication.¹⁴ For a concentration greater than 2%, the GaAs layer surface becomes oxidized. Then the surface morphology is bad and the etching is not uniform.

Figure 3(a) shows the temperature dependence of GaAs and Al_{0.22}Ga_{0.78}As etch rates in a solution of citric acid with 2% H₂O₂ at pH 6.2. Etch rates are proportional to $e^{-Ea/kT}$ where Ea is the activation energy, k is the Boltzman constant and T the temperature. Then, activation energies of 0.43 eV (9.9 kcal mol⁻¹) and 0.75 eV (17.3 kcal mol⁻¹) are deduced for GaAs and Al_{0.22}Ga_{0.78}As, respectively. Consequently, the selectivity defined as the ratio of GaAs to AlGaAs etch rates, has to evolve exponentially with temperature [Fig. 3(b)]. The selectivity increases when the temperature decreases. We obtain a very high selectivity value of 510 at 0 °C. We can solve which etching mechanism dominates because the etch rates follow an Arrhenius law and activation energies are higher than 7 kcal mol⁻¹.¹⁶ So etch rates are chemical reaction rate limited, and then

FIG. 3. (a) Evolution of GaAs and Al_{0.22}Ga_{0.78}As etch rates vs temperature. (b) Evolution of GaAs/Al_{0.22}Ga_{0.78}As selectivity vs temperature.

- (i) the etched depth is linearly proportional to the etching time. It confirms the etch rate value determination as the ratio of the etched depth on etching time,
- (ii) etch rates are unaffected by stirring or agitation of the liquid etchant,
- (iii) slight changes in relative proportions of etchant components can result in large changes in etch rates.

We can see in Fig. 4 that the GaAs etch rate is quasi-independent of the doping concentration. But for an undoped GaAs sample the surface morphology is bad and nonuniform.

Figure 5 shows the high citric acid solution stability over the time. We observed a decrease of only 10% after 2 h and

FIG. 4. Evolution of GaAs etch rate as a function of doping concentration.

FIG. 5. Stability of the citric acid/hydrogen peroxide/ammonium hydroxide solution over the time.

the selectivity remains better than 150 after 24 h. It proves that the selective etching is very stable and reproducible.

III. OPTIMIZATION OF GATE RECESS

A. Experiment

The HFET structure used for gate recess studies was grown by solid source molecular beam epitaxy as shown in Fig. 6. It consisted of a 700 Å *n*⁺ GaAs cap layer with a doping of 5 × 10¹⁸ cm⁻³, an undoped Al_{0.22}Ga_{0.78}As of 300 Å, a Si δ doping (4 × 10¹² cm⁻²), and an In_{0.22}Ga_{0.78}As doped channel (2 × 10¹⁸ cm⁻³). The HFET fabrication started with device isolation through mesa etching, followed by deposition of Ni/Ge/Au/Ti/Au ohmic contacts, annealed at 400 °C for 40 s. Then the wafer was patterned using electronic resist with a first layer of 1500 Å PMMA 950 K and a second layer of 6800 Å copolymere 14%.

Before etching, the wafer was deoxidized with a solution of 10 ml H₂SO₄/80 ml H₂O for 1 min and blown dry with N₂. The sample was then etched without stirring in the citric

GaAs 5.10 ¹⁸ cm ⁻³	70 nm
Al _{0.22} Ga _{0.78} As	30 nm
GaAs	0.4 nm
δ -Si 4.10 ¹² cm ⁻²	
GaAs	0.4 nm
Al _{0.22} Ga _{0.78} As	3 nm
GaAs	1 nm
In _{0.22} Ga _{0.78} As 2.10 ¹⁸ cm ⁻³	12 nm
GaAs	2 nm
Al _{0.22} Ga _{0.78} As	150 nm
GaAs	300 nm
GaAs	substrate

FIG. 6. Schematic of the HFET structure.

FIG. 7. (a) Evolution of etched width in citric acid solution vs etching time for 0.1, 0.2, and 0.3 μm gate length openings. (b) Viewgraph of a recess profile using citric acid solution with 2% H_2O_2 at pH 6.2 for a 0.2 μm opening and 3 min etching at 20 °C.

acid/hydrogen peroxide/ammonium hydroxide solution in the proportion of: 1.5 g citric acid for 100 ml H_2O , mixed with 2% H_2O_2 (30%). At 20 °C, the pH was adjusted by ammonium hydroxide (30%) at 6.2. The etching time varied from 15 s to 4 min. Etching was stopped by rinsing in H_2O for 1 min and in three $\text{HCl}/\text{H}_2\text{O}$ solutions for 1 min for each bath. Finally the Ti/Pt/Au gate was deposited. The gate recess width was measured by electron beam microscopy. The drain current and breakdown voltage values were electrically characterized in static conditions.

B. Results and discussion

Different etching times were performed through 0.1, 0.2 and 0.3 μm electronic resist openings to see the dependence on HFET's characteristics. For an etching time lower than 45 s, the drain current decreases rapidly due to the etching of the doped cap layer. For a longer etching time, the drain current remains constant to its nominal value (800 mA/mm). This experiment confirms electrically the wet etching selectivity.

Figure 7(a) shows the under etching evolution versus etching time for 0.1, 0.2, and 0.3 μm gate length openings. After 30 s, the etched width is a quasilinear function of the etching time independently of the gate length. It shows once again that it is chemical reaction rate limited and not diffusion limited. The lateral etch rate is about 700 Å/min and we have an anisotropy of 1.4.

In Fig. 7(b), we can see the gate recess profile by electron beam microscopy performed for 3 min etching time with a 0.2 μm gate length patterned in a resist mask. The etched

FIG. 8. Evolution of breakdown voltage value vs etching time in diode configuration and static conditions for 0.2 μm gate length.

depth is 700 Å. It is the depth of the cap layer. This viewgraph proves the etching selectivity and the good surface morphology of the AlGaAs surface. According to these figures, it is possible to choose the under etched width, so the breakdown voltage value by the etching time. After gate metal deposition, we can see in Fig. 8 the evolution of breakdown voltage value in diode configuration versus etching time performed in static conditions. The drain-source distance is 1.3 μm . The breakdown voltage value increases linearly with the recess width. It is normal, because the breakdown voltage value is proportional to the gate depletion region length.¹⁷ Finally, a very high breakdown voltage value has been obtained for a short drain-source distance (20 V for an etching time of 4 min).

The etching solution used for this gate recess is very selective. Then the drain current keeps its high value. It is possible to control the under etching of the gate recess and then to choose the breakdown voltage value. Consequently, it is possible to obtain a very high breakdown voltage value and to keep a high drain current value necessary for power applications.

IV. CONCLUSION

Gate recessing optimization of GaAs/Al_{0.22}Ga_{0.78}As using citric acid/hydrogen peroxide/ammonium hydroxide is reported. A selectivity better than 200 at room temperature is obtained with a very good surface morphology and a large stability of the solution over the time. To our knowledge, this is the best result. This high selectivity coupled with a moderate GaAs etch rate offers a large control of the lateral gate recess. We have demonstrated the possibility to choose the under etching length by adjusting the etching time. The breakdown voltage depends essentially on the under etching, then, for power applications, high breakdown voltage values are reachable while ensuring very substantial drain current.

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