Optimization in noble metal hard mask selectivity in chlorine-based plasma etch

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Abstract

This paper evaluates GaAs-based epitaxial layer etch with a noble metal hard mask in inductively-coupled plasma platforms using a chlorine-based chemistry. The effects of bias and ICP powers on etch rate of an InGaAs layer and metal mask are studied on blanket wafers to explore the optimum etch conditions with high InGaAs to noble metal etch selectivity, while maintaining the InGaAs etch rate. Metal etch rates varied more strongly than InGaAs etch rates by decreasing the bias power due to increased dependence of the metal etch rate on the ionic aspect of the etch, as opposed to InGaAs. The etch at 50% RF1 bias power and 140% RF2 ICP power shows a significantly improved InGaAs-to-Metal corresponding etch selectivity of ~9.4:1 compared to ~5.4:1 for the control etch condition RF1 and RF2, on the blanket wafers. The results from the blanket wafers were used to select the optimum etch conditions and compare with the control condition on patterned device wafers. The measured electrical resistance of the metal structures on the patterned wafers was used to calculate the amount of metal mask remaining post etch. A significant drop of 23% in electrical resistance was observed, indicating that considerably less metal was etched with the 50% RF1 bias power and 140% RF2 ICP power condition. The within wafer non-uniformity increased slightly by ~1%.

INTRODUCTION

Plasma etching using inductively coupled plasma (ICP) is a common method for the manufacturing of GaAs-based epitaxial layer stacks in several devices, including those which require a hard mask for the etch [1-3]. The ICP configuration provides the ability to control ion energy and plasma density independently by varying the radio frequency (RF) bias power applied to the wafer and ICP power. This creates an independent lever over the physical sputtering process. Since the main mechanism in the dry etching of the metal hard masks is physical sputtering [4,5], this control is especially important for mitigating the metal erosion for the etch processes which depend on a noble metal as an element of the device.

In this paper, we will introduce a controlled study on the plasma etch of the InGaAs with high selectivity to metal in an epitaxial layer structure which uses a noble metal as the hard mask. In this study, the tuning between the bias power and ICP power was evaluated to increase the InGaAs-to-metal mask etch selectivity while maintaining the etch performance. This includes the InGaAs etch uniformity and rate.

EXPERIMENTAL

Epitaxial layers on six-inch GaAs wafers grown by MOCVD methods are used as the initial device substrates. The wafers then cycle through multiple lithography, deposition, etch, diffusion and thermal processes to define the device structure at each layer. This includes the layer with the noble metal hard mask. The layer with the hard mask is defined by dry etch using an ICP configuration with a chlorine-based chemistry. Keeping the dry etch process parameters, including the flow rates and chamber pressure constant, the ICP and bias powers were varied compared to a baseline control setpoint for bias (RF1) and for ICP (RF2). The experiments were divided into two parts: blanket wafers and patterned device wafers etch.

In the first part, blanket metal and blanket wafers with epitaxial layers were etched separately using an identical set of ICP and bias powers. The thickness of the metal etched for an equivalent time period on the blanket metal wafers was measured using the four-points probe measurement before and after the etch, to determine the metal etch rates. On the blanket wafers with epitaxial layers, the InGaAs, with a known thickness and a stop layer underneath, was removed and the etch time was used to measure the InGaAs etch rate.

In the second part, patterned device wafers with metal hard mask were etched using the selected ICP and bias powers that was used for etching the blanket wafers. The InGaAs etch time to reach the underneath stop layer was used to measure the InGaAs etch rate similar to the blanket wafers. Microscope and profilometer data of partially etched patterned wafers were used to measure the etch uniformity on the patterned device wafers. The resistance of metal structures on the patterned hard mask after the etch was used to evaluate the metal etched on the patterned wafers.

RESULTS AND DISCUSSION

Fig. 1 shows the InGaAs etch rate and the metal etch rate versus the bias and ICP powers, relative to control values, on the blanket wafers. The inset shows the corresponding InGaAs to Metal selectivity. The bias power was reduced (compared to the control value) to decrease the physical aspect of the etch, and the ICP power was increased (compared to the control value) to compensate for the reduced etch rate and uniformity. The bias power was varied from the RF1 value to 75%, 50% and 25% of the RF1, while the ICP power was varied from RF2 value to 120% (rev1) and 140% of the RF2 (rev2). Lower bias and higher ICP power ranges were not selected for this study because of the significant InGaAs etch rate drop and inconsistent process results in these ranges, respectively. Both InGaAs and metal etch rates increase consistently by increasing the bias power from 25% to 100% of the RF1. While the metal etch rate shows a ~800% increase, the InGaAs etch rate only increases by ~270%, indicating improved selectivity is possible. This is due to physical sputtering, as this is the only mechanism for etching noble metals, which relies on the ion energy in the sheath region. Increasing the ICP power from 120% to 140% of the RF2 in the 50% RF1 region, increases the InGaAs etch rate by about 100 Å/min, while the metal etch rate remains almost constant. The cause of this condition is the increased plasma radicals that are the main contributors for etching the InGaAs. In the 75% RF1 bias power region however, the increase in ICP power from 120% to 140% of the RF2 causes a decrease in both InGaAs and metal etch rates. The higher ICP power increases the plasma density, which potentially causes further recombination and a decrease of the ions in the plasma. The decrease in ions results in the lower physical etch, for both InGaAs and metal. Overall, the 50% RF1 bias and 140% RF2 ICP power levels, (marked in the inset with the green circle) offer the optimum fabrication conditions for high InGaAs-to-metal etch selectivity of ~9.4:1 compared to the control conditions that give ~5.4:1 selectivity.

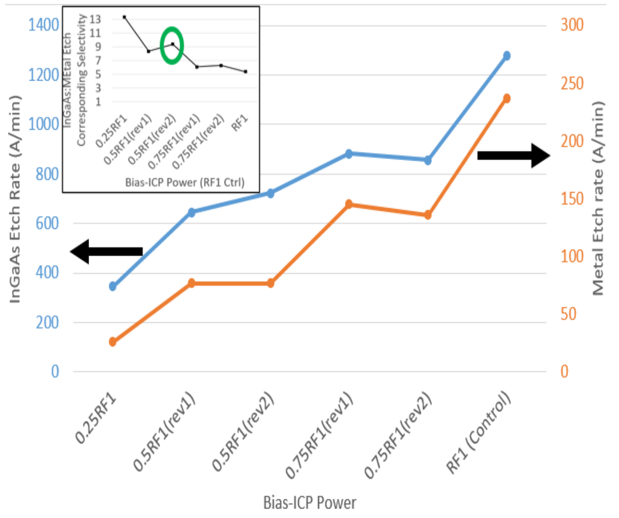

Fig. 1. InGaAs and metal etch rate variation with bias-ICP power on blanket wafers.

Based on the etch performance on the blanket wafers, control values of the RF1 bias and RF2 ICP powers as reference and 50% RF1 and 75% RF1 bias powers both at 140% RF2 ICP power were selected to etch and measure the etch performance on the patterned wafers. Lower bias power 25% RF1 or lower ICP power 120% RF2 were not selected because of their low InGaAs etch rate properties. Fig. 2 shows the InGaAs etch rate of the patterned wafers and the metal etch rates measured on the blanket wafers for the three etch conditions. The inset here also shows the corresponding InGaAs-to-Metal selectivity calculated from InGaAs etch rate on the patterned wafer to metal etch rate on the blanket wafers. Similar to the blanket wafers, the InGaAs etch rate is directly proportional to the bias power on the patterned wafers. However, the InGaAs etch rates of the patterned wafer are ~15-30% lower than the rates of the blanket wafers. The reason is the simplicity of the etchants to reach the InGaAs layer and byproducts to transfer out of the etched layer for the blanked wafers as opposed to the patterned wafers. There is almost a linear relation between the InGaAs etch rate and the three etch conditions. The InGaAs etch rate drop from RF1 and RF2 to 50% RF1 and 140% RF2 marked in the inset with the green circle was ~475 A/min based on the patterned wafers results and the estimated drop in metal etch rate was ~160 A/min based on the blanket wafers results. The corresponding InGaAs-to-Metal etch selectivity increased from ~4.1:1 to ~6.6:1 for this circled condition compared to the control condition. Because of the lower InGaAs etch rates, 50% RF1 and 75% RF1 for the first and second conditions require longer etch time to remove the same InGaAs layer on the patterned wafers as opposed to the control condition with RF1 bias power. Even though the lower bias powers cause less ionic based metal erosion, the longer etch time acts in the opposite direction from the metal erosion aspect for the first two etch conditions.

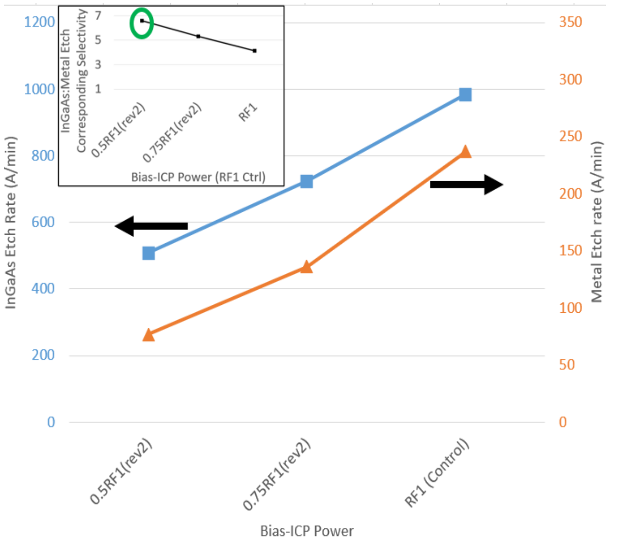

Fig. 2. InGaAs and metal etch rate variation with bias-ICP power on patterned device wafers.

In order to relatively compare the amounts of the eroded metals on the patterned wafers resulted from each of the etch conditions, the electrical resistance of a patterned metal structure was measured after the etch. Fig. 3 shows the results of the resistance measured for the three etch conditions discussed above for the Fig. 2. The second condition 75% RF1 and 140% RF2 resulted metal structure resistance less than 1% different from the control condition with RF1 bias power and RF2 ICP power (normalized resistance is equal to 1 for the control condition). However, the second condition with 50% RF1 and 140% RF2 shows noticeable decrease of more than 23% metal structure resistance after the etch compared to the control etch condition. The lower electrical resistance shows a thicker metal left after the etch which indicates the smaller metal etched. While the first etch condition required the highest etch time because of the lowest InGaAs etch rate, the total metal etched was the lowest compared to the other etch conditions with higher bias power. The reason is the nonlinear relationship between the metal etch rate and the three etch conditions shows in Fig. 3 as opposed to the relatively linear correlation between the InGaAs etch rate and the three etch conditions shown in Fig. 2. Since the metal etch rate mainly relies on physical aspect of the etch, the 50% RF1 bias power drops the metal etch rate nonlinearly by lowering the energy of ions.

The etch non-uniformity within the wafer was ~1% higher for the 50% RF1 bias power and 140% RF2 ICP power optimum condition with the lowest metal erosion properties compared to the control condition. The lower bias power causes the decrease in InGaAs etch uniformity by reducing the physical etch but the higher ICP power compensates for the etch rate and uniformity by increasing the plasma density for the optimum condition compared to the control condition.

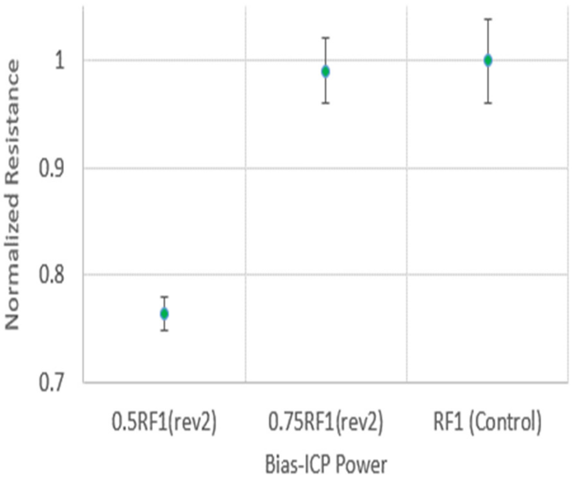

Fig. 3. Hard mask structure resistance of the etched patterned device wafers.

CONCLUSIONS

This paper provided comparative evaluations of InGaAs and a noble metal ICP etching used for the formation of the main epitaxial layer using the metal hard mask in epitaxial-based devices. The effects of bias and ICP powers on epitaxial layer and metal etch rates were investigated on blanket wafers. Conditions with a 50% RF1 bias and 140% RF2 ICP power results in a high InGaAs-to-Metal corresponding etch selectivity ~9.4:1 as opposed to ~5.4:1 for the control condition with RF1 bias and RF2 ICP power. On patterned device wafers with the metal hard mask, 50% and 75% bias power with 140% RF2 ICP power were chosen as the first and second etch conditions to be evaluated and compared with the control condition. The InGaAs etch rates on the patterned wafers were 15-30% lower than the blanket wafers because of more complexity of etchant and byproduct materials transfer in and out of the patterned wafers. The corresponding InGaAs:Metal etch selectivity for the 50% RF1 bias power and 140% RF2 ICP power on the patterned wafers was improved to ~6.6:1 as opposed to 4.1:1 for the control condition. On the patterned metal structure electrical resistance for the 50% RF1 bias power was considerably lower than the other two etch conditions with higher bias powers because of the metal etch rate relying mainly on ionic etch. The lower electrical resistance represents the lower metal etched on the patterned wafers. The 50% RF1 bias power and 140% RF2 ICP power provided an optimum of more than 23% decrease in the metal structures electrical resistance while the non-uniformity increased only ~1% and InGaAs etch rate decreased less than 50% compared to the control condition on the patterned device wafers.

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ACRONYMS

ICP: Inductively Coupled Plasma
RF: Radio Frequency