Selective reactive ion etching for short-gate-length GaAs/AlGaAs/InGaAs pseudomorphic modulation-doped field effect transistors

A. A. Ketterson, E. Andideh, I. Adesida,[a] T. L. Brock, J. Baillargeon, J. Laskar, K. Y. Cheng,[a] and J. Kolodzey[a]
Department of Electrical and Computer Engineering, University of Illinois, Urbana, Illinois 61801

(Received 31 May 1989; accepted 12 July 1989)

Selective reactive ion etching of GaAs on AlGaAs in $SiCl_4/SiF_4$ plasma is reported. A selectivity ratio of 350:1 has been obtained at low power. A small decrease in the saturation current of gateless MODFET structures has been observed after etching the GaAs cap layer and has been ascribed to be due to low-power ion damage of the AlGaAs layer. This process was applied to the fabrication of 0.2 μm T-gate pseudomorphic MODFET's. The dc and microwave performance of reactive-ion-etched devices and wet-etched devices were identical. However, for these short-gate-length devices a threshold voltage standard deviation of 30 mV was obtained for the reactive-ion-etched devices as compared to 230 mV for the wet-etched devices.

I. INTRODUCTION

Reactive ion etching (RIE) has become important in the fabrication of lasers, high-speed GaAs devices, and optoelectronic integrated circuits. Equietch rates for GaAs and AlGaAs are required for the fabrication of laser facets, whereas for the fabrication of modulation-doped field-effect transistors (MODFETs), the selective removal of GaAs from underlying thin AlGaAs layers is important. Prior approaches for selective etching relied mainly on CCl_2F_2-based plasmas.[1-5] This approach has been used to fabricate MODFETs with gate lengths in the 1 μm regime.[1,4,6] It has been shown that this method yields better uniformity in the dc characteristics of the devices which is important for the realization of high-performance integrated circuits. Etch selectivity has been attributed to the conversion of Al to nonvolatile AlF_3 by fluorine containing gas species.[3] A by-product of etching in CCl_2F_2-based plasma, however, is the formation of a thin layer of polymer which must be removed to obtain useful metal–semiconductor interfaces.[5] This can be avoided by using gas a chemistry which does not contain fluorocarbons. Furthermore, by using separate chlorine and fluorine containing process gases, the selectivity can be controlled by varying the gas ratios. Such a mixture of $SiCl_4$ and SF_6 has been used to selectively etch quarter-micron gate MODFET's, although no device results were presented.[7] In this paper, we present our results on the selective reactive ion etching of GaAs on AlGaAs in $SiCl_4/SiF_4$ plasmas. This process has been applied to the fabrication of 0.2-μm gate-length GaAs/AlGaAs/InGaAs pseudomorphic MODFETs. The influence of RIE on the dc and microwave device properties will be discussed and the results compared to wet-etched MODFET's

II. EXPERIMENTAL PROCEDURE

The samples used in this study were grown by molecular beam epitaxy on semi-insulating (100) GaAs. Etch rates and selectivity were measured on structures with a 200 nm undoped GaAs cap on a 5 or 15 nm $Al_{0.3}Ga_{0.7}As$ etch-stop layer on a 1 μm undoped GaAs buffer layer. Saturation current and Hall mobility measurements were made on a GaAs/AlGaAs MODFET structure consisting of a 20 nm n^+-GaAs (5×10^{18} cm^{-3}) cap, a 35 nm n^+-$Al_{0.3}Ga_{0.7}As$ (2×10^{18} cm^{-3}) donor layer, a 8 nm undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, and a 1 μm undoped GaAs buffer layer. Finally, device results are from a pseudomorphic MODFET with a 10 nm n-GaAs (1×10^{18} cm^{-3}) cap, a 40 nm Si-doped $Al_{0.25}Ga_{0.75}As$ (2×10^{18} cm^{-3}) donor layer, a 4 nm undoped $Al_{0.25}Ga_{0.75}As$ spacer layer, a 15 nm undoped $In_{0.15}Ga_{0.85}As$ channel layer, and a 1 μm undoped GaAs buffer layer. The pseudomorphic MODFET had a 77 K sheet carrier concentration and mobility of 1.9×10^{12} cm^{-2} and 17 800 cm^2/V s, respectively.

Reactive ion etching was performed in a Plasma Technology RIE system with a 30 cm diam. chamber. A load-locked nitrogen-purged glove-box is fitted on top of the chamber to prevent atmospheric contaminants from reacting with residue gases. The 17 cm diam cathode is made of alumina coated aluminum, rf powered at 13.56 MHz, and is covered with a $\frac{1}{4}$-in.-thick quartz plate. The cathode and anode are spaced 5 cm apart and water cooled to maintain a nominal temperature of 24 °C. For all experiments, the chamber is initially pumped to about 100 mTorr by a Roots blower/mechanical pump combination. A turbomolecular pump is then used to pump the system to a base pressure of 5×10^{-6} Torr. During etching, only the Roots blower is used to pump process gases.

A $SiCl_4/SiF_4$ gas ratio of 3:7 (10 sccm total) and a chamber pressure of 30 mTorr was used for all experiments. Power levels of 10, 25, and 50 W corresponding to self-bias voltages of -70, -120, and -180 V, respectively, were used. The lower power levels are especially important for MODFET gate recess etching because the thin AlGaAs barrier and underlying channel are very susceptible to ion damage.[8,9] No detectable ion damage was reported when a CCl_2F_2/BCl_3 selective etch was used at -80 V self-bias.[9] However, when CCl_2F_2/He at -85 V self-bias was used, Schottky diodes showed increased ideality factors, reverse saturation currents, and depletion widths compared to the bulk values.[8] The damage at this low energy in the latter case was attributed to light helium ions, and it was postulated that RIE damage could be minimized by using heavier ion species.[8] The $SiCl_4/SiF_4$ gas chemistry reported here should therefore minimize such damage.

III. RESULTS

A. Etch characteristics

The two etch selectivity test samples with 5 and 15 nm $Al_{0.3}Ga_{0.7}As$ barrier layers and a bulk GaAs test sample were etched for increasing times at 10 W (0.044 W/cm^2) and 50 W (0.22 W/cm^2). Figure 1(a) shows the results obtained at 10 W, and it demonstrates the markedly different etch rates of the thin AlGaAs layer compared to GaAs. An AlGaAs etch rate of 1.1 nm/min is indicated from the flat portion of the graph where it took about 275 s to etch through the 5 nm layer. Given a GaAs etch rate of 390 nm/min, the selectivity ratio of this etch is approximately 350 to 1. Such a selectivity ratio is adequate for the MODFET gate recess and is comparable to those obtained with other selective etch gas chemistries.[5,7] At 50 W power an AlGaAs etch rate of between 4.2 and 4.8 nm/min is obtained from the 5 and 15 nm barrier layers, respectively. The GaAs etch rate has increased to approximately 540 nm/min, giving a GaAs to AlGaAs selectivity ratio of about 120. The decrease in selectivity at this higher power is attributed to an increase in the nonselective physical etching component which acts to remove the nonvolatile AlF_3. An etch initiation delay time of about 20 and 12 s at 10 and 50 W, respectively, are observed in Fig. 1, which is due to the native oxide present on the layers.[1]

The effect of $SiCl_4/SiF_4$ selective etching on the electrical properties of GaAs/AlGaAs MODFET material was assessed by measuring the saturation current as a function of etch time and power. Figure 2 shows the effect of etching on the saturation current measured between two 100 μm wide contacts separated by a 3 μm gap. A control sample was etched in a selective wet etch (selectivity about 20 to 1) with a GaAs etch rate of about 17 nm/min. As expected, the dry etched samples show a rapid decrease in current as the highly doped GaAs cap layer is removed and then reaches a saturation level when the AlGaAs layer is reached. This saturation current level is 10% lower at 10 W as compared to the wet-etched sample with the cap removed (about 70 s) and decreases by about 20% as the RIE power is increased from 10 to 50 W. Even at these relatively low-power levels, ion damage may be the cause of this decrease. The damage, however, does not appear to increase with overetching for the 10 and 25 W samples where even an 800% overetch resulted in

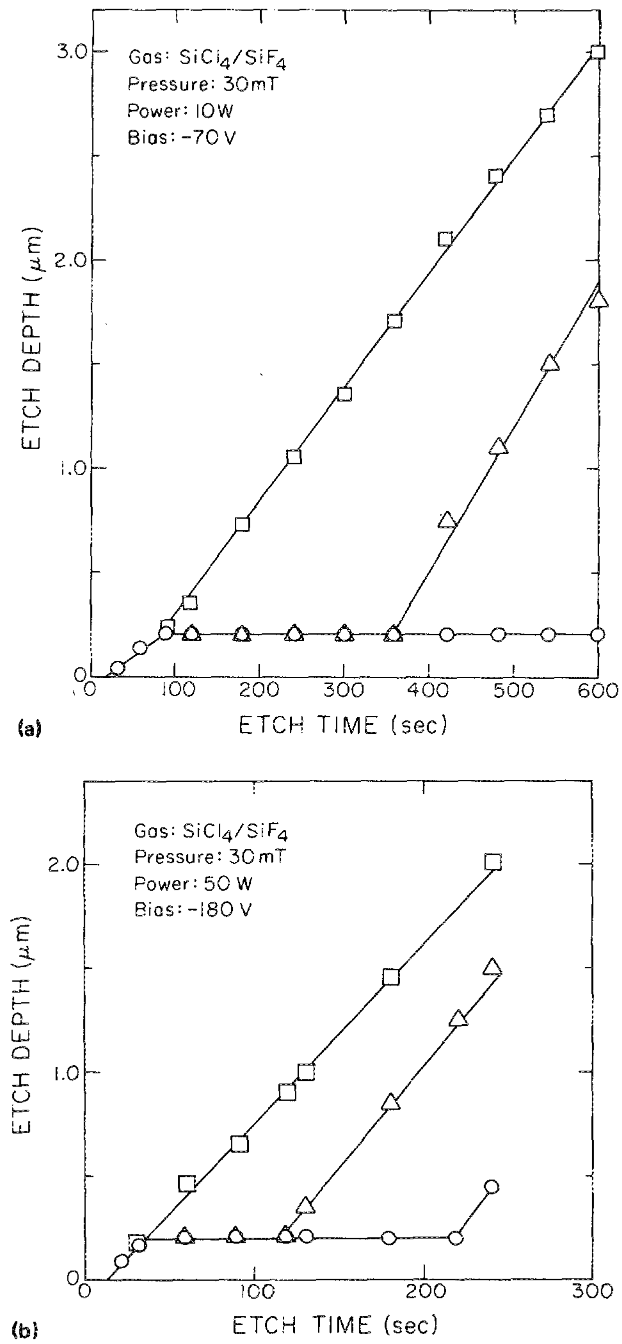

FIG. 1. Etch depth versus time for (□) GaAs, (○) 200 nm GaAs/15 nm $Al_{0.3}Ga_{0.7}As$, and (△) 200 nm GaAs/5 nm $Al_{0.3}Ga_{0.7}As$ at (a) 10 W and (b) 50 W. Etch selectivity ratios of 350 and 120 are observed at 10 and 50 W, respectively.

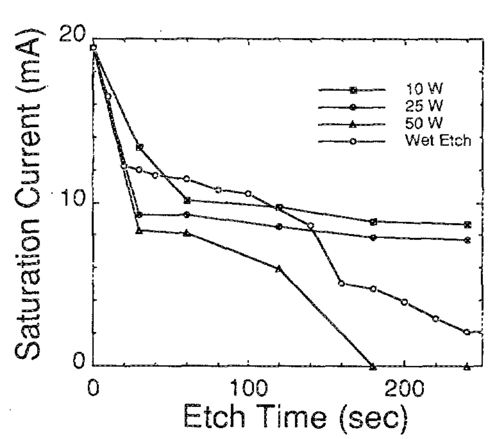

FIG. 2. Plot of MODFET saturation current as a function of etch time for various RIE power levels. A chemically wet-etched control is also included for comparison. Current is measured on a GaAs/AlGaAs MODFET structure between two 100 μm contacts separated by a 3 μm gap at 3 V.

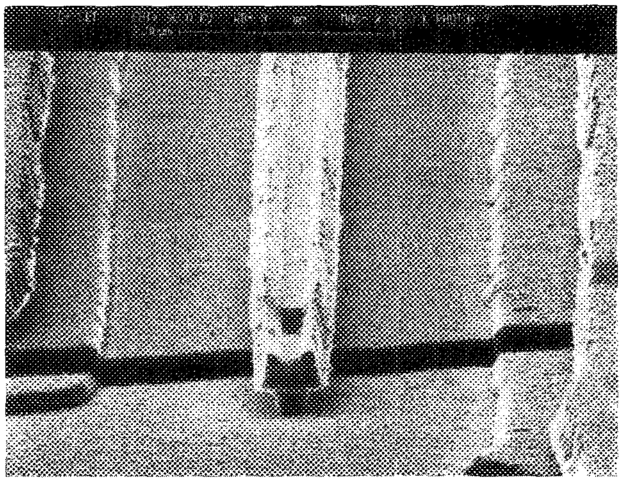

FIG. 3. SEM micrograph of a typical 0.2 μm T-gate MODFET.

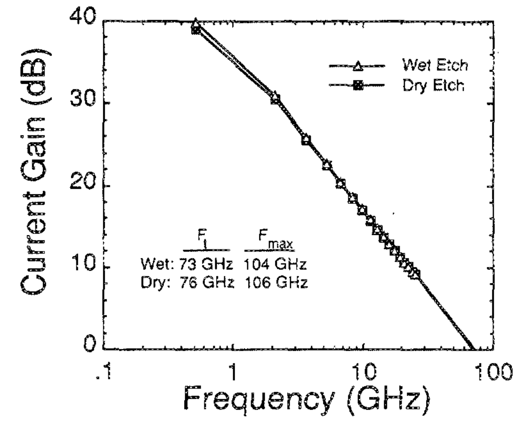

FIG. 5. Short-circuit current gain $|h_{21}|$ vs frequency for a typical dry-etched and wet-etched 0.2×100 μm pseudomorphic MODFET.

a minimal current decrease. The rapid decrease in the 50 W sample is caused by the etching of the AlGaAs layer due to the poorer selectivity of the etch at this power and not due to increased damage. Hall measurements performed on samples which had their GaAs caps removed by etching 30 s at 50 W and by selective wet chemical etching show nearly identical 77 K mobilities of 113 000 and 110 000 cm^2/V s, and sheet carrier concentrations of 5.6×10^{11} and 5.5×10^{11} cm^{-2}, respectively. No sign of ion damage is observed in this sample for such a short dry etch time; however, preliminary Hall results indicate a 40% drop in mobility and a 30% lower sheet carrier concentration after an additional 30 s of etching. This result is consistent with the saturation current data and is currently being investigated.

B. MODFET characteristics

Pseudomorphic GaAs/AlGaAs/InGaAs MODFETs were fabricated with 0.2 μm T-gates (see Fig. 3) using electron-beam lithography on a Cambridge 6.5 EBMF lithography system. Device fabrication details are described elsewhere.[10] Consecutive gate definition, recess, and metallization steps were performed on the same wafer using dry and wet selective etching. The dry recess etch was performed for 90 s in a 3:7 $SiCl_4/SiF_4$ plasma at 30 mTorr and 10 W (0.044 W/cm^2) of power. The wet etch was performed in a *p*H-adjusted H_2O_2/NH_4OH selective etch until the gateless saturation current equaled the dry-etched sample. Samples were dipped in a 1:2 $HCl:H_2O$ solution just prior to Ti/Au metallization. Devices within a 3×4 mm area (~ 70 devices) were measured for threshold voltages and transconductances. The average transconductance for the wet and dry devices is 360 and 380 mS/mm, respectively, the difference being due perhaps to layer nonuniformity or slight process variations. Figure 4 shows a histogram of threshold voltage for the wet and dry devices. The mean threshold voltages for these depletion-mode MODFET's are -1.23 and -1.32 V for the wet and dry etch, respectively. The standard deviation of the wet-etched devices is 230 mV, whereas the dry-etched devices show a significantly lower value of only 30 mV. This threshold voltage standard deviation, while not suitable for large-scale integrated circuits, is encouraging in light of the short gate lengths of the devices.

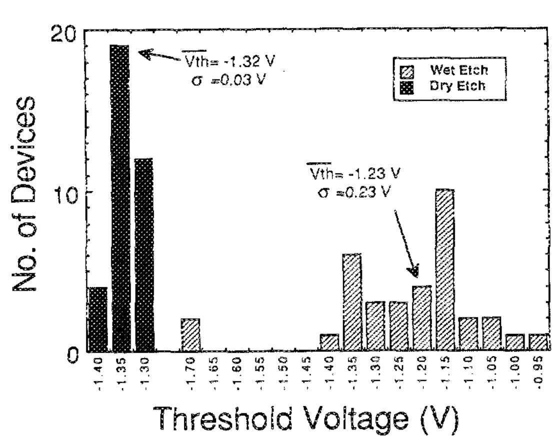

FIG. 4. Histogram of threshold voltages for pseudomorphic GaAs/AlGaAs/InGaAs MODFET's with 0.2 μm gate lengths.

To further characterize the effect of dry etching, a representative number of both dry- and wet-etched MODFET's with similar threshold voltages were on-wafer microwave tested.[10] Figure 5 shows the current-gain $|h_{21}|$ versus frequency for a typical wet- and dry-etched 0.2 μm T-gate MODFET. Both devices are virtually identical with unity current-gain cutoff frequencies f_t of about 75 GHz and a unilateral power-gain cutoff frequency f_{max} of 105 GHz. These microwave results provide further evidence that the low-power $SiCl_4/SiF_4$ selective etch does not significantly affect the MODFET device performance.

IV. CONCLUSIONS

In conclusion, we have characterized a new selective etch for GaAs over AlGaAs based on $SiCl_4$ and SiF_4 gas chemistry. A selectivity of 350 to 1 has been obtained at low power (10 W, -70 V) and pressure (30 mTorr). A small decrease in the saturation current of MODFET structures as compared to wet-etched samples was observed and is attributed to ion damage of the AlGaAs layer. The decrease in current, however, is only about 10% at 10 W of power and does not appear to worsen with overetching. This etch has been used for the gate recess etch of 0.2 μm T-gate pseudomorphic MODFET's. Dry-etched MODFET's exhibit identical dc and microwave characteristics to wet etched devices and with a threshold voltage uniformity that is almost eight times better than the wet-etched devices.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the technical contributions of John Hughes, Hong Chang, and Mike Gribbons. This work was partially supported by NSF Grant CDR 85-22666.

[a] Center for Compound Semiconductor Microelectronics, Coordinated Science Laboratory.

[1] K. Hikosaka, T. Mimura, and K. Joshin, Jpn. J. Appl. Phys. **20**, L847 (1981).
[2] A. Seabaugh, J. Vac. Sci. Technol. B **6**, 77 (1988).
[3] K. L. Seaward, N. J. Moll, and W. F. Stickle, J. Vac. Sci. Technol. B **6**, 1645 (1988).
[4] J. Vatus, J. Chevrier, P. Delescluse, and J.-F. Rochette, IEEE Trans. Electron Devices **ED-33**, 934 (1986).
[5] C. M. Knoedler and T. F. Kuech, J. Vac. Sci. Technol. B **4**, 1233 (1986).
[6] B. J. F. Lin, S. Kofol, C. Kocot, H. Luechinger, J. N. Miller, D. Mars, B. White, and E. Littau, IEEE GaAs IC Symposium, 1986, 511.
[7] S. Salimian, C. B. Cooper III, R. Norton, and J. Bacon, Appl. Phys. Lett. **51**, 1083 (1987).
[8] C. M. Knoedler, L. Osterling, and H. Shtrikman, J. Vac. Sci. Technol. B **6**, 1573 (1988).
[9] H. F. Wong, D. L. Green, T. Y. Liu, D. G. Lishan, M. Bellis, E. L. Hu, P. M. Petroff, P. O. Holtz, and J. L. Merz, J. Vac. Sci. Technol. B **6**, 1906 (1988).
[10] A. A. Ketterson, J. Laskar, T. L. Brock, I. Adesida, J. Kolodzey, O. A. Aina, and H. Hier, IEEE Trans. Electron Devices (in press).