CH4/H2/Ar ECR plasma etching for AlGaAs/InGaAs/GaAs pseudomorphic HFETs

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was performed by connecting the pulse output of the inverter to the substrate removal process. Digital modulation of this VCSEL was successful in bonding the wire to the laser top contact without any damage to the thin film.

The horizontal scale is 1 μm/div. The upper trace is the input pulse to the CMOS and the vertical scale is 2 V/div. The lower trace is the laser output measured on a photodetector and the vertical scale is 0.5 V/div.

The L-I and V-I characteristics of the laser are shown in Fig. 2. These characteristics were unchanged from those obtained before the substrate removal process. Digital modulation of this VCSEL was performed by connecting the pulse output of the inverter to the laser top using probes. Traditional wire-bonding techniques were unsuccessful in bonding the wire to the laser top contact without any damage to the thin film. Fig. 3 shows the inversion obtained when using a 5 V, 1 μA pulse input on the CMOS, with P = 5 V on the CMOS. The speed of operation was limited by the probes and also by the carrier diffusion time in the large area detector that was used to measure the optical output of the laser. The slow roll-off in the optical output did not change with either the pulse amplitude or the duty cycle of the pulse, indicating that this was not due to an inherent speed limitation in the laser.

In conclusion, we have shown for the first time the direct integration of a GaAs VCSEL onto a processed CMOS chip with the substrate removal process with no loss in laser performance. Future work is planned to integrate the lasers with interconnect transmission lines.

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CH₄/H₂/Ar ECR plasma etching for AlGaAs/InGaAs/GaAs pseudomorphic HFETs

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Indexing terms: Plasma etching, Semiconductor technology

The effect of electron cyclotron resonance (ECR) plasma etching using CH₄/H₂/Ar on Si-doped pseudomorphic AlGaAs/InGaAs/ GaAs heterostructures and field-effect transistors has been investigated. Hall measurements were performed as a function of temperature (T = 300K) and the Hall mobility and the sheet density compared to wet chemically etched reference samples. Direct current and high-frequency measurements were performed on dry gas-recessed PMHFETs.

Introduction: Dry etching offers many advantages over wet etching in III-V semiconductor technology because of their better uniformity, reproducibility and compatibility with cluster tool systems. In a few applications ECR-based plasma processes have proven to induce less damage compared to conventional reactive ion etching (RIE) [1, 2].

In this Letter the influence of CH₄/H₂/Ar ECR plasma etching on the transport properties of pseudomorphic heterostructures is investigated by temperature-dependent Hall measurements as a function of the additional process bias. The Hall mobility and the sheet density of pseudomorphic heterostructures as functions of
annealing temperature are compared to wet etched reference samples. Annealing is necessary to recover the passivation of the Si donors due to the formation of Si-H complexes [3]. Remarkable recovery of the Hall mobility was observed if an additional Si-doped layer was incorporated. In the literature, identical experiments have been reported with CH₃/Ar and chlorine-based RIE processes [4–7]. Finally, the results obtained on dry recessed pseudomorphic HFETs will be discussed.

Experiment: Two AlGaAs/InGaAs/AlAs pseudomorphic heterostructures have been grown by molecular beam epitaxy (MBE). The first structure (W540) consists of an undoped GaAs buffer layer, a 15nm undoped In₀.₃Ga₀.₇As channel, a 5nm undoped Al₀.₃Ga₀.₇As spacer, a 30nm 10⁹/cm³ silicon-doped Al₀.₃Ga₀.₇As donor layer and a 40nm highly doped (2 × 10⁹/cm³) GaAs cap layer. In the second structure (W483) a 5 × 10⁹/cm³ silicon-doped layer was additionally incorporated on top of the AlGaAs spacer. After defining the Hall bar by optical lithography and wet etching, and GaNAs ohmic contact evaporation and annealing, the GaAs cap layer was removed at a temperature at different process biases (~20, ~40, ~80V). Hall measurements were performed as a function of temperature (5–300K) and the results were compared to wet chemically etched reference structures. The plasma process conditions have already been reported [2]. The reference structure without a δ-doped layer showed a Hall mobility of 3.1 × 10⁶/cm²Vs and a sheet density of 1.1 × 10¹⁵/cm² at a temperature of 6.4K. After removing the GaAs cap layer by the plasma no Hall measurements could be performed as a function of the measurement and annealing temperature, even after annealing at 425°C for 4 min. This was independent of the plasma energy used.

The experiments suggest that enormous damage is created within the structure as a consequence of the methane, hydrogen argon ECR plasma process. Identical observations have been made in GaNAs transistors fabricated later. With the additional δ-doped layer the structures could be measured.

Table 1: Recovery of Hall mobility and sheet density of pseudomorphic heterostructure with a δ-doped layer after annealing for 1 min at 425°C compared to a wet chemically etched reference Hall bar.

<table>
<thead>
<tr>
<th>Process Bias</th>
<th>Sheet Density (10¹²/cm²)</th>
<th>Hall Mobility (10⁴/cm²Vs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20V</td>
<td>1.72</td>
<td>2.49</td>
</tr>
<tr>
<td>-40V</td>
<td>1.60</td>
<td>2.52</td>
</tr>
<tr>
<td>-80V</td>
<td>1.62</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Fig. 1: Recovery of sheet density as a function of annealing and measurement temperature of a pseudomorphic heterostructure.

Table 2 lists, from the DC and microwave measurements, the extracted maximal transconductance gₑ, the output conductance gₒ, the drain-source saturation current Iₛ, the threshold voltage Vₑ, the frequency of unity current gain fₑ, and the maximum frequency of oscillation fₒ. Although the DC characteristics improve, a slight degradation is observed in the high-frequency parameters. However, to obtain these results a few annealing steps at a temperature of 400°C for 1 min had to be introduced during the gate recess. By this alternating process sequence the electrical activity of the silicon donor atoms was restored and a silicon buffer layer was present to act, in an identical way to the Si δ-doped layer, as a shield for the CH₃/H₂:Ar ECR plasma. It was observed that without these intermediate annealing steps the plasma etching was deleterious for the structure.

After etching 40nm of the 70nm-thick GaAs cap layer, little current remained, even after annealing for a few minutes at 400°C. We suggest that the remaining current flows through the cap layer and that a parallel MESFET is measured with transconductances of 20mS/mm and a fₒ of 17GHz. The other part of the structure is damaged, as also observed in the heterostructures. On the other structure (W540) no intermediate annealing steps were performed during the gate recess. Results identical to those listed in Table 2 are obtained.
Conclusions: It has been shown that an additional silicon 6-doped layer in AIGaAs/InGaAs/GaAs behaves as a shield or buffer for damage introduced by CHJ/H, plasma etching. Identical behavior was observed in transistor fabrication, where intermediate annealing steps were necessary to restore the activity of the donors to act as a shield. By direct current and high-frequency measurements on dry recessed pseudomorphic HETs, good performance was obtained in comparison to wet chemical processed transistors.

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References

**Hydrogen incorporation in GaN, AlN, and InN during Cl2/CHJ/D2/Ar ECR plasma etching**


Hydrogen concentrations up to >10^18cm^-3 in GaN and AlN and >10^17cm^-3 in InN are found to be incorporated during ECR plasma etching in Cl2/CHJ/D2/Ar at 170°C. Even very short duration (10s) etch treatments produce hydrogen incorporation depths >0.2μm ahead of the etch front, and may lead to electrical passivation effects within this region. Post-etch annealing at 450-500°C restores the initial conductivity.

Unintentional incorporation of hydrogen during crystal growth or device processing is of major concern in both Si and III-V semiconductors because of near-surface dopant passivation and device gain instability due to field-induced debonding of hydrogen from neutral dopant-hydrogen complexes [1, 2]. Hydrogen plays an especially important role in the III-V nitride materials currently of interest for use in blue/UV LEDs and diode lasers. The realization of p-type GaN occurred only after Mg-doped layers grown by metal organic chemical vapour deposition (MOCVD) were subsequently treated by e-beam irradiation or thermal annealing at -700°C to break-up neutral Mg-H complexes [3, 4]. We have previously reported that GaN, AlN and InN samples deliberately exposed to H, plasma for 30min at 250-400°C contain concentrations of hydrogen >10^18cm^-3 throughout a ~1μm thick film [5]. This raises the question of what will happen during device fabrication steps such as CVD of dielectric films using SiH4 or dry etching with CHJ4-based plasma chemistries.

In this Letter we report the unintentional incorporation of hydrogen into the binary nitrides during electron cyclotron resonance (ECR) plasma etching in Cl2/CHJ/D2/Ar at 170°C.

Deuterium was substituted for hydrogen to allow high sensitivity detection by secondary ion mass spectrometry (SIMS). Dry etching of nitrides by conventional reactive ion etching is relatively slow (~500Å/min) even under high cathode self-bias conditions. Much higher rates (up to 5000Å/min) have been observed with ECR discharges in which the ion densities are one to two orders of magnitude larger than in RIE plasmas [6]. In addition, a slightly elevated substrate temperature (~150°C) is desirable to enhance removal of etch products such as InCl, which are not particularly volatile at room temperature. The Cl2/CHJ/D2 plasma chemistry has proven effective in producing high etch rates for III-V semiconductors, including the nitrides [7]. The etching is smooth and anisotropic, but there has been no investigation of the incorporation of hydrogen during the plasma exposure.

The GaN, AlN, and InN were grown on p-type Si substrates by metal organic molecular beam epitaxy (MOMBE) using ECR plasma generated nitrogen and the group III sources trimethylalum- ium, triethylamine alane, and triethylsilane [8]. The layers are defective single crystals with 10^6 - 10^7 cm^-2 threading dislocations and stacking faults because of the lattice mismatched epitaxy. The samples were exposed to Cl2/CHJ/D2/Ar ECR discharges (flow rates of 10 sccm, 15 sccm, and 100sccm, respectively) for 40min at 170°C. The process pressure was 1 m torr, the microwave power 850W, and the RF power applied to the sample position was 150W, producing a DC bias of ~165V. The etch depth was ~400Å on the epilayer films, which were initially ~6000Å thick. The deuterium profiles were measured by SIMS using a CAMECA IMS 4f system with a Cs+ beam. The concentration scales were established by calibration with ion implanted standards and the depth scales obtained from stylus profilometry.

**Fig. 1** SIMS profile of deuterium in GaN/Si sample after short etch in Cl2/CHJ/D2/Ar ECR plasma

![Fig. 1 SIMS profile of deuterium in GaN/Si sample after short etch in Cl2/CHJ/D2/Ar ECR plasma](image-url)